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Using palynology for high resolution dating of sub-recent Small Water Body sediment cores from North East England

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Using Palynology as a tool for high resolution dating of short sub-recent Small Water Body sediment cores

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Abstract

Little is known about the burial rates of carbon in Small Water Bodies (SWBs <10 km^2), since most research has been on larger lakes. Obtaining carbon burial rates of sub-recent (<20 years) sediments requires a high resolution dating technique which permits sub-decadal error ranges. Typically, isotope dating is used to date young sediment cores but is limited to error ranges of 10-20 years.

This thesis examines whether the pollen and testate amoebae record of different types of SWBs from North East England can be matched to records from vegetation monitoring, crop harvests, and rainfall measurements in order to allow precise dating. High resolution pollen and testate amoebae assemblages from short sediment cores of three different types of SWBs are compared with an eighteen-year vegetation dataset. Utilising research on pollen grain morphology and representation, coupled with records from modern pollen surface sediment samples and vegetation mapping, aid the interpretation of pollen assemblages in the SWB sediment cores with the vegetation monitoring record.

The results suggest that the ability of a pollen-vegetation record dating approach is controlled by the type and size of the individual SWB. High resolution pollen analysis and vegetation matching can be used on an open semi-natural SWB to obtain coherent dates throughout the sediment core. SWBs that are constructed to $1m^2$, or have vegetation growing in the pond, cannot be used for dating. There is a minimum size required for the calculation of sedimentation rates on SWBs, as the $1m^2$ constructed SWBs were not suitable. Reworking of pollen grains, particularly in the small constructed ponds is identified by the occurrence of a carboniferous spore (*Lycospora*), reducing the accuracy of matching the pollen and vegetation assemblages in these pond types.

This technique can be applied to other SWBs to further our understanding of sub-decadal carbon burial rates. The approach also allows a documentation of the palynological interactions occurring within a variety of types and sizes of SWBs.

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Abbreviations

C/N   Carbon/Nitrogen

CONISS   Stratigraphically constrained cluster analysis

HUMPOL   Hull Pollen Deposition Modelling

OC   Organic Carbon

P29   Pond 29

P8   Pond 8

PCA   Principle Components Analysis

PAST   PAlaeontological STatistics

PRIMER   Plymouth Routines In Multivariate Ecological Research

PSA   Pollen Source Area

RBP   Reed Bed Pond

RPSA   Relevant Pollen Source Area

SNP   Semi Natural Pond

SWB   Small Water Body

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Author's declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is my own work. I also confirm that the opinions, ideas and contributions from the work of others have been fully acknowledged.

I declare that the Word Count of this Thesis is 20,544 Words

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Signature:

Date: 01/02/2016

1 Introduction

The influence on and contribution of Small Water Bodies (SWBs) to the global carbon cycle has remained relatively neglected in past research, but recent studies have estimated that SWBs can sequester carbon at rates up to 400 times greater than inland seas (Downing, 2006; Boyd, et al., 2010). Lehner & Doll (2004) suggested that there are 8 million natural lakes >0.01km^2 in the world however, their estimate did not include water bodies < 1.2 km^2. Downing et al. (2006) developed this with an estimated total of 304 million lakes, covering an area of approximately 4.2 million km^2, dominated by several millions of SWBs with an area of less than 1 km^2 (Downing et al., 2006; 2010). Given the high volume of SWBs, it is of vital importance to understand their role within the global carbon cycle by examining the burial rates of carbon within their sediments. Age control is required to calculate burial rates and is typically achieved using isotope (^{210}Pb and ^{137}Cs) dating (Heathcote & Downing, 2012). The majority of sediment cores from lakes for carbon sequestration studies have been >1m deep (Mackay et al., 2012).

However, obtaining high resolution ages for sub-recent sediments with current dating techniques, encounters several limitations. The calculation of organic carbon (OC) burial rates in recent lake sediments (50-150 years) utilises ^{210}Pb and ^{137}Cs isotope dating, as ^{210}Pb has a half-life of 22.26 ± 0.22years (Walker, 2005; Chen et al., 2014; Kirchner, 2011). The use of ^{210}Pb as a dating tool alone lacks sufficient accuracy and is typically integrated with ^{137}Cs (Kirchner, 2011; Dong et al., 2012; Brothers et al., 2013). However even the combination of ^{210}Pb and ^{137}Cs dating can produce error ranges of 10-20 years within the past 100 years (Brothers et al., 2013) and consequently does not provide high enough resolution dating for sub-recent events, therefore a methodology with sub-decadal error ranges is needed. This study will test whether high resolution pollen analysis can be used to date sub-recent short sediment cores from SWBs. The study will also test, how far high resolution analysis of these short records can be used to accurately reconstruct vegetation and hydrological changes around SWBs.

In order to test the potential of high resolution palaeoecological studies for dating sediments, four short sediment cores were taken from two types of SWBs (semi-natural and 1m^2 constructed) from Low Hauxley, Northumberland, UK. Three of

the four cores were analysed for palynology, testate amoebae and geochemical data. This study also uses vegetation data compiled of cultivated crop records from the surrounding fields and abundance counts of the macrophyte communities within the thirty constructed ponds in the field (Jeffries, 2008). This was compared with the short (<20 cm) pollen records to see if the vegetation dataset was reflected in the pollen assemblages of the different SWBs. Precipitation data from Boulmer weather station, Alnmouth, UK was used to investigate the hydrological sensitivities of different types of SWBs, which was combined with testate amoebae and Carbon/Nitrogen (C/N) ratios. Pollen surface samples from the four SWB sediment cores and vegetation mapping locations within the same site were analysed to understand the dynamics of the different SWBs and their pollen signals.

The principle focus of this study is to determine whether multiple dates can be obtained through the comparison of high resolution palynological analysis of short sediment cores from SWBs and a vegetation monitoring dataset (1995-2013). Further to this is to identify whether testate amoebae records, C/N ratios and rainfall data support the interpretations made between the pollen and vegetation datasets. Pollen dispersal, transport and deposition affect pollen representation (Bunting, 2003; Fontana, 2005; Goring et al., 2013) in the sediment core while the size, type and location of the SWB have influence on the pollen-vegetation relationship (Waller et al., 2012). The high resolution changes in pollen signatures of short cores have shown vegetation trends (Waller et al., 2012). The use of an eighteen year macrophyte record of thirty constructed ponds in Hauxley Nature Reserve collected by Jeffries (2008) will provide the vegetation component to compare with pollen assemblages collected from sediment cores in SWBs also in Low Hauxley Nature Reserve. Observing the relationship between the pollen and vegetation records will determine if the short sediment cores from the SWBs have the capability of illustrating high resolution changes.

This thesis will attempt to date short sediment cores from SWBs in Low Hauxley Nature Reserve using palynological and vegetation data. Supporting datasets of testate amoebae, precipitation and geochemical data will contribute to the understanding of the hydrological sensitivities of the different SWBs over a short (<20years) time period. The results will be explained in relation to carbon cycling, pollen dissemination, representation and relationship with vegetation.

2   Scientific background

2.1   Small water bodies and carbon burial

The research on carbon cycling, carbon sequestration, palaeohydrology, and ecohydrology has been extensive on large water bodies and peatlands however, there is limited research on SWBs (Turner et al., 2014; Loisel & Garneau, 2010). Accumulation rate, input of biomass, diagenesis (change of sediments through pressure), isotopic composition and water status can contribute to changes of the palynological signal within the lake (Meyers & Ishiwatari, 1993; Lehmann et al., 2002; Smol, 2002). Changes in the carbon isotopic content of organic matter in sediments occur during the early stages of diagenesis, through selective degradation of organic matter components and microbial reworking, which can result in different levels of carbon in surface sediments (Meyers & Ishiwatari, 1993; Lehmenn, et al., 2002). The input of biomass into a lake system can be divided into two sources, allochthonous (outside the water body) and autochthonous (within the water body such as algae, aquatic animals and plants) (Smol, 2002). Rates of accumulation in sediment and traps are different and have shown 30-40% organic matter depletion in sediments due to diagenesis (early stages 0-3yr) (Lehmann et al., 2002). Meyers & Ishiwatari (1993) found land-derived and algal organic matter have different rates of diagenesis shown by C/N ratios fluctuating with depth.

C/N ratios are used as a proxy to indicate change from where biomass has come from, whether it is algae or macrophyte related (Meyers & Ishiwatari, 1993; Smol, 2002) and have been shown to be affected by allochthonous sources (Lehmen et al., 2002). Increases in C/N ratios through sediment cores indicates a high quantity of terrestrial organic matter has entered the lake and conversely decreases indicate high levels of algal organic matter (Kaushal & Binford, 1999). A C/N ratio of 4-10 indicates algae and >20 indicates terrestrial organic matter (Kaushal & Binford, 1999). There are two main states of SWBs; macrophyte and phytoplankton dominated, which is determined by the morphology of the lake (Meyers & Ishiwatari, 1993). Alternate equilibria occur in shallow lakes which refer to the switch between macrophyte (relatively clear water) or phytoplankton (generally turbid) dominated states which can be identified through C/N ratios (Smol, 2002). The C/N ratio and testate amoebae analyses can indicate the

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eutrophic, ombrotrophic or minerotrophic status of the SWB, therefore indicating climate conditions. (Borgmark & Schoning, 2006; Andersdon & Schoning, 2010).

The water status of the lake has shown to have an influential role on carbon burial through the effects of oxygenation of organic matter which is increased in anoxic conditions (Lehmenn et al., 2002). Carbon burial is propelled by the addition of nutrients which eutrophication provides and therefore, inland waters such as SWBs play an integral part of long-term carbon burial and storage (Heathcote & Downing 2012). Research has shown that carbon burial rates are higher in phytoplankton dominated lakes (82% permanently buried) than macrophyte dominated lakes (34% permanently buried) (Brothers et al., 2013). OC burial rates in small natural ponds along Druridge Bay, Northumberland, UK were some of the highest recorded (Gilbert et al., 2014) showing permanently submerged sediments have the highest %OC and temporary pond sediments in arable fields had the lowest %OC. This research supported findings from Downing et al., (2008) and Boyd et al., (2010).

