THE UNIVERSITY OF HULL

Reconstructing Palaeoenvironments of the White Peak Region of Derbyshire, Northern England

being a Thesis submitted for the Degree of Doctor of Philosophy

in the University of Hull

by

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Declaration

I hereby declare that the work presented in this thesis is my own, except where otherwise stated, and that it has not been previously submitted in application for any other degree at any other educational institution in the United Kingdom or overseas.

Abstract

Sub-fossil pollen from Holocene tufa pool sediments is used to investigate middle – late Holocene environmental conditions in the White Peak region of the Derbyshire Peak District in northern England. The overall aim is to use pollen analysis to resolve the relative influence of climate and anthropogenic landscape disturbance on the cessation of tufa production at Lathkill Dale and Monsal Dale in the White Peak region of the Peak District using past vegetation cover as a proxy.

Modern White Peak pollen – vegetation relationships are examined to aid semi-quantitative interpretation of sub-fossil pollen assemblages. Moss-polsters and vegetation surveys incorporating novel methodologies are used to produce new Relative Pollen Productivity Estimates (RPPE) for 6 tree taxa, and new association indices for 16 herb taxa. RPPE's of Alnus, Fraxinus and Pinus were similar to those produced at other European sites; Betula values displaying similarity with other UK sites only. RPPE's for Fagus and Corylus were significantly lower than at other European sites.

Pollen taphonomy in woodland floor mosses in Derbyshire and East Yorkshire is investigated. Significant variations in tree pollen percentages within 1 metre quadrats of continuous moss cover are found, with micro-topography and aspect suggested as primary controls. Pollen taphonomy is investigated at the River Wye in Derbyshire to provide a context for the palaeoenvironmental study. The taphonomic model at the River Wye field site was found to be more similar to a small enclosed lake, contradicting the model proposed for open fluvial systems.

Sub-fossil pollen evidence suggests that climatic change exacerbated by catchment-scale anthropogenic deforestation was the dominant mechanism influencing tufa cessation at both the White Peak field sites. The Monsal Dale field site is suggested as being in the early stages of degradation, and the Lathkill Dale field site suggested as representing the terminal stage of the tufa system shut-down.

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I would like to acknowledge the help, support, patience and encouragement of my whole family during the completion of this research, and would particularly thank my father and mother who never stopped believing in me or my goals. This thesis is therefore dedicated to the memory of my mother Sylvia Kitcher who, although unable to see the work completed, has remained a constant companion throughout this journey.

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Chapter 1: Introduction

The Peak District region is located in the southern Pennines of Derbyshire and forms the dominant upland area in Central England. The Peak district consists of two contrasting geological sub – regions; the White Peak, which is a dissected Dinitian limestone plateau of 300 – 370 m OD with deeply incised dry and active river valleys, and the Dark Peak which is underlain by Namurian sandstone and mudstone. The Peak District region is rich in prehistoric archaeology, with the majority of Neolithic ritual monuments and Bronze Age barrows located in the White Peak (Barnatt & Smith, 1991). The White Peak experienced increasing levels of human settlement and population pressure from 6500 ka BP onward, representing the core prehistoric settlement location within the Peak District region due to the availability of more fertile soils on the upland ledges and in the river valleys (Barnatt & Smith, 1997). Increasing population, settlement and anthropogenic landscape management in the Peak District reflects the wider pan-Europe development of cultural landscapes which occurred from the early Neolithic onward across Northwest Europe (Berglund *et al.*, 1996), with step-wise cultural development often displaying a high degree of synchronicity with climatic shifts (Berglund, 2003).

Very little palaeoenvironmental data has been acquired on the vegetation history of the White Peak during the Holocene (Wiltshire & Edwards, 1993; Taylor *et al.*, 1994). Low pH anaerobic sediments conducive to the preservation of micro fossils such as pollen grains are rare on the White Peak limestone plateau due to the free-draining karst hydrology. This contrasts with the Millstone Grit of the adjacent Dark Peak, where extensive low pH peat sediment provides a more detailed record of past vegetation change (Hicks, 1971; 1972; Williams, 1985; Tallis & Switsur, 1990; Tallis, 1991). In limestone karst landscapes where there is a lack of traditional low Ph environments, sediments contained in fossil tufa systems can act as archives of palaeoclimatic and palaeoenvironmental data (Taylor *et al.* 1994; Pentecost, 2005) containing pollen, diatoms and algae (Capezzuoli *et al.*, 2014). Tufa is a freshwater continental carbonate (limestone) associated with ambient temperature calcium bicarbonate – rich ground waters (<20°C) in karst limestone regions (Pedley, 1990; Pentecost & Viles, 1994).

Tufa production in the White Peak was high during the Holocene Thermal Maximum between 7 – 4.2 ka BP, a period of warm and humid climate in the region (Ford & Pedley, 1996), when landscape – scale tufa systems formed in river valleys (Pedley *et al.*, 2000). From 5.5 ka BP onward a pan – European 'switch- off' of calcareous tufa systems occurred (Goudie, 1993), with cessation of barrage-building tufa systems in the White Peak estimated between 4.2 - 3.8 ka BP (Pedley *et al.*, 2000), which is synchronous with a period of increased settlement and anthropogenic disturbance in the Peak District landscape as agriculture developed (Bradley, 1984). Factors influencing cessation of European cool water tufa production are suggested as natural climatic changes affecting river discharges and water chemistry, anthropogenic landscape impacts such as woodland clearances and increased soil erosion and fluctuations in global CO_2 levels (Ford, 1989; Goudie, 1993; Preece & Day, 1994; Taylor *et al.*, 1994; Griffiths & Pedley, 1995; Taylor *et al.*, 1998; Banks *et al.*, 2011).

Neolithic and Bronze Age anthropogenic woodland clearances in the White Peak are associated with the termination of tufa production (Taylor *et al.*, 1994), with clearance events synchronous with Holocene barrage-tufa cessation (Pedley *et al.*, 2000). A close relationship between tufa production and climate effectively means that tufa acts as a proxy for water availability, meaning that climatic change may also have been a factor affecting both termination of tufa production (Pedley, 2009) and woodland decline. The Neolithic – early Bronze Age transition in northern Europe was a wet/cool period associated with increased deforestation and catchment soil erosion events (Berglund, 2003). The termination of tufa systems in the Peak District region may potentially be a product of anthropogenic impacts, climatically-driven, or a combination of these factors acting together. Pollen analysis can allow identification of factors driving change in past woodland composition (Shugart, 1984; Delcourt & Delcourt, 1991. To more clearly define factors contributing to the termination of Holocene White Peak tufa systems, pollen analysis is used as an environmental proxy to investigate catchment woodland composition prior to, during and after cessation of tufa production. Sub – samples of tufa pool sediment across 'switch – off' horizons identified by the transition from autochthonous carbonate sedimentation to clay-rich allochthonous sediments are used for pollen analysis. Percentage pollen diagrams are then produced, and changes in vegetation composition examined allowing hypotheses regarding ‘switch-off’ mechanisms to be developed.

Reconstruction of the extent of past vegetation at the Lathkill Dale and Monsal Dale field sites uses a process-model based approach (Prentice, 1985; Sugita, 1994). Modern day pollen - vegetation calibration data is used to provide relative pollen productivity estimates (RPPE’s) which can be used in the conversion of sub-fossil pollen percentages into vegetation, based on the pollen – vegetation ratio (RPPE) and environmental controls on individual taxa (Broström *et al*. 2004; Broström *et al*. 2008). Pollen-rich moss-polster surface samples and vegetation survey data are acquired at multiple upland valley woodland sites in the White Peak and in East Yorkshire in order to produce RPPE’s for vegetation reconstruction. Indicator taxa are often used to identify human impacts on past cultural landscapes i.e. (Behre, 1986; Dapples *et al*. 2002), and provide useful additional information on past landscape openness, edaphic conditions and anthropogenic landscape management (Mazier *et al*., 2006). Association tables of herb taxa indicator species are produced using vegetation survey data and pollen percentages.

Spatial bias in pollen deposition in modern – day surface samples has always been assumed (Räsänen *et al*. 2004; Broström *et al*. 2004), with post depositional transport of pollen grains influenced by water gravity flows and invertebrate movements within sediments (Irwin, 1989; Joosten & De Klerk, 2007). Spatial variations in pollen percentages across a sediment surface may bias RPPE datasets acquired from lake sediments and mosses (Broström *et al*. 2008) and in Tauber traps and Cundall traps (Pardoe *et al*. 2011). Pollen percentage variations within a small (<1m) defined area in terrestrial surface sediment were examined by a single study of alpine herb taxa (Pardoe, 1996); *no study has yet examined spatial variation in pollen percentages of woodland tree taxa in surface samples within a small (<1m) defined area*. Pollen taphonomy in woodland floor mosses is examined using moss sub - samples from within a 1m quadrat at valley-woodland field sites in Derbyshire and East Yorkshire to assess spatial variations in pollen percentages across a continuous moss surface.

Fluvial pollen taphonomy is examined at a field site on the River Wye in Derbyshire to provide a context for understanding spatial bias present in sub-fossil pollen percentages from the Lathkill and Monsal Dale Holocene barrage – tufa field sites, and to increase understanding of pollen dispersal and deposition models applicable to riverine pool sediment surface samples in karstic river catchments. Previous investigation of fluvial pollen taphonomy has examined patterns and processes in lakes with inflowing streams (Pennington, 1979; Holmes, 1994) and river catchments on non – karst geology (Brown *et al*. 2007), or has been based on flume tank experiments (Brush & Brush, 1972; Holmes, 1990). No examination of pollen taphonomy in karstic catchments has yet been carried out. Fluvial pollen taphonomy is investigated at the River Wye in Derbyshire in order to understand which pollen dispersal and deposition models are applicable to riverine pool sediment surface samples in karstic river catchments. Greater understanding of the degree of variation in pollen dispersal and deposition in modern – day karstic riverine environments will provide an additional interpretative aid in estimating past vegetation change at the Lathkill Dale and Monsal Dale tufa sites based on sub – fossil pollen percentage diagrams.

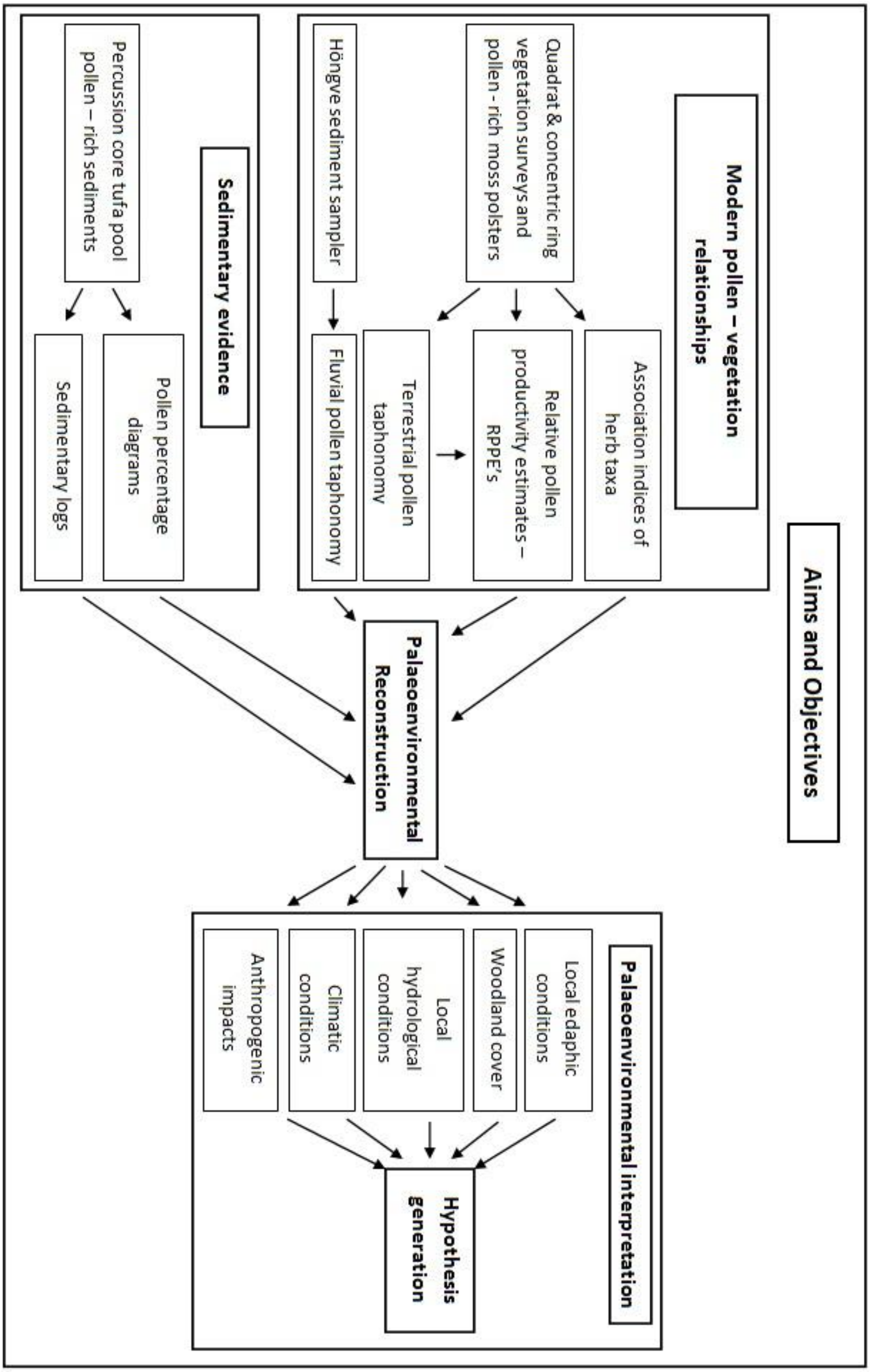
The primary aim of this thesis is:

1) To resolve the relative influences of climate and anthropogenic landscape impacts on the termination of Holocene tufa systems in the White Peak, Derbyshire, UK in the mid - late Holocene using sub-fossil pollen as an environmental proxy.

To address the primary aim, four sub aims are presented:

1) Acquire RPPE data for woodland tree taxa to enable semi-quantitative estimates of past vegetation based on fossil pollen percentage data from White Peak fossil tufa systems.
2) Acquire association indices data of herb indicator taxa to identify edaphic conditions and human impacts based on fossil pollen percentage data from White Peak fossil tufa systems.
3) Investigate terrestrial pollen taphonomy to examine spatial variation in pollen percentages which occur within a woodland floor moss of defined size.
4) Investigate fluvial pollen taphonomy in order to establish a taphonomic model for rivers on limestone karst geology.

Figure 1.1: Flow diagram describing the aims and objectives of the thesis



Chapter 2: Research Strategy

2.1. Studying long-term vegetation dynamics

The study of long term vegetation change can be approached in several ways: long-term monitoring, space-for-time substitution, historical research and palaeoecological approaches. Long-term vegetation monitoring records a series of repeated observations of permanent plots over an extended time period, and can provide insights into slow-scale vegetation change and the effects of stochastic events such as disturbance. This approach can however take many years before providing meaningful results (Peterken, 1996). With space-for-time substitution, an assumption is made that the spatial heterogeneity of successional stages of modern vegetation communities within a landscape accurately reflects a sequence of changes that would occur in the system following primary succession and/or disturbance (Delcourt & Delcourt, 1991). Pickett (1989) critiques this assumption, asserting that it is unrealistic to assume that sites of differing ages would have identical environments and ecological histories. Historical records (e.g. estate documents) can provide information on land usage on decadal to centennial scales, but often lack ecological detail as they were created for other purposes (Nielsen & Odgaard. 2004). Palaeoecological investigation can use pollen grains as a proxy in order to identify and examine episodes of past vegetation change, and identify if the observed changes are systematic, random or cyclic (Shugart, 1984), and is often the only method of acquiring data about past ecosystem composition and function (Birks, 1996). Hypotheses can then be generated regarding potential causal mechanisms responsible for the observed events in the local, extra-local or regional vegetation.

2.2. Why choose palaeoecological methods

Provided pollen-rich sediment has accumulated rapidly enough to record the effects of disturbance events (e.g. anthropogenic woodland clearance), and contains ecologically meaningful information (e.g. identifiable pollen grains) in sedimentary horizons which ideally allow the temporal sequence of change to be observed, it should be possible to make inferences about external processes such as anthropogenic clearance events or autogenic processes (Delcourt & Delcourt, 1991). Because pollen records vegetation in different ways, dependant on the size of sedimentary basin (e.g. forest hollow, small lake) and the type of sediment (e.g. sapropel peat, lake sediment), the palaeoecological approach can be used to select field sites that provide the most appropriate data to answer research questions (Jacobson & Bradshaw, 1981; Birks, 1986: Jackson, 1994). It was important for the purposes of this study to define the scale at which the ecological processes relevant to the research aim would have occurred (e.g. local & extra-local changes in forest composition, grassland development). This was to ensure as far as possible that patterns of vegetation change observed in the palaeoecological record would be relevant to the scale of processes under investigation.

2.3. Challenges in Palaeoecology

The main scientific challenge to the validity of palaeoecological research is that it is not possible to design a replicable ecological experiment. This is because the ecosystem being investigated may have developed under very different climatic and environmental conditions to those of the present day e.g. Mid-Holocene climatic optimum at 7000 BP (Delcourt & Delcourt, 1991); the 'experiment' has effectively already been run. Palaeoecological research can however seek evidence of events occurring temporally and spatially, and use these changes or events as 'past experiments' to test null hypotheses (Diamond, 1986). The sampling strategies available to the palaeoecologist are more restricted than those available to modern ecologists; this is because the palaeo-ecosystem is long dead, and research questions must be answered using proxies (e.g. pollen, diatoms etc.) which represent the palaeo-ecosystem. Proxy environmental indicators may have been altered through processes of diagenesis and transport (Birks & Birks, 1980), meaning that taphonomic processes are a fundamental consideration in proxy-based interpretation of past environments. In order to address this consideration, the taphonomy of pollen deposited in an active fluvial system are examined to provide a context for palaeoenvironmental

The interpretation of observed patterns of past biotic change can also be problematic, as it may be difficult to establish if change is driven by external e.g. climatic or anthropogenic, or autogenic e.g. successional processes within the ecosystem (Birks, 1986). Processes driving environmental, ecological and vegetation community change in the past e.g. fire, changing soil chemistry, climate change, cycles of succession or anthropogenic disturbance, are indicated by the resulting patterns or ecological 'products' of events that are registered in the sedimentary record e.g. a reduction in pollen signal from thermophilous woodland taxa, or vegetation changes due to soil podsolization. The necessity of linking causation mechanisms to effects (patterns/events) often requires the study of patterns and processes in modern-day ecosystems as an aid to understanding past changes, e.g. investigation of modern pollen dispersal and deposition processes, or how the relationship between pollen assemblages and scale of vegetation mosaics be applied as a modern analogue to past patterns or events (Delcourt & Delcourt, 1991). Similarly, landscape equifinality (i.e. similar pollen signals generated by ecologically distinct landscapes) also represents a potentially problematic issue when interpreting palaeo-pollen assemblages (Bunting & Middleton, 2009).

2.4. The approach used in this study

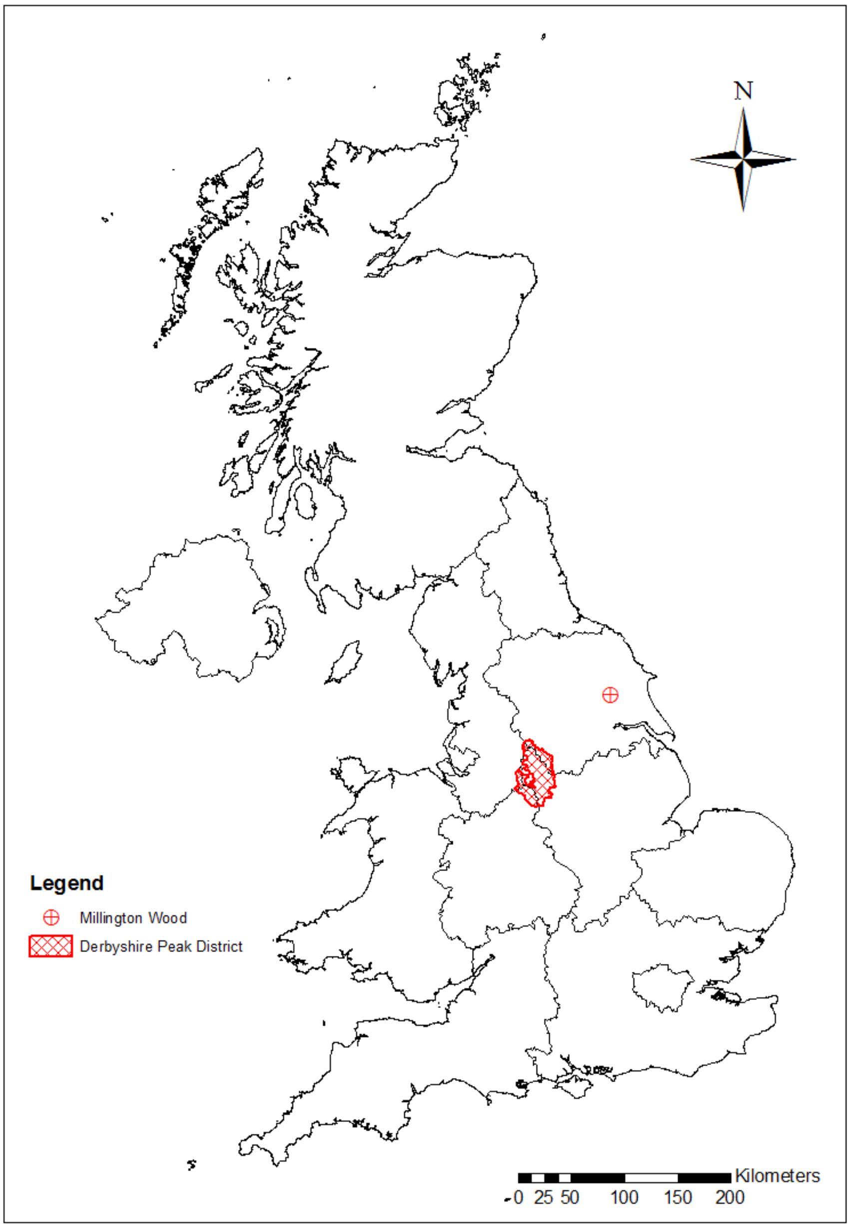
This study adopts a palaeoecological approach which uses pollen analysis to address the primary research aim specified in chapter 1. Sub-fossil pollen grains are contained in sapropel peats in buried Holocene tufa systems and can be used as a proxy for past vegetation change at Lathkill Dale and Monsal Dale during the temporal period encompassing tufa system shutdown (e.g. Mid-Late Holocene). This approach can allow the development of hypotheses regarding causal mechanisms (e.g. anthropogenic, climatic influencing any observed changes in vegetation composition at Lathkill Dale and Monsal Dale, allowing evaluation of the relative influence of these causal mechanisms on tufa system switch-off at both field sites. This study then uses process – based models of pollen dispersion and deposition in order to aid the interpretation of vegetation composition in the palaeoenvironment of Monsal Dale and Lathkill Dale during the middle – late Holocene. Step one aims to calibrate the dispersal and deposition model for key tree taxa (section 6.1 in chapter 6), and produce association indices for herb taxa (section 6.2 in chapter 6). Step two investigates poorly understood aspects of the taphonomy of pollen grains; taphonomy of pollen on the woodland floor is examined (section 6.3 in chapter 6), and then the taphonomy of pollen in small partially connected basins in narrow gorge floodplains is examined (section 6.4 in chapter 6). These steps are combined to assist the palaeoenvironmental study presented in section 6.5 of chapter 6.

Chapter 3: Study Region and Study Sites

The White Peak

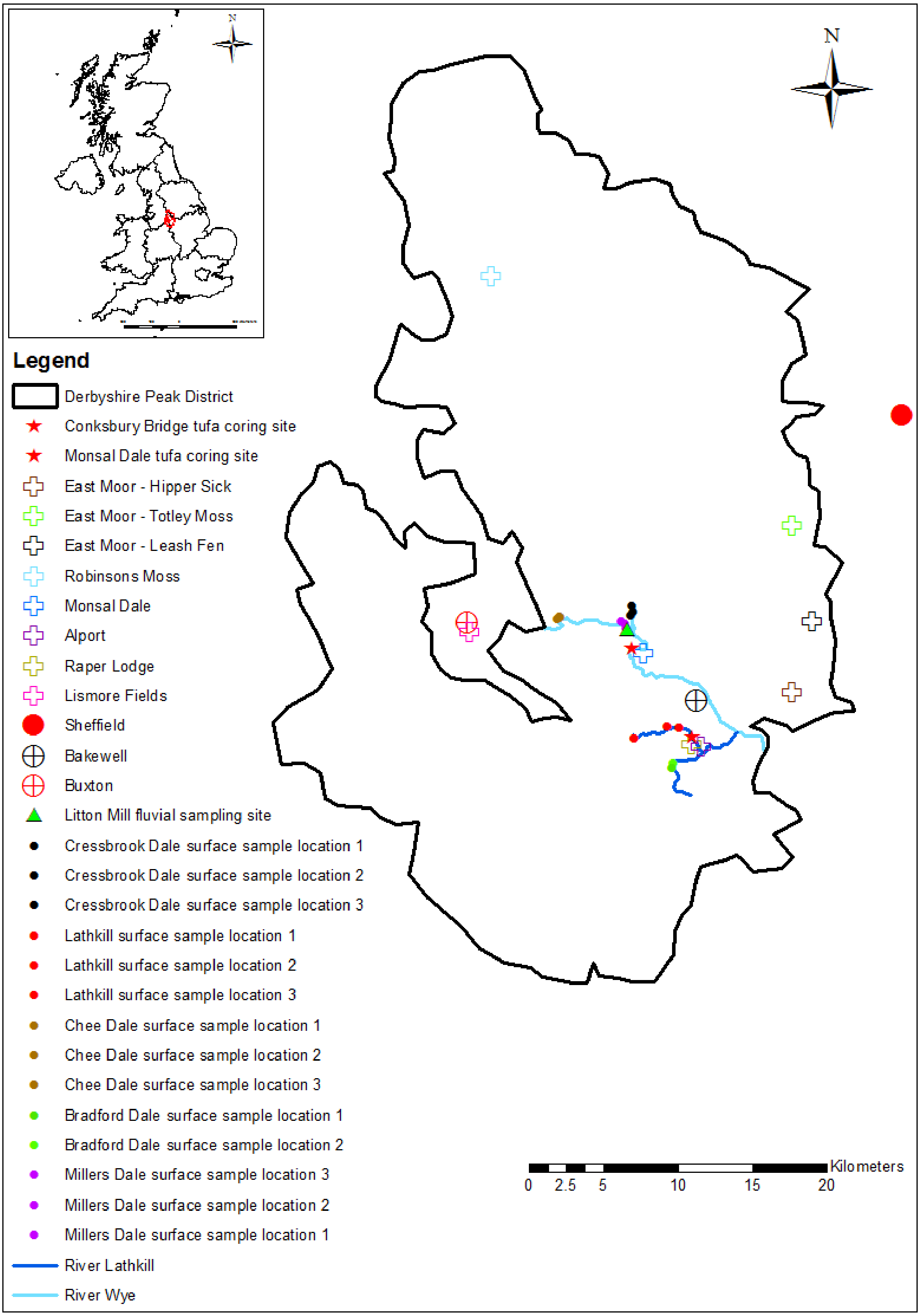
The Derbyshire Peak District is a range of mountains and hills separating North West England from North East England. The Peak District is divided into three sub-regions on the basis of geology, geomorphology and vegetation; the White Peak occupies a central position in the district, and is bordered by the Dark Peak to the north, west and east, and the South West Peak to the south. The relative position of the Peak District within the UK is displayed in figure 3.1 below, with study sites and other locations discussed in the text illustrated in figures 3.2 to 3.5 below.

Figure 3.1: Regional context of the Peak District within the UK.



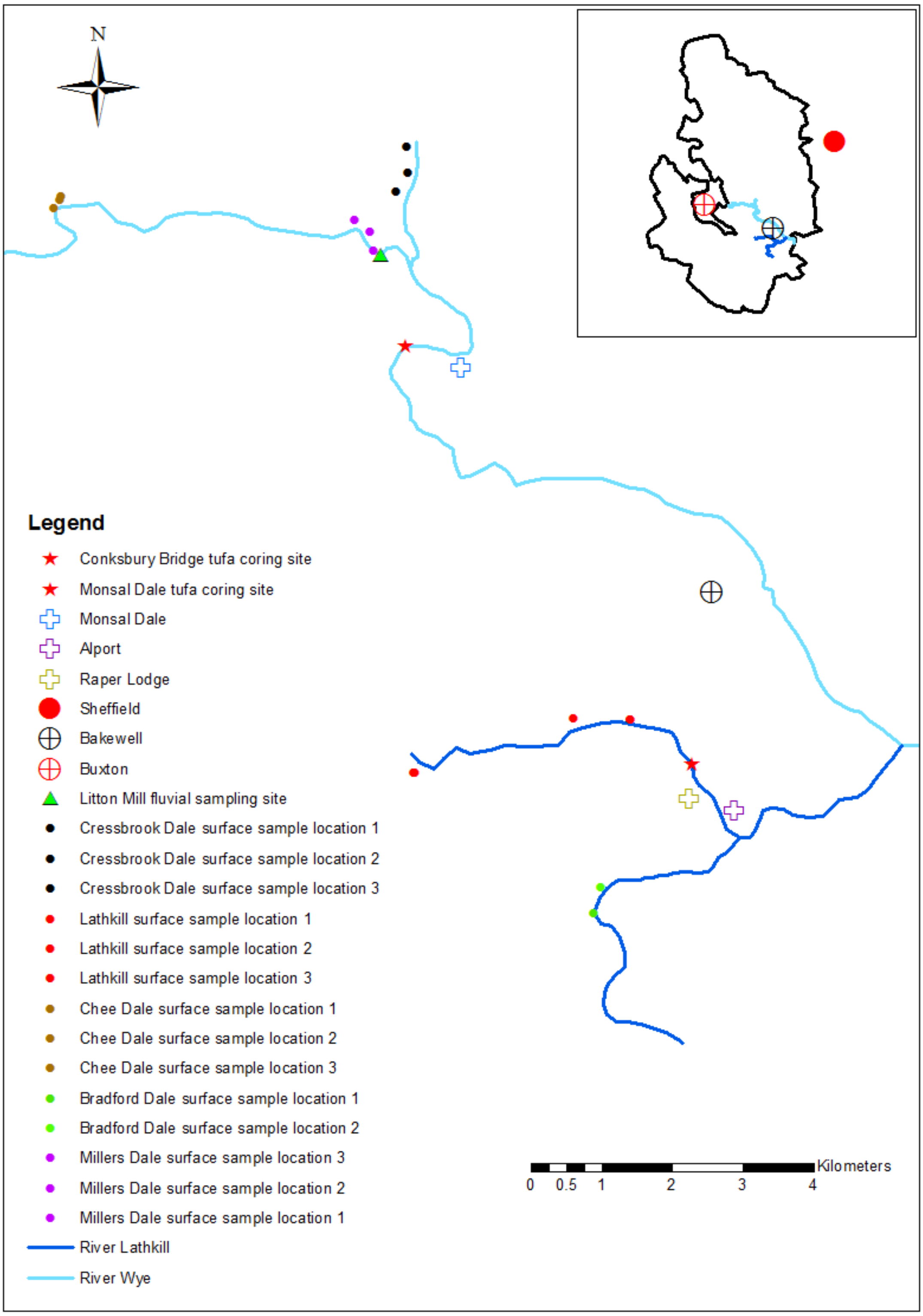
The sub - region used in this study is the White Peak, an upland limestone plateau characterised by long rolling limestone ridges which rise from shallow upland basins cut by deep dry valleys.

Figure 3.2: Peak District and study sites and locations discussed in the text.



Numerous rivers in deep – cut gorges drain to the south and east, and limestone shelves characterised by deep alkaline soils and spring lines are situated between the river valley bottoms and the limestone plateau. The White Peak has been a site of human settlement from the Mesolithic onward, and is an area of archaeological importance within the British Isles (Barnatt & Smith, 1991).

Figure 3.3: Location of study sites in the Wye and Lathkill valleys, Derbyshire



Millington Wood

Millington Wood is situated in Lily Dale adjacent to the village of Millington in the East Yorkshire Wolds the eastern coast of the England. The Yorkshire Wolds are an upland area of chalk hills and dales which are primarily used for agriculture. Millington Wood represents one of the few remaining fragments of ancient woodlands in the Wolds. The relative spatial location of Millington Wood and the study sites is illustrated in figures 3.4 and 3.5 below.

Figure 3.4: Location of Millington Wood study site relative to the Peak District

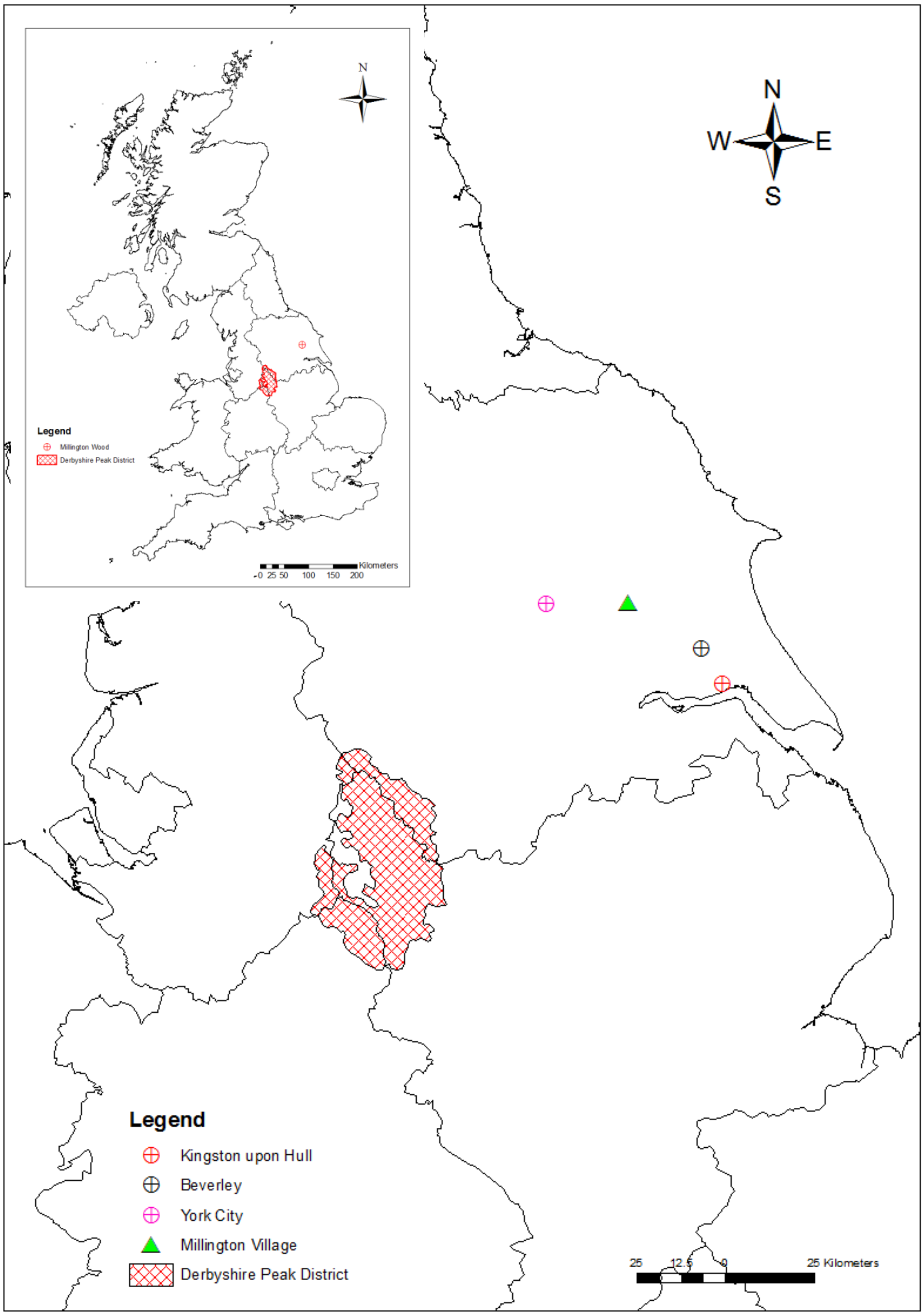
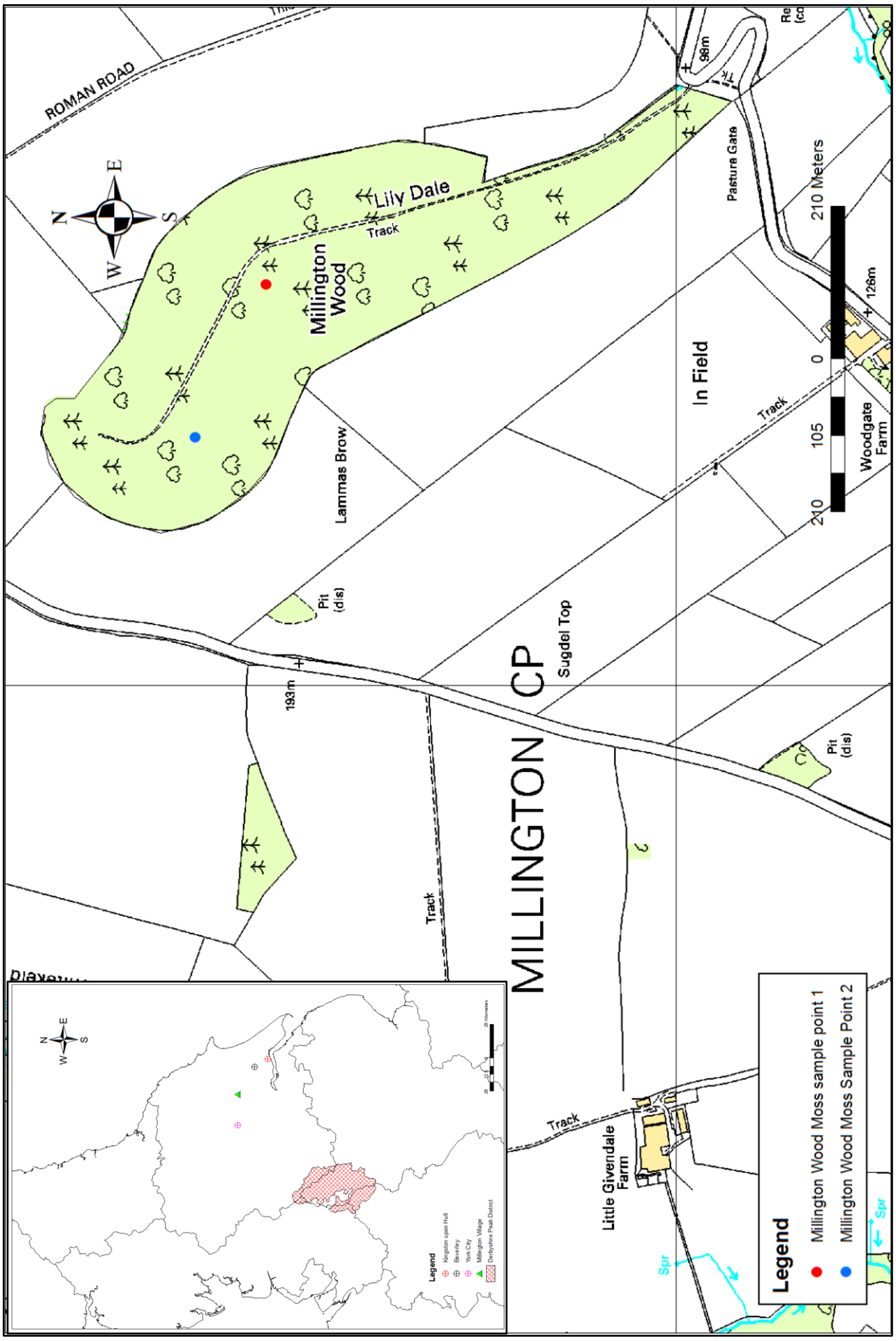


Figure 3.5: Location of sample locations 1 and 2 in Millington Wood, East Yorkshire; Map sourced from Digimap - 1: 10 000 OS Raster MasterMap.



3.1 Study field sites

Introduction

This study utilises multiple study sites in the White Peak in Derbyshire and two study sites at Millington Wood in Lily Dale, East Yorkshire; the regional and local context of these study sites is displayed in figures 3.2 – 3.5. Moss polster surface samples containing modern pollen are taken from Cressbrook Dale, Millars Dale, Lathkill Dale, Bradford Dale and Chee Dale in the White Peak, and from Millington Wood in East

Yorkshire. Fluvial sediments containing modern pollen are taken from a single study site at Litton Mill on the River Wye. Holocene sediments containing sub-fossil pollen are taken from a site in Monsal Dale adjacent to the River Wye; a sediment core taken from a site adjacent to the River Lathkill at Conksbury Bridge in Lathkill Dale as a part of a previous study is also utilised in this present study. These study sites are described further below, and photographs of the field sites are presented in chapter 5.

Cressbrook Dale

Three field sites were used for surface sampling at Cressbrook Dale, Derbyshire. Sample location 1 (BNG: 417066/373601) is situated on a valley-side slope within Acer – Fraxinus woodland and was used to provide moss polster sub-samples for the RPPE study and the terrestrial pollen taphonomy study. Sample location 2 (BNG: 417227/373859) is situated at the base of a valley-side slope with Acer – Fraxinus woodland and Corylus scrub adjacent to the sampling location and was used in the RPPE study. Sample location 3 (BNG: 417218/374237) is situated on the valley floor adjacent to a small tributary stream of the River Wye, with Acer – Fraxinus and Alnus wet woodland adjacent to the sampling site and was used in the RPPE study.

Chee Dale

Three field sites were used for surface sampling at Chee Dale, Derbyshire. Sample location 1 (BNG: 412311/373476) is situated at the top of a steep slope within Fraxinus – Acer woodland and was used to provide moss polster sub-samples for the RPPE study and the terrestrial pollen taphonomy study. Sample location 2 (BNG: 412221/373367) is situated at mid – slope on a steep valley side within Acer – Fraxinus dominated woodland and was used in the RPPE study. Sample location 3 (BNG: 412328/373531) is situated at the base of the valley slope adjacent to the River Wye, with Acer –Fraxinus and Alnus – Salix the dominant woodland type and was used in the RPPE study.

Millars Dale

Three field sites were used for surface sampling at Millars Dale, Derbyshire. Sample location 1 (BNG: 416750/372761) is situated within Acer – Fraxinus dominated woodland on a gentle slope at the edge of the plateau and was used to provides moss polsters for the RPPE study. Sample location 2 (BNG: 416689/373022) is situated within Fagus - Acer woodland on a steep slope at the edge of the plateau and was used to provide moss polsters for the RPPE study. Sample location 3 (BNG: 416484/373194) is situated on a gentle slope on the plateau within mixed woodland dominated by Fraxinus, Betula and Corylus, and was used to provide moss polsters for the RPPE study.

Lathkill Dale

Three field sites were used for surface sampling at Lathkill Dale, Derbyshire. Sample location 1 (BNG: 417329/365355) is situated within Fraxinus – Corylus – Crataegus woodland at the base of a plateau slope adjacent to the River Lathkill, and was used to provide moss polsters for the RPPE study. Sample location 2 (BNG: 419583/366116) is situated within Fraxinus – Acer – Corylus woodland at the base of a river valley slope adjacent to the River Lathkill, and was used to provide moss polsters for the RPPE study. Sample location 3 (BNG: 420384/366100) is situated within Fraxinus – Acer – Pinus woodland at mid – slope on a plateau ledge above the River Lathkill and was used to provide moss polsters for the RPPE study.

Bradford Dale

Two field sites were used for surface sampling at Bradford Dale, Derbyshire. Sample location 1 (BNG: 419872/363362) is situated within Fraxinus – Acer – Pinus – Tilia woodland at the base of a valley slope adjacent to the River Bradford, and was used to provide moss polsters for the RPPE study. Sample location 2 (BNG: 419964/363719) is situated within Acer – Fraxinus woodland at the middle part of a valley slope adjacent to the River Bradford, and was used to provide moss polster surface samples for the RPPE study.

Millington Wood

Two field sites were used for surface sampling at Millington Wood in East Yorkshire. Sample location 1 (BNG: 453564/483551) is situated in mixed Fraxinus – Acer – Pinus woodland at a mid – point on a gentle slope, and was used to provide moss polster sub-samples for the terrestrial pollen taphonomy study and the RPPE study. Sample location 2 (BNG: 453662/483341) is situated in Fagus – Fraxinus – Pinus woodland at a mid – point on a gentle slope, and was used to provide moss polster surface samples for the RPPE study.

Litton Mill

A single field site located near Litton Mill on the River Wye in Derbyshire was used to investigate fluvial pollen taphonomy (UK Grid Reference: SK 16004 73022). The field site is a pool of approximately 100 metres in length and 20 metres in width which is positioned on the inside of a bend in the river. The river Wye at this point is set in a deep valley of approximately 80 metres depth, with mixed Acer – Fraxinus woodland communities on the valley slopes, and grassland and Betula-Corylus – Crataegus scrub woodland on the adjacent plateau and valley tops.

Monsal Dale

A single field site in Monsal Dale adjacent to the River Wye was used to extract Holocene tufa pool sediments in order to investigate mid-late Holocene local and extra-local vegetation change at the period encompassing cessation of tufa production in Derbyshire during the late Holocene. The field site is set in a deep and wide valley surrounded by pasture grassland on the adjacent plateau and valley shelves, with Betula-Corylus-Crataegus scrub patches on the valley slopes.

Conksbury Bridge

A sediment core taken from a buried Holocene barrage tufa at a site adjacent to the River Lathkill at Conksbury Bridge in Lathkill Dale, Derbyshire as a part of previous sedimentological investigation by Pedley *et al*. (2000) was used in the present study. Lathkill Dale is a relatively deep and wide valley with extensive valley slope woodland communities of Acer and Fraxinus, and extensive areas of grassland on the plateau with Betula-Corylus-Crataegus scrub on the plateau edges and valley shelves.

3.2. Modern climate

The modern-day climate of the Peak District is influenced by the prevailing wind direction which is from the south and south west and the topography and altitude of this area of the southern Pennines which ranges from 100 – 623 m OD. Orographic lifting of weather systems as they encounter the Pennine uplands results in a cooler and wetter climate in the northern portion of the Dark Peak and on the South West Peak, with the south and east of the region experiencing a drier and warmer climate. The Peak District region as a whole experiences a significantly higher average rainfall than the UK national average, exceeding the national average in every month and the annual average by 175 mm. The influence of topography on the climate of the Peak District is exemplified by the annual rainfall, which at Buxton to the west of the White Peak is 1329 mm (Peak District National Park Authority, 2014). This contrasts with Sheffield to the east of the Peak District which has an annual average rainfall of 834 mm (Met Office, 2014).

Between 1981 and 2010 the overall average maximum temperature at Buxton in the western part of the Peak District was 11.5°C, with the highest temperatures being recorded in July and August. Annual average minimum temperature at Buxton was 5.3°C, with the lowest average temperatures recorded in January and February. These temperatures contrast with those on the eastern edge of the Peak District at Sheffield, where the average maximum temperature is 13.4^{0}C and the average minimum temperatures is 6.6^{0}C (Met Office, 2014). The average annual number of sunshine hours for the Peak District region is lower than the UK national average by 38 hours; however the summer months of July, August and September are slightly higher than the UK national average. The average annual number of sunshine hours at Buxton from 1981 - 2010 was 1334; this contrasts with an average annual number of sunshine hours of 1444 in Sheffield to the east for the same time period (Met Office, 2014).

3.3. Geology

The White Peak is situated in the Peak District region of the southern Pennines and forms part of the Derbyshire Dome. A geological map of the Peak District is presented in figure 3.4 below; the Dinitian limestone representing the White Peak, and the Millstone Grit Group representing the Dark Peak. This uplifted sedimentary sequence of Carboniferous sedimentary rocks, comprising older limestones and younger Millstone Grit sandstones and shales, was subjected to anti-clinal folding and subsequent faulting (Whittow, 1992) as a result of the Variscan orogeny during the

Palaeozoic Era. Subsequent erosion of the uplifted landscape has produced the limestone massif of the White Peak, a plateau of primarily Mountain Limestone which originally underlay the sandstones and shales prior to denudation.

Figure 3.4: Regional geology of the Peak District.

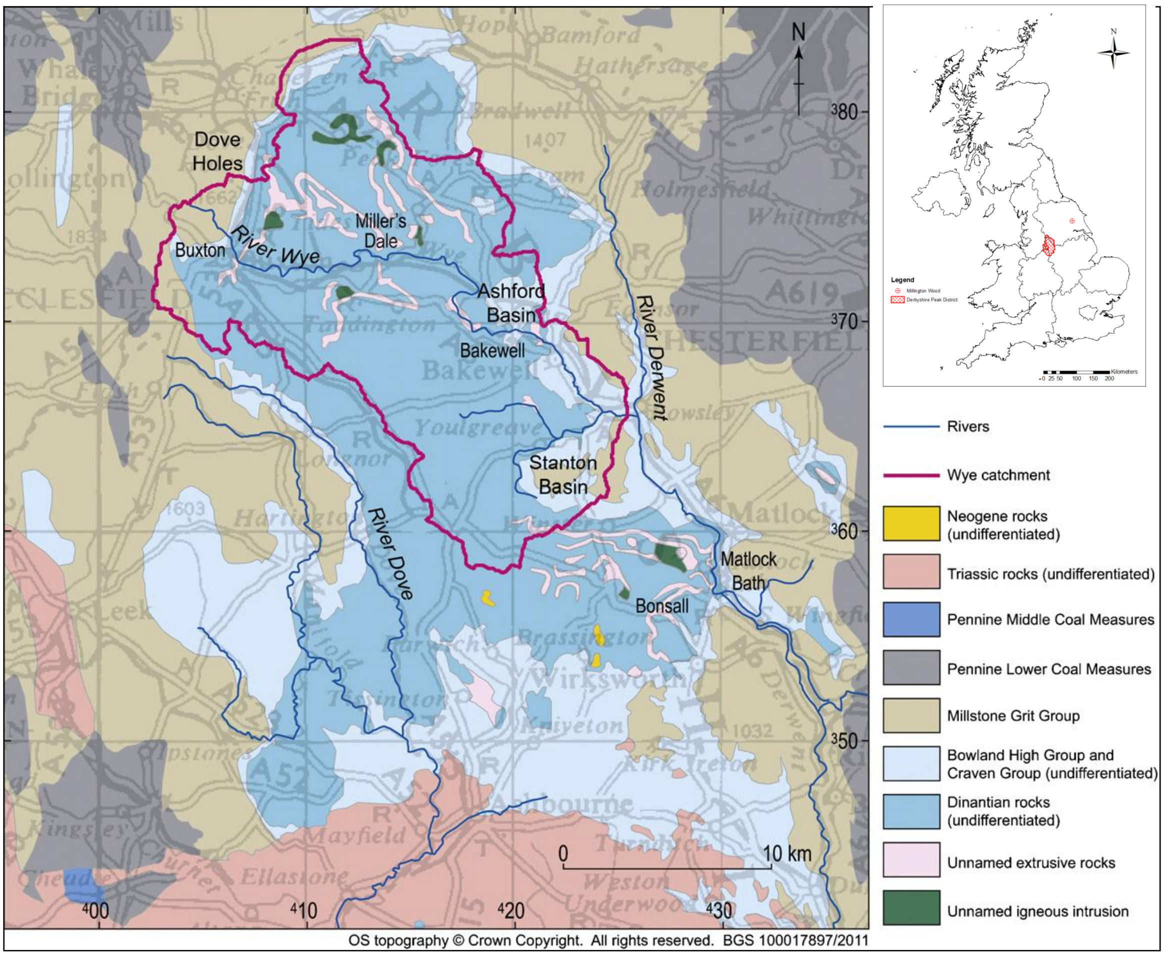


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Image taken from Banks et al. (2012)

Three distinct facies (of differing degrees of hardness) of Carboniferous Limestone indicative of differing depositional environments are present (Simpson, 1982); shelf limestone, basin limestone and reef limestone. Sporadic volcanic activity synchronous with the deposition of the Carboniferous Limestone Series resulted in basaltic lava flows and ash layers which have produced grey-green crystalline rocks and clays known collectively as toadstones (Edwards, 1970). The toadstone beds are impermeable and act as an aquaclude to groundwater flow so influencing both subterranean drainage, and affecting geomorphology through valley-side landslips and preferential surface erosion to create depressions. Isolated relict Tertiary sediments occur as sands and clays scattered over the limestone, the best known of which is the Brassington Formation.

Drainage of the White Peak plateau occurs through numerous river valleys which are illustrated in figure 3.5 below. Many of the headwaters of these rivers rise from the impermeable Namurian Grits and Shale of the adjacent Dark Peak, illustrated in figure 3.4, which has subsequently been eroded leaving much of the present-day drainage network on Carboniferous limestone resulting in many dry or ephemeral river valleys.

Figure 3.5: Drainage System and Dry Valley Network of the Peak District

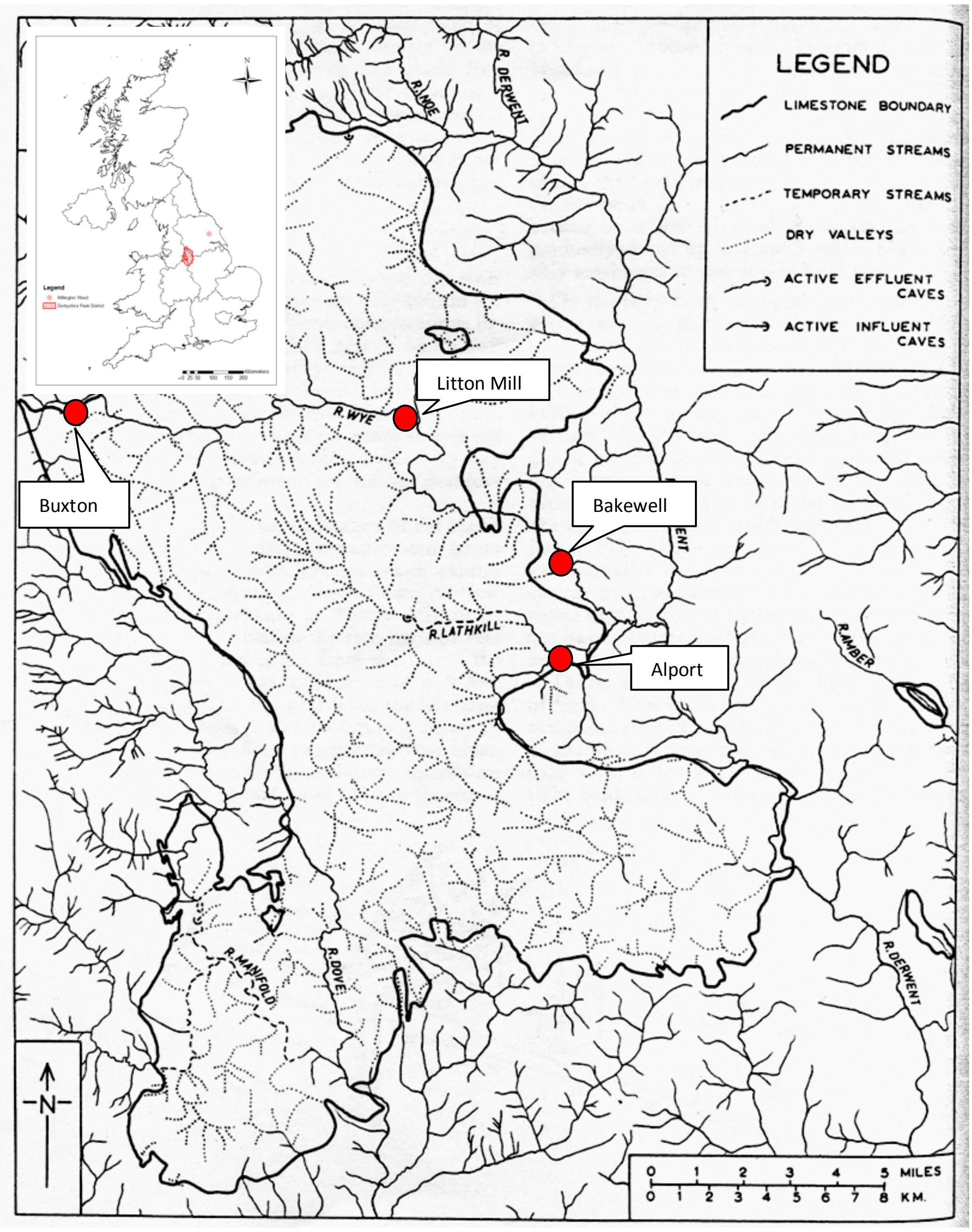


Image taken from Warwick (1964)

This has resulted in the lowering of the water table into the more permeable Dinantian limestone geology illustrated in figure 3.4, leaving a network of dry tributary valleys some of which ‘hanging’ above the active present-day watercourses. Today the limestone plateau of the White Peak is dissected by five main rivers; the Derwent, the Manifold, the Dove, the Lathkill and the Wye.

All the active rivers of the White Peak have relict drainage features, dry valleys having been formed in the upper reaches of each watercourse; some streams are ephemeral; some watercourses are predominantly subterranean and/or seasonally dry. The present-day river morphology is suggested as being a product of preferential erosion of an initial land-surface of impermeable Namurian geology i.e. grits and shales. The removal of the impermeable strata and subsequent incision of the river channels into the limestone is suggested to be responsible for a lowering of the regional water table, resulting in the extensive dry valleys found in the incised gorges of the present-day river valleys (Whittow, 1992).

3.4. Soils

Soil development on the White Peak is based primarily on a thin loessic drift (Johnson, 1971), and is suggested as being deposited by aeolian processes during the Devensian glaciation (Pigott, 1962). The virtual absence of glacially transported Pleistocene deposits i.e. tills, on the White peak suggests that although ice sheets were in the immediate locale during the last glaciation, they largely circumnavigated the limestone uplands. Dependant on the local soil forming factors of Jenny (1946), the soils of the White Peak are; rendzinas, rankers, brown earths gley soils, peaty gleyed podzols and organic soils (Johnson, 1971). The majority of the present-day plateau soils are well drained brown earths with local rendzinas and rankers. The limestone dales are designated a part of the Sprink Complex (Bridges, 1966), and are a mixture of brown earths, rendzinas and rankers.

The alluvial soils of valley-bottom sites, where drainage characteristics may be highly variable, are observed to be subject to gleying and can often be of organic characteristic. The loam which forms the basis of the majority of the soils on the White Peak is often well mixed with limestone weathering residue, which has been integrated into the loam through periglacial processes such as cryoturbation. The source area for the loess which forms the primary constituent of the loam is suggested as the adjacent Millstone Grit plateaus and escarpments to the north (Pigott, 1962).

3.5. Modern Vegetation

The Peak District, Derbyshire

The Peak District is divided into three sub-regions; the Dark Peak, the South West Peak and the White Peak, with each sub – region having a distinctive suite of vegetation defined by underlying geology type, altitude, land use and amount of precipitation (Natural England, 2014_a).

The upland flora of the Dark Peak and South West Peak plateaus is dominated by taxa such as *Calluna vulgaris*, *Empetrum nigrum* and *Eriophorum vaginatum* on extensive Holocene blanket peat deposits, with large areas of acid grassland containing taxa such as *Molina caerulea*, *Axonopus fissifolious*, *Festuca ovina* and *Pteridium aquilinum* at the peripheries of the peat deposits. Wet grassland dominated by *Holcus lanatus*, *Anthoxanthum odoratum*, and Cyperaceae taxa occurs on shale slopes where springs or flushes are present. Small pockets of semi – natural *Quercus robur* and *Quercus petrea* woodland are restricted to moorland fringes, valley heads or 'cloughs' and steeper valley sides of the Dark Peak and South West Peak, with *Betula pendula*, *Betula pubescens*, *Corylus avellana* and *Sorbus aucuparia* the principal secondary woodland components. Wet woodland in the Dark Peak and South West Peak is primarily *Alnus glutinosa* with *Betula pendula* and Salix, which occurs on flushed alluvium sites in river valleys and on valley slopes. Large areas of open heath and grassland on the Dark Peak and South West Peak have been planted with coniferous taxa such as *Pinus sylvestris*, *Pinus nigra* and *Picea sitchensis*, and broadleaf plantations of *Acer psuedoplatanus* and *Fagus sylvatica*. Farmland comprising permanent grassland used for livestock grazing and silage production is the predominant habitat in the lower – lying river valleys of the Dark Peak and the South West Peak (Natural England, $2014_{a,\ b}$).

The natural woodland types of the White Peak can be broadly divided into three groups which are organized according to local topography and edaphic conditions. Semi – natural ancient *Fraxinus excelsior – Acer campestre* (classified as **W8** *Fraxinus excelsior – Acer campestre – Mercuralis perennis* woodland in Rodwell, 1991) woodland is located in steep – sided limestone valleys or 'Dales', with *Acer psuedoplatanus* and *Fagus sylvatica* present as non – native invasive taxa; see figure

3.6 below. Although dominated by *Fraxinus excelsior* and *Acer campestre*, *Quercus robur* and *Tilia cordata* are a secondary component in these valley woodlands. The late leafing of the *Fraxinus excelsior* woodlands allows a diverse suit of herb taxa such as *Anemone nemerosa*, Allium ursinum, *Hyacinthoides non-scripta* and *Convallaria majalis* on the woodland floor.

Figure 3.6: Acer – Fraxinus valley woodlands in Chee Dale, Derbyshire.

Remnants of semi – natural wet *Alnus glutinosa* woodland (Classified as **W7** *Alnus glutinosa – Fraxinus excelsior – Lysimachia nemorum* woodland in Rodwell, 1991), in association with taxa such as Salix, *Prunus spinosa* and *Viburnum opulus*, is found on valley slopes flushed by springs and at valley bottom sites where active rivers allow soils to remain wet and nutrient rich; see figure 3.7 below.

Fragments of once extensive *Quercus petraea – Betula pendula* woodlands (Classified as **W11** *Quercus petraea – Betula pendula – Oxalis acetosella* woodland in Rodwell, 1991) are located on the limestone plateau edges and valley tops on leached acid soil types.

Figure 3.7: Fraxinus – Alnus wet woodland in Cressbrook Dale.

Fragments of once extensive *Quercus petraea* – *Betula pendula* woodlands (Classified as **W11** *Quercus petraea* – *Betula pendula* – *Oxalis acetosella* woodland in Rodwell, 1991) are located on the limestone plateau edges and valley tops on leached acid soil types.

Scrub woodland is important component of the White Peak flora with extensive *Corylus avellana* scrub woodlands located at sites on dale side slopes once occupied by *Fraxinus excelsior* – *Acer campestre* woodlands; see figure 3.8 below. Taxa such as *Populus tremula*, *Ligustrum vulgare*, *Cornus sanguine* and *Viburnum opulus* often form secondary components of these *Corylus avellana* scrub woodlands, with *Mercurialis perennis*, *Teucrium scorodonis* and *Convallaria majalis* the dominant herb taxa on the scrub woodland floor. Scrub woodlands are also a feature of the edges of the limestone plateau, where *Crataegus monogyna* and *Prunus spinosa* scrub is present, often spreading rapidly onto permanent grassland when stock grazing is reduced, with small broken stands of *Ulex galli scrub* also found at the top of valley slopes and plateau edges on areas characterised by thin acidic soils.

Figure 3.8: Crataegus – Corylus scrub woodland in Lathkill Dale, Derbyshire.

Ancient grassland is extensive and extremely species rich in on the limestone plateau, and can be separated into three types. Calcicolous grassland is characterised by *Festuca ovina*, *Briza media and Helictotrichon pratense* and supports a diverse suite of herb taxa including *Galium sterneri*, *Linum catharticum*, *Lotus corniculatus* and *Centaurea nigra*. Neutral grasslands are associated with deeper and more productive soils on the plateau and characterised by taxa such as *Anthoxanthum odoratum*, *Alopecurus pratensis* and *Festuca rubra* in association with herb fauna including *Lotus corniculatus*, *Galium verum*, *Primula veris* and *Leucanthemum vulgare*. Calcicolous grassland and scrub is illustrated in figure 3.9 below.

Areas of rough acid grassland, sometimes extensive, occur on poor leached soils on the upper edges of some dales and on steeper sections of the plateau and are associated with taxa such as *Agrostis capillaris* and *Festuca ovina* and herbs such as *Galium saxatile*, *Potentilla erecta* and *Juncus squarrosus*. The influence of stock grazing, especially by sheep, is a key driver of grassland species composition in all three grassland types.

Figure 3.9: Crataegus – Corylus scrub and calcicolous grassland on limestone shelves and plateau in Millers Dale, Derbyshire.

Fragments of once extensive limestone heath are present on areas of the White Peak plateau such as dale top edges and high parts of the plateau where acid soils have developed on Holocene windblown silt; taxa associated with limestone heath include *Calluna vulgaris*, *Vaccinium myrtillus* and *Ulex galli* and *Deschampia flexuosa*. Extensive agricultural 'improvement' for silage production has resulted in the loss or serious damage to between 50% and 75% of species-rich neutral grassland previously used in hay production since the early 1980's, with the majority of the White Peak now farmed land.

Grazing by livestock such as sheep and cattle is an impacting factor in the regeneration of the semi-natural valley side *Fraxinus excelsior* woodland as is the introduction of *Fagus sylvatica* and *Acer psuedoplatanus* in commercial plantations, which has led to these taxa invading the ancient semi-natural *Fraxinus excelsior* valley woodlands (Natural England, 2014$_c$).

Millington Wood, East Yorkshire

Millington Wood is located in Lily Dale in the Yorkshire Wolds near Pocklington in East Yorkshire, and is illustrated in figure 3.10 below. The Wolds are an arcuate range of rounded hills with dry valleys rising to a maximum height of 250 m OD extending north from the River Humber to Flamborough Head on the East Yorkshire coast. Soils include shallow rendzinas and brown calcareous earth soils formed on drift overlying Upper Cretaceous Chalk. Species –rich chalk grassland, once the predominant habitat of the Wolds, is now reduced to 1.3% of the total land area; the present-day landscape is dominated primarily by arable farmland and unimproved grassland with scattered forestry plantations.

Figure 3.10: Fraxinus – Acer – Fagus valley woodland at Millington Wood, East Yorkshire.

The Yorkshire Wolds are sparsely wooded with only a small number of calcareous Fraxinus woodlands present in dry valley sites, with Millington wood representing the best example of ancient calcareous woodland in East Yorkshire. Millington Wood supports a small area of ancient Fraxinus - Acer campestre woodland, with the remaining woodland comprising Picea, Pinus and Fagus introduced as plantation woodland; see figure 3.5. Ground layer herbs include taxa characteristic of ancient calcareous woodland including *Anemone nemerosa*, *Mercuralis perennis*, *Convallaria majalis*, *Campanula trachelium*, *Galium odoratum* and *Hyacinthoides non-scripta* (Natural England, 2014_d).

Chapter 4: Climate, vegetation and human impact in the Peak District during the Holocene

4.1. Vegetation and Climate History

Introduction

The Holocene vegetational history of the Peak District is based on a relatively low number of palaeoecological and archaeological research papers. These are broadly divided into those investigating the Dark Peak uplands, and those which investigate the contrasting environments of the White Peak. This review will take the format of a chronological overview of the vegetational development on the White and Dark Peak from the Late Glacial onward based on existing palaeoecological research carried out in the Derbyshire region. The pollen data from the adjacent counties of Cheshire, Lancashire and Staffordshire will also be reviewed in order to set the Holocene vegetational history of the White Peak into a wider geographical framework.

4.1.1. The Late Glacial

There is no late Glacial pollen record yet reported from the Peak District region. The maximum extent of ice cover during the Devensian is given as 150 km north of Kinder Scout (Manley, 1959; Johnson *et al*., 1990), the Pennine region being ice-free during the last glaciation. Evidence of periglacial landforms and deposits such as gelifluction benches, protalus ramparts and moraines in north Derbyshire are discussed in Johnson *et al*. (1990).

Between c. 15, 000-18,000 Cal. yr BP the Devensian glaciation came to an end, this phase being classified in the UK as the Oldest Dryas. The late glacial period then experienced a tripartite climate oscillation comprising an interstadial moderately-warm period between c. 15, 000-13, 000 Cal. yr BP (Windermere Interstadial), a stadial cold period from 11, 500 Cal. yr BP (Loch Lomond stadial) when glacial re-advance occurred and the inception of our present warm interstadial period, the Holocene (Roberts, 2002). Vegetation associations typical of late-glacial environments would include dwarf shrubs such as *Betula nana* (Roberts, 2002) and herb taxa as part of a tundra vegetation association. Tree taxa such as *Betula pubescens* and *B. pendula* were present in the British Isles from c. 13, 500 BP (Birks, 1989), but declined during the

Loch Lomond Stadial (c. 11, 000-10, 200 BP); isolated low values of Corylus have been observed in the late -glacial record. Common NAP associations observed in the British palynological record are Cyperaceae-Gramineae-Artemisia in Staffordshire (c. 13, 000-11, 000 BP: Bartley & Morgan, 1990), Betula- Cyperaceae- Gramineae-Juniperus in Norfolk (c. 12, 600-9500 BP: Bennett, 1983) and Cyperaceae- Betula- Gramineae-Hippophaë in Holderness (c. 13, 100-11, 500 BP: Beckett, 1981). Tree taxa tolerant of lower mean temperatures i.e. Betula and Corylus were able to re-colonize the UK from the early Holocene, and were well established in eastern England, Scotland and Ireland by c. 9000 yr BP onward (Huntley & Prentice, 1993)

4.1.2. The Holocene Development of the Forest (c.10, 000 -7,000 BP)

The White Peak

Research by Taylor *et al*. (1994) examined buried Holocene barrage tufa pool deposits at low altitude valley-bottom sites adjacent to the River Wye and the River Lathkill in the limestone White Peak, Derbyshire. Multiple low altitude valley-bottom sites were investigated using relic Holocene barrage tufas (located through resistivity) as sedimentary archives for fossil pollen and ostracod data; three cores were taken from separate sites in the Wye and Lathkill river valleys. All three cores were radio-carbon dated, the oldest date being 9860 yr BP ± 100 from the Monsal Head core in the Wye valley. The conclusions from pollen analysis of the core data were that a spread in Betula dominated woodland was facilitated by early Holocene temperatures reaching a maximum between 8565 and 7885 yr BP. This is suggested as a being relatively late date in the context of previously suggested northern and central England colonization (Birks, 1989) at c. 10,000 yr BP; the discrepancy in chronology is suggested as potentially a product of the well-drained and thin soils formed on the local limestone. A similar late arrival of Corylus is suggested at 8800 yr BP (400 years later than the arrival date on the Dark Peak), with thermophilous taxa such as Quercus, Tilia, Ulmus and Fraxinus established by 8700 yr BP.

The Dark Peak

As part of an investigation of the Holocene erosional and depositional history of the Seal Edge Coombes (an upland valley site) on the Dark Peak (500m AOD), a peat monolith was used to produce a radio-carbon dated pollen diagram from an exposure at Middle Seal Clough (Johnson *et al.*, 1990). The base of the diagram shows a typical suite of NAP taxa at c. 10000 BP, with herbaceous shrub (Juniperus-Corylus) and herb taxa (Tubuliflorae-Filipendula) constituting 90% of total pollen, tree taxa represented are Salix and Betula. By c. 8800 BP NAP values decline sharply with a reciprocal sharp rise in Corylus and Pinus values. The pollen data suggests that by c. 8500 BP a significant area around the Seal Clough site was covered by Pinus-Betula forest, with Corylus-Salix present as the scrub and understory component. These dates, and especially the Corylus expansion at c. 9000-9200 BP, display broad correlation with the upland site at Robinsons Moss (Tallis & Switsur, 1990), and the lowland site at Red Moss in the East Lancashire Plain (Hibbert *et al.*, 1971). However, the Corylus rise at Middle Seal Clough predates both the aforementioned sites by c. 200-400 years. Potential radio-carbon dating errors of up to c. 460 years are highlighted by the authors as a product of root penetration from woody plants occupying higher peat layers.

An extensive investigation at Robinsons Moss near Longdendale (a saucer-shaped shallow basin 0.5 km in diameter at 485m AOD), and at adjacent sites at Alport Moor (540m AOD) and Soyland Moor (385m AOD) in the southern Pennines uplands of Derbyshire (Tallis & Switsur, 1990) utilised peat monoliths to produce a series of radiocarbon-dated pollen diagrams. Pollen percentage diagrams produced from the three sites revealed early Holocene successional dynamics with the basal part of each diagram displaying high NAP pollen values (i.e. Calluna, Empetrum and Gramineae) with Salix and Betula establishment at c. 9000 BP, Corylus establishment at c. 8800 BP and Alnus establishment at c. 7700 BP. Subsequent arrival of thermophilous immigrant taxa such as Tilia, Quercus, Ulmus, and Fraxinus, in conjunction with human management and clearance practices beginning in the early Mesolithic, is suggested as marginalizing the early post-glacial flora. Tallis & Switsur (1990) suggest that as competition increased and climate improved during the early/mid Holocene, pioneering taxa such as Betula were displaced to greater altitudes whilst later successional arrivals such as Corylus and Pinus also became marginalized as a scrub and forest zone at higher altitudes as the thermophilous mixed-broadleaf woodland became established. The authors point out that the relative spatial inhomogeneity of taxa is more pronounced in upland areas, where temperature decreases rapidly with altitude.

At Soyland Moor, an upland (389m AOD) mire site in the Pennine uplands, a typical post-glacial vegetational sequence is observed initially with Betula and particularly Corylus dominant in the early Holocene (Williams, 1985). Potentially Corylus was over-represented through adopting a tree form as opposed to an understory component where pollen production is greatly increased. Radio-carbon dated pollen diagrams show an expansion of Quercus and Pinus at c. 8110 BP, with a fall in Corylus values and an expansion of NAP values. At c. 7640 BP Pinus values are still high with the initial rise in Alnus values noted whilst NAP values continue to rise; from c. 6975 BP Corylus values are falling as Calluna values rise.

Northern England

In Cheshire, Holocene palaeoecological records are summarised in the wetland survey report (Leah *et al.*, 1997). Of primary importance to this review are the records adjacent to the Pennine region i.e. the northern and eastern mosses and meres, the south western mosses and the wetlands adjacent to Crewe. Radio-carbon dated pollen data was derived from a series of cores taken in the region and described in the relevant chapters; no complete Holocene dated records were produced, rather a series of chronological ‘snap-shots’. Pollen studies at White Moss (Lageard, 1992) concluded that the mire was formed from a late-Glacial lake, based on radio-carbon dates of c.10861-10500 cal BC taken from gyttjas. Following an initial characteristic late-Glacial vegetation sequence at White Moss, an acceleration of paludification occurred at the site.

The eastern sites of Danes Moss, Lindow Moss and Walkers Heath display pollen records of an early Holocene association of a minor Pinus, Corylus component, with a dominant Betula woodland from *c.* 8960-7500 yr Cal. BC. From 7500 Cal. BC Corylus rises dramatically in association with Pinus, with thermophilous taxa such as Quercus and Ulmus establishing as a minor canopy component at this time. In the south-east of Cheshire, investigations of the wetlands adjacent to Crewe have produced palaeoecological data for sites at Crewe Hall, White Moss (Lageard, 1992) and at Wybunbury Moss (Birks, unpublished data).

Research by Bartley *et al*. (1990) produced radio-carbon dated pollen diagrams showing vegetation development from the early Holocene at 5 different locations in the Craven District adjacent to the Northern Pennines in North Yorkshire; the White Moss study site near Settle (190m AOD) occupies a shallow depression approximately 500m by 500m in size, and was initially a lake before peat formation began. The site is underlain by boulder clay and morainic drift deposits over shale - limestone geology. A date of c. 9900 BP is given for Betula-Corylus and Gramineae being present, with Ulmus and Quercus being present from c. 9500 BP and Alnus arriving at c. 8500 BP. Patterns of tree-spreading and forest development are broadly similar across the region; this model is discussed by previous research (Woodman, 1982; Bennett *et al*., 1986; Birks, 1989; Spikins, 2000).

Summary

The available literature suggests a general pattern of re-colonisation occurring after the cold period produced by the Loch Lomond stadial; re-establishment of Betula coming primarily from the east coast (Birks, 1989), Corylus from the west coast and Pinus from the east/south east coast. A key point raised is the late arrival of Betula and Corylus into the White Peak in comparison with both the Dark Peak and the northern Pennines in Yorkshire. A key variable in this delay is suggested as the well-drained and relatively young and thin soils formed on the local Carboniferous limestone; this contrasts with the poorer drainage of the Millstone Grit sandstone uplands with their rich loess soils.

4.1.3. Maximum Forest Diversity (7000 - 5000 BP - mid-Holocene)

Models of maximum forest diversity and its spatial extent during the Holocene are linked to both regional and local climate, altitude and latitude (Huntley & Prentice, 1988). During the mid-Holocene thermophilous taxa such as Quercus and Ulmus expanded north from glacial refuges in mainland Europe and re-colonised the UK between c. 9000-6000 yr BP (Birks, 1989; Huntley & Prentice, 1993) as mean temperatures increased leading to a relatively dry and warm climate (Tallis, 1991) during this period. The maximum elevational limits of thermophilous tree taxa in central Europe is suggested as occurring at c. 6000 yr BP, this date marking the peak elevation of the tree-line; maximum growing season warmth in the UK occurred between c. 7000-6000 yr BP (Huntley & Prentice, 1993). This period of maximum forest diversity encompasses a period of warm and wet climate historically referred to as the 'Atlantic Period, which has been observed in both pollen records (Tallis, 1991; Tallis & Switsur, 1990), and in peat stratigraphy (Barber, 1982).

The inception of a phase of wetter climate (c. 7500-5000 BP) during the period of maximum forest diversity in the mid-Holocene led to important changes in upland environments within Great Britain. Water-collecting basins acted as nuclei for peat development, leading to paludification, soil deterioration and the spread of blanket-peat (Tallis, 1991) at the expense of forest and scrub communities. In the southern Pennines, these changes were some 1500-2500 years earlier than in other British upland sites. Paludification as a product of climatic deterioration, associated soil leaching and increased herbivore grazing can be a climate-induced natural process (Tallis, 1991). However in the southern Pennines, human disturbance practices are seen as exacerbating the natural climate-driven paludification process, as no topographical or altitudinal differences exist between sites where no early paludification and significantly earlier peat development (i.e. Southern Pennines) is recorded. Therefore forest clearance patterns in the southern Pennines must have accelerated the speed and scale of natural paludification.

The White Peak

Radio-carbon dated pollen diagrams were produced from cores taken from riverine valley peats at Lismore Fields (300m AOD) near Buxton (Wiltshire & Edwards, 1993). The earliest dated pollen zone shows an overall increase in woodland taxa, particularly Betula and Alnus between c. 7130-6090 BP, with Quercus maintaining consistently high values until the end of the zone. Values for Ulmus and Tillia are also consistent, with Fraxinus established before the maxima of NAP values consistent with open conditions towards the end of the zone. Therefore the forest maximum at the site can be placed at approximately c. 7000 BP, based on the rising AP values. However the presence of open-ground indicators such as Rumex and Pteridium does suggest that gaps and clearings were present, though of human or natural origin is open to investigation.

The authors infer that the landscape around the site at this period was well-wooded; but in comparison with the adjacent uplands of the Dark Peak at this timescale (Conway, 1947; Tallis, 1964; Hicks, 1971, 1972; Tallis & Switsur, 1990) the locality was relatively open. The more open woodland conditions are proposed as potentially an indicator of early human clearance for browse; this hypothesis is supported by a reciprocal fall in Gramineae values as ruderal NAP values increase suggesting grazing by wild or managed herbivores in the area. Between c. 6090-5045 BP there is a reduction in Quercus, Alnus, Betula and Corylus values suggesting human clearance in the surrounding area.

During the woodland decline, a rise in Plantago, Rumex and Potentilla values is observed suggesting that clearance was for both increased herbivore grazing and primitive cereal cultivation; at c. 6000 BP cereal-type pollen is noted in the pollen record. The reduction in extent of the local canopy is suggested as allowing the influx of more distant and extra-local pollen to the site. Although no clear Ulmus decline is noted at the site, a fall in values at c. 5740 BP is noted based on low numbers of pollen grains. Pollen diagrams produced from buried Holocene barrage-tufa pool sapropel sediments in Lathkill Dale near Alport (Taylor *et al.*, 1994) indicate that the adjacent hillslopes to the Raper Lodge coring site supported a mixed deciduous forest. Associations of Corylus, Quercus, Ulmus and Tillia are present at c. 5780 BP, with *Ulmus* and *Tilia* the dominant forest canopy components, with Fraxinus virtually absent from the pollen record. From c. 5190 BP a marked reduction in Ulmus and Tillia values is observed, with an increase in Corylus and Gramineae values from the same date. Another potential disturbance phase is noted at c. 5600 BP, when arboreal pollen values fall and a concomitant rise in Chenopodium values is observed. The chronology of disturbance patterns between Lathkill Dale and Lismore Fields is broadly similar suggesting synchronous agricultural human incursion into the White Peak.

The Dark Peak

Maximum forest diversity in the Pennines probably occurred c. 7000 BP (Tallis, 1991), when the upland plateaus and valleys were heavily forested up to a height of c. 500-600m AOD. Above this altitude Betula and Corylus communities were dominant with only limited mire communities. Evidence to support this hypothesis comes from

Robinsons Moss (a saucer-shaped basin 495-510m AOD), Derbyshire (Tallis & Switsur, 1990). Pollen data from Robinsons Moss and other sites suggests that forest and scrub communities had achieved stability by c. 6700-6800 BP. The data suggests that in the south Pennines Alnus, Tillia and Fraxinus were the lowland component, Pinus, Quercus and Ulmus comprised the upland forest and Betula, Corylus and Salix constituted the scrub component. Thus, the arrival of thermophilous immigrant taxa such as Tilia, Quercus, Ulmus, and Fraxinus in the southern Pennines uplands (Tallis & Switsur, 1990), (in conjunction with human management and clearance practices beginning in the Mesolithic), is suggested to have marginalizing the early post-glacial flora.

Tallis & Switsur (1990) suggest that as competition increased and climate improved during the mid Holocene, taxa such as Betula were displaced to greater altitudes whilst Corylus and Pinus also became marginalized as a scrub and forest zone at higher altitudes as the thermophilous mixed-broadleaf woodland became established. The authors point out that the relative spatial inhomogeneity of taxa is more pronounced in upland areas, where temperature decreases rapidly with altitude.

The hypotheses suggested previously by Tallis & Switsur (1990), are supported by the earlier findings of Hicks (1971; 1972) at the East Moors uplands adjacent to the White Peak. The important pioneering palynological work by Hicks on the gritstone East Moors upland (Hicks, 1971; 1972) of Derbyshire produced radiocarbon dated pollen data going back to 6.3 ka BP. Hicks divided her work into three main zones, A to C, with sub-zones subdividing each main zone. Analysis of zone A suggested that the date of peat inception was 6.3 ka BP, based on the date achieved from the junction of the peat with the underlying mineral soil. Hicks suggests that prior to 6 ka BP the upland landscape at East Moor was comprised of a dense forest which thinned out as altitude increased to the tree line. The plateau itself is suggested as supporting an herbaceous flora with Betula/Alnus woodland established where conditions were suitable. From 6 ka BP with the onset of wetter and cooler conditions at the Boreal/Atlantic transition, mixed-oak woodland had replaced the Pinus/Corylus canopy at lower altitudes; Betula/Alnus Carr occupying poorly drained environments in association with reed-swamp.

Investigation at Soyland Moor, an upland (389m AOD) mire site in the Pennine uplands (Williams, 1985) examined pollen data primarily for human disturbance. The site is suggested as being less than 300m in diameter up to the elm decline, and is today situated on deep peats over Millstone Grit geology. Radio-carbon dated pollen diagrams indicate that prior to clearance, the forest maximum at Soyland Moor occurred at c. 5025 bc; Pinus relatively late in establishment at the Soyland Moor site, though producing higher pollen values than observed in the south and east of Britain. The potential for Pinus to be over-represented through long-distance/regional pollen transport is highlighted by Williams based on studies of Pinus pollen dispersal characteristics (Birks & Birks, 1980) and subsequent over-representation in the pollen record. Williams (1985) also highlights an interesting point in the subordinate nature of Quercus, Tillia, Ulmus, Alnus and Fraxinus in respect to Pinus at the pre-disturbance woodland maximum. This is attributed to factors such as altitude, migration rates or unknown local edaphic conditions.

The Wider Region

Investigations at Red Moss near Horwich in Lancashire examined a large lowland basin peat deposit adjacent to the watershed of the rivers Croal and Douglas; the site is suggested to have been initiated as a raised bog in the early Holocene (Hibbert *et al*. 1971). Radiocarbon dates were derived from peat monoliths taken from a deep peat profile exposed during a road construction project, and pollen diagrams produced for the early-mid Holocene period. Maximum forest diversity at the Red Moss site begins at c. 7100 BP when Quercus, Ulmus and Alnus are the dominant forest taxa; Pinus is still present but at reduced values. At c. 5399 BP maximum values for Tilia and Fraxinus are reached prior to a fall in Ulmus values and indicators of human activity at c. 5010 BP.

An extensive environmental survey of the wetlands in Staffordshire (Leah *et al*., 1998) has produced Holocene palaeoecological records for the region. Central Staffordshire appears to have marked a transition zone of woodland dominant taxa in the early Holocene; as such Stafford marked the southern limit of the ‘northern-type’ of Corylus dominated woodland (Bartley & Morgan, 1990). This contrasts with sites a little further south where Pinus was the dominant woodland taxon. The north-westerly margins of the early-mid Holocene range of Tilia is ascribed to this region of the county (Bartley & Morgan, 1990); with Tilia dominated woodland to the south and Tilia poor woodland to the north. Maximum Pinus values and the inception of the Alnus expansion are suggested as occurring at *c*. 6000-5000 cal BC. At King's Pool, this coincides with the appearance of charcoal in the sediment record; the cause of the burning is undecided between human agency or natural ignition from lightening strikes.

4.1.4. Woodland Clearance and Decline

The broad pattern of forest clearance and decline in northern England begins at a small-scale local level during the late Mesolithic c. 6500 BP. Forest decline during the mid-Holocene has the potential to be a natural process, the result of human disturbance/management and a combination of the two. Anthropogenic woodland management practices/disturbance can exacerbate natural processes i.e. soil deterioration through increased nutrient leaching (Tallis, 1990). The primary factors in natural forest retreat are driven by climatic change i.e. as a product of wetter climatic conditions, and include soil leaching, paludification and subsequent acidification of soils resulting in peat formation which can form extensive areas on upland sites as blanket bogs.

The human influence on these climate-driven processes can be critical in accelerating soil poverty. Through removal of natural vegetation i.e. trees, both soil stability and nutrient cycling equilibriums are disturbed potentially resulting in mechanical erosion of soil profiles particularly on slopes and nutrient leaching as already described. Another significant factor in retreat of woodland taxa is herbivore grazing; either natural i.e. red deer, aurochs etc, or managed i.e. sheep and cattle. It is suggested that Mesolithic humans first began to 'disturb' the natural successional woodland in order to provide browse initially to attract game animals and hold them in a certain area.

These early management practices were small scale and primarily involved burning, charcoal being plentiful in sites associated with Mesolithic humans. As human populations expanded during the Neolithic, European colonists brought domesticated animals such as goats and sheep which were presumably kept pastorally or later in enclosed areas. Evidence suggests that clearances during the Neolithic increased significantly in scale, and in conjunction with wetter climatic conditions significantly accelerated soil acidification and subsequent peat formation. The southern Pennines experienced rapid peat spreading in the uplands between c. 8000-4000 BP (Tallis, 1990), and significantly sooner than any other British upland region.

Large scale forest clearance for farming during the Bronze and Iron Ages used improved metal technology to support ever increasing populations, and reduced many upland sites to acid soils. Once soils were unfit for arable farming some areas would have been left as rough pasture where livestock prevented any forest growth resulting in a landscape dominantly colonised by Calluna and Empetrum, maintaining soil acidity further precluding tree recolonisation.

Forest Clearance Evidence from the White Peak

Investigations at Lismore Fields near Buxton in the White Peak, Derbyshire utilised a valley riverine peat deposit situated on a river terrace adjacent to the River Wye (Wiltshire *et al*., 1993). This site is at a comparatively low altitude (300m AOD) when compared with the >500m AOD sites described in the Dark Peak section. Based on three radio-carbon dated cores taken at the site, pollen analysis revealed the presence of cereal-type pollen from 6000 ka BP. Prior to this date, in the earliest dated horizon at 7215-7130 ka BP, a dominant Alnus signal with some Gramineae is interpreted as representing a local alder-Carr environment with some open ground present locally. The presence of charcoal at this horizon is interpreted as Mesolithic domestic burning or browse-orientated fire disturbance of local vegetation; the authors admit however this is a tenuous hypothesis.