Changes in vegetation are influenced by ecological regime shifts which are abrupt changes in the functionality of a system (Rull, 2010) and are understood to have a possible impact on carbon cycling (Brothers et al., 2013). In the case of SWBs, this can be a change from a clear water regime of submerged macrophytes to turbid phytoplankton regimes, and could derive from anthropogenic land-use influences which could cause eutrophication (nutrient enrichment).

2.2 Limitations of dating recent sediments

Dating recent lake sediments (50-150 years) typically uses ^{210}Pb and ^{137}Cs isotopic dating to calculate the burial rate of OC as ^{210}Pb has a half-life of 22.26 $\pm$ 0.22 years (Walker, 2005, Kirchner, 2011 & Chen et al., 2014). The use of ^{210}Pb as a dating tool alone should be used in conjunction with another dating method as sediment age information is not exact, which explains the integration of the time-independent tracer ^{137}Cs (Kirchner, 2011; Dong et al., 2012; Brothers et al., 2013; Tylmann et al., 2013). ^{137}Cs is an anthropogenic induced radionuclide that shows peaks at 1963 (atomic weapons testing) and 1986 (Chernobyl accident), corroborating ^{210}Pb dates (Kirchner, 2011). The assumption of ^{210}Pb dating models that there is a constant rate of supply of ^{210}Pb, have been known to be unrealistic as hydrological input can change the status of the lake water, such as

sediment resuspension in shallow zones and higher sedimentation rates influenced by the coring location in the lake (Tylmann et al., 2013). However, these two dating techniques do not provide high resolution dates for events occurring after the 1990's due to a lack of time independent markers (Tylmann et al., 2013) and therefore, high resolution pollen analysis is being used. Matching recorded vegetation events with the occurrence of pollen in a sediment core assemblage has been performed successfully, but there are limited studies which have conducted this on cores <100 years (Taylor et al., 2006; Anderson et al., 2010; Waller et al., 2012).

2.3 Pollen representation and vegetation relationship

In order to use palynology as a dating tool, the factors which influence the pollen vegetation relationship must be known in detail. The processes affecting pollen representation have been extensivley researched and models developing this information have been used to further understand the pollen vegetation relationship and consequently permit environmental reconstructions (Sugita, 1994; Bunting et al., 2005; Waller et al., 2005; Turner et al., 2014). The factors which affect the species representation of vegetation communities in a pollen assemblage are the production, transport, deposition and preservation of pollen (Meltsov et al., 2011; Goring et al., 2013; Sugita, 2013). Pollen representation incorporates the production and dispersal biases, and calculates how much the pollen percentages over or under-represent the relative abundance of plant taxon (Prentice, 1985).

The efficiency of pollen dissemination for each species must be known when interpreting a pollen spectrum (Davis, 1960). Each species interacts differently to dispersal factors, and the dispersal of each pollen grain is governed by how it is pollinated; either through entomophily (insect), anemophily (wind), hydrophily (water), epihydrophily (on water surfaces) or hydroautogamy (self) (Wiltshire, 2006 & Goring et al., 2013). Anemophily (wind) is the dominant type of pollination in terms of the numbers of pollen taxa dispersed and transported from plants (Zhang et al., 2010). The size, shape and quantity of the pollen grains are vital in their anemophilious dispersal as it will determine the distance travelled. Large pollen grains which are heavy tend to have fast fall rates such as *Abies* and *Picea* (Gavin et al., 2005). Poaceae, also anemophilious, has poor dispersal ability especially over long distances, so the locality of the pollen from the plant

theoretically will not be far apart (Tweddle et al., 2005). Hydrophilious and epihydrophily are two of least common forms of pollen dispersion utilising water as the vector for pollen transport. The species having this ability vary in its importance within the ecosystem. It is believed that the freshwater plants of Lemnaceae (duckweed family) and *Callitriche* (water starwort) are hydrophilious but it is not yet fully proven how dissemination occurs within both plants (Cox 1998). Despite dispersal methods, the majority of pollen grains are deposited near the parent plant (Wiltshire, 2006). Dispersal and deposition are the two main interacting factors which effect the representation of individual taxa in pollen diagrams (Brayshay et al., 2000; Soepboer & Lotter, 2009). Quantifying individual taxa representation raises the major problem encountered in most pollen-vegetation studies, which is distinguishing between local and more distant pollen sources (McGlone & Moar, 1997).

Pre sub-recent pollen assemblages cannot be directly related to plant abundance (Fontana, 2005). However, temporal and spatial variations of vegetation have been found to correlate between pollen assemblages and vegetation composition (Jackson & Williams, 2004). Consequently, the pollen assemblage is unable to directly represent the vegetation communities and successions which caused the pollen production in the first place, but do reflect broad community groupings (McGlone & Moar, 1997).

Taking into consideration the production and dispersal characteristics of plant taxa, plants closer to the sampling point are considered to have a greater influence on the pollen signal than plants further away and therefore, map vegetation in more detail closer to the sampling point (Prentice, 1985; Sugita, 1994; Bunting, 2003). The connectivity between every factor influencing pollen assemblages is complex and intricate and therefore must be taken into account when analysing any aspects or changes of a pollen diagram.

Another point to note is the evenness within the pollen assemblage. Pollen percentages are sensitive to evenness and therefore, when interpreting the pollen assemblage for vegetation patterns, the pollen productivity of taxa must be understood (van der Knapp, 2009). Pollen productivity varies greatly between species and as such, individual pollen taxa do not represent the equivalent existence to the individual plant species and some taxa never enter the sedimentary record, despite its locality to the sediment sink (Jackson & Williams,

2004; Goring et al., 2013). Interspecific variation among competing taxa in the same site can heavily influence the pollen assemblage as the relative abundance of one taxon can alter another (Jackson & Williams, 2004). There have been attempts to overcome evenness in pollen representation calculated through various methodologies; two examples of which is RATEPOL software (van der Knaap, 2009) and Simpson evenness index (Meltsov et al., 2011). van der Knaap (2009) explained that counts for all individual pollen types must be divided by their pollen productivity estimates before estimating rates of change, but believes this objective is far in the future.

2.4 Pollen source area and pollen modelling

This study is focused on SWBs and it is therefore important to consider the role of the Pollen Source Area (PSA), as PSA can dramatically vary even with a small change in the size of the hollow sampled. The PSA, assuming a homogenous vegetation structure, is the area from which a certain proportion of the pollen deposited at a site originates (Nielsen & Sugita, 2005). Factors contributing to this change can be taxon, site or region specific (MacDonald & Edwards, 1991; Gavin et al., 2005). Jackson (1990) found that PSAs of small lakes not under a closed canopy are significantly larger than ones under canopy. Sugita's (2007a; b) modelling for source areas predicts 2 m radius sites (small forest hollows) to have a 50-100 m Relevant Pollen Source Area (RPSA) and 50 m sites (small lakes) have a 300-400 m (Seppa & Bennett, 2003). RPSA is the distance from a pollen deposition point beyond which the relationship between vegetation composition and pollen assemblage does not improve (Sugita, 1994). Despite small lakes having a smaller PSA in comparison to the PSA of larger lakes, they retain the ability to palynologically record tree and shrub fluctuations, but little is known on what herbaceous, aquatic and other taxa groups illustrate in the pollen assemblage of small lakes. A large amount of research has been performed on source areas and pollen representation (e.g. Prentice, 1985; Fyfe, 2006; Sugita, 2007a; 2007b; Matthias & Giesecke, 2014) first presented by Prentice (1983) in the unified theory of pollen analysis. Quantifying PSA showed that basin size affects pollen deposition, but further extensions to the model are required when applying to lake deposition (Prentice, 1985). The Prentice model of pollen dispersal and deposition assumes no mixing of pollen after deposition and the Sugita form of the Prentice model assumes mixing of pollen before entering the

sediment record (Waller et. al., 2012). There have been more key parametres included in modelling, such as pollen loading of a basin per year, distance-weighted plant abundance and regional and local estimates of vegetation. These allow a more accurate explanation of the pollen assemblage of a selected site by determining the fluctuations of long and short distance pollen grains (Sugita, 2007b). The development of pollen modelling is a fundamental part of the pollen-vegetation relationship interpretations as the simulations have illustrated the point from which correlations between pollen loading for all taxa and vegetation abundance do not continue to improve (Sugita, 2007a, 2007b).

Pollen modelling provides an insight into the behaviour and interactions of pollen, vegetation and the landscape in which it can be found. The simulations from pollen modelling aid the interpretations of pollen assemblages from small scale studies, as the simulation results provide insight into the sensitivities of landscape change (Fyfe, 2006). The Hull Pollen Deposition Modelling (HUMPOL) works with an integrated Geographical Information Systems (GIS), allowing a simulation of landscapes and vegetation communities (Fyfe, 2006). One of the clearest results from the simulations highlighted that cereal taxon in samples > 350 m were recorded in levels below 0.1 % showing that the likelihood of cereal pollen existing in sediment assemblages was extremely low. The simulations also showed woodlands and woodland ecotones were dominated by tree pollen and very little herbaceous taxa (Fyfe, 2006).

2.5 Palynological studies on short sub-recent sediment cores

Model simulations of pollen production from small ponds were completed using the Prentice model of pollen dispersal and deposition which assumes pollen is not remobilised after initial deposition. This was to show if and how coppicing patterns could be visible and revealed patterns in woodland management that correlated with pollen data available from northern Alpine forelands and ^{210}Pb and ^{137}Cs chronology (gained from the constant rate of supply model) (Waller et al., 2012). One of the main drawbacks of palaeolimnological research on SWBs with low sedimentation rates, is that benthic communities and wind induced currents in shallow lakes can cause bioturbation and other sediment mixing processes to occur which has not made studies favourable (Smol, 2002; Meyers & Ishiwatari, 1993). However, Waller et al's., (2012) results indicate that sediment mixing in small hollows similar to this study does not has an adverse effect on the

pollen record. Another significant finding of Waller et al's., (2012) research was that pollen grains indicative of open ground were low for all sites during periods of high tree presence near the hollow. This study was one of the first quantitative analyses focused on understanding pollen production affecting small hollows, finding that some taxa can be palynologically invisible under some coppicing regimes. Since this has been shown to affect small hollows, it is important to note the possibility of it occurring in a similar environment such as SWBs in close proximity to tall vegetation.

2.6 Reconstructing hydrological changes using testate amoebae

Testate amoebae (Protozoa: Rhizopoda) are single celled organisms which have a nucleus and cytoplasm encased within a shell built from proteinaceous, calcareous or siliceous material (Charman, (2001). The cytoplasm determines the intake of water and consequent encystment process following drought and also forms the pseudostome, used for movement, attachment or feeding (Charman, et al., 2000). Testate amoebae are extremely sensitive hydrological indicators mainly living in freshwater and have a short life span of approximately two weeks (Charman, et al., 2000, Booth, 2001; Mattheeussen et al., 2005). Rapid reproduction through mostly asexual binary fission results in 10-27 generations per year (Charman, 2001). Even within the same population, there is high morphological variability of shell size, answerable to environmental factors such as food source, temperature and insecticides (Mitchel et al., 2008). They can be between the sizes of 20-200 μm and thrive off various food sources, such as protists, bacteria, fungi, organic matter and micro-metazoa (rotifers) (Mitchel et al., 2008). The variability in size at genus level can differ significantly (Charman et al., 2000), and this factor, coupled with limited identification sources highlights the complexity of testate amoebae investigations. Some testate amoebae species have restricted geographical distributions and further research is required to clarify their geographical extent (Bobrov et al., 1999; Woodland, 1998; Mitchell et al., 2008; Bobrov & Wetterich, 2012).

Testate amoebae are a very useful proxy for reconstructing habitats (macrophyte or sphagnum dominated to minerotrophic or peatland) (Charman, et al., 2000, Booth, 2001; Mattheeussen et al., 2005). They have demonstrated their sensitivities to habitat changes on a micro-scale (bog hummocks to lawns) and macro-scale (different geographical regions) (Mitchel et al., 2000). Surrounding

vegetation and C/N Ratios influence trophic status and have been shown to affect the species distribution of testate amoebae (Charman, 2001). There has been increasing focus on what proxies can be used to indicate change in SWBs (Smol, 2002) and changes in hydrological conditions in SWBs have been identified using testate amoebae as a proxy (Turner et al., 2014). Testate amoebae have become increasingly utilised alongside pollen analysis to support reconstructions of vegetation and moisture conditions (Mitchel & Charman, 2008; Payne et al., 2011).

An increasing wealth of information on their habitat preference and hydrological indicator values has permitted a greater use of them in multi-disciplinary dataset studies to support climatic and environmental findings (Charman et al., 2000; Charman, 2001; Alves et al., 2010). There has been little work on taxonomy recently which ceased with the two main identification glossaries of Charman (2000) and Clarke (2003). A large proportion of studies since have been focused on the use of testate amoebae as environmental indicators. The majority of research on testate amoebae has been conducted on peatbogs and wetlands most recently in Canada, Switzerland and New Zealand (Payne et al., 2011). There is an increasing amount of research on testate amoebae completed on British sites, often included in multi-proxy studies (Woodland, 1998). Testate amoebae exist in marine and lacustrine environments but, despite increasing research, little is known of lacustrine testate amoebae and few studies on fossil core assemblages have been completed (Patterson et al., 2012).

The modern shell of testate amoebae and its fossil counterparts have been directly compared in previous studies, but problems occur during microscopic identification due to fossilisation effects and morphological variability (Charman, 2001). Certain species have been shown to hold different decay rates in woodland soils and further research is required to identify what species do this and over what timescale (Woodland, 1998). It is important to be aware that some living testate amoebae can survive short term environmental fluctuations by a survival mechanism called encystment, whereby the cystoplasm seals their aperture and can be transported longer distances by wind and potentially animals (Charman et al., 2000). Research has not yet shown that this is the case for all species (Charman et al., 2000). Testate amoebae, which can encyst and excyst rapidly, have an advantage to survive longer in highly variable conditions as they

can feed during favourable conditions (Sullivan & Booth, 2011). Competing against these types of testate amoebae, are ones with wide tolerances but weak competitors for resources, which can result in these species being excluded as populations will reach carrying capacity (Sullivan & Booth, 2011).

Trends in hydrology, such as peaks in wet periods have been identified in testate amoebae records, by wet indicator testate amoebae peaking in a similar trend (Woodland, 1998). Woodland (1998) modelled the mean water table depth tolerance for individual species illustrating a wide variance between genera. Centropyxidea, Arcellinida, Trinematidae, Euglyphida and Diffugiidea have been shown to exist in plankton, aquatic macrophyte, and aquatic sediment communities, which is not as selective as Hyalosphenidae and Plagiopyxidae (Alves et al., 2010). Woodland (1998) modelled the mean water table depth tolerance for individual species, illustrating a wide variance between genera. Other environmental changes known to affect their distribution is the surrounding vegetation, sediment grains size, nutrient input and C/N Ratios (Charman, 2001). There is very little known on the transport dynamics of testate amoebae therefore a limited amount of information is known on the interrelationships between pond environments which are in close proximity. However, this lack of transportation information is partly overlooked due to the speedy reproduction and encystment ability of testate amoebae (Charman, 2001).

Studies on testate amoebae have begun to approach quantitative analysis rather than qualitative, to better understand the dynamics of testate amoebae and their habitat preferences (Bobrov et al., 1999). Multivariate statistical tests have shown testate amoebae to be sensitive to water table depth and the interpretation of results suggest that testate amoebae community dynamics are affected by short term environmental variables and high-intensity flooding events (Swindles et al., 2014). Ecological relationships between plant species and testate amoebae which implied wet/dry phases have also been shown (Amesbury et al., 2013).

3 Aims, Research questions and Objectives

The main aim is to identify whether recent sediments can be dated to a high temporal resoluation using the analysis and interpretation of different palynological records, observational data and geochemical analysis. The following research questions and subsequent objectives are:

Research questions

1. Do vegetation mapping and pollen surface samples from the same field-site indicate that the location of vegetation to the pollen sink is important?

2. Does the vegetation monitoring record identify the wet and dry years in the rainfall record?

3. Can the vegetation monitoring record be identified in the SWB's pollen records and therefore allow dating?

4. Is there a relationship between testate amoebae, C/N ratios and recorded rainfall to see if the wet/dry years can be identified, and can this link support the pollen-vegetation dating technique?

5. Do the different types of SWBs record a pollen signal that can be matched to the vegetation records and therefore allow dating?

6. Can the crop record be identified in the pollen sedimentary record of any of the SWBs?

7. Are there any similarities in pollen taxa assemblages in any of the different SWB sediment records?

Objectives

i. Evaluate the representation of pollen taxa in the surface sediment samples with the vegetation mapping locations.

ii. Identify whether the vegetation record shows the wet and dry years by comparing it with rainfall data.

iii. Identify the similarities in occurrence between the pollen assemblages from each SWB and the vegetation dataset.

iv. Examine if the testate amoebae and C/N ratios indicate wet/dry years.

v. Critically compare the pollen taxa occurrence in each SWB with the vegetation record to identify if there are any similarities indicating possible dates for sections of the sediment core.

vi. Identify if any of the crop records are reflected in the SWB pollen records.

vii.   Investigate the similarities and differences of the pollen assemblages from the different SWBs in terms their pollen taxa.

4   Study Site

Hauxley Nature Reserve (55° 19' 4'' N; 1° 33' 22'' W) is at the northern end of Druridge Bay, within the Northumberland Rivers catchment. The site is within the South East Northumberland Coastal Plain, characterised by large mixed farming fields, restored and open cast coal mines and sandy bays (Natural England, 2013). The predominant farming practices within the lowland of Northumberland are arable, taking up 76 % of the total area, of which tillage is accountable for 31 % (wheat, barley, sugar beet, potatoes, vegetables, fruit and grass leys) (Swan, 1994). The site was previously an open cast coal mine until the 1960s which was transformed into a nature reserve in 1983 back-filled and topped with a layer of clay and ~50 cm of topsoil (The Wildlife Trusts, 1999; Jeffries, 2011). Since the addition of the layer of topsoil, there has been no known or recorded anthropogenic reworking of the sediment on-site. The site is exposed to seasonal flooding and therefore, periods of wet and dry are common (Jeffries, 2008). *Crataegus* (hawthorn) and *Prunus spinosa* (blackthorn) hedges are along the east side of the field, and *Alnus* spp. (alder) and *Salix* spp. (willow) on the south. *Pinus* spp. (pine) trees grow to the west of the field which run the length of the field and are densely planted. The vegetation within the field is largely Poaceae spp. (grasses) and Cyperaceae spp. (sedges) with seasonal plants such as, Asteraceae spp. (daisy family), Fabaceae spp. (bean family), Plantaginaceae spp. (plantain family) and Ranunculaceae spp. (buttercup family)*.* Within the summer of 2014 a vegetation survey of the field site showed high presence of *Carex* sp. (sedge)*, Juncus articulatus* (jointleaf rush)*, Polygala* sp. (milkwort)*, Ranunculus flammula* (greater creeping spearwort)*, Stellaria* sp. (chickweed) and a near continuous cover of *Leptodictyum riparium* (moss) in the understory.