From 5650-5045 ka BP significant reduction of taller woodland taxa such as Quercus, Ulmus and Tilia, and smaller woodland taxa such as Betula, Corylus and Alnus occurred; this is suggested as non taxa-specific woodland clearance. The rationale for this clearance is an increase in woodland management associated with the continuing cereal cultivation at the site, suggested as following the more widely noted UK transition from hunting/gathering to agriculture (Edwards, 1988) during the late Mesolithic. By 4000 ka BP, forest-farming practices of woodland clearance for cereal production at the Lismore Fields site meant soil impoverishment was widespread; the acidification of local soils as agriculture land-pressure increased is reflected in rising

Calluna and Pteridium pollen values from this date. Cleared woodland subsequently utilised for agriculture only remained productive for several decades (representing a prehistoric 'slash-and-burn' or Landnam); hence the clearance of even marginal land such as the alder-Carr from 3745 ka BP onward. An effect of the opening-up of the landscape at Lismore Fields was that the regional as well as the local and extra-local pollen signal is represented at the site from 3745 ka BP onwards; this has been observed at other regional sites during the Neolithic clearances (Bartley & Morgan, 1990). An associated increase in Corylus and Salix pollen values at this time is suggested as potentially revealing the management of these taxa through coppicing. These hypotheses of anthropogenic clearance are however open to alternative, ecological mechanisms as proposed by Brown (1997). Unselective woodland clearance continues through to the youngest radio-carbon dated horizon at 3225 ka BP, with pollen signals indicating some periodic recovery of woodland taxa.

Research by Taylor *et al*. (1994) examined buried Holocene barrage tufa pool deposits at low altitude valley-bottom sites adjacent to the River Wye at Monsal Dale and the River Lathkill at Raper Lodge and Alport in the White Peak, Derbyshire. Clearance events are suggested at Lathkill Dale at 5600 yr BP and 5190 yr BP. These primary deforestation events correlate with disturbance phases recorded in the pollen spectra at the adjacent East Moors upland site in the Dark Peak (Hicks, 1971). These pollen signals are suggested by Taylor *et al*. (1994) as recording anthropogenic disturbance events on the White Peak, not local Dark Peak clearance. A subsequent major woodland clearance event at 4100 yr BP is suggested as causing the virtual deforestation of the adjacent landscape.

In addition to a significant reduction in arboreal pollen values at the 4100 yr BP clearance event, sedimentological indicators within the Raper Lodge core suggest episodic influxes of calcareous mud into the tufa pool sapropel peat deposits. These rapid changes in sediment type may represent extreme events in the hydrological run-off regime, which were perhaps initiated and exacerbated by large scale removal of local and/or extra-local woodland resulting in increased soil erosion. Large scale episodic sediment influxes which occurred as a result of soil erosion after anthropogenic woodland clearances in the late Neolithic have been suggested as a potential forcing mechanism in the 'switching-off' of large fluvial barrage tufa systems in the Holocene (Goudie *et al.*, 1993; Baker & Simms, 1997). There is palynological evidence that anthropogenic woodland clearance at 4100 yr BP was a widespread phenomena in both the Dark Peak (Hicks, 1971; Barnatt & Smith, 1991) and the White Peak (Wiltshire & Edwards, 1993; Taylor *et al.*, 1994), possibly representing both an increase in population and an increasing reliance on agriculture as part of a more sedentary social structure.

Forest Clearance Evidence from the Dark Peak

From 6 ka BP onward Hicks (1971; 1972) suggests a series of human woodland clearance events at the East Moors on the Dark Peak. The first event at 5000 yr BP is suggested as small scale and initiated by Late Neolithic pastoralists. A second clearance event at 4 ka BP is of a slightly greater magnitude, and occurs in association with archaeological evidence of clearance technology in the form of polished stone axe-heads recovered from the East Moors upland. Further human clearance at 3.8 and 3.5 ka BP is suggested as being representative of pastoralist immigration from the adjacent limestone uplands of the White Peak as a result of increased population and subsequent demand for grazing resources. From 2.5 ka BP Hicks suggests that in certain areas of upland direct human clearance had ceased; however subsequent grazing pressure from sheep and cattle effectively nullified any regeneration of cleared woodland. The introduction of Iron Age technology, in regard to woodland clearance, from 2.5 ka BP is suggested as producing significant woodland clearance resulting in large open areas presumably serving as pasture. A transition from pasture to cereal cultivation is suggested by Hicks from 2 ka BP onward based on the increased cereal pollen percentages; Hicks suggests that this level of cultivation and pasturing continued until the Norman Conquest.

A more recent paper by Long (1994) investigated late Holocene human influence and woodland disturbance associated with a Neolithic/Bronze Age prehistoric field system at Stoke Flat on the gritstone Dark Peak. Drawing upon two radio-carbon dated core samples with an oldest horizon date of c. 4000 ka BP, Long produced pollen diagrams outlining eight regional pollen assemblage zones on the basis of species richness, succession, human clearance and post-clearance woodland regeneration. The local and regional pollen signal revealed in the Stoke Flat core data suggests that close correlations with previously described regional pollen assemblage zones (Hicks, 1971, 1972; Tallis & Switsur, 1973) were evident. The conclusions of Long (1994) are that the date of the tree decline at Stoke Flat c. 2050 ka BP shows a strong correlation with similar declines in arboreal pollen observed at the other sites investigated in the Peak District (Hicks, 1971, 1972; Tallis & Switsur, 1973), albeit each site displays a variable (10-50%) percentage of decline.

In concluding the investigation at Stoke Flat, two observations emerged which are of note. The first is that arboreal pollen values declined after arable agriculture had ceased at the Stoke Flat site; the mechanism behind this decline may potentially be explained by a continuance of pastoral activity on cleared previously arable areas. The second is that the increased precipitation and declining temperatures of the sub-Atlantic transition period at c. 2500 ka BP, a popular cited mechanism of tree decline (Lamb, 1977; Barber, 1982), precedes the decline in arboreal pollen in the region. Notably no record of regional vegetation changes associated with increased wetness was observed in the Stoke Flat peat sediments during the sub-Atlantic transition. The hypothesis that management practices such as coppicing and controlled browsing declined and eventually ceased as upland farms on the Dark Peak uplands were abandoned at the end of the first millennium is suggested. The change to an uncontrolled upland grazing regime after upland abandonment would effectively nullify woodland regeneration through browsing and trampling by stock in areas previously enclosed and managed (Piggott, 1983).

At Soyland Moor, an upland (389m AOD) mire site in the Pennine uplands (Williams, 1985) four sediment cores provided radio-carbon dated pollen data for signs of human disturbance. The site was less than 300m in diameter up to the elm decline, and is today situated on deep peats over Millstone Grit geology. The site represents a nucleation basin which is covered by subsequent extensive peat. Cereal-type grains were present in diagrams immediately prior to the Mesolithic/Neolithic transition (c. 3870 BC), and clearance patterns (interpreted from pollen records) continued from their inception in the Mesolithic up to the Elm Decline at site. Several phases of forest clearance and recovery are indicated in the pollen record. Between c. 5950-5200 BC NAP values rise gradually from 4%-35%, tree values are very gradually rising and Corylus values fall dramatically from 55%-20%. These changes are interpreted as forest grazing increasing in intensity over the period as more woodland was cleared and regeneration of remaining trees being negated by browsing herbivores. A rapid decline in NAP values at c.5300 BC, and subsequent rise in Calluna signifies cessation of management. Subsequent clearances between c. 4650-2915 bc are suggested based on rising NAP values, the later date signifying maximum deciduous woodland on the plateau. The woodland clearance at c. 2915 BC (during the middle Neolithic) represents the culmination of a series of early clearance/recovery cycles. This final phase so degraded the plateau soils as to allow invasion of Calluna and acidification of the soil after the abandonment of the site.

Forest Clearance Evidence from the Wider Region

Leah *et al*. (1997) examined wetland sedimentary archives in the Cheshire region including the eastern sites of Danes Moss, Lindow Moss and Walkers Heath. At *c*. 5840-5000 Cal. BC a transition from a woodland taxa dominated peat to Eriophorum/Calluna dominated peat is initiated. Associated rise in Alnus and significant rises in Sphagnum values suggest a typical ‘Boreal-Atlantic’ transition sequence marked by increasing precipitation and the onset of paludification. The latter hypothesis also correlates with a marked rise in charcoal values suggesting anthropogenic woodland clearances though burning; this may have accelerated and/or initiated environmental change from the established fen-carr woodland to acid mire formation characterised by the Eriophorum/Calluna communities.

Investigations of the northern meres of Cheshire focused on Rostherne Mere, Tatton Mere, Tabley Mere, Pick Mere and Budworth Mere. This group of kettle-holes and fluvio-glacial lakes have revealed two phases of late Holocene woodland clearance occurring adjacent to the Rostherne Mere site, (Nelms, 1984) beginning at approximately c.366 cal BC – cal AD 60 and at c. cal AD 1260 – 1470. Worked flint finds occurred at all the wetland sites, the majority were late Neolithic to Bronze Age in antiquity (c. 3200-800 cal BC), with isolated artefacts dating to the late Mesolithic/early Neolithic (c.6700-3200 cal BC) interpreted as representing only occasional foraging visits to the periphery of the counties wetlands (Middleton *et al.*, 1995).

In the south-east of Cheshire, investigations of the wetlands adjacent to Crewe have produced palaeoecological data for sites at Crewe Hall, White Moss (Lageard, 1992) and at Wybunbury Moss (Birks, unpublished data). Limited pollen studies at Crewe Hall suggested paludification of the previously dryland areas from c.6000 BC, then followed by multiple clearance events suggested by mineral soil in-wash represented as silty clay bands in the core-sample stratigraphy. Palynological research at Extwistle Moor, Lancashire (Bartley & Chambers, 1992) produced pollen diagrams from an upland site (360 m AOD) on the western flank of the Pennines near Burnley. Radiocarbon dates were produced, but are acknowledged as potentially inaccurate. The site was probably grassland before peat development began at *c*.3000 yrs cal BP, extensive woodland clearance creating further grass-pasture and an extension of the bog. This date correlates with changes in peat type (Tallis & Switsur, 1973) noted in Derbyshire at 830 BC, and is ascribed to late Bronze Age woodland clearances. This hypothesis is supported by decreased arboreal values and increased Calluna and Cyperaceae values; however the authors acknowledge that climatic deterioration at *c*.1000 BC leading to increased soil wetness may have independently influenced bog formation in association with anthropogenic actions. A continuation of episodic woodland clearance is noted throughout the subsequent late Iron Age continuing into the Romano-British period. It is at the end of this period that the spread of wet, acid grassland in association with Sphagnum is noted, taken as indicative of climatic deterioration after *c*.400 AD. The short period of woodland recovery after 400 AD suggesting a post-Roman period (100 yrs) of agricultural decline and forest regeneration.

Investigations at the Forest of Bowland, an upland (250 m AOD) blanket mire on the western flank of the Pennines in Lancashire (Mackay & Tallis, 1994), produced a radiocarbon dated pollen record of the late-Holocene. Based on palynological interpretation, a significant drop in arboreal pollen values (60%) is recorded at c.100 BC – 36 AD. Interpretation of this event is suggested as an extensive Iron Age clearance phase of the steeper sections of the Bowland uplands; Corylus and Betula being the principal taxa cleared. A subsequent rise in Calluna values is seen as both an expansion of the acidification of the mire soils and an indicator of improving climatic conditions that followed clearance. The increasing use of the uplands for agriculture following this climatic improvement are suggested as representing an expansion in use of local resources accessible to the local population. Subsequent clearance in the Romano-British period is represented by increasing Plantago, Cereal-type and Gramineae pollen values. However grassland is suggested as replacing the cleared woodland as much of the clearance was in the creation of pasture for stock, with only limited amounts of crop production occurring.

Study of an upland site (410 m AOD) at Rishworth, West Yorkshire produced evidence for woodland clearances occurring in the uplands of the Yorkshire Pennines from early-Neolithic times (Bartley, 1975). Radio-carbon dated pollen analyses suggest that prior to c.5490 BP the local environment was open, grassy woodland, with grasslands occupying the greater altitudes. A change from mineral soil to peat is noted after this time culminating in an increased Calluna and Cyperaceae pollen signal at c.3540 BP suggesting an acidification of the local environment; as the site was now such an environment, all subsequent arboreal pollen sedimentation is presumed to represent woodland located on slopes below the peat. A reduction in tree pollen including the disappearance of Tilia from c. 5000 BP to c. 2060 BP (Late Neolithic/Early Bronze Age) is interpreted as representing minor human woodland management; an increase in associated clearance/disturbance indicator taxa such as Plantago and Rumex pollen values support this hypothesis.

The palynological transition from lightly managed upland woodland to widespread woodland agricultural-based clearance is observed from c.470 BC to c.30 AD through the substantial decrease in arboreal pollen, increase in NAP values and significant rises in Plantago, Gramineae and cereal-type pollen. This decrease in woodland extent is ascribed to an increasing dependence on pasture for stock and the rise of cereal cultivation during the Iron Age; the woodland being cleared on the valley slopes below the upland peats. Similar patterns of vegetation change and woodland clearance have been observed in Derbyshire (Hicks, 1971; Tallis & Switsur, 1973), with generic clearances occurring almost synchronously across the Pennines from the Iron Age into Romano-British times. The lack of Bronze Age agriculture at this particular site indicates an initial seasonal upland-pasture land use i.e. summer grazing, followed by an intensive integration of almost all available cleared land including environmentally marginal uplands, for both pasture and crops from the Iron Age onward.

Summary

In the context of the literature reviewed above, the White Peak has the earliest recorded regional date for cereal pollen at c. 6000 BP; the Dark Peak at Soyland Moor has a similar date c. 3870 BC. The difference between the two may be a product of dating error or may be genuine indication that early arable agriculture was first tried on the limestone rather than the Millstone Grit. An increase in the scale of clearance observed in the limited data available for the White Peak suggests that soil poverty was vastly accelerated by the clearances and subsequent loss of nutrients via leaching and loss of litter. A date of c. 6000 BP for the inception of clearance events is broadly synchronous for the Pennines and the wider region as a whole, and shows that clearance was not biased between the different two upland environments. This observation is however open to interpretation. The onset of the Neolithic (c. 4000 BC) correlates with these dates and is indicative of a reaction of the local human population to an increase in woodland extent (both laterally and vertically as the tree-line increased in altitude) promoted by the warm climate of the mid-Holocene. This may be why a preference for clearances in upland environments is seen in the earliest period of the chronology of clearance events.

The absence of a pollen record from the late Bronze Age onward at the White Peak sites does not allow comparison with the Dark Peak or the wider regional context. Substantial Bronze Age and Iron Age clearances are clearly observed in pollen data from both the Dark Peak and the wider region. The pollen records describing the mid-Holocene forest maximum on the White Peak are based on only two low-resolution papers (Wiltshire & Edwards, 1993; Taylor et al., 1994). Although allowing an insight into the vegetation development during this period, there are issues requiring clarification which finer resolution research could resolve such as the degree of openness in the adjacent woodland. The effect of climatic change leading to increased temperatures and precipitation on the White Peak limestone uplands in relation to the adjacent Millstone Grit uplands also requires clarification.

4.2. Human landscape impact - the Archaeological Record of the Pennines and the Peak District

The archaeological investigation of the Derbyshire Peak District began in the early 19th century with the investigation of barrows and caves by Bateman (1841; 1861). The uplands of both the White and Dark Peaks have since been extensively surveyed through a combination of field-walking and excavation of ritual and settlement sites. Settlement patterns in the White Peak are displayed in figure 4.1 below.

Figure 4.1: Settlement patterns in the Peak District.

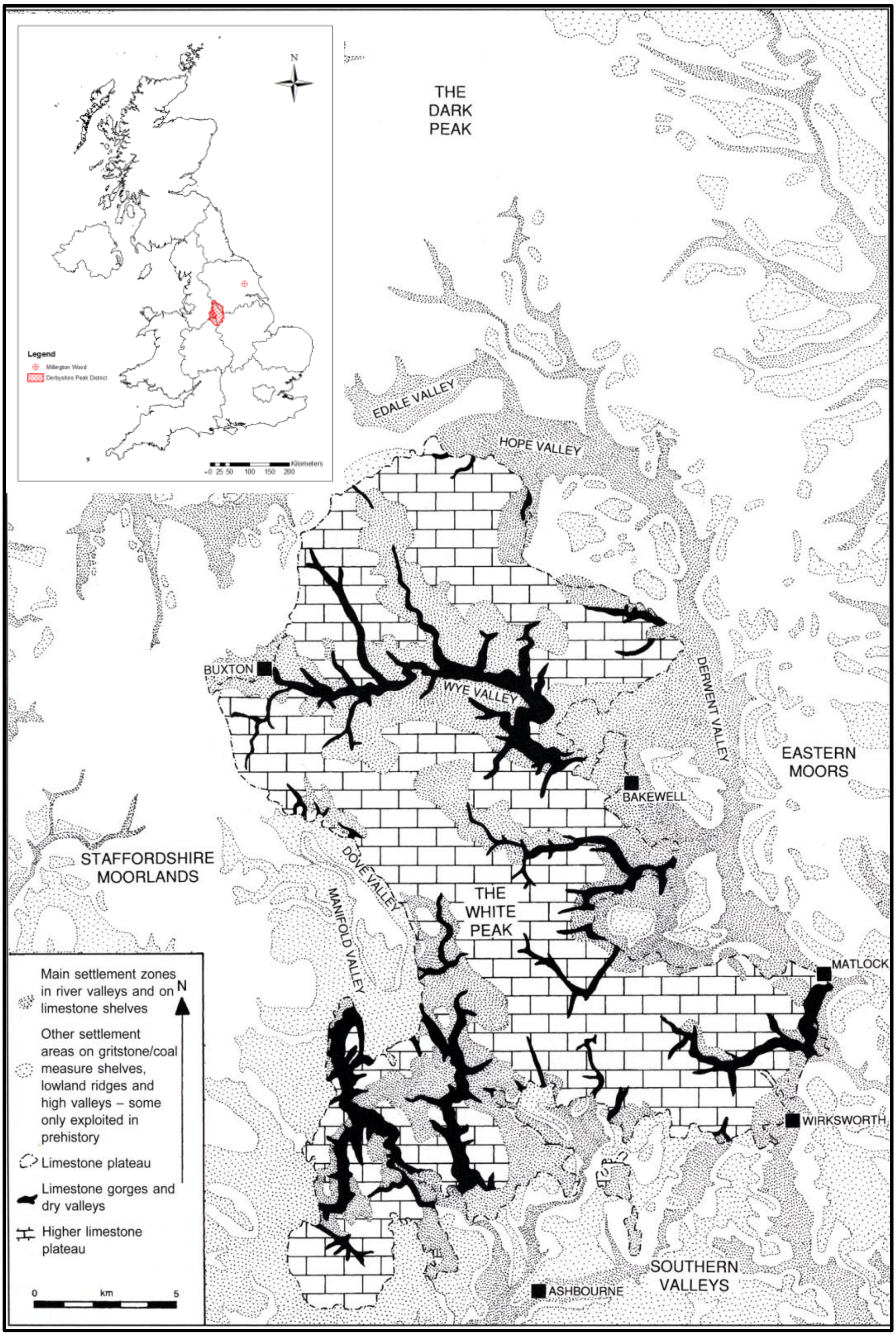


Image taken from Barnatt & Smith (1997).

Modern day systematic survey of the region began with the work of Jeffrey Radley during the 1960's (Radley, 1966; 1968; Radley & Cooper, 1968). It is important to note here at the outset that the variability of C^{14} dates from materials used to differentiate periods and transitions chronologically (i.e. wood, soil horizons, pollen etc.) can be used to pull archaeological/ecological assemblages backwards or push assemblages forwards to suit temporal periods (Woodman, 2000). The focus of the research that will result from this thesis will focus primarily on the middle-late Holocene. Therefore this literature review will examine previous archaeological research up to and including the Iron Age.

4.2.1. The Mesolithic

The Mesolithic period extends from c. 8500 BC to the Neolithic transition at c. 4000 BC (Mithen, 2005), the earliest radio-carbon dated Mesolithic site (c. 8415 BC) in Britain being Thatcham in Berkshire (Godwin & Willis, 1964). The Mesolithic has been subdivided into 'early' and 'late', the differentiation based on changes in the microlith component of the 'tool-kits' of the period; broad-bladed microliths signify early Mesolithic assemblages (Buckly, 1924) along with 'Maglemosian' bone and antler tools and weapons (Mellars, 1974). Narrow-bladed microliths introduced at between c. 6800-6500 bc characterise the late Mesolithic (Switsur & Jacobi, 1975), which is represented in many more sites than the Early Mesolithic (Williams, 1985); the shift in microlith design is attributed to the landscape becoming more densely wooded hence requiring different hunting technology and strategies (Myers, 1989). The transition period of the early to late Mesolithic, given as 8650 BP (Myers, 2004), is suggested as a period of increased competition amongst humans for food resources already being influenced by environmental change.

One fundamental point regarding all flint artefacts found in the Peak District is that all flint was of necessity imported; there are no local sources save chert of variable quality found on the Carboniferous limestone (Garton, 1991). Local chert is associated with late Mesolithic and Bronze Age flint scatters and artefacts in the Peak District (Radley, 1968). In particular the black local chert (sourced in the Wye and Manifold river valleys) has a wide distribution within the Peak District and its scale of use may signify both an intimate geographical knowledge of local raw materials, and that flint was not necessary to local Mesolithic populations before the importation of differing flint types during the Neolithic. An imported opaque light grey mottled flint sourced from the Yorkshire or Lincolnshire Wolds is more commonly in use in the region during the Neolithic (Hart, 1981). Other sources of imported flint are suggested as sites adjacent to the River Trent south and east of the Peak District and sites to the west including the Cheshire Plain which provided a brown/grey translucent flint. It is suggested that the Lismore Fields site may have represented a junction or hub of differing flint collection areas (Garton, 1991); the transition from local chert to imported flint (sourced in the west and east of the Pennines) occurring from the late Mesolithic/early Neolithic supporting the hypothesis of Radley (1968). Similar importation of raw materials is observed in adjacent Pennine sites at Malham Tarn and Great Close Mere in North Yorkshire (Williams *et al*. 1987). Local poor quality chert and imported Derbyshire higher-grade black chert are observed at Mesolithic sites; the authors suggest that chert was used increasingly throughout the Pennines during the Mesolithic, becoming increasingly important during the later Mesolithic.

Early evidence of Mesolithic occupation of the Peak District was primarily found in the gritstone pastoral upland areas of the Dark Peak during the early and middle 20th century (Reviewed in Myers, 2000). Find-spots of flint artefacts are recorded from the Central and Southern Pennines from eroded areas of the moor-edges on a regular basis (Armstrong, 1924) from an early date. In contrast, early 20th century find-spots from the pastoral limestone uplands of the White Peak were scarce (Lomas, 1959). This dearth of occupational evidence was subsequently addressed by Manby (Manby, 1959); whose investigations into flint scatter distribution sought to reveal the archaeological potential of non-gritstone upland sites within the Peak District as areas of human activity and occupation during the Mesolithic.

Investigations at Soyland Moor, an upland (c.400 m AOD) site on the Kinderscout Grit of the central Pennines identified multiple clearance and regeneration phases aimed at encouraging herbivores through browse production occurring from the early Mesolithic onward (Williams, 1985). Evidence of early human occupation of the limestone regions of the Derbyshire Peak District has been from cave sites such as Ash Tree Cave near Whitwell (Armstrong, 1956) and rock-shelter sites at Whaley (Armstrong, 1938: Radley 1967) on the Magnesian Limestone. On the Carboniferous limestone a cave site at Foxhole Cave (Bramwell, 1971) and a rock-fissure site at Sheldon (Radley, 1968) have both produced Mesolithic artefacts.

A conceptual model was developed by Hawke-Smith (1979), who suggests a 'Land-Facets' model based on geology, topography and altitude in the Dove-Derwent interfluve. These variables were used to formulate a series of population growth models for late Mesolithic/Neolithic population-environment interactions with the surrounding biotic communities and environment. Using analogues drawn from modern-day soils, vegetation and land use, Hawke-Smith suggests that the introduction of livestock into the economy of the late Mesolithic/Early Neolithic helped to amalgamate both high and low altitude environmental resources (i.e. upland pasture and valley cultivation sites) into a single economic structure.

Extensive archaeological investigations by Hart (1981) concluded that all the geological regions of the Peak District had been utilised by humans during the Mesolithic to a greater or lesser degree. Williams (1985) suggests that herding of red deer or aurochs in the Pennines began in the late Mesolithic (c. 5959 bc); phases of cereal production beginning at c. 3780 bc are at a similar date to the Lismore Fields site suggesting that agriculture was not exclusive to lower altitude sites on the adjacent limestone. During the 1980's several Manpower Services Commission funded archaeological field investigations focused more specifically on the Magnesian and Carboniferous limestone of the White Peak. Investigations by Barnett (Barnett, 1987) utilized an ambitious field-walking project to identify type and density of artefact scatters across a NE - SW transect incorporating the Derwent valley, the Wye valley, through Arbor Low and into the Dove valley in order to test Hawke-Smith's hypothesis of a changing landscape use through time. The field survey findings supported Hawke-Smith's hypothesis that the central limestone plateau of the White Peak was the central point of anthropogenic activity from the early Neolithic onward. It also established the widespread occurrence of Mesolithic archaeology at many previously uninvestigated Peak District sites; supporting the hypothesis of Hart (1981) that large areas of the Peak District were utilized during the Mesolithic.

4.2.2. The Mesolithic-Neolithic Transition

Spikins (1999) and Myers (1989) support the hypothesis that during the late Mesolithic and Neolithic river valley sites supported permanent settlements from which hunting parties (and perhaps herding parties in the Neolithic) moved seasonally into the upland areas of the White Peak. Hawke-Smith (1979) suggests that the primary rationale for Neolithic occupation of the White Peak was the use of livestock such as cattle, the latter requiring both forage and water. Based on Hicks (1971) proposal of intermittent clearance and pastoral farming practices, stone axes found on the limestone uplands, evidence of cereal cultivation adjacent to the Trent and seasonal occupation of limestone caves Hawke-Smith suggested that the latter constituted evidence of early agriculture within the White Peak. This would have used the lowland sites for arable cultivation, the leaf-fodder available in the limestone uplands and the opportunistic seasonal hunting opportunities presented by the limestone and gritstone uplands (Hawke-Smith, 1979). Bradley & Hart (1983) suggest that during the late Mesolithic/early Neolithic the population continued to use landscapes already modified for either farming or browse, and that woodland margins were still a prime source of fresh food resources.

Landscape resources such as permanent water-courses, which would be mainly subterranean on the limestone uplands, would have been a key driver in settlement patterns as pastoralism became established alongside cultivation in the Neolithic. Garton (1991) points to archaeological evidence of early Neolithic occupation favouring both river valley and dale settlement sites such as that excavated at the Roystone Grange valley site (Marsden, 1982). Early Neolithic colonization of the limestone is considered by Hawke-Smith as resulting from population growth and the initiation of cereal cultivation on the fertile loess soils available on the White Peak. Upland environments still provided traditional (i.e. Mesolithic) food resources from seasonal hunting during the Mesolithic/Neolithic transition. A shift from seasonal exploitation to long-term settlement of the outlying limestone uplands signalled both the introduction of an arable component as a supplement to hunter/gather resources, and expansion of upland grazing resources from the limestone plateau on to the gritstone. This latter hypothesis finds support in palynological evidence of woodland-clearance and pastoral-indicator pollen observed on the adjacent gritstone (Hawke-Smith, 1979) at this period.

Lismore Fields

This field site near Buxton, Derbyshire was investigated archaeologically in 1984 (Garton, 1991). Subsequent excavations by the Trent and Peak Archaeological Trust, which were continued up until 1987 (Garton, 1987), give substantive evidence of settlement of the site from the Mesolithic to the Neolithic. The site occupies an upland (300m AOD) position in the River Wye valley where the Carboniferous limestone and the Millstone and Corbar Grits intersect (Garton, 1991). Subsequent palynological investigation was undertaken at the Lismore Fields, a valley peat site situated on an interfluve (Wiltshire & Edwards, 1993). The results of the Lismore Fields palaeoenvironmental site investigation (Wiltshire & Edwards, 1993) revealed that fire was potentially being utilized as an environmental management tool; palynological investigation suggested small scale localized clearance events potentially as far back as the Mesolithic with pollen data suggesting continuous cultivation from the early Neolithic to the Iron Age. Evidence of cereal cultivation at Lismore Fields is suggested by the authors as continuing from 6000 BP onwards near the site. Representing one the earliest farming sites in the UK, the authors cite evidence of soil impoverishment at c. 4000 BP as evidence of continuous cultivation in the intervening two millennia. Flint artifacts ascribed to the later Mesolithic (along with later early Neolithic flint artefacts and 'Grimston-type' pottery) have been found at the site as well as an extensive series of buildings evidenced by post-holes suggesting construction of an extensive permanent settlement in the early Neolithic (Garton, 1991). This contrasts with the scant evidence of early Neolithic settlement buildings found on the limestone plateau (Barnatt & Smith, 1997), suggesting that the uplands may have been utilized only seasonally or for residences of only a few years at this stage. It was noted by Garton (1991), that the Lismore Fields site contrasted with sites outside the White Peak through the paucity of flint-work found in the three pits attributed to the early Neolithic; sites outside the Peak district being characterized by pottery and flint-work in pits with rare flint-scatters and evidence of building. Garton (1991) also notes that the Lismore Fields site also contrasts with other early Neolithic sites recorded within the Peak District; the paucity of diagnostic early Neolithic flint-work at the Lismore Field site contrasting with the abundance of early Neolithic settlement evidence such as flint artefact scatters recorded on the limestone plateau. Despite no evidence in the form of archaeological artefacts from the Bronze and Iron Ages at the Lismore Fields site, the pollen data suggests that human activity remained high in the area (Wiltshire & Edwards, 1993) during these periods.

4.2.3. The Neolithic

The Neolithic period (subdivided into three stages-early, middle and late: for chronology see Whittle, 2005) encompasses the timescale of c. 4000-2500/2200 BC (Whittle, 2005) and initiated change in culture, perception and human interactions (Barrett, 1994; Whittle, 1996) with the landscape.

Cultural change during the Neolithic is represented by monument buildings such as barrows and ditched enclosures, and changes in human-environment interactions manifest as extensive woodland clearances and the associated rise in arable farming and pastoralism using non-indigenous stock i.e. sheep and pigs (Tilley, 1994). However, these observed changes in material culture, based on chronological phases, may have masked a more complex process of change (Woodman, 2000). The gradual influence of these changes serve to differentiate the more sedentary (though still partially mobile) Neolithic from the highly mobile Mesolithic pattern of seasonal rounds of hunting/gathering supplemented by a pastoral/herding landscape use. The shift in lifestyle was a gradual process, whereby European practices disseminated though the existing Mesolithic population via seafaring continental settlers. However, there is still debate as to the precise mechanisms of change regarding the material culture and economy of the Neolithic period (Woodman, 2000). The early, middle and late Neolithic is well represented in Derbyshire.

Over 500 upstanding earth works are recorded in the gritstone and Carboniferous limestone uplands of the Peak District region (Barnatt, 1996), dating from 6500 BP (Barnatt & Smith, 1997). Neolithic buildings in the Peak District include ritual monuments such as burial cairns i.e. Minninglow (Barnatt & Smith, 1997), rock shelters i.e. Calling Low rock shelter (Piggott, 1953) and the henge at Arbour Low (Barnett, 1987). The distribution of Neolithic cultural monuments within the Peak District is displayed in figure 4.2 below.

Figure 4.2: Distribution of Neolithic barrows in the Peak District.

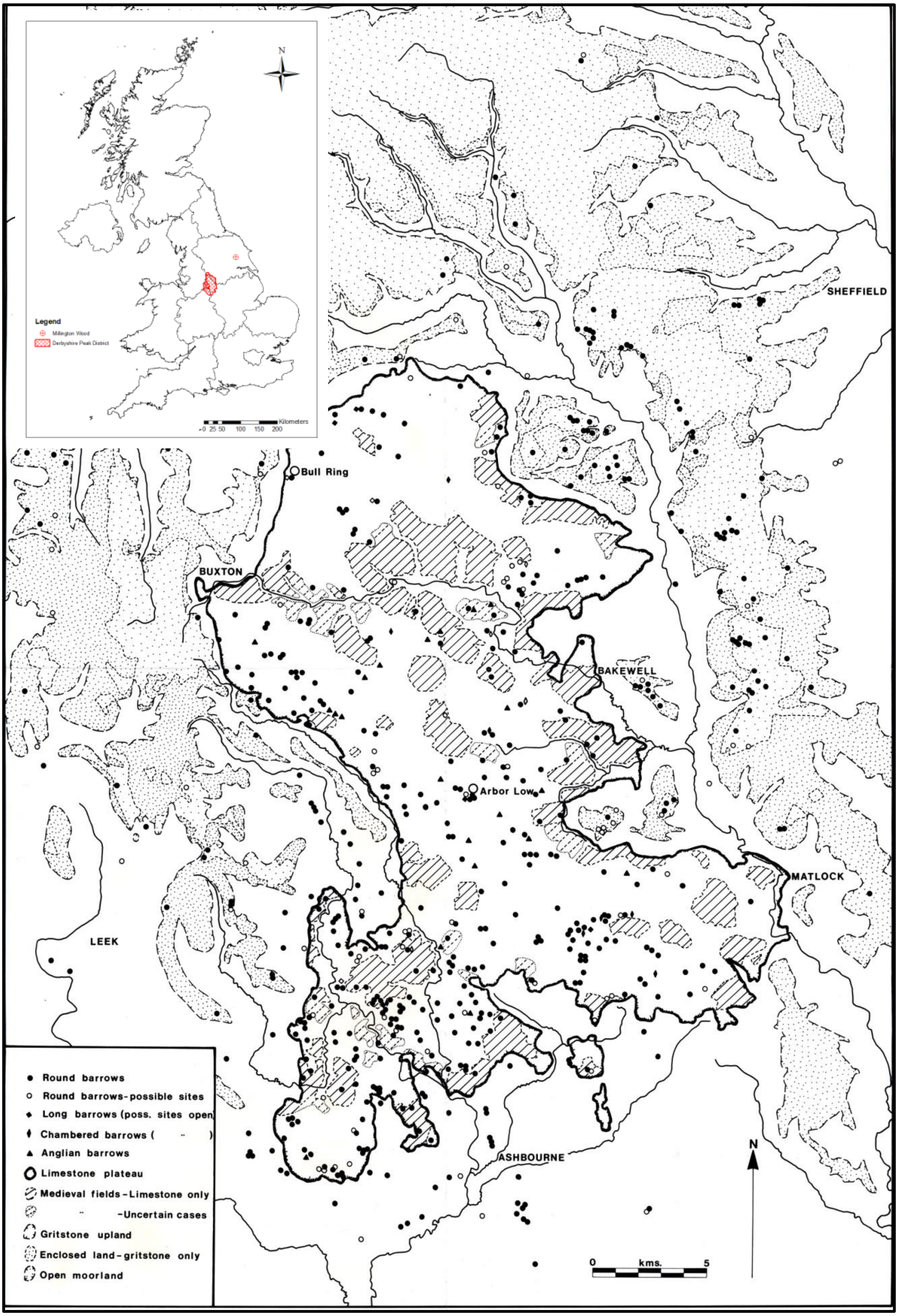


Image Taken from Hodges & Smith (1991)

These constructions are identified as products of increasing population pressures and social/structural development of larger static communities; such cultural features identifying landscape-ownership, territories and group tenure of areas of existing and potential cultivation and pasture (Megaw & Simpson, 1992) in an environment of growing population and the need to signify possession of environmental resources.

The placement of burial mounds and barrows may have signified a veneration of the dead, allowing ancestors to be kept more effectively in the collective memory; their placement on the landscape may therefore have signified a group's ancestral tenure over the adjacent area. The White Peak has a significant number of the Neolithic monuments recorded in the Peak District as a whole when compared to the paucity of structures/monuments observed on the adjacent gritstone (Barnatt & Smith, 1997).

This has been attributed to location and topography, the limestone plateau being encircled by valleys acting as corridors used to access the uplands and hence push different groups together in competition for the upland resource; the gritstone Dark Peak may in turn, being at the margins of the Pennines as a whole, have seen lower numbers of interactions or conflict over resources. The numbers of monuments and artefacts in existence during the Neolithic and up to the Neolithic/Bronze age transition at 4000 BP adds support to the hypothesis of a larger population pursuing a more sedentary lifestyle (Barnatt & Smith, 1997). The thin, fertile soils of both the White Peak and adjacent gritstone uplands would have provided ideal environments for early agriculture to develop from isolated sites during the Mesolithic (Barnatt & Smith, 1997) and continue to develop in magnitude during the Neolithic.

Pollen analysis of sites at East Moors an upland gritstone site to the east of the White Peak, (Hicks, 1971; 1972) suggests multiple Neolithic woodland clearance episodes associated with semi-nomadic pastoralism beginning at c. 5 ka BP. Hicks (1971) suggests that the East Moors pastoralists were immigrants who established a pioneer settlement, the uplands of the White Peak still being occupied by hunter/gatherer groups at the late Mesolithic/Neolithic transition. Similar investigation at Soyland Moor, and upland site (389m OD) on the Kinderscout Grit in the central Pennines (Williams, 1985) noted that cereal grains were present immediately prior to the Mesolithic/Neolithic transition (c. 3870 bc), and that clearance patterns (interpreted from radio-carbon dated pollen records) continued from their inception in the Mesolithic up to the Elm Decline at site. A woodland clearance at c. 2915 bc during the middle Neolithic is suggested as the culmination of a series of Mesolithic clearance/recovery cycles which finally so degraded the plateau soils as to allow invasion of Calluna and acidification of the soil after the abandonment of the site.

The limestone plateau and valley shelves of the White Peak probably still offered the preferred settlement sites (Barnatt & Smith, 1997); the adjacent less fertile gritstone sites being colonized as a product of both expanding local population and the need for new livestock forage. The effects of pastoralism on areas deliberately cleared or managed, as well as existing clearings, would be to inhibit recovery of the woodland (Pigott, 1983), adding more pressure through soil erosion and degradation. The latter in tandem with increasing local populations and new immigrants would accentuate the value of fertile land with access to water (Garton, 1991). The valley environments of the Peak District as a whole during the Neolithic Period are suggested as presenting settlers with shelter, the valleys being densely wooded (Barnatt & Smith, 1997). The uplands approaching the tree-line, it is proposed, would have provided more suitable clearance areas of sparser existing woodlands.

The evidence for Neolithic landscape impact in the UK is discussed by Woodbridge *et al*. (2012), who argue that the mid-late Holocene woodland decline and subsequent increases in open landscapes resulted from the establishment and consolidation of cereal-based agricultural farming systems. Woodbridge *et al*. (2012) also argue that anthropogenically-driven landscape change was a nationwide phenomenon within the British Isle, which gained considerable momentum from 4400 cal. BP onwards as a result of the technologies, trade, and societal organization which developed during the transition from the Neolithic to the Bronze Age. Based on the scant palynological evidence of Neolithic agricultural impacts on the White Peak valleys, cereal agriculture is suggested as beginning at 6000 BP (Wiltshire & Edwards, 1993), with subsequent significant declines in arboreal pollen suggesting an almost complete and unselective removal of woodland from 4100 BP onward (Taylor *et al*. 1994).

Sedimentological evidence from a core taken at Raper Lodge in Lathkill Dale (Taylor, 1994) suggests increased soil erosion at 4500 yr BP. This observation is supported by the pollen record from that horizon, which suggests an almost complete deforestation of the Lathkill Dale catchment at this time. The removal of vegetation for agricultural production of cereals, in association with pastoral practices which were also detrimental to both vegetation regeneration and resilience of the thin rendzina soils e.g. sheep, would introduce a significantly higher organic and inorganic (e.g. colluviums) content into the pools formed in the River Lathkill. Pedley *et al*. (2000) note that after 4 ka BP lime muds become increasingly clay-rich upsection, grading into dark-brown clay soils. Both sedimentary (Pedley *et al*., 2000) and palynological evidence (Taylor *et al*. 1994) suggests that tufa production may have been negatively influenced by allogenic terrigenous sediment entering the river system. The magnitude of erosional sediment input to the Derbyshire fluvial systems may have been exacerbated by an increase in precipitation in the UK at approximately this same time period (Anderson *et al*. 1998), which in association with the removal of catchment vegetation resulting in decreased interception, would have contributed to the termination of the tufa systems in Derbyshire. The effect of reduced interception resulting from woodland clearance may also have been a factor in increasing terrigenous sediment input to the fluvial system in the period before the increased precipitation described by Anderson *et al*. (1998) i.e. increased flood peaks without the need for increased precipitation.

4.2.4. The Bronze Age

The Bronze Age covers the period c. 2600 - 700 bc (Pearson, 2005), and is subdivided into early (c.2600-1600 BC), middle (c. 1600-1200 BC) and late (c. 1200-700 BC). The Bronze Age characterized cultural and social change and the further development of agriculture; cultural markers such as the appearance of 'Beaker' pottery and the introduction of copper and bronze tools and weapons accompanied an acceleration and expansion of woodland clearance and land-management. Significant building works such as hillforts (Haselgrove, 2005), field systems using low dry-stone walls or 'reaves' to signify territorial rights and subsequent division of environmental resources and a change in burial practices in the later Bronze age whereby the dead were no longer deposited in the elaborate tombs reflect the changing outlook of Bronze Age people (Champion, 2005).

In the Peak District, construction of approximately 400 barrows (mainly on the White Peak plateau, with significantly fewer on the adjacent millstone grit uplands), and some of the most extensive field systems and cairnfields in the northern England are attributed to Bronze Age settlers (Barnatt & Smith, 1991). Settlements and field systems at East Moors on the Dark Peak are displayed in figure 4.3 below.

Figure 4.3: Bronze Age Settlements on the Dark Peak at East Moors, Derbyshire.

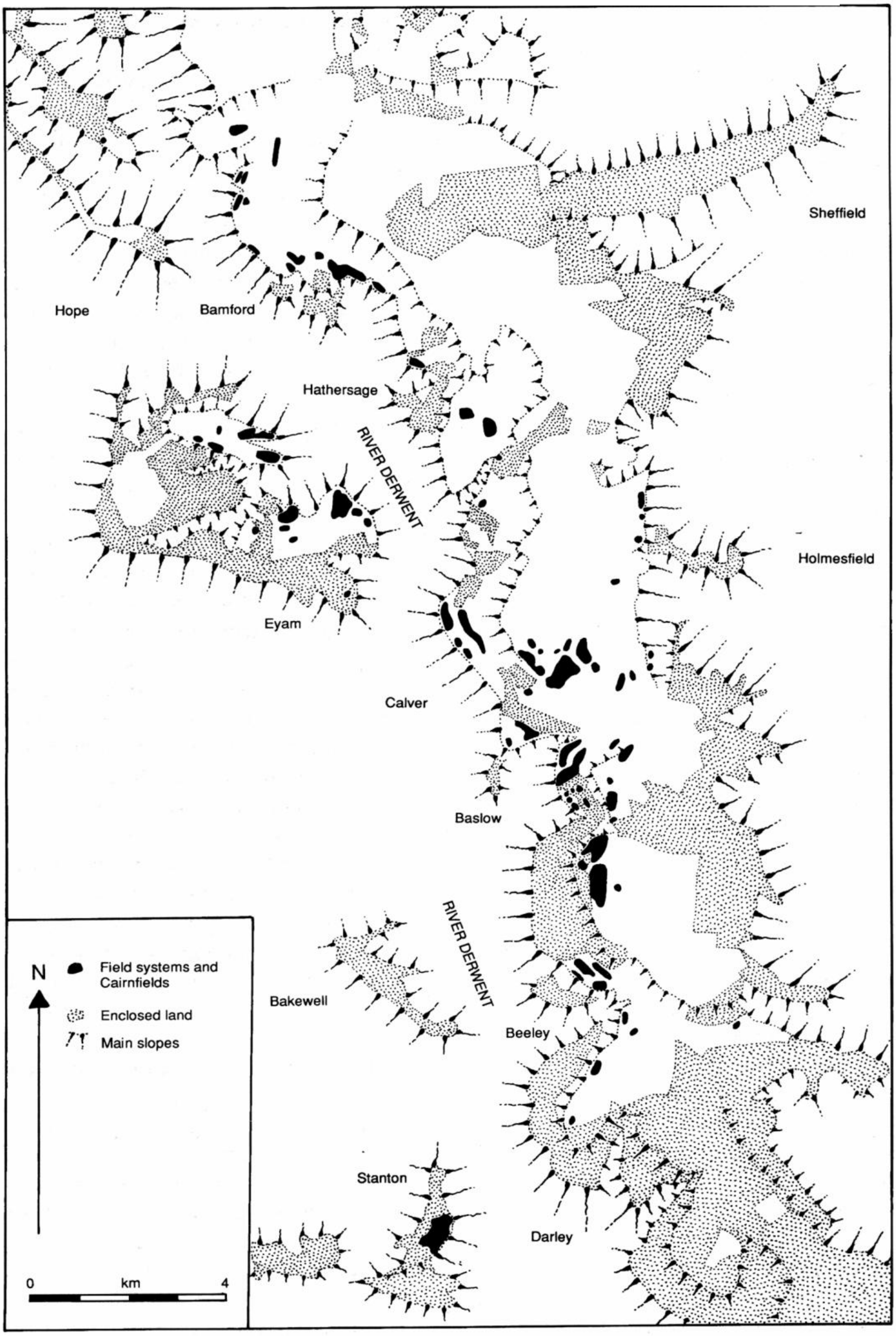


Image taken from Barnatt & Smith (1997)

Evidence of mixed farming practices on the gritstone upland shelves suggests that up to 50 field systems had been established by c. 3000 BP (Barnatt & Smith, 1997; Barnatt, 2000), i.e. on the Dark Peak at sites such as at East Moors (Hicks, 1971). Woodland clearance of the upland shelves for cultivation on both the gritstone (Hicks, 1971; Long, 1994) and the Carboniferous limestone (Wiltshire & Edwards, 1993) is suggested by radio carbon dated pollen data as occurring from the late Neolithic onwards. Climatic deterioration at c. 3000 BP is suggested (Barnatt & Smith, 1997) as marking a decline of cultivation on the gritstone uplands, and the onset of peat development at higher altitudes as climate became wetter and cooler during the sub-Atlantic transition (Barber, 1987). However no significant change in the regional vegetation pollen signal was noted at the Stoke Flat site on the East Moors gritstone uplands during this period (Long, 1994); Long (1994) cites a possible change to grazing practices as accentuating woodland degeneration also observed in modern times (Pigott, 1983). Investigations at other sites on the East Moors uplands (Hicks, 1971) suggest that although it is impossible to distinguish between human and climatic landscape changes, human woodland clearance is a primary driver in accelerating paludification as a product of changing climate.

Human impact on the upland landscape of the Peak District accelerated during the Bronze Age (Barnatt & Smith, 1991), with a high percentage of burial mounds ascribed to the southern margins of the White Peak (Barnatt & Smith, 1991). The limestone uplands of the White Peak are considered (Bradley, 1984) as representing a 'core' settlement and agricultural position within the Peak District as a whole during the Bronze Age. The millstone grit of the Dark Peak during the Bronze Age representing a 'periphery' area colonized by lower ranking social groups; this hypothesis is still open to debate (Barnatt & Smith, 1991). The increase in magnitude of woodland clearance during the late Neolithic and Bronze ages is suggested as being associated with both the increase of crop cultivation as immigration increased, and the use of flint and subsequently bronze axes as aids to more felling more substantial trunk sizes and spatial areas of woodland (Hicks, 1971; Garton, 1991). The higher incidence of recorded Bronze Age artefacts on the millstone grit of the Dark Peak is suggested as reflecting a more suitable post-depositional environment than that of the White Peak

(Barnatt & Smith, 1991); the artefact density not necessarily ascribing a greater population density for that region.

4.2.5. The Iron Age

The Iron Age does not have a single archaeological horizon clearly demarcating the transition from the Upper Bronze Age, however the accepted chronology is set at c. 700 BC - 100 AD (Haselgrove, 2005). The Iron Age in northern Britain is described as being characterized by 'site-dominated' evidence rather than upon the artefact assemblages used during the preceding periods (Harding, 2004: 6), that is to say by hillforts, field monuments, long-cist cemeteries and homesteads; examples include the Arras Culture in east Yorkshire and the Hownam Culture in Roxburghshire in the Scottish borders.

Over 6000 Iron Age sites are recorded, mainly as upstanding monuments and cropmarks; regional variation in settlement types are observed i.e. linear earthwork complexes in south-east England and village-sized open settlements in eastern England (Haselgrove, 2005). Field systems, linear boundaries and trackways are typical components of the later Iron Age landscape. These features are often associated with hillforts, many of which are suggested as being initially constructed during the later Bronze Age and subsequently extended or modified as populations and trading networks expanded (Harding, 2004). The onset of the Iron Age within the Peak District reveals archaeological evidence suggesting many of the upland field systems and settlements were abandoned as the climate deteriorated (Barnatt & Smith, 1997). However, Bevan, (1999) suggests that agriculture continued uninterrupted throughout the first millennium BC. A decrease in tree pollen observed (Hicks, 1971; Long, 1994) in the last millennium BC suggest that many upland sites had been completely cleared for cultivation before abandonment as the climate deteriorated.

A subsequent change in land use from cultivation to upland pasture would negate any woodland regeneration (Pigott, 1983); thus in combination with an increase in moorland vegetation (i.e. Calluna) and wetter, cooler climate paludification became commonplace. Iron Age fortifications (of which eight are recorded) within the Peak District such as the Mam Tor hill fort near Castleton, are characterized by a single rampart (Barnatt & Smith, 1997) in most instances; all the forts are on either the limestone plateau or the adjacent shelves. The location of hill fort sites in the Peak District is illustrated in figure 4.4.

Figure 4.4: Location of Iron Age hill fort sites within the Peak District.

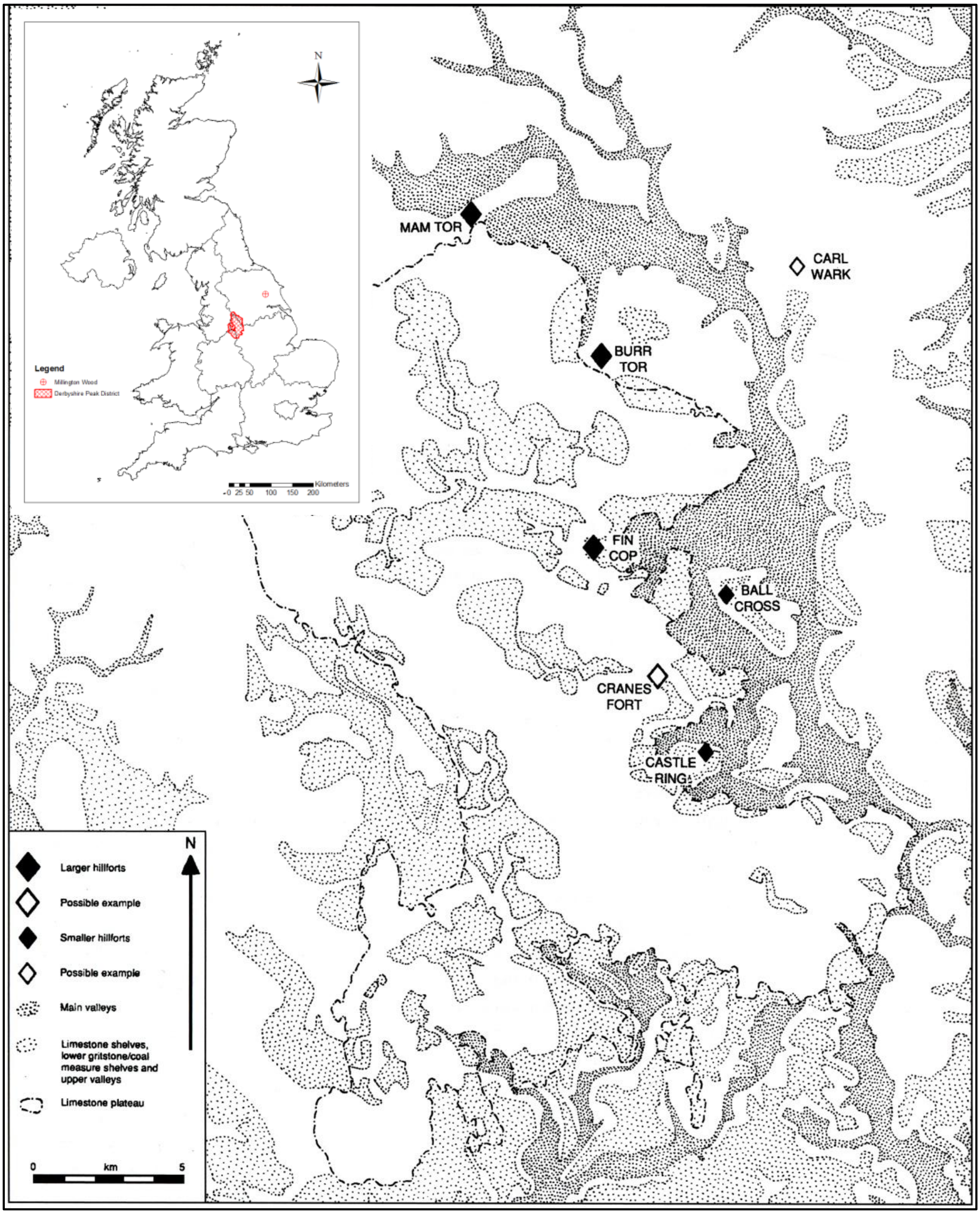


Image taken from Barnatt & Smith (1997)

The hill forts are each associated with a focal settlement, and generally occupy positions of high topography on upland areas overlooking the settlement. Iron Age burial sites are rare in the Peak District (Beswick & Wright, 1991), with the only recorded instance at an upland site on the Carboniferous Limestone of the White peak at Winster between Matlock and Bakewell. Artefacts retrieved from the burial include pottery, an awl, a ploughshare bar and quern stones suggesting an agricultural association. The assemblage is described unique, and representing 'the most explicit expression of an agrarian association with burial yet recognized in Iron age Britain', (Beswick & Wright, 1991; 53).

The construction of fortified settlements is suggested as resulting from both a decline in productive agricultural land resources on the gritstone Dark Peak uplands (Long *et al*., 1998) at the end of the last millennium BC, and the need to defend the remaining land resources of the limestone plateau against displaced human immigrants (Barnatt & Smith, 1997). A percentage of the population displaced from the millstone grit uplands may have settled in adjacent valley sites; evidence of continued agricultural activity is suggested by the recovery of rotary beehive querns from such sites on the eastern fringes of the Peak District (Bevan, 2000). The southern Pennine hillforts may represent a focus point for local communities controlling local agricultural and mineral resources as part of a larger trade network. Analogues for this proposition are the hill forts to the west in Cheshire and at Morecambe Bay where local communities are suggested to have controlled access to the Irish Sea trade routes and local salt production (Harding, 2004).

The paucity of late Iron Age fields, villages and farms in the Peak District is attributed to permanent settlement in the region being abandoned and replaced by seasonal incursions by groups exploiting the summer pasture (Hodges & Wildgoose, 1981; Harding, 2004). Indeed Harding (2004) suggests that by the fifth or fourth centuries BC all the hill forts in the southern Pennines could potentially have been abandoned through the effects of climatic deterioration in late Bronze Age; the only significant revitalization occurring after Roman occupation when lead mining began. However, an alternative hypothesis put forward for the White Peak (Beswick & Wright, 1991) suggests that many later Iron Age sites may have been buried beneath subsequent settlements; the authors citing the fact that water resources provided by spring-lines represents a significant factor for both historical and modern towns and villages in the limestone dales.

Chapter 5: Methods

Introduction

Fossil pollen extracted from buried barrage tufa pool sediments at two field sites in the White Peak, Derbyshire is used as an environmental proxy in order to examine if local vegetation change is a significant environmental factor influencing the cessation of barrage-building tufa systems in the Wye and Lathkill valleys, Derbyshire at 4.2-3.8 ka BP in the mid-late Holocene (Pedley *et al*., 2000). Pollen analysis is used to produce percentage diagrams and then a process-model based approach to landscape reconstruction is then utilised (Prentice, 1985; Sugita, 1994). A modern vegetation calibration dataset providing relative pollen productivity estimates (RPPE's) of White Peak tree taxa and association tables of herb taxa is acquired to allow the degree of overrepresentation and underrepresentation of mid-late Holocene vegetation to be considered in a semi-quantitative reconstruction of past vegetation at the two tufa pool sites.

Moss surface samples and vegetation survey data are acquired from five upland valley woodland sites in Derbyshire and one upland valley woodland site in East Yorkshire, enabling RPPE's of tree taxa and association tables of indicator species of herb taxa to be produced. Pollen taphonomy in mosses is examined at three valley woodland locations in the White Peak, Derbyshire to provide insight of spatial variations in pollen deposition and post-depositional processes affecting pollen in mosses which can influence the accuracy of RPPE datasets. Fluvial pollen taphonomy is examined at a section of the River Wye in Derbyshire in order to provide a context for the interpretation of fossil pollen assemblages acquired from the Holocene tufa pool sediments. The locations of study sites described in this chapter are displayed in figures 3.1 – 3.5 in chapter 3.

5.1 Relative Pollen Productivity Estimates (RPPE) study, Association Indices study and Moss Polster Pollen Taphonomy study

5.1.1 Selection of sites

The RPPE dataset and the association index dataset were used in a semi – quantitative interpretation of fossil pollen data representing upland valley woodland vegetation in the Wye and Lathkill valleys in Derbyshire at the period encompassing tufa decline during the mid – late Holocene. This dictated that site selection should be based on similar modern day ancient or ancient semi-natural upland woodland sites on similar limestone geology (Lytle & Wahl, 2005). Woodland field sites in Derbyshire and East Yorkshire were identified using Google Earth in association with the Ancient Woodlands Inventory facility available online from the Natural England MAGIC internet portal (Natural England, 2014_e).

The Ancient Woodland Inventory defines ancient woodland as land that has had a continuous woodland cover since at least 1600 AD, and may be ancient semi-natural woodland (ASNW) which retains a native tree and shrub cover that has not been planted. This woodland type may have been managed by coppicing or felling and allowed to regenerate naturally, or be a plantation on an ancient woodland site (PAWS) where the original tree cover has been felled and replaced by planting, often with conifers, usually over the last century. The selected field sites were then used to acquire moss surface samples and carry out vegetation surveys necessary for the RPPE, association index and terrestrial pollen taphonomy studies.

A total of 6 valley woodland field sites were identified for sampling of moss polsters. Five field sites were located in the White Peak, Derbyshire with a single field site located in the East Yorkshire Wolds. In the White Peak, moss polsters were taken from 3 field sites in Cressbrook Dale, 3 field sites in Millars Dale, 3 field sites in Chee Dale, 3 field sites in Lathkill Dale, and 2 field sites in Bradford Dale. In East Yorkshire, moss polster surface samples were taken from two locations within Millington Wood in Millington Dale. All field sites are situated on limestone uplands and classified as ancient or semi-natural woodland; field site locations are illustrated in figures 3.2 to 3.5 in chapter 3.

The rationale for the terrestrial pollen taphonomy study was to use 10 spatially discrete moss surface sub-samples from within a defined spatial area (1 metre) at each field site as a method of identifying if pollen deposition across the moss surface displayed spatial variation or was uniform within the defined 1 metre area. The three field sites chosen for this study each display a range of unique micro-topographic features such as differences in height above the woodland floor and degree of steepness of slopes across the moss surface. At each quadrat, sub-samples were taken from topographic high points, middle slope locations and lower slope locations. This approach allowed the potential of topographic height and slope processes affecting pollen deposition and post depositional pollen transport at the ten sub-sampling points to be evaluated at each field sites based on the pollen percentages of tree and herb taxa recorded at each sub-sample location.

5.1.2 Sampling strategy and fieldwork

In order to produce estimates of pollen productivity (RPPE), a prerequisite is an empirical knowledge of the distance weighted plant abundance (DWPA) around the moss polster sampling location (Prentice & Webb, 1986). This requires vegetation survey techniques which allow vegetation to be recorded as taxon-specific percentage cover at incremental distances away from the pollen assemblage sampling point. A variety of vegetation survey techniques suitable for creating RPPE datasets are described by Broström *et al.*, (2008). A modified version of these methods has been developed by Dr Jane Bunting at Hull University for use with the SURVEY software suite developed at Hull University by Dr Bunting and Mr Richard Middleton as a part of the Crackles Project. This method uses a combination of quadrat sampling up to a 10 m radius of the sampling point, with visual assessment of vegetation associations and individual tree taxa carried out from 10 - 100 m radius of the sampling point. The percentage cover data is then entered into dedicated SURVEY software to produce estimates of DWPA for use in ERV models.

Vegetation field surveys at the Derbyshire and East Yorkshire field sites utilised the Hull University Crackles Project vegetation sampling methodology, which utilise twenty one 1 metre quadrats within a 10m radius from the surface sample point; both herb and tree taxa are recorded within this radius (Bunting, personal communication). Vegetation beyond the 10 metre radius was then surveyed out to a 100m radius from the central sampling point, with tree communities and isolated tree taxa recorded to allow percentage cover to be estimated; non-vegetated areas were recorded as non-pollen producing. Tree communities in the 10 – 100m survey area were defined using a combination of field survey data in conjunction with land-cover satellite data in a GIS (Broström *et al.*, 2008). Areas of vegetation of the same canopy colour and texture were identified in a GIS as potential tree communities; ‘ground-truthing’ and validation of the identified tree communities and associations was then carried out during the vegetation survey to a radius of 100m around the sampling point.

5.1.3 Sample collection and laboratory processing

Surface sampling at the Derbyshire and East Yorkshire field sites took place in January 2010 and January 2011 as this is a period when no pollen release occurs, and pollen dispersed from the previous flowering season is integrated into mosses. Moss surface samples were taken from each of the six field sites and each sampling location was then georeferenced using a Garmin handheld GIS. Moss surface samples were all collected in the same way, with each sample being collected from a single moss polster using *Sphagnum* spp. where possible. Approximately 20cm^3 of the green parts of the moss were snipped off and stored in sealed polythene bags in a refrigerated store prior to laboratory preparation. The field sampling strategy for the terrestrial pollen taphonomy study used a hoop with a diameter of 1 m which was placed over an area of continuous *Sphagnum* spp. forest floor cover. Within the 1 m hoop, ten sub-samples were taken from different locations within the hoop area using the same methodology previously described for the RPPE sampling. The location of each sub-sample within the 1 m hoop was marked with a numbered tab and each survey area was then photographed. Sample locations are displayed in figures 3.2 and 3.3 in chapter 3, and field site photographs are displayed in figures 5.1 – 5.3 below.

Figure 5.1: Chee Dale quadrat, Derbyshire.

Figure 5.2: Cressbrook Dale quadrat, Derbyshire.

The cross-sectional topography of the moss within the quadrat was measured in the field using a 1m wooden rule and a retractable 5m measuring tape, with topographic height being measured in relation to a fixed point on the woodland floor adjacent to the quadrat.

Figure 5.3: Millington Dale quadrat, East Yorkshire.

Moss samples were stored in the Geography Department cold store at Hull University prior to sample processing and pollen extraction. For the purposes of this study only the green part of the moss polsters were utilised, as this portion of a moss sample has been identified as an effective pollen trap which records a minimum of 1 – 2 years of pollen deposition (Räsänen *et al*. 2004). A subsample of 2cm^3, measured by displacement, was taken from each moss polster for processing. Pollen extraction followed protocols described by Moore *et al*. (1991), and utilised acetolysis for removal of organic residues. The use of an exotic marker, following the protocols of Maher (1981), was applied to all samples for the purpose of defining pollen concentration. Pollen identification was carried out with an Olympus BX45 binocular microscope using x400 magnification, with a pollen sum of 500 grains per sample point being counted. Pollen identification utilised pollen keys in Moore *et al*. (1991) and the Martyn Waller reference collection at Hull University. Pollen taxonomy and nomenclature follows Bennett *et al*. (1994).

5.1.4 Models of the pollen – vegetation relationship

The spatial scale of the vegetated landscape which is 'sensed' (Prentice, 1988) by pollen is of prime consideration in attempting to reconstruct past vegetation patterns based on fossil pollen. There are two primary approaches to calibrating pollen data: the representation or correction factor approach (Birks & Gordon, 1985), and the comparative approach (Janssen, 1966; Räsänen, 2001).

The modern analogue technique is the most widely used example of the comparative approach, and has been used to interpret past pollen assemblages (Andersen *et al*., 1989; Broström *et al*. 1998). The modern analogue technique compares modern pollen assemblages from known vegetation units with fossil assemblages, and uses numerical methods to identify the best match (Wahl, 2004). However past communities may not necessarily resemble any known modern analogue assemblages (Delcourt & Delcourt, 1981), meaning the problem of how to interpret non-analogue past communities remains.

The second approach to pollen-vegetation calibration is the representation factor approach, which is based on the assumption that the relationship between pollen and vegetation takes the form:

$$P=f\,(v) \qquad \text{(i)}$$

In the equation, P represents a sedimentary pollen assemblage and v is the composition of the vegetation surrounding the site at the time of deposition. Von Post (1967) recognized that modern pollen assemblages displayed systematic variation with the composition of the surrounding vegetation, and this assumption has formed the basis of most subsequent theories of pollen analysis. The recognition that some taxa are consistently under or over represented in pollen assemblages has resulted in the necessity to obtain a more precise understanding of how vegetation is recorded by pollen assemblages (Jackson, 1994).

The Davis Model

The representation factor approach to pollen–vegetation calibration is based on the fundamental assumption developed by Davis (1963) that pollen productivity is both variable in magnitude between individual taxa, and that some species have more effective pollen dispersal strategies resulting in higher proportions of the pollen of these taxa in pollen assemblages. In order to derive vegetation coverage from pollen assemblages Davis calculated taxon-specific correction factors or ‘R-values’ where the relationship between pollen and vegetation in a specified area (A_i) takes the form:

$$P_{ik} = r_{ik}\, v_{ik} \qquad \text{(ii)}$$

Where P_{ik} represents a sedimentary pollen assemblage, v_{ik} is the composition of the vegetation surrounding the site at the time of deposition and r_{ik} is the taxon-specific correction factor.

Based on Davis’s model, if species *a* represents 40% of the vegetation surrounding site A_i and 80% of the pollen percentage in the sedimentary pollen assemblage P_{ik}, an R –

value for species *a* is derived by division of the pollen percentage of species *a* by the vegetation percentage of species *a* giving a correction factor (R – value) of 2. This R – value can then be applied to fossil pollen percentages to correct for over or under representation of a species. In the case of species *a*, an over – represented species, the correction factor of 2 suggests it is either a very effective pollen disperser and/or has very high pollen production. The fundamental flaw with the R-value model was that it did not recognise or acknowledge the 'background' pollen component which entered the pollen assemblage from vegetation situated outside the specified area A_i. The R-value model also did not clearly define the pollen source area, and did not account for the site-specific and region-specific variations in pollen productivity for individual taxa.

The Andersen Model

The R–value model was subsequently refined by Andersen (1970) to include a background component, ω_i, which entered the pollen assemblage from outside the survey area. The Andersen pollen-vegetation calibration model takes the form:

$$Y_{ik}=\alpha_i X_{ik}+\omega_i \qquad \text{(iii)}$$

Where α_i and ω_i are taxon specific constants: α_i = relative pollen productivity for species i, ω_i = background term denoting pollen arriving from outside the survey area for taxon i at site k (an influx term, measured in grains per unit area per time unit), Y_{ik} = pollen influx (grains per area per unit time), X_{ik} = absolute abundance of taxon i within a fixed distance around site k. The Andersen model, whilst providing a solution to the 'constant' background pollen input utilised pollen influx data which, while being linearly related to absolute vegetation data, is extremely difficult to obtain and highly variable within and between sedimentary basins of different sizes and with differential sedimentary processes (Maher, 1981; Davis *et al.*, 1984).

The Prentice Model

The model of Prentice (1985) was developed to provide a quantitative theory to explain characteristics of pollen production, dispersal and deposition processes and to predict pollen source areas and the influence of basin size. A core component of the

Prentice Model are the integrated equations of Sutton (1953) to approximate the behaviour of particles released from a ground-level source, a hypothesis which may initially appear counter-intuitive. The influence of pollen grain weight is stressed as an important parameter related to pollen transport and hence the scale of representation of a plant species. Prentice argued that in woodlands, trees do not behave as elevated pollen sources as the forest canopy acts as a particle sink situated at source level intercepting airborne pollen grains and increasing sedimentation on the forest floor; pollen still airborne at the forest edge is down drafted onto land or water sedimentary surfaces. The Prentice Model describes pollen loading at the central point of a sedimentary basin, making this model applicable to predicting pollen deposition on sites such as peat bogs where no, or very limited, post-depositional mixing occurs.

The Prentice – Sugita Model

The Prentice model (Prentice, 1985) was modified by Sugita (1994) to describe pollen loading on the entire surface of a sedimentary basin, being developed to predict pollen deposition in lakes where complete mixing of pollen types occurs; the resulting Prentice –Sugita model effectively representing two extremes of a continuum from no mixing to complete mixing Jackson & Lyford, 1999).

ERV method of parameterising the Prentice – Sugita Model

The pollen-vegetation model of Andersen (1970) was further developed by Prentice & Parsons (1983), who used pollen percentages instead of pollen accumulation rates and incorporated an additional term to correct for the 'Fagerlind Effect' (Fagerlind, 1952) whereby the linear relationship between the absolute variables becomes non-linear when they are expressed as percentages. Sugita (Sugita, 1993; 1994) concluded that distance-weighting of plant abundance data is fundamental to obtaining a 'pollen's view of the landscape', as vegetation closer to the pollen sampling point has a greater influence on a pollen assemblage than vegetation further away. The 'Extended R – value' or ERV model comprises 3 sub-models, sub-models 1 and 2 (Prentice, 1985) and sub-model 3 (Sugita, 1994). Each sub-model estimates relative pollen productivity and background pollen by comparing pollen percentage data with distance weighted vegetation data from different distances around the pollen sampling point.

Sub-models 1 and 2 (Prentice, 1985) assume minimal post-depositional mixing of pollen and is a reasonable simulation of bogs and mires where sediment movement is limited. Sub-model 3 (Sugita, 1994) assumes total mixing of pollen between deposition and incorporation into sediment, and was designed to simulate pollen loading in lakes. The ERV model (Prentice, 1985; Sugita, 1999) uses a maximum likelihood method to calculate likelihood function scores representing the negative value of the 'Support Function' (Sugita, 1994), which are plotted as a function of distance from the pollen sampling point. The distance (or the radius of the vegetation survey carried out around the pollen sampling point) away from the pollen sampling point at which the likelihood function score curve reaches an asymptote indicates the relevant source area of pollen (RSAP) beyond which the fit of the pollen-vegetation data does not improve (Sugita, 1994).

The basic ERV model takes the form:

$$P_{ik} = \alpha_i \, v_{ik} f_{k} + z_i \qquad \text{(iv)}$$

Where P_{ik} = pollen percentage of taxon i at site k, α_i = relative pollen productivity of taxon i, v_{ik} = vegetation data for taxon i within a defined radius of pollen deposition site k, f_k = a 'site correction factor' for site k which is a function of all the α and z values for all the taxa at site k (the formula for f_k varies between ERV sub-models; in sub-model 2 the correction is applied to P_{ik} not v_{ik}), and z_i = a corrected background component representing input of pollen beyond distance z (again the formula varies between ERV sub-models). The equation of the ERV models separates pollen deposition into two components, a variable component $\alpha_i \, v_{ik}$ which represents pollen from within a certain radius of the pollen deposition point, and a constant background component z_i which represents the pollen input from outside this radius.

Pollen counts and distance-weighted vegetation abundance data are analysed using computer programmes developed for the ERV models e.g. ERV version 6 (Sugita, unpublished) or PolERV (Bunting & Middleton, 2005). As there are 2 unknown parameters in the equation in all ERV sub-models e.g. α z, an algebraic solution is not possible. Numerical 'best fit' estimates of the values of α_i and z_i are therefore derived from setting up a series of simultaneous equations (using all known values of P_{ik} and v_{ik} for all taxa) using the Maximum Likelihood method (Prentice & Parsons, 1983). Each sub-model estimates RPPE (α_i) and background pollen (z_i) by comparing a pollen dataset with multiple vegetation datasets, each collected at different distances around the pollen sampling point e.g. the vegetation survey radius. Pollen productivity (α_i) for taxon *i* is described in relation to other taxa included in the sample, one of which is set to unity e.g. α =1.0; the PPE of the other taxa are then calculated relative to this reference taxon e.g. Poaceae. Poaceae is often used as a standard reference taxon for both herb and tree RPPE studies e.g. Hjelle (1998; Mazier *et al.*, 2008), as it is a widespread taxon which is well represented in both modern and fossil pollen assemblages Broström *et al*. (2004). However the suitability of Poaceae as a reference taxon has been questioned by Broström *et al*. (2008) on the grounds that the taxon has many region-specific species which display differences in pollen productivity which will in turn affect the RPPE of other taxa.

ERV sub-models 1 and 2 have been tested with empirical pollen and vegetation data from lakes within closed forested landscapes, and produced α values that were consistent and *z* values similar in magnitude and ranking between models (Parsons & Prentice, 1983). Subsequent development of the Prentice ERV sub-models (Prentice, 1985) by Sugita (1994) produced an ERV sub-model which describes pollen loading on the entire surface of a sedimentary basin, where deposited pollen becomes completely mixed before sedimentation, and was developed for predicting pollen deposition in lakes. The Sugita ERV sub-model differs from the two sub-models (1 & 2) of Prentice & Parsons (1983) in that both sub-models 1 and 2 use pollen and vegetation data that are expressed as percentages, whereas the Sugita sub-model 3 (Sugita, 1994) uses pollen percentages and vegetation expressed in absolutes values. The distance weighting methodology of the Sugita ERV model also differs from the Prentice ERV sub-models, as the spatial distribution of each taxon is expressed as a function of distance in metres from the centre of the depositional basin. The Sugita ERV sub-model assumes and estimates constant background pollen loading between sites, the Prentice ERV sub-model 1 assumes a constant background in terms of species-specific pollen proportion, and the Prentice ERV sub-model 2 assumes a constant proportion of background in the ratio of pollen loading to total plant abundance of all the taxa involved (Prentice & Parsons, 1983). For all the ERV models, the assumption of a constant background pollen (z_i) input is reasonable as long as the z_i is small relative to total pollen deposition (Jackson & Kearsley, 1998). For the purposes of this study, which uses pollen and vegetation data expressed as percentages, the ERV sub-models (1 & 2) of Prentice (1985) are used to estimate RPPE (α_i) and background pollen (z_i).

Distance weighting of vegetation

Distance weighting of vegetation includes step-wise inverse weighting, 1/d, (Prentice & Webb, 1986), step-wise inverse square weightings, ($1/d^2$) (Webb *et al.*, 1981; Calcote, 1995; Jackson & Kearsley, 1998), and step-wise taxon-specific distance weightings (Prentice, 1985; Sugita, 1994; Calcote, 1995) which takes into account both the distance between the source plant and the pollen sampling point as well as the 'transportability' of the pollen grain specific to each taxon. Step-wise taxon-specific distance weighting (Prentice, 1985; Sugita, 1994; Calcote, 1995) utilises a model of pollen dispersal and deposition based on Suttons equation for diffusion of small particles from a ground - level source (Sutton, 1953; Prentice, 1985). The atmospheric diffusion model of Sutton (1953), as applied by Prentice (1985), integrates a turbulence parameter, a vertical diffusion coefficient, wind speed and the fall speed of each pollen taxon; the first two parameters can be treated as constants, using the values prescribed for neutral atmospheric conditions (Chamberlain, 1975; Prentice, 1985). Wind speed can be set to a level in m/s applicable to the aims and objectives of the research question. Taxon-specific fall speeds are available in the existing literature (Sugita 1993, 1994; Broström *et al.*, 2004), or can be size measurements using Stokes Law (Gregory, 1973).

Pollen source areas

The 'relevant source area of pollen' or RSAP Sugita (1994) represents the distance from the sampling point beyond which correlation between DWPA and pollen loading does not improve in the ERV model, displayed graphically as an asymptote. Provided the background pollen is consistent, minimal further information concerning the linear relationship between pollen and plant abundance can be obtained by surveying vegetation beyond the RSAP (Sugita, 1994), and in order to produce robust calibrations of pollen-vegetation relationships the vegetation sampling area (i.e. the vegetation survey radius) should incorporate the RSAP (Bunting et al., 2004). The spatial scale of pollen source area can be regionally variable between lakes and peat bogs of similar dimensions (Sugita, 1994), and is influenced by the size and spatial distribution of vegetation patches within the landscape mosaic (Bunting *et al.*, 2004; Broström *et al.*, 2005; Hellman *et al.*, 2009$_a$; Hellman *et al.*, 2009$_b$).

Reconstruction of past vegetation based on pollen analysis is dependent on assumptions about the relationship between pollen source area and basin size and type e.g. bog or lake (Prentice, 1985; Calcote, 1995), taxon pollen production and dispersal properties (Jackson & Lyford, 1999), and vegetation patterning in the landscape (Bunting *et al.,* 2004). Pollen source area is known to vary with the size of the depositional basin (Prentice, 1985; Sugita, 1994), the differing dispersal characteristics of pollen types (Prentice, 1985; Jackson, 1994) and the spatial distribution of taxa types in the vegetation (Sugita, 1994). Small basins such as forest hollows 'sense' pollen coming from local vegetation (Calcote, 1995; Sugita, 1994) within a radius of 50 – 100m which is superimposed on a constant regional pollen signal. In lake basins, as the perimeter size of the lake basin increases, the pollen loading (per unit area) from local pollen sources declines; pollen loading (per unit area) from regional vegetation remains constant because regional pollen deposition is similar across the entire lake surface (Davis, 2000; Nielsen & Sugita, 2005).

The most robust RPPE data is obtained using vegetation data from the area surrounding the pollen sampling point that represents the 'source area' for local pollen input (Mazier *et al.*, 2008). Pollen source area can be defined theoretically in several different ways. In homogenous vegetation, the 'characteristic source area' (Prentice, 1988; Sugita, 1993) which predicts that the source area for a particular taxon will vary dependant on the size and type of site as well as the properties of the pollen type (Tauber, 1965; Jacobson & Bradshaw, 1981; Bradshaw & Webb, 1985). Most vegetation is in reality often patchy, being formed of heterogeneous mosaics of different vegetation types within the landscape (Sugita, 1994; Bunting et al., 2004). In this scenario, the pollen - vegetation relationship is more complex and requires a different concept of pollen source area; Sugita (1994) stressed the importance of basin size and vegetation structure, and proposed that the 'relevant source area of pollen' or RSAP is primarily influenced by these factors. The RSAP is an important parameter for estimating an appropriate spatial resolution at which reconstruction of past vegetation can take place. Through estimation of RSAP, it is then possible to identify the percentage contribution of local pollen component at a site e.g. 30% which is superimposed on the consistent 'background' pollen component common to the regional pollen spectrum (Sugita, 1994). Factors influencing RSAP include vegetation patch size and distribution, number of taxa analysed, wind speed, and method of distance weighting vegetation Nielsen (2004).

Sugita (1994) used the Prentice ERV model to separate the local pollen signal from the background pollen in a series of simulation experiments using hypothetical 'patchy' landscapes, using a maximum likelihood method to calculate relative pollen productivity estimates (RPPE's) and the background extra local/regional pollen component. Likelihood function scores were then plotted as a function of distance from the pollen sampling point (Sugita, 1994, 1999); the point where the curve reaches an asymptote represents the relevant source area of pollen e.g. the fit of the pollen-vegetation data to the model does not improve beyond this distance (Sugita, 1994). Sugita (1994) suggested that little further information about the linear pollen – vegetation relationship would be gained by surveying vegetation beyond the RSAP e.g. the distance from the sampling point beyond which correlation between distance weighted vegetation and pollen loading does not improve. Distance weighting of vegetation abundance data is important in order to obtain the 'pollens view of the landscape', as plants growing closer to the sampling point will have a greater influence on a pollen assemblage than those growing further away (Prentice, 1986; Sugita, 1994).

Methods of reconstruction

The reliability of pollen analysis as a tool to reconstruct past vegetation is dependent on a precise understanding of how vegetation composition is reflected in pollen assemblages (Broström, 1998), with a number of approaches available which can be utilised to analyse the pollen-vegetation relationship. The comparative approach (Gaillard *et al*., 1992), examines relationships between modern-day vegetation and pollen assemblages in order to reconstruct past vegetation and landscape composition i.e. the modern analogue technique (MAT) (Overpeck *et al.* 1985; Gaillard *et al.,* 1994; Calcote, 1995; 1998) 'matches' a fossil pollen spectrum with one or more modern pollen spectra using numerical methods such as dissimilarity coefficients (Wahl, 2004), with resemblance being taken as evidence for a similarity in vegetation composition and structure. The MAT has been viewed as problematic by Delcourt & Delcourt (1991), as past communities may not have an existing modern analogue due to the different abiotic (e.g. climatic conditions and soil properties) and biotic (e.g. vegetation types) conditions which existed in the past. If the MAT approach is applied to research questions, it is necessary that the past and modern analogue samples come from matched environmental contexts in order to produce meaningful reconstructions (Gaillard *et al.*, 1992; 1994; 1998).

Examples of process-based modelling include the mechanistic modelling approach POLLSCAPE of Sugita (1999), which uses the pollen fall speed and relative pollen productivity of individual taxa, vegetation maps, locations and sizes of depositional basins, and wind speed to produce computer simulations of pollen dispersal and deposition which can then be compared to empirical datasets for validation of the simulated outputs. Vegetation reconstruction models such as the Landscape Reconstruction Algorithm (LRA) of Sugita ($2007_{a,\ b}$) and the Multiple Scenario Approach (MSA) of Bunting & Middleton (2009) provide an alternative, and complimentary, method of vegetation reconstruction that is applicable to non-analogue past environmental investigation (Broström, 2002). In a critique of the pollen - vegetation relationship, Jackson & Lyford (1999) suggest that variations in both wind speed and direction are complicating factors associated with pollen release which must be considered in mechanistic model simulation.

The LRA utilises an inverse form of the ERV models, and requires pollen percentage datasets from multiple large sites (>100 – 500 ha) such as lakes in conjunction with RPPE data to estimate past regional vegetation cover (Hellman et al., 2008) using the REVEALS model component of the LRA (Sugita 2007_a). The LOVE component of the LRA utilises pollen percentage data from multiple small sites, the RSAP of the small sites and RPPE data (2007_b), the regional vegetation estimate from the REVEALS model is then used to quantify and then subtract the ‘background’ pollen and provide an estimate of local vegetation composition at a site. The Multiple Scenario Approach (MSA) is an iterative simulation approach to the reconstruction of past landscape – vegetation relationships (Bunting & Middleton, 2009) which utilizes deterministic and probabilistic ‘rules’ for taxon placement; a combination of modelling and analogue matching (Bunting *et al*; 2008), and provides a tool to address the problem of equifinality whereby different landscape mosaics produce the same pollen signal. Alternative quantitative landscape-vegetation reconstruction models such as the MAT (Calcote, 19980 and the Landscape reconstruction algorithm (Sugita, 2007$_{a}$, $_{b}$), are reliant on, and limited by, the availability of modern surface samples from locations representing possible past communities.

The MSA reconstruction process can be carried out with a single pollen record, although multiple sites with a strong chronological framework are suggested as producing more robust results (Pratt, 2006). Reconstructions are carried out for individual time points described as 'time – slices', which are spatially explicit two-dimensional vegetation maps representing a single time period. The time slices are then stacked chronologically at each sample location generating a hypothetical reconstruction of landscape dynamics at that point. Once the taxa of interest have been selected and the biotic and abiotic parameters of the taxa have been combined with the ecological requirements in LANDSCAPE (Middleton, unpublished data, 2006), possible vegetation coverage scenarios can be generated. Unless landscapes are given 100% coverage of with a patch community, random placement factors will generate multiple maps from each combination of landscape rules; these outputs are described as 'families' (Bunting & Middleton, 2009). Pollen assemblages are then simulated at a specific location, using multiple members of each family. These simulated pollen assemblages are then compared with actual fossil pollen assemblages, and the most likely families are identified using squared chord distance cut-off values (Wahl, 2004). Larger numbers of replicates are then run for each likely family member to identify the 'best-fit' scenarios, again using squared chord cut-off values. Vegetation reconstruction maps displaying vegetation mosaics can then be produced, allowing a visualisation of the simulation to be examined.

5.1.5 Numerical methods

RPPE

The ERV method deals with taphonomic issues by using specific models; the Prentice sub-models 1 & 2 assume no mixing of pollen, and is therefore applicable to sampling sites such as mires, bogs and forest hollows, the Prentice-Sugita sub-model (model 3) assumes complete mixing in a water column i.e. lake or pond. In all the ERV sub-models there are two unknown parameters in the equation, α and z, meaning an algebraic solution is not possible. Numerical estimates of α and z can be made by setting up simultaneous equations which use all the known values of P_{ik} and v_{ik} for all taxa. The value of α for one taxon must be set to 1.0 to serve as a reference taxon in order to allow relative values of α for all other taxa to be sensibly expressed. The selected reference should display a gradient in both pollen and vegetation proportions, and be consistently present at all sites e.g. Poaceae (Broström *et al.*, 2004; Mazier *et al.*, 2008). A series of iterations are then carried out using all known values of P_{ik} and v_{ik} and the set of estimates displaying the best fit are then determined using the Maximum Likelihood method Prentice & Parsons, 1983).

Percentage pollen counts and DWPA data from each of the 14 field sites provided the inputs necessary to run the POLERV models (Bunting & Middleton, 2005) and obtain relative pollen productivity estimates (RPPE's) for both tree and herb taxa. Acer was used as the reference taxon since it is abundant in the woodlands at all sites. Taxa present in the vegetation surveys but absent from pollen counts (11 taxa) were removed from the datasets. Taxa present in the vegetation at less than 4 locations, and taxa present in pollen counts at less than 4 locations (15 in total) were also removed from the datasets. Of the remaining 17 taxa, six had less than 6 pollen-vegetation pairs. These six (6) taxa were not used further in the ERV data analysis. As 32 taxa had been removed from the initial data, pollen sums were reduced to between 323 and 471 grains, therefore the pollen sums of the remaining taxa at all sites were corrected to an equivalent sum of 500 grains for ERV analysis. Sedimentary basin size was set to zero in the POLERV software, and sub-models 1 & 2 were used. Pollen fall speeds used are displayed in table 7.1.

Association Indices

The relationship between pollen percentages and vegetation composition is complex (Davis, 1984), and pollen-vegetation relationships have been investigated through studies focusing on how the pollen production and dispersal of individual taxa is represented in pollen assemblages (Davis, 1963; Andersen, 1973; Prentice, 1985; Sugita, 1994). An important component of this relationship is the interpretation of past anthropogenic activity e.g. pastoralism and/or arable agriculture using fossil pollen diagrams (Behre, 1981; Hicks, 1988; Hjelle, 1999). Interpretations of anthropogenic activity are often based on inferences drawn from arboreal pollen percentages (AP), where a decline in pollen percentages of tree taxa may be associated with anthropogenic landscape disturbance. Non-arboreal pollen (NAP) types such as Poaceae and Rumex are often used as indicators of the degree of landscape openness and to detect the presence of agricultural or pastoral activity in past landscapes (Behre, 1981; Birks, 1990); evidence of anthropogenic disturbance and landscape management can also be represented through the presence of charcoal in sediments (Conedera & Tinner, 2000).

Herb taxa used as indicators of cultural landscapes (Mazier *et al*. 2006) often produce small amounts of pollen that is poorly dispersed (Faegri & Iversen, 1989) and thus have a very small relevant pollen source area i.e. <2 m (Bunting, 2003), meaning that pollen of these taxa may not be present in sub-fossil pollen assemblages unless pollen source plants were adjacent to the sampling site. Herb taxa identified as strong indicators of human activities may be classified as local (i.e. Centaurea) or regional (i.e. Plantago & Rumex), dependant on the magnitude of pollen production and effectiveness of pollen dispersal of each indicator taxa and the location and densities of the pollen-producing source plants within the landscape; indicators classified as regional reflecting a less precise relationship with specific human-influenced environments (Brun, 2011). Presence-absence data of pollen morphotypes and associated plant taxon have been used to calculate indices of under-representation, over-representation and association for plant taxa in order to identify those pollen types which accurately reflect local vegetation communities (Behre, 1981; Davis, 1984; Hjelle, 1997; Bunting, 2003; Mazier *et al*. 2006). Plants which are present both in the local vegetation and in pollen assemblages obtained from surface samples produce high association index values. Taxa can have low association index values because the pollen is present in the assemblage but the pollen producing plant is absent in local vegetation, or the pollen may be absent from the assemblage but the pollen producing plant is present in the local (surveyed) vegetation.