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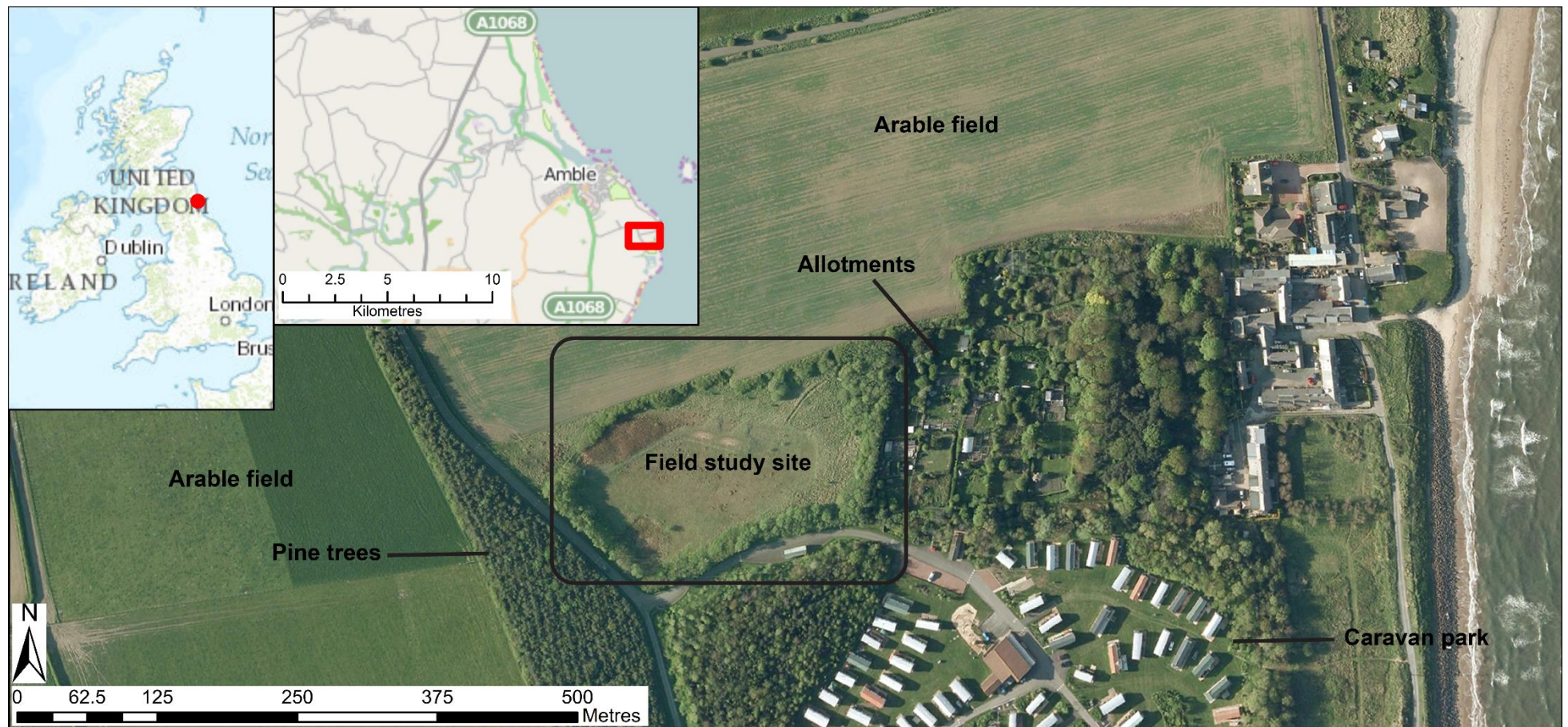
Figure 1: Location of the site in the United Kingdom and the SWBs where the sediment cores were sampled. (Getmapping plc, 2015 & ESRI, 2015).

Study site
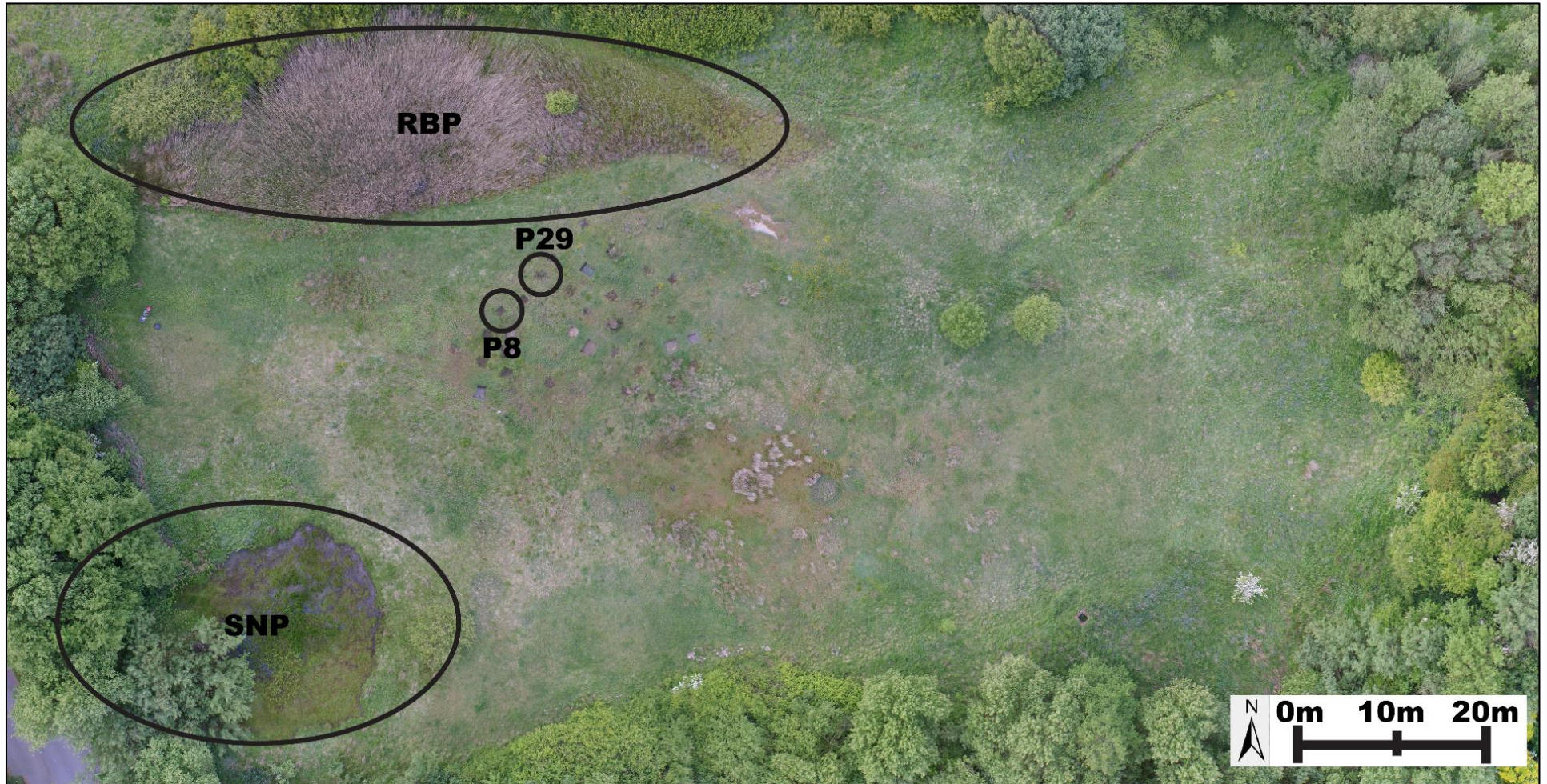
Figure 2: Location of the ponds within the field site. Reed Bed Pond: Blue, Semi-Natural Pond: Purple, Pond 8: Yellow, Pond 29 Orange.

Three types of ponds were studied in Low Hauxley nature reserve, Semi-Natural Pond (SNP), Reed-Bed Pond (RBP) and constructed ponds (Figure 2). SNP created in 1995 is in the south-east corner of the field would be National Vegetation Classification (NVC) S19 *Eleocharis* (spikerush) swamp, characteristic of British lowlands which can have standing or running water 50 cm deep (Rodwell, 1995). SNP has a slight inflow of water from the northern end which drains from the RBP. The RBP was created in 1995 by creating a ridge on the field site to impound water (
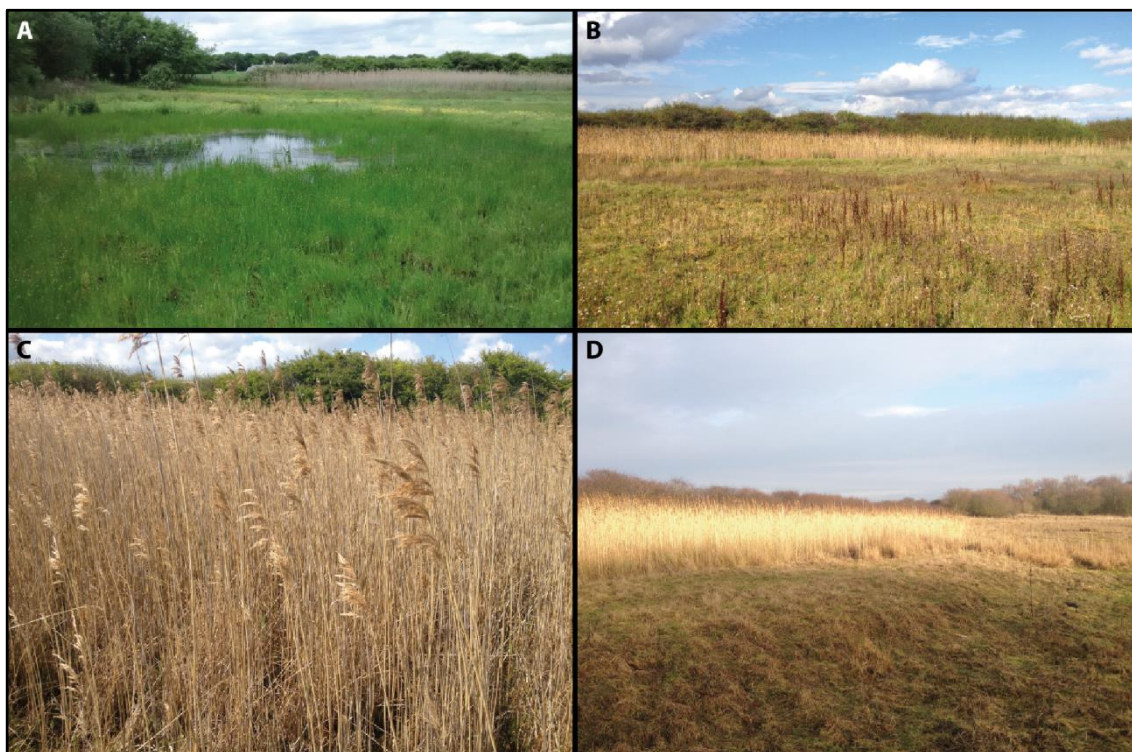
Figure 4) and is located in the north of the field with predominantly *Phragmites* (reed). *Phragmites* were not introduced into the pond and arrived naturally (Jeffries, unpublished data). There are two visible points where the water can flow out onto the field and can infiltrate the constructed ponds and SNP. The constructed ponds (P29 and P8) are two of thirty experimental ponds (1 m² and 30-40 cm deep) excavated in 1994 as part of a long term ecological study

(Jeffries, 2008) and a selection are shown in
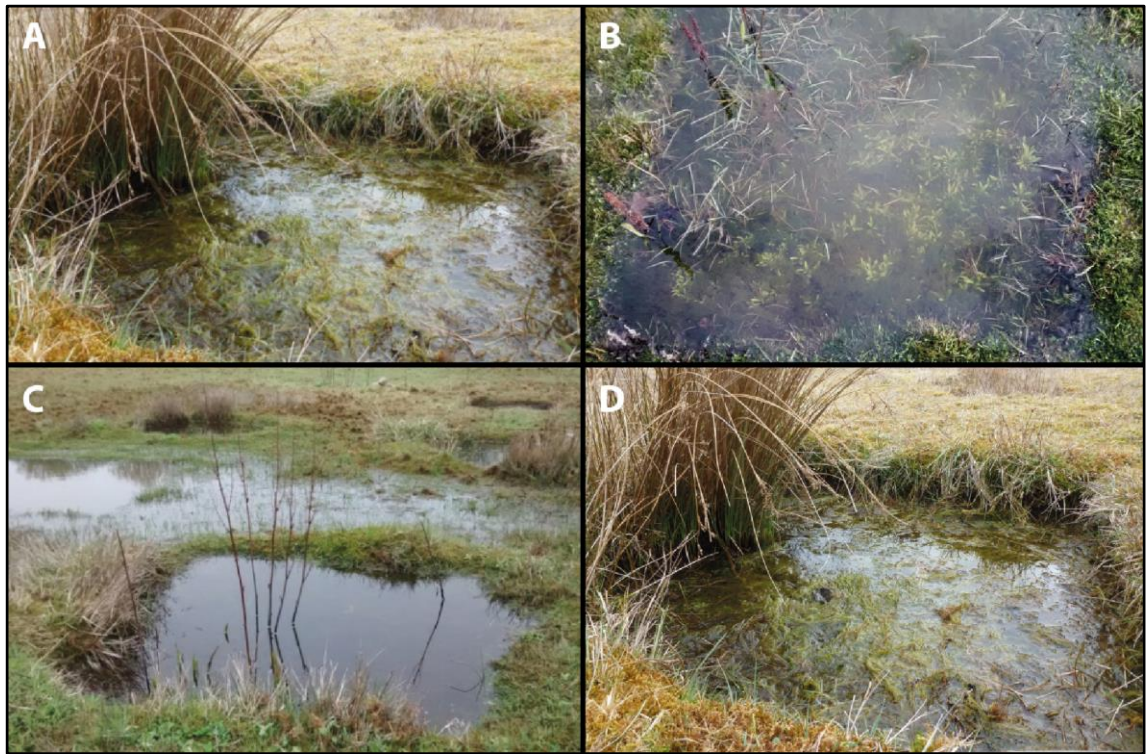
Figure 5. P29 and P8 were chosen for analysis and are both located in the area prone to flooding. These ponds have been inundated (floods join several ponds together) frequently (Jeffries, 2008) providing the opportunity for hydrophilious (water) pollination.
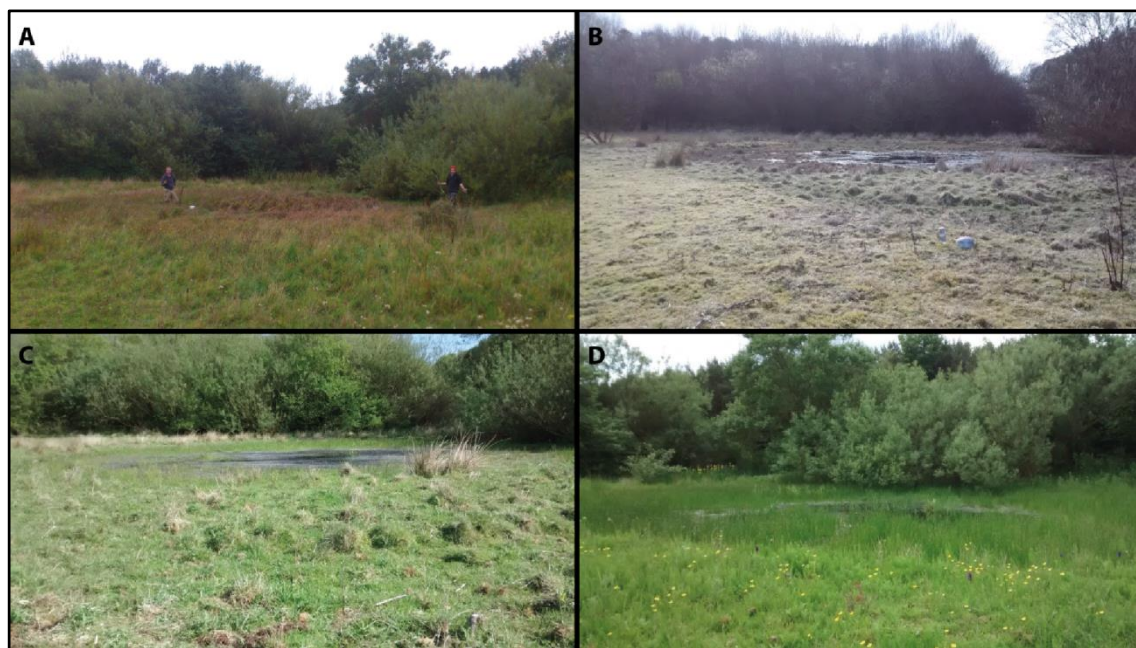
Figure 3: **A-D**: Semi-Natural pond (SNP), NVC S19. **A**: November, **B**: February, **C**: May and **D**: June 2014.
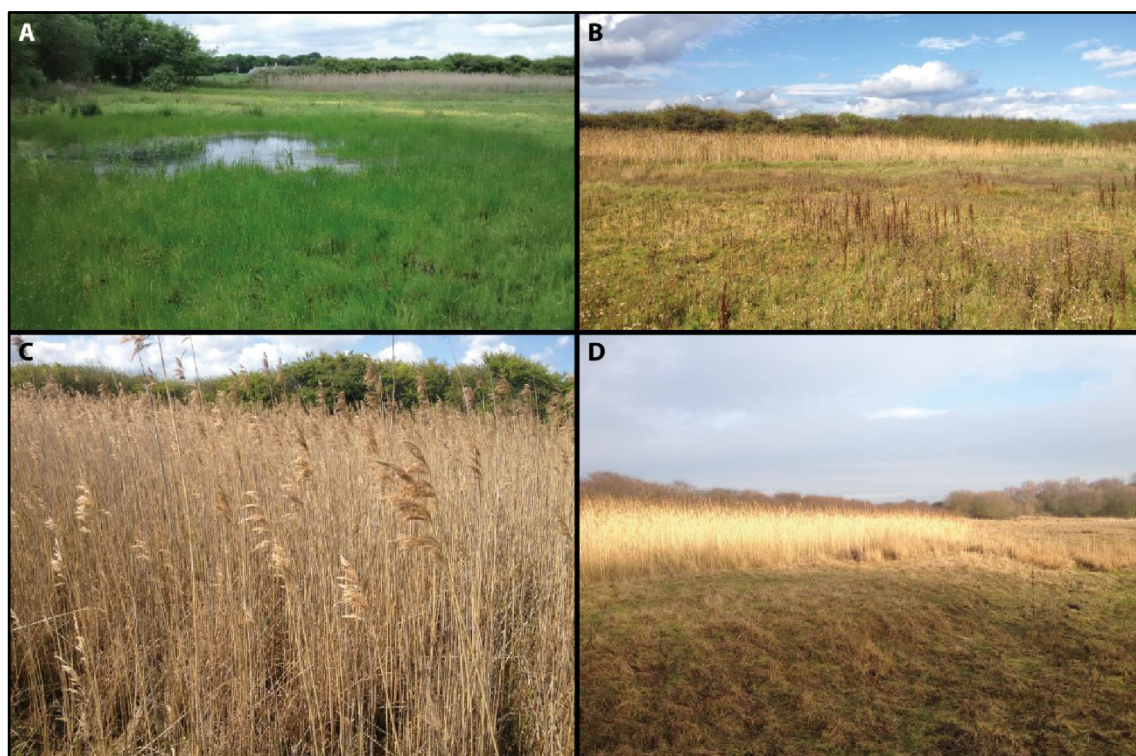
Figure 4: **A-D**: The RBP is on a raised section of the field. **A** and **B** shows its position in relation to SNP in the bottom left of image A. **C** shows the intensity of *Phragmites* grown in the RBP and **D** illustrates a close-up image of the raised bed.
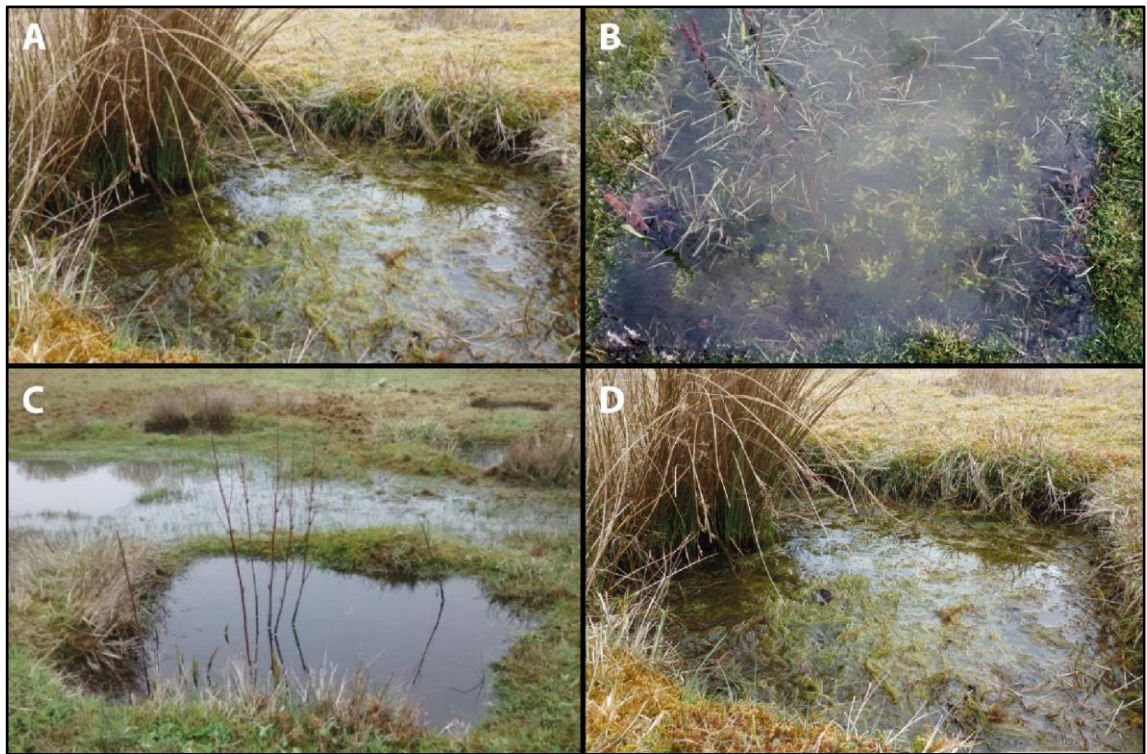
Figure 5: **A, B, C** and **D** are some of the experimental ponds taken November 2013. **A** has a high concentration of algae and is very homogenous with macrophyte vegetation. **B** shows how grasses are encroaching into the 1 m2 pond. **C** is prone to flooding and has expanded over its 1m2. **D** is heavily populated with macrophyte vegetation and has encroaching Cyperaceae and Poaceae from the edges.