It is important to differentiate between these two pollen-vegetation scenarios, so additional indices are utilised to define both under and over representation of individual taxa. Under-represented species are often taxa which have autogamous, cleistogamous and more specialized zoophilious flowers which have very poor pollen production and dispersal (Faegri & Iversen, 1989). Pollen types which are highly under-represented can be categorized as taxa with very poor pollen production and/or poor dispersal; or taxa with very poor pollen production which have good dispersal properties i.e. anemophilous taxa (Davis, 1984). Pollen types which are highly overrepresented must have extremely efficient pollen dispersal as the taxon is absent in the local vegetation which has been incorporated into the survey methodology; pollen production of highly overrepresented taxa may be either high or low (Davis, 1984).

The index of association A is calculated by the formula:

$$A = \frac{B_o}{P_o + P_1 + B_o} \tag{v}$$

Where B_o = number of locations in which the pollen type is present in the surface sample and the associated plant taxon is present in the vegetation survey of the location; P_o = the number of locations in which the pollen type is present in the surface sample but absent from the vegetation survey, and P_1 = the number of locations in which the plant taxon is present in the vegetation survey but the pollen type is absent from the surface sample.

The under-representation index U is calculated by the formula: (vi)

$$U = \frac{P_1}{P_1 + B_o}$$

Where P_1 and B_o are defined as for the association index.

The over-representation index O is calculated by the formula: (vii)

$$O = \frac{P_o}{P_o + B_o}$$

Where P_o and B_o are defined as for the association index.

All indices range in value from 0.0 to 1.0. The association index *A* is a measure of whether the presence of a pollen type in a surface sample is an indication of the presence of the associated plant within the local vegetation. A low association index value for a pollen type can occur when pollen is present but the plant absent from the local vegetation (over-represented), or when the plant is present but the pollen absent (under-represented). The under-representation index *U* ranges from 1.0 for pollen types that are never found when the plant is present, to 0.0 for pollen types that are always present when the plant is present. The over-representation index *O* ranges from 1.0 for pollen types that are always present when the plant is never found, to 0.0 for pollen types that are always present when the plant is present.

5.2 Fluvial pollen taphonomy study

5.2.1 Selection of sites

The area chosen for this study is the Wye Valley in the White Peak district of the southern Pennines within the boundaries of the Peak District National Park in Derbyshire, England. This study required a site which could allow greater insight into pollen taphonomy in river pools in areas of karstic hydrology; this rationale being dictated by the primary aim of this thesis which is to use sub-fossil pollen extracted from fluvial sediment deposited during the mid-late Holocene as an environmental proxy for catchment vegetation change. The field site location is displayed in figure 3.2 and 3.3 in chapter 3; a photograph of the sampling site is presented in figure 5.4 below.

Environmental setting

The catchment geology of the River Wye is primarily Lower Carboniferous Dinitian shelf limestone characterised by a mature karstified subterranean hydrological system influenced by significant faulting, which forms zones of resurgence (the point at which a subterranean stream reaches the surface and flows overland), and defines hydrological boundaries within the White Peak district (Banks *et al*. 2012). The River Wye is approximately 25 km in length, falling from 300m OD at Buxton to 98m OD at the confluence with the River Derwent at Rowsley and is the primary river draining the White Peak. The River Wye has a catchment area of 154 km^2 (Centre for Ecology and Hydrology, 2014$_a$) which influences the gauging station at Ashford, and flows through steep-sided and heavily vegetated gorges in its upper and middle reaches i.e. Millars Dale, whilst the lower reaches of the Wye below Ashford-in-the-Water typically run through relatively open pastureland. Modern land use in the Derbyshire Dales adjacent to the River Wye is primarily upland pasture; the total grassland as a percentage of farmed land was 89.3% in 2010, and arable land use e.g. percentage of farmed land used for cereals, was 8% in 2010 (Derbyshire Partnership Forum, 2013). Ancient and semi-natural upland ash woodlands are located in valley sites adjacent to the River Wye i.e. Cressbrook Dale and Millers Dale.

Modern hydrological setting

The river flow in the River Wye is provided by both autogenic (local recharge groundwater captured and held in the limestone aquifer) and allogenic (recharge groundwater captured outside the limestone aquifer which enters the regional limestone aquifer) springs in the Buxton area. The baseflow index of River Wye, Derbyshire is 0.75 (75%) (Centre for Ecology and Hydrology, 2014_b), which is typical of rivers on permeable geology such as limestone (Banks *et al*. 2012). The hydrological effect of these recharge mechanisms, via the White Peak's karstic aquifer, results in river flows of the River Wye and adjacent White Peak rivers such as the Lathkill, Bradford and Manifold being less 'flashy' than river flows in catchments on impermeable geology such as sandstones or granite, and effectively 'damps' the influence of short-duration high precipitation events which would result in flood-level river flows in catchments developed on non-karstic geology.

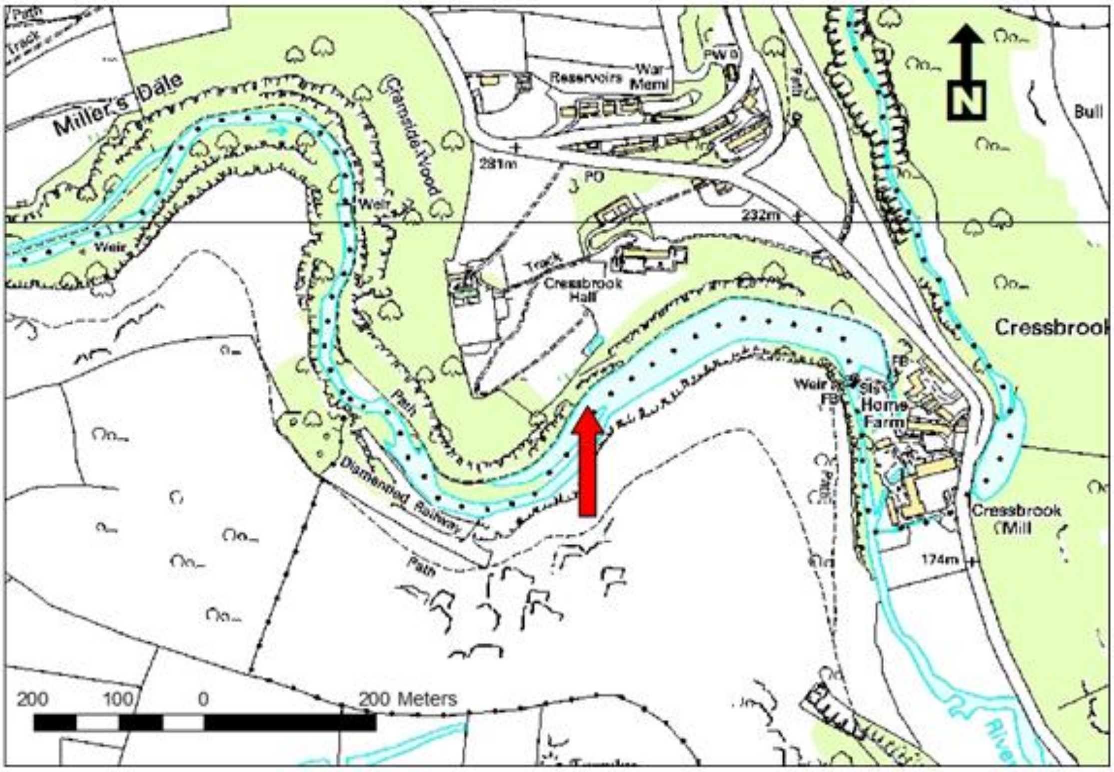
The mean flow of the River Wye between 1965 and 2012 at Ashford-in-the-water was 3.23m^3/s (Centre for Ecology and Hydrology, 2014_c), based on gauged daily flow time series data, making the Wye a relatively slow-moving river in comparison to similar sized rivers developed on non-karstic catchments. The Q_{95} flow (the flow in cubic metres per second which was equalled or exceeded for 95% of the flow record) for the River Wye at the Ashford gauging station between 1965 and 2012 is 1.001m^3/s, and the Q_{10} flow (The flow in cubic metres per second which was equalled or exceeded for 10% of the specified term – a high flow parameter which, when compared with the Q_{95} flow provides a measure of the variability, or 'flashiness', of the flow regime) for the

River Wye at the Ashford gauging station between 1965 and 2012 is 6.188m^3/s (Centre for Ecology and Hydrology, 2014$_c$).

Study site selection

Field site selection was based on locating a river study site in the White Peak which would contain a suitable water depth, sediment type and flow regime to allow pollen rich sediment to be deposited over a number of years, for access to the site be available, and for the site to be safe to sample from a small boat. The geographic location of the Litton Mill field site is shown in figures 3.2 and 3.3 in chapter 3, the pool used as a field site is displayed in figures 5.4 and 5.5 below, and a photograph of the Litton Mill study site is presented in figure 5.6 below.

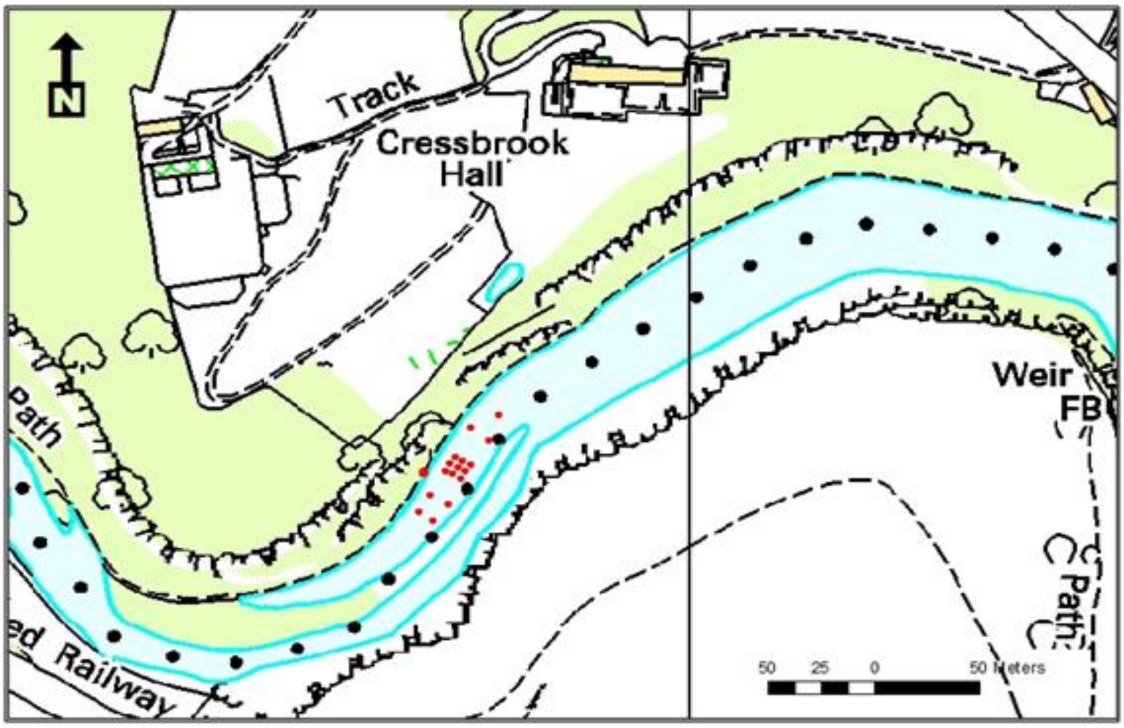
Figure 5.4: Litton Mill field site; note vegetated point bar to the south of the study site.



Map sourced from Digimap - 1: 10 000 OS Raster MasterMap.

A site was identified on the River Wye approximately 1 km downstream of Litton Mill in Millars Dale, Derbyshire. The study site is not a typical pool in fluvial terms, in that the chosen site is located on the inside of a meander bend and is protected by a point bar which extends down the site in the centre of the channel, making the site more analogous to a low energy backwater.

Figure 5.5: Sampling points at Litton Mill. Red dots signify sampling points; note vegetated point bar to the south of the study site.



Map sourced from Digimap - 1: 10 000 OS Raster MasterMap.

The rationale for selection of this type of field site was that no alternative sites were available on the River Wye which offered both a suitable depth of sediment for sampling and for which access could be obtained.

Figure 5.6: Litton Mill study site on the River Wye, Derbyshire; photo was taken looking upstream from the centre of the site – note the vegetated point bar to the left of the photo.

A additional criterion in sampling site selection was that the site should be comparable in size and flow regime to the Holocene barrage tufa pools referred to in the palaeoenvironmental section of this thesis; these pools typically being wide (>20m), shallow (<2m) and characterised by low river flows making these sites more analogous to a series of fluvial ponds (M. Pedley: personal communication). The implications of choosing a field site of this type are that catchment-scale sediment transport input from the main channel to the site would be limited to episodic high flow/flood events due to the ‘sheltering’ effect of the point bar. Additionally, the significant proportion of baseflow associated with the limestone karst hydrology of the White Peak means that flows in the River Wye are generally low, with a Q_{10} flow velocity of only 6.188 m^3/s. Sedimentation of organic particles such as pollen entering the water column at the site should be primarily via an airborne pollen transport vector meaning that pollen loading in sediment at this site should be more representative of the local and extra-local vegetation surrounding the site as opposed to a catchment-wide pollen load dominated by fluvial transport vectors.

At the section of the river selected for sampling, the valley is relatively narrow and steep-sided; valley sides are thickly wooded with Fraxinus, Acer and Corylus, with sheep-pasture grasslands dominating on the adjacent southern plateaux. The sampling site is a pool situated on the inside of a 90 degree meander bend adjacent to Cressbrook Hall. A vegetated point bar of approximately 150m which extends from centre, or ‘elbow’, of the 90 degree bend effectively divides the pool into two parts. The outer (southern) part of the pool carries the main flow of the River Wye; the inner section, where samples were taken from, has significantly lower current speeds and only receives the full river flow during ephemeral flood events. As the majority of high river flows do not affect the sampling site, the potential for sediment resuspension events and subsequent pollen mixing will be reduced at this site. Pool depths in the sampling areas range from 0.5m – 1.5m, and the river width at the sampling site is approximately 25 m.

5.2.2 Sampling strategy

Sediment sampling at the Litton Mill fluvial field site was carried out using a Höngve soft sediment sampler (Wright, 1980) with a sampling diameter of 80mm using a rope in conjunction with a dingy; see figure 5.7 below. Sampling was carried out in October 2011, which is the period after the main flowering season in May-June and before the late-autumn floods occur. A grid sampling pattern was adopted which encompassed the upper, middle and lower reaches of the pool. This aspect of the research design was adopted in order to examine the effect of both water speed and water depth on the taxonomic diversity of pollen assemblages at different locations at the site. The river at this point has very low flow speeds, and samples were collected from the lower, downstream section of the pool upward towards the top, upstream portion of the site in order to avoid sediment contamination. Surface sediment was transferred from the Höngve sediment sampler directly to a dedicated numbered sample bottle at each of the pool 16 sub-sample locations displayed in figure 5.5 previously.

Figure 5.7: Höngve corer used for sediment sampling at the Litton Mill field site.

Water depth at each sampling point was measured using a plumb line. A single moss polster was taken from the water's edge of the pool using the same methodology as previously described for the RPPE and micro-scale sampling strategy. The rationale for using a single terrestrial sample was to provide a contextual land-based pollen count for the study site riverbank which could provide a comparison to the pollen counts derived from fluvial sediment.

5.2.3 Models of pollen transport

Pollen transport - Fluvial

Investigation of pollen transport mechanisms into large and medium-sized lakes that have an inflowing stream suggests that the dominant process is fluvial transport from river catchments (Peck, 1973; Bonny, 1980; Brown, 1985). In river catchments situated on non-karstic geology, the vast majority of pollen transport occurs during flood events; this has been demonstrated by the study of Brown *et al*. (2007) who monitored fluvial pollen transport in the Exe basin in SW England and found that 91% of pollen in the catchment was transported by flood events, and in a small river catchment in North Yorkshire, England by Peck (1973) who found that 91% of pollen in the catchment was transported by flood events. Typically these fluvial inputs are strongly affected by seasonal river flow variations resulting from increased precipitation in the spring and autumn months, and by extreme weather events which produce flash floods.

Brown (1985) examined the variation in pollen load using hydrographs from June - the flowering and pollination season of many species, September – after the flowering season, and January on a small catchment in southern England and observed significantly higher pollen loading during flood in September and January. Brown (1985) attributed the increased pollen loading observed in September to a higher discharge rate than the June event, resulting in the re-entrainment of pollen accumulated in the channel system during the summer low flows and to increased proportions of pollen already deposited on the ground surface of the catchment entering the water column via overland flows as a result of the high precipitation levels. The increased pollen loading in January is attributed to higher river discharge rates and to the re-entrainment of older pollen grains through soil and channel bank erosion; Brown (1985) was able to identify a significant increase in corroded and degraded pollen in the water column during the September and January flood events, which supports his assertion that the higher magnitude flood events associated with autumn and winter rains mobilises pollen, already deposited during the June flowering season, from storage in catchment soils, channel banks and river bed sediment and into the river channel.

Pollen transported within-channel during flood events, including pollen re-entrained from bed sediment, is well mixed (Meade *et al*., 1990) and is not differentially sorted at velocities over 0.30 m/sec (Holmes, 1990; 1994); pollen inputs into a lake are displayed in figure 5.8 below. The fluvial pollen load is a combination of several distinct components (Brown *et al*., 2007), including an airborne component (e.g. entering directly into the channel from local, extra-local and regional sources), a riparian component (e.g. leaf drip), a 'rain-out' component, an overland flow component, a bank-erosion component and a bed-sediment component which reentrains older pollen deposits already integrated into the river bed sediment which are resuspended during flood events. By analogy with forest gaps and lakes (Jacobson and Bradshaw, 1981), for rivers under 30m in width the riparian component, the overland flow component (which includes tributary channels), the bank-erosion component, and the bed sediment component are the significant terms regarding pollen input to river channel bed sediments.

Figure 5.8 Summary diagram of the pollen transport inputs to a lake basin.

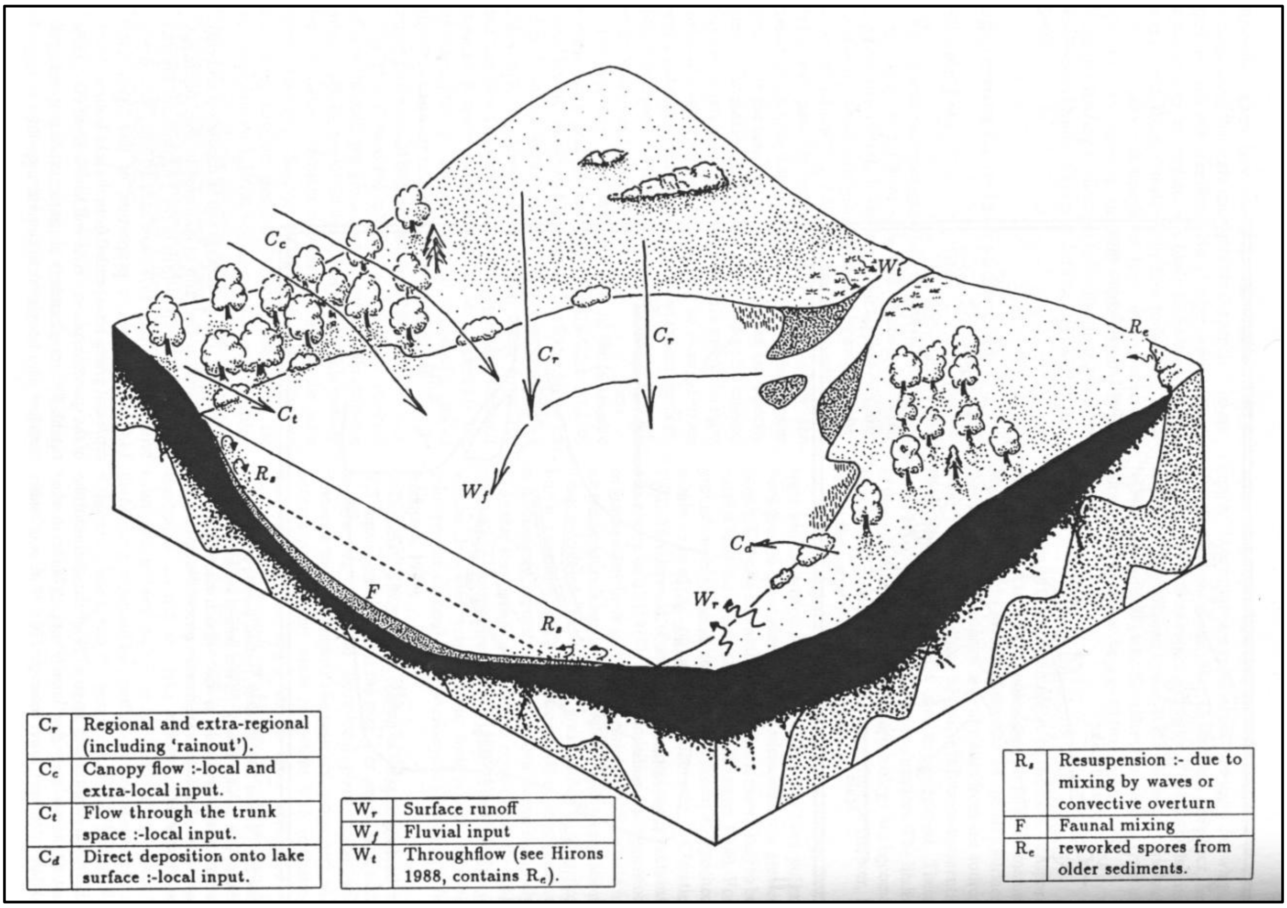


Image taken from Holmes, (1994)

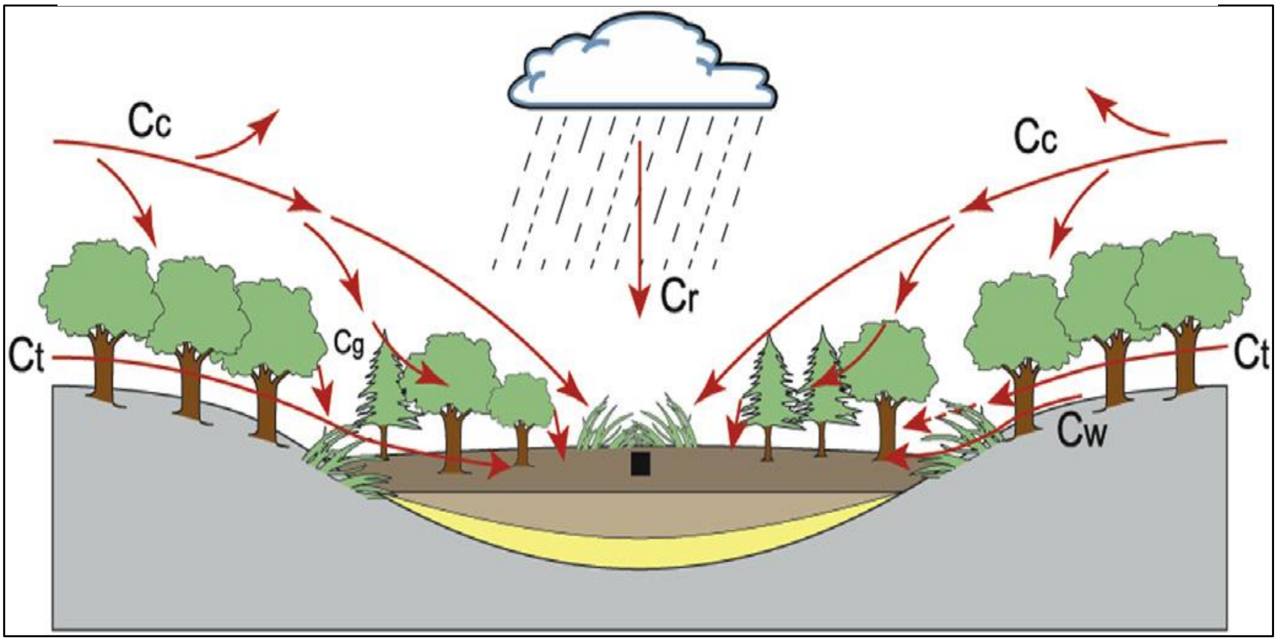
River flows in catchments on non-karstified geology react significantly faster to increased precipitation levels than rivers within karstified catchments, resulting in significant input from overland flows, erosion of river banks and bed sediment resuspension during flood (Brown *et al.*, 2008). However, rivers developed on karstic geology display lower annual flow regimes, due to stabilizing effect of the significant groundwater contribution, and display an almost complete absence of overland flows. Pollen transport via overland flow component, bank erosion component, and reentrained bed sediment component are likely to be minimal in highly karstified catchments such the River Wye in Derbyshire, and the primary pollen transport mechanisms in these river systems are suggested as being the airborne and riparian gravity component illustrated in figure 5.8 above and figure 5.9 below.

Pollen transport – Airborne

Airborne pollen transport from a forest canopy to a sampling site is described by Tauber (1965) as being a combination of a trunk space component (Ct), an above-canopy component (Cc), a gravity component (Cg), a 'rain-out' component (Cr), and a waterborne component (Cw); these mechanisms are illustrated in figure 5.9 below.

Prentice (1985) modified the terminology of Janssen (1973) to describe airborne pollen input to a sedimentary basin in four components; a local component representing pollen input from vegetation within 20 m of the basin, an extra-local component representing vegetation 20 m to 2 km from the basin, the regional component representing vegetation 2 – 200 km from the basin, and the extra-regional component which represents pollen transported from over 200 kilometres. Tinsley & Smith (1974) observed a rapid decrease in pollen deposition away from a woodland edge; this 'edge-effect' suggests pollen dispersal up to 100 m away from a woodland edge is dominated by the local trunk space component (Ct).

Figure 5.9: The Tauber model (Tauber, 1965) of pollen taphonomy into a surface sample in a mire/peat bog (equivalent to a moss in that the pollen once trapped by the vegetation remains static). Cr = long-distance component delivered by precipitation, CC = canopy component, Ct = trunk space component, Cw = runoff component, Cg = gravity component. Image sourced from Bunting *et al*. (2013).



Relative height of the source plant is suggested as a significant factor in the distance a pollen grain travels before being deposited (Janssen, 1984; Jackson & Lyford, 1999), and will influence the 'skip distance' of pollen between the source and point of deposition (Jackson, 1994). Prentice (1985) suggests that in forested landscapes, the canopy would act as a particle sink situated at source level (e.g. the pollen is emitted at canopy height, making the canopy analogous to a ground surface), and that pollen would either be intercepted by the canopy and then fall to the forest floor or be transported over the canopy and be quickly down-drafted into a lake or bog. Jackson & Lyford (1999) challenged this model by suggesting that the canopy does not behave as an ideal source-level particle sink as it is a dynamic, often multi-layered environment allowing air and particle movement and particle deposition within the canopy structure, and therefore not analogous to the surface of the ground.

Aerial pollen transport to a site of deposition can therefore be considered to be complex and often site-specific. Pollen capture in sedimentary basins reflects vegetation within the landscape surrounding the sedimentary site; however the spatial area of the vegetation recorded in the pollen record at a sedimentary site is determined by the site type e.g. forest hollow, lake, or peat bog, the size of the basin (Prentice, 1988; Sugita, 1994; Calcote, 1995), and the size and relative spatial position of the vegetation mosaic within the landscape Bunting *et al*. (2004) to the sampling site. Sugita (1994) modified Prentice's model, which assumes no post-depositional mixing, to simulate aerial pollen deposition on the surface of a lake basin where pollen becomes completely mixed.

The geomorphological character and structure of the local landscape surrounding a sampling site can also influence and exaggerate the principal pollen transport model described by (Prentice, 1985) i.e. in upland landscapes, typified by the Derbyshire Dales, vertical air movements influenced by diurnal warming/cooling cycles can cause topographic funnelling down valleys (Bunting *et al*. 2008). Markgraf (1980) suggests that pollen dispersal in mountain/valley areas can be influenced by differences in wind direction occurring diurnally, observing that night-time downslope winds did not increase pollen dispersal to lower areas but that day-time upslope winds could significantly enhance pollen dispersal to areas of higher altitude.

Influence of pollen morphology on fluvial transport

Field studies of fluvial pollen dynamics are rare, but the influence of pollen morphology (i.e. size and density) on taphonomic processes in water has been investigated in laboratory studies (Brush & Brush, 1972; Holmes, 1990; 1994), and in field studies (Peck, 1973; Pennington, 1979; Bonny, 1980; Brown *et al.*, 2008). Laboratory studies examining differential pollen sorting in the water column suggest that the primary controls are water current velocity and pollen grain size (Brush & Brush, 1972; Fall, 1987; Holmes, 1994). In current speeds of 0.20 m/sec most small pollen grains of greater than 32µm will remain in suspension; larger grains of > 54µm will remain in suspension at current speeds greater than 0.35m/sec (Holmes, 1994, therefore pollen sorting is by type size and density (Holmes, 1990; 1994). It is assumed that the difference between air and water fallspeed is only in magnitude, which does not affect rank order; pollen fallspeeds have been calculated as being 67 times slower in water of 10^0 C temperature, and 9 times slower in water of 20^0 C temperature (Bunting, 2013 – personal communication).

At current velocities exceeding 0.20 m/sec, pollen and spores in the vertical water profile are well mixed, with a higher concentration (50% - 20%) of 'new' pollen located at the water surface (Brown *et al.*, 2007). This degree of pollen loading at the surface of a water column is suggested as a function of the saturation time of airborne pollen inputs (Traverse, 1988), meaning that re-entrained 'old' pollen released from storage in river sediment would already be fully saturated and would therefore form a proportion of the well mixed and unsorted pollen transported in the middle and lower portions of the water column. Smirnov *et al.* (1996) suggest that high surface concentrations of pollen are due to input from riparian vegetation adjacent to the river channel, also large (83µm) saccate pollen grains such as *Pinus* are extremely buoyant when undamaged and may consequently be transported greater distances before settling through the water column (Holmes, 1994), although no distances are specified in this study. A flume was used by Holmes (1994) to investigate the relationship between pollen deposition and flow velocity using saturated pollen grains of taxa having differing grain sizes and densities. The pre-saturated Pinus pollen was found to remain in suspension at flow velocities >25cm/sec, an almost identical flow velocity to that required to for much smaller non-saccate pollen grains such as Lycopodium

(32µm) to remain suspended in the water column; Pinus pollen where the saccate bladders are intact and unsaturated are reported as retaining buoyancy for up to 4 years (Holmes, 1994). Most deciduous pollen types entering a body of water from the atmosphere only float for 5 to 10 minutes before being saturated and sinking through the water column (Hopkins, 1950); in an experiment to mimic fetch using a 13km/h breeze, Hopkins (1950) found that Quercus pollen sank within 1 metre of landing on the water surface. Once saturated, pollen becomes mixed and unsorted by type at current velocities exceeding 0.20 m/sec (Brush & Brush, 1972); at flow velocities under 0.20m/sec, differential pollen type sorting is a function of distance travelled and the saturation time of the pollen grain (Holmes, 1990).

River bed sediment roughness is a significant factor influencing pollen transport and deposition, as is turbulence within the river flow (Holmes, 1990; 1994), and can affect the current velocity necessary for differential pollen sorting to occur (Fall, 1987). Turbulent eddies in the water column can increase the fall-speed of pollen grains by increasing the velocity of pollen grains toward the river bed. This can effectively increase pollen sedimentation rates, as pollen grains are carried to the river bed more quickly than their 'un-accelerated' individual fallspeed. At the river bed, pollen becomes trapped by turbulent eddies shed by sand grains; pollen grains are then not resuspended but become integrated into pores and interstices in bed sediment. This effect of water turbulence is analogous to the effect of wind gusts and atmospheric turbulence in increasing the entrainment of pollen from anthers and foliage (Jackson and Lyford, 1999). In a series of flume experiments which investigated the effects on pollen deposition of no bed material and both medium (0.15 – 0.72 mm) and coarse 0.8 – 2.2 mm) sand bed material, Holmes (1994) was able to demonstrated that bed forms such as ripples increased the pollen deposition rate whilst using medium sand and that pollen deposition increased at a critical velocity (>15cm/sec) whilst using coarse sand bed sediment.

Choosing the fluvial taphonomic model

The model of fluvial taphonomy in lakes is discussed by Holmes (1994) and in river systems by Brown *et al*. (2007). In lakes with inflowing streams, the aerial component, the surface runoff component, and the stream or river input are believed to constitute the principal pollen flux to a basin. Where stream influx is the dominant pollen input to a lake basin the highest pollen concentrations are often found close to the stream inlet, where pollen concentrations decrease with distance out into the lake; this is illustrated in figure 25 below. Pollen delivered to a lake by a stream, and pollen transported subsequently within the lake by currents and surface winds, is also influenced by grain size and density, in that heavier grains are deposited closer to an inlet and lighter grains are transported further out into a lake by an inflowing stream. Pollen taphonomy in rivers is assumed to be primarily controlled by the hydrology of the watershed, where > 90% of pollen transport occurs during seasonal flood events Brown *et al*. (2007).

The two principal aerial taphonomic models are the Prentice Model (1985) and the Prentice-Sugita model (1993) which both assume that pollen flux is delivered aerially by both wind above the canopy and gravity beneath the canopy and that pollen source area increases with basin size. The Prentice model assumes that all pollen deposited at a point in the centre of a lake basin is deposited directly from the atmosphere with no subsequent pollen transport or redeposition occurring after deposition. The Prentice-Sugita model assumes that pollen deposited across the surface of the entire basin becomes mixed and homogenized, which allows fast fallspeed grains with poor dispersal or highly localised riparian pollen deposited at lake margins to be represented across the whole basin. The Prentice model assumes no post depositional mixing, and so does not allow for poorly dispersed local and/or heavy pollen grains to be equally represented across the basin. As depositional basin size increases, pollen source area become larger allowing greater representation of widely dispersed taxa in pollen assemblages. The most suitable taphonomic model for the fluvial study may be either the Prentice Sugita model (1993), or the fluvial model proposed by Holmes (1994). The degree of mixing and potential influence of fluvial processes in pollen transport and taphonomy within the pool is what this study will assess.

Diagenetic factors influencing pollen taphonomy in fluvial systems

The two principal influences on pollen diagenesis in fluvial systems are mechanical damage to the pollen grain exine occurring during overland and fluvial transport, and desiccation associated with wetting and drying cycles (Campbell, 1991). Corroded pollen grains may also indicate if a pollen assemblage has been chemically (Tweddle & Edwards, 2010) or biologically (Havinga, 1964) degraded, or has been contaminated by reworked contemporaneous pollen (Hall, 1989). The presence/absence of these digenetic indicators can yield useful information about the taphonomy of a pollen assemblage, allowing the analyst to develop working hypotheses about pollen transport vectors to the site of sedimentation.

5.2.4 Numerical methods

Principal Components Analysis (PCA)

Numerical techniques were used in the study of fluvial pollen taphonomy to explore the relationship between pollen and sample locations and identify correlations between pollen type and environmental variables e.g. sample location at the field site. Ordination analysis was applied to pollen counts and fluvial sample locations in order to examine the underlying structure of the data; the ordination analyses were carried out using the CANOCO software programme (Ter Brakk, 1987_a; 1987_b). The ordination method used was Principal Components Analysis (PCA), which is a linear ordination technique considered one of the most effective methods of analysis when the production of an ordination based on environmental/biotic data alone is necessary (Kent, 2012). PCA allows the problems of intercorrelation and duplication within the original species/variables in the dataset to be removed through the reduction of large datasets of variables e.g. pollen types into highly correlated combinations of variables of typically 5 or fewer ‘components’ (Kent & Coker, 1992). The major patterns of variation in the data are concentrated into the first few principal components with less highly correlated patterns or ‘noise’ relegated to the later components (Birks, 1995). The PCA analysis is illustrated graphically using CANOCO biplots where variation in the data set is accounted for by using axes, with the highest variation displayed on axis 1 and decreasing amounts of variation in the pollen data displayed in the second, third and fourth axes respectively. In the data set for the fluvial taphonomy study, pollen is expressed as percentages of the total arboreal pollen types counted in each sample.

Two-way indicator species analysis (TWINSPAN)

Two-way indicator species analysis (TWINSPAN) is a widely used ordination method which allows polythetic divisive classification through by dividing spatial data into groups on the basis of species composition of a quadrat or sampling point e.g. pollen assemblage. This is achieved through using reciprocal averaging or correspondence analysis to create a series of dichotomies or divisions of quadrats or pollen assemblages characterised by differential species. Two-way indicator species analysis in the fluvial taphonomy study was carried out using TWINSPAN software (Hill, 1979; Gauch & Whittaker, 1981). TWINSPAN requires a series of 'pseudospecies' in order to adapt abundance data e.g. pollen percentages, into classes allowing division. Pseudospecies scores for Litton Mill data were derived using quartiles (pseudospecies 2, 3, and 4), and a value for zero (pseudospecies 1).

5.3 Holocene Palaeoenvironmental study of the White Peak

Introduction

Fossil pollen extracted from Holocene tufa pool sediments at two field sites in Lathkill Dale and Monsal Dale in the White Peak, Derbyshire is used to examine the relationship between tufa decline and local vegetation at these sites during the period of tufa cessation. Derbyshire barrage tufa systems in Lathkill Dale are suggested as beginning to degrade from 4.2 ka BP (Pedley *et al*. 2000). This date agrees with the chronological framework of Pan – European tufa decline which occurred from 4500 ka BP. onward (Goudie, 1993). The White Peak was a region of active barrage tufa formation during the early-mid Holocene, with extensive valley-fill tufa systems in the Wye and Lathkill valleys (Pedley, 1993) which began to degrade from approximately 4500 ka BP. As yet no substantive explanation has been found for the influences leading to the termination of tufa production in Derbyshire, although either climatic change (Griffiths & Pedley, 1995) or human landscape impacts (Baker & Simms, 1998) are often cited as primary factors.

The availability of fossil proxy archives in the White Peak is constrained by regional karst processes which have altered the hydrology of the limestone to such a degree that permanently saturated, low Ph organic rich sedimentary deposits are rarely available (Ford & Williams, 1989), resulting in a paucity of sedimentary environments suitable for the long-term storage and preservation of fossil pollen. Sapropel peats formed behind Holocene barrage tufa dams provide the best available sedimentary archive with which to examine environmental changes using pollen analysis; pollen has already been successfully extracted from core samples taken from Holocene barrage-tufa systems situated in buried valleys at Monsal Dale and Lathkill Dale in the White Peak (Pedley, 1993; Taylor *et al*. 1994). Fossil pollen will be used in this study as an environmental proxy for resolving the relative influences of climatic and anthropogenic impacts on the degradation of White Peak tufa systems which occurred in the mid-late Holocene.

A variety of causal mechanisms has been suggested for tufa cessation in NW Europe during the mid-late Holocene. Goudie (1993) suggests that natural environmental factors such as declining precipitation, the subsequent effect on river flows and changes in water chemistry are potential mechanisms contributing to tufa cessation, and also highlights the potential of anthropogenic impacts such as the clearance of woodland for agriculture during the early – late Neolithic. Removal of plateau and particularly valley-side woodland would have the effect of reducing interception of precipitation, impacting the production of tufa through both the introduction of significant volumes of terrigenous sediment as a result of increased erosion of the newly cleared landscape and increasing flood peaks without the need for increased precipitation. Goudie also suggests the potential of a combination of both natural and anthropogenic factors as pushing the tufa systems to a tipping point leading to the shutdown of the tufa system.

The primary areas of environmental interest in this study are the upland woodlands on the White Peak plateau and the local valley-side and riparian woodlands of the Wye Valley and the Lathkill Valley during the time period when cessation of tufa occurred at the locations. This requires an understanding of the development of the local riparian and valley – side vegetation and environment of several kilometres radius surrounding the field site using pollen analysis, meaning a small pollen-sensing basin with a radius of 10 – 20m would be required for sediment sampling. An active mid – Holocene barrage tufa pool would approximate to this spatial scale (10 – 20m radius) and would effectively represent an 'open' basin (Sugita, 1994) with a larger pollen source area than a 'closed' basin due to the potential of water-transported pollen from the wider catchment effectively increasing the pollen input to the basin. The potential for enhanced pollen loading to the tufa pool would be mitigated in part by the typically low surface flows of rivers representing the surface hydrology of karstic limestone regions (Banks *et al.*, 2011). A proportion of the pollen deposited in the active tufa pool basin would represent the regional pollen rain, however without using core samples from multiple small sites (<100 ha) or a combination of small and large (>100 ha) sites with an appropriate research strategy combining modelling and a simulation approach such as the Landscape Reconstruction Algorithm (LRA) developed by Sugita ($2007_{a,b}$) the regional pollen component and hence vegetation cover cannot be quantitatively defined.

5.3.1 Selection of sites

Holocene fossil tufa field sites suitable for investigation of White Peak vegetation at the local spatial scale during the mid - late were identified from the existing literature (Pedley *et al*. 2000), and from personal communication with Dr M. Pedley at the University of Hull. The location of a buried Holocene barrage tufa system near the River Wye in Monsal Dale in Derbyshire was known from a previous sedimentological and environmental investigation by Taylor *et al*. (1994), and identified in the field by Dr Pedley during the core sampling fieldwork. A second buried Holocene barrage tufa system adjacent to the present – day course of the River Lathkill in Lathkill Dale, Derbyshire was investigated as a part of previous sedimentological research carried out in Derbyshire (Pedley *et al*. 2000). A 5 metre sediment core containing pollen – rich sapropel river peats was taken during the 2000 study of Pedley and kept in storage in the Hull Geography cold store, where it was available for pollen analysis for this present study.

5.3.2 Sampling strategy and fieldwork

A sediment core containing 2.8 metres of sediment was extracted at the Monsal Dale field site using a percussion corer with a sampling diameter of 90mm; the percussion corer and the Monsal Dale field site are illustrated in figures 5.10 and 5.11 below. The sediment core was taken at a point judged by Dr Pedley to be the deepest part of the pool deposits (the ‘depo-center’) formed behind the primary phytoherm tufa barrier, as this section of the tufa system is where pollen – rich organic sapropel peat sediments were most likely to be located: this is illustrated in figure 5.12 below.

As the sediment in the Monsal Dale core was relatively friable stratigraphic logging of Monsal Dale core sediment was carried out in the field with changes in sediment type, colour and degree of lithification and/or consolidation being recorded. The Monsal Dale core sediments contained no siliceous sand or gravel, being comprised of detrital tufa, marl, oncoidal tufa and organic-rich lime muds; stratigraphic logs of the Conksbury Bridge core and the Monsal Dale core are presented in figure 6.49 and figure 6.51 in the results chapter, chapter 6; the section of each core selected for pollen analysis is indicated by dashed red lines in figures 6.49 and 6.51.

Fig 5.10: Percussion coring equipment and a section of the Monsal Dale core at the Monsal Dale field site; note the present-day River Wye in the background.

Core sub-samples were transferred directly into numbered plastic ‘ziplock’ sample bags prior to storage in the Hull Geography cold store facility. The Conksbury Bridge core, taken as part of previous study by Pedley *et al*. (2000) near Alport in Lathkill Dale, comprised 5 metres of sediment which was stratigraphically logged in the field at the time of extraction before being divided into sub –samples stored in numbered ‘ziplock’ sample bags in the Hull University Geography cold store. The Conksbury Bridge core sediments contained no siliceous sand or gravel, being comprised of detrital tufa, marl, oncoidal tufa and organic-rich lime muds.

Fig 5.11: Core logging a 2.8 meter sediment core extracted from a relict Holocene barrage tufa pool at the Monsal Dale field site with my second supervisor, Dr Martyn Pedley of Hull University.

Figure 5.12: Cross –illustrative sectional view of an idealised active transverse barrage tufa system: red line denotes approximate location of extraction point of the Monsal Dale and Lathkill Dale cores within the tufa pool structure. Note that image is not to scale.

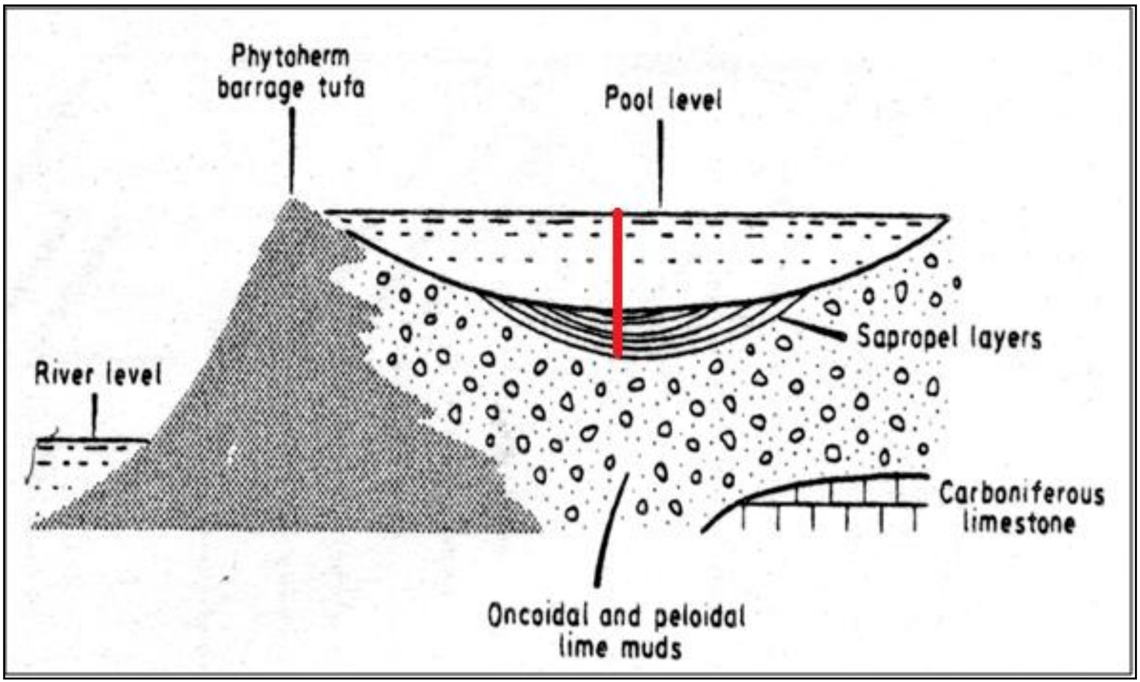


Image taken from Taylor *et al*. (1994)

The sub-sampling strategy used with the Monsal Dale and Lathkill Dale core samples aimed to utilise sub-samples from across the sedimentary ‘event-horizon’ associated with cessation of tufa production at the Derbyshire sites. The change in environmental conditions across the catchments of the River Wye and River Lathkill is represented in the Monsal Dale and Conksbury Bridge core samples by the sedimentary transition from autochthonous tufa and lime mud sediments indicating that both the catchment and hence the tufa systems were in a steady state, to allochthonous terrigenous clay sediments e.g. colluvium suggesting that environmental conditions had changed in the catchments of both the River Wye and River Lathkill and that the landscape surface of both catchments had become destabilised. This transition from autochthonous to allochthonous sedimentation at both field sites is suggested as marking the termination of the tufa systems at both of the field study sites (Dr. M. Pedley: personal communication), meaning that local environmental conditions in the River Wye catchment and the River Lathkill catchment may have changed significantly contributing to the termination of tufa production.

5.3.3 Laboratory methods

On the basis of the observed changes in sedimentology discussed in the previous paragraph, 11 sub-samples were selected for pollen analysis from the Monsal Dale core, and 12 sub-samples were selected for pollen analysis from Conksbury Bridge core. The sections of the Monsal Dale and Lathkill Dale cores used for pollen analysis are marked by red dashed lines in figures 6.49 and 6.51 displayed in sub-section 6.5 of chapter 6 of this thesis. Pollen was extracted from clays using sediment-specific protocols developed through a series of pilot studies. Pollen extraction protocols were refined and developed from standard pollen extraction techniques (Faegri and Iversen, 1989; Moore *et al.*, 1991), and included the use of HF treatment and acetolysis and coarse and fine sieving; pollen was mounted onto glass slides using silicone oil. The use of an exotic marker (Maher 1981), was applied to all samples for the purpose of defining pollen concentration.

Pollen identification was carried out at Hull University Geography Department with an Olympus BX45 binocular microscope using x400 magnification and with a pollen sum of 500 grains being counted per sample point. Pollen identification utilised pollen keys in

Moore *et al*. (1991) and the Martyn Waller reference collection at Hull University. Pollen taxonomy and nomenclature follows Bennett *et al*. (1994). Pollen counts were processed through Psimpoll software (Bennett, 1997) to produce pollen percentage diagrams.

Chapter 6: Results

This chapter presents the results of the RPPE study (sub aim 1), the Association Indices study (sub aim 2), the Terrestrial Pollen Taphonomy study (sub aim 3), and, the Fluvial Pollen Taphonomy study (sub aim 4). The results chapter then concludes with the results of the Palaeoecological study which addresses the primary aim of this thesis, which is to resolve the relative influences of climate and human landscape impacts on the termination of barrage-building tufa systems in the White Peak in the mid - late Holocene using pollen analysis. The results of the RPPE study are presented in section 6.1, the results of the Association Indices study are presented in section 6.2, the results of the Terrestrial Pollen Taphonomy study are presented in section 6.3, the results of the Fluvial Pollen Taphonomy study are presented in section 6.4 and the results of the Palaeoecological study are presented in section 6.5.

6.1 Relative Pollen Productivity Study

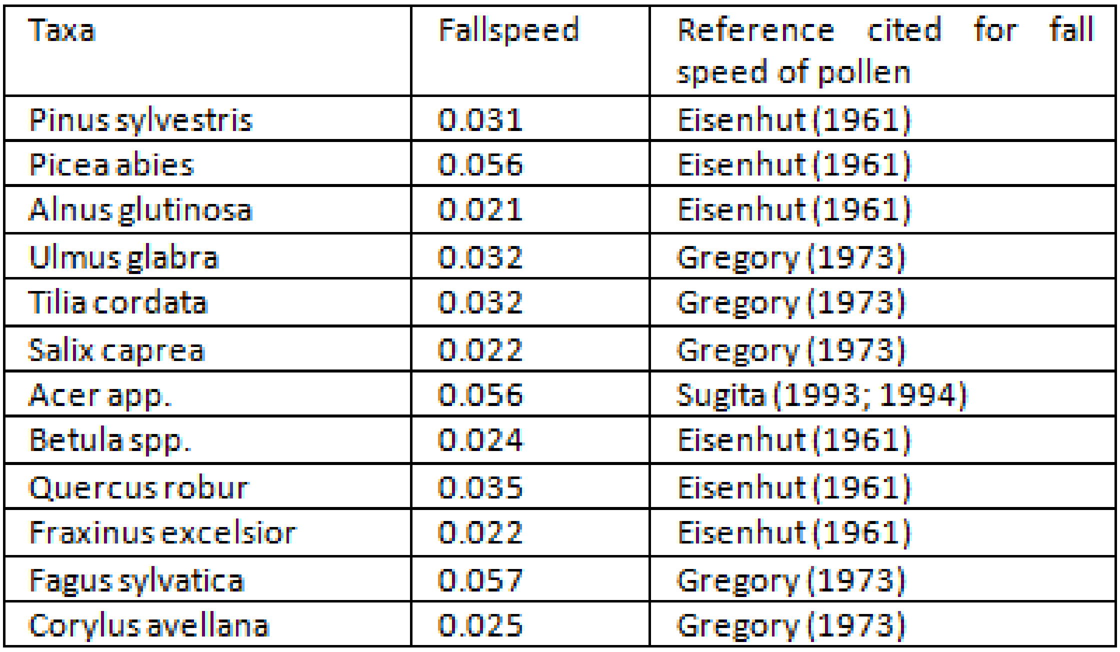
Introduction

This study aims to produce relative pollen productivity estimates (RPPE) for tree taxa using moss polster surface samples in conjunction with vegetation surveys taken at 5 study sites in the White Peak, Derbyshire and at a single study site in East Yorkshire. Study sites are described in chapter 3 and methodology is described in chapter 5. This new RPPE dataset will add to the current European database of RPPE data, and assist in the semi-qualitative interpretation of pollen percentage diagrams based on sub-fossil pollen assemblages as part of a palaeoecological investigation of the White Peak discussed in this thesis.

6.1.1 Results

Percentage pollen counts and DWPA data from each of the 16 field sites (described in Chapter 3) provided the inputs necessary to run the POLERV models (Bunting & Middleton, 2005) and obtain relative pollen productivity estimates (RPPE's) for both tree and herb taxa. Acer was used as the reference taxon since it is abundant in the woodlands at all sites. Taxa present in the vegetation surveys but absent from pollen counts (11 taxa) were removed from the datasets. Taxa present in the vegetation at less than 4 locations, and taxa present in pollen counts at less than 4 locations (15 in total) were also removed from the datasets. Of the remaining 17 taxa, six had less than 6 pollen-vegetation pairs. These six (6) taxa were not used further in the ERV data analysis. As 32 taxa had been removed from the initial data, pollen sums were reduced to between 323 and 471 grains, therefore the pollen sums of the remaining taxa at all sites were corrected to an equivalent sum of 500 grains for ERV analysis. Sedimentary basin size was set to zero in the POLERV software, and sub-models 1 & 2 were used. Pollen fall speeds used are in POLERV are displayed in table 6.1 below.

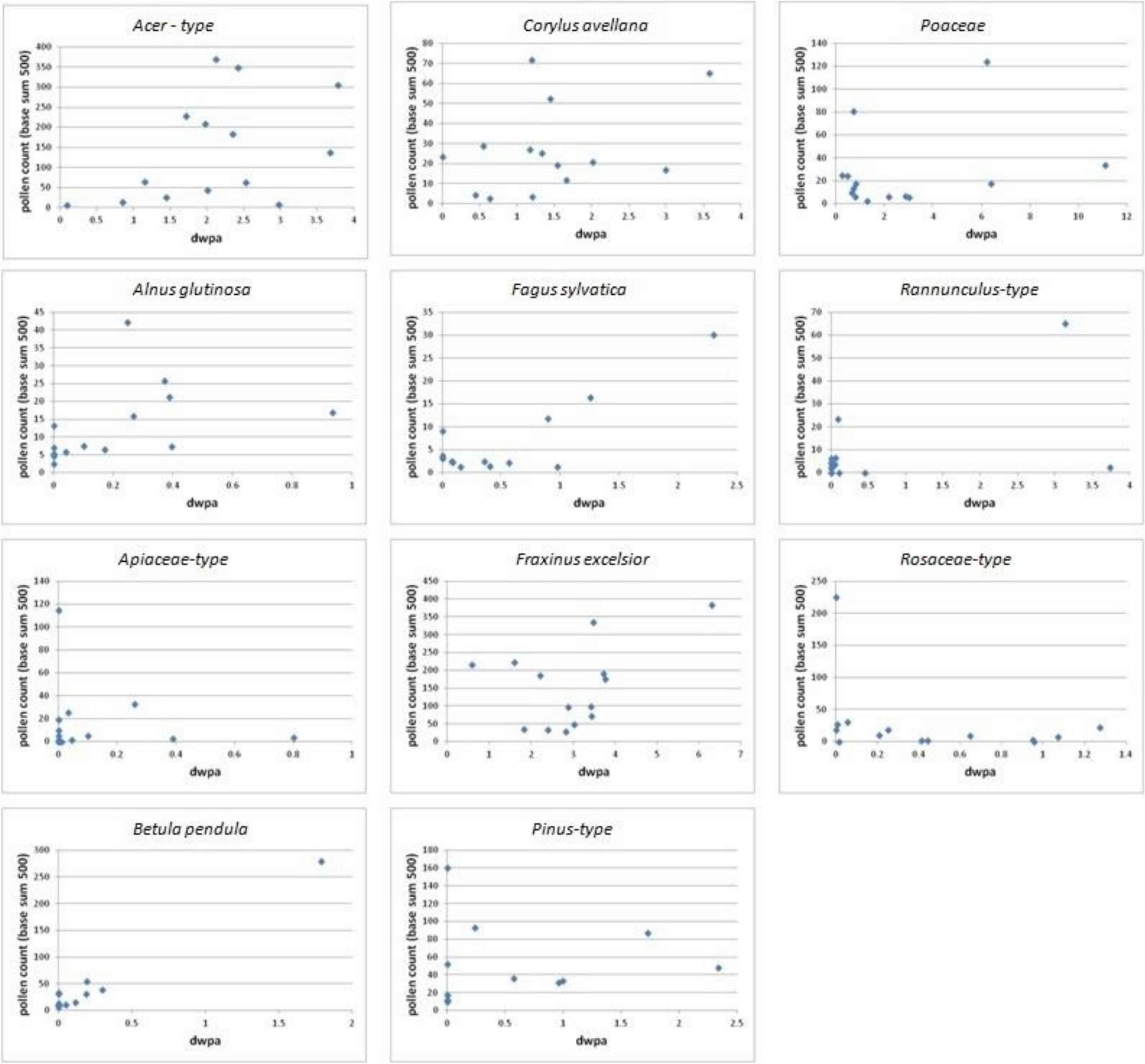
Table 6.1: Fallspeed of taxa used in the RPPE study



Taxa	Fallspeed	Reference cited for fall speed of pollen
Pinus sylvestris	0.031	Eisenhut (1961)
Picea abies	0.056	Eisenhut (1961)
Alnus glutinosa	0.021	Eisenhut (1961)
Ulmus glabra	0.032	Gregory (1973)
Tilia cordata	0.032	Gregory (1973)
Salix caprea	0.022	Gregory (1973)
Acer app.	0.056	Sugita (1993; 1994)
Betula spp.	0.024	Eisenhut (1961)
Quercus robur	0.035	Eisenhut (1961)
Fraxinus excelsior	0.022	Eisenhut (1961)
Fagus sylvatica	0.057	Gregory (1973)
Corylus avellana	0.025	Gregory (1973)

The ERV sub-models attempt to find the best linear relationship between pollen and vegetation by using an iterative method to adjust the estimate of parameters i.e. PPE (α) and background pollen (ω), within the sub-model. The goodness-of-fit of the data to the ERV model-estimated relationship (pollen against vegetation) can be visualized on scatter diagrams. The raw data of pollen percentages against vegetation proportion Distance Weighted Plant Abundance (DWPA) are presented in figure 6.1 below.

Figure 6.1: Sutton weighting DWPA scatters showing pollen count against DWPA to 100 metres



Acer - type

Corylus avellana

Poaceae

Alnus glutinosa

Fagus sylvatica

Rannunculus-type

Apiaceae-type

Fraxinus excelsior

Rosaceae-type

Betula pendula

Pinus-type

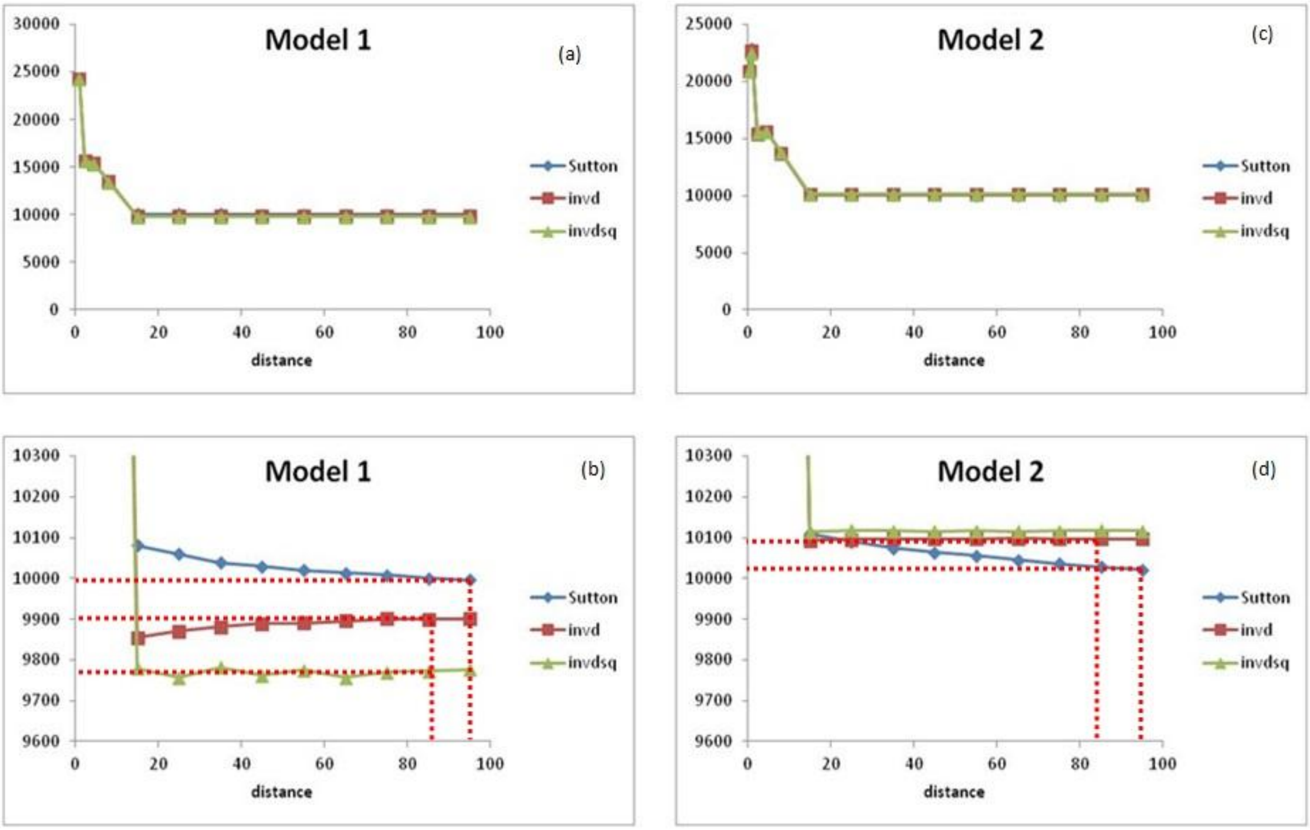
Pollen proportion versus vegetation proportion

The 11 taxa are presented as raw-data scatter plots of corrected (to a 500 grain sum) pollen count against Sutton DWPA in figure 6.1. Acer-*type* displays a high degree of variation in pollen and vegetation proportions between sites. *Corylus avellana* displays a wide variation in pollen and vegetation proportions between sites, and also trends toward a better representation in the pollen than vegetation. Poaceae displays an overall trend of low variation between sites, with several low pollen/high vegetation outliers. *Alnus glutinosa* displays a high degree of variation between sites, and is better represented in the pollen than the vegetation. *Fagus sylvatica* displays a relatively equal degree of representation between pollen and vegetation, although some pollen values at some sites have zero vegetation. Rannunculus-*type* displays an overall trend of low variation between pollen and vegetation between sites, but has several high value pollen and vegetation outliers. Apiaceae-*type* displays a similar trend to Rosaceae-*type* of high variation in vegetation proportions between sites with high pollen/zero vegetation and high vegetation/zero pollen outliers. Fraxinus displays a large variation between pollen and vegetation, with several low pollen/high vegetation outliers. Rosaceae-*type* displays high variation in vegetation proportions between sites, and has a concerning single high pollen/no vegetation outlier. *Betula pendula* displays a high degree of linearity; a single high pollen outlier may represent an anther being deposited on or very close to the moss sample. Pinus-*type* displays some variation between pollen and vegetation, with 4 zero-vegetation pollen values and a concerning high pollen/no vegetation outlier. The three herb taxa, Rannunculus-*type*, Rosaceae-*type* and Apiaceae-*type* are potentially concerning. All three taxa are a part of the understory herb-vegetation component which is primarily entomophilous; the taxa can also potentially be missed in the vegetation survey depending on what part of the year the survey is carried out.

Relevant source area of pollen

Figure 6.2 displays the likelihood function (lf) scores plotted as graphs obtained using ERV sub-models 1 and 2 with three distance-weighting functions; 1/d, 1/d^2 and Sutton weighting. The lf scores are plotted as a function of distance away from the pollen sampling point. The point at which the decay curve becomes asymptotic represents the distance from the pollen sampling point at which the fit of the pollen-vegetation data to the model does not improve, providing the estimated RSAP. In the graphs displayed in figure 6.2, RSAP distance in metres is displayed on the X axis, and Likelihood Function Score is displayed on the Y axis. In sub-model 1 the lf scores are relatively similar; the Sutton weighting produces the highest lf score of 10,000, the 1/d weighting produces an lf score of 9900, whilst the 1/d^2 weighting produces the lowest lf score of 9780. In sub-model 2, the lf scores are also similar in value with a smaller range of lf scores between the different weighting methods than is observed in sub-model 1. The lowest lf score in sub-model 2 is 10,010 with the Sutton weighting, 1/d gives an lf score of 1080, and 1/d^2 gives an lf score of 10110.

Figure 6.2: Likelihood function (lf) score plots for 16 samples (8 taxa): (a) ERV sub-model 1 using 1/d, $1/d^2$, and Sutton weighting; (b) Fine resolution plot of plot (a); (c) ERV sub-model 2 using 1/d, $1/d^2$, and Sutton weighting; (d) Fine resolution plot of plot (a). Dashed line represents suggest RSAP in plots (b) and (d). Note: Y axis denotes Likelihood Function Score.



Based on the lf scores displayed in figure 6.2, estimates of RSAP for the dataset range from 85 – 95 m. The weighting methods 1/d and $1/d^2$ produced the lower estimated figure of 85 m in both sub-models 1 & 2, and the Sutton weighting producing the higher estimated RSAP figure of 95 m in both sub-models 1 & 2. Because the lowest lf scores should theoretically correspond to the best goodness-of-fit between the pollen and vegetation data and the ERV sub-model (Sugita, 1994), ERV sub-model 1 with $1/d^2$ weighting would appear to be the best method of calculating RPPE's with my dataset. However as can be observed in figure 6.3b below, the $RPP_{acer\text{-}c}$ for Betula appears to be unrealistically high with the 1/d weighting, and the $RPP_{acer\text{-}c}$ for Betula to be hugely disproportionate using the $1/d^2$ weighting method as illustrated in figure 6.3c. The most realistic $RPP_{acer\text{-}c}$ seems to be those displayed in figure 6.3a, which were produced using the Sutton weighting method; likelihood function scores for the Sutton weighting being very similar in both ERV sub-model estimates. The likelihood function score plots displayed in Figures 6.2b and 6.2d indicate that Sutton weighting estimates an RSAP for this dataset of approximately 95 -100m using both ERV sub-models. Standard deviations for RPPE values derived by the three distance weighting functions are presented in table 6.2 below.

Figure 6.3a**:** Raw Relative Pollen Productivity estimates (RPPE) using Sutton weighting with standard deviations (thinner lines) for 8 taxa using 13 samples; Acer is set to unity (α=1.0), and the RPPE values for the other taxa are relative to Acer.

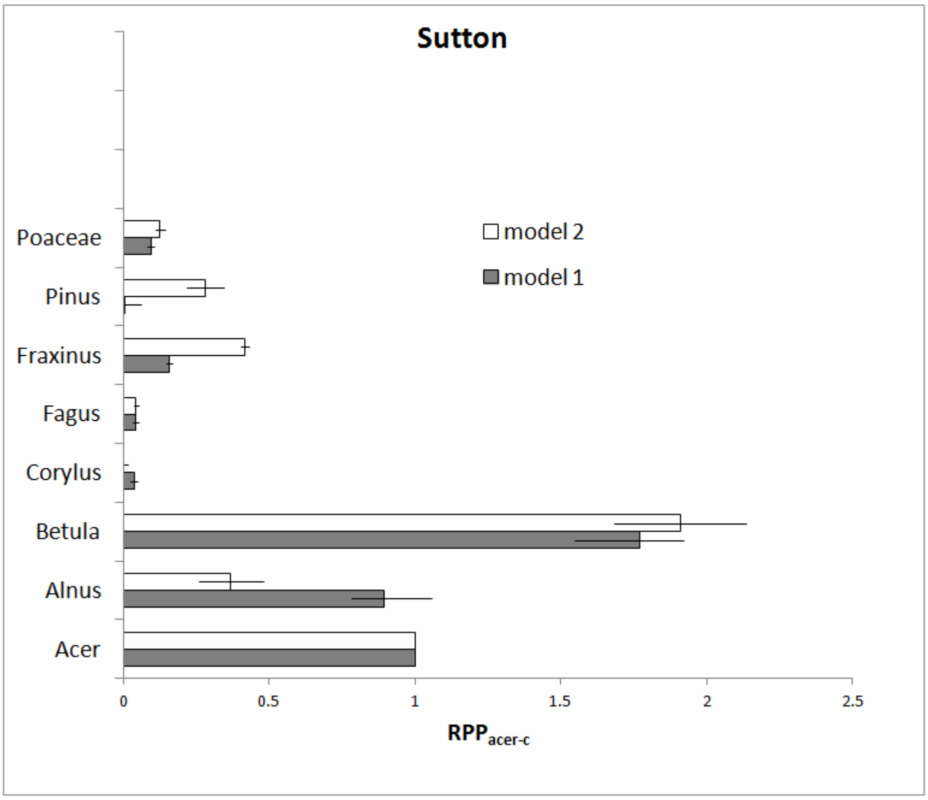


Figure 6.3b**:** Raw Relative Pollen Productivity estimates (RPPE) using Inverse Distance weighting (1/d) with standard deviations (thinner lines) for 8 taxa using 13 samples; Acer is set to unity (α=1.0), and RPPE values for the other taxa are relative to Acer.

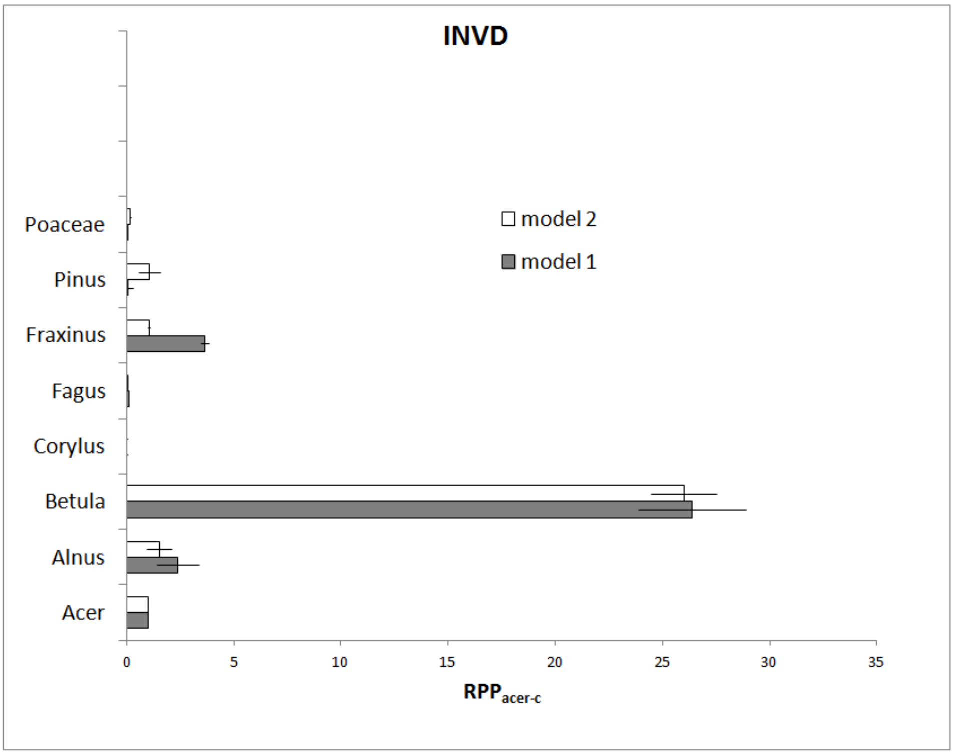


Figure 6.3c: Raw Relative Pollen Productivity estimates (RPPE) using Inverse Distance Squared weighting ($1/d^2$) with standard deviations (thinner lines) for 8 taxa using 13 samples; Acer is set to unity (α=1.0), and the RPPE values for the other taxa are relative to Acer.

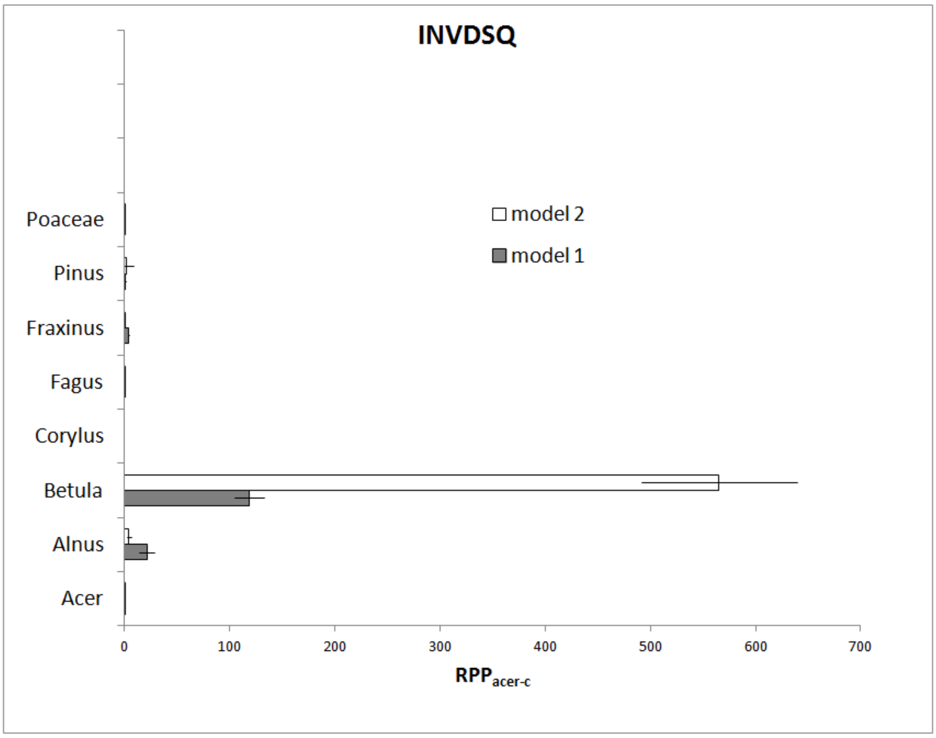


Table 6.2: Standard deviations (SD) for Sutton, 1/d and $1/d^2$ weighting methods RPPE outputs: note differing SD for ERV models 1 and 2; Acer is the reference taxon so has no SD values.

Weighting Model	ERV Model	Acer	Alnus	Betula	Corylus	Fagus	Fraxinus	Pinus	Poaceae
Sutton	ERV 1	0	0.1618	0.1482	0.009	0.0084	0.0079	0.0621	0.01
	ERV 2	0	0.1114	0.2265	0.0162	0.0091	0.0142	0.0647	0.0171
1/d	ERV 1	0	0.985	2.5283	0.0069	0.0181	0.1836	0.2532	0.007
	ERV 2	0	0.5682	1.5543	0.0222	0.0123	0.0562	0.5073	0.0075
$1/d^2$	ERV 1	0	7.2419	14.129	0.001	0.0016	0.1746	0.8797	0.0007
	ERV 2	0	2.2181	74.246	0.022	0.0164	0.0609	6.3887	0.01

6.1.2. Discussion

One of the main challenges when using ERV sub-models to derive RPPE's lies in selecting the most appropriate method of quantifying vegetation composition. The prolific aerial dispersal properties of pollen necessitates that some form of distance-weighting must be applied to the vegetation data in order to approximate 'a pollen samples view of the landscape ' (Prentice & Webb, 1986). Each ERV sub-model calculates relative pollen productivity estimates (α) and background pollen (ω) by comparing one set of pollen data with multiple vegetation datasets collected from different distances (which are dependent on the vegetation survey methodology) around the pollen sample points. A wide variety of distance-weighting methods has been applied in pollen-vegetation calibration and landscape reconstruction, e.g. equal weighting to individual plants at all distances (Calcote, 1995), giving greater weight to proximal vegetation through inverse distance-weighting (1/d) (Prentice & Webb, 1986), or inverse squared distance ($1/d^2$) (Webb *et al.*, 1981; Sugita, 1993; 1994).

Comparison of the effect of different distance-weighting methods on estimates of RSAP illustrated in figures 6.3a – 6.3c indicates that these methods produce different RSAP estimates. In both ERV sub-models when 1/d and $1/d^2$ weighting is applied, the Lf scores reach an asymptote at a shorter distance than the Sutton weighting. This is more easily observed in figure 6.2b and 6.2d, which display the lf scores at a finer resolution. The Sutton weighting RSAP of 95 m is comparable to the findings of Jackson & Kearsey (1998) when using $1/d^2$ weighting, and to the findings of Calcotes (1995) investigation of pollen source area around forest hollows. Calcote (1995) demonstrated that $1/d^2$ can represent a close approximation to the Prentice-Sutton taxon-specific distance-weighting in the case of forested vegetation. Investigation of RPPE's in Norfolk woodlands, England by Bunting et al. (2005) suggested an RSAP of 50 to 150 metres using the Sutton weighting method.

The range of RPPE's produced using 1/d and $1/d^2$ appears unrealistically high in comparison with the RPPE's produced using the taxon-specific Sutton weighting, this finding is supported by similar results in Sweden (Broström *et al.*, 1994). Therefore, the taxon-specific Sutton weighting RPPE does appear the most realistic in comparison with the two other methods. In ERV sub-models 1 and 2 both the pollen and vegetation data is expressed in proportions e.g. percentages; in order to produce a linear pollen-vegetation relationship (where the slope represents α & the intercept represents ω) either the vegetation percentage data is adjusted (model 1), or the pollen percentage data is adjusted (model 2). Using the Sutton weighting, both ERV sub-models produce very similar RPPE's for Betula, Fagus and Poaceae, with sub-model 1 producing slightly higher estimates for Alnus, and sub-model 2 producing slightly higher estimates for Pinus and Fraxinus. RPPE's of seven White Peak taxa are presented in table 6.3 below; table 6.4 displays the RPPE's adjusted to give a Poaceae RPPE of 1.0 e.g. 0.25 x 4 = 1.0. Acer is the reference taxon, and is set to a value of 1.0. The range of values given for Fraxinus, Betula and Alnus in tables 6.3 and 6.4 below reflect the differences in RPPE outputs between ERV Model 1 and ERV Model 2 for these taxa; see figure 6.3a for more information.

Table 6.3: RPPE's and Fallspeeds of 7 White Peak taxa used in this study – Acer is the reference taxon and is set to 1.0

Taxon	RPPE	Fallspeed (m/s)
Poaceae	0.25	0.035
Pinus	0.25	0.031
Fraxinus	0.25 – 0.5	0.022
Fagus	0.1	0.057
Corylus	0.1	0.025
Betula	1.75 - 2.0	0.024
Alnus	0.5 – 0.75	0.021

Table 6.4: Adjusted White Peak RPPE's (raw RPPE's multiplied by 4 e.g. Poaceae 0.25 x 4 = 1.0) Acer is the reference taxon and is set to 1.0

Taxon	RPPE	Fallspeed (m/s)
Poaceae	1.0	0.035
Pinus	1.0	0.031
Fraxinus	1.0 – 2.0	0.022
Fagus	0.4	0.057
Corylus	0.4	0.025
Betula	7.0 – 8.0	0.024
Alnus	2.0 – 3.0	0.021

RPPE's produced from previous European pollen productivity studies are presented in table 6.5 below. It can be seen that a range of RPPE's exists dependant on the environmental characteristics of the site e.g. Bunting et al. (2005) produced RPPE's from fen Carr woodlands where Alnus, Corylus and Fraxinus are competitively advantaged, and the elevation of the sampling sites e.g. Mazier et al (2008) utilised sites in the Swiss Jura Mountains where the field sites are 1100 – 1550 m a.s.l.

Table 6.5: RPPE's for study areas in Europe

Taxon	Study	Location	RPPE	Sampling medium
Alnus	Bunting *et al.* (2005)	U.K	11.4	Moss polster
Alnus	Broström *et al.* (2004)	South Sweden	4.2	Moss polster
Corylus	Sugita *et al.* (1999)	South Sweden	1.4	Moss polster
Corylus	Broström *et al.* (2004)	South Sweden	1.4	Moss polster
Corylus	Soepboer *et al.* (2008)	Swiss Plateau	2.58	Lake
Fagus	Broström *et al.* (2004)	South Sweden	6.7	Moss polster
Fagus	Mazier *et al.* (2008)	Swiss Jura	1.39	Moss polster
Fagus	Nielsen (2003)	Denmark	3.6	Lake
Fagus	Soepboer *et al.* (2008)	Swiss Plateau	0.76	Lake
Betula	Bunting *et al.* (2005)	U.K	8.06	Moss polster
Betula	Von Stedingk *et al.* (2008)	Central Sweden	2.24	Moss polster
Betula	Broström *et al.* (2004)	South Sweden	8.90	Moss polster
Betula	Soepboer *et al.* (2008)	Swiss Plateau	2.42	Lake
Fraxinus	Broström *et al.* (2004)	South Sweden	0.70	Moss polster
Fraxinus	Bunting *et al.* (2005)	U.K	0.91	Moss polster
Fraxinus	Soepboer *et al.* (2008)	Swiss Plateau	1.39	Lake
Pinus	Soepboer *et al.* (2008)	Swiss Plateau	1.35	Lake
Pinus	Nielsen (2003)	Denmark	1.41	Lake
Pinus	Broström *et al.* (2004)	South Sweden	5.70	Moss polster
Pinus	Von Stedingk *et al.* (2008)	Central Sweden	21.58	Moss polster
Tilia	Broström *et al.* (2004)	South Sweden	0.39	Moss polster

The key factors influencing RPPE outputs may be classified into two types (Broström *et al.*, 2008). *Methodological factors* such as the vegetation survey methods, pollen sampling medium e.g. moss polsters or lake sediments, and the often very site-specific edaphic, abiotic and biotic factors associated with individual sampling & survey sites, and *environmental factors* such as differences in vegetation structure, species composition and climate, and the land-use and/or land management between study areas.

The choice of reference taxon used in individual RPPE studies is dictated by the availability in the local vegetation of a taxon that is consistently present e.g. has a large gradient in both pollen and vegetation proportions to allow consistent values of α (Mazier *et al.*, 2008). For this White Peak-based study, Acer was used as the reference taxon as it is common in both pollen and vegetation datasets in my region; however Sugita et al. (1999) used Juniperus in southern Sweden, and Bunting *et al.* (2005) used Quercus in England. Poaceae is the 'standard' reference taxon for the RPPE studies illustrated in table 6.5, based on the premise that the pollen productivity of Poaceae is relatively uniform in all study areas regardless of regional variations in Poaceae species, climate and the local/regional land use(s) (Broström *et al.*, 2004). This premise is obviously tentative as variations in regional species diversity and composition and climate do occur, resulting in differences in pollen production for different Poaceae species; this in turn will influence the RPPE of other taxa when Poaceae is used as the reference taxon (Broström *et al.*, 2008). However the ubiquity of Poaceae in a wide variety of landscapes, the characteristic of the species as an intermediate pollen producer in many RPPE studies, and the large spread of Poaceae values observed in the majority of pollen-vegetation datasets often dictates Poaceae as the only realistic choice of reference taxon. The weaknesses as well as the strengths of this choice should be considered when comparing pollen productivity from multiple studies (Broström *et al.*, 2008).

A number of taxa from the White Peak display similar RPPE values to those produced in NW Europe from previous RPPE studies as previously illustrated in table 6.5. The White Peak RPPE for Pinus of 1.0 is comparable to the lake-sediment derived Pinus RPPE's of Nielsen (2003) and Soepboer *et al.* (2008); however the moss-polster derived Pinus RPPE's of Broström *et al.* (2004) and Von Stedingk *et al.* (2008) display significantly higher RPPE values. The Swiss Plateau study area of Soepboer *et al.* (2008) shares similar though not exact altitudinal characteristics to the White Peak study sites; the Danish study of Nielsen (2003), although set in a very flat landscape shares similarities in woodland structure. Fraxinus RPPE values at the White Peak sites range in value from 1.0 – 2.0, with ERV Model 1 giving an RPPE of 1.0 and ERV Model 2 giving an RPPE of 2.0. This value range is most similar to the RPPE studies of Soepboer *et al.* (2008), who derived RPPE data from lake sediments in the high altitude pasture woodlands on the Swiss Jura Mountains in Switzerland. The Fraxinus RPPE values of Bunting *et al.* (2005) also display a degree of similarity to the White Peak Fraxinus values; this may be attributable to a degree similarity between the two sites, which both receive local pollen input from adjacent wet woodlands.

Values for Fagus in the White Peak are significantly lower than all of the RPPE values displayed in table 6.5, with the closest NW European RPPE value that of Soepboer *et al.* (2008) derived from a study on the Swiss Plateau. This suggests that altitude may be a factor related to the relatively low RPPE values observed at both the Swiss Plateau and Derbyshire field sites. Fagus vegetation was also quite localized in the Derbyshire inter-site vegetation surveys, occurring as very small stands or isolated trees on the upper valley slopes, suggesting that small patch size and landscape position i.e. elevation of Fagus vegetation may have influenced the relatively low RPPE. The effect on pollen dispersal of the pollen fallspeed of Fagus in the White Peak is an additional factor to be considered, as Fagus pollen has a higher fallspeed velocity (see table 6.1) than many taxa which may be a significant factor contributing to the relatively low RPPE values observed in Derbyshire. The RPPE for Corylus in the White Peak is also significantly lower than the other European RPPE values displayed in table 6.5. In heavily shaded environments Corylus is suggested as a low pollen producer (Tinner & Lotter, 2001; Broström *et al.*, 2004). At the majority of the White Peak vegetation survey sites Corylus vegetation was chiefly an understory component within the Acer-Fraxinus dominated woodlands, with dense Corylus stands restricted to woodland edges, woodland openings and plateau edge/valley top locations. The spatial location of Corylus vegetation observed in the Derbyshire valley woodland surveys suggests pollen production of Corylus may be suppressed by the high degree of shading and predominantly understory location of the taxa at the White Peak valley woodland sites, producing a low RPPE for Corylus in Derbyshire.

The most similar European RPPE values for Betula, as displayed in table 6.5 above, to the White Peak values from this present study were recorded in Norfolk by Bunting *et al*. (2005) and in southern Sweden by Broström *et al*. (2004). The RPPE for the White Peak in this study and at the southern Sweden study of Broström *et al*. (1994) and the Norfolk field site of Bunting et al. (2005) are significantly higher than the other European estimates produced in central Sweden (Von Stedingk *et al*. 2008) and in Switzerland (Soepboer *et al*., 2008). The similarity in high RPPE values with the Norfolk study of Bunting et al. (2005) may result from the similarity of the environmental conditions at the Norfolk and Derbyshire survey sites, which in the Norfolk study was a fen carr environment and in the White Peak was a river valley. However Betula is also a significant woodland component on the valley slopes and plateau edges of the White Peak, meaning that pollen is likely to be more effectively dispersed from these positions which are topographically elevated above the moss surface sampling location. The White Peak RPPE values for Alnus are lower than those displayed in table 6.5, although a degree of similarity is observed with the southern Swedish study of (Sugita, 1999). The other United Kingdom RPPE value for Alnus of Bunting *et al*. (2005)

is significantly higher; the large discrepancy between the RPPE between the Norfolk site and the Derbyshire site may be related to differences in study site selection. The Norfolk study was carried out using a relatively flat wet alder-carr woodland field site, whilst the White Peak Alnus RPPE vale may be influenced by the effect of topography on the effectiveness of pollen dispersal as the surface sample sites were situated above the Alnus vegetation adjacent to the stream running along the valley bottom.

As was discussed in the introduction, the factors influencing observed differences in RPPE values from different sites are primarily methodological factors e.g. site type, pollen sampling medium, and vegetation survey design, or environmental factors e.g. vegetation structure, climate, and land-use/landscape management. Pollen taphonomy is also an important consideration which can influence the species diversity of pollen assemblages at individual sampling sites, e.g. lakes, moss polsters, and so affect estimates of RPPE. The Prentice- model of pollen dispersal (Prentice, 1985) utilises the atmospheric diffusion model of Sutton (1953), which is based on particles released at or near ground level under stable atmospheric conditions. A critique of this pollen dispersal model is presented in Jackson & Lyford (1999), who suggest as most pollen release occurs under unstable atmospheric conditions and is from an elevated source, that this will result in significant differences in pollen dispersal patterns and subsequent estimates of RSAP. Nielsen (2003) demonstrated that, using simulations, differences in wind speed would not significantly affect estimates of RSAP, and testing of the effect of stable vs. unstable atmospheric conditions on distance-weighting and RSAP by Gaillard et al. (2008) found that differences in atmospheric conditions do not significantly affect the robustness of RSAP estimates. The topography of the White Peak valley woodlands is diverse, with vegetation located at different heights at locations on the often very steep valley sides that rise up from the river channel and adjacent floodplain. Pollen dispersal in this setting would be influenced to some degree by local atmospheric conditions such as the effect of diurnal wind on pollen dispersal (Markgraf, 1980) e.g. daytime upslope winds and downslope winds in the evening.