5 Methodology

5.1 Field, laboratory and data collection

5.1.1 Sediment core sampling

The sediment cores were excavated with a spade, which caused no compaction

or   slumping   of   the   core   (

Figure 6). The cores are relatively short: SNP 19 cm, RBP 9.5 cm, constructed P8, 5.5 cm and P29 6 cm. Piston corers, such as the Russian peat corers were

not used as they cause compaction and are unable to penetrate through roots adequately which would consequently distort the stratigraphy (Ellison, 2008).

The four SWB cores were extracted in the same way via an access pit as demonstrated in

Figure 6 A, B and C. The SNP core was taken from the pond in October 2013 whilst it was dry and the RBP was extracted in September 2014. It was not possible to drain the water from the access pit of the RBP, as it was significantly larger than the constructed ponds. Thick rooting throughout the sediment made it particularly difficult to extract the core from the RBP. The P 29 and P 8 were

used in this study as the pond's sediment was also being used in a PhD research study on carbon sequestration.

Figure 6: **A-E**: Method of extracting the sediment cores in the field. **A**: Access pit dug to drain pond and retrieve the pond sediment with no compaction. **B**: The sediment core sliced along each side ready for extraction. RBP (**C**) and P8 (**D**) sediment cores in the laboratory to be sub-sampled in 0.5 cm. **E**: The sediment layers (pictured in P8) of the pond and anthropogenic infill material along the base.

5.1.2 Sample preparation for palynological analysis

The SNP, RBP, P 8 and P 29 cores were wrapped in aluminium foil to prevent contamination from modern pollen and stored in a fridge at 4°C until sub-sampling to avoid mould growth. In order to obtain high resolution pollen assemblages, the sediment cores were sub-sampled at 1 cm (SNP and P 29) and 0.5 cm (RBP and P 8) resolution. The SNP and P 29 cores were sub-sampled in the laboratory using a sterilised sharp blade and scissors. The RBP and P 8 (

Figure 6D and E) were sampled after SNP and P 29 and were partly frozen to ensure higher resolution (0.5 cm) could be obtained. This method allowed a sharp blade to cut through a thinner section of sediment without the structure of the sub-sample being affected. The preparation of sub-samples for pollen analysis followed the standard palynological treatment as described by Faegri & Iversen (1989). Sub-samples from all the cores were weighed and *Lycopodium* spores were added to check on pollen recovery and to quantify pollen concentration (Stockmarr, 1971).

For the laboratory palynological analysis of the sediment core, two to four grams of sub-sample was weighed in a 50 ml centrifuge tube. If large pieces of organic matter were in the sample, they were weighed closer to 4 g since the sieving process would retain them leaving less sediment to process. One *Lycopodium* tablet was added to each sample and dissolved in 10 ml of 10 % hydrochloric acid (HCl) to remove carbonates. The tube was filled to 50 ml with distilled water and centrifuged for 3 minutes at 3000 rpm to collect the sediment in the bottom of the tube. The supernatant was discarded and 10 ml of 10 % potassium hydroxide (KOH) was added to remove humic acid and the sample deflocculated, mixed with a stirring rod and put in a water bath at 80°C for 3 minutes. The tube was shaken once to agitate the sediment and break up large particles. Immediately after the water bath the sample was put through a 250 μm sieve and washed through with distilled water. Some samples were sieved with a 125 μm mesh but microscopic analysis showed this did not aid the clarity of the samples so the sieving was maintained at 250 μm. After centrifuging for 3 minutes at 3000 rpm the sample was washed with distilled water and centrifuging repeated until the supernatant was clear. Some samples had a very dark supernatant suggesting they contained high amounts of humic acid (Faegri & Iversen, 1989). Another set of 10 ml of 10 % of HCl and centrifuging was performed before the samples were put through hydrofluoric acid (HF) treatment. The HF process, which removes siliceous matter, was completed by a laboratory trained technician. After HF treatment, acetolysis treatment was carried out to sterilise the surface of the pollen grains and remove some organic matter. Samples were then dehydrated with Ethanol (EtOH) and tert-butyl alcohol (TBA) was added to the sample. Silicone oil was added into the glass vials to cover the sample, covered with a paper towel and placed in a fume cupboard to evaporate. Once the TBA had evaporated more silicone oil was added if needed. Samples were embedded in silicone oil and mounted on glass slides for microscope analysis (Moore & Webb, 1978). Microscopic analysis was conducted using a Leica Microscope with 200x 400x and 1000x magnification and images were taken with the in-built camera (ICC50 HD).

5.1.3 Sample preparation for testate amoebae analysis

The preparation of testate amoebae followed standard palynological procedures, including HF treatment (Faegri & Iversen, 1989) and were recorded

simultaneously with pollen counts. As testate amoebae counts were around 20 per sub-sample a laboratory test was completed on testate amoebae preparation to identify whether more amoebae tests survived the less chemically intensive procedures. The preparation was a simple alkaline digestion (Charman, et al., 2000) involving one *Lycopodium* tablet per sample and boiling the sample in 100ml distilled water for 8 minutes to disaggregate. They were then washed through a 300 µm sieve and back-sieved through a 15 µm mesh. The remains were washed into 50 ml centrifuge tubes, centrifuged at 3000 rpm for 5 minutes and stored in distilled water. However, after microscopic analysis of these samples was performed, there was no significant difference in the number, types or quality of the amoebae tests, so the information from the first procedure was used for analysis. Payne et al., (2011) found similarities between both preparations and the differences were not substantial unless using the data for transfer functions. This supports the approach of using the palynologically-prepared testate amoebae counts in this study for qualitative analysis and is shown not to be detrimental to the palaeoecological signal.

5.1.4 Compilation of the vegetation datasets

This section explains how the vegetation datasets were compiled and provides detail on how the monitoring took place. There were four sections to the vegetation dataset; annually monitored macrophyte vegetation of thirty ponds from 1995-2013 (Jeffries 2008), observational data from the field site in Low Hauxley nature reserve (Jeffries, unpublished data), crop records from 1996-2011 and vegetation mapping of four locations within the field site in 2014.

5.1.4.1 Annually monitored thirty ponds (1995-2013)

Thirty experimental ponds were constructed at the field site in 1994, and vegetation monitoring began in 1995 (Jeffries, 2008). This has resulted in a comprehensive knowledge of the vegetation from within the ponds perimeters, but excludes the surrounding areas. Therefore, the vegetation dataset cannot be used to examine the sources of pollen beyond the extent of the ponds. The annually monitored macrophyte vegetation coverage was recorded within a 1 m^2 quadrat with 10 cm grid wire intervals providing 81 sample points for each pond (Jeffries, 2008). Each of the thirty pond's vegetation assemblages were recorded once a year in late May/early June, depending on whether the ponds dried out quickly. To get an overview of the vegetation in the field the thirty ponds vegetation data were amalgamated. Since the dataset had point sample values for each species in every pond for eighteen years, the dataset was too large and unnecessarily detailed for this study. Therefore, an average of the coverage of each plant species in all of the thirty ponds was calculated. These averages were entered into Tilia (1.7.16) (Grimm, 1988) and converted into percentages. Stratigraphically constrained cluster analysis (CONISS) (Grimm, 1987) was used to select the stratigraphical zones of vegetation change. The vegetation data was displayed in a percentage diagram like the pollen data to allow clear comparison.

5.1.4.2 Ponds close to Pond 8

To investigate if ponds within the same field were sensitive to vegetation changes and displayed large differences to the vegetation dataset representing the whole field, only vegetation counts close to P8 were used. The ponds close to P8 were 5, 6, 7, 8, 9, 10 and 11 in which the yearly averages of the vegetation occurrence were calculated and plotted into a separate Tilia graph (Figure 11). It is worth noting that Jeffries (2008) eighteen year macrophyte vegetation dataset provides

detail on what types of vegetation were in the constructed ponds but does not record the vegetation in or around the field.

5.1.4.3 Observational data

The observational data by Jeffries (unpublished data) recorded the occurrence of certain vegetation abundances within the field site of Low Hauxley Nature Reserve. The high abundance of *Epilobium* were recorded in several years around the SNP SWB, and *Phragmites* was also noted, however no date was recorded.

5.1.4.4 Crop records (1996-2011)

The crop records were sourced from the owner of the fields which provides crop names and the year they were planted in the field next to the study site. There are seven years (1994, 1995, 1999, 2007, 2012, 2013, 2014) which do not have any crop information. This crop record section of the vegetation datasets, observational data and macrophyte vegetation monitoring, contain calendar dates and abundances of when taxa were present in and around the field site which were compared with taxa in the pollen assemblage. The remaining section of the vegetation dataset was the vegetation mapping which took place in 2014 and is detailed in section 5.1.6.