A primary environmental control on the pollen productivity of a taxon is temperature (Autio & Hicks, 2004), so a proportion of the dissimilarity between the White Peak RPPE's and those from other field sites in England and Northern Europe may be attributable to climatic factors associated with the autoecology of the taxa in these locations. Other significant environmental controls on the Derbyshire RPPE's are the topography of the valley woodland sites, the soil species, and the drainage characteristics of the valleys and adjacent plateau. Some of the field sites are significantly elevated above a proportion of the surveyed vegetation e.g. > 50m. This difference in topography may be particularly relevant to the taxa associated with moving or still water such as Alnus and Fraxinus. The drainage characteristics of the upper valley-sides are characterised and controlled by the underlying limestone geology and the shallow rendzina soils typical of the White Peak, meaning that taxa associated with high water tables and/or wet soils such as Alnus or Quercus are competitively disadvantaged in these locations.

The similarity of the Betula RPPE values from the White Peak to the estimates from Norfolk (Bunting et *al*., 2005), suggest that this taxon is equally productive on the well drained rendzina soils of Derbyshire as in wet woodlands in Norfolk. It was noticeable with respect to Fagus that, as observed in the vegetation surveys, the taxon was restricted primarily to the well drained upper slopes of the valleys and plateau edges where it was a minor component in local woodland; this abiotic control may be a contributing factor in the relatively low RPPE for Fagus at the Derbyshire sites. As illustrated in table 6.2, Fagus has a relatively heavy pollen grain with a fast fallspeed which may be an additional factor affecting the effectiveness of Fagus pollen dispersal in these valley woodland locations.

The lower slopes of many of the Derbyshire valley-woodland sites are typically very steep; in these locations and down to the toe slope, where the soil profile is often deepest and most mature, Fraxinus is often the dominant taxa in the local woodland. These edaphic and abiotic site-specific factors may be influencing the relatively high RPPE values for Fraxinus at the White Peak sites. At many of the Derbyshire sites Pinus, as previously discussed for Fagus, is typically absent from valley-bottom sites, with the taxon being restricted to the drier, more stable upper slopes and crests of the valleys. Higher wind speeds at the upper elevations near the plateau edge may result in reduced local pollen fallout of Pinus pollen, already entrained into the atmosphere, on to the low-elevation survey sites. The increased wind speeds on the plateau would potentially transport greater volumes of Pinus pollen regionally (Markgraf, 1980), to be deposited at much greater distances from the pollen source.

6.1.3. Conclusion

Relative pollen productivity estimates for 6 valley woodland tree taxa have been produced which represent the first RPPE dataset for the White Peak, Derbyshire, England. A high degree of similarity is observed between the Derbyshire RPPE's and those from previous RPPE research in NW Europe for Betula, Fraxinus and Pinus, with Alnus suggested as displaying broadly similar values to those from the southern Sweden study values displayed in table 6.5 on page 111.

Derbyshire Corylus RPPE values are significantly lower than the existing NW European RPPE presented in table 6.4, as are the Fagus RPPE values produced in this Derbyshire study. The low RPPE for Corylus and Fagus in this Derbyshire study may be attributed to environmental factors at the field sites (Broström *et al.*, 2008) i.e. the position of Corylus and Fagus within the vegetation structure at the Derbyshire field sites, the autoecology of these taxa and to site-specific factors at the field sites such as topographical constraints associated with valley side woodland and edaphic factors affecting soil s at different locations on the valley slopes and plateau edges.

This new RPPE dataset represents a useful addition to the single existing UK RPPE dataset of Bunting *et al.* (2005), and provides a new comparative RPPE dataset of tree taxa previously to researchers examining modern pollen production in upland valley woodland. The finding of this pollen productivity study will provide an additional interpretive tool to aid investigations of past landscape vegetation cover in upland limestone regions. This Derbyshire RPPE dataset addresses one of the sub-aims of this thesis described in chapter 1 in providing a new interpretive tool to assist a semi-quantitative reconstruction of the mid-late Holocene vegetation in order to assess past environmental conditions in White Peak which forms the primary aim of this thesis.

6.2 Association Indices Study

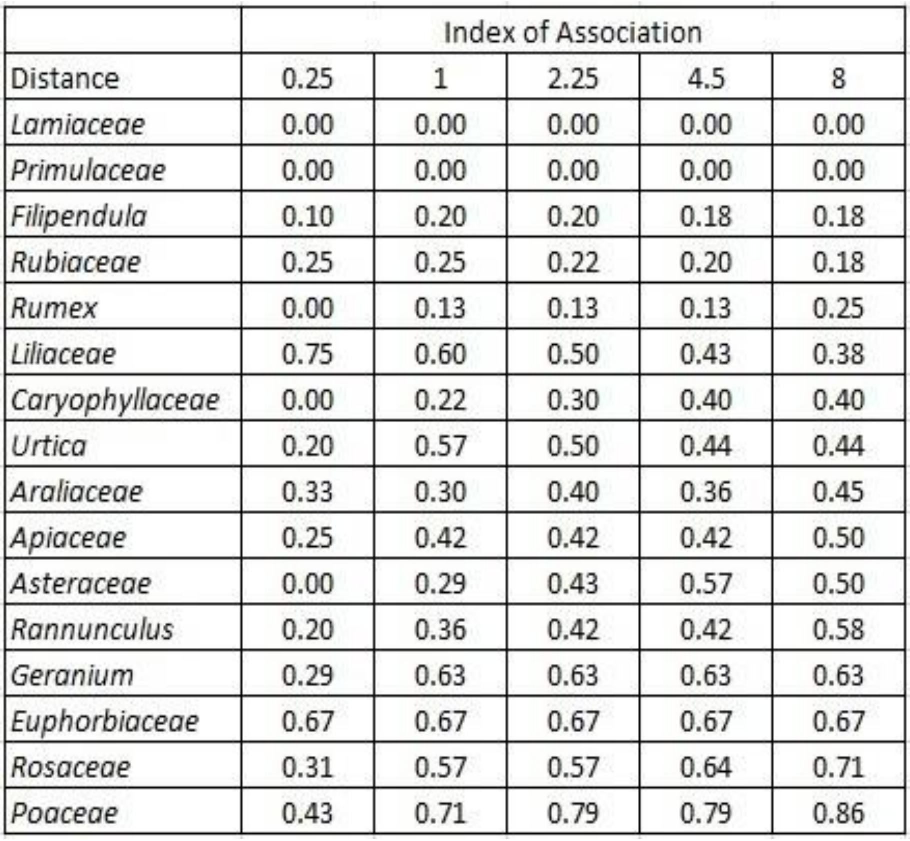
Introduction

Herb taxa are often used as indicators of environmental conditions and landscape change associated with anthropogenic activity, allowing disturbance in palaeoenvironments based on analysis of fossil pollen to be better understood (Behre, 1981; Brun, 2011) through the study of modern-day pollen – vegetation relationships of herb taxa, and association indices tables can be used to identify pollen types that accurately reflect vegetation patterns (Davis, 1984). Indices tables produced from this study will assist investigation of Holocene environmental change in the White Peak region using pollen analysis as a component of this thesis. Study sites used in this study are described in chapter 3 and study methodology is described in chapter 5.

6.2.1 Results

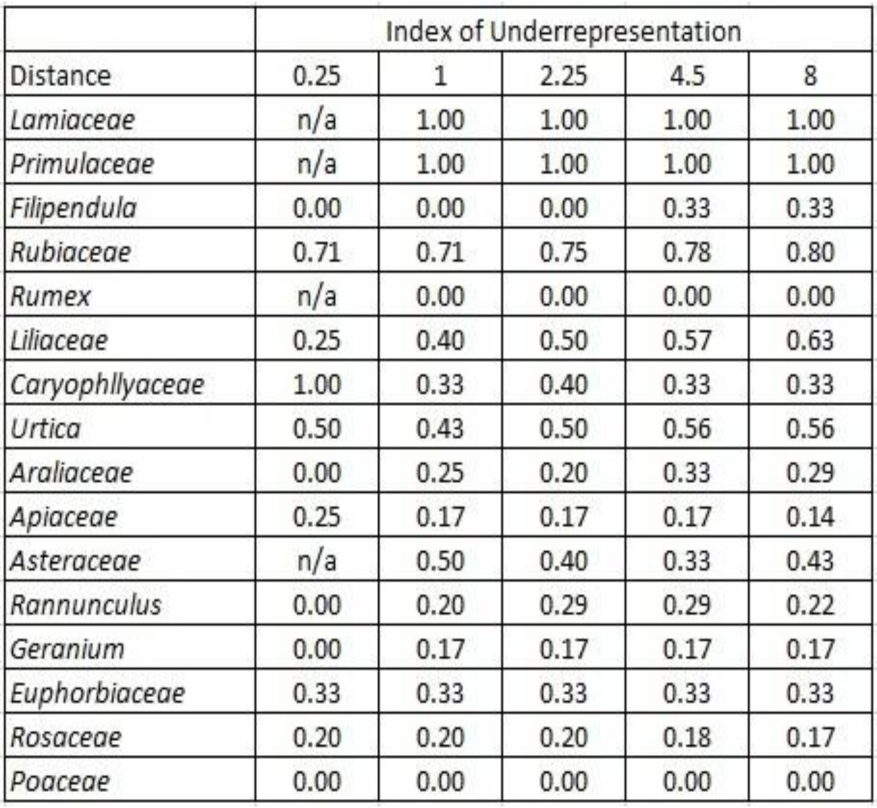
Indices of association, overrepresentation, and underrepresentation index values for 16 taxa are presented in tables 6.6, 6.7 and 6.8 below.

Table 6.6: Index of Association for 16 White Peak NAP taxa.



	Index of Association				
Distance	0.25	1	2.25	4.5	8
Lamiaceae	0.00	0.00	0.00	0.00	0.00
Primulaceae	0.00	0.00	0.00	0.00	0.00
Filipendula	0.10	0.20	0.20	0.18	0.18
Rubiaceae	0.25	0.25	0.22	0.20	0.18
Rumex	0.00	0.13	0.13	0.13	0.25
Liliaceae	0.75	0.60	0.50	0.43	0.38
Caryophyllaceae	0.00	0.22	0.30	0.40	0.40
Urtica	0.20	0.57	0.50	0.44	0.44
Araliaceae	0.33	0.30	0.40	0.36	0.45
Apiaceae	0.25	0.42	0.42	0.42	0.50
Asteraceae	0.00	0.29	0.43	0.57	0.50
Rannunculus	0.20	0.36	0.42	0.42	0.58
Geranium	0.29	0.63	0.63	0.63	0.63
Euphorbiaceae	0.67	0.67	0.67	0.67	0.67
Rosaceae	0.31	0.57	0.57	0.64	0.71
Poaceae	0.43	0.71	0.79	0.79	0.86

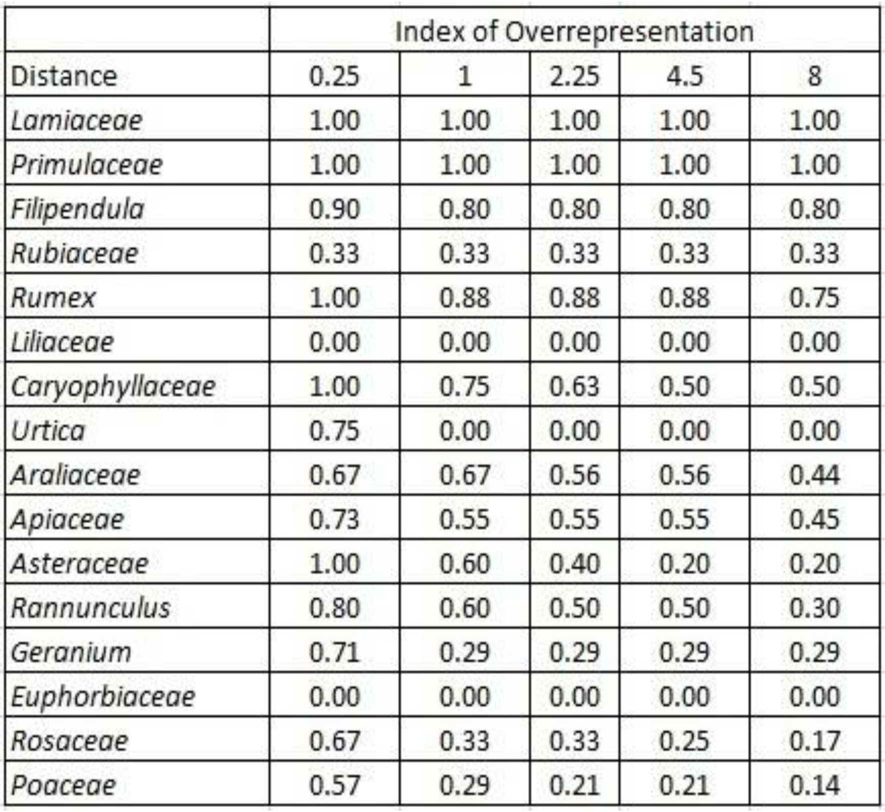
Table 6.7: Index of Underrepresentation for 16 White Peak NAP taxa.



	Index of Underrepresentation				
Distance	0.25	1	2.25	4.5	8
Lamiaceae	n/a	1.00	1.00	1.00	1.00
Primulaceae	n/a	1.00	1.00	1.00	1.00
Filipendula	0.00	0.00	0.00	0.33	0.33
Rubiaceae	0.71	0.71	0.75	0.78	0.80
Rumex	n/a	0.00	0.00	0.00	0.00
Liliaceae	0.25	0.40	0.50	0.57	0.63
Caryophllyaceae	1.00	0.33	0.40	0.33	0.33
Urtica	0.50	0.43	0.50	0.56	0.56
Araliaceae	0.00	0.25	0.20	0.33	0.29
Apiaceae	0.25	0.17	0.17	0.17	0.14
Asteraceae	n/a	0.50	0.40	0.33	0.43
Rannunculus	0.00	0.20	0.29	0.29	0.22
Geranium	0.00	0.17	0.17	0.17	0.17
Euphorbiaceae	0.33	0.33	0.33	0.33	0.33
Rosaceae	0.20	0.20	0.20	0.18	0.17
Poaceae	0.00	0.00	0.00	0.00	0.00

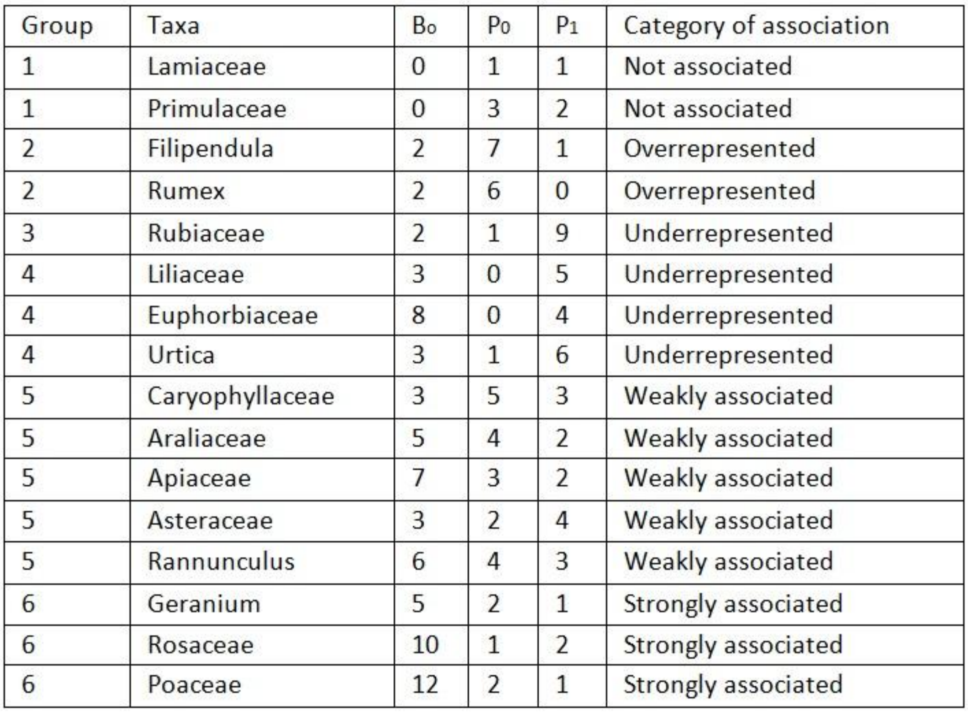
Araceae, Boraginaceae, Cruciferae, Grossulariaceae, Labiateae, Leguminosae, Onagraceae, Orchidaceae, Oxalidaceae, Potentilla, *Pteridium aquilinum*, Scrophulariaceae and Violaceae are present as plants only (i.e. 100% under-represented), and therefore are not used in further calculations. The indices tables display these values over 0.25m – 8m distance away from the moss surface-sample sites

Table 6.8: Index of Overrepresentation for 16 White Peak NAP taxa.



	Index of Overrepresentation				
Distance	0.25	1	2.25	4.5	8
Lamiaceae	1.00	1.00	1.00	1.00	1.00
Primulaceae	1.00	1.00	1.00	1.00	1.00
Filipendula	0.90	0.80	0.80	0.80	0.80
Rubiaceae	0.33	0.33	0.33	0.33	0.33
Rumex	1.00	0.88	0.88	0.88	0.75
Liliaceae	0.00	0.00	0.00	0.00	0.00
Caryophyllaceae	1.00	0.75	0.63	0.50	0.50
Urtica	0.75	0.00	0.00	0.00	0.00
Araliaceae	0.67	0.67	0.56	0.56	0.44
Apiaceae	0.73	0.55	0.55	0.55	0.45
Asteraceae	1.00	0.60	0.40	0.20	0.20
Rannunculus	0.80	0.60	0.50	0.50	0.30
Geranium	0.71	0.29	0.29	0.29	0.29
Euphorbiaceae	0.00	0.00	0.00	0.00	0.00
Rosaceae	0.67	0.33	0.33	0.25	0.17
Poaceae	0.57	0.29	0.21	0.21	0.14

Table 6.9: Groups of taxa displaying similar indices values.



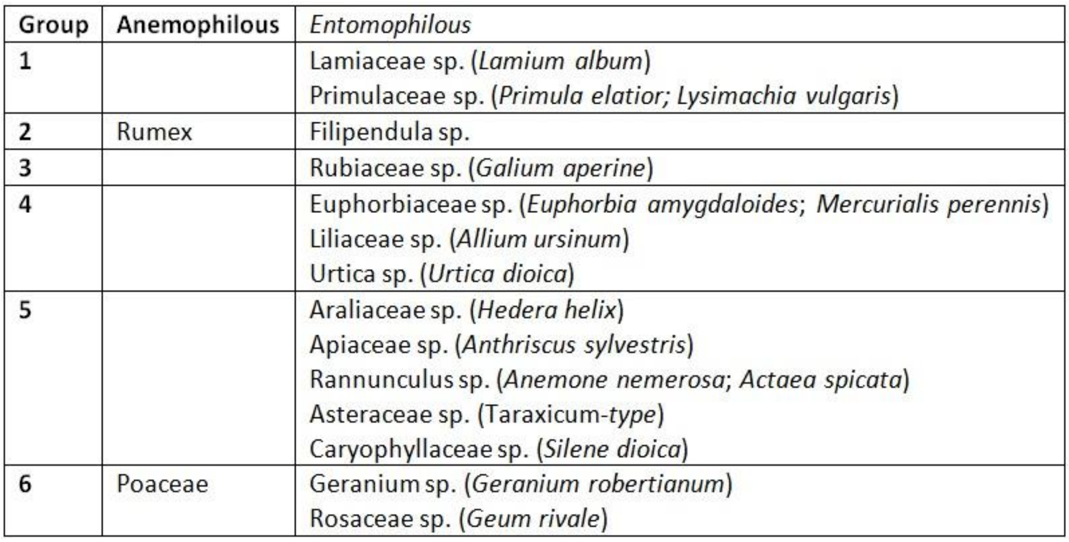
Group	Taxa	B_0	P_0	P_1	Category of association
1	Lamiaceae	0	1	1	Not associated
1	Primulaceae	0	3	2	Not associated
2	Filipendula	2	7	1	Overrepresented
2	Rumex	2	6	0	Overrepresented
3	Rubiaceae	2	1	9	Underrepresented
4	Liliaceae	3	0	5	Underrepresented
4	Euphorbiaceae	8	0	4	Underrepresented
4	Urtica	3	1	6	Underrepresented
5	Caryophyllaceae	3	5	3	Weakly associated
5	Araliaceae	5	4	2	Weakly associated
5	Apiaceae	7	3	2	Weakly associated
5	Asteraceae	3	2	4	Weakly associated
5	Rannunculus	6	4	3	Weakly associated
6	Geranium	5	2	1	Strongly associated
6	Rosaceae	10	1	2	Strongly associated
6	Poaceae	12	2	1	Strongly associated

Within the results six groups of plant taxa can be identified as displaying similar patterns within the *A*, *O* and *U* indices tables. The groups which display similar patterns are identified in table 6.9 above and are divided into 6 groups. Groups 2 – 6 are illustrated in figures 6.4 – 6.9; Group 1, Lamiaceae and Primulaceae are present as either plants or pollen, and so are not displayed graphically.

Group 1

The group Lamiaceae (sp. *Lamium album*) and Primulaceae (sp. *Primula elatior;* Lysimachia *sp*.) are not associated, as both taxa are present as either plants or pollen. Lamiaceae plants are found at a single field site, *Lamiaceae* pollen is present at one site; Primulaceae plants are found at 2 sites, and Primulaceae pollen at 3 sites. Both taxa have relatively small pollen grain sizes i.e. 26µm, (see tables 6.10 and 6.11 below) and are entomophilous, with sp. *Lamium album* also able to regenerate vegetatively to form clonal patches through rhizome growth. The preference of sp. *Lamium album* for lightly shaded sites (Grime *et al*., 1996) characterized by occasional disturbance i.e. hedgerows, may suggest why the plant is absent from all but one survey. In the case of Primulaceae, *Primula elatior* is described as a ‘forest herb’ and is acknowledged as a good indicator of forest habitats with high biodiversity (Rossum, 2008). No persistent seed bank is formed by this taxon, and seed dispersal is often restricted to short distances potentially making this a localized taxon occurring in small, discrete patches.

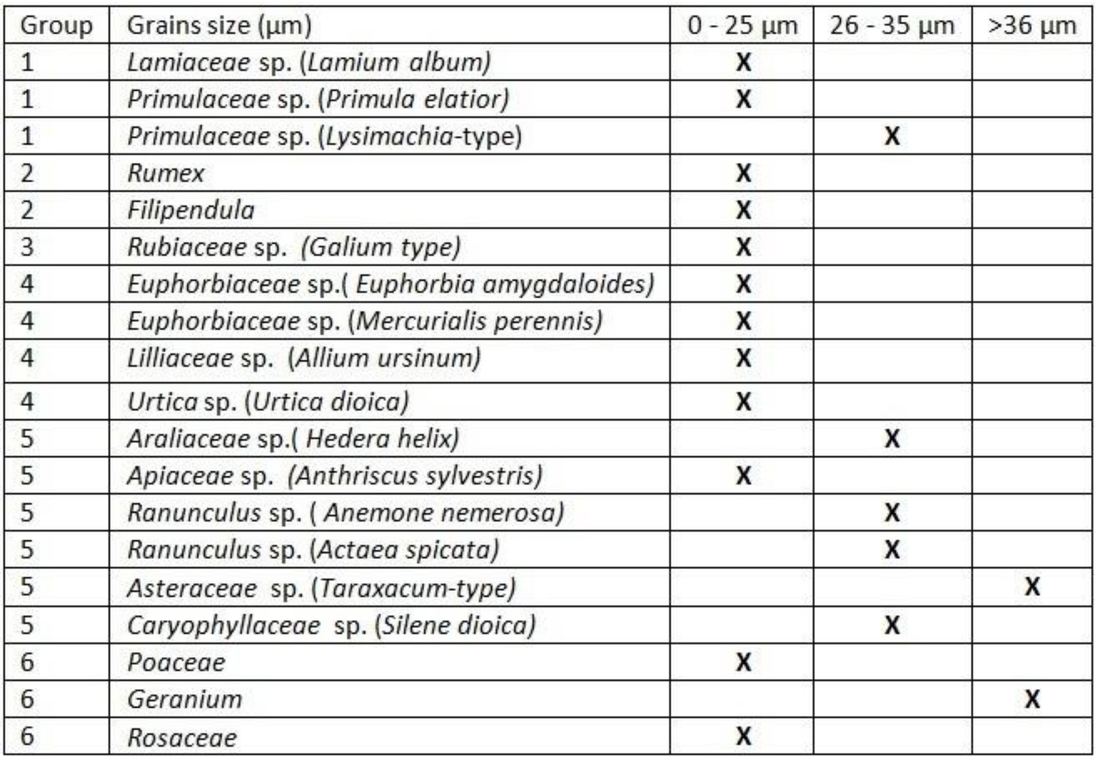
Table 6.10: Pollination strategies of taxa discussed in the text.



Group	**Anemophilous**	*Entomophilous*
1		Lamiaceae sp. (*Lamium album*) Primulaceae sp. (*Primula elatior; Lysimachia vulgaris*)
2	Rumex	Filipendula sp.
3		Rubiaceae sp. (*Galium aperine*)
4		Euphorbiaceae sp. (*Euphorbia amygdaloides; Mercurialis perennis*) Liliaceae sp. (*Allium ursinum*) Urtica sp. (*Urtica dioica*)
5		Araliaceae sp. (*Hedera helix*) Apiaceae sp. (*Anthriscus sylvestris*) Rannunculus sp. (*Anemone nemerosa*; *Actaea spicata*) Asteraceae sp. (Taraxicum-*type*) Caryophyllaceae sp. (*Silene dioica*)
6	Poaceae	Geranium sp. (*Geranium robertianum*) Rosaceae sp. (*Geum rivale*)

Low densities of Lamiaceae (sp. *Lamium album*) and Primulaceae (*Primula elatior;* Lysimachia *sp*.) plants in the field site vegetation surveys and poor pollen dispersal are suggested as the most likely hypotheses for the zero *A* values recorded for these taxa.

Table 6.11: Grain sizes of taxa discussed in the text; taken from Bunting *et al*. (2013)

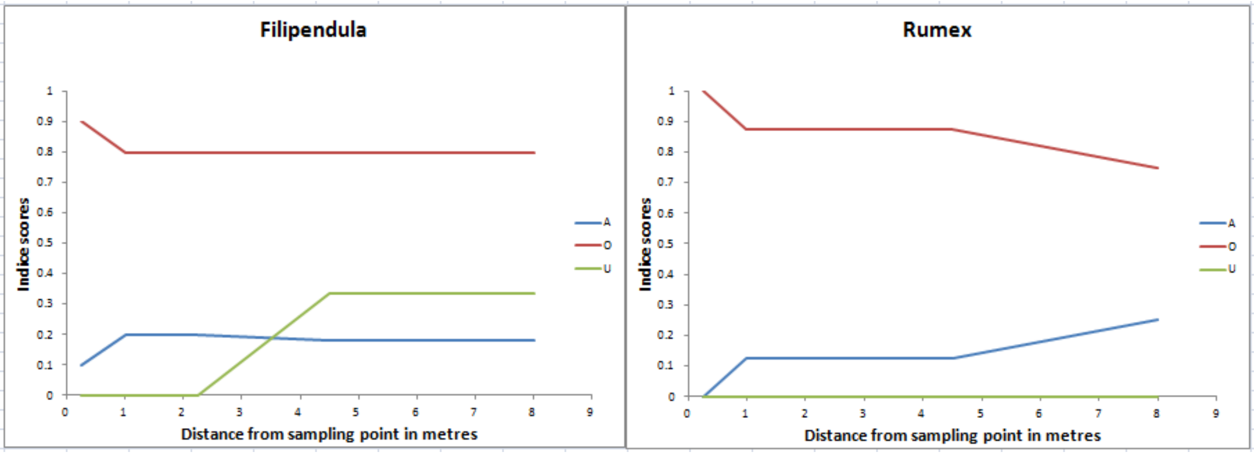


Group	Grains size (µm)	0 - 25 µm	26 - 35 µm	>36 µm
1	*Lamiaceae* sp. (*Lamium album*)	**X**		
1	*Primulaceae* sp. (*Primula elatior*)	**X**		
1	*Primulaceae* sp. (*Lysimachia*-type)		**X**	
2	*Rumex*	**X**		
2	*Filipendula*	**X**		
3	*Rubiaceae* sp. (*Galium type*)	**X**		
4	*Euphorbiaceae* sp.(*Euphorbia amygdaloides*)	**X**		
4	*Euphorbiaceae* sp. (*Mercurialis perennis*)	**X**		
4	*Lilliaceae* sp. (*Allium ursinum*)	**X**		
4	*Urtica* sp. (*Urtica dioica*)	**X**		
5	*Araliaceae* sp.(*Hedera helix*)		**X**	
5	*Apiaceae* sp. (*Anthriscus sylvestris*)	**X**		
5	*Ranunculus* sp. (*Anemone nemerosa*)		**X**	
5	*Ranunculus* sp. (*Actaea spicata*)		**X**	
5	*Asteraceae* sp. (*Taraxacum-type*)			**X**
5	*Caryophyllaceae* sp. (*Silene dioica*)		**X**	
6	*Poaceae*	**X**		
6	*Geranium*			**X**
6	*Rosaceae*	**X**		

Group 2

The second group Rumex and Filipendula-*type* are generally over-represented within the 10m sampling radius used for this study suggesting that pollen dispersal is effective for these taxa; Group 2 is illustrated in figure 6.4 below.

Figure 6.4: Group 2, Rumex and Filipendula are generally over-represented.



This observation is interesting in that Rumex is anemophilous (see table 6.9) and Filipendula is entomophilous (Hickey & King, 1981). Anemophilous taxa are often characterised by high pollen production (Mauseth, 1995), releasing high volumes of pollen from numerous tiny flowers. Anemophilous taxa are more likely to display a propensity for high *O* values than entomophilous taxa which are often reliant on specific co-evolutionary insect vectors for successful cross-pollination. Flowering and seed set of Filipendula is retarded at shaded sites (Grime *et al*., 1996) e.g. under a dense tree canopy. However in this study many of the sampling sites where Filipendula sp. was recorded were of a more open aspect with gaps in the tree canopy, potentially allowing higher pollen production at these sunnier sites; also at several of the sampling locations, streams and wet areas were present, Filipendula being strongly associated with damp and/or marshy habitats. The similarity in over-representation may also be a function of the relative height of the plants in relation to the effectiveness of pollen dispersal of each taxa as Rumex sp. *Rumex obtusifolius* is typically >100 cm in height, and Filipendula is typically >100 cm in height.

Both Rumex and Filipendula are characterised by a relatively small (<26µm) pollen grain size (see table 6.11), which may aid pollen dispersal. Over-representation of Rumex may be influenced by the ecological preferences for low pH sites characterised by an open aspect and/or episodic disturbance, meaning it would be a ubiquitous taxa in the grazed grasslands of the White Peak region. As all the sampling sites used in this study are in undisturbed ancient woodland on limestone soils, it is perhaps to be expected that the presence of Rumex would be at low densities. This hypothesis is supported by the occurrence of Rumex plants at only 2 sampling sites, with pollen recorded in surface samples at 8 sites. Pollen productivity of Rumex in RPPE studies has been found to be high (Broström *et al*. 2004), meaning that a proportion of the Rumex pollen found in the White Peak pollen assemblages may be regional background pollen input (Brun *et al*., 2007). The over-representation of Filipendula may be influenced by the numerous flowers e.g. >100 in a cymose panicle (Grime *et al*., 1996) which provide sunning sites for insects which aid pollen dispersal , the height of the foliage and flowers of the plant, and the ability of the taxa to form dense stands (through vigorous rhizomatous growth) on suitable sites. Filipendula plants are present at only 3 of the 14 sampling locations, and pollen is represented in 10 surface samples.

Group 3

Group 3 comprises a single taxon, Rubiaceae, and is illustrated in figure 6.5 below.

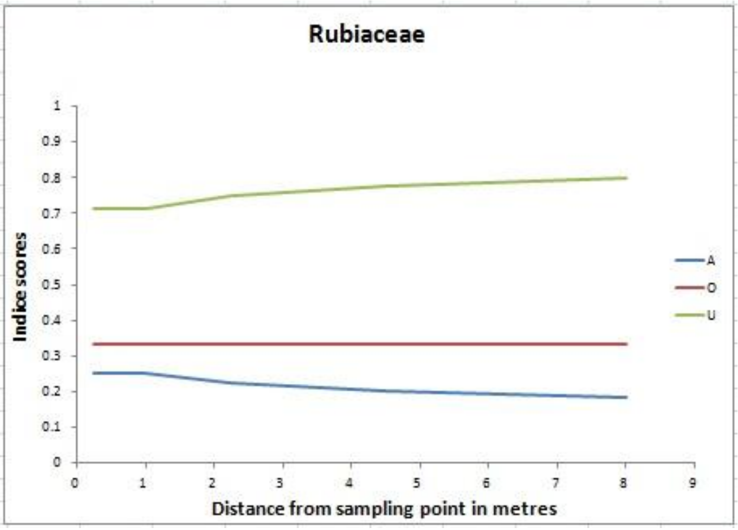


Figure 6.5: Group 3, Rubiaceae is generally under-represented; association values display a decrease with distance.

The under-representation index values of Rubiaceae increase with distance from the sample point, whilst the *A* index values display a decrease with distance. This inverse relationship suggests that the primarily entomophilous pollination strategy (some Rubiaceae species are self-pollinating) common to this family is influencing the index scores either through poor pollen dispersion and/or low pollen production – see table 6.10. Rubiaceae plants were recorded at 9 of the 14 sampling sites visited; pollen was present in surface samples at only 3 sampling locations. Within the Rubiaceae family, taxa such sp. *Galium aperine* (recorded at 9 White Peak sites) reach foliage and flower height of <1.2 m, which could potentially aid pollen dispersal through 'pollen-loss' from travelling insects. However Rubiaceae sp. *Galium aperine* flowers are hermaphrodite and few in number suggesting that potentially insects play only a minor role in the pollination of this taxon.

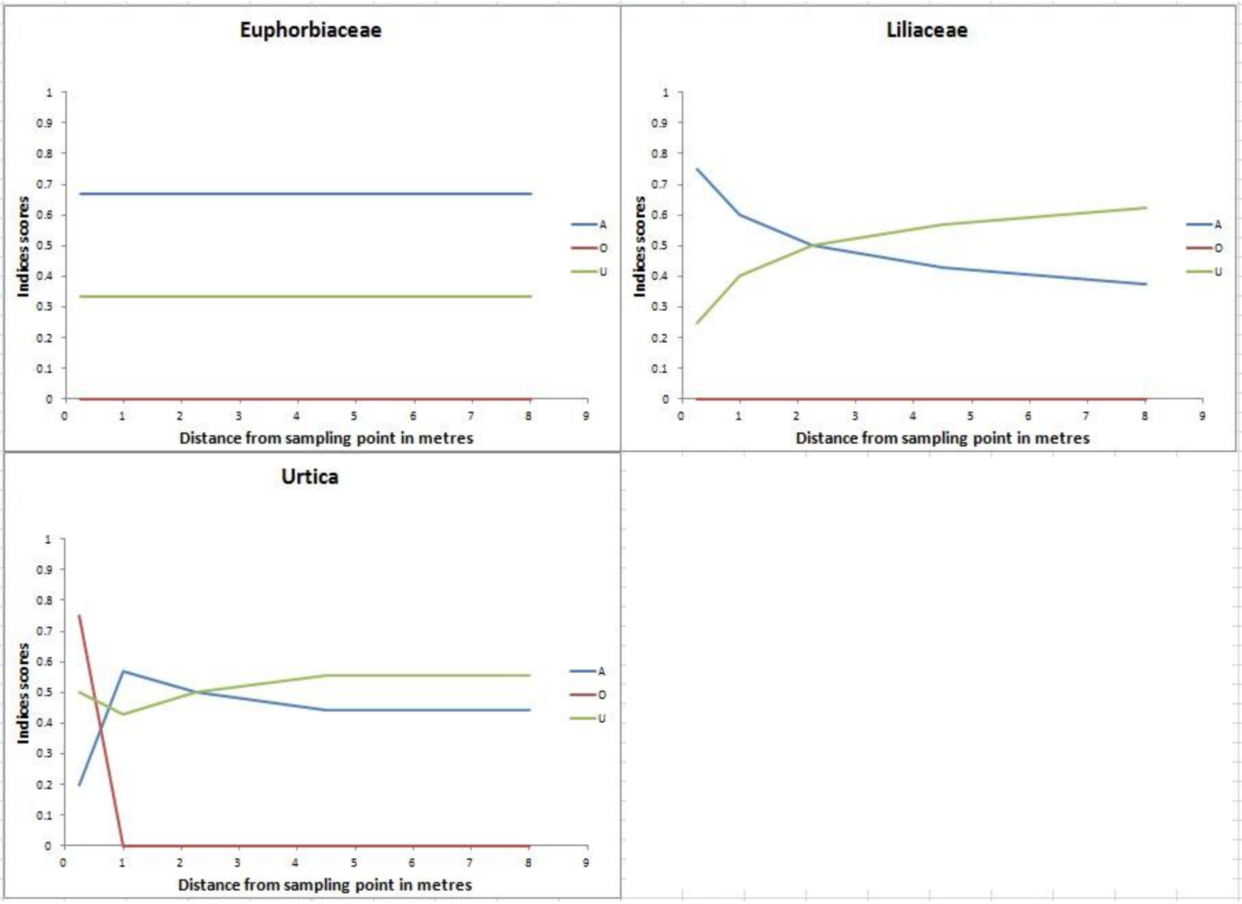
Fewer insect visits to a plant would potentially result in a lower proportion of pollen being transported and distributed via 'pollen-loss' whilst in flight, and from visiting flowers on different plants. The relatively small pollen grain size (26µm< - see table 6.11) appears not to be a significant influence in improving pollen dispersal in the case of *Galium aperine*. It may be the case that as the taxon is often self-pollinating, low pollen productivity rather than ineffective pollen dispersal is a factor influencing what appears to be a highly localized pollen signal for this taxon. Alternatively, the preferred reproductive strategy for *Galium aperine* may be vegetative spread or self-fertilization resulting in very low pollen production and very poor dispersal.

Group 4

The fourth group comprises Euphorbiaceae, Lilliaceae and Urtica, which display a trend of zero over-representation meaning that these taxa tend toward underrepresentation. Group 4 is illustrated in figure 6.6 in the text below.

Within this group, the Euphorbiaceae taxa (sp. *Euphorbia amygdaloides; Mercurialis perennis*) display contrasting pollination strategies; *Euphorbia amygdaloides* is entomophilous, whilst *Mercurialis perennis* is anemophilous. Lilliaceae plants are entomophilous, whilst Urtica is anemophilous – see table 6.10. Euphorbiaceae plants (sp. *Euphorbia amygdaloides; Mercurialis perennis*) were recorded at 12 sampling sites, whilst pollen was present in surface samples at 8 sites.

Figure 6.6: Group 4, Euphorbiaceae, Liliaceae and Urtica have mostly zero over-representation, so tend to be under-represented.



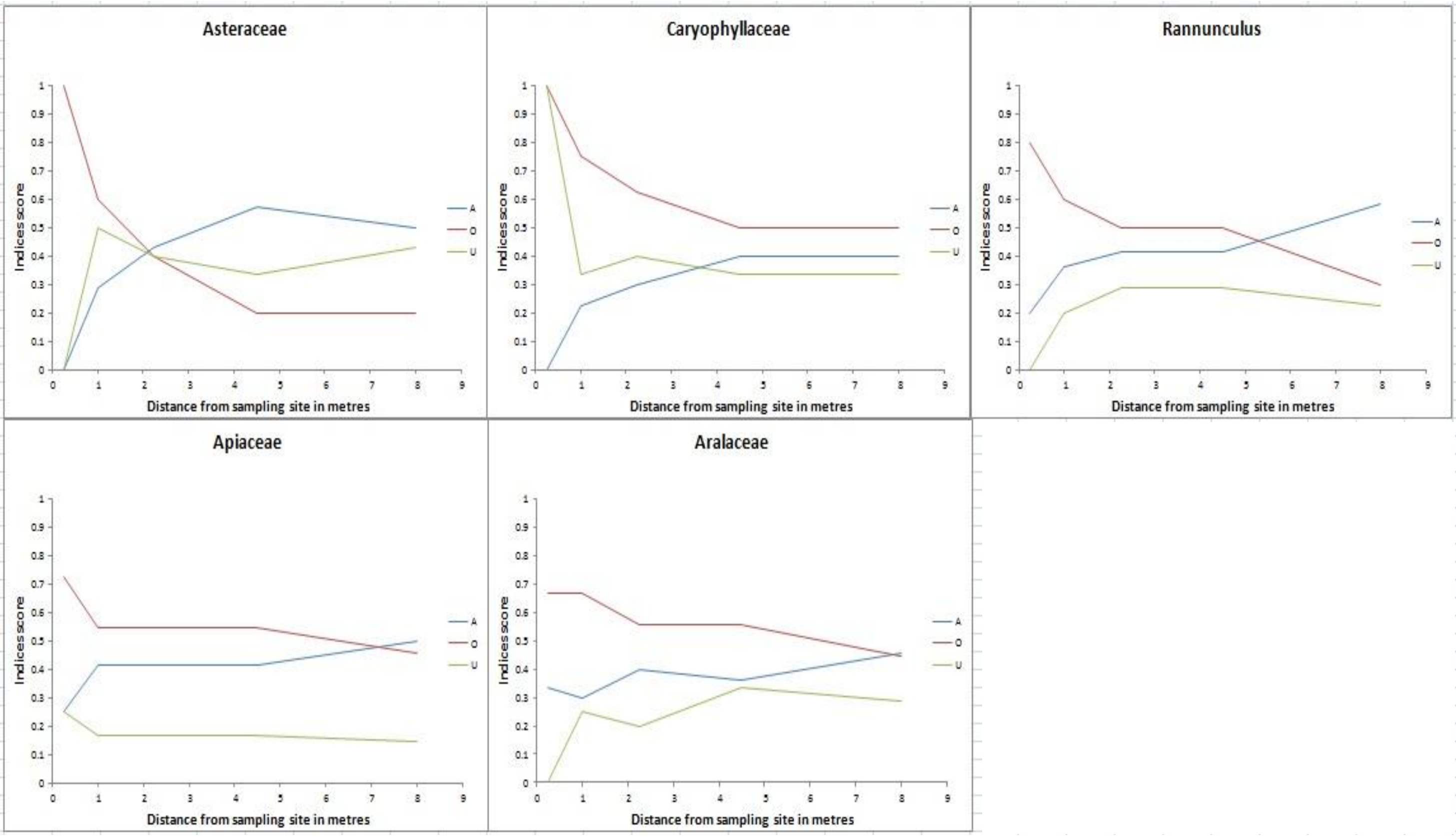
Lilliaceae plants (sp. *Allium ursinum*) were recorded at 8 sites, with pollen present in samples from 3 sites. Urtica plants (sp. *Urtica dioica*) were present at 9 sites, with pollen present in surface samples from 4 sites. A significant feature of this group is the under-representation of Euphorbiaceae taxa; although the plant was often recorded at high percentage cover at 12 of the 14 field sites, pollen was present in assemblages at only 8 field sites. The dominant Euphorbiaceae type at these sites was sp. *Mercurialis perennis* which, being anemophilous and with a small pollen grain size (<26 µm), should display relatively effective pollen dispersal and high pollen production – see tables 6.10 and 6.11. The absence of Euphorbiaceae pollen at the 4 sites where plants were present and pollen absent suggests that low wind speed below the canopy at these sites and the relatively small stature of the adult plant (<400 mm), may retard local pollen dispersal. It may be the case that the majority of the pollen produced falls very close to the plant e.g. <1 m. Additionally, it may be that a proportion of plants at the Derbyshire sites are using vegetative reproduction to form clonal patches.

Association index values (*A*) for Liliaceae (sp. *Allium ursinum*) decrease with distance away from the sampling point, whilst underrepresentation index values (*U*) increase with distance away from the sampling point. Liliaceae pollen was absent from surface samples at 5 sites where plants were recorded. This suggests a localized pollen signal, which may be influenced both by the low stature of the adult plant (<400 mm), and the ability of sp. *Allium ursinum* to spread by vegetative regeneration in addition to insect pollinators. It is noticeable that sp. *Urtica dioica*, which is primarily anemophilous, also displays declining *A* index values with distance away from the sampling point whist *U* index values decrease away from the sampling point. The small pollen grain size (< 26µm) and anemophilous pollen dispersal strategy of Liliaceae sp. *Urtica dioica* would suggest that if significant amounts of pollen were being produced, then a high percentage would be deposited locally. This, as is also proposed for Lilliaceae (sp. *Allium ursinum*), suggests either a extremely localized pollen signal for sp. *Urtica dioica*, or a preference for vegetative regeneration forming clonal patches. The latter hypothesis is supported by the ecological requirement of the taxa for a 16 hour day-length for flowering and subsequent pollen production (Grime *et al*., 1996). This constraining autecological factor would potentially limit pollen production to less shaded sites outside the scale of the survey area utilised in Derbyshire.

Group 5

The fifth group Araliaceae *(*sp. *Hedera helix*), Apiaceae (sp. *Anthriscus sylvestris*), Ranunculus (sp. *Anemone nemerosa*; *Actaea spicata*), Asteraceae (sp. *Taraxacum*) and Caryophyllaceae (sp. *Silene dioica*) all display decreasing *O* and increasing *A* with distance away from the sampling point. The *A* index values for Araliaceae *(*sp. *Hedera helix*) display an increase with distance away from the sampling point. This rise in *A* values is accompanied by a concomitant fall in both *O* and *U* index values as distance from the sampling point increases. Araliaceae *(*sp. *Hedera helix*) is entomophilous, and has a relatively large (26 - 35µm) pollen grain size – see tables 6.109 and 6.11. Plants of sp. *Hedera helix* were recorded at 7 field sites, whilst pollen was present in surface samples at 9 of the 14 field sites; however pollen is present in small quantities (maximum of 21 grains from a sum of 500 at the 9 sites where pollen was recorded). Regeneration can occur either through pollen dispersal by insect pollinators (in unshaded locations), or through vigorous regenerative spread of clonal plants where shade is prevalent e.g. woodlands.

Figure 6.7: Group 5, Araliaceae, Apiaceae, Ranunculus, Asteraceae, and Caryophyllaceae all display decreasing *O* and increasing *A* values with distance away from the sampling point.



In shaded woodland sites, such as were used in this research, sp. *Hedera helix* rarely produces sexually mature flowers (Grime *et al*., 1996). This autecological constraint suggests that at the 9 sites where sp. *Hedera helix* pollen was recorded in surface samples, pollen may have been transported via insect pollinators from sexually mature flowers on plants in local un-shaded locations i.e. woodland edges. An additional consideration is that sp. *Hedera helix* is able to climb tree trunks to heights of > 10m whilst seeking optimum light conditions; this would potentially enhance pollen production and dispersal in otherwise unsuitable sites. A proportion of the pollen recorded in the surface samples may therefore have been transported (via 'pollen losses' from insects in flight and visiting different flowers on different plants) from woodland edge sites, or from less shaded sites in the woodland canopy itself. This suggests that, due to the shaded nature of the majority of the sampling sites, a high percentage of the sp. *Hedera helix* plants recorded in the survey may be non-flowering clones.

The *A*, *U* and *O* index values of Apiaceae (sp. *Anthriscus sylvestris; Chaerophyllum temulentum; Heraculum sphondylium*) display a trend of *A* values increasing with distance away from the moss-polster sampling point, whilst both *O* and *U* index values decline away from the surface sampling point. Apiaceae plants were recorded at 7 field sites, with pollen present in surface samples at 9 of the 14 sampling sites. Apiaceae is a primarily entomophilous taxon, with >50 flowers per umbel in sp. *Anthriscus sylvestris*, and > 150 flowers per umbel in sp. *Heraculum sphondylium* (Grime *et al*., 1996) – see table 6.10. Grain size for Apiaceae (sp. *Anthriscus sylvestris*) is relatively small (<26µm) – see table 6.11. The capacity for shade-tolerance of this group suggests that the increasing-with-distance *A* index values represents successful exploitation of, and establishment in, local woodland sites. The flowering height of the Apiaceae family is also a consideration as regards pollen dispersal, with sp. *Chaerophyllum temulentum* flowering height < 1m, sp. *Anthriscus sylvestris* flowering height 1.5m< and sp. *Heraculum sphondylium* flowering height> 2m. The relatively high *O* values at all distances suggest that pollen dispersal is good for this taxon, with flower height a potential influencing factor. As insects are the main pollinators of Apiaceae, it may be the case that significant amounts of pollen are dispersed and subsequently deposited on the woodland floor by both 'pollen-loss' during flight and by aerialization as the insect takes off from the flower.

The *A*, *U* and *O* index values of Ranunculus (sp. *Anemone nemerosa*; *Actaea spicata*) suggest that association increases significantly with distance away from the sampling point whilst *O* and *U* values display a reciprocal fall in values with distance. Ranunculus plants were recorded at 9 sites, with pollen present in surface samples at 10 sites. Both taxa are entomophilous, with cross-pollination occurring through insect vectors; sp. *Anemone nemerosa* also has the capacity to produce clonal patches through rhizomes, and is associated with ancient or long-established woodlands. Both Ranunculus sp. are relatively small in stature, with sp. *Anemone nemerosa* < 0.35mand having a single terminal flower, and sp. *Actaea spicata* 0.6m< having small multiple flowers in terminal racemes. The A values for Ranunculus remain relatively flat until approximately 6m distance away from the sampling point, when values increase significantly. This trend suggests the plant is established in the local vegetation, which is classified as ancient woodland, perhaps primarily as the Ranunculus sp. *Anemone nemerosa* in long-established clonal patches.

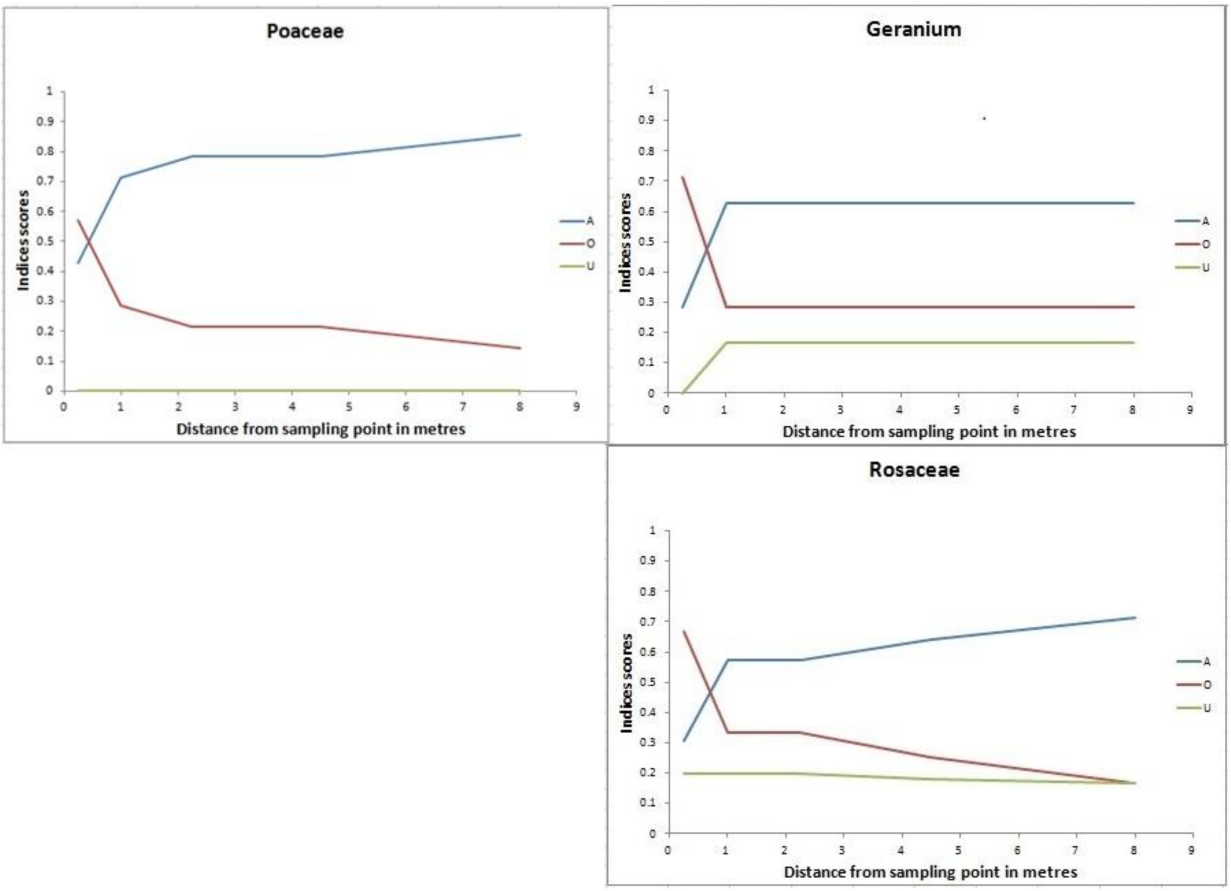
The *A*, *U* and *O* index values of Caryophyllaceae (sp. *Silene dioica*) and Asteraceae (sp. *Taraxacum*) differ slightly from those of Araliaceae *(*sp. *Hedera helix*), *Apiaceae* (sp. *Anthriscus sylvestris*) and Ranunculus (sp. *Anemone nemerosa*; *Actaea spicata*). Both sp. *Silene dioica* and sp. Taraxacum-*type* are entomophilous, with sp. *Silene dioica* reaching a flowering height of 0.9m< and sp. Taraxacum-*type* reaching a flowering height of 0.4m< (Grime *et al*., 1996). Caryophyllaceae (sp. *Silene dioica*) is recorded as a plant at 6 of the 14 field sites, with pollen recorded in surface samples at 8 sites albeit at low values i.e. < 5 grains from a count of 500 grains. The Asteraceae sp. Taraxacum - *type* is recorded as a plant at 7 field sites, with pollen present in surface samples at 5 locations at low values i.e. < 5 grains from a count of 500 grains.

The association index (*A*) values for both Caryophyllaceae sp. *Silene dioica* and for Asteraceae sp. Taraxacum-*type* rise rapidly from zero at the central surface sample location, to around 5.5 for sp. Taraxacum-*type*, and 4.0 for sp. *Silene dioica* at approx. 4.5m distance from the central sampling point. The *A* values for both taxa then remain relatively flat across the remainder of the 10m radius of the sample/survey area, with a slight decreasing trend noticeable in *A* values for sp. Taraxacum-*type* starting from approximately 5m distance away from the central sampling point. Interestingly both sp. *Silene dioica* and sp. Taraxacum-type display marked falls in overrepresentation with distance away from the central sampling point. This decrease is more significant in the case of sp. Taraxacum-*type*, which from around 5 – 10m becomes increasingly underrepresented; the 5m point is also the distance where the highest A values for this taxa were observed. This would suggest that, based on this research, that sp. Taraxacum-*type* may produce a more localized pollen signal than sp. *Silene dioica*. It is also noteworthy that sp. *Silene dioica* is much more likely to flower and produce pollen in lightly-shaded habitats, but can survive in a non-flowering condition in deep shade. As the majority of the 14 field sites were shaded, this shade-intolerance may explain the paucity of both adult plants and pollen percentages observed in this taxa. In western Norway, Hjelle (1997) also observed that sp. *Silene dioica* has relatively good association index scores and low underrepresentation index scores despite relatively low pollen production levels.

Group 6

Group 6, Poaceae, Rosaceae and Geranium, are illustrated in figure 6.8 below.

Figure 6.8: Group 6, Geranium, Poaceae, and Rosaceae are characterized by A values >0.50, suggesting a significant level of correspondence between plant presence and pollen.



This group is characterized by *A* values > 0.50, this score suggesting a significant level of correspondence between the presence of these plant types and the associated pollen morphotypes in local pollen assemblages. Rosaceae sp. *Geum rivale* and Geranium sp. *Geranium robertianum* are entomophilous, Poaceae is anemophilous. In western Norway Hjelle (1997), observed similarly high *A* score of Poaceae and suggested that high pollen production and effective pollen dispersal was a significant factor for highly associated taxa. Although scoring high association index scores, both Rosaceae and Geranium are entomophilous; this observation is also supported by Hjelle (1997) who used PCA scatter plots to suggested that the best associated taxa were anemophilous, but also found that entomophilous taxa with anthers partially concealed also displayed high association index values e.g. sp. *Trifolium repens*.

6.2.2. Discussion

Perhaps the most interesting observation from the Derbyshire sites is the degree of pollen production and effective pollen dispersal of some of the entomophilous taxa. In some cases entomophilous taxa, e.g. sp. *Hedera helix* which are characterised by relatively large pollen grain sizes (26 - 35µm) display effective pollen dispersal over a scale of tens of metres at the Derbyshire sites. Entomophilous taxa in this Derbyshire study are also relatively highly overrepresented e.g. Caryophyllaceae (sp. *Silene dioca*) see table 6.8. Within the context of previous research utilising presence–absence indices to investigate the spatial resolution of the plant – pollen relationship (Davis, 1984; Hjelle, 1997; Bunting, 2003), similar patterns of overrepresentation were also observed in entomophilous taxa at other field sites (Brun *et al*., 2007).

Davis (1984) found that most taxa with high overrepresentation scores (> 0.50) had low pollen percentages where the taxon was absent; where both plant and pollen were present pollen percentages were less than 10% of the pollen sum. These observations are similar for taxa in the Derbyshire study sites, e.g. Caryophyllaceae (sp. *Silene dioica*) pollen percentages are< 1% of the pollen sum of 500 (1 – 3 grains per 500). Another similarity with the findings of Davis (1984) is that in the Derbyshire study taxa that are well represented in the vegetation survey appear to produce small amounts of pollen based on their association scores. Often these taxa have entomophilous flowers, and have low percentages values in moss-polster surface samples. An example of this is Rubiaceae (sp. *Galium aperine*), which is recorded as a plant at 10 field sites in Derbyshire; however Rubiaceae pollen is recorded at only 4 field sites and (with the exception of one high-value outlier) at minimal pollen percentage values of < 2%.

Investigations by Hjelle (1997), found that entomophilous taxa with few freely exposed anthers or concealed anthers displayed good association index scores, but were generally underrepresented; however Hjelle's study examined meadow/heath plant-pollen relationships, more open environments not analogous to the valley woodland field sites used in this present Derbyshire study. Hjelle (1997) also suggests that anemophilous taxa and entomophilous taxa with open blossoms and numerous exposed anthers were found to be the best associated and in some cases the most overrepresented, and that pollen grain size (40µm<) was a factor in both overrepresentation and association scores. Results from the Derbyshire field sites display some similarities and disparities in comparison to the Norwegian research. At the Derbyshire sites, only two of the recorded plant taxa have small pollen grains (<25µm) and are anemophilous; e.g. Rumex and Poaceae. Although highly overrepresented in Derbyshire, Rumex is displays poor association values within the survey area suggesting a significant regional background pollen input to the surface samples. This contrasts with Poaceae which has relatively low overrepresentation values but is very highly associated. The high degree of overrepresentation observed for Rumex in the White Peak agrees with Bunting (2003), who found a similar degree of overrepresentation for Rumex in Scottish heath environments. This contrasts with the Norwegian study of Hjelle (1997), which although different in survey methodology and site type, found that Rumex was highly associated and poorly overrepresented in meadow/pasture locales; this follows the suggestion of Grime (1996) that Rumex is ubiquitous in meadow and pasture habitats, and has high pollen production (Broström *et al*. (2004). The low association values for Rumex observed in this Derbyshire study may be related to a different species mixture at the field sites, as Hjelle (1997) investigated open heath and meadow sites where *Rumex acetosa* is ubiquitous; this study is based on assemblages from valley woodlands where *Rumex obtusifolius* may be the pollen producing taxa.

The association values of Ranunculus from the Derbyshire sites (at 8m distance) display some similarity with the Norwegian data from meadow/pasture of Hjelle (1997). Although Ranunculus is significantly more overrepresented at distances closer to the surface sampling point at the Derbyshire sites, as distance away from the central sampling point increases overrepresentation values decrease and association values increase. This observation in Derbyshire shows a strong similarity to the Norwegian meadow/pasture values for Rannunculus. The high association index values for Poaceae in Derbyshire are similar to those of both the Norwegian study of Hjelle (1997), and the Scottish study of Bunting (2003). The overrepresentation and underrepresentation scores for Poaceae in Derbyshire display almost identical values to those reported by Bunting (2003) in Scotland; no overrepresentation or underrepresentation values are given for Poaceae in the Norwegian study. Many taxa from the Scottish study share similarities with the Derbyshire results. Apiaceae overrepresentation scores from Scotland are slightly higher at 0.90 than the Derbyshire result of 0.73 at 0.25m; however Apiaceae displays higher association values and underrepresentation values in the Derbyshire results. Rosaceae (sp. Geum-type) association values in the Scottish study are also similar at 0.38, with Derbyshire association values for Rosaceae of 0.33 at 0.25m; association rises with distance in Derbyshire, increasing to 0.71 at 8m.

6.2.3. Conclusion

Based on the indices results presented in table 6.9, six groups of taxa are identified as displaying similar patterns of representation and association; these similar patterns are influenced by the pollination strategy, pollen grain size, degree of pollen production, and effectiveness of pollen dispersal of the individual taxon. Ruderal anemophilous taxa such as Rumex are often used to infer anthropogenic disturbance from fossil pollen assemblages (Brun, 2011). Rumex is overrepresented in Derbyshire pollen assemblages used for this study; effective pollen dispersal of this taxon means that Rumex pollen is reflecting both the local *and* regional Rumex vegetation around the Derbyshire sites as the plant is often not recorded adjacent to the sampling site during the vegetation survey. The Rumex type recorded in the White Peak is *Rumex obtusifolius*, which proves an accurate indicator taxon of both ruderal and pastural communities (Behre, 1981) as the primary agricultural landscape of the modern-day White Peak is dominated by upland pasture. Filipendula is also an overrepresented taxon, and provides a useful indicator of damp and marshy environmental conditions in the landscape.

Entomophilous taxa with open flowers and/or numerous anthers such as Geranium (*Geranium robertianum*) and Rosaceae (*Geum rivale*) appear to provide good indicators of the presence of local woodland, as both these herb taxa display a significant level of correspondence between plants observed in the valley woodland vegetation surveys and pollen presence in assemblages at the Derbyshire sites. Other herb taxa associated with woodland edges such as Apiaceae (*Anthriscus sylvestris*), and with ruderal habitats and riverbank forest (Behre, 1981) such as Araliaceae (*Hedera helix*) display increasing association with distance away from the pollen assemblage sample point. This suggests that pollen of Geranium, Rosaceae, Apiaceae and Araliaceae observed in fossil pollen assemblages will represent plants of these taxa in local vegetation proximal to the coring location at the time of pollen deposition, and will indicate that woodland was present in the local area; absence of these taxa indicating that woodland may have been not have been present locally. The anemophilous Euphorbiaceae taxon *Mercurialis perennis* is underrepresented at the Derbyshire field sites, and is a reliable indicator of local woodland.

Brun (2001) stresses the need to develop an understanding of the *local* pollen-vegetation relationship, environmental constraints and synecology of modern herb indicator taxa in order to assist environmental reconstructions of past vegetation based on fossil pollen by allowing hypotheses to be developed regarding local environmental conditions at the time of fossil pollen deposition (Brun, 2011). This study has examined local modern pollen – vegetation relationships of herb indicator taxa at valley woodland field sites in the White Peak, Derbyshire and produced a new dataset of association indices for the White Peak region. These finding represent a useful interpretative aid when utilising fossil pollen in environmental reconstructions of the mid-late Holocene vegetation in the White Peak which is discussed in section 6.5 of this chapter, and in the case of Geranium, Rosaceae, Apiaceae and Araliaceae will allow the presence of local woodland to be inferred; and in the case of Rumex will allow the inference of local and regional landscape disturbance.

6.3 Terrestrial Pollen Taphonomy Study

Introduction

This study aims to examine spatial variation in local pollen deposition in woodland floor moss polsters within a 1 metre quadrat at two upland woodland sites in the White Peak in Derbyshire and one site in valley woodland in East Yorkshire. Site locations are described in chapter 3 and illustrated if figures 3.2 and 3.3; the study field sampling methodology is described in chapter 5. The rationale for this investigation is that relative pollen productivity estimates (RPPE) produced from modern-day field studies often use moss polsters in conjunction with vegetation surveys to derive RPPE datasets, which are subsequently applied to semi-qualitative and quantitative reconstructions of vegetation in past landscapes based on fossil pollen assemblages. Variation in local pollen deposition in moss polsters is a consideration of research design in RPPE studies e.g. Räsänen *et al*. (2004), and techniques such as the amalgamation of multiple moss samples have been used to mitigate any effects of any assumed local pollen depositional variation Broström *et al*. (2004). No study has yet examined the range of variation in local pollen deposition in woodlands on a sample-by-sample basis within a small (<1m) defined area.

The variability in pollen deposition in a small, controlled area has been investigated by very few previous researchers (Adam & Mehringer, 1976; Pardoe, 1996), and so offers scope for further detailed investigation. Pardoe (1996) suggests that a high degree of local variability in pollen deposition and the spatial complexity of pollen source areas can result in a unique pollen spectrum from spatially discrete sites within relatively small areas (16m^2), and concludes that an 'amalgamated' moss polster consisting of 20 well mixed subsamples is necessary to avoid collecting a sample that does not accurately represent the local pollen rain through depositional biases. The research of Pardoe (1996) focused on alpine plant communities in open landscapes in Norway, and is therefore not comparable with valley woodland contexts in lower latitudes such as Derbyshire in the UK.

The Derbyshire and East Yorkshire sampling sites used for this study can be classified as forest hollows *sensu* Calcote (1995), as all 3 field sites are located within established ancient or semi-natural woodland with a well developed woodland canopy. The contrast between a relatively open high altitude pro-glacial site in Scandinavia and deciduous valley woodland sites in Derbyshire and East Yorkshire in central England is non-trivial in terms of vegetation structure and pollen source area (Bunting *et al*. 2004). Pardoe (1996) stresses the interpretational implications of depositional variability when examining Holocene sub-fossil pollen profiles, which are often based on a single sediment core, from which retrospective vegetation reconstructions are developed, and concludes that an 'amalgamated' moss polster of 20 well mixed subsamples is necessary to avoid collecting a sample that does not accurately represent the local pollen rain through depositional biases. This conclusion is supported by Räsänen *et al*. (2004), who suggest that a single moss surface sample can be argued to be more comparable with a sample from a peat core than a bulk sample as a peat core represents a single point in the palaeoenvironmental record.

6.3.1. Results

Pollen counts were processed in PSIMPOLL software, and pollen percentage diagrams produced. A percentage diagram of tree taxa is presented in figure 6.9, and a composite percentage diagram of both tree and herb taxa is presented in figure 6.10. The three study site locations in both figures are indicated on the right of the diagrams.

AP pollen percentage values are high at both the two Derbyshire sampling sites and the East Yorkshire sampling site, dominating the pollen sum at all three sites. Acer is the dominant taxon at Millington Wood and Chee Dale, with Fraxinus the dominant taxon at Cressbrook Dale. The field sites are described individually below.

Figure 6.9: Pollen diagram will be inserted here as an A3 sheet.

Figure 6.10: Pollen diagram will be inserted here as an A3 sheet.

Chee Dale

The Chee Dale quadrat is dominated by Acer, which displays pollen percentage values which range from 50 – 70% across the 10 samples within the 1m quadrat. Fraxinus is the second dominant taxon at Chee Dale, displaying a wide range of pollen percentage values from 10 – 30%. Pollen percentage values of Pinus at Chee Dale are variable, with percentages ranging from 5 – 20% across the 10 samples. Ulmus values at the Chee Dale quadrat display a range of variation in pollen percentages of between 1 – 7%. Betula pollen percentages at Chee Dale are variable across the 10 samples, with pollen percentage values ranging from 1 – 7%. Pollen percentage values of Alnus at the Chee Dale quadrat display a range of 1 – 4% across the 10 sub-sample points. Corylus displays relatively low pollen percentages at Chee Dale, with values ranging from 1 – 5%. Picea pollen percentage values at Chee Dale are relatively low, with values <3 % in all 10 sub-samples, and pollen percentage values of <0.5% observed in 3 of the 10 quadrat samples. Fagus is present at low pollen percentage values at the Chee Dale quadrat, with percentage ranging from 1 – 7%. Salix is present at very low pollen percentage values of <0.5% in only eight of the ten sub-samples. Larix is present at pollen percentage values of <1% in only two of the 10 sub-samples. Carpinus is present at pollen percentage values of <0.5% at only one sub-sample point in the Chee Dale quadrat. Ilex is present at three sub-sample points within the Chee Dale quadrat at pollen percentage values of <0.5%. Populus and Tilia are present in only one sub-sample at a pollen percentage value of <0.5%. Quercus is present at pollen percentage values of <0.5% in only one sub-sample in the Chee Dale quadrat.

Cressbrook Dale

The Cressbrook quadrat sub-samples are dominated by both Fraxinus and Acer pollen. Acer percentage values range from 30 – 50% across the 10 sub-samples, with Fraxinus percentage values ranging from 25 – 40%. Pinus displays relatively high percentage values in the Cressbrook sub-samples, with values ranging from 10 – 25%. Pollen percentage values of Ulmus range from 4 – 6% at the Cressbrook site sub-samples. Pollen percentage values of Betula are relatively uniform at the Cressbrook site, with values across the 10 sub-samples ranging from 3 – 6%. Corylus values at Cressbrook are also relatively uniform at all 10 sub-sample points within the quadrat; with nine of the sample values at 4%, with a single value of 1%. Alnus pollen percentage values at Cressbrook are relatively uniform with values of 5% observed in 9 of the quadrat sub-sample points. Pollen percentage values of Fagus are low in all the Cressbrook sub-samples with observed values of <5%. Picea pollen percentage values at Cressbrook display a variation in percentage values of 1 – 5% across the 10 sub-samples. Larix displays very low pollen percentages of <1% at Cressbrook, and is absent from 7 of the sub-sample points. Quercus is absent from seven of the ten sub-sampling points at the Cressbrook quadrat, and present at pollen percentage values of <2% in the three sub-samples where the taxa is recorded. Tilia is absent from eight of the ten Cressbrook sub-samples, and is recorded at pollen percentage value of <0.5% in the two sub-samples where the taxa is present. Salix is present at eight of the Cressbrook sub-samples at low pollen percentage values of <0.5%. Carpinus, Ilex and Populus are entirely absent from all of the Cressbrook quadrat sub-samples.

Millington Dale

The dominant tree taxon at the Millington study site in East Yorkshire is Acer, which displays high, relatively uniform pollen percentage values of 60 - 70% at across the ten sub-sampling points. Pollen percentage values of Fraxinus are low overall at Millington, with percentage values ranging from 1 – 5% across the ten sub-sample points. Pollen percentage values of Pinus at Millington are relatively low, and display a range in percentage values from 2 – 9% across the ten sub-samples. Ulmus pollen percentage values at Millington are relatively low, with percentages values across the 10 sub-samples ranging from 3 – 7%. Pollen percentage values of Betula at Millington are uniformly low at <3% at all 10 sub-sample points. Corylus pollen percentage values are also uniformly low across all ten sub-samples, with percentage values displaying a range from 0.5 – 5% across the quadrat. Alnus pollen percentage values at the Millington quadrat are variable across the 10 sub-sampling points, with percentage values ranging from 1 – 5%. Larix is present at very low pollen percentage values of <1% in only eight of the Millington quadrat sub-samples, the taxon being completely absent at two sub-sampling points. Fagus is present at very low percentage values of <1% in all ten sub-sample points at the Millington quadrat. Pollen percentage values of Picea at Millington are low at Millington, with values ranging from 1 – 2.5% across the ten sub-samples. Salix pollen percentages at Millington are very low, with percentage values of <1% in the nine sub-sample points where the taxon was recorded. Tilia is recorded at a pollen percentage of <0.5% in only one sub-sample at the Millington quadrat from. Carpinus, Ilex and Populus pollen is entirely absent from all of the Millington quadrat sub-samples.

Confidence Interval Analysis

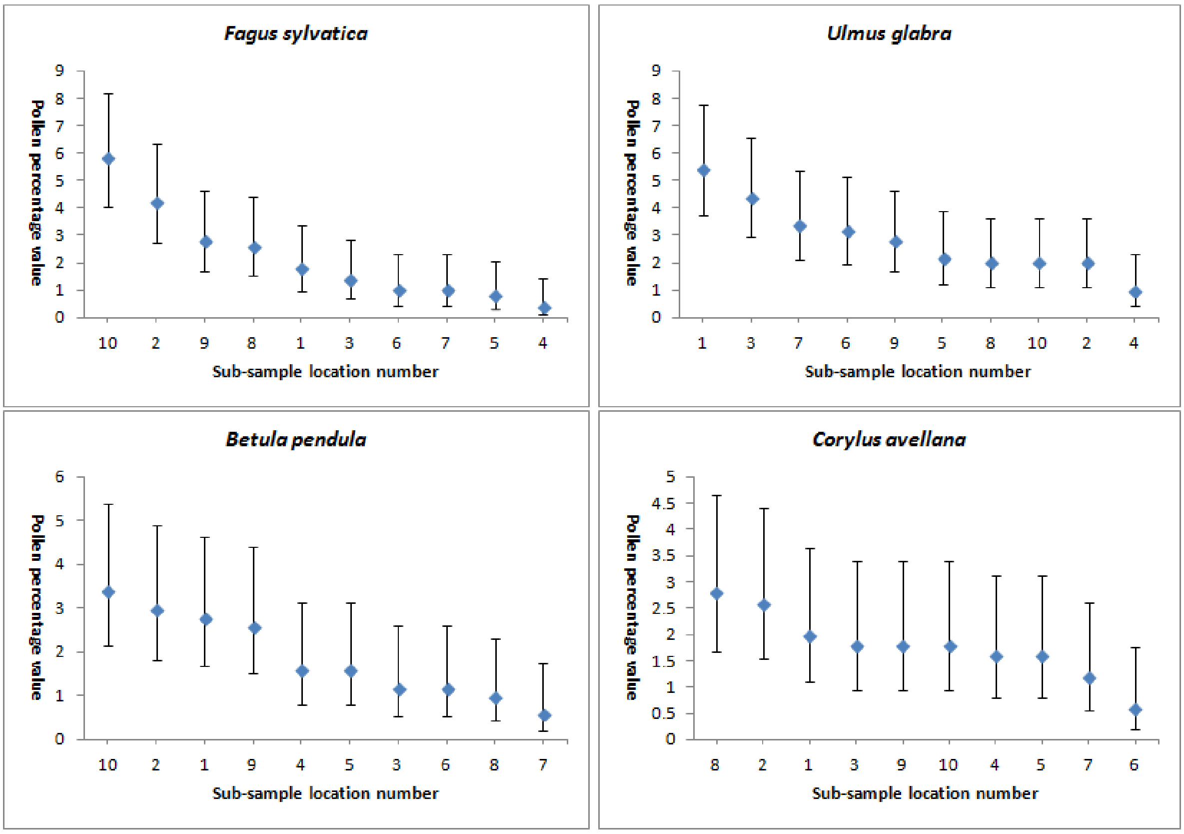
A confidence interval technique was used to examine the degree of error that results from sample size (pollen count sum) in the 30 sub-samples. The use of confidence intervals is an established non-parametric statistical method in palynological research which assumes a multinomial distribution in the data and deals effectively with the interdependence of pollen percentages (Maher, 1972). The confidence interval technique allows real differences in pollen percentages in the individual quadrat sub-samples to be identified and is sufficient for the purposes of this study to indicate any differences present in individual sub-samples due to more than just pollen count size, thereby effectively mitigating for factors such as pollen counting error. Pollen percentage datasets cannot be divided 'a priori' without looking at values, making alternative statistical analysis which requires predefined classification of the data i.e. ANOVA or the Kruskal Wallis H-test unsuitable for this type of study. Useful future research could investigate the suitability of statistical techniques such as bootstrapping as a method to examine pollen percentage variation in multiple sub-samples.

Excel charts displaying 95% upper and lower confidence limits for pollen percentage values of tree taxa at the three study sites are presented in figure 6.11 for the Chee Dale site, in figure 6.12 for the Cressbrook Dale site and in figure 6.13 for the Millington Wood site. Confidence limits are based on a pollen count of 500 grains per sample. Sub-samples are arranged by percentage value, which decreases to the right; sub-sample number is given on the x-axis, pollen percentage value is given on the y-axis. It can be observed that a wide range of confidence intervals is displayed both between taxa and between study sites. Taxa accounting for a high proportion of the pollen count in sub-samples have higher pollen percentages i.e. Acer and Fraxinus in figure 6.11, and display less asymmetry between upper and lower confidence limits than taxa with relatively low pollen percentages i.e. Salix and Picea in figure 6.11. This is because the range of a confidence interval is primarily affected by the sample size i.e. pollen sum (Maher, 1972), and for the purposes of this study it is assumed that when confidence intervals of a taxon at a site sample do not overlap that this represents a statistically significant difference between the samples (Schenker and Gentleman, 2001).

Chee Dale

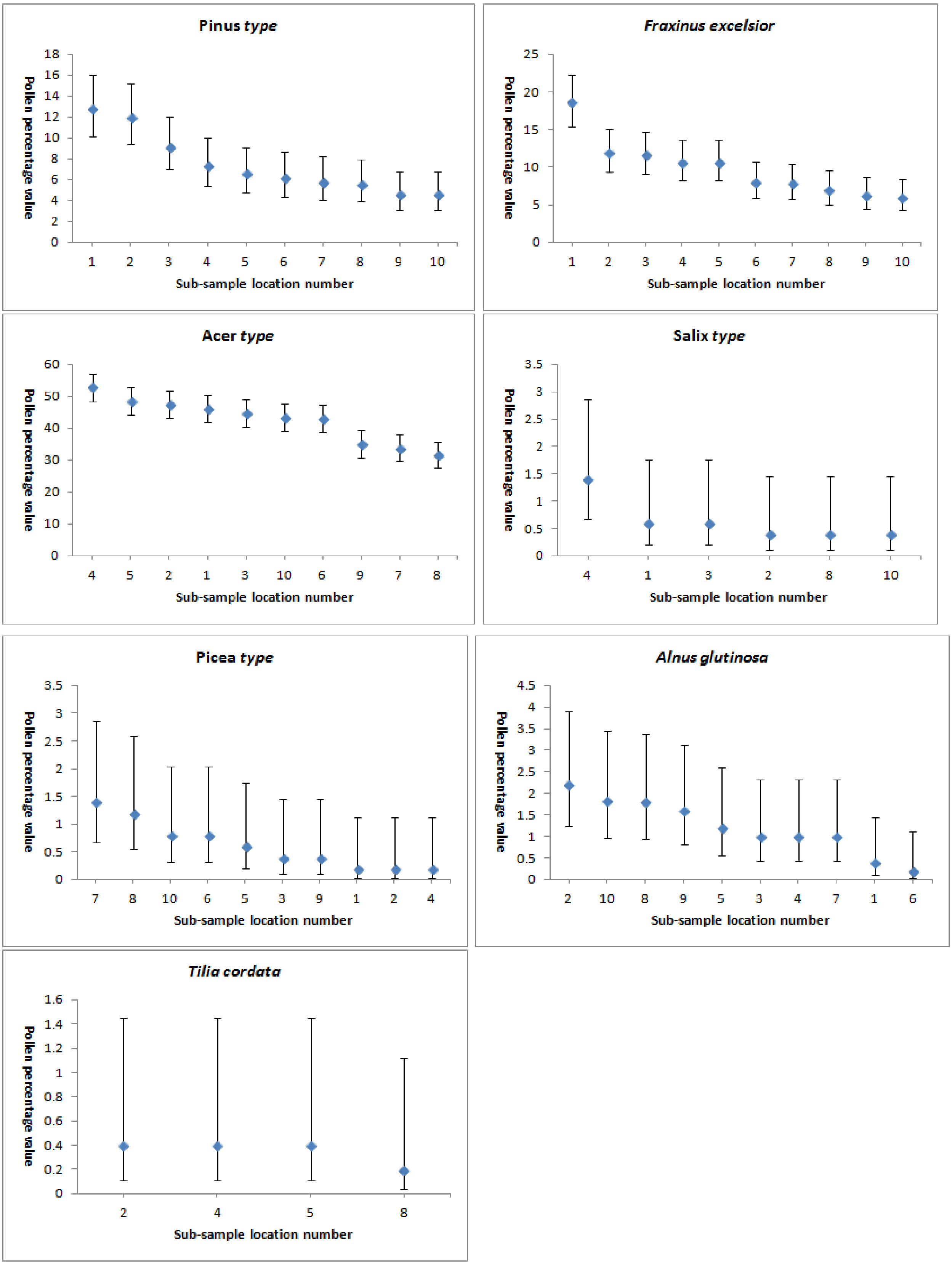
It can be observed in figure 6.11 that confidence interval bars for Salix *type*, *Corylus avellana*, *Tilia cordata*, and Picea *type* are overlapping across the 10 sub-samples, suggesting that there is no significant difference between the 10 sub-samples samples for these taxa.

Figure 6.11: Chee Dale confidence intervals based on pollen percentages of tree taxa.



Pinus-*type*, Acer-*type*, *Fraxinus excelsior*, *Betula pendula*, *Ulmus glabra*, *Fagus sylvatica*, and *Alnus glutinosa* all have sub-samples with confidence interval bars which do not overlap, suggesting that these sub-samples are significantly different from others taken within the quadrat. Pinus-*type* sub-samples 1, 2, and 3 display the highest percentage values within the 10 quadrat sub-samples, and are considered as outliers. Acer-*type* sub-samples 7, 8, and 9 display the lowest percentage values within the 10 quadrat sub-samples and considered as outliers.

Figure 6.11 - continued: Chee Dale confidence intervals based on pollen percentages of tree taxa.



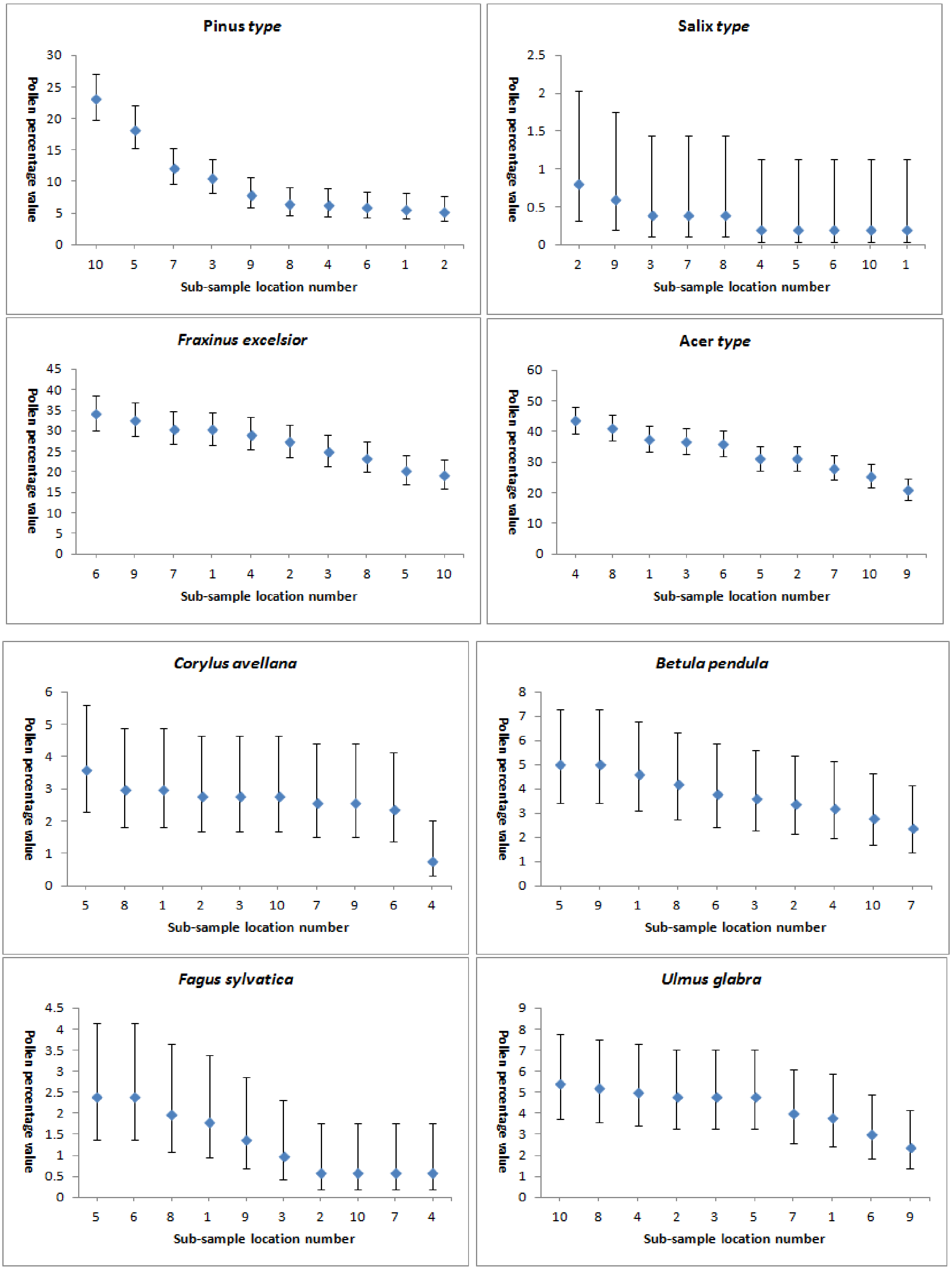
Fraxinus excelsior sub-samples 9 and 10 of display the highest percentage values of the 10 samples, and sub-sample 1 of *Fraxinus excelsior* displays the lowest percentage value; these 3 significantly different sub-samples are considered as outliers. *Betula pendula* sub-sample 7 of displays the lowest percentage value within the 10 quadrat sub-samples, and is considered as an outlier. *Ulmus glabra* sub-sample 4 displays the lowest percentage value of the 10 sub-samples, and is considered an outlier. *Fagus sylvatica* sub-samples 2 and 10 display the highest percentage values within the 10 quadrat sub-samples, and sub-sample 4 displays the lowest percentage value within the 10 quadrat sub-samples at Chee Dale; all 3 sub-samples are considered outliers. *Alnus glutinosa* sub-sample 6 displays the lowest percentage value of the 10 sub-samples, and is considered an outlier.

Cressbrook Dale

Confidence intervals for Cressbrook tree taxa are displayed in figure 6.12. It can be observed that confidence interval bars for Larix-*type*, *Fagus sylvatica*, *Ulmus glabra*, *Betula pendula*, and Salix-*type* are overlapping across the 10 sub-samples, suggesting that there is no significant difference in pollen percentages between sub- samples for these taxa. *Fraxinus excelsior*, Pinus-*type*, Acer-*type*, *Corylus avellana*, *Quercus robur*, and Picea-*type* all have sub-samples with confidence interval bars which do not overlap, suggesting that the pollen percentages of these taxa at these sub-sample locations are significantly different from other sub-samples taken from within the quadrat.

Fraxinus excelsior sub-samples 5, 8, and 10 display the lowest percentage values within the 10 quadrat sub-samples and are considered as outliers. Pinus-*type* sub-samples 5, 7, and 10 display the highest percentage values, and are considered as outliers. Acer-*type* sub-samples 9 and 10 display the lowest percentage values within the 10 quadrat sub-samples at Cressbrook, and are considered as outliers; *Acer type* sub-samples 4 and 8 display the highest percentage values within the 10 quadrat sub-samples at Cressbrook, and are considered as outliers.

Figure 6.12: Cressbrook confidence intervals based on pollen percentages from 10 sub-sample locations.