5.1.5 Modern pollen rain

Modern pollen rain was measured over 9 months; January to September (2014). Eight pollen traps, four Tauber-style and four Behling-Style (Pollen Monitoring Programme, 2003; Giesecke et al., 2010; Jantz et al., 2013) were constructed following the designs in Figure 7 A and B respectively. These were distributed randomly over the field site in four locations; one of each style was positioned by the side of one another to capture the modern pollen rain. There were two different types of traps to identify which style worked better in this environment. Although only two traps were required, six extra traps were set up to see if there was any difference in the pollen rain within the same field and also as a precautionary measure if some traps were destroyed by floods. The traps recorded the flowering season between the end of January to September (2014). The traps were sampled at the end of September and were checked twice before the end of the summer season to make sure there was no damaged or

obstruction. Both the Behling and Tauber traps were repaired once in March 2014 as the covering mesh was destroyed potentially by sea birds. They were left for four months over the summer and when checked again, there were a very large amount of terrestrial gastropod molluscs (slugs) in all of the Tauber and two of the Behling traps. These samples were not suitable to be processed due to the high level of contamination. Therefore, only the one Behling trap was processed and had very low counts of pollen/spore. Therefore, to get an idea of the modern pollen rain the surface sediment samples (1 cm) from the SNP, RBP P8, and P29 were used. These were the sediment samples from the cores already extracted and consequently underwent the standard palynological preparation procedure.
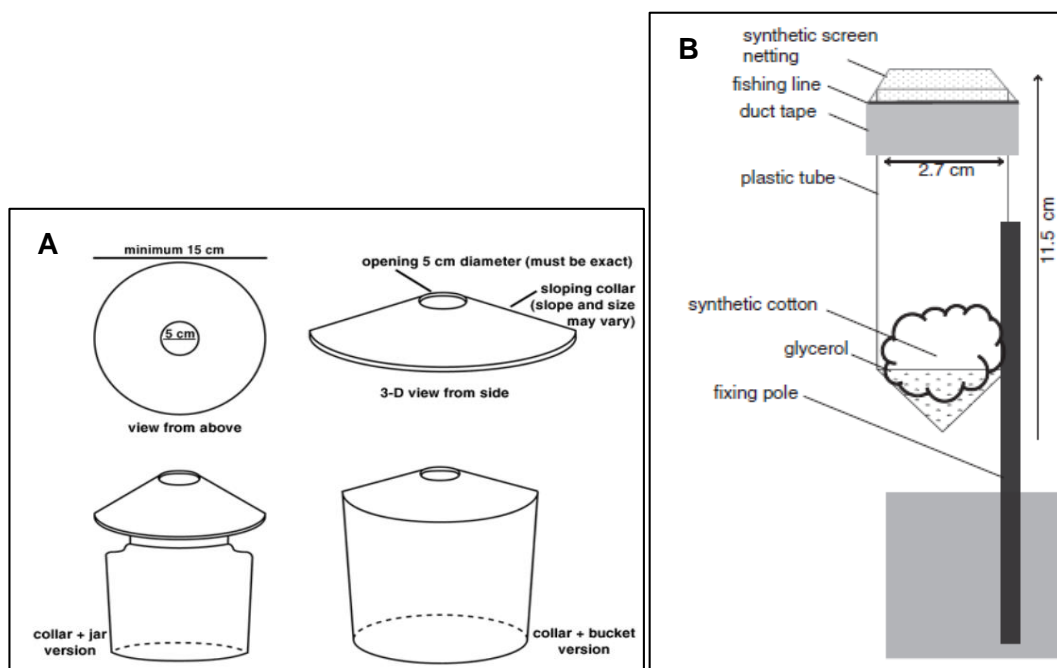
Figure 7: A: Tauber trap design (Pollen Monitoring Programme, 2003) and B: Cross-sectional view of the Behling trap design (Jantz et al., 2013).

5.1.6 Vegetation mapping

The additional vegetation mapping took place in July 2014 and was completed as part of the modern pollen rain section of this thesis. Figure 8 shows a schematic for the field site with mapping locations and the mapping strategy for the vegetation, which was adapted from Bunting (2003). The central point was the pollen trap and there were two concentric rings around it (first ring expanding 2m and the second 4m (Figure 8). The vegetation in each concentric ring was very homogenous and only one quadrat was needed to sample the vegetation. The 1 m² quadrat with 10 cm grid wire intervals provided 81 sample points. Each

vegetation type was recorded by counting how many crosshairs it covered and was then converted into percentages. The plant nomenclature followed Stace (1997). This process was completed around all four pollen trap locations and an extra quadrat was recorded in the 4m concentric ring at vegetation mapping location 3 as there was a clear change in vegetation types.

This methodology provided distance measurements of the vegetation types around each pollen trap which aimed to identify the distance weighted abundance of pollen taxa. However, since the pollen traps did not yield the information expected, the vegetation mapping data was used to compare with the pollen surface samples from the sediment cores from SNP, RBP, P 8 and P 29. To make the vegetation data collected through this methodology comparable to the pollen data from the surface sediment samples, the counts from each quadrat around the same mapping location were added together and made a percentage so there was one value for each of the four locations in the field (see Figure 8 for locations).
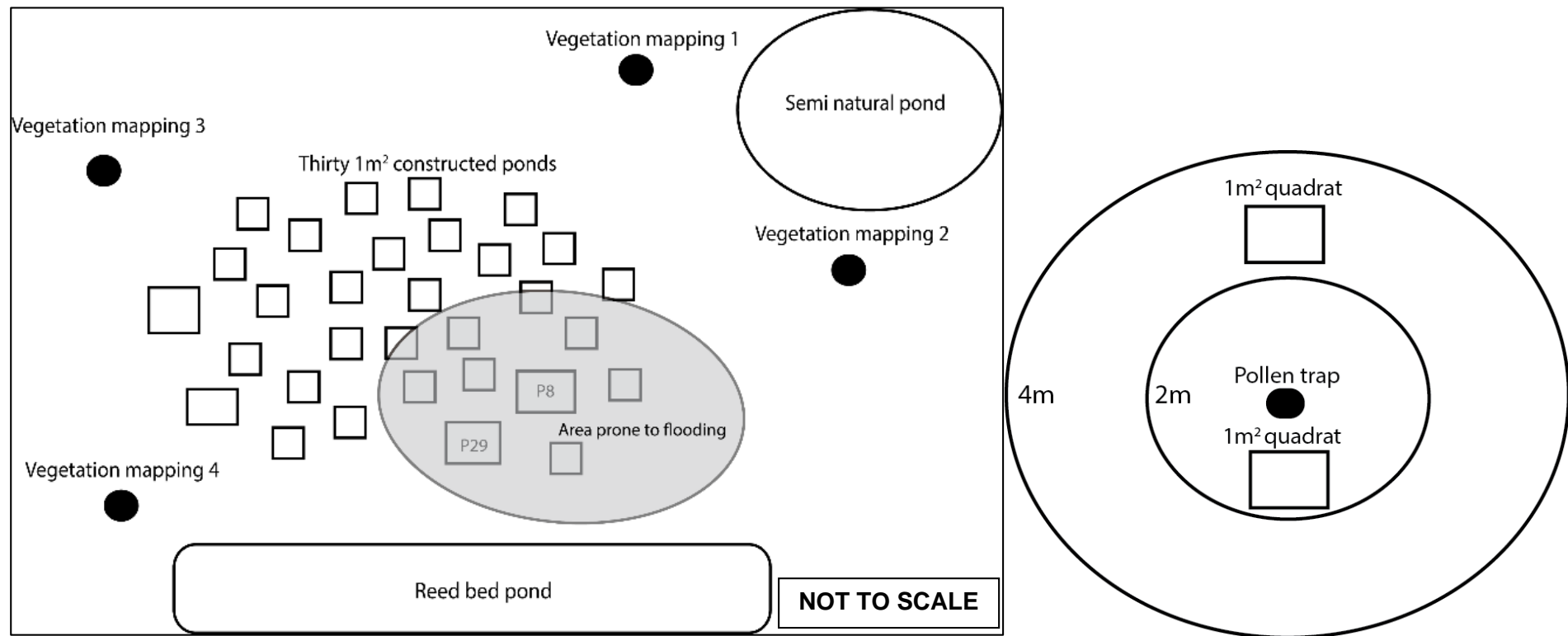
Figure 8: Schematic of the field site with locations of the vegetation mapping points (same as pollen trap locations) and a diagram of sampling strategy for mapping the field vegetation (adapted from Bunting, 2003).

5.1.7 Carbon and nitrogen concentrations

The C/N ratios of the SWB sediments are used as a proxy to indicate change from whether the biomass has originated from algae or macrophyte related biomass (Meyers & Ishiwatari, 1993; Smol, 2002). Carbon and nitrogen concentrations were determined using a FLASH 2000 CHNS/O Analyser. The sub-samples were weighed to 4-5g dry-weight, wrapped in aluminium and put through the analyser. A blank sample was put through the analyser every ten, followed by a triplicate sample to check on accuracy. Carbon and nitrogen values were shown in ratios and displayed on a line graph so the fluctuations could be clearly identified throughout the sediment depths. C/N ratios indicate where biomass has come from, algal or macrophyte, therefore comparing the ratio fluctuations with vegetation assemblages could potentially infer and/or backup possible dates within the sediment core profiles.

5.1.8 Rainfall record: Boulmer weather station

The rainfall dataset was obtained from the British Meteorological weather station at Boulmer, Alnwick (Ordnance Survey NU 253 142) and covers 1994-2014. This is the closest weather station to Low Hauxley and is 11.0 miles North of Low Hauxley at 55° 25' 22'' N, 1° 36' 3'' W. The data was displayed as a line graph that showed annual fluctuation of rainfall and was visually compared with the fluctuations in wet indicator species in vegetation and testate amoebae. The data was also part of the compilation of datasets (section 5.2.4) to support interpretations.