Pinus type

Salix type

Fraxinus excelsior

Acer type

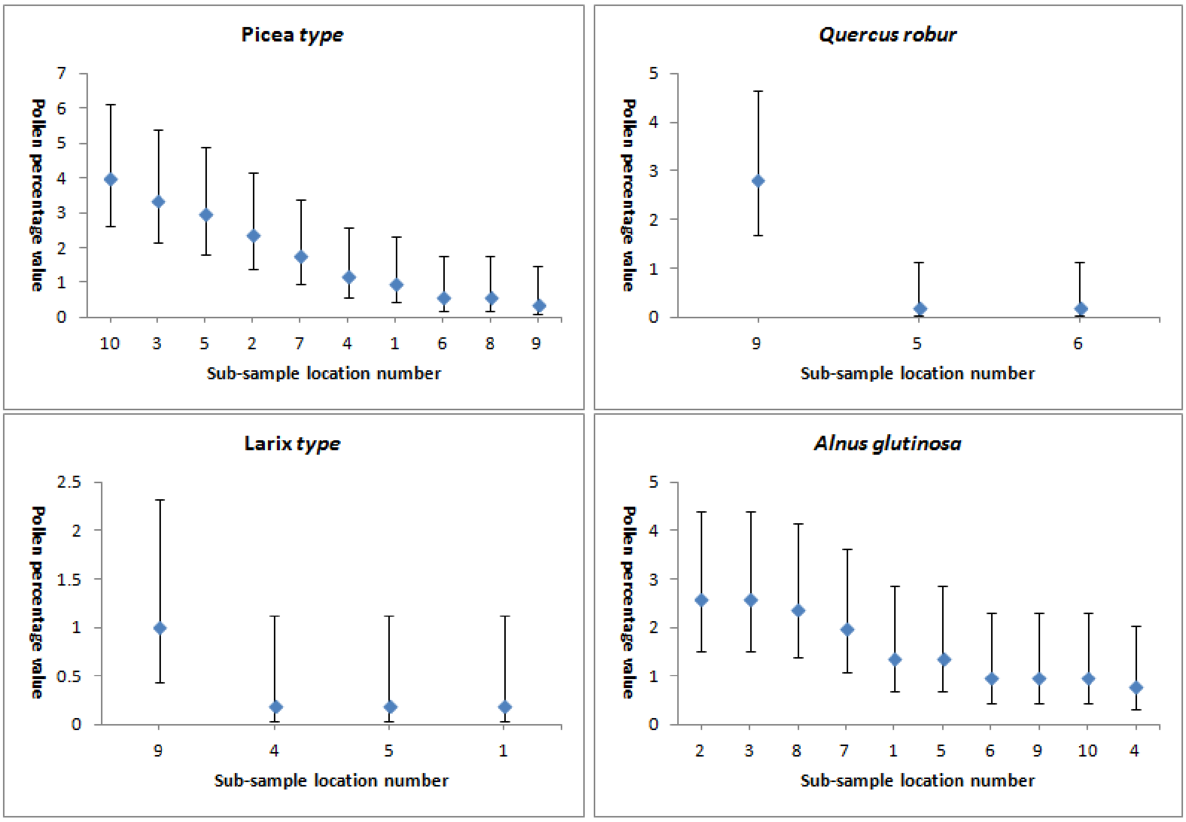
Corylus avellana

Betula pendula

Fagus sylvatica

Ulmus glabra

Figure 6.12 - continued: Cressbrook confidence intervals based on pollen percentages from 10 sub-sample locations.



Corylus avellana sub-sample 4 of displays the lowest percentage value of the 10 sub-samples, and is considered an outlier. *Quercus robur* sub-sample 9 displays the lowest percentage value of the taxa within the quadrat, and is considered an outlier. Picea-*type* sub-samples 1, 6, 8, and 9 display the lowest pollen percentage values of the 10 quadrat sub-samples, and are considered outliers; Picea-*type* sub-sample 10 displays the highest pollen percentage value and is considered an outlier.

Millington Dale

Confidence intervals for Millington Wood tree taxa are displayed in figure 6.13. It can be observed that confidence interval bars for *Alnus glutinosa*, Larix-*type*, Picea *type*, *Fagus sylvatica*, *Ulmus glabra*, *Corylus avellana*, and Salix *type* are overlapping across the 10 sub-samples, suggesting that there is no significant difference in pollen percentage between samples for these taxa. Pinus-*type*, Acer-*type*, *Betula pendula*, *Quercus robur,* and *Fraxinus excelsior* all have sub-samples with confidence interval bars which do not overlap, suggesting that these sub-samples are significantly different from others taken within the quadrat.

Figure 6.13: Confidence intervals for Millington tree taxa based on pollen percentages from 10 sub-sample locations.

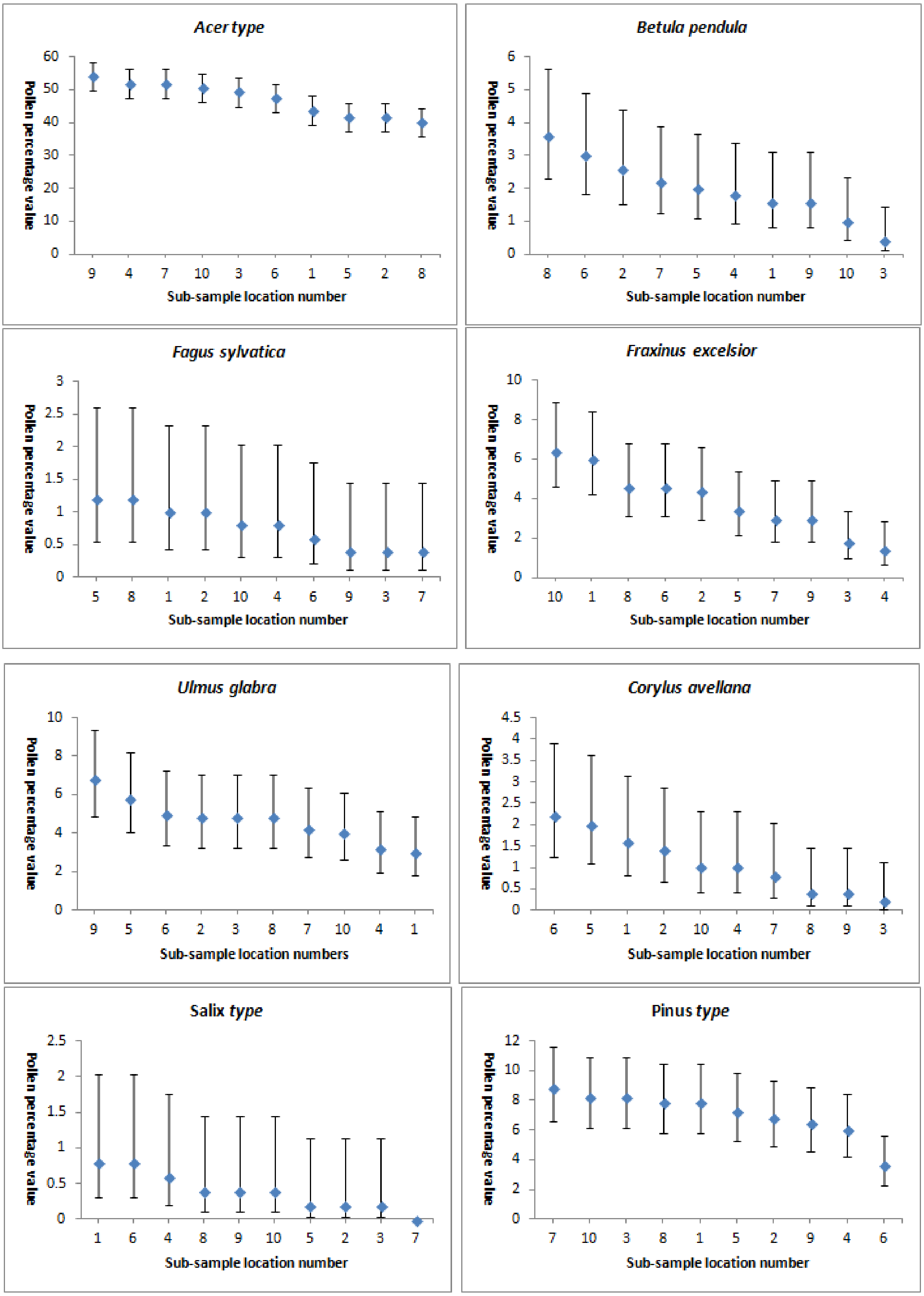
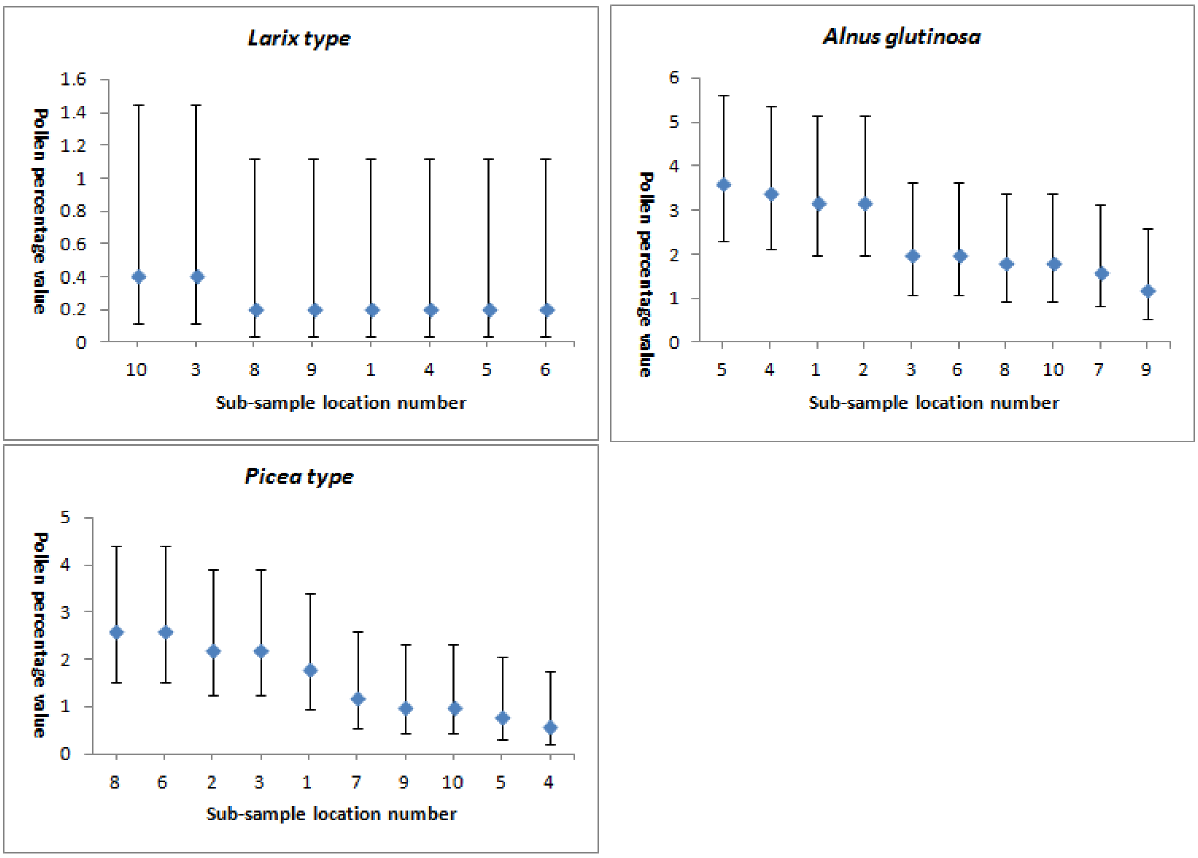


Figure 6.13 - continued: Confidence intervals for Millington tree taxa based on pollen percentages from 10 sub-sample locations.



Sub-samples displaying significantly different pollen percentage values are described as follows. Pinus-*type* sub-sample 6 displays the lowest percentage value of across the 10 sub-samples, and can therefore be classified as an outlier. *Betula pendula* sub-sample 3 displays the lowest percentage value at Millington and can be classified as an outlier. *Quercus robur* sub-sample 9 displays the lowest percentage value of the 10 quadrat sub-samples, and can be classified as an outlier. *Fraxinus excelsior* percentage values in sub-samples 3 and 4 are significantly lower than the other Millington quadrat sub-samples, and are classified as outliers. Acer-*type* sub-samples 5, 2, and 8 display the lowest pollen percentage values of the 10 quadrat sub-samples and are classified as outliers.

Microtopography

In order to understand the influence of microtopography on the pollen percentages observed in the sub-samples within each quadrat, a series of sketches displaying the location of the sub-samples within each 1m quadrat and the topography of each quadrat are presented in figures 6.14 to 6.16; photographs of the three quadrat sampling sites are then presented in figures 6.17 to 6.19.

Figure 6.14a: Relative spatial positions of moss sub-samples within the Chee Dale quadrat, Derbyshire. Microtopography of the quadrat is displayed on the right of the figure, note upper r/h sketch is south-north and lower r/h sketch is west-east orientation.

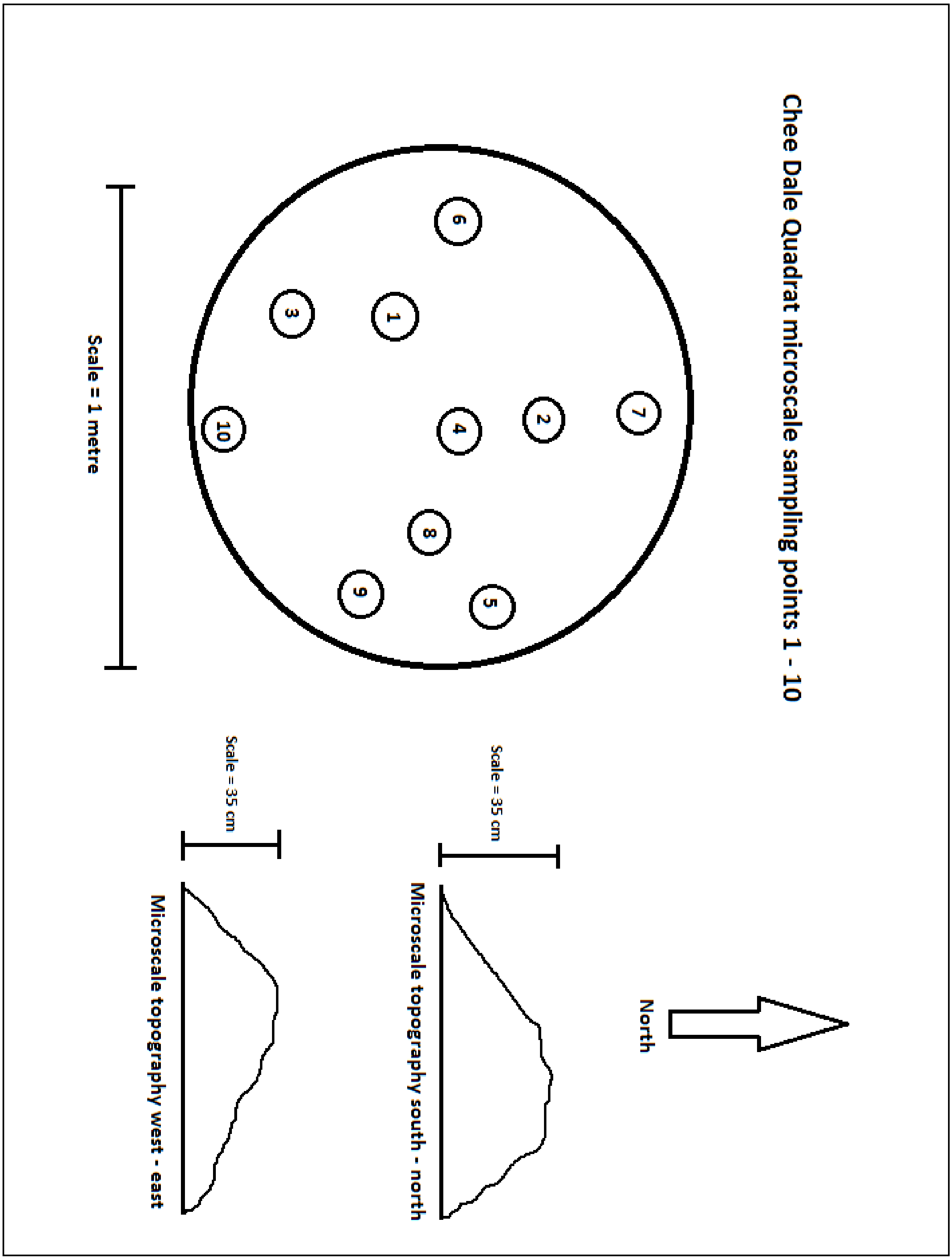


Figure 6.14b: Position of differing local woodland communities surrounding the Chee Dale quadrat field site. Bold lines within the larger circle denote boundaries of differing woodland community types; note differing scales below circles.

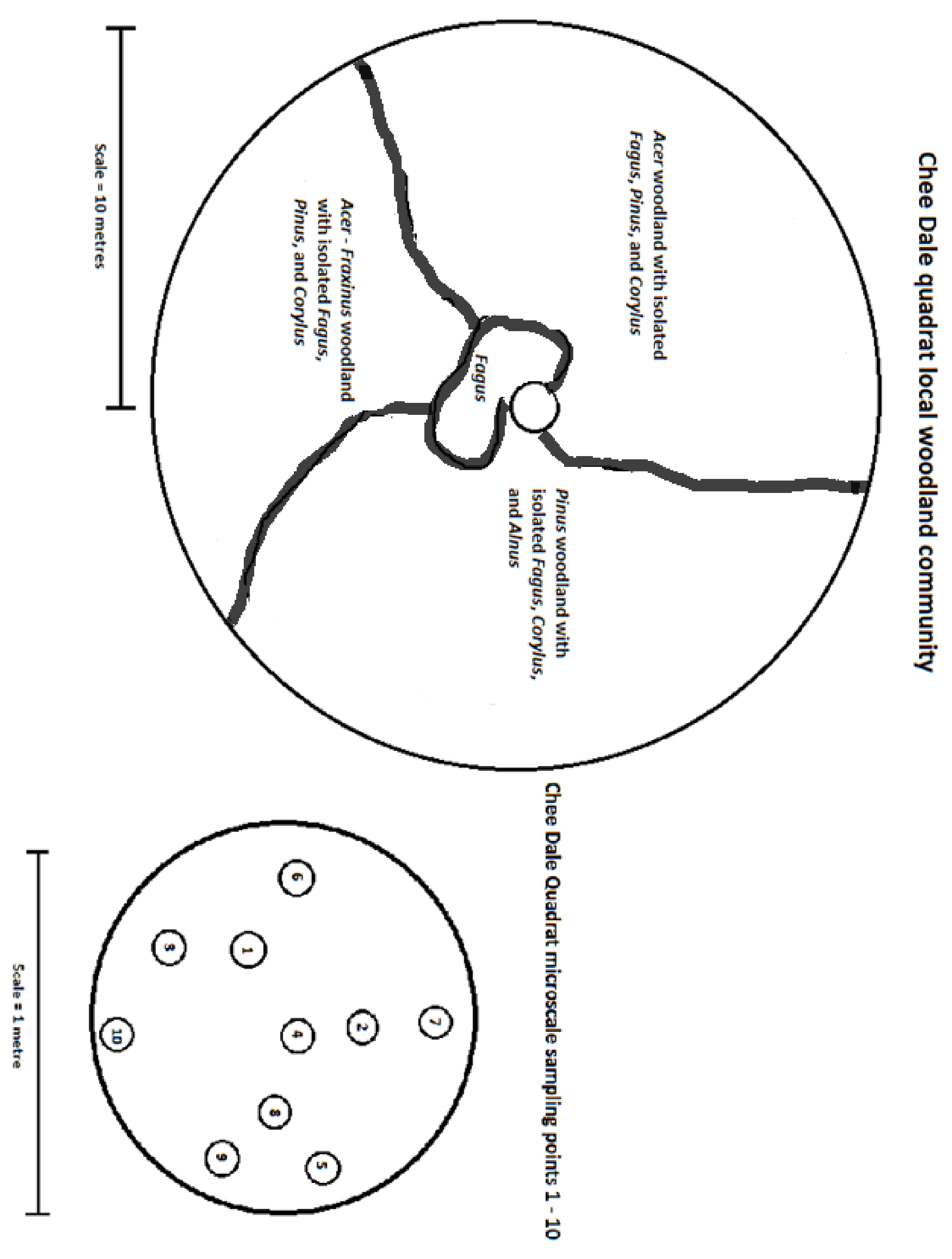


Figure 6.15a: Relative spatial positions of moss sub-samples within the Cressbrook Dale quadrat, Derbyshire. Microtopography of the quadrat is displayed on the right of the figure, note upper r/h sketch is south-north and lower r/h sketch is west-east orientation.

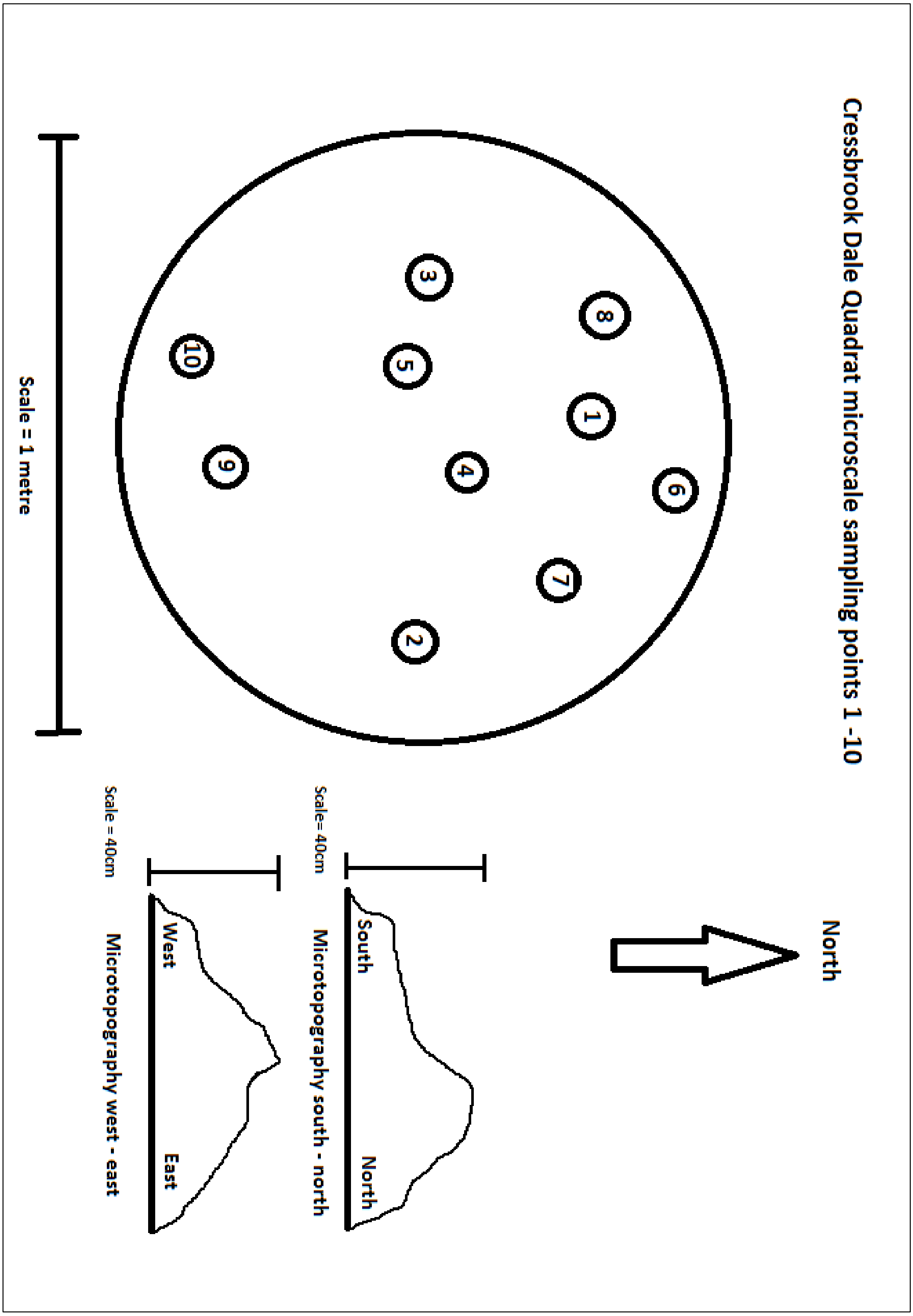


Figure 6.15b: Position of differing local woodland communities surrounding the Cressbrook Dale quadrat field site. Bold lines within the larger circle denote boundaries of differing woodland community types; note differing scales below circles.

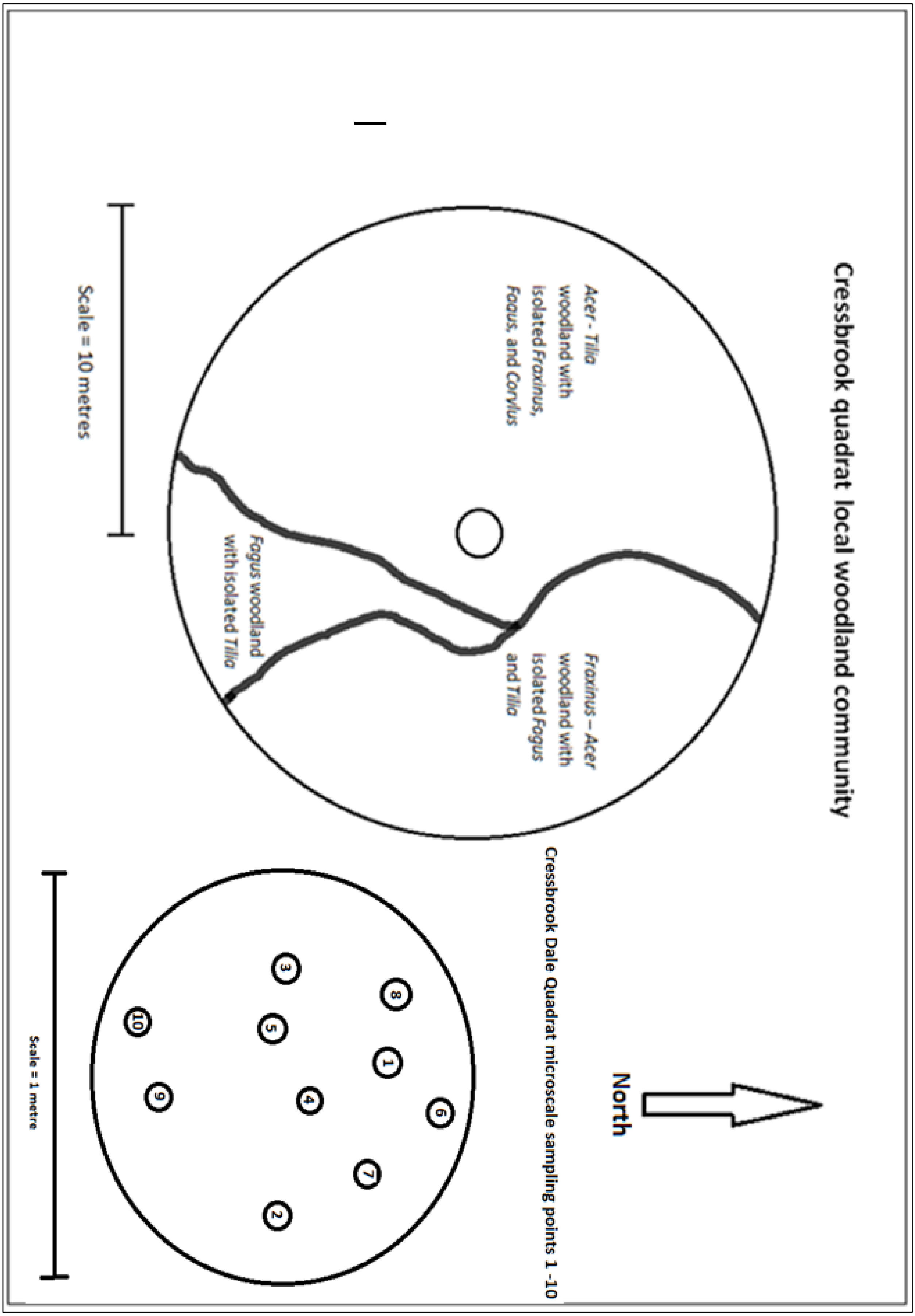


Figure 6.16a: Relative spatial positions of moss sub-samples within the Millington Wood quadrat, East Yorkshire. Microtopography of the quadrat is displayed on the right of the figure, note upper r/h sketch is south-north and lower r/h sketch is west-east orientation.

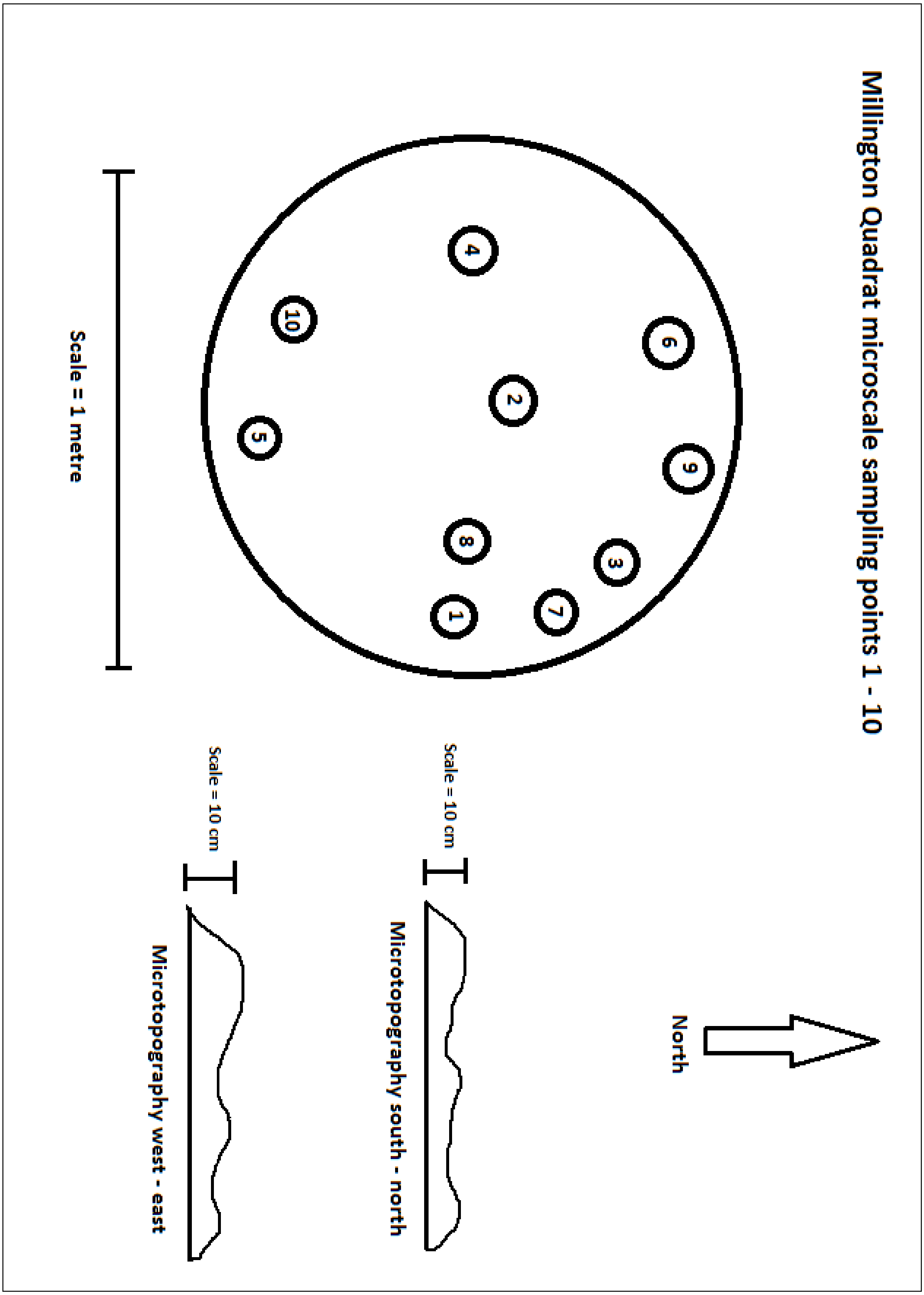


Figure 6.16b: Position of differing local woodland communities surrounding the Millington Wood quadrat field site. Bold lines within the larger circle denote boundaries of differing woodland community types; note differing scales below circles.

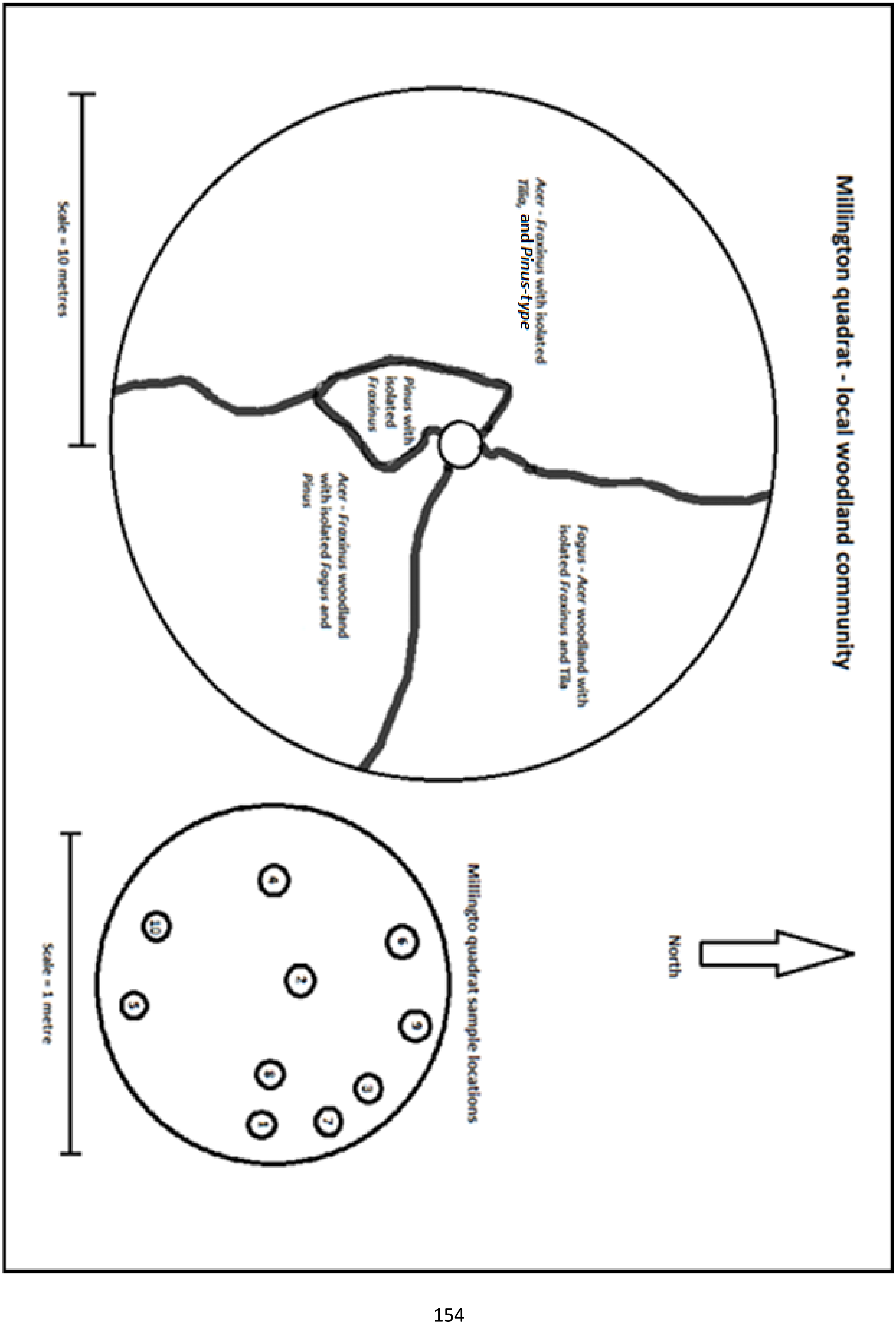


Figure 6.17: Chee Dale quadrat, Derbyshire.

Figure 6.18: Cressbrook Dale quadrat, Derbyshire.

Figure 6.19: Millington Dale quadrat, East Yorkshire.

The three quadrat sampling sites displayed in figures 6.11 to 6.19 each have a variety of microscale topographic features such as topographic highs, lows, and hollows. Each field site has a unique topography, with the two White Peak quadrats at Chee Dale and Cressbrook Dale being characterised by greater height and slope angles than the relatively level Millington Wood quadrat. The potential influences of these microscale features on pollen percentages at the sub-sample locations within the quadrat at each field site include the preferential deposition of airborne pollen onto topographic highs, the reworking of pollen down and/or across the moss surface and within the moss matrix, and the preference of insect pollinators depositing entemophilous pollen preferentially on portions of the quadrat which receive more sunlight during the day. As all three quadrats are located within mature woodlands, the anemophilous pollen input is likely to be significantly influenced by the composition of local tree communities, and the proximity of individual trees to the quadrat itself. For the purposes of this study slope angle was not quantified using exact measurements in degrees, instead slope angle was qualitatively estimated by eye. A ‘high’ angle slope is defined as >60°, a ‘medium’ angle’ slope is defined as 60-35° and a ‘shallow’ slope is defined as 35°<. Future research could utilise a more quantitative research design in parameterising slope angle.

The primary mechanisms of pollen dispersal in woodlands are the trunk space component (Ct), the local or gravity component, and to a lesser degree the canopy component (Cc) (Tauber, 1965; Moore et al., 1991); the influence of insect pollinators must also be a consideration at the study sites. Woodland floor pollen assemblages are often suggested as being dominated by local vegetation growing adjacent to the sampling site (Jackson & Kearsley, 1998). Jackson and Lyford (1999) suggest that the influence of unstable atmospheric conditions which are often associated with aerial pollen release, and elevated sources of pollen release e.g. trees, results in a wider dispersal of pollen than suggested previously e.g. Prentice, (1985). At the three sampling sites used for this study, the sites at Cressbrook and Chee Dale are in closed woodland, with the third site at Millington adjacent to a woodland edge.

Chee Dale

As can be observed in figures 6.14a, 6.14b and 6.17 the ten Chee Dale surface sample locations within the 1 metre quadrat display a degree of topographic variety in their spatial location e.g. some samples points being on slopes, some sample points being elevated, and some sample points being at the same level as the woodland floor. Samples 2, 4, and 7 are significantly elevated along the south – north bearing, with samples 1, 6, and 8 significantly elevated along the west – east bearing. Samples 1, 3, 4, 9, and 10 are south facing and situated on slopes, which may be a potential factor as regards sun-seeking insect pollinators using the south facing aspect of these sample points within the quadrat in preference to the less sunny e.g. north, west, and east aspects. Elevated portions of the Chee Dale quadrat have the potential for pollen deposited in these locations to be reworked laterally both across the surface of the moss, and through the matrix of the moss down-slope. These post-depositional taphonomic mechanisms could potentially enhance pollen concentrations in samples situated at altitudinally lower points in the quadrat e.g. samples 5, 8, 9, and 10, and decrease pollen concentrations in samples situated the upper portions of the quadrat leading to pollen focusing at the middle and lower portions of the slopes displayed in figures 6.14b and 6.17. Secondary pollen transport by invertebrates or water within the moss matrix may have the effect of relocating pollen from the original site of deposition on the moss surface and integrating it within the matrix of living and dead moss at a secondary deposition point where the re-worked pollen then becomes stabilized (Joosten & de Klerk, 2007).

Acer-*type* is the dominant taxon in terms of pollen percentages at the Chee Dale sampling locations, with pollen percentage values ranging from 30 – 55% across the 10 sample locations. The highest Acer-*type* pollen percentages are observed at sample locations 2, 4, and 5. Locations 2 and 4 occupy the highest locations at centre of the site and have a northerly aspect; and sample location 5 is on a slope in north NE portion of the quadrat. The lowest pollen percentage values of Acer-*type* are observed at sample locations 7, 8, and 9, with sample 7 situated at the base of a northerly slope, and samples 8 and 9 located in the middle of (8) and at the base of (9) an easterly slope. Acer-*type* is the dominant woodland taxon both in the 10 metre, and 100 metre vegetation survey carried out around the Chee Dale site. At the 10 metre scale, Acer-*type* dominates the woodland to the north, west, south and SE around the site, and as such must be the dominant pollen type in the local and extra-local pollen rain. The influence of local Cg and Ct pollen vectors may account for the very high Acer-*type* pollen percentages associated with the topographic high points of the Chee Dale site, as the local pollen rain could land at the these sample locations preferentially. Pollen deposition appears to be influenced by the slope-angle of sample locations for Acer-*type*, as lower pollen percentages are associated with sub-sample locations on high slope angles i.e. 7, 8, and 9, and the higher pollen percentages are associated with sub-sample locations on relatively level areas of the quadrat i.e. locations 2 and 4, or with sites with low slope angles i.e. sub-sample location 5. Pollen percentages of Acer-*type* at sub-sample locations 7, 8, and 9 are considered outliers in the confidence intervals displayed in figure 6.11.

Fraxinus excelsior is a co-dominant in the local woodland community to the south of the Chee Dale field site, and a co-dominant with Acer-*type* in the extra-local woodland. *Fraxinus excelsior* is the second most dominant taxon in terms of pollen percentage values at the Chee Dale site, with pollen percentage values ranging from 6 – 18% across the 10 sample locations. The highest *Fraxinus excelsior* pollen percentage values are observed at sub-sample locations 1, 2, and 3; of which sub-sample locations

1 and 3 are situated on medium angle slopes in the SW of the quadrat, and sub-sample location 2 is situated on the north-facing topographic high-point at the top of a high angle slope. The lowest *Fraxinus excelsior* pollen percentage values are observed at sub-sample locations 8, 9, and 10; locations 8 and 9 occupying middle and lower slope locations on the high angle slope in the east of the quadrat, and location 10 positioned at the base of a low angle slope in the south of the quadrat. High pollen percentages of *Fraxinus excelsior* appear to be correlated with the position of the *Fraxinus excelsior* in the local woodland, as sub-sample locations 1 and 2 are facing the local *Fraxinus excelsior* woodland, and sub-sample 2 is located at a topographic high-point. The influence of secondary pollen transport across and within the moss matrix, potentially by a rainwater vector, at sample locations 1 and 2 may also contribute to the high pollen percentages recorded at these locations. The high *Fraxinus excelsior* pollen percentages at sub-sample locations 9 and 10, and the low *Fraxinus excelsior* pollen percentage observed at sub-sample location 1 are considered as outliers in the confidence interval tables in figure 6.11.

Pollen percentage values of Pinus-*type* at Chee Dale range from 4 – 12.5% across the ten sub-sample locations, with the highest percentage values observed at sub-sample locations 7, 8, and 9. Samples 7 and 8 occupy high altitude locations, whilst sample 9 is situated on a SE slope. The main area of Pinus-*type* dominated woodland is to the east of the quadrat, which is adjacent to sample locations 7 and 8, and to a lesser degree sample location 9. The lowest pollen percentage values for Pinus-*type* are observed at sub-sample locations 1, 2, 3, and 4, which all display a bias to the western side of the quadrat. There appears to be a trend of higher pollen percentage values of Pinus-*type* at sample locations which are both facing the main area of Pinus—*type* local woodland to the east of the quadrat, and which are positioned on slope locations. The observation that the lowest pollen percentage values of Pinus-*type* are observed at sample locations occupying topographic high points i.e. sample locations 2 and 4 of the quadrat suggests that post-depositional downslope pollen transport may be occurring via rainwater or invertebrate vectors, both on the surface of and within the matrix of the moss, resulting in a reduction in pollen concentrations at these topographically higher sub-sample locations. The high Pinus-*type* pollen percentage sub-sample locations 1, 2, and 3 are considered as significant outliers in the Chee Dale confidence interval chart displayed in figure 6.11.

Percentage values of *Fagus sylvatica* in the 10 sub-samples taken at the Chee Dale quadrat range from 0.1 – 5.7%, with the highest pollen percentage values found at sample locations 2, 9, and 10 (see figures 6.14b and 6.17). Sub-sample location 9 is located in the south-easterly portion of the quadrat, sample location 10 is in a southerly position, and sample location 2 occupies a topographic high-point in the northern portion of the quadrat. Sample locations 9 and 10 are the closest of the 10 sub-samples to the *Fagus sylvatica* community illustrated in the sketch vegetation map in figure 6.14a, which is immediately south and SW of the quadrat, and could therefore be receiving preferential Cg and Ct pollen input to this portion of the quadrat; sample 10, as a topographically high-point within the quadrat could also be receiving larger amounts of pollen from the *Fagus sylvatica* community from both Cg and Ct vectors. Sub-sample locations 4, 5, and 7 display the lowest *Fagus sylvatica* pollen percentage values observed at the Chee Dale quadrat. Sample 4 is located on a level plateau at the highest point in the centre of the quadrat, sample 5 occupies a position at the bottom of the eastern slope of the quadrat, and sample 7 is located at the bottom of a steep slope at the northern edge of the quadrat. As sample locations 5 and 7 are facing away from the local *Fagus sylvatica* woodland to the south of the quadrat, the lower pollen percentage values at these locations may be a result of local pollen landing on the southern slopes first, or being transported over the quadrat onto the woodland floor. The low pollen percentages observed at sub-sample location 4 are more problematic as this location represents the highest topographic sub-sample location within the quadrat. This point should theoretically receive pollen without hindrance from all four compass bearings, suggesting that secondary pollen transport downslope via rainwater or invertebrate vectors may be a factor contributing to the low pollen percentages observed at sample location 4. The high *Fagus sylvatica* pollen percentages at locations 2 and 10, and the low *Fagus sylvatica* pollen percentage observed at location 4 are suggested as significant outliers based on the confidence intervals for the Chee Dale tree taxa displayed in figure 6.11.

Corylus avellana pollen percentage values at Chee Dale quadrat range from 0.6 – 2.1%, with the highest percentage values observed at sub-sample locations 1, 2, 3, and 8. All these sub-sample locations, with the exception of sample location 3 which is situated at the base of the southern slope of the quadrat, are situated on or adjacent to topographic high points in the western and northern portions of the quadrat. Within the local woodland communities surrounding the Chee Dale quadrat, *Corylus avellana* is a very minor community component being present as isolated single trees. It is noticeable that the highest pollen percentage values of *Corylus avellana* are clustered around the highest central point within the quadrat at sample locations 1, 2, 3, and 8, and yet the lowest *Corylus avellana* values are at sample points 6 and 7, which both occupy high altitude slope sites very close to the two highest value samples e.g. 1 and 2. As *Corylus avellana* does not occupy a dominant position in the local woodland, and does not have a potential directional bias i.e. large *Corylus avellana* component to the east of the quadrat, no clear processes to explain the variation in pollen deposition for *Corylus avellana* are apparent.

Alnus glutinosa is present as a minor woodland component to the north-east and east/south-east of the Chee Dale quadrat site. Pollen percentage values of *Alnus glutinosa* at Chee Dale display a range of values from 0.1 – 2.2%, with samples 2, 8, and 10 having the highest observed percentage values. Sample location 2 is at the top of the north-facing high-angle slope adjacent to the topographic highpoint within the quadrat, sample location 8 is at the mid-point of an easterly facing slope, and sample 10 is situated on the south facing slope. The higher pollen percentage values of *Alnus glutinosa* at locations 2 and 8 may be related to the proximity of the *Alnus glutinosa* woodland component at this portion of the quadrat, with preferential pollen deposition via Ct and Cc vectors. The high pollen percentage value observed at sample location 10 may be a product of direct Ct and Cc input, and/or secondary pollen transport downslope via rainwater either on the surface of the moss during high precipitation levels or as a gravity flow within the fabric of the moss during and after high precipitation events (Joosten & De Klerk, 2007). The lowest pollen percentage values of *Alnus glutinosa* are observed at sub-sample locations 1 and 6 on the western side of the quadrat, and at sample location 7 in the north of the quadrat; all these sample locations are situated on relatively steep slopes. A*lnus glutinosa* is absent from the local woodland to the west of the quadrat, which may explain the low pollen percentages at sampling locations 1 and 6. The very low *Alnus glutinosa* pollen percentage observed in sample location 7, where A*lnus glutinosa* is adjacent to the quadrat in the local woodland, may be influenced by the sub-sample location type. Sub-sample location 7 occupies a position on a very steep slope on the moss on the northerly edge of the quadrat, and may therefore be more likely to be influenced by rainwater-driven transport of pollen away from this portion of the quadrat. The low A*lnus glutinosa* pollen percentage observed at sub-sample location 6 is suggested as a significant outlier based on the confidence interval table displayed in figure 6.11.

As no *Ulmus glabra* was present in the local woodland at Chee Dale, this suggests that *Ulmus glabra* pollen arriving at the Chee Dale quadrat must have been transported via Cc and Ct from outside the 100 metre survey area. Pollen percentage values of *Ulmus glabra* at the Chee Dale quadrat are relatively low, ranging from 1 – 5.2% with the highest values at sample locations 1, 3, and 7. Sample locations 3 and 7 occupy low elevation slope locations in the SW and northern portions of the quadrat, and sample 1 is situated on a high altitude slope to the west of the centre of the quadrat. The lowest *Ulmus glabra* pollen percentage values are observed at sample locations 2, 4, 8, and 10; locations 8 and 10 are slope locations and have a south and SE aspect, samples 2 and 4 occupy the highest topographic locations within the quadrat which have a northerly aspect. The spatial pattern of *Ulmus glabra* pollen percentages at Chee Dale suggests that locations situated on southern aspect slopes receive the highest proportion of the pollen rain for *Ulmus glabra*. The low *Ulmus glabra* pollen percentage observed at sub-sample location 4 is suggested as an outlier based on the confidence intervals displayed in figure 6.11.

No *Betula pendula* was recorded in the local woodland at Chee Dale, suggesting that that aerial Cc and Ct transport vectors are delivering pollen from regional and extra-local pollen sources to the Chee Dale moss sub-sample locations. Pollen percentage values of *Betula pendula* at the 10 Chee Dale sub-sampling locations are low, ranging from 0.5 – 3.2%, with the highest percentage values observed at sample locations 1, 2, 9, and 10. Sample locations 1 and 2 are topographic high points situated approximately in the centre of the quadrat; sample locations 9 and 10 are situated on the slope in the south and south-eastern portion of the quadrat. The lowest pollen percentage values of *Betula pendula* were observed at sample locations 3, 6, 7, and 8, which are located on slopes in the SW portion of the quadrat (locations 6 & 8), the northern portion of the quadrat (7), and in the eastern portion of the quadrat (8). *Betula pendula* pollen percentage values are highest in the southern portion of the quadrat, and at the highest point of the Chee Dale quadrat; however *Betula pendula* pollen deposition also appears to be relatively stochastic at the Chee Dale quadrat, as contrastingly low pollen percentage values are also observed at sample locations in the southern portion, and the highest point of the quadrat. The low *Betula pendula* pollen percentage observed at sample location 7 is suggested as an outlier based on the confidence intervals displayed in figure 6.11.

Tillia cordata is present at 4 of the 10 Chee Dale sample locations at very low pollen percentages ranging from 0.2 – 0.4%, and was not recorded in the vegetation surrounding the Chee Dale quadrat. Sample locations 2, 4, and 5 have a pollen percentage value of 0.4% and sample location 8 has a pollen percentage value of 0.2%. These 4 samples are clustered around the topographic high-point, with sample locations 2 and 4 occupying the topographic high and sample locations 5 and 8 on the NE and eastern slopes. *Tilia cordata* utilises an entemophilous mode of pollen dispersal, and so pollen concentrations are often associated with 'sunning' insects. The relatively tight cluster of *Tilia cordata* around the high-point of the quadrat suggests that this location may be used as a resting and/or sunning location in preference to the other quadrat sample locations.

Pollen percentage values of Picea-*type* at Chee Dale are very low, ranging from 0.1 – 1.4% across the 10 sampling locations. No Picea-*type* was recorded in the local woodland vegetation surrounding the site, suggesting that pollen deposited on the moss at the Chee Dale quadrat has been transported aerially via Ct and Cc vectors from extra-local pollen sources. The highest Picea-*type* pollen percentages are recorded at sample locations 7, 8, and 10, which occupy northern, eastern and southern slope locations respectively. The lowest Picea-*type* pollen percentage values are recorded at sample location 1 which is situated on the western slope of the quadrat, and sample locations 2, and 4 which are situated on the topographic highpoint within the quadrat. The higher pollen values observed at sample locations 7, 8, and 10 suggest that pollen rain is relatively uniform across the quadrat and that as these latter locations are all positioned at the bottom of, or very near the bottom of, slopes that some secondary pollen transport is occurring downslope via rainwater gravity flow resulting in higher concentrations of Picea-*type* pollen at these locations. This hypothesis would also explain the observation of lower levels of Picea-*type* pollen at the two topographic highpoint locations 2 and 4, and at upper-slope sample location 1, where pollen may have been relocated downslope via rainwater gravity flow.

Pollen percentages of Salix-*type* are very low at the Chee Dale quadrat, and range in percentage value from 0.3 – 1.4% across the 6 sub-sample locations where Salix-*type* pollen was recorded. No Salix-*type* trees were recorded in the local woodland vegetation, suggesting an aerial pollen transport vector via Cc and Ct from extra-local pollen sources. The highest Salix-*type* pollen percentage value is observed at sample location 4, which occupies a level plateau on the highest topographic point in the quadrat and so has no pronounced impediment to pollen deposition from any point on the compass. The lowest Salix-*type* pollen percentages are recorded at sample locations 8 and 10, which are situated on slopes on the eastern and southern slopes of the quadrat. This trend of higher pollen percentages at the topographic highpoint suggests that, in the case of Salix-*type*, sampling locations that are a greater distance above the forest floor receive more of the extra-local pollen rain. The lower pollen percentage values recorded at the two slope sample locations, 8 and 10, suggest that either pollen deposition is preferential on the northern and western side of the quadrat or that sample locations 8 and 10 are subject to secondary pollen transport downslope via rainwater.

Cressbrook Dale

The Cressbrook Dale quadrat site is a moss–covered boulder situated on the woodland floor, and as can be observed in figures 6.15b and 6.18 which illustrate the microtopography of the Cressbrook Dale quadrat, the quadrat location displays both diversity in relief i.e. height above the woodland floor, and degree of slope angle. Sub-sample locations 1, 4, 7, and 8 occupy the highest points within the quadrat, sample locations 9 and 10 occupy positions at the lower slope of the south-north traverse, and sample location 6 is situated on the north facing slope at the northern edge of the quadrat. Sample locations 3 and 5 are situated at the foot of the slope on the western side of the quadrat, with sample location 2 situated on the eastern slope.

The Cressbrook Dale quadrat displays high relief in the centre of the quadrat, with relatively steep slope angles on both the south-north and west-east traverses. The potential for pollen to be reworked downslope, either by rainwater or invertebrate transport mechanisms both on the surface and within the matrix of the moss, could potentially result in pollen loss at the higher placed sample locations and a concomitant increase in pollen concentration at the sample points situated at locations on the middle and lower slopes e.g. 3 and 5. These reworking influences may be offset by the potential of the more elevated portions of the quadrat to act as a site of preferential pollen deposition for the trunk space component (Ct) due to the greater height above the woodland floor, and hence closer to the woodland canopy. The south-facing slope of the Cressbrook Dale quadrat is initially steep, before levelling out to a relatively shallow angle. This slope would potentially provide a sunning spot for invertebrate pollinators, which could enhance the potential of the lower slope sites for deposition of entemophilous pollen such as Acer or Tilia.

Three taxon associations were recorded at Cressbrook Dale, Acer-*type*/*Tilia cordata*, Acer-*type*/*Fraxinus excelsior*, and *Fagus sylvatica*. The relationship between the quadrat sample locations and the local woodland vegetation associations is displayed in figure 5.9. The dominant taxon in terms of pollen percentage values at Cressbrook Dale is Acer-*type*, which displays percentage values ranging from 22 – 45% across the 10 sample locations. The highest pollen percentage values are observed at sample locations 1, 4 and 8 which are situated at central and NW topographic high points within the quadrat. The lowest percentage values are observed at sample locations 7, 9, and 10 which are situated at lower height locations in the NE and south of the quadrat. Acer-*type* woodland is dominant to the west, with Acer-*type* a second dominant in the *Fraxinus excelsior* woodland to the east. The three high pollen percentage value sample locations 1, 4 and 8 are facing the main Acer-*type* woodland to the west. Of the three lowest pollen percentage value sample locations, locations 9 and 10 are facing the *Fagus sylvatica* woodland to the south, and location 7 is facing the *Fraxinus excelsior* dominated woodland to the east. As illustrated in the Cressbrook Dale confidence intervals displayed in figure 6.12, sample locations 1 and 4 are considered outliers based on the significantly higher pollen percentages at these locations. Significantly low pollen percentage values of Acer-*type* at sample locations 9 and 10 are also considered outliers.

Fraxinus excelsior is the second dominant taxon in terms of pollen percentage values observed at Cressbrook Dale, and is also the dominant taxon in the local woodland to the west of the quadrat. Pollen percentages of *Fraxinus excelsior* range from 21 – 43.6% across the 10 samples. The highest pollen percentage values of *Fraxinus excelsior* are observed at sample locations 6 and 7 in the northern portion of the quadrat, and at sample location 9 which is located at the southern edge of the quadrat; Sample location 6 is considered an outlier based on the significantly higher pollen *Fraxinus excelsior* percentage observed at this location, as is displayed in the confidence interval chart in figure 6.12. The lowest pollen percentage values of *Fraxinus excelsior* are observed at sample locations 5, 8, and 10, which are situated to the SW of the quadrat; sample locations 5, 8, and 10 are also considered outliers on the basis of the significantly lower pollen percentages observed at these locations. It can be seen in figure 6.15a that the *Fraxinus excelsior* dominated woodland is to the west of the quadrat, this suggests that western-aspect sampling locations may receive more local pollen via Cg and Ct. The significantly higher pollen percentage values of *Fraxinus excelsior* at sample locations 6 and 7 may also be linked to the position of the sample locations within the quadrat. Both sample locations are situated at the bottom of high-angle slopes, where secondary pollen transport via rainwater could have the effect of increasing pollen concentrations at these location types. Slope position may also play a part in the significantly low *Fraxinus excelsior* pollen percentage values observed at sampling locations 5, 8, and 10. All these locations are at mid-slope on high-angle slope profiles; this would suggest that a proportion of the pollen rain may be transported downslope and away to the bottom of the slope. Additionally, the low pollen percentage value sample locations 5, 8, and 10 are all to the west of the quadrat, whereas the *Fraxinus excelsior* dominated woodland is to the east of the quadrat.

Pinus-*type* displays a range of pollen percentage values ranging from 5 – 22% across the ten sampling locations, no Pinus-type was recorded in the local woodland vegetation. The highest Pinus-*type* pollen percentage values are observed at sample locations 5, 7, and 10, which are located in the west, NE, and south of the quadrat respectively. The higher pollen percentage values at these three locations are significantly different to the rest of the sample locations and are treated as outliers on the basis of the confidence intervals displayed in figure 6.12. Locations 5 and 10 are on high-angle slopes, and location 7 is situated at the bottom of high-angle slope. The lowest pollen percentage values of Pinus-*type* are observed at sample locations 1, 6, and 2 which are located in the north and east of the quadrat respectively. Sample location 1 is on the high plateau in the quadrat centre, and sample location 2 is on a high angle slope, and sample location 6 is situated at the bottom of high-angle slope. Pinus-*type* is present as a significant component of the extra-local woodland vegetation in the area, and it is this, as well as the regional influx, that may provide the pollen rain to the Cressbrook Dale quadrat. The variation in pollen percentage values across the quadrat appears to be influenced by slope position of the sample location, as the high value locations i.e. 5, 7, and 10 are all situated on or adjacent to the bottom of high-angle slopes. Of the low pollen percentage locations, sample location 1 is situated on the high central plateau, and sample location 2 is situated at the mid-point of a steep slope. These locations may be subject to secondary pollen transport via rainwater flowing through/over the moss. Sample location 6 is more problematic, as it occupies a position at the base of a steep slope where high Pinus-*type* pollen percentages are recorded.

No significant outliers are observed in the pollen percentage values of *Ulmus glabra* at the Cressbrook Dale study site, with pollen percentages ranging in value from 2 – 5.4% across the ten sample locations. No *Ulmus glabra* was recorded in the local woodland vegetation, meaning pollen sources must be extra-local or regional. Sample locations 8 and 10 display the highest pollen percentage values, and are positioned at slope-bottom locations in the NW and SW of the quadrat respectively. Sample locations 6 and 9 display the lowest observed pollen percentages, and are positioned at slope bottom positions to the north and south of the quadrat. As both the highest and lowest *Ulmus glabra* pollen percentage values are observed in slope-bottom locations, the more westerly aspect of sample locations 8 and 9 suggests that extra-local and regional pollen may be transported to the site by westerly winds.

Pollen percentage values of *Fagus sylvatica* range from 0.5 – 2.4% across the 10 sample locations. *Fagus sylvatica* is present as a minor component in the woodland associations to the west and east of the quadrat, and as a dominant component of the local vegetation to the south and east-SE of the quadrat. The highest *Fagus sylvatica* pollen percentages are observed in sample 5 which is located at a mid-slope location on the western side of the quadrat, and sample location 6 which is located at a slope-bottom location in the north of the quadrat. Sample locations 4, and 7 display the lowest *Fagus sylvatica* pollen percentages, and are located at the high-point plateau and at a mid-slope location in the NE of the quadrat respectively. Pollen rain deposited at locations 4 and 7 may be transported away from these locations downslope by rainwater, resulting in lower pollen percentages at these sample locations; higher pollen percentage values observed at locations 5 and 6 may be influenced by this secondary pollen transport downslope.

Pollen percentage values of Salix-*type* at Cressbrook Dale range from 0.2 – 0.8% across the 10 sample locations. No Salix-*type* was recorded in the local woodland vegetation, meaning that pollen deposited at the quadrat must have been aerially transported via Ct and Cc vectors from the extra-local pollen sources. The highest pollen percentage values are found at locations 2 and 9, which are situated at the base of the SE and southern slope of the quadrat. The lowest pollen percentage values are observed at locations 1 and 10 which are situated on the high-point plateau, and mid-slope in the SW portion of the quadrat. The pattern of high pollen percentage values at the base of slopes, and lower pollen percentage values at topographically higher and mid-slope sites appears to apply to Salix-*type* in the Cressbrook Dale quadrat.

Pollen percentage values of *Betula pendula* range from 2.2 – 5% across the 10 Cressbrook Dale sample locations. No *Betula pendula* was recorded in the local woodland vegetation meaning that pollen deposited at the quadrat must have been aerially transported via Ct and Cc vectors from the extra-local pollen sources. The highest pollen percentage values are observed at sample locations 5 and 9 situated mid-slope in the SW and at the slope base in the south of the quadrat. The lowest pollen percentage values are observed at sample locations 10 and 7, which are positioned at mid-slope in the SW and mid-slope in the NE of the quadrat. The high pollen percentage value observed at sample location 9, at the southern slope base, may be a product both of primary pollen deposition direct to the location, and secondary slope wash pollen inputs. Sample location 5 is more problematic in that the mid-slope sites are often associated with lower pollen values; however location 5 is positioned very close to a slope base which may increase pollen concentrations at this location. The internal fabric of the moss at location 5 may be less permeable, with smaller interstices within the moss having the effect of reducing flow velocities at this point resulting in a higher proportion of the pollen transported down-slope by water being focused at this position; or it may simply be that a SW aspect is most favourable to the aerially transported pollen rain. One of the lowest pollen percentage value locations, location 7, is located on the NE portion of the quadrat, which if aerially transported pollen sources were situated to the south/SW could potentially receive lower amounts of pollen rain as southern site would intercept pollen first. The other low pollen percentage location, sample location 10, is problematic in that it is south/SW facing, however the high slope angle at location 10 may result in a high degree of secondary pollen transport away from this location via rainwater throughflow.

Pollen percentage values of *Corylus avellana* range from 0.5 – 3.7% across the 10 sample locations; Corylus avellana is recorded as a minor component in the local woodland vegetation to the west of the quadrat as displayed in figure 5.9. The highest pollen percentage values are observed at locations 5 and 8, which are situated on mid-slope and slope base positions in the SW and NW respectively. The lowest *Corylus avellana* pollen percentage values are observed at sample locations 4 and 6, both situated at mid-slope positions on steep, high angle slopes in the SE and north of the quadrat; the *Corylus avellana* pollen percentage value at sample location 4 is significantly lower than the other 9 Cressbrook Dale samples based on the confidence intervals displayed in figure 6.12. The two highest pollen percentage value locations are both facing the woodland association containing *Corylus avellana*, which is to the west of the quadrat, suggesting that pollen transport via Ct and Cc may be more favourable to these locations. Additionally, sample location 8 is a slope base location, and sample location 5 is adjacent to a slope base location where secondary pollen transport driven by rainwater and gravity flow may have the effect of concentrating pollen percentages through pollen removed from topographically higher parts of the moss. The two low pollen percentage value sample locations, 4 and 9, do not face the local *Corylus avellana* components in the local woodland to the west, which may be a factor in reducing pollen deposition from the local woodland component as a result of pollen rain being deposited on the western side of the quadrat preferentially through Ct and Cc aerial pollen transport. Additionally, the high slope angle at sample locations 4 and 6 may be a factor, as pollen may be transported away from these sites by rainwater gravity flows.

Quercus robur is only recorded at 3 of the 10 Cressbrook Dale sub-sample locations, and is not recorded in the local woodland vegetation meaning pollen input to the quadrat mosses must derive from extra-local or regional aerially transported pollen rain. Pollen percentage values of 0.1% were recorded in sample locations 5 and 6, and 2.8% at sample location 9. The *Quercus robur* pollen percentage value recorded at sample location 9 is significantly higher than the other sample values based on the confidence intervals displayed in figure 6.12. Sample location 9 is situated at a slope base location in the south of the quadrat, sample location 5 is on a steep slope adjacent to a slope base on the western side of the quadrat, and sample 6 is situated at a mid-slope location in the north of the quadrat. The extra-local pollen input to the quadrat may be transported from the south, which could result in the higher pollen percentage values observed at sample location 9; additionally some slope base locations, such as sample location 9, appear to collect pollen transported down slope from topographically higher areas of the moss resulting higher pollen percentage values. Sample locations 5 and 6 have western and northern aspects respectively, which may contribute to low levels of pollen deposition if the *Quercus robur* extra-local pollen rain is transported aerially from trees to the south of the quadrat. Both the low pollen percentage value sample locations are on steep slopes, which may result in pollen losses via rainwater throughflow.

Pollen percentage values of Picea-*type* range from 0.2 – 4% across the 10 Cressbrook Dale sub-sampling locations. No Picea-*type* was recorded in the local woodland vegetation, meaning that pollen must be transported to the quadrat aerially from extra-local or regional pollen sources. The highest pollen percentage values are observed at sample locations 3 and 10, which are situated at mid-slope positions on steep slopes to the west and south of the quadrat respectively. The lowest pollen percentage values of Picea-*type* are observed at sample locations 6, 8, and 9, which are located on the mid-slope positions in the north and NW, and at a slope base location in the south of the quadrat. Sample locations 1, 6, 8, and 9 all display Picea-*type* pollen percentage values which are significantly different from those observed at the other Cressbrook Dale sub-sample locations. Sample locations 3 and 10 both have a southerly aspect, suggesting that the pollen rain may be transported from extra-local trees to the south of the quadrat. Three of the low pollen percentage value Picea-*type* sample locations (1, 6, and 8) have a northerly aspect, which may support this hypothesis of a southern-trending pollen source; these 3 sample locations are also on steep mid-slope positions where pollen may be transported away down slope by rainwater vectors. However sample location 9, which displays the lowest pollen percentage values for Picea-*type* at the Cressbrook quadrat, is on a south-facing slope base. Slope base sites are often associated with high pollen percentage values; low pollen percentage values at sample location may therefore be the product of the stochastic nature of aerial pollen transport.

Larix-*type* pollen was recorded at only 4 of the 10 Cressbrook Dale quadrat sampling locations at percentage values ranging from 0.2 – 1%, the taxa was not recorded in the local woodland vegetation meaning that pollen is transported aerially from extra-local and/or regional pollen sources to the Cressbrook Dale quadrat. The highest Larix-*type* pollen percentage value is observed in sample location 9, which is situated on a slope base in the south of the quadrat. The lowest Larix-*type* pollen percentage values are recorded in samples 1, 4, and 5 which are located in the west/NW of the quadrat and situated on the topographic high point and mid-slope positions on high angle slopes respectively. As with Picea-*type*, it may be that the extra-local and/or regional pollen source for Larix-type is situated to the south of the quadrat, meaning that pollen deposition would be greater on moss with a southern aspect. This hypothesis is supported by the observation that all the low pollen percentage values of Larix-*type* are recorded in the north/NW of the quadrat at Cressbrook Dale. Additionally, the low pollen percentage values sites are positioned on high angle mid-slopes where secondary pollen transport away from this type of location may reduce pollen percentages.

Millington Wood

The sub-sample locations and topography of the Millington Wood quadrat are displayed in figures 6.16a, 6.16b and 6.19. It can be immediately observed that the Millington Wood quadrat is lower in height and displays less variation in relief than either the Cressbrook Dale or Chee Dale quadrats. The more elevated sub-sample locations are 2, 4, 5, and 10, with the remaining sub-samples taken from topographically lower locations within the quadrat. Height differences between locations across the quadrat as a whole are only in the order of 2 – 3cm, low points within the quadrat were purposely avoided in this sampling location, as the moss cover was less developed in these areas.

Sample locations 2, 4, 5, and 10 may still have the potential to receive more Cg and Ct pollen influx than the topographically lower sites due to greater elevation at these locations. Sample locations 4 and 7 are positioned on breaks in slope on the moss; this may influence pollen concentrations at these locations due to the influence of slopewash processes driven primarily by rainwater. The influence of invertebrates and insect pollinators may also be a factor in pollen deposition and secondary relocation at the Millington Wood quadrat. The quadrat site is situated on a slope with a southerly aspect, and due to the ‘hill and dale’ microtopographical character of this relatively flat quadrat there are a series of south facing micro-slopes which may be used by ‘sunning’ insects. This contrasts with the more significant height and slope angles in the topography of the Chee Dale and Cressbrook Dale quadrats, which results in considerably more shade across the quadrats as a whole. The more open, southerly aspect of the Millington Wood quadrat site may have an effect on preferential deposition of entemophilous pollen e.g. Acer-*type* and *Tilia cordata*.

As can be observed in figure 6.16a, the local woodland associations are dominated by Acer-*type* and *Fraxinus excelsior*, with smaller a community of Pinus-*type* adjacent to the south-west corner of the quadrat. Some communities feature isolated, single trees of taxa such as *Tilia cordata* and *Fagus sylvatica*. The dominance of Acer-*type* and Pinus-*type* in the local vegetation is reflected in the high pollen percentages of these taxa recorded in the 10 surface samples in the quadrat. The range of Acer-*type* values across the quadrat is from 40 – 60 % of the total land pollen, with the highest percentage values recorded at samples 4, 7, 9, and 10. Samples 4 and 10 are two of the most elevated in this quadrat, and samples 4 and 7 are situated on slope breaks. This suggests that the higher elevation sample locations within the quadrat may receive a higher proportion of the pollen rain and that sample locations situated on slopes may be influenced by slope wash processes reworking and transporting pollen. The relatively uniform high Acer-*type* pollen percentage values across the whole quadrat may also be influenced by the relatively low and even topography of the Millington quadrat, and the south-facing aspect of the quadrat providing attractive sunning sites for insect pollinators to deposit entemophilous pollen such as Acer-*type*.

Pollen percentage values of Pinus-*type* at the Millington Wood quadrat range from 3.9 – 8.8% across the 10 sample locations. Pinus-*type* is present as a dominant woodland component to the south of the quadrat, and as a minor component in woodland associations to the west and SE of the quadrat. The highest pollen percentage values for Pinus-*type* are recorded at sample locations 7 and 10, to the east and SW of the quadrat respectively. Sample location 10 is situated on a raised area of moss, whilst sample 7 is situated at woodland floor level. The lowest pollen percentage values of Pinus-*type* are observed at sample locations 4 and 6, which are situated to the west and NW portion of the quadrat. Sample location 4 is at woodland floor level, and sample location 6 is situated on a raised area of moss; sample location 6 is significantly lower than the other Millington Wood samples displayed in the confidence interval charts in figure 6.13 and is considered an outlier. The high Pinus-*type* pollen percentage at sample location 10 may be attributed to the proximity of the location to the Pinus-*type* community to the south of the quadrat, where Cg and Ct pollen transport vectors may dominate. Sample location 7 is situated in the NW portion of the quadrat away from the Pinus-*type* community to the south; the input of local Ct and Cg pollen transport may also be an influence at this location, as Pinus-*type* is present as isolated trees. Pinus-*type* is also well represented in the extra-local woodland, which may supply a proportion of the extra-local pollen influx to the Millington Wood field site. The two lowest pollen percentage value locations, 4 and 6, are more problematic, in that both these locations are adjacent to the local Pinus-*type* woodland community; both samples also occupy identical topographic positions to the two high pollen percentage values sample locations. The stochastic nature of pollen flux is attributed to the low pollen percentage values at these locations.

Pollen percentage values of *Fraxinus excelsior* range from 1 – 6.6% across the 10 sample locations. Fraxinus excelsior is present as second dominant in woodland associations to the west and SE of the quadrat, and as a minor woodland component in associations to the north, east, south and SE of the quadrat. The highest pollen percentage values of *Fraxinus excelsior* are recorded at sample locations 1 and 10, situated to the east and SW of the quadrat respectively; both sample locations are on raised mosses. The lowest pollen percentage values of *Fraxinus excelsior* are observed at sample locations 3 and 4, which are situated in the NE and SW of the quadrat respectively; sample 3 is situated on a raised moss, sample 4 is situated on the woodland floor. Sample locations 1 and 10 are both adjacent to the local woodland associations where *Fraxinus excelsior* is a second dominant; higher pollen percentages at these sample locations could be a result of both enhanced Ct and Cg pollen input to the mosses in this portion of the quadrat. Of the two low pollen percentage value sample locations 3 and 4, sample location 3 is located in the NE of the quadrat where Fraxinus excelsior is only a very minor component of the local woodland association. Sample 4 is more problematic in that has the lowest *Fraxinus excelsior* pollen percentage recorded at the Millington Wood quadrat, and yet is adjacent to the woodland association to the west where *Fraxinus excelsior* is a co-dominant with Acer-*type*. The Pinus-*type* community to the south and SW also could be a potential influence; however sample location 4 also displays very low Pinus-*type* pollen percentages.

Pollen percentage values of *Ulmus glabra* at Millington Wood range from 3 – 6.8% across the 10 sample locations. No *Ulmus glabra* was recorded in the local woodland vegetation, meaning that pollen deposited at the Millington quadrat must be derived from extra-local and/or regional pollen sources. The highest *Ulmus glabra* pollen percentages are recorded at sample locations 5 and 9, which are situated at the southern and northern edges of the quadrat respectively; sample location 5 is on a raised moss, and sample 9 is situated on the woodland floor. The lowest *Ulmus glabra* pollen percentages are recorded at sample locations 1 and 4 in the east and west of the quadrat respectively; sample 1 is located on a raised moss, sample 4 is taken from moss on the woodland floor. As no local *Ulmus glabra* is recorded locally, extra-local/regional pollen sources must be contributing to the high pollen percentages at sample locations 5 and 9. The raised moss locations in the south and north from which both of these samples were taken may be sites of preferential deposition for pollen transported aerially by Cc and Ct vectors, as the small advantage in height may allow more of the pollen rain to land on these elevated sites. The low pollen percentage value sample locations are located to the east and west of the quadrat, suggesting that *Ulmus glabra* pollen influx may be coming in to the quadrat from the north or south and depositing pollen rain onto elevated parts of the quadrat preferentially as winds traverse the quadrat.

Pollen percentage values of Acer-*type* range from 40 – 55% across the 10 sample. Acer-*type* is the dominant taxon in the local woodland associations to the west, north and south of the quadrat location. The highest pollen percentage values of Acer-*type* are recorded in sample locations 9 and 4, which are located in the north and west of the quadrat respectively; the high pollen percentage value sample 9 is considered significantly different to the other Millington Wood Acer-*type* samples on the basis of the confidence intervals displayed in figure 6.13. Sample 4 is located on the woodland floor, and sample 9 is situated on a raised moss. The lowest Acer-*type* pollen percentage values are recorded at sample locations 2, 5, and 8, which are located in the centre, south and SW of the quadrat respectively. All samples are situated on raised mosses, and are considered significantly lower than the other Millington Wood Acer-*type* samples on the basis of the confidence intervals displayed in figure 6.13. The Acer-*type* dominated woodland associations are to the north, west, south, and SE of the quadrat. This would suggest that a high proportion of the pollen deposition onto the quadrat would be primarily through gravity (Cg) and trunk-space (Ct) pollen transport vectors from these trees. Both the high pollen percentage values sample locations are adjacent to these woodland associations, which would suggest that the local pollen rain is influencing the high pollen percentage values observed at these sites. Of the low pollen percentage value locations, only location 5 is adjacent to the local Acer-*type* dominated woodland association with location 2 situated in the centre of the quadrat and location 8 situated in the SW of the quadrat. What is problematic is that, with the exception of sample location 4, both the low pollen percentage value and high pollen percentage value locations are situated on raised mosses, meaning that altitude may not be a control on Acer-*type* pollen concentrations across the quadrat.

Pollen percentage values of *Fagus sylvatica* are very low at the Millington Wood quadrat, and range from 0.4 – 1.2% across the 10 sample locations. *Fagus sylvatica* is recorded as a dominant component of the local woodland to the north, NE and east of the quadrat, and as a minor component in the *Acer-type* & *Fraxinus excelsior* woodland association to the SE and south of the quadrat. The highest pollen percentage values of *Fagus sylvatica* are recorded in sample locations 5 and 8, which are both situated on raised mosses in the south and SE portion of the quadrat. The lowest pollen percentage values of *Fagus sylvatica* are recorded at sample locations 3 and 7, which are also both situated on raised mosses in the NE portion of the Millington quadrat. The relationship between *Fagus sylvatica* vegetation and *Fagus sylvatica* pollen deposition at Millington Wood appears complex, in that the sites nearest to the vegetation i.e. 3 and 7, display the lowest pollen percentage values and the sites furthest away from the *Fagus sylvatica* vegetation i.e. 5 and 8, display the highest pollen percentage values. Also, both the low value and high values locations are all situated on raised mosses, suggesting that enhanced altitude in not a significant factor controlling *Fagus sylvatica* pollen deposition at the Millington Wood quadrat. This depositional pattern may be related to the 'skip-distance' of pollen described by Jackson & Lyford, (1999), whereby the local Cg and Ct transported pollen from the local *Fagus sylvatica* woodland is not being deposited on the woodland floor in large concentrations on the NE side of the quadrat as a result of the pollen still being airborne over that portion of the quadrat.

Pollen percentage values of Salix-*type* are low at Millington Wood, with values ranging from 0.1 – 0.8% across the 9 sub-sample locations where the taxon was recorded. The taxa is not recorded in the local woodland vegetation at Millington, meaning that Salix-*type* pollen recorded in the quadrat mosses is transported to the site aerially from extra-local pollen sources via Ct and Cc transport vectors. The highest pollen percentage values of Salix-*type* are observed in sample locations 1 and 6, which are situated in the SE and NW portions of the quadrat; both locations are on raised mosses. The lowest pollen percentage values of Salix-*type* are observed at sample locations 2 and 3, which are situated in the centre and NE of the quadrat respectively; both locations are situated on raised mosses. As both the highest and lowest pollen Salix-*type* percentage values are taken from raised moss locations within the Millington Wood quadrat, height above the woodland floor cannot be a significant influence on preferential pollen capture. Higher pollen percentages recorded at sample location 1 in the SE and at sample location 6 in the NW of the quadrat suggests that pollen is being transported aerially via Ct and Cc vectors from extra-local source plants; the wind direction transporting Salix-*type* pollen may be from either the SE or NW, resulting in higher values on that bearing across the mosses in the quadrat.

Pollen percentage values of *Betula pendula* are relatively low, ranging from 0.2 – 3.5% across the 10 Millington Wood sub-samples. No *Betula pendula* was recorded in the local woodland vegetation, meaning that pollen deposited at the Millington Wood quadrat must be transported aerially via Cc and Ct vectors from extra-local and/or regional pollen sources. The highest pollen percentage values of *Betula pendula* are recorded at sub-sample locations 6 and 8, which are situated on raised mosses in the NW and SE of the quadrat. The lowest pollen percentage values of *Betula pendula* are recorded at sub-sample locations 3 and 10 which are situated on raised mosses in the NE and SW portions of the quadrat. Sample location 3 displays pollen percentage values significantly lower than the other Millington Wood sub-samples and is considered as an outlier based on the confidence intervals displayed in figure 6.13. As was observed with *Salix-type* pollen percentages, height above the woodland floor does not appear to be a significant factor in pollen capture *of Betula pendula* pollen at the Millington quadrat as both the highest and lowest pollen percentage values are recorded from raised moss sub-sample locations. As with *Salix-type*, the highest *Betula pendula* values are observed in the NW and the SE of the quadrat suggesting extra-local and/or regional pollen is transported to the Millington Wood quadrat primarily by either NW or SE winds. Pollen deposition variations at Millington Wood may also be influenced by local sub-canopy atmospheric characteristics which favour pollen settling at the NW and SE portions of the quadrat.

Pollen percentages of *Corylus avellana* are low at the Millington Wood quadrat, ranging in value from 0.1 – 2.1% across the 10 sub-sample locations. No *Corylus avellana* was recorded in the local woodland vegetation, meaning that pollen recorded at the Millington Wood quadrat is transported aerially via Cc and Ct vectors from extra-local and/or regional pollen sources. The highest pollen percentage values are recorded at sample locations 5 and 6, which are situated on raised mosses in the SE and NW portions of the quadrat. The lowest pollen percentage values of *Corylus avellana* are recorded at sample locations 3 and 9, which are both located in the north/NE portion of the quadrat; sample location 3 is on a raised moss, and sample location 9 is located on moss on the woodland floor. Sample location displays the lowest pollen percentage values of *Corylus avellana* recorded at the Millington Wood quadrat, and is considered an outlier based on the confidence intervals for Millington Wood displayed in figure 6.13. It appears that height above the woodland floor may not be as significant a factor as prevailing wind direction and local sub-canopy atmospherics in controlling Ct and Cc pollen transport of *Corylus avellana* pollen to specific areas of the Millington Wood quadrat. As with Salix-*type*, and with *Betula pendula* the highest pollen percentage values of *Corylus avellana* are found on a NW – SE transect across the quadrat, and the lowest pollen percentage values are observed on a NE –SW transect across the quadrat. This would suggest that *Corylus avellana* pollen from extra-local and/or regional pollen sources is carried to the Millington Wood study site primarily by either NW or SE winds.

Pollen percentage values of Larix-*type* at Millington Wood are very low, ranging in value from 0.2 – 0.4% in the 8 sub-sample locations where the taxa was recorded. No Larix-*type* was recorded in the local woodland vegetation, meaning that Larix-*type* pollen recorded at Millington Wood must be transported to the quadrat aerially via Cc and Ct vectors. The highest pollen percentage values of Larix-*type* are recorded at sample locations 3 and 10 which are located in the NE and SW of the quadrat respectively; both sample locations are situated on raised mosses. The lowest pollen percentage values of *Larix-type* are recorded at sample locations 5 and 6 which are situated in the SE and NW of the quadrat respectively; both sample locations are situated on raised mosses. Pollen percentage values of Larix-*type* are both very low and relatively uniform at the Millington Wood site, suggesting that the pollen influx may be either regional or from small numbers of separate extra-local trees. Larix-*type* does not display the trend of higher pollen percentage values along a NW – SE transect which is displayed by Salix-*type*, *Betula pendula*, and *Corylus avellana*. It may also be the case that extra-local Larix-*type* trees are located to the SW or NE of the Millington Wood quadrat, meaning that pollen from these trees is not transported in such large quantities as trees situated in the NW and SE due to the prevailing wind direction being dominated by the NW and SE winds.

Pollen percentage values of Picea-*type* are low at the Millington Wood quadrat, ranging in value from 0.5 – 2.5% across the 10 sub-sample locations. No Picea-*type* was recorded in the local woodland vegetation, meaning that Picea-*type* pollen recorded at Millington Wood must be transported to the quadrat aerially via Cc and Ct vectors. The highest pollen percentage values for Picea-*type* are recorded at sample locations 6 and 8, which are situated in the NW and SE portions of the quadrat respectively; both sample locations are situated on raised mosses. The lowest pollen percentage values of Picea-type are located at sample locations 4 and 5 which are situated in the west and south portions of the quadrat; sample location 4 is taken from moss on the woodland floor, sample location 5 is situated on a raised moss. Picea-*type* follows the directional depositional trend displayed by Salix-*type*, *Betula pendula*, and *Corylus avellana* of higher pollen percentage values on a NW – SE transect across the quadrat. This would suggest that Picea-*type* pollen from extra-local and/or regional pollen sources is carried to the Millington Wood study site primarily by NW or SE winds as, in keeping with observations of the spatial variation of pollen percentage values of Salix-*type*, *Betula pendula*, and *Corylus avellana*, lower pollen deposition is observed along a NE – SW transect at the Millington Wood quadrat.

Pollen percentage values of *Alnus glutinosa* are low at the Millington Wood quadrat, with percentage values ranging from 1 – 3.5% across the 10 sub-sample locations. No *Alnus glutinosa* was recorded in the local woodland, meaning that *Alnus glutinosa* pollen recorded at the Millington Wood quadrat must have been transported to the quadrat aerially via Cc and Ct vectors from extra-local and/or regional pollen sources. The highest pollen percentage values of *Alnus glutinosa* are recorded at sample locations 4 and 5, which are situated in the western and southern portions of the quadrat respectively; sample 4 is located on moss on the woodland floor, sample 5 is situated on a raised moss. The lowest *Alnus glutinosa* pollen percentage values are recorded at sample locations 7 and 9, which are located in the NE and northern portions of the quadrat; both sample locations are on raised mosses. The high *Alnus* *glutinosa* pollen percentage value locations in the Millington Wood quadrat appear to occupy spatial positions i.e. NW and SE, within the quadrat similar to the trend already observed with Salix-*type*, *Betula pendula*, and *Corylus avellana*, in that the highest pollen percentage values appear to be aligned along a NW – SE direction across the quadrat. As previously discussed, this would suggest that *Alnus glutinosa* pollen from extra-local and/or regional pollen sources is carried to the Millington Wood study site primarily by NW or SE winds, and that extra-local *Alnus glutinosa* trees sited to the south east or north west will deliver more aerially transported pollen to the quadrat then trees positioned to the south west or north east. The spatial variation in *Alnus glutinosa* pollen percentage values observed across the quadrat may also be influenced by the sub-canopy atmospheric characteristics around the Millington Wood quadrat i.e. the canopy may be slightly more open to the NW and SE of the site.

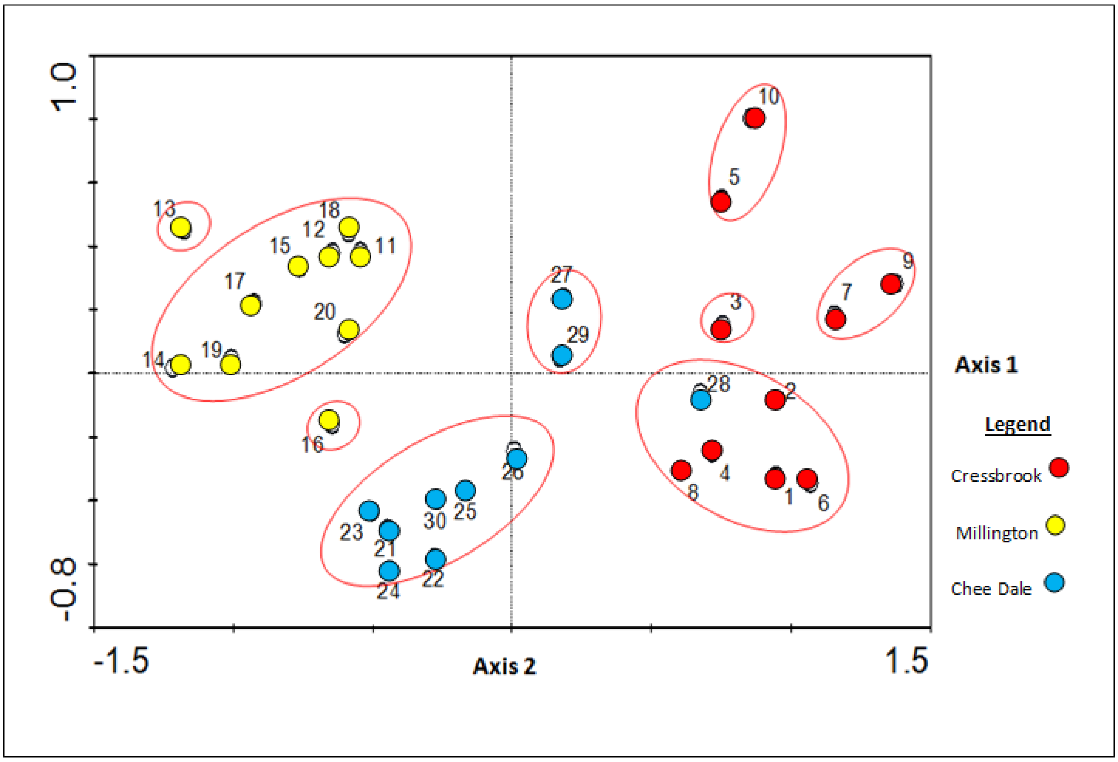
Pollen percentage values of *Quercus robur* are low at the Millington Wood quadrat, with pollen percentage values ranging from 0.3 – 2.5% across the 10 sub-sample locations. No *Quercus robur* was recorded in the local woodland, meaning that *Quercus robur* pollen recorded at the Millington Wood study site must have been transported to the quadrat aerially via Cc and Ct vectors from extra-local and/or regional pollen sources. The highest *Quercus robur* pollen percentage values are observed at sample locations 1 and 2, which are located in the SE and NW portion of the quadrat respectively; both sample locations are situated on raised mosses. The lowest *Quercus robur* pollen percentage values are observed at sample locations 4 and 9, which are located in the western and northern portions of the quadrat. Sample location 4 is situated on a moss taken from the woodland floor and is the lowest percentage value location for Quercus robur at Millington Wood; as such this sample is considered as an outlier based on the confidence intervals displayed in figure 6.13. Sample location 9 is located on a raised moss.

Quercus robur pollen percentage values appear to be higher on the NW – SE transect, as previously discussed in the case of *Salix-type*, *Betula pendula*, *Corylus avellana* and *Alnus glutinosa* all of whom display a similar trend of higher pollen percentage values along the NW – SE axis within the quadrat. Height above the woodland floor does not initially appear to be the primary control of spatial patterns of pollen deposition for *Quercus robur*, as the low pollen percentage value sample 9 is located on a raised moss very similar to the high pollen percentage value samples 1 and 2. More problematic is the low pollen percentage value sample location 4, which is in the west of the quadrat and is very close to the 'high percentage value' NW – SE axis. Sample location 4 is taken from moss on the woodland floor, suggesting that height above the woodland floor may be a factor affecting *Quercus robur* pollen deposition at the Millington Wood study site.

Principal Components Analysis

Ordination analysis was carried out on the pollen percentage data derived from the quadrat sub-samples at the three field study sites. Similarity in species composition between the 30 sub-samples from the three field study sites is examined using Principal Components Analysis (PCA). Component scores have been plotted after standardisation and centring. The distance between sub-samples represents the degree of similarity of sub-sample species composition and associated pollen percentages e.g. sub-sample sites which are clustered are more similar in species composition and associated pollen percentages, sub- sample sites which are split away are less similar in species composition and associated pollen percentages. PCA plots are presented in figures 6.19 to 6.21 below.

Figure 6.19: Axis 1 vs. Axis 2 PCA ordination plot of sub-sample pollen percentages from Cressbrook (1- -10), Millington (11 – 20), and Chee Dale (21 – 30) quadrat samples; red circles indicate clusters of sub-samples which display a high degree of similarity both in species composition and in pollen percentages of the similar species.



As can be observed in figure 6.19, the three woodland study sites are clearly separated along the principal axis, with each woodland site displaying differing degrees of similarity and separation. The Millington woodland sub-samples (11 – 20) display the highest degree of similarity, with sample points 13, 14, 17, and 19 the most significant in terms of weighting the principal component on axis 1. Points 13 and 16 are suggested as outliers, with sub-sample point 16 displaying an equally high degree of similarity to the Chee Dale woodland site main cluster. The Chee Dale woodland sub-samples (21 – 30) form one cluster displaying high similarity which includes points 21 – 26, and 30; this cluster is dominated by the second component on the second axis. Chee Dale points 27 and 29 forms a second cluster displaying high similarity, but is less similar to the main Chee Dale cluster; point 29 is dominated by the principal component on axis 1, point 27 is dominated by the second component on axis 2. Chee Dale point 28 displays a higher degree of similarity to the Cressbrook sample points than to the Chee Dale clusters, and is dominated by the principal component on axis 1. The Cressbrook woodland site displays the highest degree of separation between the sub-sample points, and has been separated into 4 distinct clusters; a main Cressbrook cluster of five points i.e. 1, 2, 4, 6, and 8, two clusters of two points i.e. 7 and 9, and 5 and 10, and a single point i.e. 3. Both the cluster 1, 2, 4, 6, and 8, the cluster 7 and 9, and the single point 3 are dominated by the principal component on axis 1. The cluster comprising sub-sample points 5 and 10 appears to be equally dominated by both axis and axis 2.

PCA ordination of the second component on axis 1 and third component on axis 2 is displayed in figure 6.20 below. The three woodland sites are separated on the secondary axis, with Chee Dale displaying the highest degree of similarity and clearly separated from the two other woodland sites. Both Millington and Cressbrook display a relatively high degree of separation. Chee Dale sub-sample points are distributed on the negative side of the second component on axis 2 i.e. 21 – 26, 28, and 30, and on the negative side of the third component on axis 3, i.e. 27 and 29. points on the positive side of the second axis, i.e. 11, 12, 15, and 18. However the remaining Millington points display a high degree of similarity with the Cressbrook samples. The Cressbrook samples form a primary cluster of five points i.e. 1, 2, 4, 6, and 8, two associations with Millington points i.e. 3, 7, 17, 19 and 20, 5 and 13 and two highly separated outlier points i.e. 9 and 10.

Figure 6.20**:** Second component (x axis) vs. third component (y axis) PCA ordination plot of sub-sample pollen assemblage percentages; data is standardised and centred - red circles indicate clusters of sub-samples which display a high degree of similarity both in species composition and in pollen percentages of the similar species.

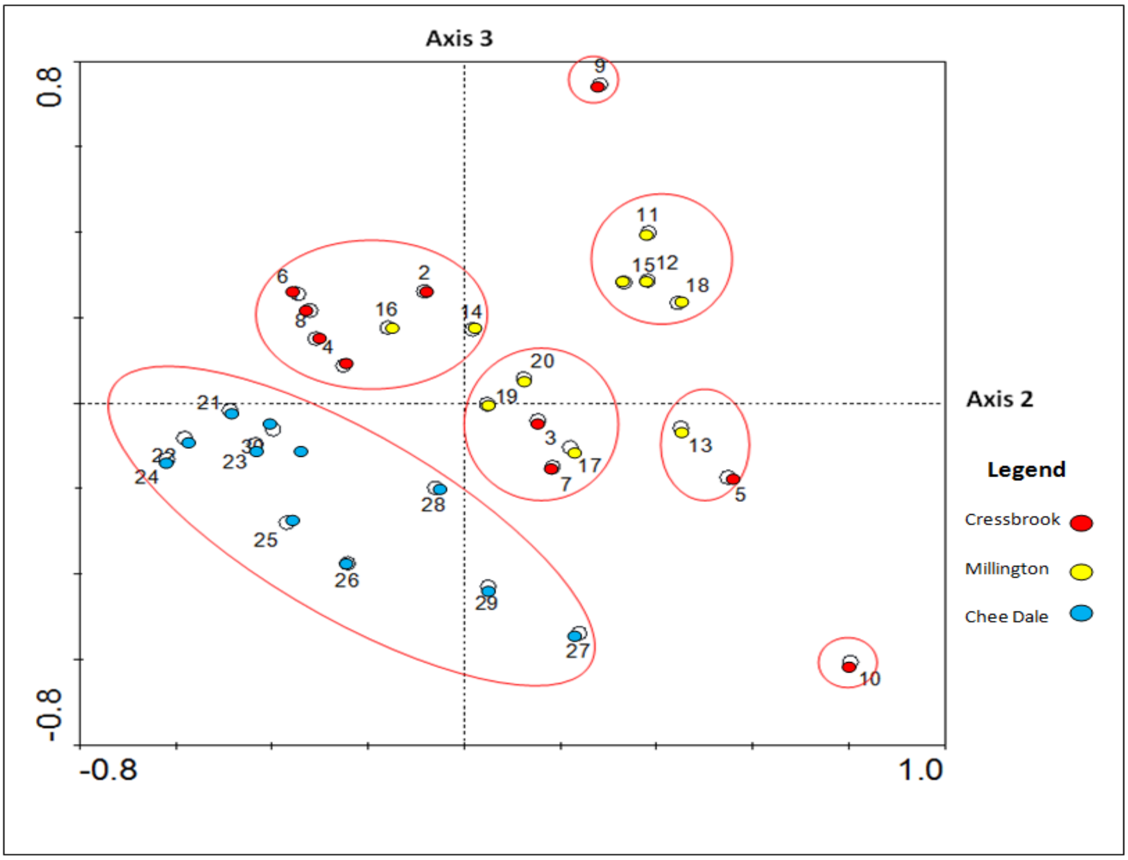
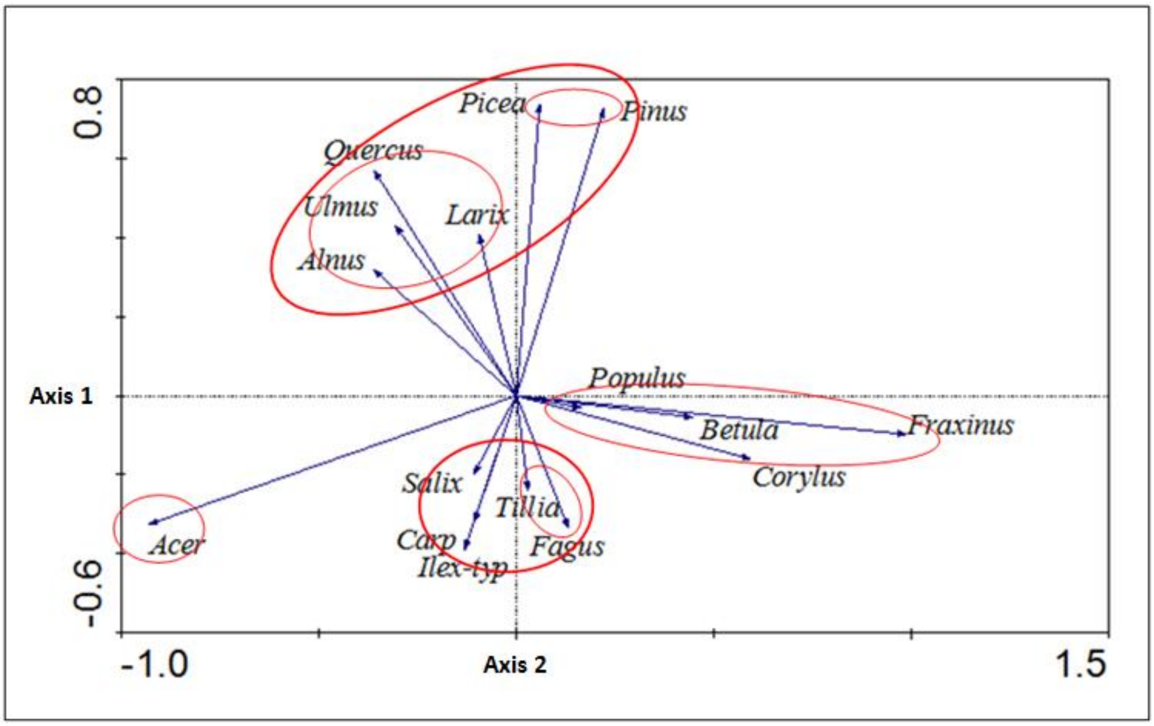


Figure 6.21**:** PCA ordination plot of study site tree taxa – plot displays the principal component (x axis) against the second component (y axis) – data is standardised and centred; red circles denote tree taxa associations displaying similarities in variance, blue arrows denote eigenvector scores.

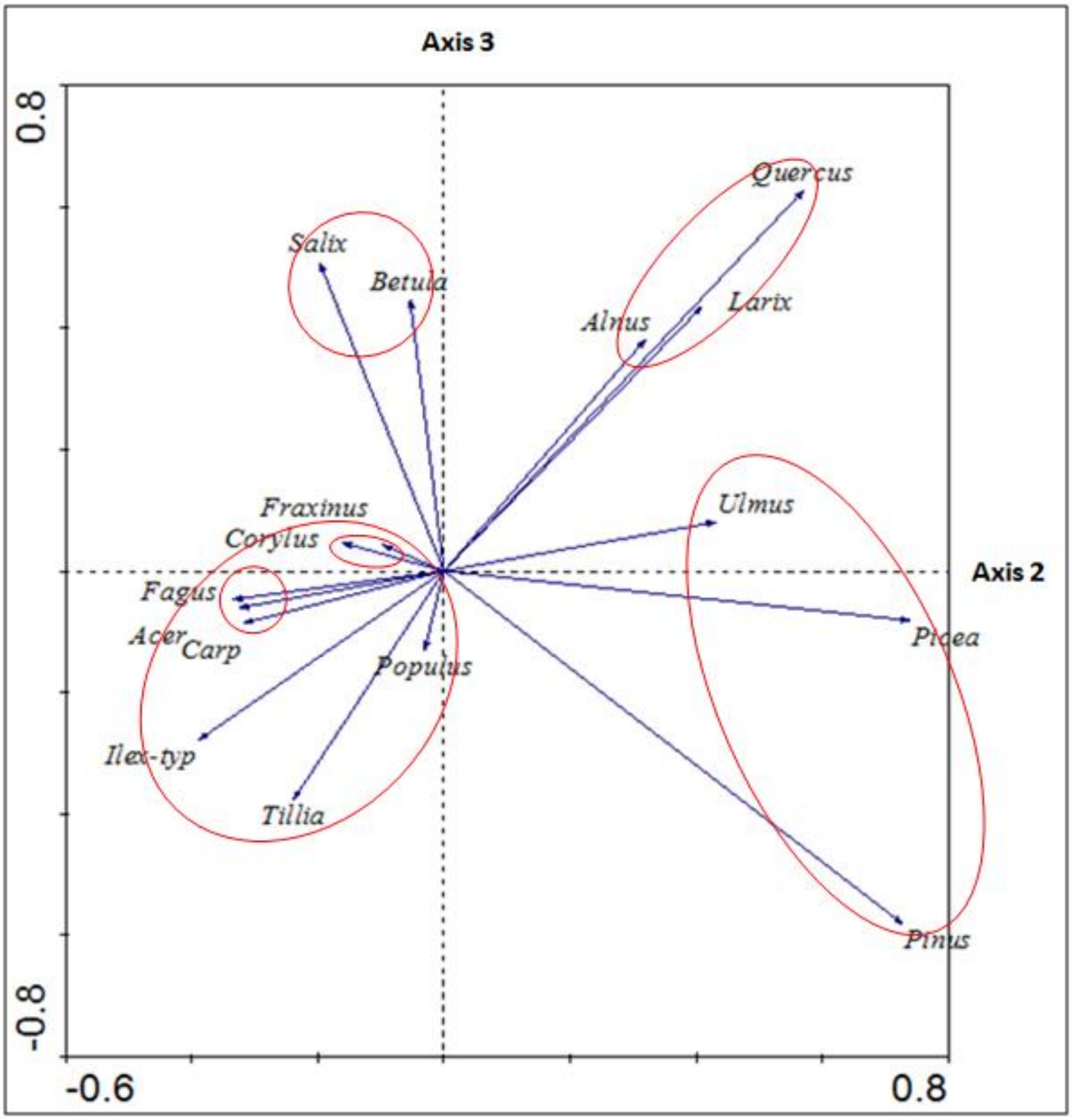


In figure 6.21 the tree taxa vectors are plotted on the same axes; significant splitting into four taxon associations of similar variance is observed. The observed associations include Populus, Corylus, Betula and Fraxinus; Salix, Tilia, Carpinus, Ilex and Fagus; Alnus, Quercus, Ulmus, and Larix, Picea and Pinus. Acer is separated away from the other taxa associations. The six taxa Alnus, Quercus, Ulmus, Larix, Pinus and Picea display a high degree of similarity, and are associated with the second component on axis 2. Within this association Quercus is the dominant taxon with Alnus and Larix the least influential taxa. The sub-association of Pinus and Picea display a high degree of similarity, and are also significantly associated with the second component on axis 2.

The association of Salix, Tilia, Carpinus, Fagus and Ilex displays high similarity, with all taxa significantly associated with the second component on axis 2; Ilex and Fagus are the most significant taxa in terms of weighting the component. The association of Populus, Betula, Corylus and Fraxinus is the weakest of all the observed associations in figure 6.21, in that the vectors all have approximately the same trajectory, but have different eigenvector scores. Within this association Betula and Corylus are the most associated in terms of similarity, with Populus and Fraxinus being the most dissimilar. This association is dominated by the principal component on axis 1, with Fraxinus the most significant taxon and Populus the least significant in terms of weighting the component. Acer has been spit away from the identifiable associations in terms of similarity, and is associated with the principal component on axis 1 to which, along with Fraxinus, it is the most important in terms of weighting.

PCA of tree taxa is displayed in figure 6.22. It can be observed that four associations of tree taxa have been separated on the second axis; these associations are highlighted in red, and display a range of similarity in variance. The greatest degree of similarity is observed in the large association highlighted on the negative side of axis 2. This association comprises eight taxa, *Tilia cordata*, *Ilex-type*, Populus-*type*, Carpinus-*type*, Acer-*type*, *Fagus sylvatica*, *Corylus avellana*, and *Fraxinus excelsior*. Within this association are two sub-associations, *Corylus avellana*, and *Fraxinus excelsior* and Carpinus-*type*, Acer-*type*, *Fagus sylvatica*; these latter associations display the highest degree of similarity of all taxa. The Salix-*type* and *Betula pendula* association is situated on the negative side of axis 2, with both taxa dominated by the third axis. The *Alnus glutinosa*, *Quercus robur*, and Larix-*type* association is situated on the positive side of axis 2, and displays a high degree of similarity of association and of trajectory away from the origin. The most separated association is situated on the positive side of axis 2, and comprises of *Ulmus glabra*, Picea-*type*, and Pinus–*type*, with Picea-*type* displaying a greater degree of association with *Ulmus glabra* than with Pinus-*type*; Pinus-*type* and Picea-*type* display the greatest weighting of this association.

Figure 6.22: Second component (x axis) vs. third component (y axis) PCA ordination plot of tree taxa from Cressbrook, Millington, and Chee Dale quadrats – data is standardised and centred: red circles denote tree taxa associations displaying similarities in variance, blue arrows denote eigenvector scores.



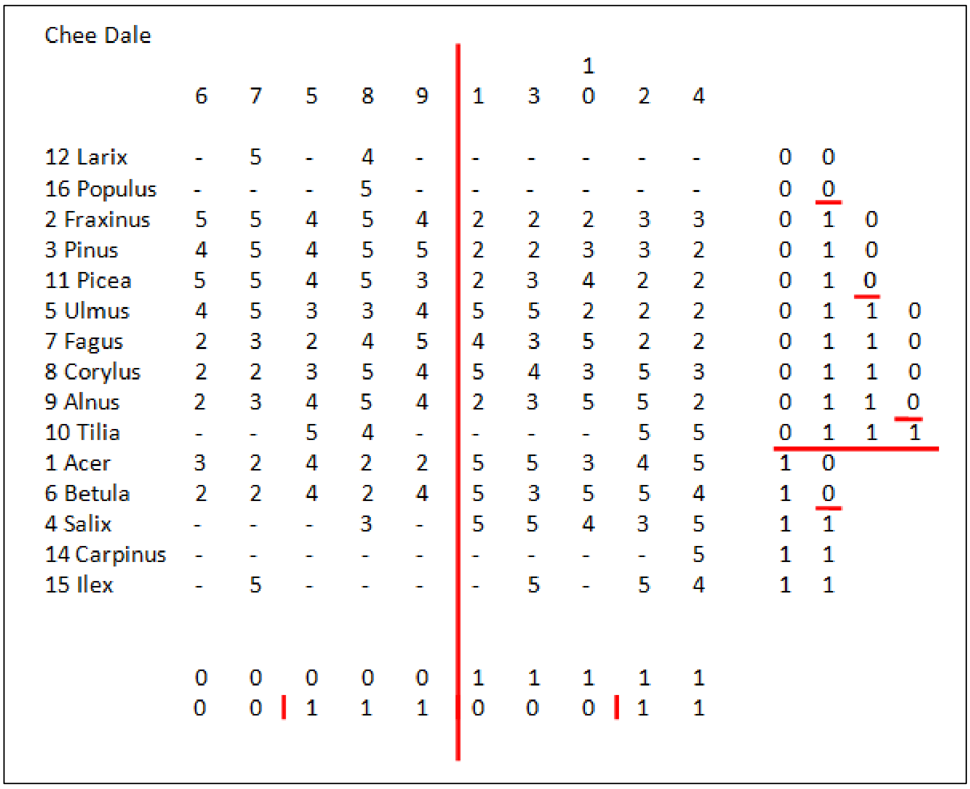
TWINSPAN Analysis

Chee Dale

Two-way indicator species analysis was carried out using TWINSPAN software. A TWINSPAN output table for the Chee Dale quadrat samples is presented in table 6.12 below. Output dendrograms displaying the hierarchical splitting of the Chee Dale quadrat samples and tree taxa are presented in figures 6.23 and 6.24 below. TWINSPAN requires a series of pseudospecies in order to adapt abundance data e.g. pollen percentages, into classes allowing division. Pseudospecies scores for Litton Mill data were derived using quartiles.

It can be observed at the bottom of table 6.12 that the Chee Dale taxa have been split into four groups. Splitting is based on high/low pseudospecies scores for *Fraxinus excelsior* at the first division, high/low pseudospecies scores *Corylus avellana* at the second division on the left, and high/low pseudospecies scores *Tilia cordata* at the second division on the right. Tree taxa divisions are displayed on the right-hand side of table 6.12. Taxa division in TWINSPAN is based on the degree to which species are confined to particular groups or community associations, rather than abundance as described by the pseudospecies scores.

Table 6.12: TWINSPAN output table for Chee Dale quadrat samples – coloured lines denote taxonomy of groups.



Chee Dale	6	7	5	8	9	1	3	10	2	4				
12 Larix	-	5	-	4	-	-	-	-	-	-	0	0		
16 Populus	-	-	-	5	-	-	-	-	-	-	0	0		
2 Fraxinus	5	5	4	5	4	2	2	2	3	3	0	1	0	
3 Pinus	4	5	4	5	5	2	2	3	3	2	0	1	0	
11 Picea	5	5	4	5	3	2	3	4	2	2	0	1	0	
5 Ulmus	4	5	3	3	4	5	5	2	2	2	0	1	1	0
7 Fagus	2	3	2	4	5	4	3	5	2	2	0	1	1	0
8 Corylus	2	2	3	5	4	5	4	3	5	3	0	1	1	0
9 Alnus	2	3	4	5	4	2	3	5	5	2	0	1	1	0
10 Tilia	-	-	5	4	-	-	-	-	5	5	0	1	1	1
1 Acer	3	2	4	2	2	5	5	3	4	5	1	0		
6 Betula	2	2	4	2	4	5	3	5	5	4	1	0		
4 Salix	-	-	-	3	-	5	5	4	3	5	1	1		
14 Carpinus	-	-	-	-	-	-	-	-	-	5	1	1		
15 Ilex	-	5	-	-	-	-	5	-	5	4	1	1		
	0	0	0	0	0	1	1	1	1	1				
	0	0	1	1	1	0	0	0	1	1				

Figure 6.23: TWINSPAN output dendrogram diagram of Chee Dale quadrat samples.

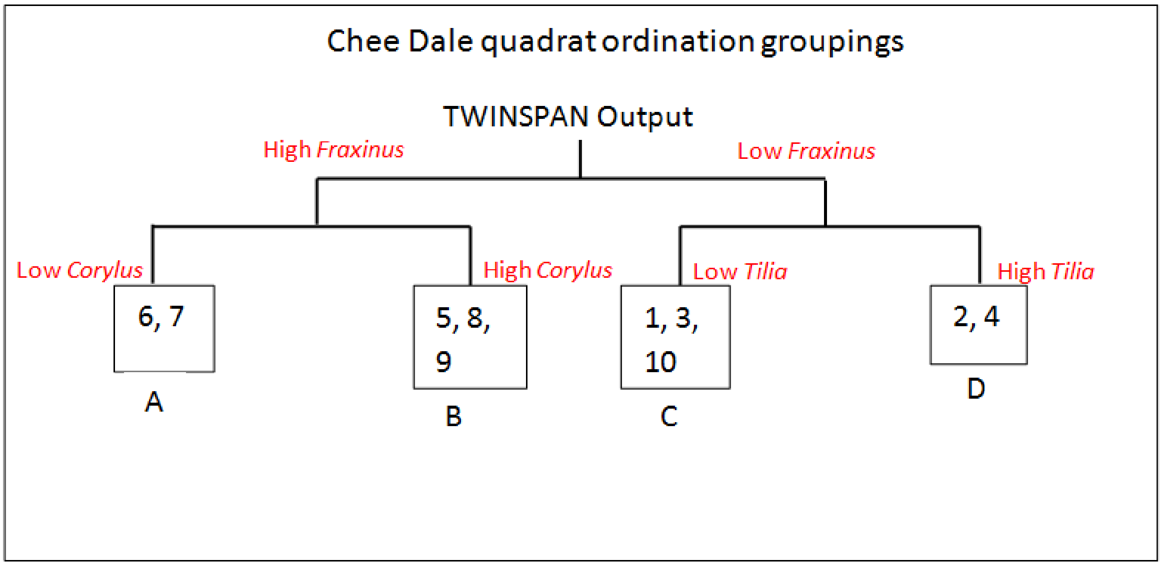
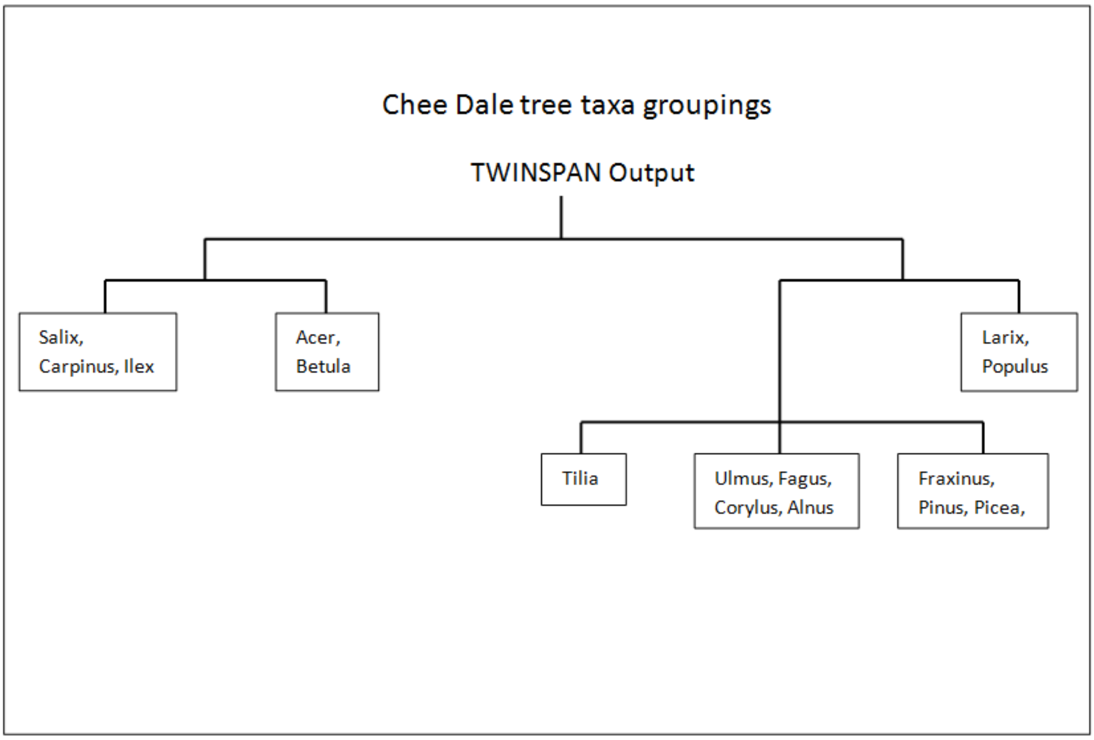


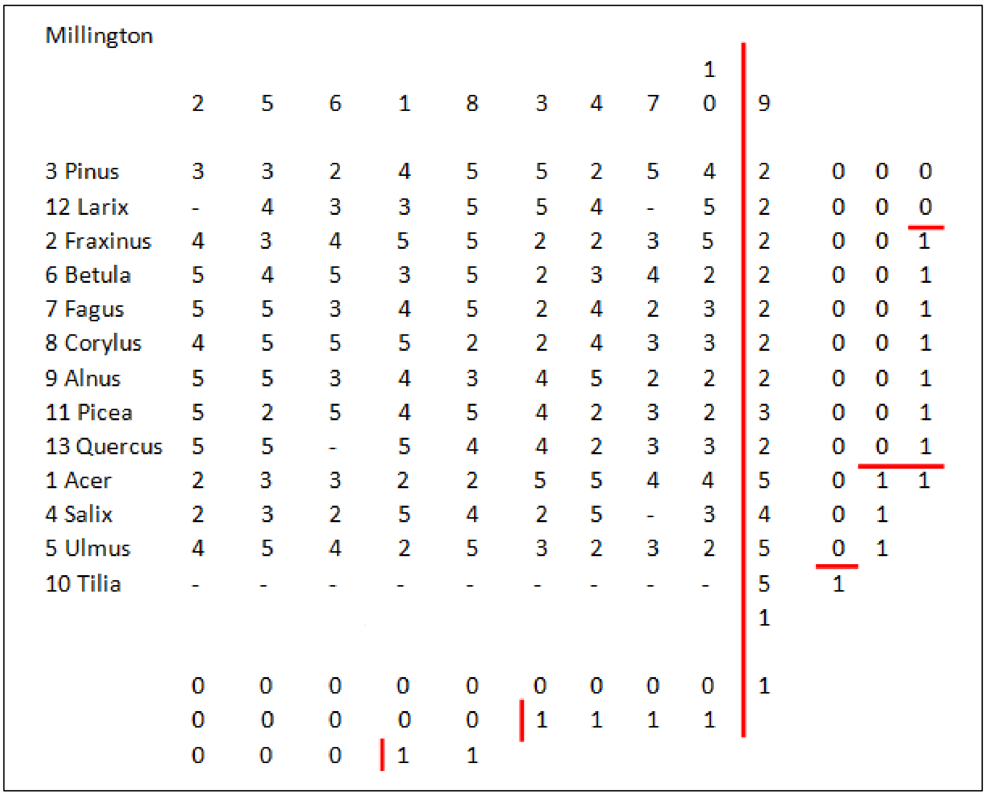
Figure 6.24: TWINSPAN output dendrogram diagram of Chee Dale tree taxa.



Millington Wood

A TWINSPAN output table for the Millington Wood quadrat samples is presented in table 6.13 below. Output dendrograms displaying the hierarchical splitting of the Millington quadrat samples and tree taxa are presented in figures 6.25 and 6.26 below.

Table 6.13: TWINSPAN output table for Millington Wood quadrat samples – coloured lines denote taxonomy of groups.



```
Millington
                                                        1 |
              2    5    6    1    8    3    4    7    0  |  9

3 Pinus       3    3    2    4    5    5    2    5    4  |  2     0  0  0
12 Larix      -    4    3    3    5    5    4    -    5  |  2     0  0  0
2 Fraxinus    4    3    4    5    5    2    2    3    5  |  2     0  0  1
6 Betula      5    4    5    3    5    2    3    4    2  |  2     0  0  1
7 Fagus       5    5    3    4    5    2    4    2    3  |  2     0  0  1
8 Corylus     4    5    5    5    2    2    4    3    3  |  2     0  0  1
9 Alnus       5    5    3    4    3    4    5    2    2  |  2     0  0  1
11 Picea      5    2    5    4    5    4    2    3    2  |  3     0  0  1
13 Quercus    5    5    -    5    4    4    2    3    3  |  2     0  0  1
1 Acer        2    3    3    2    2    5    5    4    4  |  5     0  1  1
4 Salix       2    3    2    5    4    2    5    -    3  |  4     0  1
5 Ulmus       4    5    4    2    5    3    2    3    2  |  5     0  1
10 Tilia      -    -    -    -    -    -    -    -    -  |  5     1
                                                          |  1

              0    0    0    0    0    0    0    0    0  |  1
              0    0    0    0    0  | 1    1    1    1  |
              0    0    0  | 1    1
```

It can be observed at the bottom of table 6.13 that the Millington quadrat samples have been split into three groups. Splitting at the first division is based on high/low pseudospecies scores for *Tilia cordata*, at the second division by high/low pseudospecies scores of Acer-*type*, and at the third division by high/low pseudospecies scores for Pinus-*type*. Tree taxa divisions are displayed on the right-hand side of table 1. Taxa division in TWINSPAN is based on the degree to which species are confined to particular groups or community associations, rather than abundance as described by the pseudospecies scores.

Figure 6.25: TWINSPAN output dendrogram diagram of Millington Wood quadrat samples.

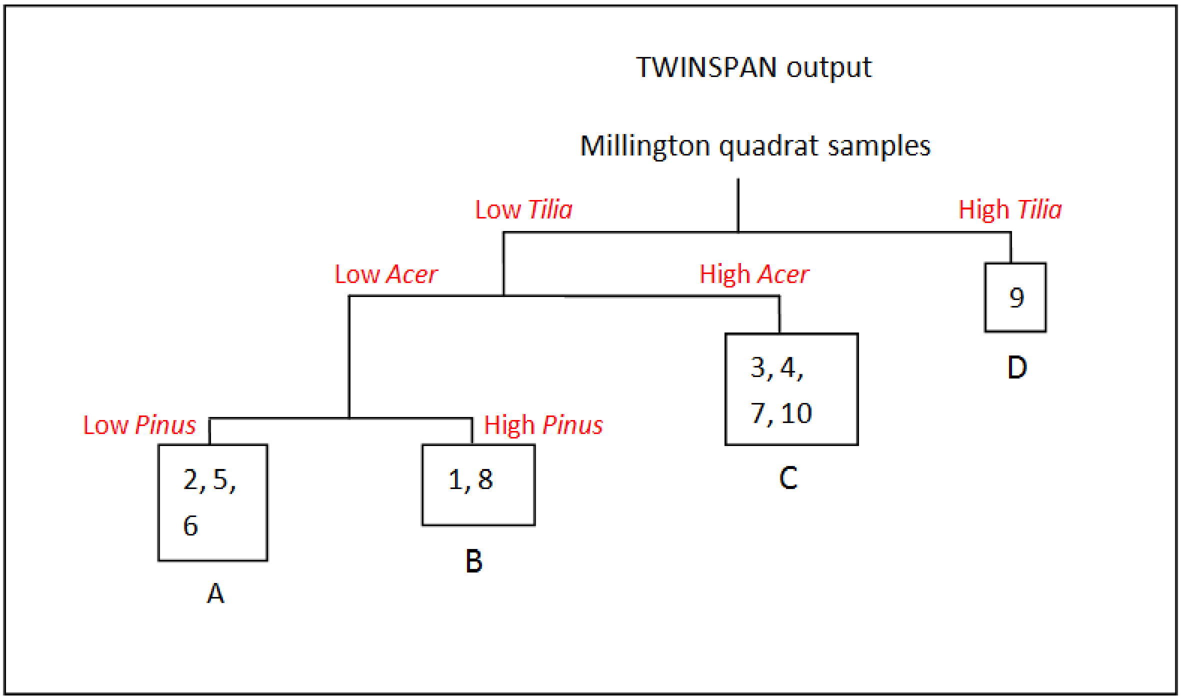
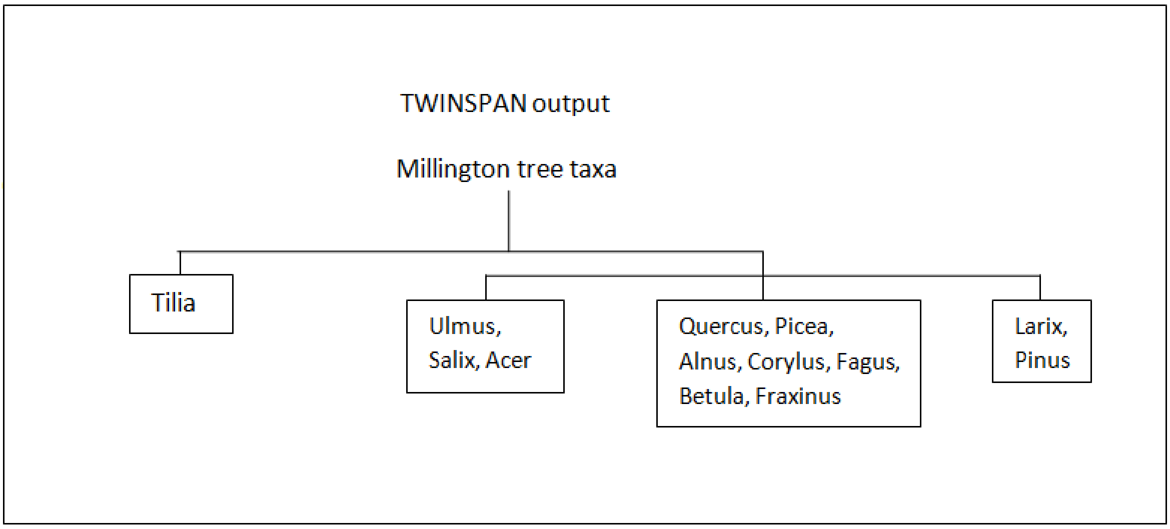


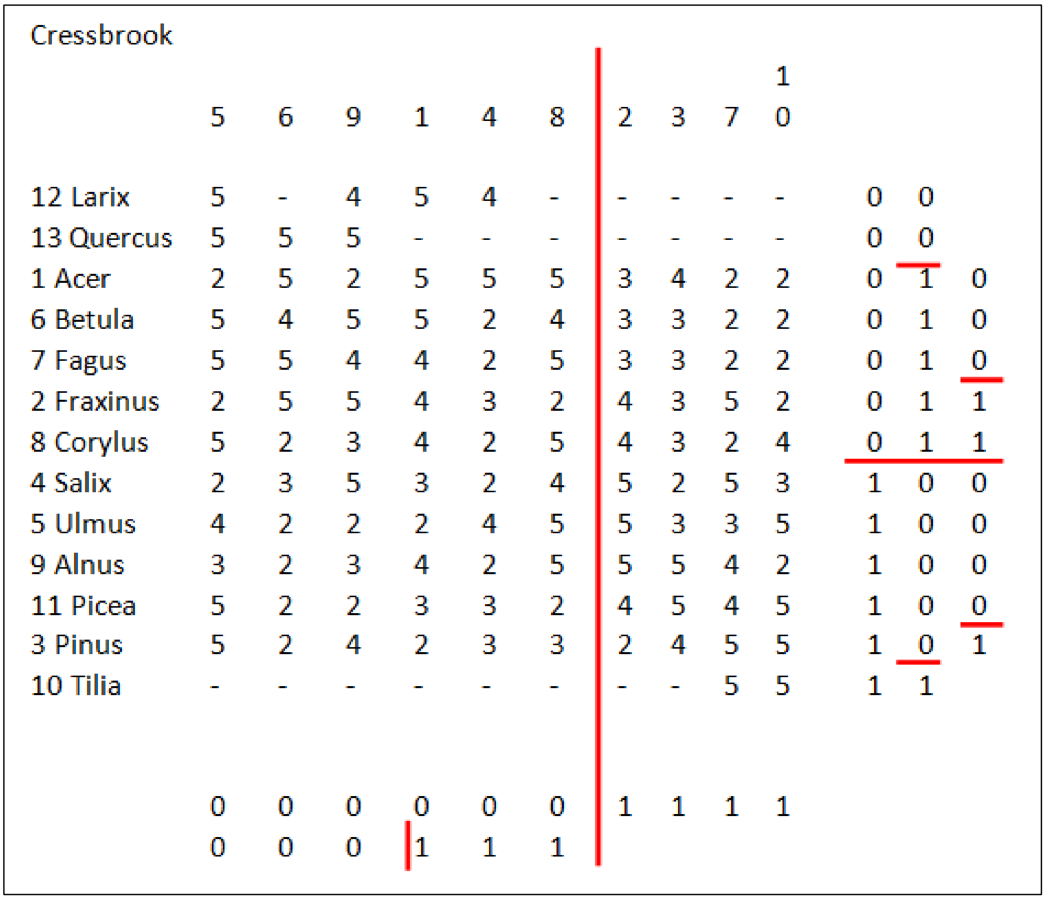
Figure 6.26: TWINSPAN hierarchical output dendrogram diagram of Millington Wood tree taxa.



Cressbrook Dale

A TWINSPAN output table for the Cressbrook Dale quadrat samples is presented in table 6.14 below; output dendrograms displaying the hierarchical splitting of the Millington quadrat samples and tree taxa are presented in figures 6.27 and 6.28 below.

Table 6.14: TWINSPAN output table for Cressbrook Dale quadrat samples – coloured lines denote taxonomy of groups.



```
Cressbrook
                                                   1
              5   6   9   1   4   8   2   3   7   0

12 Larix      5   -   4   5   4   -   -   -   -   -    0  0
13 Quercus    5   5   5   -   -   -   -   -   -   -    0  0
1 Acer        2   5   2   5   5   5   3   4   2   2    0  1  0
6 Betula      5   4   5   5   2   4   3   3   2   2    0  1  0
7 Fagus       5   5   4   4   2   5   3   3   2   2    0  1  0
2 Fraxinus    2   5   5   4   3   2   4   3   5   2    0  1  1
8 Corylus     5   2   3   4   2   5   4   3   2   4    0  1  1
4 Salix       2   3   5   3   2   4   5   2   5   3    1  0  0
5 Ulmus       4   2   2   2   4   5   5   3   3   5    1  0  0
9 Alnus       3   2   3   4   2   5   5   5   4   2    1  0  0
11 Picea      5   2   2   3   3   2   4   5   4   5    1  0  0
3 Pinus       5   2   4   2   3   3   2   4   5   5    1  0  1
10 Tilia      -   -   -   -   -   -   -   -   5   5    1  1


              0   0   0   0   0   0   1   1   1   1
              0   0   0   1   1   1
```

It can be observed at the bottom of table 6.14 that the Cressbrook quadrat samples have been split into three groups through two levels of division. Splitting at the first division is based on high/low pseudospecies scores for *Betula pendula*, *Fagus sylvatica* and Picea-*type*, and the second division is based on high/low pseudospecies scores of *Quercus robur*.

Tree taxa divisions are displayed on the right-hand side of table 6.14. Taxa division in TWINSPAN is based on the degree to which species are confined to particular groups or community associations, rather than abundance as described by the pseudospecies scores.

Figure 6.27: TWINSPAN output dendrogram diagram of Cressbrook Dale quadrat samples

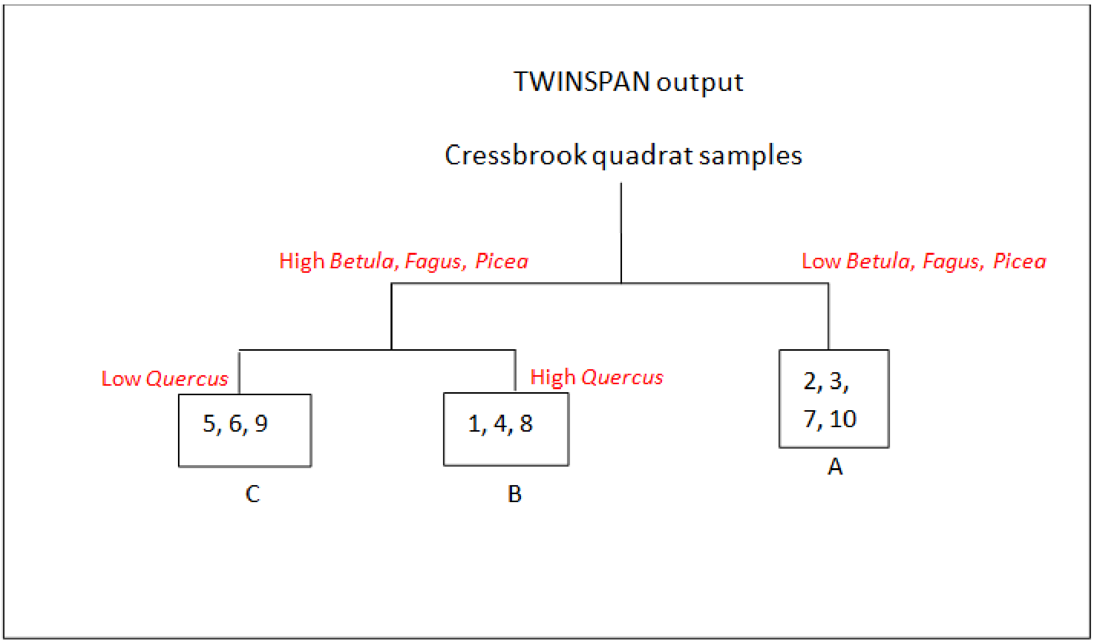
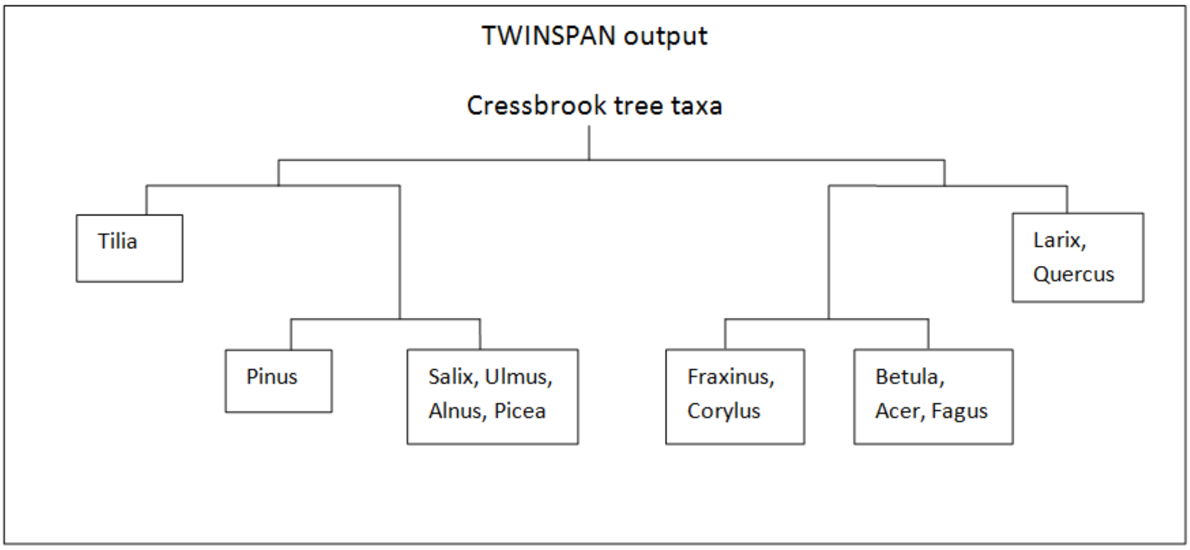


Figure 6.28: TWINSPAN output dendrogram diagram of Cressbrook Dale tree taxa.



6.3.2. Discussion

There are three key findings that emerge from the results section. Firstly, based on the confidence intervals displayed in figures 6.11 to 6.13, there does appear to be statistically significant differences in pollen percentages deposited at different sub-sample locations within the 1 metre quadrat. Secondly, taphonomic processes occurring after initial pollen deposition on the moss surface may be causing bias in pollen percentage values at certain sub-sampling locations within the 1 metre quadrat. Thirdly, pollen dispersal characteristics and pollen grain size of different taxa appear to be a factor influencing pollen representation and taphonomic processes within the 1 metre quadrat at the 3 field sites.

Pollen grain size does not always have a linear relationship to pollen transport, as it is both size and weight which affect pollen dispersal. For this reason studies of the pollen-vegetation relationship such as RPPE utilise the pollen fallspeed of a taxon, not pollen grain size as a measure of dispersal when parameterising ERV models (Broström *et al*., 2008). This can be observed in table 6.15 below, where 'large' grains such as Pinus have a very similar fall speed in to 'smaller' pollen grains such as Tillia and Quercus.

Table 6.15: Grain size and fall speed of taxa discussed in the text (grain size measured on longest axis – based on single measurements from photographs in Moore *et al*. (1991).

Taxon	Grain size (μm) Taken from in Moore *et al*. (1991).	Fall speed (cm s^{-1}) Personal communication Dr M. Bunting
Pinus	85	0.031
Betula	32	0.024
Corylus	42	0.025
Quercus	43	0.035
Tilia	44	0.032
Alnus	39	0.021
Larix	130	0.126
Fraxinus	32	0.022
Acer	31	0.056
Salix	27	0.022
Ulmus	32	0.032
Fagus	43	0.057

At the Millington Wood field site in East Yorkshire, outliers of Pinus, Betula, Acer, Quercus and Fraxinus are characterised by comparatively low pollen values. At the Chee Dale field site in the White Peak, taxa which display statistically different pollen percentages within the quadrat are Pinus, Acer, Fraxinus, Betula, Ulmus, Fagus and Alnus. Pinus, Fraxinus and Fagus all display outliers of high pollen values, whilst Acer, Betula, Ulmus, Alnus and Fraxinus display statistically significant pollen percentages representing low pollen percentage value outliers. Fraxinus is interesting in that the taxon has both high and low value outliers within the quadrat. At the Cressbrook Dale field site in the White Peak, the taxa which display statistically different pollen percentages at sub-sample locations within the quadrat are Fraxinus, Pinus, Acer, Corylus, Quercus and Picea. Fraxinus, Acer, Corylus, Quercus and Picea display statistically significant pollen percentages which are low-value outliers, Pinus and Picea display statistically significant pollen percentages which are high-value outliers; Picea is interesting in that it displays both high and low value outliers. Millington is clearly characterised by low-value outliers, and both the White Peak sites are characterised by a dominance of low-value outliers within the observed data.

Overall the trend appears to be for the statistically significant outliers to be low-value across all three field locations, which suggests that some taxa may be underrepresented in pollen assemblages when only one sub-sampling point is used. The observed variation in pollen percentages at the three sampling sites suggests that either taphonomic processes are causing secondary pollen transport at the quadrats resulting in non-uniform pollen percentages across the moss surface, or that the variation is due to preferential pollen deposition related to proximity of vegetation and environmental factors such as prevailing wind direction. A third hypothesis is that both taphonomic and environmental factors in combination are significant in influencing pollen deposition, resulting in a significant variation in pollen percentage values across the moss surface of the field site. Micro-topography does not appear to be a significant control influencing spatial variation in pollen deposition across the Millington quadrat illustrated in figure 6.16a and figure 6.19; this is demonstrated by the occurrence of both the maximum and minimum percentage values of taxa on very similar micro-topographic features such as raised areas of moss within the sampling quadrat. However at the Cressbrook Dale and Chee Dale quadrat sites in Derbyshire there appears to be a trend of higher pollen percentages being associated with raised areas of moss in middle-upper slope sub-sample locations, and lower pollen percentage values of taxa being associated with sub-sample locations on middle and lower slopes. This observation may be related to the relative height difference of moss surfaces above the woodland floor between the Millington Wood field site, illustrated in figures 6.16a and 6.19, and the White Peak field sites, illustrated in figures 61.4a, 6.15a, 6.17 and 6.18, and the steepness of slope the moss sub-sample was taken from.

The Millington quadrat has a relatively level surface and averages a height of 10 cm above the woodland floor, and does not have the steep slopes characteristic of the Derbyshire quadrats where post-depositional pollen transport may be more likely to occur. The Cressbrook Dale and Chee Dale quadrats have heights of 40 cm and 35 cm respectively above the woodland floor, with both field sites having a pronounced central ‘high-point’ with relatively steep slope angles leading from the high-point to the woodland floor. These steep high-angle slopes are a factor which may influence primary pollen transport downslope on the surface of the moss either as a ‘dry’ and gradual gravity downslope process, or as a ‘wet’ downslope process where pollen is entrained into rainwater flowing over the moss surface. The steeper high and medium angle slopes at the Chee Dale and Cressbrook Dale quadrats would result in downslope rainwater velocities being higher at these sites than would occur on the lower-angle slopes observed at the Millington quadrat. Downslope water flows would also penetrate the matrix of the mosses during prolonged periods of precipitation, resulting in pollen captured from the woodland canopy during rainfall and pollen already deposited on the surface of the moss being transported within the fabric of the moss (Clymo & Mackay, 1987; Irwin, 1989; Joosten & De Klerk, 2007). Portions of the moss matrix where interstices are smaller may cause a reduction in within-matrix flow velocities resulting in the re-sedimentation of pollen at these locations. This hypothesis was not investigated during this study, but future study of within-matrix pollen transport dynamics would provide useful insight into this aspect of pollen taphonomy.

The influence of prevailing wind direction may also be a factor in preferential pollen deposition at the three quadrat field sites. At the Chee Dale site there appears to be a trend of high pollen percentages to be associated with southerly slopes within the quadrat, and for low pollen percentages to be associated with northerly sub-sampling locations. The trend at Millington appears to be for high pollen percentages to be associated with sub-sampling locations with a south/south-westerly aspect; low pollen percentages display a trend to a north/ north easterly aspect. Cressbrook displays a trend of high pollen percentages in the south/ south westerly sub-sample locations; low pollen percentages displaying a trend toward the north. The overall trend of the three field sites appears to be higher pollen deposition on the south easterly/south/south westerly portions of the quadrat. The relationship between pollen deposition at the quadrats and the position of vegetation recorded within the 100 metre survey area is an important consideration. At all three field sites Acer is the dominant taxon in the local vegetation, with Fraxinus and Pinus representing the secondary dominants in the vegetation surveys. The dominance of taxa in the local vegetation is reflected in the pollen assemblages at the field sites. Pollen percentages of Acer recorded in the White Peak surface samples displayed a relatively wide range of values from 50 – 70% at Chee Dale, and from 30 – 50% at Cressbrook. As illustrated in table 6.15, Acer has a relatively small pollen grain size (31µm) but has a relatively fast pollen fallspeed (0.056 cm s^{-1}). Other taxa which display a wide range of pollen percentage values at the Chee Dale and Cressbrook Dale quadrat sites include Fraxinus with values ranging from 10 – 30% at Chee Dale and 25 – 40% at Cressbrook, and Pinus which displays a range of values from 5 – 20% at Chee Dale, and 10 – 25% at Cressbrook.

As illustrated in table 6.15, pollen grain size of Fraxinus is similar to Acer (0.31µm) but with a significantly smaller fallspeed velocity (0.22 cm s^{-1}), Pinus has a very large pollen grain size (83 µm) but a relatively slow fallspeed velocity (31 cm s^{-1}) At the Millington field site *Acer* pollen percentages range from 60 – 70% across the 10 surface sub-samples; Fraxinus and Pinus are also secondary dominants in the vegetation, but display both lower pollen percentages overall and much smaller ranges in percentage values than those observed at the White Peak sites with percentage values of Fraxinus ranging from 1 – 5%, and percentage values of Pinus ranging from 2 – 9% across the 10 surface sub-samples. The difference in range of Acer, Fraxinus and Pinus at the Millington field site may be related to the comparatively low height above the woodland floor of the moss and the relatively small differences in relief within the sampling area. These factors suggest a more uniform pattern of deposition by the local pollen rain may be occurring. When the relationship between pollen fallspeed, dominance in the surveyed vegetation and the relatively small range in pollen percentages observed at the sub-sample locations is considered, the dominance of this taxon in the pollen percentages recorded at all three quadrat field sites may result from Acer pollen being transported a shorter distance from the pollen source. Both Fraxinus and Pinus are co-dominants at the vegetation at all three quadrat field sites, however the significantly slower fallspeed velocities of Fraxinus and Pinus in comparison with Acer suggests that pollen of these taxa may be dispersed over greater distances. The larger surface area and saccate nature of Pinus pollen, which has two 'bladders' attached to the grain, would enhance the dispersal potential of this taxon.

The local woodland community at Chee Dale is dominated by Acer to the north, west, south and south-east of the quadrat. Pinus is the dominant woodland community member to the east of the surface sampling location, and Fraxinus is a co-dominant with Acer to the south-west, south and south-east. Based on the observed trend of high Acer pollen percentage values in assemblages on the southern side of the Chee Dale quadrat, and the dominance of Acer in the local vegetation to the north, north west, west, south-east, south, and south west it would appear that a prevailing wind direction from the south may be a primary control on high Acer pollen deposition rather than position of the taxa in the local vegetation. This appears to be the same for Fraxinus, which is a co-dominant in the local vegetation to the south of the Chee Dale quadrat, and which has the highest pollen percentage values in assemblages located on the southern side of the quadrat. In the case of Pinus, which is the dominant to the east of the site, the high Pinus pollen values observed in the southerly portion of the quadrat may represent a background pollen input, and not a fully local pollen signal.

At the Cressbrook field site, the Acer dominated vegetation community is situated to the north, west and south of the quadrat, the Fraxinus dominated woodland community is situated to the north east, east and south east of the quadrat, and Pinus is absent from the 100 m radius of the vegetation survey. The relative position of Acer in the local vegetation would suggest that pollen deposition at the quadrat should be relatively uniform in pollen assemblages situated in the north, west and south of the quadrat as this is the position of the pollen producing local Acer dominated vegetation. However as was observed at Chee Dale the highest Acer pollen percentages are recorded in the southern portion of the quadrat, suggesting that a southerly prevailing wind direction is a significant influence affecting pollen dispersal and deposition at this site also. Fraxinus pollen percentage values are highest in the southern portion of the quadrat and lowest in the western portion of the quadrat, with the Fraxinus dominated woodland located to the north east, east, and south east side of the sampling location. This suggests that Fraxinus pollen dispersal is also affected by a prevailing southerly wind, and that only a small proportion of the local pollen rain is transported to the western side of the quadrat. Pinus is not present in the vegetation, so all pollen input to the Cressbrook site must represent the regional background pollen signal. However regional Pinus pollen transport to the Cressbrook field site may follow a different dynamic, as the highest pollen percentages were recorded in sub-samples taken from the western portion of the quadrat.

6.3.3. Conclusion

This study has found significant variation in observed pollen percentages of tree taxa within the 1 metre sampling area at all 3 field sites. This variation is attributed to variability in the local pollen rain influenced by the pollen grain size and fallspeed and the position of the pollen producing vegetation in the survey area, the microtopography of the moss surface influencing secondary pollen transport through precipitation-driven vertical and/or lateral water flows on both the surface of the moss and within the moss matrix and the prevailing wind direction at the Derbyshire and East Yorkshire field sites.

Due to the thickly wooded nature of the sampling sites, the dominant pollen transport mechanisms within the 100 radius of the vegetation survey area at the field sites are suggested as the canopy component and the local gravity component; the skip distance of taxa in relation to the height of the pollen producing canopy and the fallspeeds of the taxa illustrated in table 6.15 may also be a significant factors affecting the observed variation in pollen percentages at the field sites. Due to the high degree of dominance of taxa such as Acer and Fraxinus in the surrounding vegetation and in the pollen assemblages at all the three field sites, the question of interdependence *sensu* Fagerlind (1952) is also a primary consideration in understanding how local vegetation is represented by pollen percentages at the field sites. The implications of the observed variation in pollen percentages at the Derbyshire and East Yorkshire study sites can be argued to be significant where moss surface samples are used for obtaining RPPE datasets. If pollen-vegetation calibrations which are based on single moss samples or portions of single moss samples have either significantly very low or very high pollen percentages this would potentially skew RPPE outputs, which would in turn potentially result in an over or underestimation of RPPE which when applied to a retrospective landscape reconstruction would have the reciprocal effect of over or under representing a taxon in the palaeo landscape. The use of a skewed RPPE dataset would also be non-trivial where the effects of climatic change i.e. tree line studies or human land use e.g. coppicing were the research aims of the investigation.

The key finding of this study is that in order to derive unbiased RPPE datasets, research designs should consider using multiple moss surface samples which are then amalgamated. These findings support the conclusions of Räsänen *et al*. (2004) and Broström *et al*. (2004), although Räsänen *et al*. (2004) suggest that although pollen proportions of taxa can be higher in bulk samples (this was statistically significant in the case of Poaceae in the Räsänen *et al*. (2004) study) where 10 sub-samples of random sizes are amalgamated, palynological richness is similar when both single and amalgamated moss surface samples are analysed. Pollen transport by water within a sphagnum moss and peat matrix has been tested using different flow regimes by Clymo & Mackay (1987), who found that lateral and vertical movement of pollen is influenced by flow through the unsaturated portions of moss and that the degree of movement is uniform for pollen grains of differing size. This observation is supported by Irwin (1989) who suggests that topography influences the downward transport of pollen from topographic high points on living mosses and by suggestion of Joosten & De Klerk (2007) who propose that pollen may become mixed in the matrix of living *Sphagnum* species as a result of small-scale vertical water movement and the horizontal mode of shoot layering associated with moss taxa.

There is currently no ‘recommended’ sample size in the context of collection of the living part of mosses to derive pollen counts, as different research aims and research designs dictate the amount of moss needed to provide the amount of pollen needed for each individual project. A methodology adopted by Räsänen *et al.* (2004) in investigating the comparative pollen trapping differences between pollen traps such as Tauber Trap (Hicks *et* al., 1996; 1999) and moss polsters, utilised a plastic tube with an opening of 4.3 cm to collect moss surface samples with an area of 14.52 cm^2. The rationale for this methodology was that the Tauber Traps used in the research had an opening of 4.3 cm; however this methodology was only utilised for single moss samples, not bulk samples which were subsequently amalgamated. The effectiveness of moss polsters as a pollen trapping medium is well established and, to generalise, pollen sums of between 500 – 1000 grains per sample are normally sufficient to satisfy the criteria and degree of palynological resolution required by most research aims. In order to achieve such a pollen sum, an area of between 2 – 12 cm^2 of living moss is sufficient in the majority of research investigations. Pardoe (1996) used a Student T-test to examine the number of samples needed to ensure that local variability in pollen deposition would be mitigated and concluded that a minimum of 20 subsamples were needed to reduce the impact of local variability to within a 95% confidence interval.

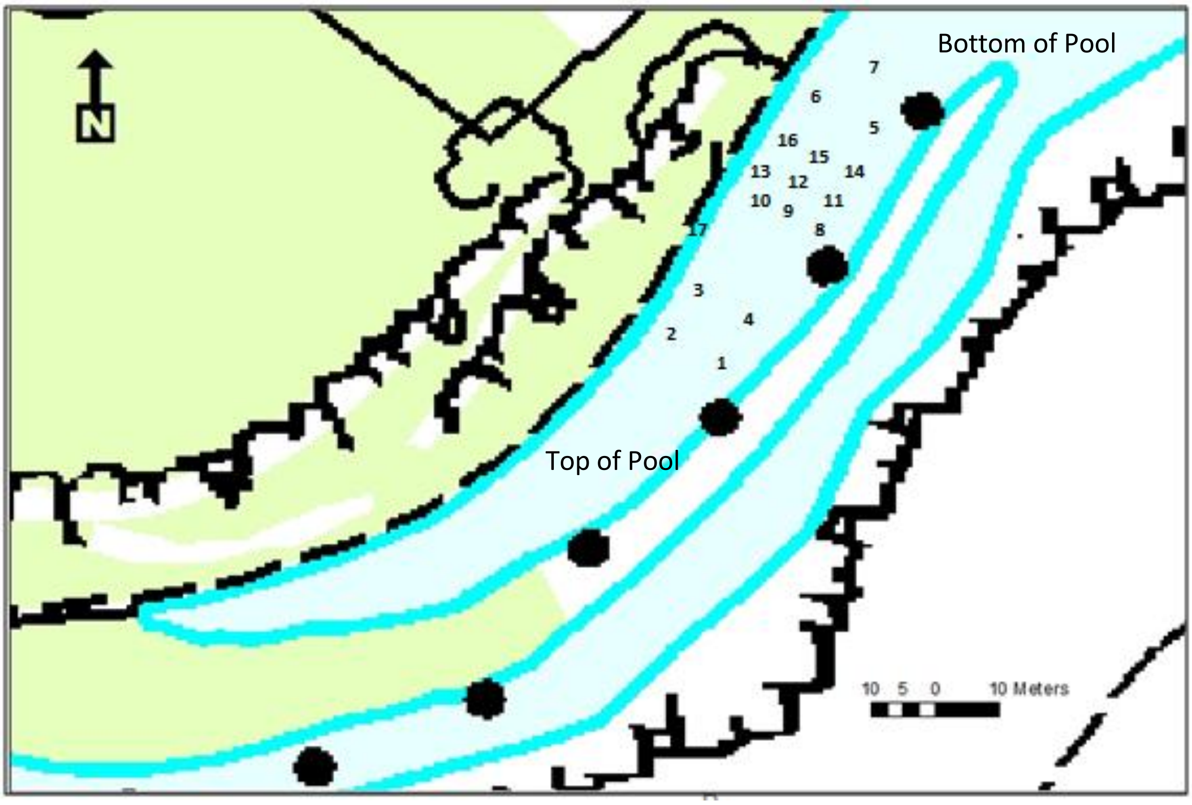
The implications of these findings for palaeoecological research agree with the conclusions of Pardoe (1996) that inferences of the local vegetation composition of past landscapes which are based on a single peat bog or mire coring location (which in effect acts as a single pollen deposition point, and in the case of peat bogs and mires can be considered analogous to a single moss polster where post depositional pollen transport is acknowledged as extremely limited (Prentice, 1985) in comparison with the acknowledged degree of post depositional pollen transport (Sugita, 1993) which occurs in lake or river sediments) must consider the degree of variation in pollen deposition occurring within a small defined that has been identified in this study. Variations in pollen percentages of up to 25% have been observed for local tree taxa based on the 10 sub-samples taken within the 1 metre quadrat, meaning that vegetation can be significantly under or over represented in the context of modern pollen-vegetation studies and in reconstructions of past vegetation.

6.4 Fluvial Pollen Taphonomy Study

Introduction

This study aims to examine spatial patterns of pollen deposition in an upland river pool in the River Wye in Derbyshire in order to understand the relationship between local and extra-local vegetation, pollen dispersal and transport, and pollen taphonomy in river bed sediment. Previous investigation of fluvial pollen transport and taphonomy has often focused on lakes with in-flowing streams, or laboratory based experiments utilising flume tanks. The study area is the Wye Valley in the Derbyshire Dales which lies in the White Peak district of the southern Pennines, and falls within the boundaries of the Peak District National Park in Derbyshire, England. The regional position of the field sites is displayed in figure 3.2 and 3.3; the UK location of the Derbyshire Peak District is displayed in figure 3.1. Methodology is described in chapter 5 and a picture of the field site location is displayed in figure 5.4 in chapter 5. The locations of the sampling points discussed in the text are displayed in figures 6.29 below.

Figure 6.29: Numbered sampling points at Litton Mill field site; note point bar to the south of the study site.



Map sourced from Digimap - 1: 10 000 OS Raster MasterMap.

6.4.1. Results

Psimpoll was used to create percentage pollen diagrams using the pollen counts from the 17 sample locations illustrated in figure 6.29. Two percentage diagrams were produced which display percentages of arboreal pollen (AP) and non-arboreal pollen (NAP) using the pollen count data from all 17 samples; the pollen sum used was 500 pollen grains per sample and diagrams display total land pollen and spores. Figure 6.30 displays both AP and NAP percentages and figure 6.31 displays AP percentages with 95% confidence intervals bars fitted to the diagram (Maher, 1972).

Arboreal pollen is dominant all 17 samples as can be observed in figures 6.30 and 6.31; the dominant tree taxa at all sample points are Acer, Fraxinus, Pinus, and Alnus, dominant NAP taxa are Rosaceae *type* and Filipendula *type*. Poaceae pollen percentages are variable dependant on size class. Size classes were used in order to make a generalized separation of the family into wild grass types, < 26µm Phragmites-*type*, 26-40 µm Deschampsia-*type*, and cereal-type Avena-Triticum *type* or large wild grass-type Hordeum-*type* represented by size class > 40 µm (Tweddle *et al.*, 2005). Poaceae class >26µm is the dominant grass taxon in terms of the highest percentage values, however these are only observed at samples 5 and 17, Poaceae class >40µm displays the most constancy in percentage values across all the 17 samples.

The principal taxa of interest in this study are the trees. Figure 6.31 below displays pollen percentages of tree taxa from the Litton Mill samples. It can be observed that there is spatial variation in values of all taxa across the 17 samples. Values of Acer are notably low at sample points at 5 and 13, and the highest values of Acer occur at sample points 1, 2, 7, and 12. Confidence intervals for Acer suggest that percentage values do not vary significantly at the 17 sample points. Spatial variations in Fraxinus values are also evident; samples 2, 15, and 17 are significantly lower than other sample points. Confidence intervals for Fraxinus suggest that there is significant variation in sample values; samples 2, 3, 15, 16, and 17 are not overlapping. Salix percentage values, where pollen is present in the sample, are consistently low at all sample points; of these low percentages, sample 8 and the terrestrial sample (17) display the greatest percentage values. Confidence intervals for Salix suggest that percentage values do not display significant variation across the 17 samples.

Figure 6.30: Pollen diagram will be inserted here as an A3 sheet.

Figure 6.31: Pollen diagram will be inserted here as an A3 sheet.

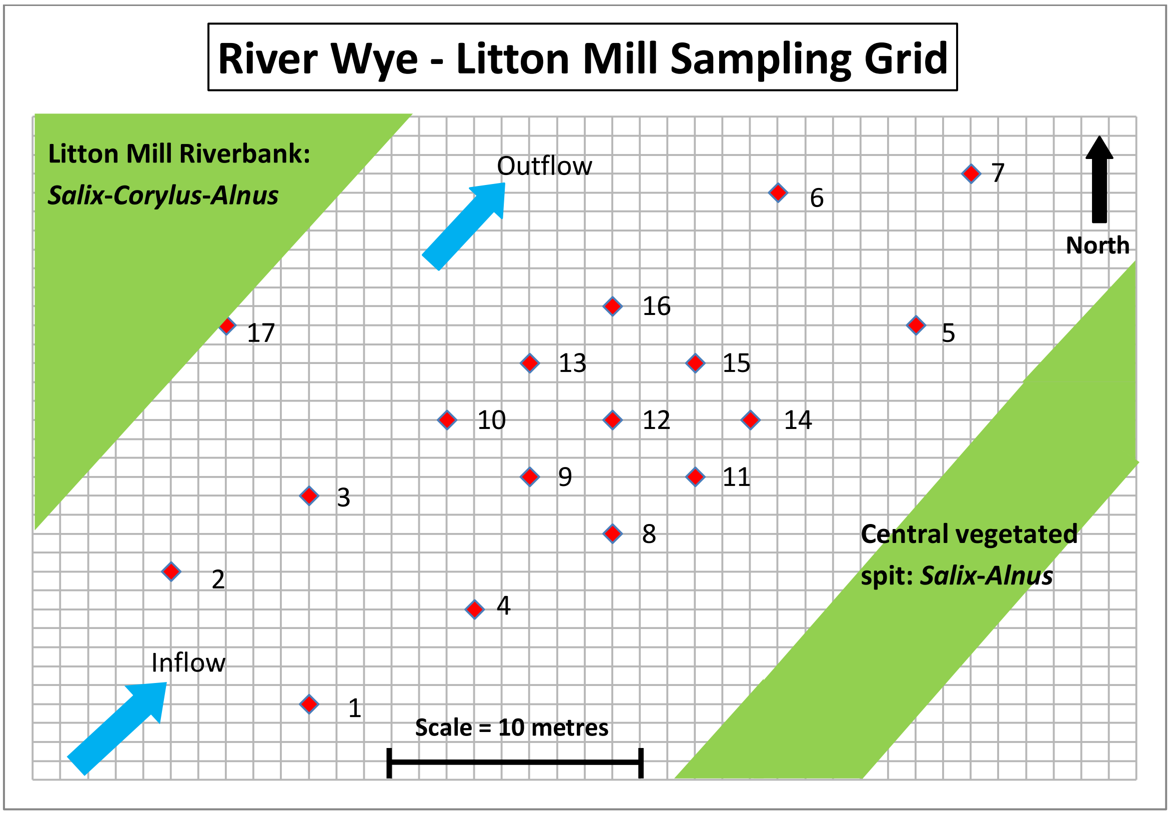
Corylus values remain relatively constant across the 17 samples, with samples 3 and 13 displaying the lowest values; confidence intervals for Corylus suggest that only sample 3 is significantly different from the other samples. Betula values are also spatially variable, with relatively low values at sampling points 6 – 12, and the highest values in samples 1 – 5; confidence intervals for Betula suggest that there is no significant variation between the 17 samples. Percentage pollen values of Picea are low at all sample points, with the greatest values observed at sample points 3, 6, and 7; confidence intervals for Picea suggest that no significant variation occurs across the 17 samples. Fagus pollen counts are relatively low as a proportion of the AP sum, the greatest percentage values are observed at sample points 2, 3, 4, 5, 11, and 17, with the lowest percentage values occurring between samples 6 – 10. Confidence intervals for *Fagus* samples suggest that only samples 8 and 12 display significant variation. Ulmus pollen counts are relatively constant at all sample locations, with low values observed at sample points 5, 8, and 17; confidence intervals for Ulmus suggest that only samples 8 and 17 display significant variation.

Values for Tilia are very low at all sampling points, with locations 7 and 9 displaying the highest values; no significant variation in percentage values is observed in Tilia across the 17 samples. Quercus values are relatively low at all sample locations, with sampling locations 1, 2, 9 and 17 displaying the highest values; no significant variation in percentage values is observed in Quercus across the 17 samples. Pinus values are spatially variable, with the high values observed in sample locations 8 – 16, low values are observed in samples 1, 4, and 7. Pinus samples 4, 11, and 17 display significant variations in percentage values. Pollen counts of Alnus display some variation, with samples 1, 3, 4, and 15 having the highest percentages and samples 7, 14, and 17 having the lowest percentage values. Confidence intervals for Alnus suggest that samples 7, 14, and 17 vary significantly in percentage values. No mechanically damaged or corroded grains were observed in the sample pollen counts, suggesting input of fluvially transported pollen from the wider catchment land surface and from river bed and riparian channel bank sediment storage is insignificant at this study site.

Pool Grid and Excel Bubble Plots

An X, Y grid was used to delineate the samples position in the pool field site at Litton Mill; this is presented in figure 6.32 below. Microsoft Excel was used to create bubble plots displaying spatial variation in pollen percentage values for selected tree taxa; bubble plots are presented in figure 6.33 below.

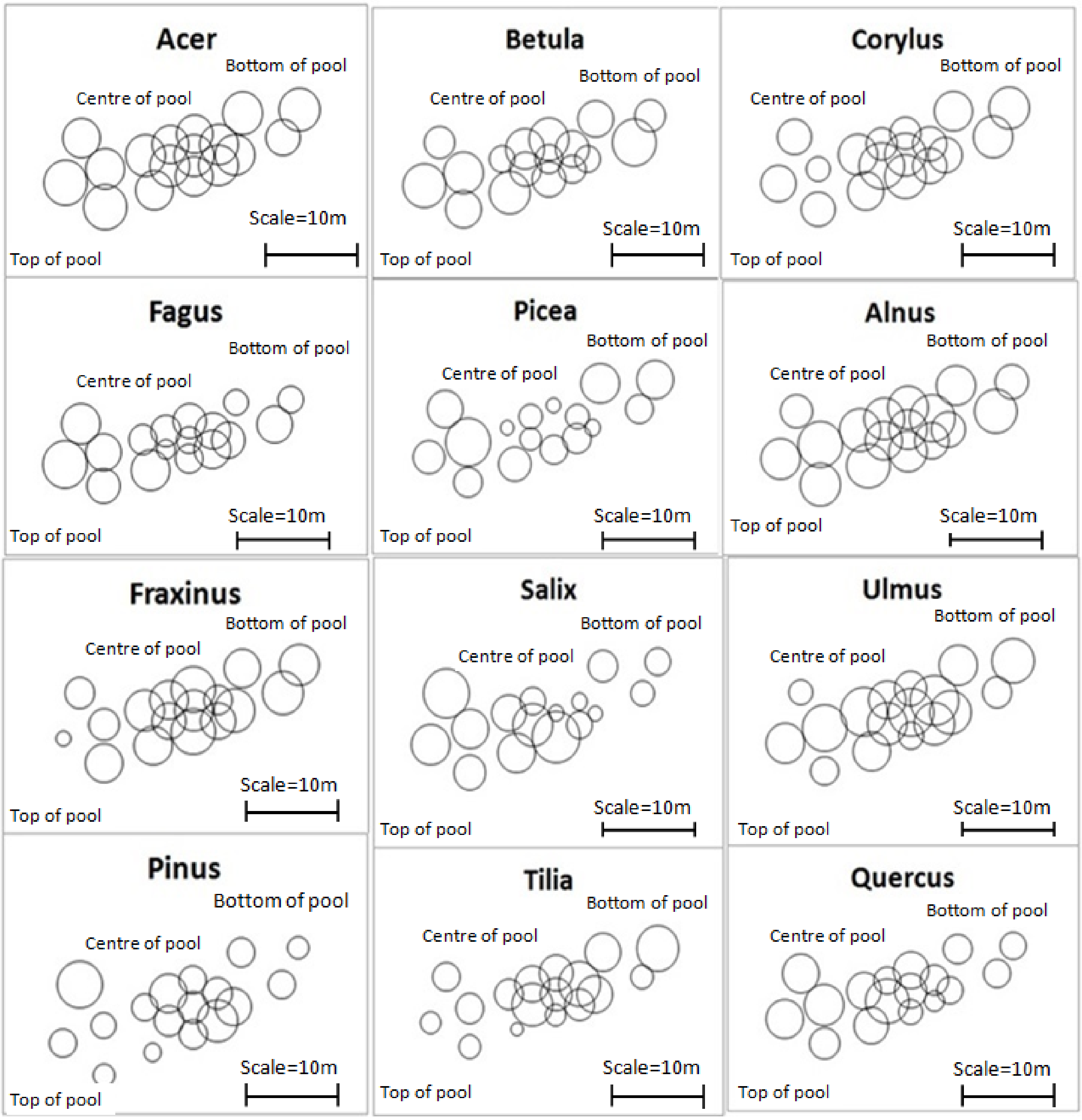
Figure 6.32**:** Scatter plot displaying the relative spatial positions of Litton Mill pool samples – see figure 6.29 for overview map of study site sample locations. Inflow indicates the top of the Litton Mill pool; outflow indicates the bottom of the field site.



Spatial patterns of pollen percentage values

When spatial variation of taxa percentages within the study site is examined in figures 6.33, it can be observed that patterns of pollen deposition differ on a taxon by taxon basis. *Acer* displays relatively uniform percentage values at all 17 sample points, with samples 5, 16, and 17 displaying the lowest percentage values. Samples 5 and 16 both trend towards the landward margins of the pool, sample 5 toward the south bank and sample 16 toward the north bank, both of these samples are situated at the downstream end of the pool; sample 17 is the moss polster, which is situated on the north bank. Water depth at the study site does not appear to be a significant control on *Acer* pollen deposition. *Fraxinus* percentage values are relatively similar at all 17 samples across the study site, with the highest overall percentage values clustered in the centre of the pool at samples 8 – 16.

Figure 6.33: Excel bubble plots displaying spatial variation in pollen percentage values of tree taxa at the Litton Mill field site; bubble diameters indicate high/low pollen percentages of individual taxa at the sample sites i.e. large bubble = high pollen percentage, small bubble = low pollen percentage see figure 6.29 for overview map of study site sample locations.



The three lowest Fraxinus pollen percentage values are observed at sample points 2, 15, and 17; sample 2 is located at the top of the pool close to the north bank, sample 15 is in the downstream portion of the central cluster, and sample 17 is the land-based moss polster which is situated on the north bank. No clear spatial trend in pollen deposition is observed for Fraxinus other than a single low-value sample, number 2, situated at the northern edge of the upper portion of the pool in shallow water. Fagus values display a spatial trend of higher values toward the top of the pool at samples 2, 4, and 17; in the centre of the pool at samples 11, 14, and 15, and at sample 5 at the end of the pool. No overall trend is apparent with Fagus other than two of the lowest percentage values, at sample points 6 and 7, being observed at the lower end of the pool. Overall, some of the higher Fagus percentage values appear to be associated with the shallower sections of the pool at the top of the study site, including sample 17 taken from the northern riverbank.

Percentages values of Pinus vary significantly across the 17 samples, and display a distinct trend of higher deposition occurring in the middle section of the pool. High percentage values of Pinus are found in samples 8 – 16 in the deeper part of the sampling area in the central section of the pool, and in sample 17 on the riverbank. Lower values of Pinus are observed at samples 1 - 4 in the shallower top portion of the pool, and at the relatively shallow sample points 5 – 7 at the bottom of the pool; all these sample points display a trend toward the outer, southern riverbank of the sampling area. Percentage values for Salix display a trend of higher percentage values in the shallow upper portion of the sampling site, with lower values trending toward the end of the pool. Samples 2, 3, 4, 8, 9, 10, and 17 display high values, with the highest overall percentage values found at sample 8 situated in the pool centre trending towards the southern riverbank, and 17 situated on the northern riverbank.

Lowest Salix values are recorded at sample points 5, 11, 12, 13, and 15. These samples are situated in deeper water depths at the down-pool portion of the pool centre, and at the end of the pool; these low value Salix samples also display a trend toward the southern riverbank in the central and lower portions of the pool. Percentage values of Ulmus are relatively uniform at the study site; however slightly lower values are observed at sample points 1, 5, 8, 16, and 17, with the lowest values at sample points 5, 8, and 17. Sample 8 is in the central part of the study site and trends toward the southern riverbank, sample 5 situated at the end of the pool also trends toward the southern riverbank, and sample 17 is the moss-polster sample situated on the northern riverbank. The overall trend for Ulmus is suggested to be one of higher deposition in the upper/central northern portions of the study site, with no obvious trend towards enhanced deposition in either shallow or deep water.

Percentage values of Tilia display a trend of high percentages being located in the central and lower sections of the study site, with the lowest percentages recorded at the upper section of the pool. Samples 1, 2, 3, 4, 5, and 8 display the lowest percentage values, with a trend of lower percentage values toward the southern riverbank; samples 1 – 4 in the upper pool are located in the shallowest section of the study site. The deeper, central portion of the sampling site has two of the highest overall values at samples 9 and 15; the central part of the lower pool also has a high value at sample 7. The overall trend is suggested as higher pollen deposition in the deeper mid – channel sections of the site in the middle and lower portions of the study site.

Quercus pollen percentage values display spatial variation at the study site, with an overall trend of higher percentage value samples points being located in the upper-middle and upper sections of the study site. Samples 1, 5, 7, 8, and 11 display the lowest percentage values, with an overall spatial trend toward the southern riverbank of the study site for these sample points. The highest Quercus percentage values are observed at samples 2, 3, and 9, these sampling points displaying an overall spatial trend toward the northern riverbank of the study site. Samples 2 and 3 are situated in the shallower upper section of the pool, whilst sample 9 is in the much deeper middle portion. Water depth does not appear to be a significant control on Quercus pollen percentages at the study site; water depth *and* flow velocity influencing the time period between which an unsaturated pollen grain lands on the surface of the water and the distance travelled before the pollen grain becomes saturated and sinks through the water column to the river bed sediment. Samples 9, 10, and 15 all display relatively high values and are situated in the widest and deepest section of the site which is in the centre of the pool. This suggests that pollen deposition at the Litton Mill site is more analogous to that of a closed basin, i.e. a fluvial pond, where the position of the riparian vegetation and the size of the basin in regard to airborne pollen input are more significant controls on pollen deposition and subsequent representation in sediment than the hydraulic controls associated with dynamic fluvial systems. The influence of surface wind-drift may also be a factor influencing the spatial pattern of pollen percentages at the study site.

Betula percentage values are relatively uniform across the study site, with an overall spatial trend of higher percentage values being located in the shallower upper and lower sections of the pool. Samples 10, 11, 12, and 13 display the lowest observed Betula percentage values and are all situated in the deeper, central section of the pool; these samples also display a trend toward the southern riverbank. The overall spatial trend of sample points with high Betula percentage values, with the single exception of sample 5, is toward the northern riverbank and to be situated in the shallower sections of the pool. Percentage values of Corylus are relatively uniform at the study site, with an overall trend of higher percentage values being observed in samples in the deeper, central portion of the pool. The lowest value samples display a spatial trend toward the riverbanks, with samples 3, 13, and 14 trending toward the northern riverbank, and samples 1, 11, and 14 trending toward the southern riverbank. There are two high percentage value clusters of Corylus at the study site, samples 8, 9, 10, and 12 in the centre of the pool, and samples 5, 6, and 7 at the end of the pool. Both of these clusters are in relatively deep water, suggesting that water depth may be a control on the deposition of Corylus pollen at this study site; see discussion above for Quercus. Corylus pollen may be entering the site via an airborne vector, meaning the point of deposition on the site surface and the time taken for the pollen to then become saturated and sink to the river bed sediment are more likely to be influenced (in the pond-like study site section of the river) by water depth and wind-derived surface drift than by river flows.

Percentage values of Picea are highest at the shallow upper and lower section of the sampling site. A high percentage cluster of Picea samples is observed at the upper part of the pool in samples 2, 3, 4, and 17, and a second high percentage cluster of samples is observed in the lower section of the pool at samples 6 and 7. The overall trend of Picea values at the study site is of low percentage values in samples in the deeper, central section of the pool. High pollen percentage values occur in sample point clusters in the shallow uppermost and relatively shallow lower sections of the pool;

this suggests that water depth may be a control on Picea deposition at this study site. Percentage values of Alnus are relatively uniform across the study site. The lowest value samples are sample point 7 at the lower section of the pool, sample points 11, 14 in the centre of the pool, and 17 on the northern riverbank. Samples 7, 11, and 14 all display a spatial trend toward the southern riverbank, and sample 17 is situated on the northern riverbank. Water depth does not appear to be a significant control on Alnus values at this study site, as high percentage values are recorded at both the deepest and shallowest section of the pool. Pinus, Salix, Quercus, Picea, and Tilia display the greatest overall spatial variation in pollen deposition at the Litton Mill field site. Salix and Quercus are characterised by lower pollen percentages at sample points in the lower- middle and lower sections of the study site, Tilia percentages are significantly higher in the middle and lower sections of the pool, Pinus percentages are significantly higher in the middle section of the pool, and Picea percentages are significantly higher in the upper and lower sections of the pool. Acer, Fraxinus, Alnus, Corylus, Ulmus, Betula, and Fagus display relatively uniform spatial pollen deposition at the 17 sampling points overall, with some north-south variation in pollen percentages observed.

Ordination

Principal Components Analysis (PCA)

Ordination analysis was applied to pollen counts and sample locations in order to examine the underlying structure of the data. The ordination method chosen is Principal Components Analysis or (PCA). PCA is considered one of the most effective methods of analysis when the production of an ordination of quadrats based on environmental/biotic data alone is necessary (Kent, 2012). Eigenvalues and cumulative percentage variance is presented in below. PCA biplots of axis 1 vs. axis 2 and axis 1 vs. axis 3 are presented in figures 6.34 and 6.35 below; Eigenvalues of pollen square root transformation are presented in table 6.16 below.

Figure 6.34: PCA output - Axis 1 versus Axis 2 plot for Litton Mill samples; main associations discussed in the text are circled in red.

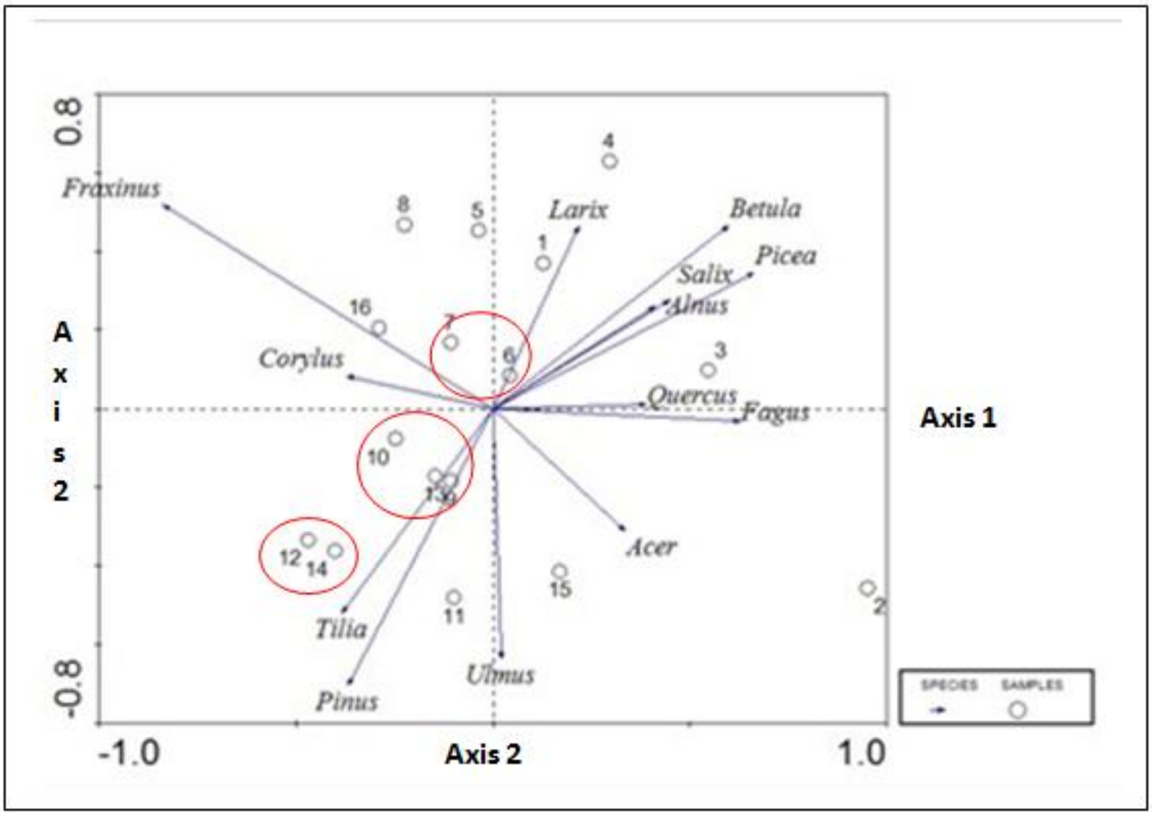


Figure 6.35: PCA output - Axis 1 versus Axis 3 plot for Litton Mill samples; main associations discussed in the text are circled in red.

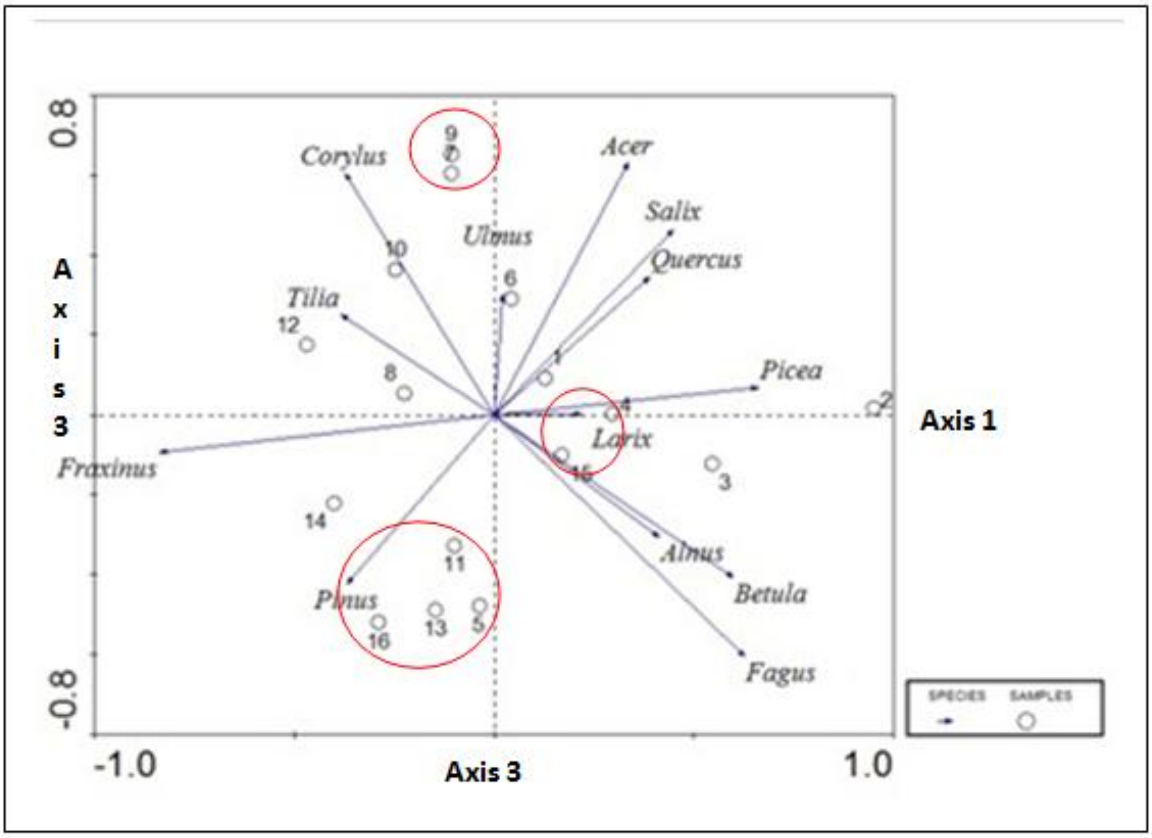
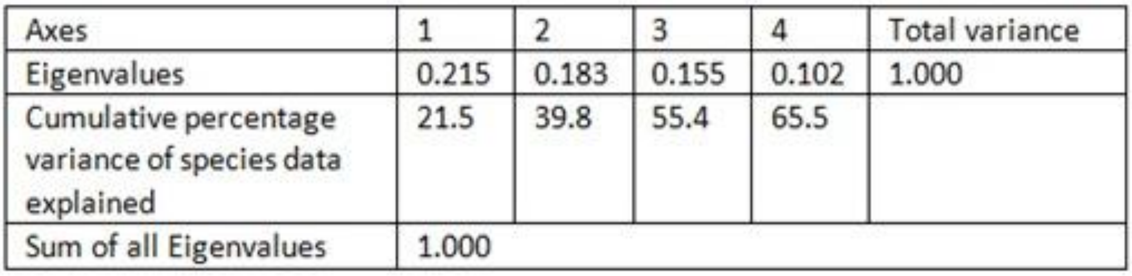


Table 6.16: Eigenvalues of pollen square root transformation



Axes	1	2	3	4	Total variance
Eigenvalues	0.215	0.183	0.155	0.102	1.000
Cumulative percentage variance of species data explained	21.5	39.8	55.4	65.5	
Sum of all Eigenvalues	1.000				

To establish a threshold to delineate the main associations, an arbitrary cut-off figure of 0.5 was applied as the maximum distance of separation between sample points; 2 points within this distance are considered non-trivial associations and classified as a group. As can be observed in figure 6.34, where axis 1 is plotted against axis 2, there are 3 groups of associated sites; the remainder of the sample points display no significant association. In figure 6.34, the groups comprise sites 9, 10 and 13; sites 6 and 7, and sites 12 and 14. Where axis 1 is plotted against axis 3, as displayed in figure 6.35, the same arbitrary figure of 0.5 was used to identify significant associations; these include site 7 and site 9, site 4 and site 15, and sites 5, 11, 13 and 16.

It can be observed in figure 6.34 that a high proportion of the sample points are only weakly correlated at best. The observed association of 12 and 14 is approximately equidistant from both axis 1 and axis 2, indicating that both the principal and secondary components are of equal influence. The association of sites 9, 10, and 13 displays a greater degree of influence from axis 2 in the case of point 10, and from axis 1 in the case of samples 9 and 13. The association identified between points 6 and 7 display relatively low influence from both components. The remainder of the sampling points in figure 6 are widely distributed. Taxon associations observed in figure 6.34 include Betula, Picea, Salix and Alnus; Tilia and Pinus; and Quercus and Fagus. Acer displays a strong inverse correlation with *Fraxinus*, and is un-associated (or extremely weakly associated with Fagus and Ulmus) and displays equal influence from both principal and secondary axes. Fraxinus is the most heavily weighted of all taxa in figure 12, and displays no significant association with any taxa. Ulmus displays a very minor association with the Tilia, Pinus association, and in figure 6.34 is almost entirely influenced by the secondary axis. Corylus is influenced primarily by the principal axis, and displays a low contribution to the variance of the dataset. The association Betula, Picea, Salix and Alnus display an inverse relationship to the Tilia and Pinus association, suggesting these two associations are influenced by different pollen dispersal and/or taphonomic factors. The association of Quercus and Fagus displays almost zero influence from the secondary axis, and has an approximately inverse relationship to Fraxinus and Corylus.

In figure 6.35, where Axis 1 is plotted against Axis 3, three associations of sampling points are observed: points 5, 11, 13 and 16; 9 and 7; and 4 and 15. The remaining sample points, although widely distributed, display a closer proximity to the origin than the dispersal trend observed in the axis 1 vs. Axis 2 plot in figure 6.34. The association of sites 5, 11, 13 and 16 display a trend of being influenced by the principal axis; this trend is also observed in the association of sample points 7 and 9. The association of sample points 4 and 15 is also influenced primarily by the principal axis. Taxon associations observed in figure 6.35 include Acer, Salix and Quercus, and Alnus, Betula and Fagus. Remaining taxa are only weakly correlated. The association of Acer, Salix and Quercus displays a relatively equal influence from both axis 1 and axis 3, with Acer trending toward dominance from the secondary axis (axis 3). The association Alnus, Betula, Fagus also appear to be subject to a relatively equal influence from both axes, with Fagus displaying the dominant influence on the weighting on both axes in this group.

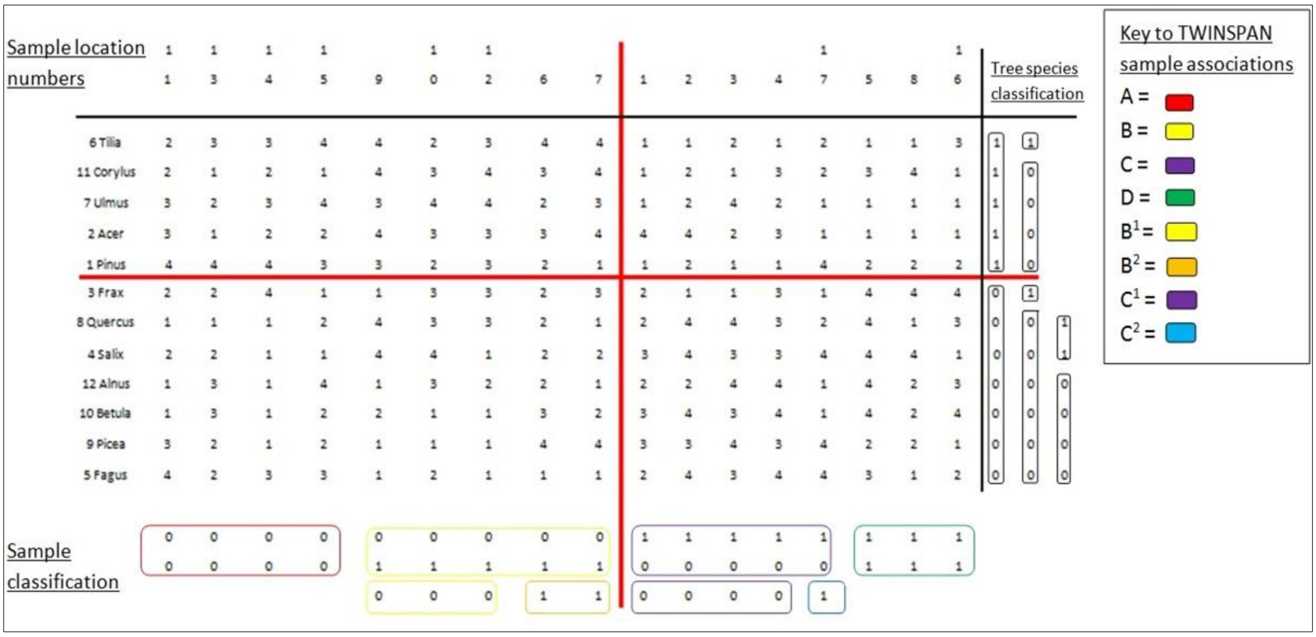
Acer displays an inverse relationship to Pinus, suggesting a significantly different set of influences affecting pollen deposition between these taxa; the same inverse relationship is observed between Fagus and Tilia and Fagus and Corylus. Fraxinus, one of the more dominant taxa in the pollen assemblages, displays an inverse relationship to the Acer, Salix, Quercus, association and to Picea. Tilia is displays a strong inverse correlation with *Betula*, *Alnus*, and *Fagus*, and is influenced primarily by the principal axis. Ulmus displays no strong association with any other taxa, and is primarily associated with the secondary axis. Picea dominates the principal axis, and apart from a significant inverse correlation with Fraxinus is un-associated with any other tree taxa.

TWINSPAN

Sample Points

Two-way indicator species analysis was carried out using TWINSPAN software. The TWINSPAN software allows polythetic divisive classification, which divides spatial data into groups on the basis of species composition of a quadrat or sampling point e.g. pollen assemblage. TWINSPAN requires a series of pseudospecies in order to adapt abundance data e.g. pollen percentages, into classes allowing division. Pseudospecies scores for Litton Mill data were derived using quartiles (pseudospecies 1, 2, 3, and 4). A TWINSPAN output table for the Litton Mill site is presented in table 6.17, and an output dendrogram of the Litton Mill samples is presented in figure 6.36 below. Sample 17 is a moss-polster taken from the river bank at the water's edge and so is not represented in the depth diagrams.

Table 6.17: TWINSPAN output table for Litton Mill sample points – coloured lines denote taxonomy of groups



Sample location numbers	11	13	14	15	9	10	12	6	7	1	2	3	4	17	5	8	16	Tree species classification		
6 Tilia	2	3	3	4	4	2	3	4	4	1	1	2	1	2	1	1	3	1	1	
11 Corylus	2	1	2	1	4	3	4	3	4	1	2	1	3	2	3	4	1	1	0	
7 Ulmus	3	2	3	4	3	4	4	2	3	1	2	4	2	1	1	1	1	1	0	
2 Acer	3	1	2	2	4	3	3	3	4	4	4	2	3	1	1	1	1	1	0	
1 Pinus	4	4	4	3	3	2	3	2	1	1	2	1	1	4	2	2	2	1	0	
3 Frax	2	2	4	1	1	3	3	2	3	2	1	1	3	1	4	4	4	0	1	
8 Quercus	1	1	1	2	4	3	3	2	1	2	4	4	3	2	4	1	3	0	0	1
4 Salix	2	2	1	1	4	4	1	2	2	3	4	3	3	4	4	4	1	0	0	1
12 Alnus	1	3	1	4	1	3	2	2	1	2	2	4	4	1	4	2	3	0	0	0
10 Betula	1	3	1	2	2	1	1	3	2	3	4	3	4	1	4	2	4	0	0	0
9 Picea	3	2	1	2	1	1	1	4	4	3	3	4	3	4	2	2	1	0	0	0
5 Fagus	4	2	3	3	1	2	1	1	1	2	4	3	4	4	3	1	2	0	0	0
Sample classification	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1			
	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	1	1			
					0	0	0	1	1	0	0	0	0	1						

Key to TWINSPAN sample associations

A = 🟥
B = 🟨
C = 🟪
D = 🟩
B^1 = 🟨
B^2 = 🟧
C^1 = 🟪
C^2 = 🟦

As can be observed in figure 6.36, pollen assemblage data has been split into groups using two division levels. The first division splits the 17 assemblages into 4 groups. These groups have been labelled A, B, C, and D respectively. A second division occurs where group B is split into group B_1 and group B_2, and where group C is split into group C_1 and C_2. The relative spatial position of the TWINSPAN groups within the pool at the

Litton Mill site is presented in figures 6.36 and 6.37 below: figure 6.36 displays the relative spatial positions of the groups identified by the principal TWINSPAN division; figure 6.37 displays the relative spatial positions of the groups identified by the secondary TWINSPAN division.

Figure 6.36**:** TWINSPAN output dendrogram of sample point groups

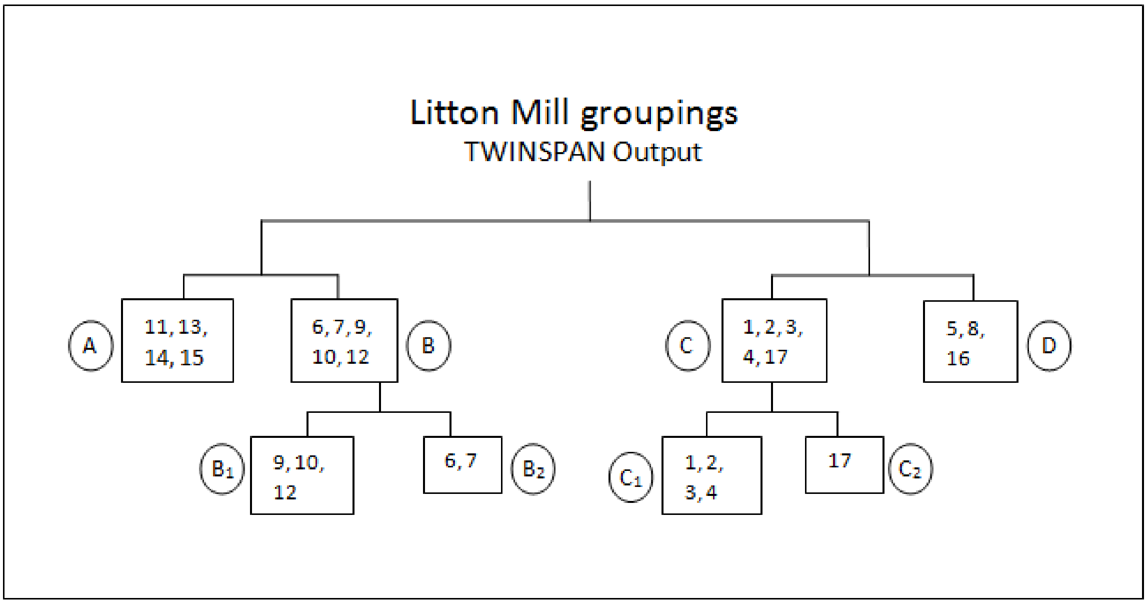
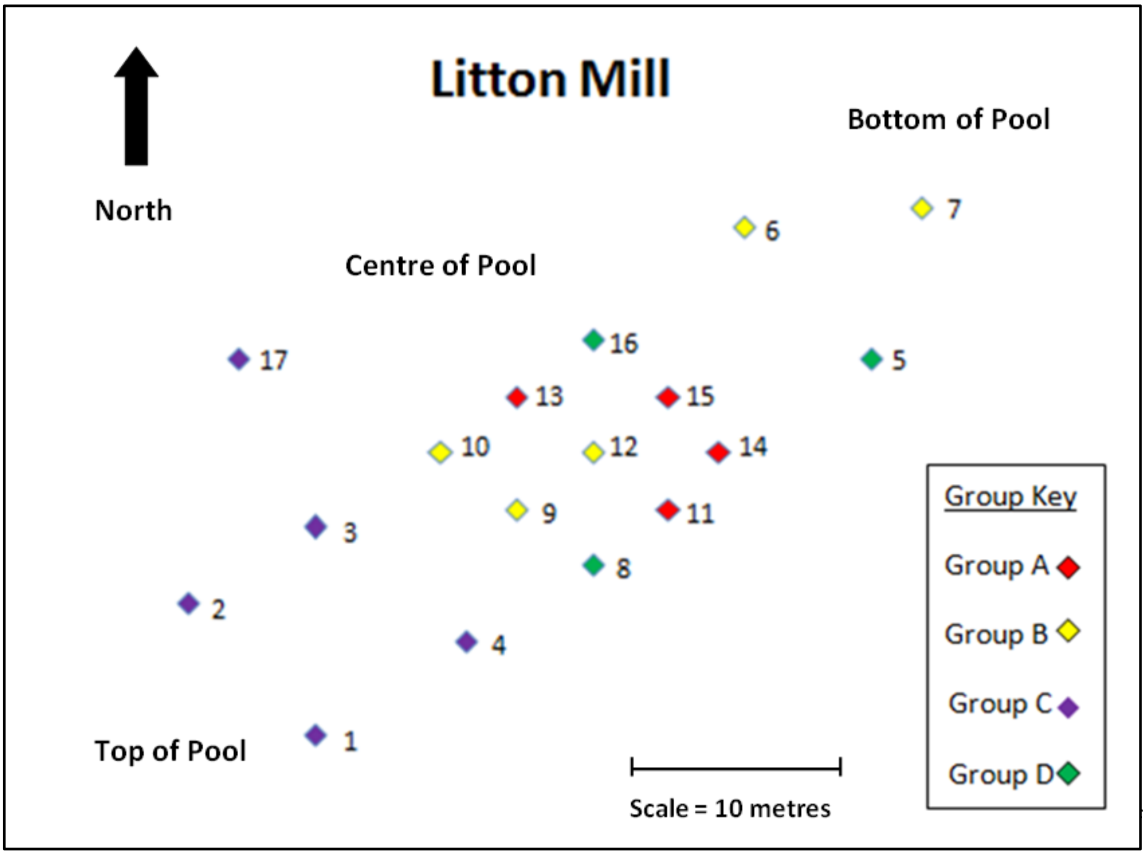


Figure 6.37: Litton Mill sample groups – spatial location of groups at principal level of TWINSPAN division; see table 6.18 below for water depths at sample locations.



sampling points in both graph plots, and displays a significant association with the upper portion of pool in both graph plots. The upper part of the pool has the shallowest observed water depths at 0.5m; water depths of the Litton Mill sample locations are displayed in table 6.18 below, spatial depth-sample group relationships are displayed in figure 6.39 below.

Table 6.18: Water depths at sample locations at Litton Mill sampling site: - note that associations are colour-coded and are relevant to figures 6.37, 6.38 and 6.39.

Sample number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Depth in metres	0.5	0.5	0.5	0.5	0.8	1.0	1.3	1.3	1.5	1.5	1.3	1.3	1.3	0.8	1.5	1.3	-
Group	C	C	C	C	D	B	B	D	B	B	A	B	A	A	A	D	C

When group C is divided, the spatial character of C_1 remains unchanged and C_2 is moved on-land to the river bank moss sample. Group A displays a strong association with the deeper central section of the pool illustrated in figure 6.38 below (0.8 – 1.3m), and displays a high degree of spatial association between the sample points; group A also displays an identical spatial arrangement in both graph plots.

Figure 6.38: Litton Mill sample groups –spatial location of groups at secondary level of TWINSPAN division.

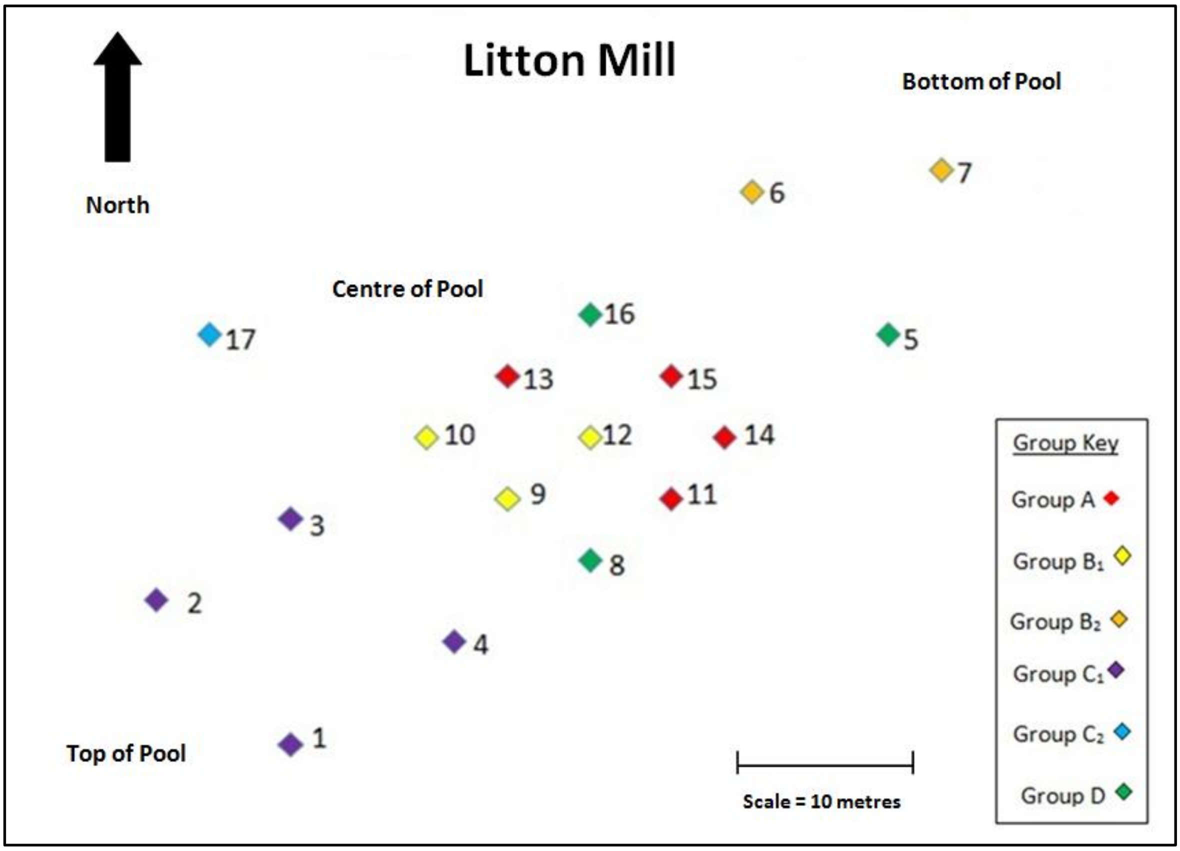
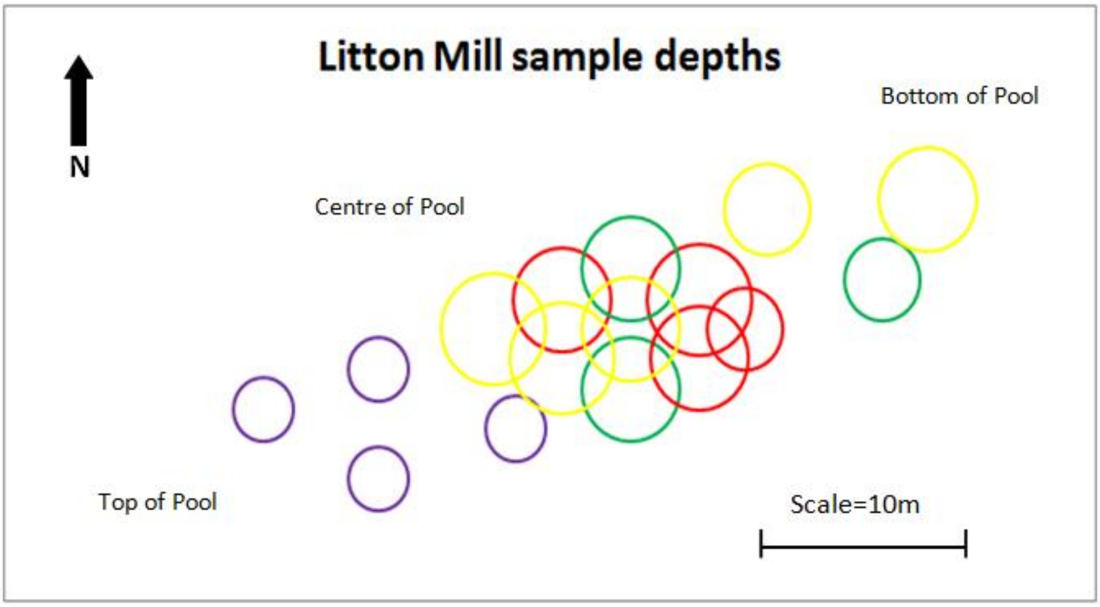


Figure 6.39: Excel bubble plot of spatial location of sample groups at the Litton Mill field site derived from principal TWINSPAN division. The bubble colour denotes group: size of bubble denotes depth i.e. large bubbles are of greater depth than small bubbles.



Group B is associated with the central and bottom sections of the pool in both figure 6.37 and 6.38, with three points (9, 10 and 12) situated in the deepest portion of the pool (1.5m), and two points (6 and 7) situated in the shallower water (1 – 1.3m) at the bottom of the pool; depth of the TWINSPAN groups being displayed in 6.39. The division of group B into B_1 and B_2 as displayed in figure 6.38 splits this cluster; group B_1 remains in the pool centre, whilst group B_2 is assigned to the bottom of the pool. Group D has two sample points (8 and 16) situated in the centre of the pool, which represents the deepest section (1.3m), and a single point (5) at the bottom of the pool in a shallower water depth of 0.8 metres.

The second level of sample group division illustrated in figures 6.38 arranges the pollen assemblage samples into more spatially defined areas and water depths of the pool sampling site, as illustrated in figure 6.39. This suggests that water depth and spatial proximity to bankside riparian vegetation may be important controls influencing taxon percentages within the pollen assemblages. This hypothesis may be supported by the terrestrial moss sample taken at the bankside (sample 17) being split into a group of 1 using the second TWINSPAN division, as this sample is directly under the riparian vegetation. Non-statistical scatter graphs of pollen percentages against depth are presented in figures 6.40 to 6.42 below. Figure 6.40 displays taxa that display a pronounced decrease in percentage values with depth, figure 6.41 displays taxa which display a moderate decrease in pollen percentage values with depth, and figure 6.42 displays taxa that display an increasing pollen percentage value with depth.

Figure 6.40: Taxa displaying a pronounced decrease in pollen percentage values with depth; please note that a non-statistical trend line is used.

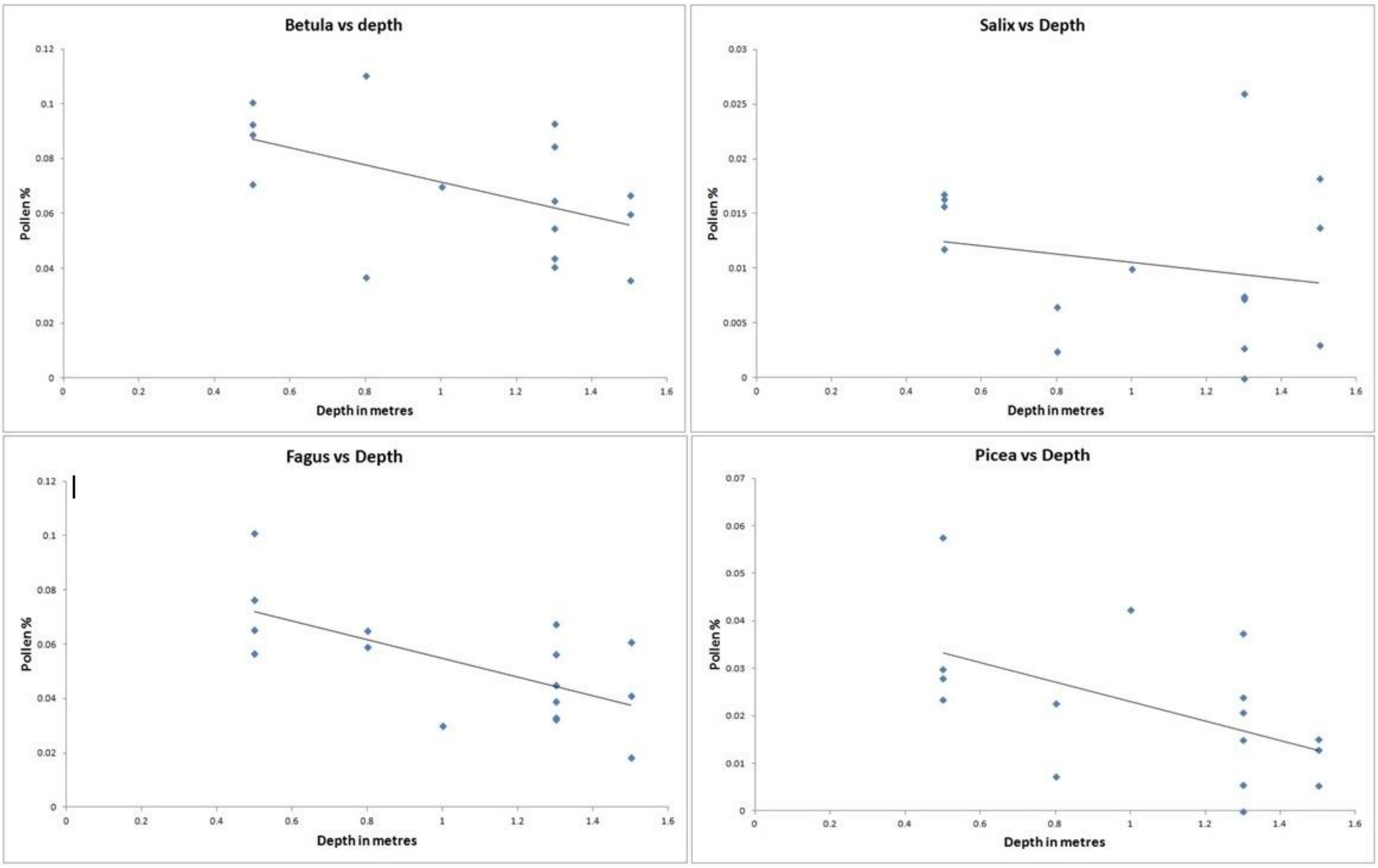


Figure 6.41**:** Taxa displaying a moderate decrease in pollen percentage values with increasing water column depth; please note that a non-statistical trend line is used.

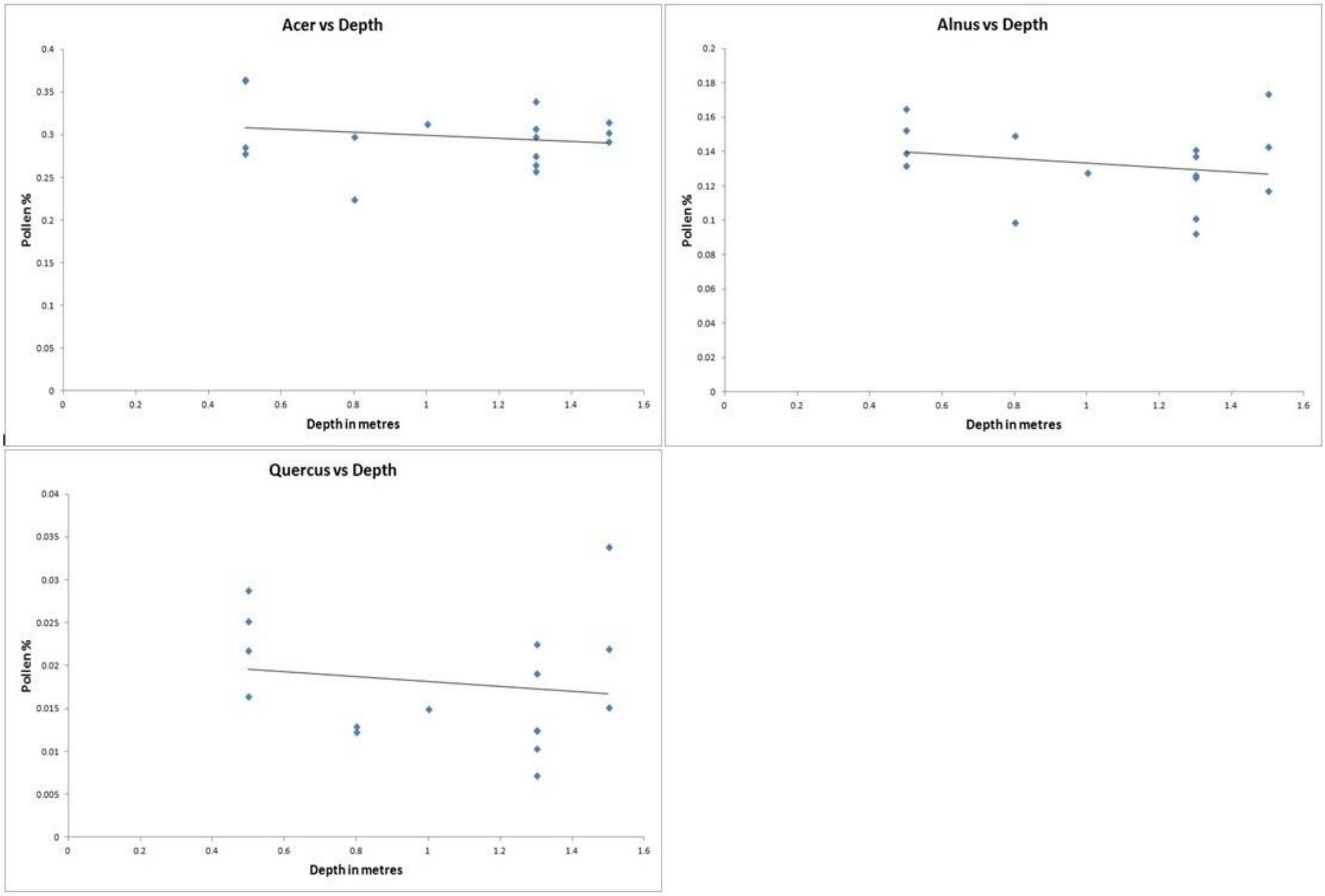
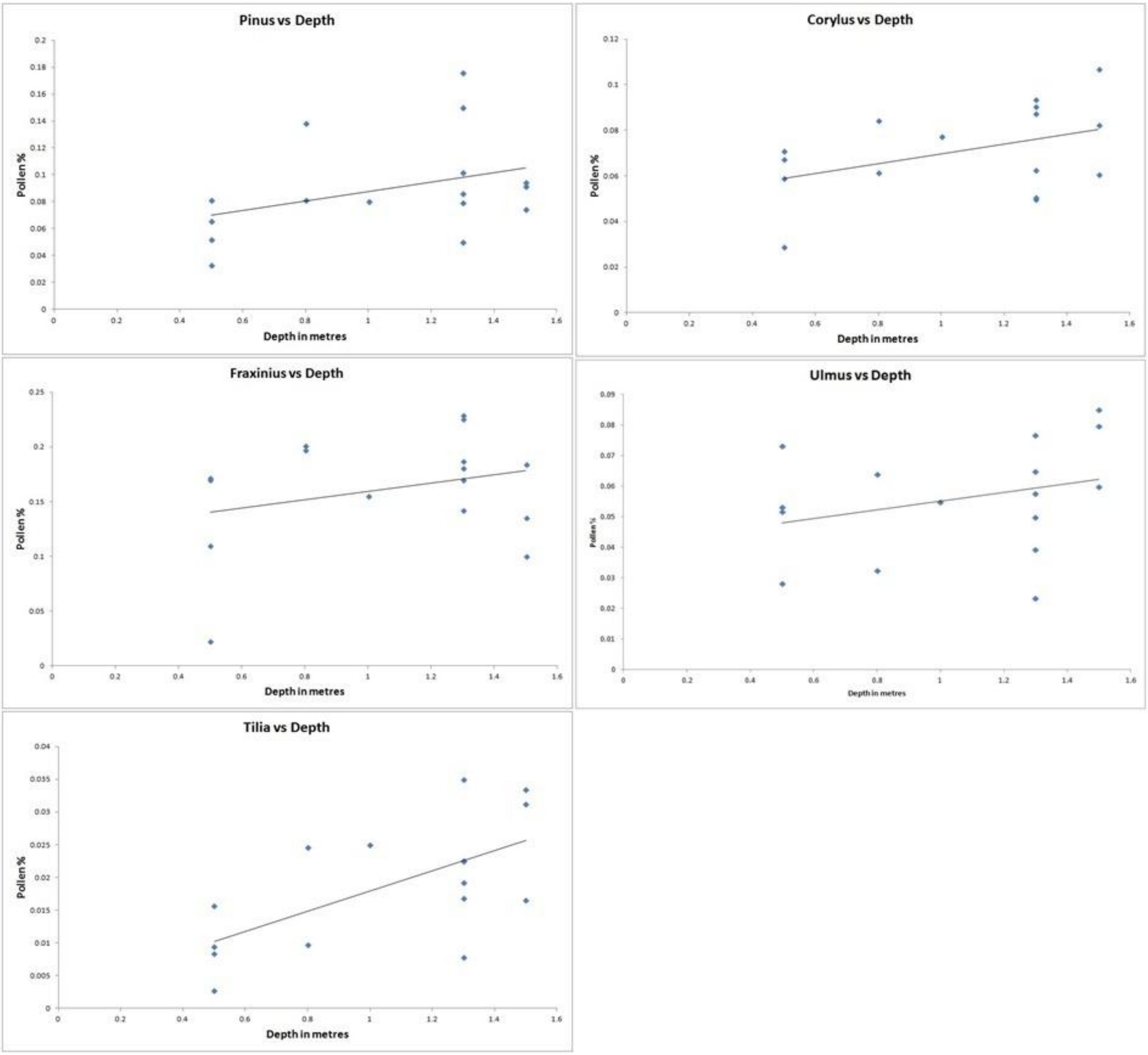


Figure 6.42: Taxa displaying an increase in pollen percentage values with depth; please note that a non-statistical trend line is used.



Pinus vs Depth

Corylus vs Depth

Fraxinius vs Depth

Ulmus vs Depth

Tilia vs Depth

Tree taxa

In order to examine how pollen dispersal and taphonomic characteristics may influence the spatial dimension of the pollen assemblage, tree taxon division is illustrated in figure 6.43 below; the ordination has produced three levels of division. Pollen fallspeed and the physiological characteristics of different pollen grains are suggested as significant factors influencing pollen dispersal and taphonomy. Pollen fallspeed velocity in air is faster than pollen settling velocity in water (Holmes, 1994); however pollen fall speed velocity in air is suggested as being analogous to pollen settling velocity in water for the purposes of this study, as the difference is in magnitude and will not affect rank order. Financial and time constraints resulted in no pollen settling velocity quantification being carried out for the purposes of this study. Selected pollen grain fallspeeds acquired were from the existing literature and are presented in table 6.19 below.

Figure 6.43: TWINSPAN output dendrogram displaying of division of tree taxon

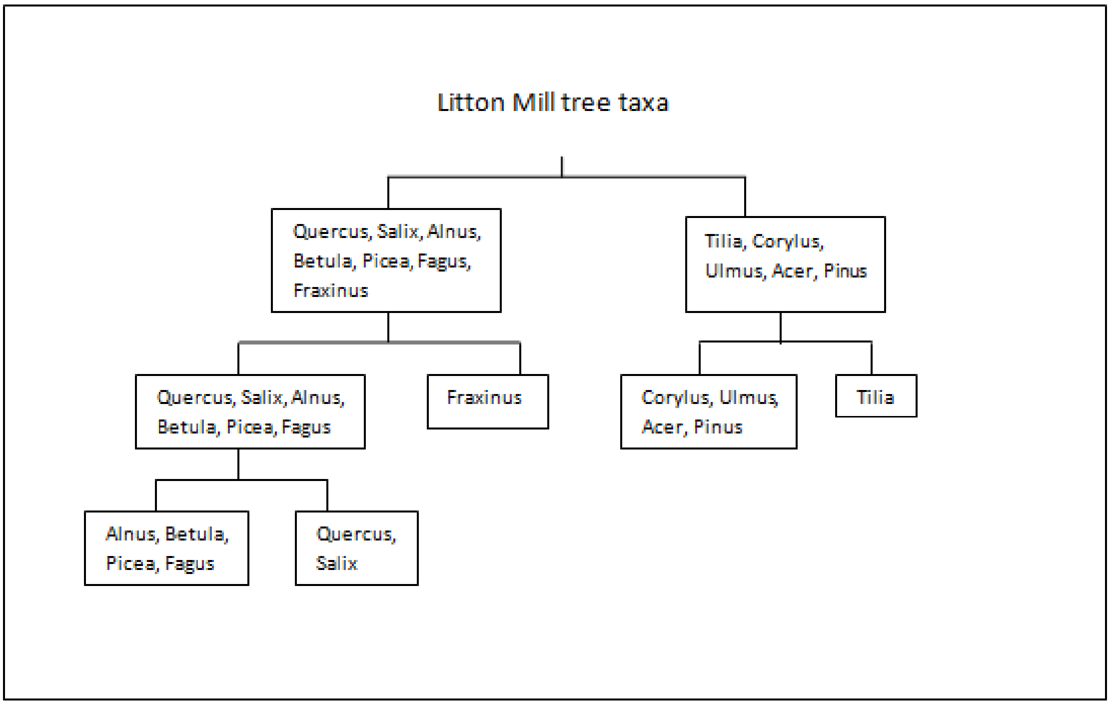
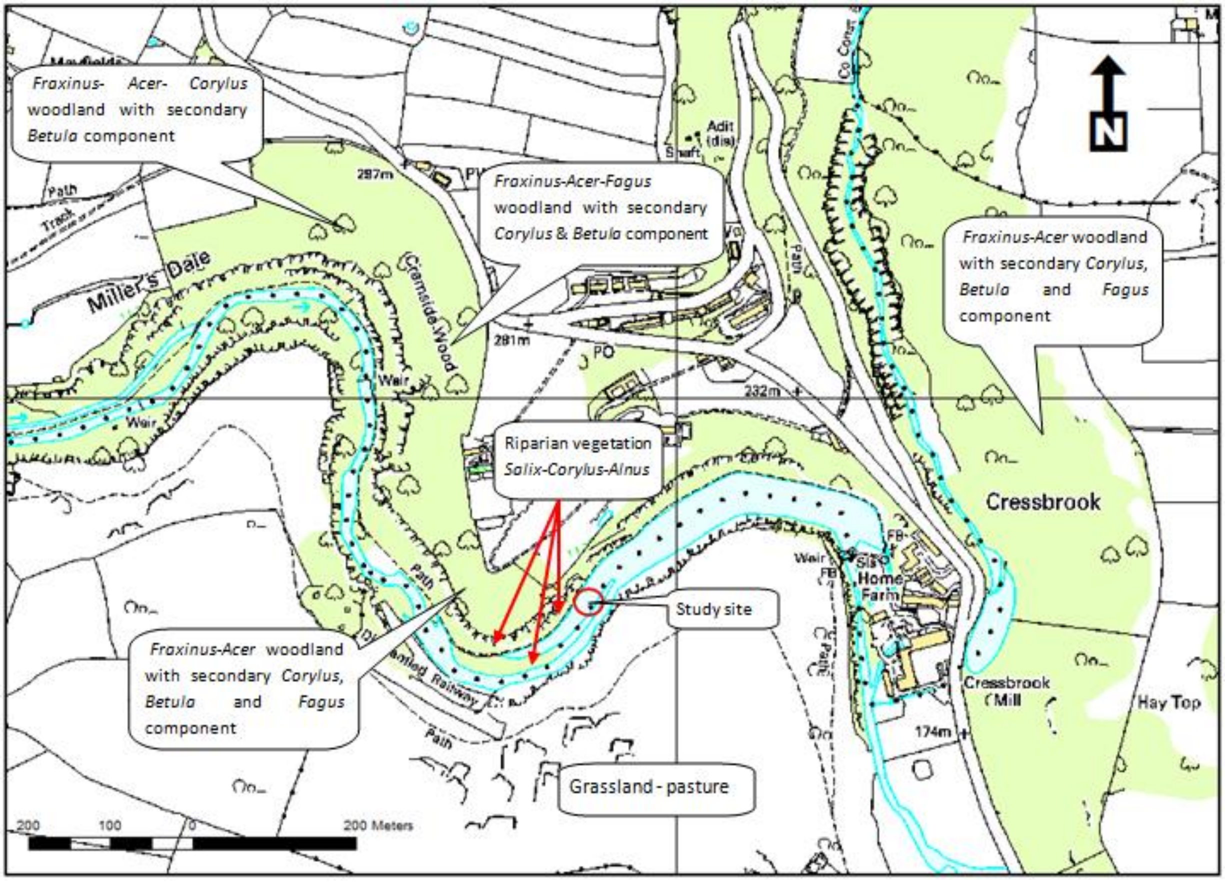


Table 6.19: Pollen fallspeed velocities of Litton Mill study tree taxa discussed in the text.

Taxa	Fallspeed	Reference cited for fall speed of pollen	Classification in the text i.e. 'fast ' or 'slow' or intermediate
Pinus sylvestris	0.031	Eisenhut (1961)	intermediate
Picea abies	0.056	Eisenhut (1961)	fast
Alnus glutinosa	0.021	Eisenhut (1961)	Slow
Ulmus glabra	0.032	Gregory (1973)	intermediate
Tilia cordata	0.032	Gregory (1973)	intermediate
Salix caprea	0.022	Gregory (1973)	slow
Acer spp.	0.056	Sugita (1993; 1994)	fast
Betula spp.	0.024	Eisenhut (1961)	slow
Quercus robur	0.035	Eisenhut (1961)	intermediate
Fraxinus excelsior	0.022	Eisenhut (1961)	slow
Fagus sylvatica	0.057	Gregory (1973)	fast
Corylus avellana	0.025	Gregory (1973)	slow

Light grains such as Salix, Fraxinus, Betula, and Corylus appear in the groups illustrated in figure 6.43 in association with heavier grains such as Picea, Fagus and Acer. In the second division on the left hand side of the diagram, Fraxinus (a slow fallspeed grain) is split off from the faster fallspeed group of Quercus, Salix, Alnus, Betula, Picea and Fagus; the latter two taxa have two of the highest fallspeeds, with Quercus also significantly faster than Salix, Alnus and Betula. The final split on the left hand side of figure 6.43 separates Fagus, Picea, Betula and Alnus away from Quercus and Salix. Here the two fastest grains (Fagus and Picea) split off with two of the slowest (Betula and Alnus). The split of Quercus and Salix groups intermediate speed (*Quercus*) taxa together with slow speed taxa (Salix). The division on the right hand side of the dendrogram is comprised of primarily intermediate speed taxa such as Tilia, Ulmus and Pinus, with the single fast taxa Picea and the single slow taxa Corylus. The final split on the right separates Tilia off into a group of one, with the remaining group comprising Picea, Ulmus, Pinus and Corylus dominated by fast and intermediate taxa.

Figure 6.44: Relative spatial positions of the local and riparian vegetation to the Litton Mill study site



Map sourced from Digimap - 1: 10 000 OS Raster MasterMap.

Group C_1 (samples 1, 2, 3, 4) is at the shallowest section of the pool at 0.5m depth where it would be expected that ‘fast’ grains would dominate the assemblage, however group C_1 is characterised by relatively high abundances of ‘slow’ fallspeed taxa such as Salix, Betula, and Alnus; and by 'fast' fallspeed taxa such as Acer, Fagus, and Picea. It can be seen in figures 6.40 and 6.41 that all these taxa display a trend of decreasing pollen percentages with increased depth. As can be observed in figure 6.44, Acer, Fagus, and Betula are abundant taxa in the extra-local and local vegetation of the slope and plateau woodlands on the northern slopes adjacent to the sampling sites; Salix, Betula, and Alnus are significant in the riparian vegetation on the northern riverbank, and on the central bar. Greater local (Cl), canopy (Cc), and trunk space (Ct) pollen input from these riparian taxa may explain why the 'slow' fallspeed taxa are present with the 'fast' fallspeed pollen which represents extra-local vegetation on the northern plateau and valley slopes.

Group B_1 (samples 9, 10, 12) is positioned at the central and deepest section of the pool, and is characterised by high pseudospecies scores of 'fast' fallspeed taxa such as Acer, Tilia, Quercus, and Ulmus, which display an increase in pollen percentages with increasing depth, and interestingly high pseudospecies scores for slower taxa such as Salix, Corylus, and Fraxinus. This section of the pool is also the most 'open', and may potentially receive an enhanced regional, extra-local and rainout pollen input. Corylus and Fraxinus follow the trend of increasing pollen percentage deposition with depth illustrated in figure 6.42; however *Salix* displays the opposite trend. As can be observed in figure 6.44, Acer, Fraxinus, and Corylus are abundant taxa in the extra-local and local vegetation of the slope and plateau woodlands on the northern slopes adjacent to the sampling sites; Salix is significant in the riparian vegetation on the northern riverbank, and on the central point bar. Greater local (Cl), trunk space (Ct), and perhaps water (Wt) pollen input from Salix may explain why a 'slow' fallspeed taxa is present with the predominantly 'fast' fallspeed pollen which represents extra-local vegetation on the northern plateau and valley slopes. Quercus and Ulmus are present, often as isolated trees, in the extra-local vegetation and the more open aspect of group B_1's position may allow an enhanced pollen input from rainout (Cr) and canopy (Cc) transported grains.

Group B_2 (samples 6, 7) is positioned in relatively deep water at the end of the pool and has high pseudospecies scores for 'fast' fallspeed taxa Acer, Picea, Tilia and Quercus, and high pseudospecies scores for 'slow' fallspeed taxa Corylus, Fraxinus and Betula. Acer, Quercus, and Picea, display a trend of pollen percentages decreasing with depth, with Tilia displaying the opposite trend. Corylus and Betula display an increase in percentage values with depth, whilst Fraxinus displays the opposite trend. The presence of 'fast' taxa and 'slow' in the group suggest that pollen fallspeed is a component of the taphonomy, the influence of the predominantly Acer and Fraxinus extra-local woodland, and the local riparian component of Corylus and Betula adjacent to the river channel may be influencing the assemblages at these sampling points. Quercus and Picea are accepted as taxa with a strong extra-local pollen signal, suggesting an airborne input from plateau and more distal attitudinally enhanced woodland stands. The high *Tilia* pseudospecies score in group B_2 suggests a local pollen source, which as the taxa is entomophilous, may have been enhanced by ephemeral slopewash events causing reentrainment of riparian and woodland floor pollen.

Group C_2 is represented by one sample, sample 17, a moss polster from a stone on the riverbank adjacent to the middle of the pool. This single terrestrial sample was taken to give a comparison between fluvial and riparian terrestrial pollen percentages at the Litton Mill study site. The assemblage is characterised by high pseudospecies scores for fast/heavy taxa such as Fagus and Picea, and values for Acer are very low. This low pseudospecies score for Acer may be a product of the limitations of receiving pollen from an airborne source to a small single point, whereas the sample points in the pool can effectively count the length of the river upstream as a depositional basin for both newly deposited and reentrained pollen. Intermediate grains such as Tilia and Quercus display medium pseudospecies scores; however the *Pinus* pseudospecies score is very high. The Pinus score may be a product of local, extra-local and regional pollen dispersal through airborne (Cc) and (Ct) transport. The potential influence of episodic increases in water level may also deposit Pinus grains as flotsam, as the saccate grains are known to float effectively enhancing fluvial transport (Traverse, 1988). High scores of Salix and medium scores of Tilia and Corylus suggest a local source for these riparian taxa.

Group A comprises 4 sample points (11, 13, 14, 15) situated in the deepest central section of the pool where depths range from 1.3m to 1.5m; sample 14 was calculated at a depth of 0.8m. This group is characterised by high pseudospecies scores of 'fast' fallspeed taxa such as Pinus, Tilia, Fagus, and Ulmus. As can be seen in figure 6.42, Pinus, Tilia, and Ulmus display an increase in pollen percentages with increasing depth, whilst Fagus displays the opposite trend; ‘slow’ fallspeed taxa such as Salix, Fraxinus, Alnus and Betula all display medium pseudospecies scores. Sample 14, which has the shallowest observed water depth of the group A samples, displays the lowest overall pseudospecies scores for the slower fallspeed taxa, suggesting that water depth may be a more significant control on pollen assemblage at this sample location. The high pseudospecies scores for the fast and medium fallspeed taxa suggest that pollen may be preferentially settling into the deeper section of the pool. As these sample points are grouped in the centre of the river channel, the high values of Fagus and Acer suggest airborne Cc, Ct, and Cr local and extra-local pollen sources. High values of Tilia, Ulmus and Pinus also suggest similar airborne transport mechanisms, as these taxa represent only a very minor component in local and extra-local slope and plateau woodlands; however the influence of episodic slopewash and flood events on the assemblages must be considered.

The lower pseudospecies scores of Salix, Fraxinus, Alnus and Betula in group A suggest that either the pollen of these taxa is being deposited locally or from riparian trees and is being carried through the pool before deposition, or that the pollen source for these taxa is extra-local and/or regional and is subsequently being deposited in lower densities along the whole river channel. The high pseudospecies score of Pinus, which represents only a very minor component of the valley-slope and plateau vegetation, suggests that group A is influenced by extra-local and regional pollen sources. Relatively low overall pseudospecies scores for ‘slow’ fallspeed taxa observed in sample 14, which is 0.5m shallower that the other sample points support the hypothesis that depth at the study site may be a control on pollen with low fallspeeds.

The influence of regular i.e. weekly stage variations as a control on pollen transport and deposition at the Litton Mill site are likely to be minor, as the karstic hydrology of the White Peak results in precipitation being rapidly captured by dissolution fissures over the catchment resulting. A mean flow of 3.23m^3/s, a Q_{95} flow of 1.001m^3/s, a Q_{10} flow of 6.188m^3/s and a high baseflow component of 0.75 for the River Wye between 1965 and 2012, suggests episodic flood events i.e. annual/bi-annual are likely to be the only significant alterations in stage level on the River Wye during the year (Centre for Ecology and Hydrology (CEH). 2014$_c$). During low flow periods i.e. $Q_{95,}$ the pool margins may be significantly shallower resulting in pollen entering the water column becoming integrated into sediment more rapidly once the pollen is saturated; or alternatively these shallower more marginal areas become dry with the result that bed sediment becomes impermeable effectively forming a barrier to pollen sedimentation. The deeper pool trough in the centre of the study site where Group A is situated is potentially the most stable area of the pool in the context of pollen sedimentation as it is unlikely to become dry during Q_{95} flows, and flow velocities at the river bed during flood events would be lower in the deeper pool trough than at the shallower areas of the pool at the top and adjacent to the riverbank.

Group D is the most spatially dispersed of all the groups, as is illustrated in figure 6.38. Sample 8 is on the southern side of the centre of the pool, and sample 16 on the northern side of the centre of the pool; both samples have a depth of 1.3m. Sample 5 is on the channel-side of the bottom of the pool and has a depth of 0.8m. Group D is displays high pseudospecies scores of ‘slow’ fallspeed taxa such as Salix, Betula, Corylus, Fraxinus and Alnus. Salix, Betula and Alnus display a trend of decreasing pollen percentages with increased depth; Corylus, and Fraxinus display an increase in pollen percentages with increasing depth. The group is characterised by medium pseudospecies scores for fast/heavy taxa such as Fagus and Picea at sample points 8 and 16, with high pseudospecies scores for these taxa at sample point 5; Acer displays very low pseudospecies scores at all three sampling points.

Pseudospecies scores of ‘fast’ fallspeed taxa such as Quercus, Ulmus and Pinus are low/medium at samples 5 and 8, with high intermediate pseudospecies scores for these taxa at sampling point 16; Tilia displays low pseudospecies scores at points 5 and 8 toward the channel-side centre of the pool, and high pseudospecies scores at sample point 16 situated on the northern side of the pool centre. Sample points 5 and 8 display high pseudospecies scores for ‘slow’ taxa such as Salix, Corylus, Betula and Fraxinus, this is contrasted at sample point 16 where pseudospecies scores for ‘slow’ taxa are low-medium overall; Fraxinus is scored very high at all samples in group D.

High pseudospecies scores for ‘slow’ fallspeed taxa Salix, Corylus, Betula and Fraxinus at the two ‘outer’ samples of 5 and 8 suggest the more open central aspect of the pool at these points favours airborne pollen transport into the channel; this hypothesis is supported by the lower overall scores for these taxa observed at the more sheltered 'bankside' sample point 16. Another influence on samples at the lower end of the study site may be local riparian pollen transported by wind-derived 'fetch' The higher pseudospecies scores for 'fast' taxa observed at sample point 5 at the bottom of the pool contrasts with the slightly lower pseudospecies score displayed at points 16 and 8 in the central section of the pool. This may be a product of the significant difference in depth between the three sites, with sample point 5 being 0.5m shallower that sample points 8 and 16 and potentially allowing heavier grains to settle preferentially in the shallower water. Sample point 16 is characterised by 'fast' fallspeed taxa such as Quercus, Tilia, Ulmus and Pinus, albeit at lower scores than sample point 5. The bankside position of sample point 16 may allow pollen transport by airborne, riparian and ephemeral slopewash mechanisms, which enhance pollen deposition at this point.

6.4.2. Discussion

As the aim of this study is to examine effects of taphonomic processes on spatial variation in pollen deposition in a pool in the River Wye, Derbyshire, conceptual taphonomic models will be introduced and then compared with findings in the results section in order to understand which model of pollen dispersal is applicable at this field site.

The two principal aerial taphonomic models are the Prentice Model (1985), and the Prentice-Sugita model (1993); both models assume that pollen flux is delivered aerially by both wind above the canopy, and gravity beneath the canopy and that pollen source area increases with basin size. The Prentice model assumes that all pollen deposited at a point in the centre of a basin is deposited directly from the atmosphere with no subsequent pollen transport or redeposition occurring after deposition, meaning that this model is often used with peat sediment or in enclosed lakes with no inflowing streams. The Prentice-Sugita model assumes that pollen deposited across the surface of the entire basin becomes mixed and homogenized, which allows fast fallspeed grains with poor dispersal or highly localised riparian pollen deposited at lake margins to be represented across the whole basin. The Prentice model assumes no post depositional mixing, and so does not allow for poorly dispersed local and/or heavy pollen grains to be equally represented across the basin. As depositional basin size increases, pollen source area become larger allowing greater representation of widely dispersed taxa in pollen assemblages.

The ‘edge effect’ described by Tinsley and Smith (1974) and ‘skip distance’ described by Jackson (1994) can also influence the proportion of pollen entering a pool or lake basin from local and riparian vegetation, meaning that the proximity and size of a vegetation type to the point of pollen deposition is an important consideration (Bunting *et al*. 2004). Where no post-depositional mixing of pollen occurs and the basin is either relatively large or has little in the way of marginal vegetation, aerially deposited regional and extra-local pollen is often focused in the lake centre (Holmes, 1994). The spatial aspect of aerially deposited pollen in unmixed lake sediments is illustrated in figure 6.45 below.

Figure 6.45: Distribution of aerially deposited pollen in an enclosed lake basin where pollen remains unmixed in lake sediments. Note that left-hand diagram refers to arboreal pollen and right-hand diagram refers to non-arboreal pollen.

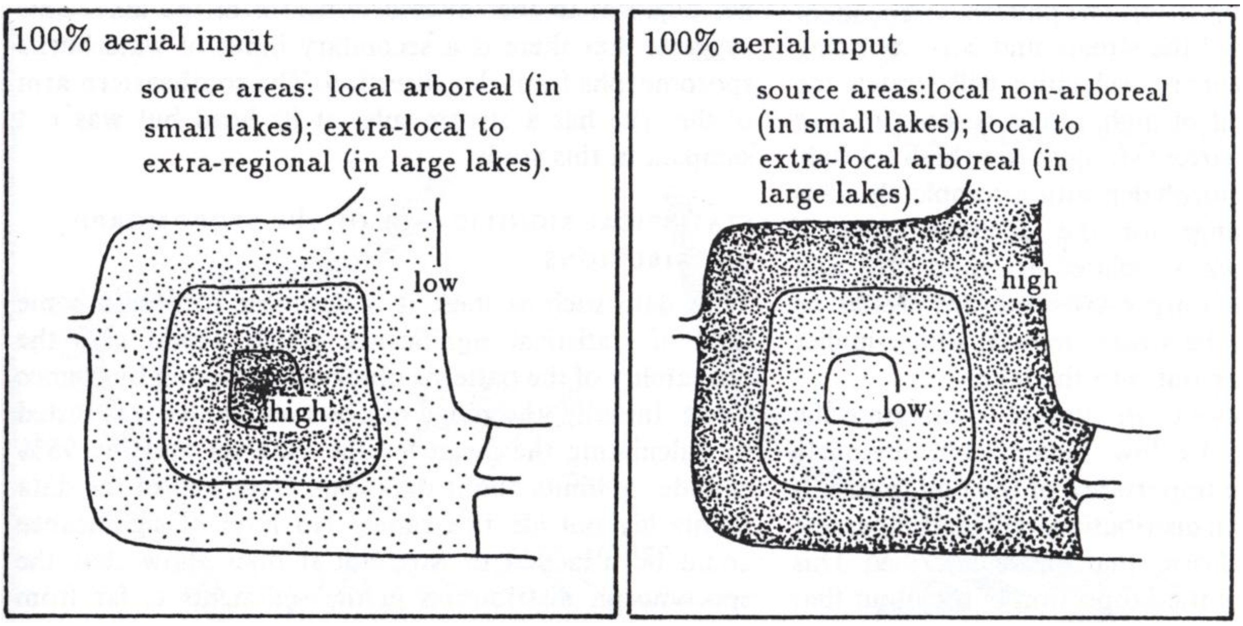


Image taken from: Holmes (1994).

In smaller basins local and riparian non-arboreal pollen is suggested as being deposited in greater volumes nearer the basin edges, whilst local and regional arboreal pollen is focused toward the centre of the lake basin (Holmes, 1994). In well mixed lakes, pollen is homogenized and transported via currents and surface fetch to deeper or more central areas of the lake (Sugita, 1994).

The model of fluvial taphonomy in lakes with and without inflowing streams is discussed by Holmes (1994) and fluvial taphonomy in river systems is discussed by Brown *et al*. (2007). In lakes with inflowing streams, the aerial component, the surface runoff component, and the stream or river input are believed to constitute the principal pollen flux to a basin. Where stream influx is the dominant pollen input to a lake basin, the highest pollen concentrations are often found close to the stream inlet where pollen concentrations decrease with distance out into the lake as is illustrated in figure 6.46 below.

Figure 6.46: Patterns of pollen distribution in lake sediments as transported by low (left) and high (right) inflowing stream velocities.

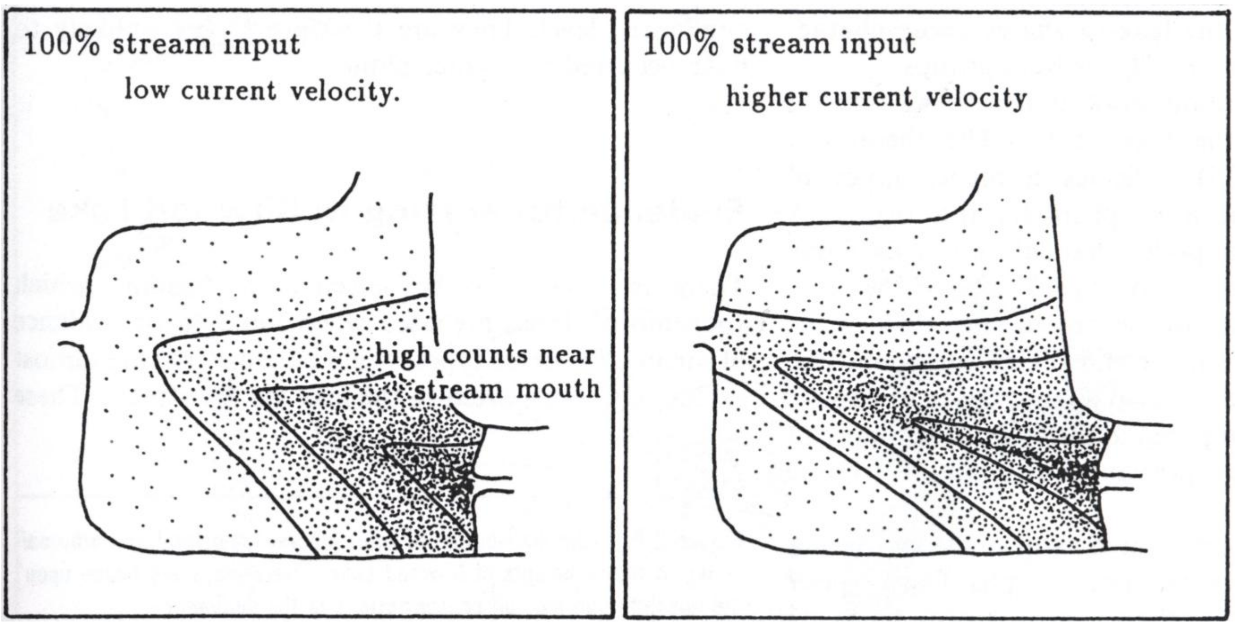
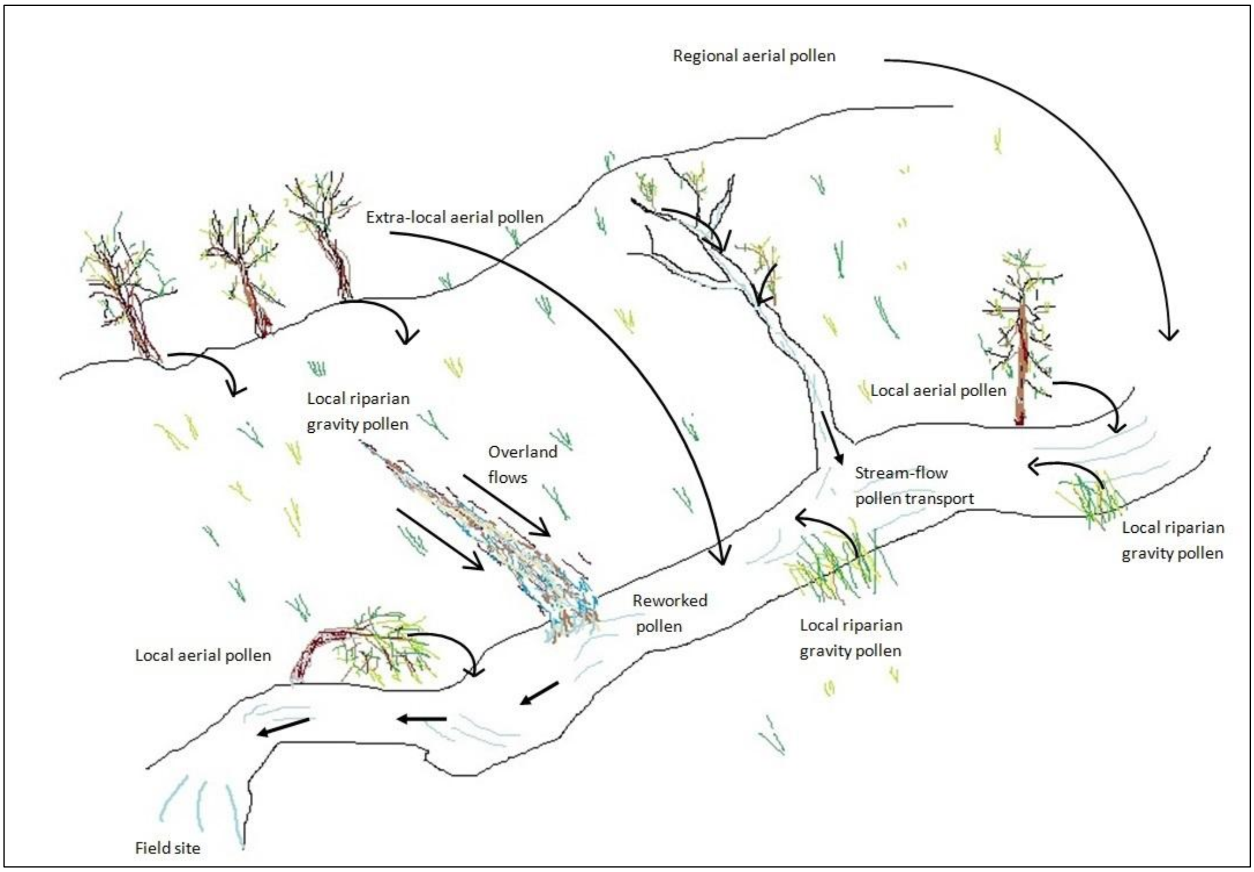


Image taken from: Holmes (1994).

Pollen delivered to a lake by a stream, and pollen transported subsequently within the lake by currents and surface winds, is also influenced by grain size and density. Heavier grains with a faster settling velocity will be deposited closer to the inlet where the stream enters the lake, whilst the lighter grains which have a slower settling velocity remain entrained in the water column for a longer duration and are subsequently transported further out into the lake before sedimentation.

Pollen taphonomy in rivers is assumed to be primarily controlled by the hydrology of the watershed, where > 90% of pollen transport occurs during seasonal flood events Brown *et al*. (2007). Sources of pollen into river systems are illustrated in figure 6.47 below.

Figure 6.47: Pollen sources into fluvial systems.



Pollen sources include the regional and local aerial component, the riparian or gravity input occurring along the length of the catchment, pollen remobilized from river bed sediments along the length of the channel during high flows and flood events, and pollen reentrained from the land surface of the wider catchment which is transported to the main river channel via overland flows and tributaries. On falling hydrographs, as river flows are returning to normal levels, pollen suspended in the water column becomes less well mixed, leading to differential sedimentation dictated by grain size and settling velocity. Heavier and often larger grains are redeposited first, leading to a grading of pollen by size/density in slower pools as is illustrated in figure 6.46 (Holmes, 1994). Fluvially transported pollen is frequently damaged (Brown, 1985), presumably as a result of mechanical damage incurred either during overland transport to the main channel or within the main channel, or from chemical or biological corrosion whilst on the land surface (Campbell, 1999).

The following scenarios are suggested for examination against the Litton Mill results.

1. An aerial model based on the Prentice Model whereby local and regional pollen flux is the primary input, no mixing has occurred, and taxon-specific differences in plant location and pollen fallspeed will result in spatial differences in pollen assemblage composition both across and down the pool.
2. An aerial model based on the Prentice-Sugita Model whereby local and regional pollen flux entering the Litton Mill site has become well mixed, resulting in relatively homogenous pollen assemblages.
3. A Fluvial Model, with heavier pollen types being deposited higher up the pool and lighter pollen types deposited progressively further down the pool due to differences in settling velocity. In this scenario pollen assemblages may also be characterised by higher levels of mechanically and/or chemically and/or /biologically damaged pollen grains.

The dominant taxa in the local vegetation, as illustrated previously in figure 6.44, on the slopes and plateau adjacent to the sampling site are Acer, Fraxinus, Fagus Betula and Corylus. The dominant riparian taxa along the riverbanks at the field site are Alnus Betula and Salix. Tree taxa such Picea, Tilia, Pinus, Quercus, and Ulmus are poorly represented in the local vegetation, meaning pollen influx to the site must be primarily a regional pollen signal. As illustrated in figure 6.38, TWINSPAN groups A, B_1, and B_2 are located in the deep central and lower sections of the pool and are characterised by higher relative abundances of 'fast' fallspeed taxa such as Acer, Picea, Tilia, Pinus, Quercus, Fagus and Ulmus and lower relative abundances of 'slow' fallspeed taxa such as Fraxinus, Salix, Betula, and Alnus. Sample 14 in group A is located on the southern side of the pool in the shallowest pool position of this group, and is notable for displaying the lowest relative abundance of riparian 'slow' fallspeed taxa. Group C_1 is located in the shallow top section of the pool, and is characterised by relatively equal abundances of both 'fast' and 'slow' fallspeed taxa. Group C_2 is located on a moss polster on the northern riverbank, and is characterised by relatively high abundances of 'fast' fallspeed taxa such as Fagus and Picea. Group D (samples 5, 8, and 16) is located in the deeper central and bottom sections of the pool, and is characterised by high relative abundances of slow fallspeed taxa such as Salix, Betula, Corylus, Fraxinus, and Alnus, with lower relative abundances of fast fallspeed taxa such as Quercus, Ulmus, and Pinus.

Scenario 1 – The Prentice Model

Evidence for scenario 1, the aerially deposited and non-mixed Prentice Model, is found in the higher relative abundance of riparian Alnus pollen at sample locations positioned closest to the riverbanks where Alnus vegetation is prolific i.e. sample locations 2, 3, 6, 10, 13 and 16 which are closest to the northern riverbank at the sampling site, and at sample locations 1, 4, 5, 8 and 11 which are closest to the southern riverbank. Alnus also has a 'slow' fallspeed based on the taxa fallspeeds presented in table 6.17, which suggests that the high Alnus pollen abundances observed at the northern and southern bankside sample locations may indicate that riparian Alnus pollen is not transported over any significant distances away i.e. downstream from the pollen producing vegetation at the Litton Mill site. This hypothesis is supported by the observation that water depths at these sample locations range from 0.5 – 1.5 metres, suggesting that water depth does not appear to be a significant control on Alnus percentage values at these sample locations due to riparian pollen settling directly from the aerial deposition point on the pool surface into bed sediment without any downstream transport occurring whilst the pollen travelling through the water column.

Samples 1, 2, 3, and 4 represent TWINSPAN group C_1 located in the narrowest and shallowest section of the sampling site at the top of the pool, this TWINSPAN group is notable for lower relative abundances of locally dominant Fraxinus and non-local Pinus pollen. This contrasts with the higher relative abundance of non-local Pinus and local Fraxinus pollen in the wider and deeper section of the sampling site at the tail of the pool. This suggests that, in the case of Fraxinus and Pinus, the narrower width of this upper section may reduce basin size at this portion of the pool effectively resulting in a reduction in aerially transported pollen input at this point. Contrastingly, the highest percentages of local Fraxinus and non-local Pinus pollen are focused in sample locations 11, 12, 13, 14, 15 and 16 situated in the more open centre and bottom portions of the pool, displaying a trend of higher pollen deposition in the centre of the basin which is analogous to the model of Holmes (1994) illustrated in the left –hand diagram of figure 6.45. The more open aspect of the central and lower portions of the Litton Mill site would effectively offer a larger basin diameter to aerially transported non-local pollen such as Pinus, Ulmus and Quercus, and to local vegetation types such as Acer, Fagus and Fraxinus which are present on the adjacent plateau and valley slopes surrounding the field site.

The shallower water depths of 0.5 m at the top of the field site, as is illustrated in the bubble plots in figure 6.33, display high percentages of local Fagus, Acer, Picea, Salix, Quercus and Betula pollen, suggesting that water depth may be a factor influencing the distribution of these pollen types at the field site. However these taxa display a range of differing fallspeeds, with Acer, Fagus and Picea being classed as 'fast' grains, Quercus being 'intermediate' and Betula and Salix being categorized as 'slow' in table 6.17. Of these taxa, Salix, Picea and Fagus display a more visible trend of higher pollen percentages being associated with the shallower upper portion of the pool at sample points 1 – 4, where water depths, as displayed in table 6.16, are 0.5m. As is illustrated in figure 6.44, Picea and Fagus vegetation is located on the adjacent plateau and valley slopes, and Salix is a dominant riparian vegetation component on the point bar in the centre of the pool. Acer displays a relatively homogeneous pollen proportion at all 17 sample locations, which suggests that as Acer is the dominant taxon in the local vegetation the aerial pollen rain input of Acer to the Litton Mill field site is therefore uniform and that post-depositional sediment movement may be limited at the field site.

Based on the fluvial model of Holmes (1994) for lakes with inflowing streams illustrated in figure 6.46 is accepted, percentages of Salix pollen would be highest at sample locations in the lower reaches of the pool due to the longer settling time required by the slower fallspeed of the smaller and lighter Salix grains. However this is not the case at the Litton Mill field site, meaning that the most likely hypothesis for the higher Salix pollen percentages observed in samples 1 -4 at the top of the pool is that, as previously discussed for Alnus, riparian Salix pollen is settling through the water column with only minimal post depositional transport downstream from the point of pollen deposition on the surface of the pool to sedimentation in pool sediment. If the hypothesis of minimal post depositional transport is accepted for 'slow' Salix pollen, then the higher percentages of 'fast' Picea and Fagus pollen observed at the shallower top part of the field site may simply represent the stochastic nature of aerial pollen deposition onto the surface of this basin. Pollen percentages of Tilia, an 'intermediate fallspeed pollen type, are higher in the deeper centre and bottom portions of the field site suggesting that differential sorting of pollen is not significant as, based on table 6.17, taxa with 'fast' fallspeeds should be focused in the upper and middle portions of the pool if fluvial transport was dominant at the site.

Scenario 2 – The Prentice-Sugita Model

Some evidence for scenario 2, the Prentice-Sugita Model whereby pollen becomes homogenised regardless of grain size, weight and fallspeed, is observed at the Litton Mill field site in the lack of a definitive, overall pattern of differential sorting by fallspeed at the sampling site. Some taxa display relatively similar pollen proportions at all of the sample locations i.e. Acer, Alnus, Fraxinus, with very few significant outliers of anomalously high or low pollen percentage values. The shallow top section of the field site appears to be a site of preferential deposition for taxa with heavy 'fast' fallspeed pollen grains such as Picea, Fagus and Acer. However as discussed in the previous scenario, it is only Fagus which has high pollen percentages exclusively in the shallow sample points 1 – 4, with Picea having high pollen percentages at sample points 6 and 7 at the deeper bottom portion of the field site. Acer, the dominant taxon in the local plateau and valley side vegetation, displays very similar pollen percentages at all sample locations in the pool; this may be a product of interdependence of pollen percentages (Prentice & Webb III, 1986) as the canopy of local Acer vegetation encroaches over the pool, and could effectively dominate the trunk space and local pollen input to the pool. Riparian taxa such as Alnus and Betula display higher pollen abundances at sample location closer to the riverbanks, but are still well represented in assemblages taken at all sampling points, suggesting that some post depositional transport and mixing of pollen is occurring. The exception to this is Salix which displays its lowest relative abundance in the deep central sample points 12 and 15; however as illustrated in the Excel bubble plots illustrated in figure 6.33, the highest relative abundance of Salix pollen in samples is observed in the shallow top portion of the pool, which is counterintuitive to the differential sorting of pollen based on settling velocity associated with the fluvial pollen transport model proposed by Holmes (1994).

Pollen percentage values of Ulmus are high at sample points located at the top (3), centre (10) and bottom (7) of the Litton Mill field site, with two of the lowest pollen percentage values observed at sample locations 1 and 5 which also represent two of the shallowest sample location depths. This degree of randomness in pollen percentages suggests that this pattern of pollen distribution either represents the same degree of randomness in pollen deposition on the surface of the pool with near zero transport from the point of deposition to the river bed, or represents a degree of post depositional transport both on the pool surface as a product of wind-driven fetch whilst the pollen becomes saturated before sinking and from wind-driven and fluvial sub-surface currents.

Scenario 3 – The Fluvial Model

Some evidence for the Fluvial Model of pollen transport can be observed in the pattern of pollen percentages for Picea, Fagus, Betula and Salix at sample locations at the top of the field site. However the absence of any mechanically damaged pollen indicative of both overland and fluvial transport as part of a sediment load (Brown, 1985), or biologically or chemically corroded grains indicative of remobilised pollen from the catchment surface or river bed sediments (Campbell, 1999) suggests that pollen transport from these vectors is episodic at the Litton Mill field site. It may be the case that as the field site essentially represents a low energy backwater, that the main pollen load in flood events is transported on the southern side of the central point bar resulting in limited fluvial transport of pollen bearing sediment to the study site. The hydrology of the White Peak limestone karst catchment results in very low river flow rates, with a Q_{95} of 3 m/sec and a Q_{10} of 6 m/sec meaning that flood events are of low magnitude in comparison with catchments on non-karstic geology. The absence of flood remobilised bed sediment pollen and of overland flows enabling transport of pollen in storage on the catchment surface suggests a predominantly aerial mode of pollen transport to the river channel; pollen which then becomes integrated into bed sediment close to the point of entry into the water column. However as discussed in scenario 2, the effects of wind-driven surface fetch may be a significant post depositional transport vector at the site, meaning pollen deposited aerially is carried along on the surface of the pool by the wind before becoming saturated to the degree required to sink through the water column and become integrated into bed sediment. Some evidence of sediment focusing is evident in that TWINSPAN groups A, $B_1$and B_2, displayed in figure 6.38, are all characterised by 'fast' fallspeed taxa such as Acer, Picea, Tilia, Pinus, Quercus, Fagus and Ulmus, are located in the deeper central and bottom portions of the field site.

6.4.3. Conclusion

Only Fagus, Salix, Betula and Picea display a trend of higher pollen percentages in the shallow upper section of the pool, the remaining taxa do not display the patterns of pollen distribution associated with the primarily fluvial pollen transport model described by Holmes (1994) and illustrated in figure 6.46. The overall pattern of pollen deposition observed at the Litton Mill field site bears a greater resemblance to the aerial model suggested by Holmes (1994) illustrated in figure 6.45. This suggests that the most credible scenario of pollen dispersion and deposition at the Litton Mill field site is scenario 2, the Prentice-Sugita Model, which effectively represents two extremes of a continuum from no post-depositional mixing to complete post-depositional mixing (Jackson & Lyford, 1999), combined with minor elements of the fluvial model of Holmes (1994) through episodic flood events. Pollen assemblages of some taxa i.e. Acer, Fraxinus, Ulmus and Acer were found to be broadly homogeneous at all the sampling locations, suggesting that some post-depositional sediment mixing may be occurring as a result of episodic variations in river flow, wind-driven surface currents and sub-surface currents; however elements of the Prentice model, where no post depositional mixing occurs, are evident at the sampling points adjacent to the riverbank where riparian pollen abundances are predominantly higher.

Some degree of focusing of heavier pollen grains is evident, notably in the deeper central and lower sections of the pool, where ‘fast’ fallspeed taxa display higher relative abundances i.e. TWINSPAN groups A, $B_1$and B_2. This focusing may simply reflect the effect of increased basin size at this section of the sampling site, which allow larger numbers of aerially transported pollen to enter the pool at this point; however the association of heavier grains with the deepest sections of the field site may also be interpreted as evidence of sediment focusing of ‘fast’ fallspeed pollen during high river stages and episodic flood events. It is argued that pollen deposition at the Litton Mill site, due to the hydrological characteristics previously discussed, essentially equates to that of pollen deposition in a slow moving lake or fluvial pond where pollen transport to the site is predominantly aerial with greater relative abundances of regional and local pollen being deposited in the widest section of the field site, which is effectively the largest pollen-sensing portion of the field site, with episodic influxes of pollen remobilised from bed sediment. High riparian taxa pollen percentages are associated with sample locations adjacent to the river banks, which are adjacent to the dominant riparian pollen sources such as Alnus, Betula and Salix. Lower relative abundances of pollen from regional and local pollen sources are observed in the more enclosed and narrow upper section of the sampling site, where overhanging riparian vegetation and the smaller 'basin' size at this section may restrict and therefore reduce aerial deposition of pollen via the canopy and rain components at this section of the pool.

Interdependence of pollen percentages at the Litton Mill site is also to be considered. The two dominant taxa in the local vegetation are Acer with an RPPE of 0.35 for Acer (Mazier et al., 2008) and Fraxinus with an RPPE of 1 – 2 (this study). Based on these figures, the significant amount of pollen contributed to the basin by these two taxa, especially Acer which is ubiquitous in the local and regional vegetation, suggests that percentages of other local and regional taxa may be overwhelmed and suppressed by this strong local signal. Interdependence has been shown to be less significant in its effect in woodlands with high taxonomic diversity amongst tree taxa (Prentice & Webb III, 1986). However at the Litton Mill field site the predominance of Acer and Fraxinus in the local woodland suggest that pollen percentages of other tree taxa recorded in assemblages may be reduced, as these two taxa exceed the 20 – 30% threshold for tree abundance discussed by Webb *et al*. (1981).

6.5 Palaeoenvironmental Study

Introduction

This study aims to investigate the environmental conditions at the time of cessation of tufa production composition in the White Peak, Derbyshire. Pollen analysis is used to examine changes in local vegetation at two buried Holocene barrage tufa sites in the White Peak in order to establish if anthropogenic disturbance in the local landscape is a significant factor in tufa cessation. Cessation of mid - late Holocene tufa production in the White Peak is synchronous with the pan-European 'Tufa Decline' described by Goudie (1993), who suggests that Neolithic woodland clearance and agricultural practices may have been significant factors in the cessation of tufa production in NW Europe. Study sites are described in chapter 3 and illustrated in figures 3.2 and 3.3.; field and laboratory methods used in this study are described in chapter 5.

6.5.1. Results

Conksbury Bridge

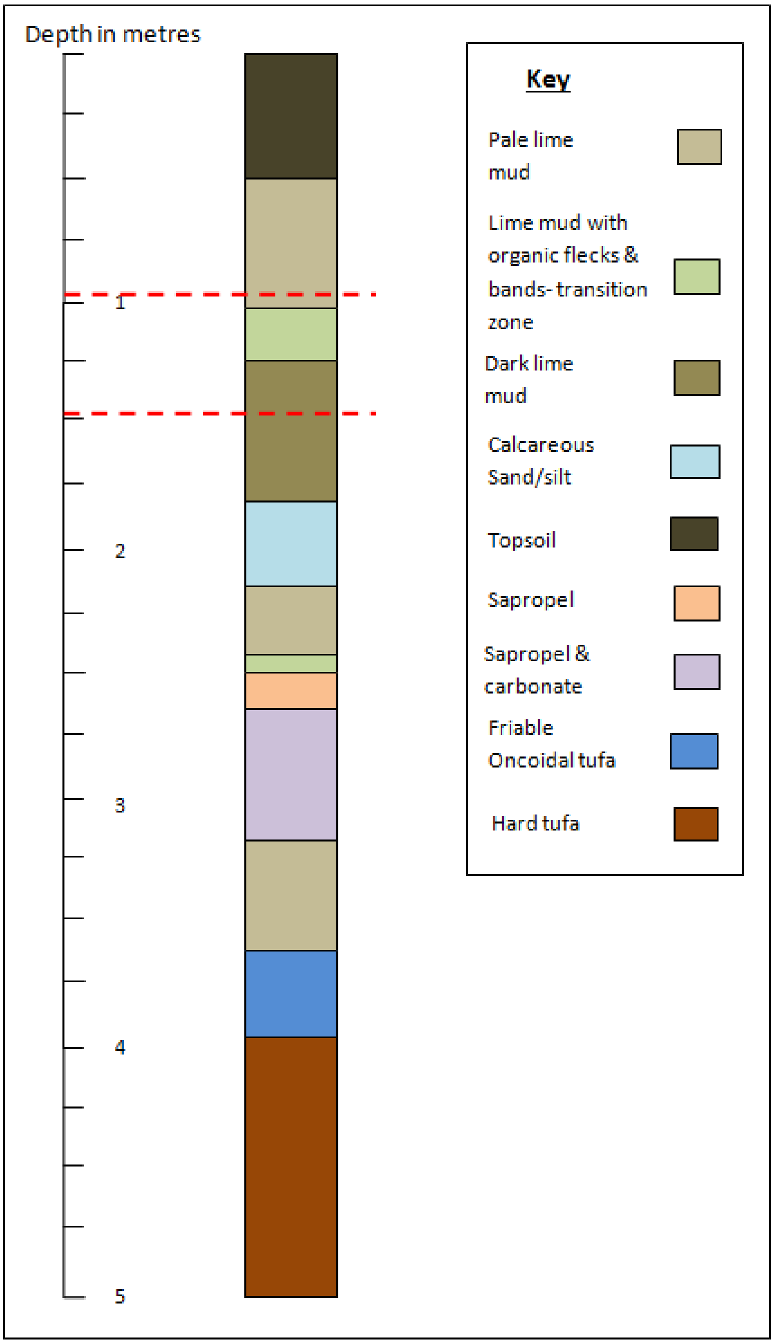
Pollen percentages are displayed in the diagram displayed in figure 6.48 below, and the stratigraphic log of the Conksbury Bridge core sediment is displayed in figure 6.49 below. Eleven samples were used to examine the pollen percentage values immediately prior to, during, and after the transition in sedimentation mechanism which is observed in figure 6.49 at a depth of 98 cm.

Two pollen zones are identified in the Conksbury diagram in figure 6.48. Zone 1 is characterised by sharply declining Calluna values and the reciprocal rise in Cyperaceae values which occurs at approximately the same depth of 112cm. Zone 2 is characterised by high Calluna percentage values and greater floral diversity in the herb taxa such as Filipendula-type, Rumex-type, Gallium-type and Potentilla-type. AP values are relatively low across both pollen zones, suggesting that woodland was not a significant feature of the local landscape during the time period under investigation. *Corylus avellana* displays the highest AP percentage values across both zones, with *Alnus glutinosa* maintaining low but relatively consistent values in zone 1 before declining sharply in zone 2.

Figure 6.48: Pollen diagram will be inserted here as an A3 sheet.

Percentage values of Pinus-type display a rise from approximately 2% in zone 1 to 6% at the inception of zone 2 before decreasing back to zone 1 values. *Fraxinus excelsior* percentage values display an increase in from 2% to 5% at the termination of zone 1, percentage values then decline back to 2% at the inception of zone 2.

Figure 6.49: Stratigraphic log of Conksbury Bridge core sediments – dashed red line indicates location within the core of the 11 samples used for analysis – 98 cm is proposed as the switch-off horizon.



Samples

- 101 samples in total
- Samples 1 – 9: pale lime mud (depth 50 – 95cm)
- Samples 10 – 15: lime mud /organic transition zone (depth 102 – 125cm)
- Samples 16 – 26: dark lime mud (depth 125 - 183cm)
- Samples 27 – 32: calcareous sand/silt + oncoids (depth 183-215cm)
- Samples 34 – 38: lime mud (depth 215-240cm)
- Samples 39 – 42: lime mud/organic transition zone (depth 20 – 252cm)
- Samples 42 – 45: sapropel (depth 252-265cm)
- Samples 46 – 68: sapropel & carbonate (depth 265 – 328cm)
- Samples 69 – 76: pale lime mud (depth 329 – 365cm)
- Samples 77 – 82: friable oncoidal tufa (depth 365-393cm)
- Samples 83 – 101: hard tufa Depth 416 – 500cm)

Percentage values of Poaceae remain relatively low throughout both zones, however percentage values of Poaceae in size classes 26-40 µm and 26< µm display a slight increase in zone 2. Percentage values of Poaceae in size class 26-40 µm increase to a maximum value of 10% at the inception of zone 2 before maintaining a value of approximately 5% across the remainder of the zone.

The low AP values and relatively high NAP values displayed in the Conksbury pollen percentage diagram in figure 6.48 suggest a relatively open landscape where tree taxa are not a significant part of the vegetation. The two most significant factors in the Conksbury percentage diagram are the changes in Calluna and Cyperaceae values observed at the transition from pollen zone 1 to zone 2, and the reduction in floral diversity of herb taxa in zone 2. Calluna is the dominant taxon in zone 1 averaging 20% of TLPS across the zone. High Calluna percentage values suggest input of extra-local and regional aerially transported pollen from the adjacent Dark Peak where extensive peat moorland and heathland provide acid soils ideally suited to Calluna dominated vegetation. Secondary fluvial transport of pollen from the Dark Peak may also be a factor in the dominance of Calluna in percentage values in zone 1, with the entire River Lathkill drainage system behaving as a depositional basin for both flow transport and overland redeposition during flood events. It is likely that, due to the low Cyperaceae percentage values observed in zone 1, that the Conksbury site may have been more open in this pollen zone. A greater degree of openness at the Conksbury site would provide a larger depositional area and consequently allow greater input of aerially transported AP and NAP pollen to the basin. If the river system as a whole had a more open aspect during this period, this would potentially allow greater volumes of aerially transported pollen to enter the catchment and, if river flows were greater, to transport a higher proportion of the aerially deposited pollen throughout the catchment. A basin with low amounts of fringing herb vegetation would also influence the amount and diversity of gravity-deposited pollen from riparian tree taxa such as *Alnus glutinosa* which displays a decline in pollen percentages in zone 2.

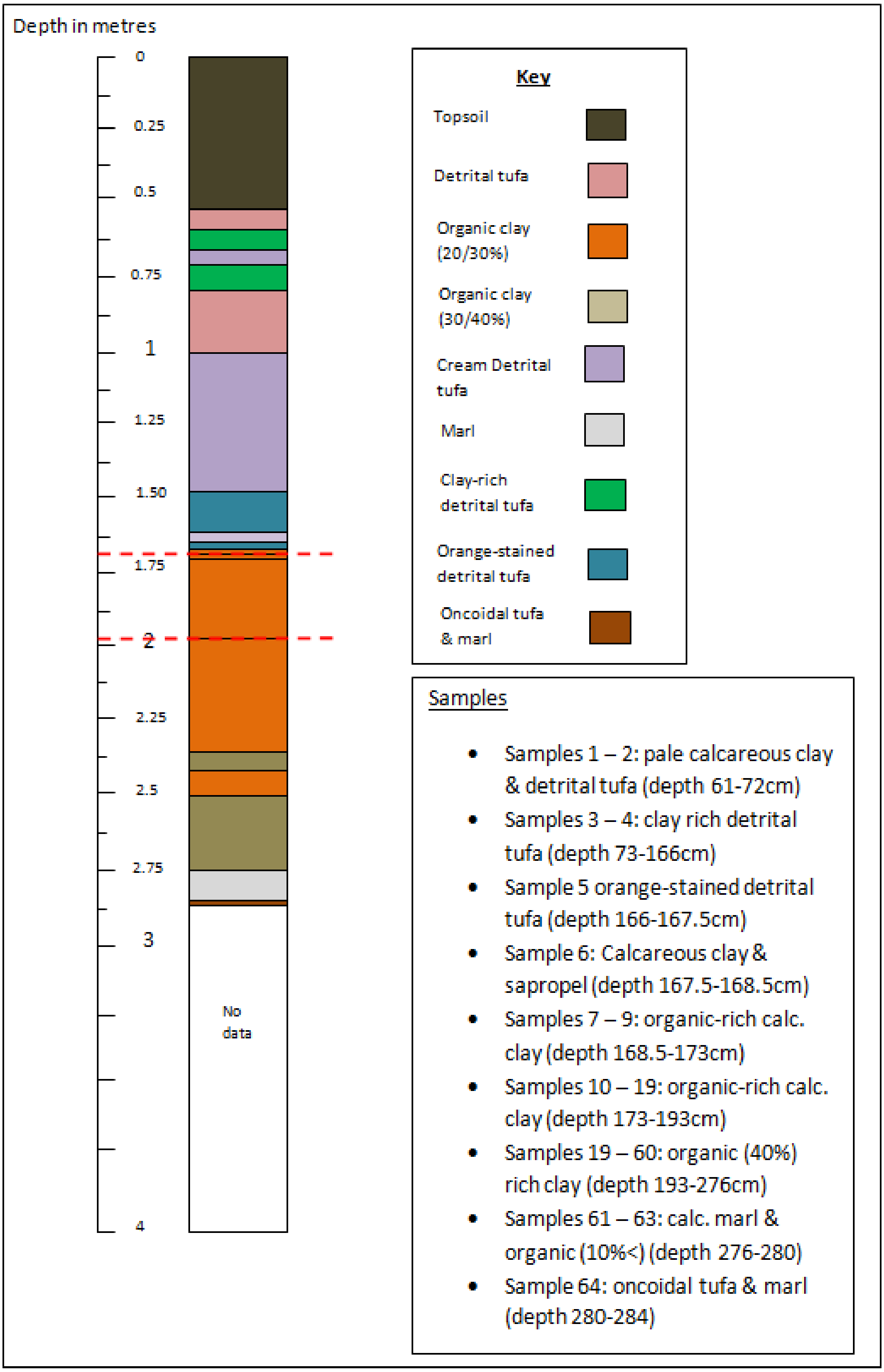
The presence of a diverse suite of herb taxa e.g. Filipendula and Rannunculus in zone 1 and the subsequent disappearance of nearly all herb taxa in zone 2 suggests that monospecific fringing stands of Cyperaceae may be dominating the local gravity pollen component at the site as basin size decreases as terrestrialization proceeds. The encroachment of riparian herb vegetation into the pool is also suggested by increasing percentage values of Lysimachia in zone 2; a taxa which is associated with wet and/or damp environments such as marshes and riverbanks (Stace, 1997). The herb taxa observed in zone 1 may still be present in the local vegetation, may be unable to transport pollen over or through the Cyperaceae stands surrounding the pool. The significant increase in Cyperaceae values observed during zone 2 suggests a transition in environmental conditions at the Conksbury Bridge site from an active fluvial system with regular flows which decline, creating a static pool/pond environment which then becomes in-filled by the littoral vegetation such as Cyperaceae. This terrestrialization process from active fluvial system to marsh/mire and then dry land would provide an ideal environment for Cyperaceae taxa such as *Carex nigra* and *Carex panacea*, which are indicative of marsh and mire environments. The presence of thermophilous tree taxa such as *Acer* in zone 1 suggest a late Holocene date for the diagram, Acer being observed for the first time in the White Peak at approximately 3000 yr BP. (Wiltshire & Edwards, 1993).

Monsal Dale

The Monsal Dale pollen percentages are displayed in figure 6.50 below and a stratigraphic log of the Monsal core sediment is displayed in figure 6.51 below. Eleven samples were used to examine the pollen percentage values immediately prior to, during, and after the transition in sedimentation mechanism which is suggested as occurring at 168.5 cm as illustrated in figures 6.50 and 6.51. The Monsal Dale percentage pollen diagram has been split into 3 sub-zones based on a visual assessment of vegetation change. The diagram is dominated by AP taxa, which remain relatively constant at approximately 80% throughout all three sub-zones. NAP values also remain relatively constant throughout sub-zones 1 – 3 at approximately 20%, with an increase in percentage values to 26% occurring at the end of sub-zone 1.

Figure 6.50: Pollen diagram will be inserted here as an A3 sheet.

Figure 6.51: Stratigraphic log of Monsal Dale core - dashed red line indicates the depth and location within the core of the 11 samples used for analysis – 168.5 cm is proposed as the switch-off horizon.



Samples

- Samples 1 – 2: pale calcareous clay & detrital tufa (depth 61-72cm)
- Samples 3 – 4: clay rich detrital tufa (depth 73-166cm)
- Sample 5 orange-stained detrital tufa (depth 166-167.5cm)
- Sample 6: Calcareous clay & sapropel (depth 167.5-168.5cm)
- Samples 7 – 9: organic-rich calc. clay (depth 168.5-173cm)
- Samples 10 – 19: organic-rich calc. clay (depth 173-193cm)
- Samples 19 – 60: organic (40%) rich clay (depth 193-276cm)
- Samples 61 – 63: calc. marl & organic (10%<) (depth 276-280)
- Sample 64: oncoidal tufa & marl (depth 280-284)

All three sub-zones are described in more detail below. Sub-zone 3 is characterised by high *Corylus avellana* values, which rise to a peak of 60% at the end of the sub-zone, value of Pinus-*type* fall from 20% at the beginning of the sub-zone to a low point of 10% at the end of the sub-zone. *Betula pendula* values remain at 10% throughout the sub-zone, before displaying a rise in values at the close of the sub-zone.

Alnus glutinosa values remain very low throughout sub-zone 3 at <3%. *Ulmus glabra* percentage values display an upward trend in sub-zone 3 rising from 1% to 4% through the sub-zone. Other AP taxa such as *Quercus robur*, Salix-*type*, and *Fraxinus excelsior* are present at very low values of <0.5%, with AP taxa such as Acer-*type*, *Fagus sylvatica*, and Sorbus-*type* being absent in sub-zone 3. NAP pollen percentage values are generally very low throughout sub-zone 3 at <0.5%, the exceptions being Cyperaceae which rises from 2% to 5% across the sub-zone and Rannunculus-*type* which falls from 2% to zero across the sub-zone. Percentage values of *Poaceae* in the <26µm and 26µm – 40µm classes are low across the sub-zone with values of <5%, *Poaceae* size class >40 µm is present at the end of the sub-zone at values of <1%.

AP values in sub-zone 2 are characterised by declining *Corylus avellana* values which fall from 55% to 25% across the sub-zone. Both *Betula pendula* and Pinus-*type* display a rise in percentage values across the sub-zone, with *Betula pendula* rising from 4% to 8% and Pinus-*type* percentage values increasing from 5% to 30%. *Alnus glutinosa* displays very low values of 1% < across the zone, with *Ulmus glabra* displaying a rise in values from 2% to 5% before declining to 2% in the middle of the sub-zone and then rising to 5% at the end of the sub-zone. Salix-*type*, *Fraxinus excelsior*, and *Quercus robur* all display a very slight rise in percentage values from 0.5% - 1% across the sub-zone. Acer-*type*, *Fagus sylvatica*, and Sorbus-*type* all display very low percentage values of <0.5% across the sub-zone.

NAP taxa display a greater diversity in sub-zone 2, with taxa such as Caryophyllaceae-*type*, Potentilla-*type*, *Urtica dioica,* and Gentianella-*type* appearing at very low values of <1% in the pollen record in this sub-zone. A rise in percentage values of Rosaceae-*type* and Filipendula-*type* values is observed across sub-zone 2, with percentage values increasing from 1% to 3% across the sub-zone. Poaceae percentage values display a slight rise across sub-zone 2, with size classes <26µm and 26µm – 40µm rising to approximately 5% and remaining relatively constant at this level before declining to <1% at the end of the sub-zone. Poaceae size class >40 µm remains very low in sub-zone 2 with values at <2%. Cyperaceae values decline slightly across sub-zone 2, before rising at the end of the sub-zone.

Sub-zone 1 is characterised by a rise in Pinus-*type* percentage values from 30% to 42%, which is accompanied by synchronous fall in *Corylus avellana* values from 25% to 6% and a fall in *Betula pendula* values from 8% to 4%. Percentage values of *Alnus glutinosa* display a slight rise to 2%, and *Ulmus glabra* values fall to 3 %<. Percentage values of other AP taxa such as *Quercus robur*, *Fraxinus excelsior*, *Fagus sylvatica*, and Sorbus-*type* remain very low at 0.5 %<. Floral diversity of NAP taxa decreases markedly in sub-zone 1, with only Rumex-*type*, Filipendula-*type*, and Rosaceae-*type* still present among the herb taxa in this sub-zone. Percentage values of Poaceae classes size classes <26µm and 26µm – 40µm display decreasing values, whilst Poaceae size class >40 µm displays an increase from 1% to 3%. Values of Cyperaceae display a small increase from 6% to 11% in sub-zone 1.

The 28.5 cm of sediment used to present the pollen assemblage displayed in figure 6.50 essentially represents a 'snapshot' of a Holocene temperate woodland landscape. However there are several factors which are striking about the changes in the Monsal Dale vegetation which are inferred from the pollen percentages displayed in figure 6.50. The first is the lack of thermophilous deciduous forest tree taxa such as *Tilia cordata*, *Acer campestre*, and *Fagus sylvatica* which are indicative of mid – late Holocene pollen assemblages. The second factor is the very high proportion of *Corylus avellana* pollen, and the relatively high proportion of Pinus-*type* pollen contained in the samples in all 3 sub-zones. A third observation is that the assemblage is dominated by AP taxa, resulting in a paucity of herb and forb taxa throughout the 3 sub-zones. Without a valid radiocarbon date, the age range of the core can only be discussed in terms of similarities of pollen values from other White Peak and adjacent Dark Peak sites where radiocarbon dating was carried out.

There are three hypotheses which may be advanced in the interpretation of the Monsal Dale assemblages:

1) The assemblages represent an early Holocene landscape.
2) The assemblages represent a middle Holocene landscape.

3) The assemblages represent both and early and a middle Holocene landscape, but has been influenced by a hiatus in deposition resulting in an interruption in the pollen record.

These hypotheses are discussed below.

1) The assemblage represents an early Holocene landscape.

The Monsal diagram suggests an early or early-mid Holocene assemblage typical of the protocratic – mesocratic transition, with high percentage values of *Corylus avellana*, Pinus-*type* and *Betula pendula* dominating the assemblage in all three sub-zones. *Ulmus glabra* and *Alnus glutinosa* are also associated with early - mid Holocene assemblages (Birks, 1989), and are present in the 3 sub-zones at low percentage values. The absence of *Tilia cordata* supports an early Holocene date for the assemblage, as *Tilia cordata* is present at the Raper Lodge site in the Wye valley from 9 ka BP (Taylor et al., 1994), and at percentages >5% at 6.6 ka BP at the Lismore Fields site of Wiltshire & Edwards (1993).

2) The assemblage represents a middle Holocene landscape.

The early Holocene hypothesis is contradicted by the presence of *Acer-type* and *Fagus sylvatica* in the Monsal Dale assemblage, as both taxa are recognized as arriving in northern England from the mid – late Holocene onward (Birks, 1980; Birks, 1989); *Fagus sylvatica* being present in the Lismore Fields assemblage from 4 ka BP, and *Acer campestre* being present in the Lismore Fields assemblage at 3 ka BP. The presence of Acer-*type* and *Fagus sylvatica* in the Monsal Dale diagram displayed in figure 6.50 may be the result of pollen counting error, as the values are 0.5% < in only 3 samples from the total of 11. A second hypothesis is that only the lower instance of Acer-*type* at 177 cm represents counting error, and that the upper occurrence of Acer-*type* at 168.5 cm does represent the presence of the tree taxa in the local landscape. This would follow the dispersal characteristics of British forest tree taxa described in Birks (1989), in that *Fagus sylvatica* would be established slightly before *Acer campestre*, this supposition is supported by the order of appearance of these two taxa at the Lismore Fields site where Fagus sylvatica appears at 4.5 ka BP and Acer-type is first recorded at c. 3 ka BP. (Edwards & Wiltshire, 1993). Based on the Monsal diagram, the occurrence of *Fagus* *sylvatica* at 172 cm would support this hypothesis. If Acer-*type* and *Fagus sylvatica* are present in the landscape, this would place the Monsal Dale assemblage in the mid-late Holocene at approximately 4.5 ka BP based on the first occurrence of *Fagus sylvatica* at the Lismore Fields site. However no *Fagus sylvatica or* Acer-*type* is recorded in the Raper Lodge diagram of Taylor *et al*. (1994).

A pollen percentage diagram from derived from a sediment core taken at Coalpit Bridge in Lathkill Dale is displayed in figure 6.52 below. The Coalpit Bridge core was taken as a part of a GPR investigation of Holocene tufa deposits by Pedley et al. (2000); the core has a sampling interval of 1 metre and is not radiocarbon dated. The Coalpit Bridge site is approximately 500m SW of the Raper Lodge coring site on the alluvial floodplain on the west bank of the River Lathkill. The Coalpit Bridge diagram displays a typical early to middle to late Holocene succession of protocratic and mesocratic vegetation succession, with the Elm decline clearly visible at 4.4 m and the Elm recovery beginning at 3.6 m. The Elm decline is also visible in the Raper Lodge diagram of Taylor *et al*. (1994) at approximately 3.3 m dating the Elm decline in Lathkill Dale to approximately 5 ka BP, with a recovery visible at 2.7 m at a date (Cal. BP) of 4.6 ka BP. Based on the radiocarbon dated cores taken by Taylor *et al*. (1994), if the Raper Lodge core Elm decline is synchronous with the same event in the Coalpit Bridge core, then the occurrence of *Fagus sylvatica* in the Coalpit core is suggested to be between 4 – 4.2 ka BP, based on the rationale that the same local pollen sources deposited *Ulmus cordata* pollen in equal amounts at both sites. Based on this hypothesis, this may potentially date the appearance of *Fagus sylvatica* at the top of sub-zone 1 in the Monsal Dale diagram to the same period.

The distance between the Monsal Dale coring site and Lathkill Dale site at Coalpit Bridge is approximately 5 km meaning that, based on the uniformity of the soils and relief between the two sites, it is possible that *Fagus sylvatica* could present in Monsal Dale at 4.2 ka BP, giving credence to the presence of the taxon in the Monsal Dale diagram and potentially providing a date for the top of the Monsal Dale diagram.

Figure 6.52: Pollen diagram will be inserted here as an A3 sheet.

The absence of *Fagus sylvatica* pollen from the Raper Lodge core may be a product of the effect on pollen dispersal produced by the large grain size (57 µm), and the relatively low pollen productivity of the taxon. The low pollen percentage values of Cyperaceae displayed at the Monsal Dale site suggest that the site remained relatively open until the very end of the temporal period covered by the pollen diagram, and that the fluvial system may have still been active during this period.

When the hypothesis that the inception of zone 1 dates to 4.2 ka BP is used, the high values of *Corylus avellana* may represent the development of hazel woodland associated with post-anthropogenic forest clearance. This clearance is suggested by Taylor et al. (1994) as an indicator of forest clearance by Neolithic pastoralists to provide pasture for livestock, and culminates in the Raper Lodge core as an almost complete removal of woodland from the Lathkill catchment at 4100 ka BP. Taylor et al. (1994) also interpret the intercalated bands of calcareous muds at 4.1 ka BP. in the Raper Lodge core as representing increased runoff transporting soil sediments into the fluvial system which contributes to the cessation of tufa production in Lathkill Dale. The dark organic-rich calcareous clay from which the Monsal Dale core samples are taken are also interpreted as representing the influx of soil sediment into the basin, which suggests the events in Monsal Dale and Lathkill Dale may be synchronous if the 4.2 ka BP hypothesis is accepted.

3) The assemblage represents both an early and a mid - late Holocene landscape, but has been influenced by a hiatus in deposition at the site.

The potential for this scenario is increased by the core's location within the buried tufa pool being suggested, based on the sedimentology of the Monsal Dale core, as representing a pool margin and not the more central main deposition centre in the main channel behind the primary tufa barrage (Dr. H.M. Pedley; personal communication). The maximum pool water depths at the Derbyshire Holocene barrage tufa systems are suggested as not exceeding two metres (Pedley, 1993), with sedimentation suggested as following vertical barrier growth as the tufa system developed. A cessation in barrage building at the site would result in a cessation in sedimentation, especially at the more marginal areas of the pool, as accommodation space would not be available. A similar hiatus was observed by Bunting & Warner

(1999) in a shrub swamp in Canada, where no net sedimentation accumulation occurred for 5800 years, and was attributed to changes in the local water table exacerbated by increased mid-late Holocene temperatures. Pedley *et al* (2000) identified a series of truncation surfaces in a buried Holocene tufa at a site Lathkill Dale, which are suggested as indicators of minor episodes of erosion and retrenchment of barrage tufa systems driven by drier regional climatic conditions affecting the water table. These periods of re-adjustment of local hydrological conditions may be linked to a series of sedimentary hiatus's at the Monsal Dale site.

6.5.2. Discussion

Based on the results and analysis section, the two sites appear to represent relatively open landscapes. The environmental conditions at the two field sites are discussed below; the Monsal Dale field site is discussed first and then the Conksbury Bridge field site.

Monsal Dale

The Monsal Dale pollen diagram displayed in figure 6.50 on page 240 appears to represent an open landscape dominated by scrub taxa such as *Corylus avellana* and *Betula Pendula*; the very high *Corylus avellana* values observed in zone 1 in figure 6.50 suggests that *Corylus avellana* was able to flower abundantly, indicating that the taxon was able to occupy significant areas of unshaded habitat within the local landscape. The steadily increasing Pinus values in zone 2 and the significant increase in Pinus values observed in zone 1 in figure 6.50 suggest increasing establishment of Pinus vegetation both on the White Peak and the adjacent Dark Peak resulting in a rise in the local and regional pollen signal for this taxon. Percentage values of Poaceae and Cyperaceae remain relatively constant throughout zone 2, when at the transition to sub-zone 1 Cyperaceae levels begin to rise and continue to increase throughout sub-zone 1. Based on the indicator-species table presented in figure 6.53, the local habitat surrounding the Monsal Dale site appears to represent a wet meadow or pasture, as Poaceae and Cyperaceae are the dominant NAP taxa. The presence of *Alnus glutinosa* at very low percentage values in sub-zone 3 suggests the site may have been more waterlogged at this period; the decreasing *Alnus glutinosa* values in sub-zone 2 suggest that the site may have become drier during this sub-zone. Thermophilous tree taxa are largely absent from the local landscape, with *Ulmus glabra* displaying relatively constant low values throughout all 3 sub-zones, and representing the dominant in the local and extra-local landscape. The presence of Acer pollen at very low values in sub-zone 3 suggests a late Holocene date for the base of the diagram, based on the appearance of *Acer* in the White Peak at 3000 yr BP. (Wiltshire & Edwards, 1993).

The landscape stage represented by the Monsal Dale stratigraphic diagram displayed in figure 6.51 appears to represent a period incorporating high terrigenous sediment transport events which have been associated with early-middle Neolithic agricultural landscape modifications discussed by Wiltshire & Edwards (1993) and Taylor *et al*. (1994). It can be seen in figure 6.51 that there are two distinct events where organic clays at a ratio of 40/50% occur in the lower section of the core between 2.75 and 2.25 metres depth, with clay rich sediment being continuously deposited into the tufa pool from a depth of 2.5 – 1.7m. The red dashed lines between 1.9 and 1.6 metres depth represent the section of the core selected for sub-sampling as the termination of the tufa system at the Monsal Dale site. This section of the core between the dashed red lines is suggested as representing the termination of terrigenous sediment input to the fluvial system, as the organic clay content decreases from 40/50% to 20/30% before being replaced by orange-stained detrital tufa sediment. No terrigenous sediment enters the tufa system after this horizon, suggesting either catchment stability or the initiation of the shutdown of the tufa system. The orange-stained detrital tufa observed after the termination of organic clay input in the stratigraphic log displayed in figure 6.51 suggests that this sediment was exposed to wetting/drying events, resulting from a reduction in flows and/or a terrestrialization of the Monsal Dale site.

The fluvial taphonomy study at Litton Mill previously described in section 6.4 of this results chapter has examined the pollen-vegetation relationship in a modern-day river pool setting on the River Wye in the White Peak in order to provide an analogue of the pollen-vegetation relationship at the Monsal Dale and Conksbury Bridge field sites when these tufa systems were still active. Based on the findings discussed in section 6.4, pollen transport to the active barrage tufa pools was likely to have been primarily aerial with a limited degree of post-depositional mixing as described by the Prentice-Sugita Model (1993); pollen transport from the wider catchment being limited to episodic flood events, meaning that pollen loading at the active and degrading barrage tufa pools would be principally comprised of the local and riparian pollen input representing the locale of the tufa pool sites and *not* the vegetation of the wider catchment.

However, the findings discussed in section 6.4 reflect the *modern* context of the White Peak landscape which has a stable vegetation cover primarily given over to grassland with woodland as a minor landscape component, and a hydrological regime that has been impacted by anthropogenic exploitation of the White Peak through both water abstraction for urban and agricultural/industrial purposes and the retrospective hydrological impacts of the lead mining industry in the White Peak during 18th and 19th centuries. In a *prehistoric* setting the hydrology of the White Peak would be unaffected by the effects of groundwater head drawdown and progressive decreases in spring discharge, river base flow and surface area of wetlands associated with post-industrial anthropogenic aquifer exploitation and disturbance (Custodio, 2002). This would suggest that river base flows would potentially be higher, greater resulting in potentially higher levels of fluvial pollen transport (Holmes, 1994) and the area of habitat suitable for fen carr woodland adjacent to the rivers of the White Peak would greater in extent. This would mean that pollen transport to the Monsal Dale and Conksbury Bridge field sites in the temporal period covered by the sub-samples at both the field sites used in this study would potentially contain a higher proportion of fluvially transported pollen representing *catchment-wide* vegetation, rather than the primarily local and riparian pollen signal representing the Prentice-Sugita model (1993) discussed in section 6.4 of this chapter.

Prior to the removal of significant areas of Tilia, Quercus and Ulmus woodland from the White Peak beginning at approximately 5 ka BP, an environmental event synchronous with the inception of early Neolithic agriculture in the region (Wiltshire & Edwards, 1993; Taylor *et al*., 1994), the catchments of the Wye and Lathkill rivers would be stabilised through the interception of rainfall regulated by interception of both valley-side and plateau vegetation. After 4100 ka BP (Taylor *et al*., 1994), the effect of an almost complete removal of trees from the hydrology of the River Lathkill catchment is recorded in the sedimentological record as a series of intercalculated bands of calcareous muds and sapropel in the Raper Lodge core of Taylor *et al*. (1994) in Lathkill Dale, and the increasingly clay-rich sediments which effectively mark the cessation of barrage-building tufa production at the Alport site of Pedley et al. (2000) at Alport in Lathkill Dale. Pedley *et al*. (2000) suggest that river flows in the Lathkill immediately prior to the influx of terrigenous sediment were similar to the modern-day flows observed at the Litton Mill site in section 6.4 of this chapter.

If the supposition is accepted that river flows in the River Lathkill *and* the River Wye were similar to modern-day flows immediately prior to the switch in sedimentation, this would effectively give two models of pollen transport to the Conksbury Bridge and Monsal Dale sites as environmental conditions altered across the catchment of both rivers. Prior to the switch from carbonate autochthonous sedimentation to terrigenous colluvium, the Prentice-Sugita Model would be most applicable to the sluggish flows suggested for stable conditions in barrage tufa pools (Pedley *et al*., 2000), analogous to conditions observed at the Litton Mill field site described in section 6.4 of this chapter. However landscape scale removal of vegetation would facilitate reduced interception of overland flows. This would result in greater run-off velocities from the catchment surface to the river channel resulting in combination the entrainment of sediment from agriculturally prepared areas. This would result in increasing flood peaks distributing terrigenous sediment throughout the fluvial system *without* a reciprocal increase in precipitation levels being necessary. Under this latter scenario, these high stage sedimentary events would follow the pollen transport model of Holmes (1994).

One of the most striking aspects of the Monsal Dale pollen percentage diagram displayed in figure 6.50 is the lack of riparian pollen input to the site from taxa such as Alnus and Salix. Based on the patterns of pollen deposition observed in the fluvial taphonomy study discussed in section 6.4 of this chapter, riparian taxa such as Alnus and Salix are well represented in the percentage diagram presented in the appendices**.** The virtual absence of Alnus and Salix suggests that the environment conditions surrounding the site may have become drier, perhaps as a result of reduced river flows. This hypothesis is supported by the high Corylus pollen percentage values observed in figure 6.50, and the low RPPE of 0.4 for White Peak Corylus produced in the RPPE study discussed in section 6.1 of this results chapter. Corylus dominates the Monsal Dale AP pollen signal in both zones 3 and 2 displayed in figure 6.50. Based on an RPPE of 0.4 this would suggest that Corylus woodland may have occupied both extensive areas on the plateau and plateau shelves after woodland clearance and agricultural abandonment, and the progressively drier riparian habit more effectively than Salix and Alnus. Based on the RPPE for Alnus of 2 – 3 (dependant on the output from ERV Model 1 or 2) produced in the White Peak relative pollen productivity study discussed in section 6.1, Alnus is a relatively high pollen producing taxon in the limestone valleys of Derbyshire meaning that, based on figure 6.50, the taxon is virtually absent from the local vegetation at the Monsal Dale site.

The absence of any significant pollen input from local tree taxa such as Fraxinus, Quercus and Tilia suggests that the time period represented by the pollen percentages displayed in figure 6.50 is after the clearance of local valley and plateau woodland on the White Peak. The only deciduous tree taxon to maintain a presence in the Monsal percentage diagram is Ulmus, which has a low RPPE value of 0.8 (Broström *et al.*, 2008), meaning that the taxon is a relatively low pollen producer. Ulmus is associated with drier, free-draining soils such as the rendzinas formed on the White Peak plateau and valley slopes, and is able to spread vegetatively to form clonal woodlands (Stace, 1997) which may give this taxon a competitive advantage against taxa reliant purely on sexual reproduction. The low but constant Ulmus values displayed in figure 50 suggest that catchment conditions, during the period when significant amounts of terrigenous clay sediment was entering the fluvial system, may have been generally drier or that Ulmus was able to occupy well-drained valley-slope habitats which were not used by the human population for agricultural or pastoral activity.

This hypothesis of drier conditions in the catchment is supported by the increasing pollen percentage values of Pinus in zones 2 and 1 displayed in figure 6.50. The RPPE of Pinus in the White Peak, based on the RPPE study discussed in section 6.1 of this chapter, is 1.0 which suggests that this taxon was increasingly able to re-establish on habitat formerly occupied by deciduous taxa now absent from the landscape such as Tilia, Quercus and Fraxinus where edaphic conditions may have changed as a result of increased soil evaporation as a result of the removal of large areas of deciduous forest cover. The re-establishment of Pinus on areas of the adjacent Dark Peak may also be a factor in the significant increase in Pinus values observed at the transition from zone 1 to zone 2, and throughout zone 1. The lack of cereal pollen in the Monsal percentage diagram suggests that if arable agriculture was occurring at the period encompassed by figure 6.50, it was on a small scale. Areas of the White Peak previously used for growing cereal would be impoverished in soil nutrients after abandonment, and perhaps more free draining as a result of the loss of topsoil which entered the fluvial system after the abandonment of agriculture at plateau shelf and edge sites. It would perhaps be these sites that Pinus would be able to re-establish in along with Betula which displays a low but constant presence in the Monsal Dale percentage diagram. Betula pollen productivity is high in the White Peak, with an RPPE of 7-8 as displayed in table 6.4 in section 6.1 of this chapter. Based on this RPPE value, it is likely that Betula was a very small component of local vegetation.

Additional evidence for a change in local environmental conditions is also found in the pollen percentages of herb taxa (NAP) displayed in figure 6.50. Rosaceae and Cyperaceae are the two most constant NAP taxa in the Monsal diagram. The findings of the Association Indices study discussed in section 6.2 of this chapter suggest that Rosaceae pollen displays a high degree of association with local Rosaceae vegetation (see figure 6.8), meaning that in a palaeoenvironmental context the presence of Rosaceae pollen can be used to infer local Rosaceae vegetation was present in the area around the coring site. Rosaceae species such as *Geum rivale*, which was a Rosaceae taxon commonly encountered in the Derbyshire vegetation surveys used in section 6.2 of this chapter, are associated with damp riverside and open woodland habitats (Stace, 1997). If, due to a drying out of the area surrounding the tufa pool, Corylus is able to replace Alnus and Salix in less waterlogged riverside habitat, the presence of Rosaceae pollen may suggest a degree of constancy in the woodland cover surrounding the site; the tree species changing synchronously with changes in edaphic conditions.

Rumex was found to be overrepresented in the Association Indices study discussed in section 6.2 of this chapter. As illustrated in figure 6.53 below, Rumex is accepted in the literature as an indicator taxon of ruderal and pastoral habitat (Behre, 1981) which produces large amounts of widely dispersed pollen. Rumex pollen percentages are very low in figure 6.50, and are restricted to zone 3 and the first part of zone 2. The low Rumex pollen percentage values suggest that landscape disturbance was also at a very low level during the time period encompassed by figure 6.50, suggesting that the terrigenous sediment may represent the progressive abandonment of agricultural sites. Cyperaceae is the dominant NAP taxon in figure 6.50, and is associated with damp habitats (Stace, 1997). This suggests that the area of open water remained constant throughout zone 3, and may have declined in area at the end of zone 2 and throughout zone 1.

Figure 6.53: Pollen types indicating anthropogenically managed habitats (A – H) in Northern Europe. Key to habitats; (A) winter cereals; (B) summer cereals and root crops; (C) fallow land; (D) wet meadows and pasture; (E) Dry pastures & heaths; (F) Grazed forest; (G) Footpath & ruderal communities; (H) natural communities e.g. mires etc.

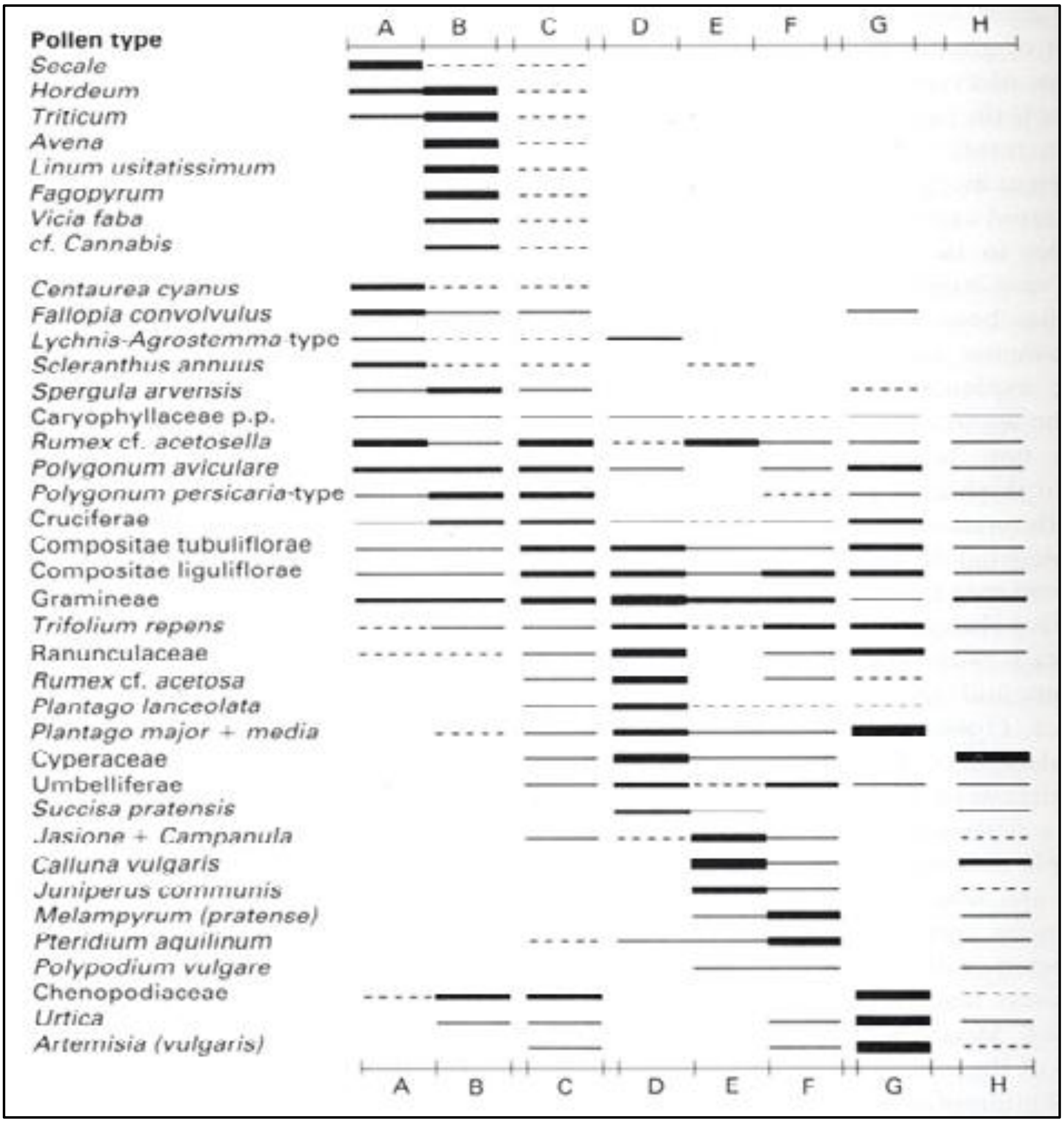


Table taken from Moore *et al*. (1991)

Conksbury Bridge

The Conksbury pollen diagram in zone 1 displayed in figure 6.48 on page 236 is initially dominated by the regional background pollen signal of Calluna, which would be associated with the acid peatland soils of the adjacent Dark Peak. Constant, relatively high Carex percentage values, in association with low but constant Poaceae values and very low Plantago and Rumex pollen values, suggest a wet meadow/pasture habitat as defined in the indicator table of Behre (1981) illustrated in figure 6.53. The pool basin at the Conksbury site then appears to become enclosed by extensive Carex stands in zone 2. Riparian Carex pollen then completely dominates the local gravity pollen component, effectively blocking pollen input from other local NAP taxa. Increases in both Poaceae and Cyperaceae pollen percentages suggest there may be a local landscape transition to a wet meadow/pasture habitat. The degree of landscape openness of the Conksbury site appears greater in zone 1, as *Corylus avellana* dominates the AP pollen input; this taxon requiring unshaded sites to flower and produce pollen effectively.

Tree taxa are present in the landscape, and the relatively high *Alnus glutinosa* values in zone 1 suggest that the riparian floodplain may have been dominated by this taxon; this supports the hypothesis that the increasing values of Poaceae during the transition from zone 1 to zone 2 and the large rise in Cyperaceae represent increased areas of wet grassland in the local landscape. The very low pollen percentages of thermophilous tree taxa throughout both zones suggest that woodland was not a large part of the local landscape. The increase in Pinus pollen values in the transition from zone 1 to zone 2 suggests an increase in the regional pollen signal which may represent an increase in landscape coverage of Pinus vegetation on the acid soils of the adjacent Dark Peak.

The Conksbury Bridge stratigraphic diagram displayed in figure 6.49 has approximately 0.80 metres of clay-rich dark lime mud between 1.25 metres and 1.83 metres depth, suggesting that this sedimentary event represents a period of landscape instability in the River Lathkill catchment. High levels of terrigenous sediment in sedimentary cores have been observed in previous White Peak palaeoenvironmental studies, and have been associated with anthropogenic woodland clearances occurring from the early-middle Neolithic onward in the Peak District (Wiltshire & Edwards (1993); Taylor *et al*. 1994). What differentiates the Conksbury Bridge stratigraphy displayed in figure 6.49 from that of the Monsal Dale stratigraphy displayed in figure 6.51 is that the influx of allochthonous sediment in Lathkill Dale occurs as a single event which is then followed by a return to autochthonous carbonate sedimentation at the Conksbury Bridge site. Prior to the prolonged period of terrigenous sedimentation is a period of autochthonous sedimentation associated with higher river flows (Dr. M. Pedley; personal communication), when carbonate sand and silt is recorded in the Conksbury Bridge stratigraphic log. This suggests that precipitation and spring levels were high during this period, and that the landscape surface of the Lathkill catchment based on the lack of allochthonous sediment at this point in the core was in a stable state.

The transition from catchment stability to instability illustrated in figure 6.51 is quite sudden, with no gradation in sedimentation type, suggesting that significant landscape-scale environmental disturbance occurred synchronously across significant areas of the River Lathkill catchment and was not restricted to the local area adjacent to the Conksbury Bridge tufa pool. A return to increasing levels of autochthonous lime mud sedimentation accompanied by reduced allochthonous terrigenous sediment input observed between 1.25 metres and 1.02 metres, suggests a gradual re-stabilization of the catchment land surface after the disturbance event observed between 1.83 – 1.25 metres. A return to fully autochthonous lime mud sedimentation is observed from 0.95 – 0.50 metres in the Conksbury Bridge core displayed in figure 6.49, suggesting that during the temporal period after 0.95 metres core depth the environmental conditions across the catchment landscape surface had fully stabilised.

Based on the pollen percentage diagram for Conksbury Bridge displayed in figure 6.48, tree cover appears to have been almost completely removed from the catchment from the inception of zone 1. The dominant tree taxa throughout zone 1 are Corylus and Alnus, which probably represent the riparian taxa at the Conksbury Bridge tufa pool site; Salix is also present at very low percentage values suggesting that edaphic conditions in the riparian areas adjacent to the tufa pool site were initially wet. Based on the Derbyshire RPPE study discussed in section 6.1 of this chapter the RPPE for Corylus, as displayed in table 6.4, in Derbyshire is 0.4, meaning that Corylus woodland may have been extensive locally on the valley sides as well as in riparian area adjacent to the tufa pool. Alnus has a relatively higher RPPE than Corylus, based on the results of the study discussed in section 6.1 of this chapter, in Derbyshire of 2 – 3 (see table 6.4) meaning that Alnus vegetation may have been restricted to the riverbank and not a significant taxon on the riparian floodplain. Alnus pollen percentages towards the end of zone 1 display a steady decrease in values, suggesting that a change to drier edaphic environmental conditions may have occurred at the Conksbury site. The drying out of the site also suggests that river flows were reducing towards the end of zone 1 which would negatively affect dispersal of Alnus seed.

Zone 1 in figure 6.49 is characterised by a diverse range of different herb taxa including overrepresented taxa indicative of human disturbance and ruderal environmental conditions such as Rumex, and underrepresented taxa such as Primulaceae which is indicative of wet soils; see table 6.9 in section 6.2 of this chapter. As discussed in the Association indices study in section 6.2 of this chapter, Rumex is an overrepresented taxon useful for indicating anthropogenic disturbance in the regional pollen rain meaning that Rumex pollen in produced in large amounts and is well dispersed (Behre, 1981). Rumex is present at low but constant values in zone 1, indicating that areas of the Lathkill catchment are still environmentally unstable; in zone 2 in figure 6.49 Rumex is absent until the close of the zone suggesting that environmental conditions in the catchment have stabilised. The presence of riparian and local woodland in zone 1 is confirmed by the low but constant pollen percentage values of Filipendula and Rosaceae observed throughout zone 1. Based on the findings discussed in section 6.2 of this chapter, Rosaceae pollen is strongly associated with the presence of Rosaceae vegetation within the 10 m survey radius, and is an indicator taxon of damp woodland. Filipendula, like Rumex, is an overrepresented taxon with widely dispersed pollen which is an indicator taxon associated with damp and marshy riverbanks and open wet woodland sites. Euphorbiaceae is also present in zone 1 and is an underrepresented taxon associated with woodland habit, meaning that pollen dispersal is poor for this taxon and that pollen signifies the presence of the plant in the local vegetation.

Despite the high terrigenous sediment input observed between 1.25 – 1.83 m in figure 6.51, the sub-fossil pollen recovered from the Conksbury Bridge sub-samples displayed minimal mechanical and biochemical damage. Pollen damaged through these transport and storage effects can be used to indicate fluvial pollen transport and remobilized pollen transported into the fluvial system via overland flows (Brown, 1985; Campbell, 1999). This suggests that pollen transport to the Conksbury site was primarily aerial during this period, and followed the Prentice-Sugita Model (1993) of pollen transport which was observed as the primary pollen transport mechanism in the Litton Mill study of modern-day pollen taphonomy described in section 6.4 of this chapter. The removal of plateau and valley side woodland would also contribute to the openness of the Conksbury site as a pollen sensing basin, in that removal of local woodland vegetation would effectively increasing the potential of the site to receive the regional pollen signal (Gaillard *et al.*, 2008). This hypothesis is supported by the high Calluna pollen percentages observed throughout zone 1, which must represent Calluna vegetation situated on the adjacent Dark Peak as Calluna is a calcifuge taxon. If the basin is more representative of regional pollen in zone 1 then the real effect of woodland clearances is seen, as only Quercus, Acer and Pinus are present at very low (<5%) percentages throughout this zone.

The transition from zone 1 to zone 2 in figure 6.48 is marked by an abrupt switch from a regional to a local riparian pollen signal, with a rapid rise in local Carex percentages synchronous with a decline in regional Calluna percentages. This suggests a significant and rapid change in environmental conditions around the Conksbury Bridge site. Carex is associated with wet edaphic conditions such as occur on riverbanks and floodplains but is not fully aquatic. This suggests that reduced river flows at the Conksbury Bridge site allowed a gradual encroachment of Carex vegetation into the tufa pool as river levels reduced, beginning a sequence of terrestrialization beginning at the transition from zone 1 to zone 2. The rise in Carex percentage values is accompanied by a concomitant rise in Poaceae values at this time, suggesting that greater areas of the local and catchment land surface were given over to grassland. This increase in Poaceae values may represent the stabilization of the catchment surface after the removal of the local woodland and the erosion of a proportion of the topsoil which undoubtedly constitutes a proportion of the clay-rich sediment observed in the stratigraphic log between 1.25 – 1.83 m in figure 6.51. Pollen transport at this period of diminishing flows is likely to have been dominated by the aerial component, and analogous to the model described by Holmes (1994) illustrated in figure 6.45 in section 6.4 of this chapter.

The hypothesis of terrestrialization as a result of reduced river flow at the Conksbury Bridge site is supported the sedimentological transition from organic-rich lime mud to pure pale carbonate mud observed at 0.95 m, as this form of autochthonous carbonate precipitation is associated with sluggish flows (Pedley *et al*., 2000) and carbonate rich lakes (Dr. M. Pedley: Personal communication). This sedimentological change occurs in the last part of zone 2 in figure 6.51, shortly before Carex values begin to decline and Calluna pollen percentage values display an increase; this may indicate that the site has become a fen-carr habitat with no remaining open water at the Conksbury site. A significant reduction in diversity of herb taxa in zone 2 suggests that changing edaphic conditions at the site may have excluded the majority of taxa observed in zone 1. Only Euphorbiaceae (*Lysimachia vulgaris*) and Rosaceae are present at in zone 2, with *Lysimachia vulgaris* values rising throughout the zone indicating wet/marshy environmental conditions are increasing at the Conksbury Bridge site and Rosaceae indicating that local/riparian woodland is still present adjacent to the Conksbury Bridge site.

6.5.3. Conclusion

Conksbury Bridge

The sediment core taken at the Conksbury Bridge site is suggested as representing a more central location in the tufa pool, as organic sapropel peats were observed in the core sediment stratigraphy displayed in figure 6.49. As was observed in the fluvial taphonomy study at Litton Mill on the River Wye presented in section 6.4 of this chapter, riparian gravity pollen input from Alnus and Corylus at pool margin sites resulted in slightly higher relative pollen abundances of these taxa being observed in locations adjacent to the riverbank, whilst pollen abundances of Alnus and Corylus at pool-centre locations displayed only slightly lower levels of relative abundance. At the Conksbury Bridge site the pollen percentage diagram illustrated in figure 6.48 suggests Alnus was a very minor component of the local riparian vegetation, a hypothesis which is supported by the relatively high White Peak RPPE for Alnus (2.0 – 3.0) previously discussed in the relative pollen productivity study presented in section 6.1 of this chapter. Based on the findings of section 6.1 of this chapter, the Corylus RPPE in the White Peak is 0.4 suggesting that at the Conksbury Bridge site Corylus was the most significant component of the riparian and local vegetation. The dominance of Corylus suggests there was very little local woodland remaining adjacent to the Conksbury Bridge site and that Corylus was able to flower abundantly in these unshaded habitats. The presence of herb taxa associated with wet and damp soil conditions i.e. Filipendula, Primulaceae and Rosaceae in zone 1, as is discussed in the association indices study section 6.2 of this chapter, suggests that local environmental conditions were characterised by wet/damp soils. Filipendula, Primulaceae and Rosaceae species are also associated with damp woodland habitat, with Primulaceae and Rosaceae being relatively shade-tolerant taxa and Filipendula associated with of woodland gaps and edges (Stace, 1997).

The very high regional pollen signal from Calluna and relatively low pollen percentages of Carex in zone 1 also support the hypothesis that the landscape around Conksbury Bridge site was open during this period, potentially allowing a more regional pollen signal to be recorded at the site (Gaillard *et al.*, 2008). A more open tufa pool site should, based on the findings of the fluvial taphonomy study presented previously in section 6.4 of this chapter, allow greater input of aerially transported pollen from local and regional vegetation. However this trend is not observed in the sub-fossil pollen assemblages displayed in the pollen percentage diagram for the Conksbury Bridge site in figure 6.48, with only very low percentages observed for Acer, Fraxinus, Ulmus, Quercus and Pinus. This suggests that these taxa were present in the regional vegetation, but at very low densities and at locations where regional pollen transport may have been limited due to the fragmentation of woodland into small patches within an open grassland landscape matrix (Tinsley & Smith, 1974).

Pinus pollen percentages display a slight increase in at the transition from zone 1 to zone 2 which may be related to the significant reduction in Calluna pollen input to the site observed in zone 2 allowing Pinus to be better represented in the regional pollen rain. The reduction in Calluna percentages in zone 2 suggests a change in environmental conditions on the adjacent Dark Peak i.e. an increase in grassland landscape cover; this hypothesis is supported by the reciprocal rise in Poaceae values at the zone1/zone 2 transition. High Calluna percentages may be swamping the true Pinus pollen input through the interdependence of pollen percentages (Prentice & Webb, 1986). However a change in the pollen-sensing characteristics (smaller basin=more local pollen signal) of the Conksbury Bridge site may have occurred through the progressive terrestrialization of the pool by Carex vegetation as a result of reduced river flows; regional Pinus pollen being primarily deposited via the 'rain-out' component from the high atmosphere (Green *et al.*, 2003), as Carex vegetation began encroaching into the pool effectively blocking-out the local AP and NAP transported by the riparian, canopy and trunk space component. The effects of progressively higher proportions of fringing Carex vegetation is also seen in the significant reduction in diversity of herb taxa in zone 2 in figure 6.48.

The findings of this study suggest that the vegetation represented in the Conksbury diagram represents a middle-late Holocene post woodland-clearance landscape. The presence of Acer at the bottom of the diagram suggests a date after 4 ka BP based on the first appearance of the taxon in pollen assemblages in the White Peak at Lismore Fields (Wiltshire & Edwards, 1993). The degree of openness in the landscape agrees with the observations of Taylor *et al*. (1994), who suggest that from 4100 yr BP the woodland vegetation of the White Peak was almost completely removed. Landscape-scale woodland clearance events are also observed in the pollen assemblages of the adjacent Dark Peak (Hicks, 1971; 1972: Barnatt & Smith, 1991) from 5 ka BP onward. Woodland clearance on the Dark Peak would influence soil degradation and allow Calluna to establish and dominated the peat soils; these events in the Dark Peak may be the source of the high Calluna values observed in the Conksbury assemblages.

The stratigraphy of the Conksbury Bridge displayed in figure 6.49 indicates that environmental conditions in a significant area of the River Lathkill catchment had been disturbed, resulting in a large influx of terrigenous soil sediment into the fluvial system during temporal period covered by zone 1 in figure 6.48. The effectiveness of overland flows in exacerbating soil erosion across the land surface of the catchment at this period would be greatly enhanced by the removal of a large proportion of the local woodland; meaning that river flows would be higher during this period due to faster runoff velocities resulting from reduced interception as a result of landscape-scale removal of catchment vegetation. This would result in a greater proportion of fluvially transported pollen representative of the wider catchment during this sedimentary event. The switch from terrigenous clay-rich sediment to pure lime muds illustrated in figure 6.49 suggests that river flows were much reduced at this period (Dr. M. Pedley;

personal communication), possibly due to reduction in the regional water table (Pedley et al., 2000); the rapid rise of Carex percentages indicates rapid terrestrialization of the tufa pool in zone 2, which suggests that this time period marked the decline of the tufa system at the Conksbury Bridge site. Pollen deposition at this terminal phase would be analogous to that suggested by Holmes (1994) as illustrated in figure 6.45, with pollen transport following the Prentice-Sugita Model described in section 6.4 of this chapter.

Monsal Dale

The Monsal Dale core is suggested as representing a pool margin as only tufa and micritic lime muds were present, and no organic, sapropel deposits associated with central, deeper sections of barrage tufa pools (Pedley *et al.*, 2000) were observed in the sediment core at this location. Pollen transport to the Monsal Dale site during the temporal period under examination may have been influenced by the removal of woodland from the wider catchment. Removal of catchment vegetation would potentially increase overland flow velocities resulting in an increased magnitude of river stand levels. A higher proportion of pollen remobilised from the catchment land surface would potentially enter the fluvial system via terrigenous sediment entrained by overland flows (brown et al., 2007). However based on the findings of the pollen taphonomy study discussed in section 6.4, which found that pollen deposition in the modern context of the White Peak is primarily aerial, the influence of the regional karst geology on the rate of terrigenous sediment transport is likely to be a significant factor in mitigating overland flow velocities.

Based on the findings of the fluvial taphonomy chapter in this thesis, pollen assemblages at pool margins should display slightly higher riparian pollen values, and slightly lower relative abundances of local and regional pollen. Corylus and Betula display high pollen percentages in sub-zones 1 and 2, and are suggested as the principal riparian taxa adjacent to the site. The findings of the Relative Pollen Productivity Estimate (RPPE) study, discussed previously in section 6.1 of this chapter, give an RPPE for Corylus in the White Peak of 0.4, suggesting that Corylus is also the dominant taxa in the local and extra-local vegetation. The RPPE of Betula in the White Peak, discussed previously in section 6.1 of this chapter, is 7.0 – 8.0 meaning that Betula vegetation is therefore a very minor component on the vegetated landscape.

Pinus pollen input to the Monsal Dale site displays a steady increase from sub-zone 3 to sub-zone 1. RPPE for Pinus, based on the RPPE chapter of this thesis, is 1.0 suggesting Pinus is a significant taxon in the landscape vegetation; however the proportion of this input representing local or extra-local vegetation is uncertain. The rising Pinus percentages are synchronous with falling Corylus values, suggesting either a reduction in Corylus or a reduction in Corylus pollen production. Another consideration in the rise in Pinus values may be the interdependence of Pinus and Corylus percentages, as the ubiquity of Corylus pollen in zone 1 and the majority of zone 2 could distort the representation of all other taxa represented in the pollen record at the Monsal Dale site. The very low pollen percentages of Ulmus, Fagus and Acer recorded in both zones in the Monsal Dale pollen diagram displayed in figure 6.50 suggest that stands of these taxa were present in the local landscape, but perhaps at distances far enough away from the sampling site to significantly reduce pollen transport to the tufa pool. This hypothesis is supported by Tinsley & Smith (1974), who observed that arboreal pollen deposition declines rapidly in open heathland within 100 metres of the woodland edge.

Rosaceae and Filipendula are the dominant herb taxa in all 3 sub-zones, suggesting the local area around the site was wet and wooded; Rosaceae and Filipendula have been observed to be associated with woodland and wet soils as discussed in the association indices study in section 6.2 of this chapter. Rumex values are very low in all three sub-zones, suggesting that the local landscape is not subject to any significant degree of ongoing disturbance in the temporal period covered by the Monsal Dale pollen diagram; Poaceae values remain constant in all sub-zones, suggesting that no significant increase in open grassland occurred during time period covered by the Monsal Dale percentage pollen diagram displayed in figure 6.50. The reduction in diversity of herb taxa in zone 3 may be associated with the rise in Cyperaceae percentages throughout zone 3, and based on the indicator species table of Behre (1981) illustrated in figure 6.53, this suggests that Cyperaceae is able to encroach and establish further into the river channel from the pool margins, potentially as a result of reduced levels in the River Wye. The rising Cyperaceae values throughout sub-zone 3 suggest a terrestrialization of the site may be beginning at the Monsal Dale site, with the increasingly dense riparian Cyperaceae vegetation potentially swamping the tree pollen signal at the end of sub-zone 3.

The sedimentary sequence of the Monsal Dale core illustrated in figure 6.51 suggests that a significant amount of terrigenous entered the fluvial system from the catchment landscape surface during the period covered by the percentage pollen diagram displayed in figure 6.50; however without radiocarbon dates it is not possible to speculate on the temporal duration of this period of catchment disturbance. In conjunction with the palaeoecological information contained in the Monsal Dale pollen percentage diagram displayed in figure 6.50, this sediment input is synchronous with an almost treeless catchment suggesting that widespread catchment-wide removal of woodland cover had occurred probably before the temporal period described by figure 6.50. Removal of significant areas of woodland from the catchment would have the effect of increasing sediment transport to the River Wye by both the destabilisation of the shallow rendzina limestone soils, and the increased overland flow velocities associated with reduced interception from catchment vegetation. The very low but constant Poaceae values throughout the 3 sub-zones in figure 6.50 suggest that grassland was a persistent component of the catchment vegetation, and the small rise in Poaceae >40µm at the end of sub-zone 1 may represent cereal pollen from arable agriculture in the White Peak region.

The findings of this study suggest that the vegetation represented by the Monsal Dale pollen percentage diagram represents a post woodland clearance landscape in the middle – late Holocene, with the large woodland tree taxa i.e. Acer, Fagus, Ulmus appear largely absent from the local landscape and potentially restricted to geographically isolated locations or patches such as the steep valley sides used in the vegetation surveys for the RPPE and pollen taphonomy studies discussed previously in sections 6.1 and 6.3 of this chapter. The significant percentages of Corylus suggest the taxon was ubiquitous in the landscape, and was able to expand and establish in the unshaded habitat created by the removal of broadleaf woodland. Corylus is capable of higher pollen production in unshaded habitats, and the suggested RPPE for Corylus in the White Peak observed in section 6.1 of this chapter has found that pollen production for Corylus is relatively low in shaded woodlands.

Chapter 7: Synthesis and Discussion

This thesis has examined pollen productivity and pollen taphonomy in the White Peak Derbyshire in order to provide a framework for the reconstruction of past vegetation from pollen analysis at two locations in the White Peak, Derbyshire.

7.1 Pollen Productivity

Pollen productivity is assumed to be constant over time for a given taxon within a specific region, with observed differences in pollen productivity estimates (PPE's) assumed to be related to methodological factors i.e. site type, pollen sampling medium i.e. moss-polster, vegetation survey methodology, and environmental factors i.e. climate, vegetation structure and species composition (Broström *e*t *al*., 2008). New relative pollen productivity estimates (RPPE's) have been produced in this thesis for Pinus, Fraxinus, Fagus, Corylus, Betula and Alnus and Poaceae using moss polster surface samples in conjunction with vegetation surveys in the White Peak, Derbyshire. This new RPPE dataset displays a significantly lower RPPE (relative to Acer) for Alnus, Corylus and Fagus than has been observed in previous research elsewhere in Europe e.g. in the Swiss Jura - Mazier *et al*. (2008), and a very similar RPPE (relative to Acer) for Betula to that previously observed in the UK by Bunting *et al*. (2005). The observed differences between these new RPPE values and the existing datasets may be attributed to both methodological factors, as the dataset represents the only RPPE data produced from a valley-woodland site-type, and to environmental factors associated with the site-type such as vegetation structure and species composition within the valley woodlands. This new dataset will add to the current database of RPPE available to researchers, and provide an additional tool assisting palynological investigation in areas of upland valley woodland.

7.2 Rare pollen types

An important component of the reconstruction of past vegetation change is the interpretation of the presence/absence of rare herb taxa in pollen diagrams in terms of anthropogenic activity such as pastoralism and/or agriculture (e.g. Behre, 1981; Hicks, 1988; Hjelle, 1997; 1999). Herb and forb taxa are often used to infer the degree of landscape openness and disturbance in past landscapes (Behre, 1981; Birks, 1990;

Bunting, 2003), and taxa such as Filipendula and Lysimachia can be used to indicate edaphic conditions around a field site. Interpretation is based on ecological knowledge (e.g. Behre, 1981), and on a categorical characterisation of the pollen-vegetation relationship as under-representation, over-representation or association (Davis, 1984; Hjelle, 1997).

New indices of association have been produced for 16 herb taxa using pollen analysis and vegetation surveys carried out in the White Peak, Derbyshire. Six groups of taxa are identified as displaying similar patterns of representation and association; these patterns appear to be influenced by pollination strategy, pollen grain size, degree of pollen production, and effectiveness of pollen dispersal of the taxa. Findings include a high degree of overrepresentation of entemophilous taxa such as *Hedera helix* and *Silene dioica*, which agrees with the findings of Hjelle (1997) and Bunting (2003); similarities with previous research (Bunting, 2003; Schofield *et al*., 2007) were also observed for taxa such as Rumex, which was highly overrepresented in Derbyshire. Entomophilous taxa with open flowers and/or numerous anthers such as *Geranium robertianum* and *Geum rivale* displayed association values >0.5, and provided indicators of local woodland at the Derbyshire site. Other woodland indicator taxa such as Apiaceae (*Anthriscus sylvestris*) and *Hedera helix* display increasing association with distance away from the pollen assemblage sample point, suggesting that pollen of these taxa observed in fossil pollen assemblages represents plants adjacent to the site and in local vegetation. This new association indices dataset is the first available for upland valley woodlands in Northern England, and provides an additional resource to researchers investigating vegetation composition and edaphic change in the palaeo record. The increase in association values with distance observed for some herb taxa e.g. *Hedera helix* give insight of the source area of rare pollen types, and may be related to the size of the surface sample e.g. basin size.

7.3 Pollen Taphonomy

Models of pollen dispersal and deposition (Prentice, 1985; Sugita, 1993) provide a theoretical framework for the reconstruction of vegetation from pollen assemblages, and pollen productivity and dispersal are significant factors controlling the representation of local vegetation in pollen archives from basins of specific sizes

(Broström et *al*., 2008). Pollen dispersal is affected by the physiology of the plant, the relative pollen production of the plant, the pollen dispersal strategy of the plant e.g. anemophilous, and abiotic environmental factors e.g. wind direction. Variation in pollen deposited at a sampling point can occur as a result of variation in annual pollen production by vegetation, position of the plant relative to the sampling point, or as spatial variation in pollen deposition across a pollen-receiving surface e.g. lake sediment, peat bog, or moss polster (Räsänen *et al*. 2004). Moss polsters are often used in conjunction with vegetation surveys to produce RPPE datasets, and research designs often incorporate techniques to mitigate annual and spatial pollen variation in moss samples e.g. amalgamation of multiple moss samples (Räsänen *et al*., 2004; Broström et *al*., 2004).

The terrestrial pollen taphonomy study discussed in chapter 6 of this thesis has found significant variation in pollen percentages of tree taxa across a 1 m diameter moss surface sampling area at the two field sites in the White Peak, Derbyshire and at the Millington Wood field site in East Yorkshire. The microtopography of the moss surface, location of local pollen source plants relative to the surface sample, and prevailing wind direction are suggested as the primary influences affecting the observed spatial variation in pollen deposition of up to 25% for local tree taxa. Post-depositional pollen transport within the moss matrix may also be a consideration in the observed variation in pollen percentages. This agrees with the findings of Irwin (1989) and Joosten & De Klerk (2007), who suggest that pollen grains become mixed in the *Sphagnum* species as a result of small-scaled vertical water movements and the horizontal mode of shoot layering. The findings of this Derbyshire study has increased understanding of post-depositional pollen taphonomic processes in moss surface samples, and provided greater insight into the modern pollen-vegetation relationship.

Significant spatial variation in pollen percentages of up to 25 % can occur across the surface of a 1 metre moss surface. Depositional variation may therefore potentially increase error in RPPE, meaning that the findings of this study support the suggestions of Broström et *al*. (2004), that in order to derive unbiased RPPE datasets research designs should use multiple moss surface samples which are then amalgamated. The study of Broström et *al*. (2004) used mosses taken from a level ground surface, the raised mosses used in this study may have different hydraulic and pollen sensing properties. The degree of variation in pollen percentages observed in surface sub-samples at the Derbyshire and East Yorkshire field sites supports the suggestion of Pardoe (1996), that local variability in pollen deposition must be a consideration in the interpretation of sub-fossil pollen diagrams when using pollen analysis to reconstruct Quaternary vegetation. The implications of this finding are that the effects of variability in pollen deposition, in the context of Quaternary vegetation reconstruction, can be mitigated by the use of multiple cores which, whilst accepting a degree of random local variation may occur at each individual coring site, allow trends such as changing frequency or presence/absence of taxa to be corroborated.

The fluvial pollen taphonomy study discussed in chapter 6 of this thesis has found that pollen taphonomy in the River Wye, Derbyshire does not resemble the fluvial model suggested by Holmes (1994), but instead displays a higher degree of similarity to the Prentice-Sugita model of aerial pollen dispersal and deposition (Sugita, 1994). Based on analysis of riverbed sediment samples, a general trend of pollen homogeneity was observed at all sample points, with minor deviations from this trend observed at selected portions of the field site. Sample locations adjacent to riverbanks were observed to display slightly higher relative abundances of riparian pollen from taxa such as Alnus and Corylus, sample locations in the widest, deepest and most open section of the field site were observed to display higher relative abundances of regional taxa such as Pinus, Tilia, Quercus and Ulmus. The degree of mixing of pollen grains at the field site in part supports the suggestion of Meade *et al*. (1990) that pollen transported within channel is well mixed, however no mechanically, chemically or biologically damaged pollen grains were observed in assemblages; these indicators being suggested as representing pollen which has reworked from river sediment during flood events (Brown, 1985; Fall, 1987) or pollen which has been reworked from terrestrial storage by overland flows (Campbell, 1999; Brown *et al*., 2007).

The findings from the Litton Mill field site suggest that pollen deposition low energy pools in the River Wye is analogous to a small lake, where pollen displays a degree of homogeneity in sediment supporting the findings of Davis (1968), but also displays a degree of spatial bias in relative pollen abundances relative to the position of the pollen source in the vegetation (Beaudoin & Reasoner, 1992). The findings of this study have implications for small oxbows or pools in pool and riffle systems in, and represent the first taphonomic study focusing on low energy upland rivers on karstic limestone geology. This new dataset provides an additional interpretative tool to researchers examining past vegetation on the basis of pollen assemblages from fluvial sediments, and provides insight into the modern pollen-vegetation relationship in river catchments with mature karstic aquifers.

7.4 Palaeoenvironmental Reconstruction

Regional Vegetation

Chapter 6 of this thesis has used pollen analysis to investigate mid-late Holocene vegetation composition from two sediment cores taken from buried barrage tufa systems at 2 separate field sites in the White Peak, Derbyshire. Two new percentage pollen diagrams, figure 6.48 and 6.50 displayed in chapter 6, have been produced from sub-fossil assemblages for the White Peak region. These new pollen percentage diagrams represent an important new addition to the very limited existing research carried out in the White Peak region e.g. Wiltshire & Edwards (1993); Taylor *et al*. (1994), and provide further insight into the mid-late Holocene vegetation composition of the Pennine uplands.

In the regional context, the absence of broad-leafed woodland in either the Conksbury or Monsal diagram suggest that both diagrams represent the time period after extensive deforestation in the White Peak, and that the landscape was relatively open at both sites. Deforestation is observed from 5 ka BP onward on the Dark Peak (Hicks, 1971; 1972), from 470 yr BC at Rishworth in West Yorkshire (Bartley, 1975), from 3 ka BP. at Extwistle Moor near Burnley in Lancashire (Bartley & Chambers, 1992), from 100 yr BC at the Forest of Bowland in Lancashire (Mackay & Tallis, 1994), from 366 cal BC at Rostherne Mere in Cheshire (Nelms, 1984), and from 830 yr BC in Derbyshire (Tallis & Switsur, 1973), and from 4 ka BP in the White Peak (Wiltshire & Edwards, 19993; Taylor., 1994). The findings from this study suggest that late Neolithic/early Bronze Age woodland clearance was ubiquitous in central and northern England from the Neolithic onward.

The pollen assemblages from Monsal Dale and Conksbury Bridge suggest a primarily open landscape with fragmented woodland patches set in a matrix of grassland. It may have been that woodland was confined to valley sides as is observed in the modern-day landscape of the White Peak, however based on the pollen percentages from Litton Mill fluvial field site both the Monsal Dale and Conksbury sites had virtually no local tree taxa apart from Corylus, which probably formed the principal woodland taxa at the Monsal field site.

When compared to the NAP from the Litton Mill field site, the NAP values in the Conksbury and Monsal dale diagrams display very similar values and floral diversity, suggesting that similar edaphic conditions may have existed at the two sites. The percentage diagrams from the two sites appear to represent different time periods, as the Monsal diagram is characterised by high Corylus values and low NAP values, and the Conksbury diagram is characterised by very low Corylus and AP values and very high NAP values. The two field sites are approximately 6 km apart, suggesting that if the two sedimentary sequences were synchronous, that a similar range of pollen percentages would be observed at both sites. The percentage diagram from the Monsal Dale site is discussed first, and then the pollen percentage diagram from the Conksbury site.

The Monsal site is dominated by AP pollen which remains relatively constant at approximately 80%; NAP taxa remains at approximately 20% before rising to >25% at the end of zone 1. Of the tree taxa, *Corylus avellana* is the dominant taxon. The low NAP values observed at the Monsal site may represent fringes between open land and forest, which may contain entomophilous herb and shrub taxa which are often underrepresented in the pollen record (Broström, 2002). High Corylus values are also observed by Hicks (1971) in the Dark Peak between 2 – 3 ka BC, suggesting the period 4.5 – 5 ka BP is the most likely time period for the Monsal assemblages

The Conksbury site is dominated by NAP pollen, with *Calluna vulgaris* pollen dominant in zone 1 and Cyperaceae pollen dominant in zone 2; *Calluna vulgaris* values in zone 1 average 25% across the zone. *Calluna vulgaris* pollen in the Conksbury assemblages is likely to be pollen transported from the Dark Peak, as low pH habitats associated with Calluna are rare on the limestone geology of the White Peak. The dominant NAP taxon in zone 2 is Cyperaceae, which averages 38% across the zone. Regarding the arboreal taxa, *Corylus avellana* and *Alnus glutinosa* are the dominants in terms of pollen of the local vegetation.

Regional Archaeology

If the tentative date of 4.5 – 5 ka BP for the Monsal Dale assemblages is accepted, then the Monsal Dale diagram is placed in the Late Neolithic – Early Bronze Age transition (Whittle, 2005; Parker-Pearson, 2005). Similarly if the tentative date of 100 – 200 BC is accepted for the Conksbury assemblages is accepted, this places the Conksbury diagram in the Iron Age at 700 BC – 100 AD (Haselgrove, 2005). These time periods are associated with significant woodland clearance events, driven by rising population and increased demand for agricultural land. The degree of openness observed in the Conksbury and Monsal Dale diagrams supports the conclusions of the existing literature e.g. Hicks (1971); Taylor *et al*. (1994), that human occupation of the White Peak was a significant factor in the removal of woodland from region. That an ever-increasing environmental pressure was placed on the White Peak plateau due to the introduction of agriculture and increasing human population is supported by the high numbers of Neolithic and Bronze Age cultural monuments located on the White Peak plateau in comparison with the Dark Peak.

Climate Change and Impacts on Tufa Systems

The primary driver in natural forest retreat in the west of Britain is climate e.g. wetter conditions resulting in nutrient leaching, paludification and acidification in soils (Tallis & Switsur, 1990). Anthropogenic landscape disturbance is seen in pollen records from before 4 ka BP in the Pennines (Hicks, 1971, Barnatt & Smith, 1991; Wiltshire & Edwards, 1993), with deforestation in conjunction with increased precipitation accelerating soil erosion and nutrient leaching in areas of thin rendzina soil profiles such as the White Peak (Tallis & Switsur, 1990). Climatic deterioration resulting in flood events (Macklin & Lewin, 2003) and mire wet shifts (Hughes *et al*., 2000) occurred from 4 ka BP onward in the UK, and would potentially damage and degrade areas of soil exposed through clearance and subsequent tilling for agriculture. Rapid peat spreading in the southern Pennines between 8 - 4 ka BP suggests wetter climatic conditions occurred in the Peak District region at this time (Tallis & Switsur, 1990), and dependant on the magnitude of the increase in regional precipitation, the effect of periodic flooding may have had a significant effect on the barrage tufa systems of Derbyshire.

The essentially paludal environments represented by the pools formed behind the tufa barrages before the tufa system shuts down are suggested as being the width of the floodplain and shallow (<1m) with very low flow rates aiding sedimentation (Pedley *et al.*, 2000). An increase in magnitude of flood peaks, as a result of reduced interception through the removal of a significant proportion of the woodland from the catchment, would also contribute to the degradation of the tufa dam both as a consequence of higher flow velocities and a smothering of the biofilms communities associated with tufa dam consolidation. Switching from a relatively low-flow system with a high proportion of ground flow, to a fluvial system dominated by increased flow rates as a result of increased precipitation and rising groundwater levels may have had the effect of breaching the tufa dams, resulting in down cutting into a single, narrower channel.

This would then effectively isolate the marginal areas of the pool from the main channel accelerating the terrestrialization of these isolated ponds by local and riparian vegetation as is suggested by the Conksbury pollen percentage diagram in the palaeoenvironmental chapter. This thesis has argued on the basis of the ecological information contained in the percentage pollen diagram that the Conksbury sediment sequence used in this study encompasses the time period 100 – 200 BC. The final truncation surface observed by Pedley *et al.* (2000) in Lathkill Dale is radiocarbon dated to approximately 4 ka yr BP, and suggests an increase in flow rate in the River Lathkill; this hypothesis is supported by the cessation of sapropel deposition in the sedimentary record at the site, sapropel deposition being associated with consistent low flow rates, and a subsequent switch in sedimentation to clay-rich lime muds.

The stratigraphy of the section of the Conksbury sediment core used in this thesis displays a transition from clay-rich lime muds to pale lime muds with organic flecks to pale lime mud. During this sedimentological transition, there is a rise in pollen abundances of riparian taxa associated with wet environments e.g. Cyperaceae in the Conksbury diagram. This thesis would argue that these two observations represent the marginalization of the area of the tufa pool from which the core was taken through an alteration in the channel morphology at the site, and that this marginal location was then terrestrialized by riparian vegetation. The date of sedimentary transition provided by Pedley *et al*. (2000) may mark the inception of tufa system shut down at the Conksbury site, this thesis would argue that the sedimentary sequence used in this thesis may represent the final stages of the tufa system shut down due to a combination of climatic and anthropogenic drivers.

This thesis has argued that the Monsal Dale sedimentary sequence represents a time period of approximately 4.5 – 5 ka BP. based on the similarities in pollen percentages between the Monsal percentage pollen diagram produced in this study and other local radiocarbon dated palynological investigations e.g. Raper Lodge in Lathkill Dale - Taylor *et al*. (1994), which suggests that the Monsal sedimentary sequence is 2.3 – 3 ka yr older than the Conksbury sedimentary sequence. This time period is just prior to the final truncation surface observed by Pedley *et al*. (2000) at Lathkill Dale which is radiocarbon dated to approximately 4 ka yr BP, and is suggested as representing an increase in flow rate in the River Lathkill due to a change in local hydrological conditions. The high relative abundance of Corylus pollen in the Monsal diagram suggests that habitat that was formerly occupied by local and extra-local woodland had become available and was being colonised, allowing both a greater density of Corylus in the landscape and greater pollen production due to an increase in unshaded habitat.

The sedimentary sequence used in the production of the percentage pollen diagram for the Monsal site displays is characterised by organic clay-rich lime muds, suggesting that allochthonous terrestrial sediment was entering the river system, potentially from agricultural sites on the adjacent plateau and valley slopes. However higher river flow rates, driven by increased regional and local precipitation (Tallis, 1990; Macklin & Lewin, 2003) may have had the effect of transporting a proportion of the sediment input to the lower reaches of the catchment. The absence of sapropel in the Monsal sedimentary sequence supports the hypothesis that higher river flows were occurring at this time period. The absence of significant relative abundances of pollen from riparian herb taxa associated with paludification and terrestrialization e.g. Cyperaceae are also largely absent from the pollen record suggesting that the tufa system was still in a steady state and that the down cutting of the principal tufa barrage proposed for the Conksbury site had not yet occurred. The slight increase in pollen abundance of

Cyperaceae at the end of sub-zone 1 at suggests that at this point, river flows may have begun to alter the morphology of the barrage tufa system at Monsal Dale in the same way as that proposed for the Conksbury site. The rise in Cyperaceae values at the top of the Monsal diagram suggests reduced pool depths and the initiation of the isolation and separation of the more distal parts of the pool from the barrage-pool system. The top of the Monsal diagram effectively represents the beginning of terrestrialization of marginal areas of the pool by riparian vegetation. This hypothesis is supported in part by the increase in Pinus values from the middle of sub-zone 2, Pinus having buoyant pollen grains which are more likely to become integrated into sediment in still water.

This thesis has argued that the influence of climatic deterioration on soil erosion in a landscape where trees are removed and topsoil is tilled for agriculture would be to increase sediment input into the fluvial systems at the Derbyshire sites. The present-day hydrology of the River Wye and River Lathkill is dominated by baseflow; however with higher levels of regional precipitation, in association with rising groundwater levels, sediment transport to the Rivers Wye and Lathkill may have occurred at the time periods represented by the sedimentary sequences used to produce the Monsal Dale and Conksbury pollen diagrams. The dark lime muds present in the sedimentary sequence at Conksbury are suggestive of terrigenous sediment input to the barrage system, as are the organic clays examined at Monsal Dale. At both the Conksbury and Monsal Dale field sites the woodland in the local landscape is largely absent. This suggests that, in conjunction with the archaeological evidence, agricultural development of the valley slopes and adjacent plateau was well advanced at the temporal period encompassed by the pollen diagrams illustrated in figures 6.48 and 6.50. Increased soil erosion, resulting in the introduction of significant volumes of terrigenous sediment into the River Lathkill and River Wye, could have impacted the demise of the Derbyshire barrage tufa systems through both mechanical damage associated with increased flood peaks and through the destruction of the delicate biofilms associated with biomediated tufa production (Rogerson *et al.*, 2008).

The change in hydrological regime suggested by the existing literature e.g. Pedley *et al.* (2000), Macklin & Lewin (2003), suggest that increased river flows resulting from increased precipitation may have been the principal drivers in the switch-off of the

Derbyshire barrage tufa systems. The influence of anthropogenic woodland clearance has been discussed from the literature, and the palynological evidence in the Monsal Dale and Conksbury percentage diagrams supports the hypotheses of previous research e.g. Hicks (1971); Wiltshire & Edwards (1993); Taylor *et al*. (1994; Pedley *et al*. (2000), that extensive anthropogenic woodland clearances in the White Peak occurred from the middle Neolithic onward. The impact of these clearances is seen in the sedimentary sequences taken from the Monsal Dale and Conksbury field sites, and in the changes in local and extra-local vegetation composition around the two sites.

7.5 Conclusion

Palaeoecological investigation of past vegetation using pollen analysis is an important tool in understanding past vegetation patterns in the landscape and examining how natural drivers such as climate and anthropogenic impacts such as agriculture can influence vegetation structure over time. Such investigations are fundamental to the development of conservation and management practices in order to restore natural ecosystems, mitigate the effects of human-induced climate change and develop strategies of landscape conservation in agriculturally active environments. Pollen analysis investigating past vegetation relies on conceptual models of pollen dispersal and deposition based on modern-day pollen – vegetation relationships in order to develop hypotheses of vegetation structure and diversity in the palaeo landscape.

Models of pollen dispersal and deposition make assumptions regarding pollen transport to a site of sedimentation and the taphonomic processes acting upon pollen after deposition, and are acknowledged as a simplification of a complex process offering the best available analytical method for understanding the pollen – vegetation relationship. Greater understanding through fieldwork-based investigation and analysis of pollen dispersal and deposition models is therefore an important contribution to the research design process in palaeoecological investigations. Relative pollen production estimates are a fundamental component of pollen dispersal and deposition models which are often utilised in reconstructing past vegetation, as although rates of pollen productivity are assumed to be constant, variation is often observed which can be dictated by local environmental variation e.g. species associations and differences in research design methods e.g. survey type.

This thesis has argued that the relative pollen production rates (RPPE) of tree taxa in valley woodland vegetation in the White Peak display some significant differences to rates observed at other European and UK sites, and proposes that the new RPPE dataset produced in the White Peak represent an important addition to the current European database of RPPE's available to environmental and ecological researchers. This thesis has argued that post-depositional taphonomy of pollen grains is a non-trivial consideration in the production of RPPE's and has found that significant variation does exist in relative pollen abundances in modern-day moss polster surface samples. The findings of this study suggest that the accuracy of palaeoecological reconstructions using RPPE datasets can be enhanced through the incorporation of research design strategies which can mitigate for spatial variability in pollen deposition such as amalgamation of multiple moss sub-samples. Investigation of fluvial pollen taphonomy has shown that traditional models of fluvial pollen transport do not accurately describe the processes operating in the River Wye field site in the White Peak, and that river pools in the River Wye are analogous to small lakes which receive pollen loading from aerial vectors an display a degree of pollen mixing. This thesis has argued that late Holocene vegetation composition in the landscapes surrounding the Monsal Dale and Conksbury Bridge field sites in the White Peak was primarily open grassland with fragmented local and extra-local broad-leafed woodland patches, and that termination of middle – late Holocene barrage tufa systems in Derbyshire was primarily influenced by climatic changes exacerbated by anthropogenic deforestation.

7.6 Future work

This work has provided a useful framework within which to consider the wider impact of anthropogenic landscape management and climate on barrage tufa systems. Future research could examine Holocene tufa deposits across a larger geographical range e.g. northern Europe, and work to establish a larger database of both sedimentary and palaeoecological evidence in order to establish a pan – European chronology for tufa cessation based on datasets generated from multiple field sites. The establishment of a longer, radiocarbon dated, palaeoecological record at both the Derbyshire field sites could yield useful information regarding both the timing of tree taxa immigration and establishment in the region, and a research design incorporating a higher sampling resolution could provide additional information regarding the inception of human impact on the local woodland in the Holocene.

Acer was the most prolific tree taxon in local vegetation at both the White Peak and East Yorkshire field sites displaying a high degree of abundance between sites both in pollen and vegetation, these factors contributing to the choice of Acer as the reference taxon used for this current RPPE study; however the pollen – vegetation relationship of Acer is not ideal. Useful and interesting insight could be gained through the selection of alternative reference taxa such as Fagus which, which although not as abundant in the local vegetation, has a more linear pollen – vegetation relationship than Acer. The two RPPE datasets could then be interestingly compared and contrasted in order to discuss the influence, or not, of reference taxon choice in the White Peak data.

The RPPE's acquired in this thesis could also provide a useful input parameter to landscape reconstruction in the White Peak utilising mechanistic models such as the Multiple Scenario approach (MSA) (Bunting & Middleton, 2009). This model can produce vegetation reconstructions from single pollen records which would allow hypothesis testing of past vegetation scenarios from both the pollen records produced in this thesis. The RPPE's from this thesis could then also be applied to the limited pollen records produced from previous research in the White Peak region, and pollen record from the Dark Peak to provide regional simulations. In conjunction with more radiocarbon dated pollen records, this would then allow a more informed chronology of regional vegetation change in the Peak District to be simulated which would be of value to both an academic and non-academic audience. The application of the LRA approach of Sugita (2007a; 2007b) would also estimation of regional vegetation abundance.

Future investigation of fluvial taphonomic processes in the White Peak could be improved through the use of multiple field sites, with a larger number of sample points then being used at each individual field site; valuable information would also be gained through an analysis of the spatial characteristics of the pollen bearing sediment i.e. spatial variation in grain size and organic content at different sampling points within the fluvial field site. This new sampling strategy would be further enhanced through the acquisition of sediment samples in the late summer after the flowering season, but before the winter rains; and in the early spring after the cessation of winter floods but before the commencement of the new flowering season. This would allow the comparison of ‘before-and-after’ pollen assemblages, in order to better evaluate the potential of the fluvial taphonomic model of Holmes (1994) in the River Wye.

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