5.2 Data processing

5.2.1 Palynological analysis

A pollen percentage diagram was completed for SNP, RBP, P 8 and P 29 using TILIA and TILIA GRAPH (Grimm, 1990). Pollen and spores were identified using the Northumbria University pollen reference collections and the following literature: Moore & Webb (1978), Faegri & Iversen (1989), Beug (2004), Willard, 1989; Wichlen et al., 1999; Blackmore et al., 2003; Tweedle et al., 2005; Zanni & Ravazzi, 2007; Demske et al., 2013. Pollen grains and spores were counted to > 300 per slide (excluding *Lycopodium*) apart from samples which had an insufficient number of grains (not enough in the sediment sample) and were not included (SNP 1, SNP 4, SNP 12 & SNP 19). The pollen and spore counts from each slide (each sub-sample depth) were entered into a Tilia data sheet and taxa assigned an individual code and grouped. *Pinus* was given an individual code so the percentage calculation could be separate from the other taxa and calculated as part of the total pollen sum. This was because the number of *Pinus* pollen in the sub-samples were over-represented and would cause the other pollen taxa not to be displayed clearly in the percentage diagram. CONISS was used to define the pollen stratigraphical zones (Grimm, 1987). The pollen concentrations for each sub sample were calculated using the *Lycopodium* (spike medium) counts and sample quantity. Once these four data sheets were completed, a Tilia graph of the pollen percentage data and concentrations was constructed (Figure 18, Figure 19, Figure 20 & Figure 21). The pollen sum used to calculate the percentages displayed in the diagram is the total pollen sum excluding *Pinus*. The pollen taxa were grouped into trees and shrubs, herbs, crops, aquatics, and vascular plants. The pollen taxa within each group where chosen by their plants' known ecological preferences such as *Phragmites* and *Lemna minor* (common duckweed) requiring wet habitats (Swan, 1993; Preston et al., 2002).

5.2.2 Testate amoebae analysis

The morphology of testate amoebae can differ between geographical locations (Bobrov et al., 1999; Mitchell et al., 2008) as there is not a unanimous identification key for taxonomic identification, therefore species separation remains difficult. Even within the same population there is high morphological variability of test size relatable to environmental factors such as food source, temperature and insecticides (Mitchel et al., 2008). Therefore, since there is limited testate amoebae research in the UK especially in pond environments, species level identification was limited.
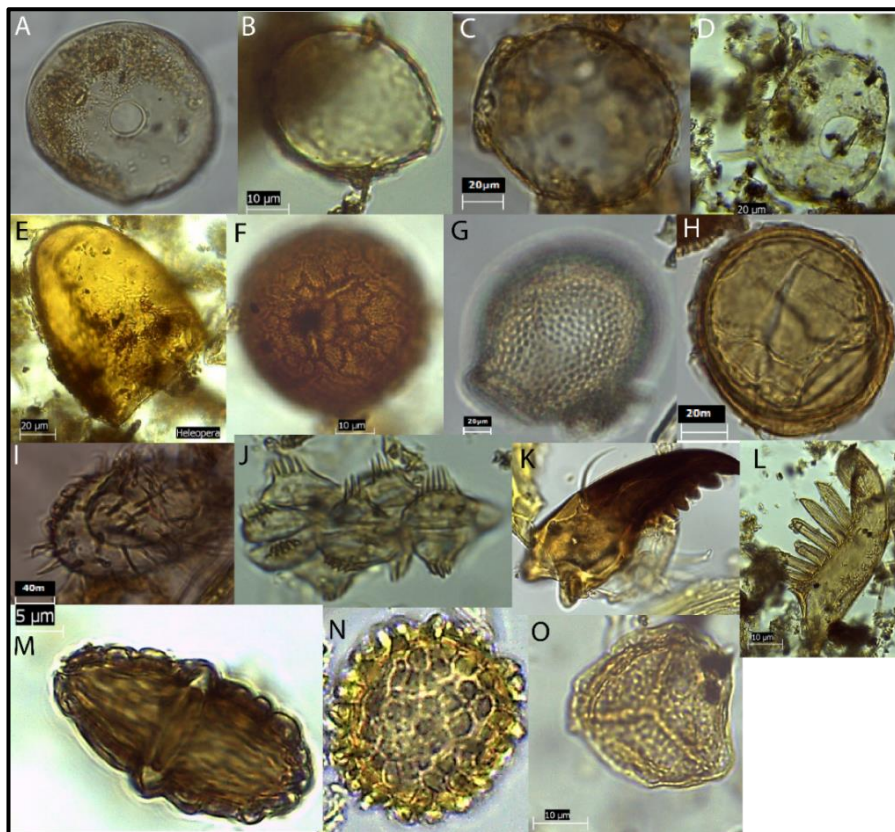
Figure 14 shows the species identified in this research and there is a key explaining their habitat preferences. This information was compiled from several testate amoebae identification keys (Corbet, 1973; Jax, 1985; Charman et al., 2000; Montoya et al., 2010; Glime, 2013).

To qualitatively compare testate amoebae assemblages from each SWB, the counts were entered into Tilia, each testate amoebae assigned a code and grouped according to their habitat preference. Percentages were calculated from the total sum of testate amoebae and were displayed in a percentage diagram (Figure 15, Figure 16 & Figure 17). CONISS was also performed to delimit zones and shown on the graph. Displaying the testate amoebae in the same format as

the pollen data allowed clear visual comparison of the occurrences throughout each pond sediment core in relation to the pollen occurrences.

5.2.3 Principle Components Analysis (PCA)

Multivariate data analysis in the form of PCA analysis was performed on the three (SNP, RBP and P 8) pollen and testate amoebae assemblages (Figure 26) and the eighteen-year vegetation record. This was to explain what environmental variables were contributing to the distribution of taxa within the dataset and identify similarities in the structure of each dataset from the SWB types. These similarities, identified by clustering of variables in the datasets were compared between PCA analyses to explain different representation of taxa in SWB types within the same field. The clusters identified from these PCA analyses would then aid the explanations and justifications of matching certain depths with the years by knowing the associations between specific pollen and testate amoebae.

PCA transforms the dataset from a set of correlated variables to a set of uncorrelated variables derived from sets of linear combinations of the original dataset in attempt to describe the variation, reduce dimensionality and represent the data graphically by detecting structure (Everitt & Dunn, 2001). The PCA was performed for the vegetation data by first averaging each species abundance in the thirty ponds over one year and then normalising the data in Plymouth Routines In Multivariate Ecological Research (PRIMER) 6, (6.1.13) (Clarke & Warwick, 2001) to reduce the dominant contribution of abundant species. The data was then transferred into PAlaeontological STatistics (PAST) 3.02 (Hammer et al., 2001) to compute the PCA. There were then three PCA analysis computed for each of the SWB (SNP, RBP and P8). Since the pollen and testate amoebae data were derived from the same SWB sediment core, they were kept together for the analysis to see if clustering of taxa would indicate if certain environmental variables were affecting specific groups of taxa. The combined pollen and testate amoebae percentage data were entered into PAST to display the multivariate ordination as a PCA scatter plot.

5.2.4 Pollen surface samples

The aim of this section of the project was to identify if the SWB types recorded a similar pollen assemblage, and to further explore the relationship between the locations of pollen deposition to the vegetation mapping locations. The pollen counts for the first 1 cm of each sediment core were converted to a percentage.

This was completed for all SWB's surface sediment samples (SNP, RBP, P8 and P29) and displayed in one table (

Table 1). This permitted the comparison of taxa occurrence between the pollen surface samples with the four vegetation mapping locations.

5.2.5 Vegetation mapping

The results for the four vegetation mapping locations were displayed in a table (Table 2). The sample point counts were converted to percentages for each taxon to compare with the pollen surface samples. The detailed nature of the vegetation mapping recorded species and genus level for the majority of vegetation. However, some of the pollen surface samples only had family level identification and therefore a percentage of each family occurrence at all four locations of vegetation mapping were calculated, to allow comparison.

5.2.6 Comparison of the pollen surface samples and vegetation mapping locations

To compare the SWB's pollen surface samples (

Table 1) and vegetation mapping locations (Table 2), the percentage occurrence of taxa in both the pollen and vegetation, were explained in relation to the distance of the sampling point to the surface sample (Figure 8) each other. The percentage of each pollen taxa in the surface sediment samples was discussed in relation to each surface sample to identify the differences in pollen representation between surface samples. Then the pollen taxa in the four different surface samples were compared with the four vegetation mapping locations, to identify which pollen taxa were represented in which location. The pollen taxa which were not present in the surface samples but present in the vegetation mapping were also noted. These comparisons gave insight into the pollen representation of certain taxa and would then be discussed in relation to their dispersal ability and grain morphology.

5.2.7 Synthesis of different datasets to identify datable events

This project aims to retrieve possible dates for the SWB sediment cores through matching the occurrence of pollen taxa and vegetation. The four sediment cores from four different SWBs in the same field provide the opportunity to critically compare the pollen assemblages and assess the ability of high resolution pollen analysis on short sediment cores. In order to see the performance of high

resolution pollen analysis on short SWB sediment cores, the pollen assemblages were compared. To compare the similarities in pollen taxa fluctuations between the SWBs, the percentage pollen diagrams for each SWB were used. The similar percentage occurrence of the same taxa was highlighted in rings and joined together with lines to clearly show the similarities in the pollen records (Figure 31).

A brief description of the vegetation monitoring record was entered into a table with the corresponding year, along with the rainfall and crop record for the same year. The matches of the pollen assemblages with the vegetation record were entered into the same row to highlight the links between the datasets. This showed the date at which the vegetation occurred along with the depth at which the pollen occurred in the sediment core. Also in the table were the C/N ratios and descriptions of the testate amoebae at that depth with supporting information to corroborate the depth and date match.

6 Results

This section firstly presents the results of the modern pollen surface samples and vegetation mapping for 2014 followed by the annually monitored macrophyte vegetation of thirty constructed ponds collected by Jeffries (2008). This data is displayed by showing the assemblages from all the thirty ponds, the vegetation recorded in P8 and the vegetation of the ponds close to P8. The next section presents the observational rainfall data from Boulmer weather station, Alnmouth, U.K. followed by the C/N ratios for each SWB (SNP, RBP P8 and P29). The subsequent sections display results from the SWBs which include testate amoebae assemblages (SNP, RBP and P8) and pollen assemblages (SNP, RBP, P8 and P29). Following this, the crop records from the surrounding fields are explained. The PCA of testate amoebae and pollen for the SNP, RBP and P8 are then presented with the PCA of the vegetation monitoring (Jeffries, 2008) and critically compared.

6.1 Pollen surface sediment samples and vegetation mapping

This section provides the results of the pollen surface samples and vegetation mapping locations which gives an insight into the connections between pollen and vegetation occurrence within the field.

6.1.1 Pollen surface sediment samples

The pollen surface samples are displayed in percentage occurrence in the first 1 cm for all of the four SWBs in

Table 1. The greyed out cells represent the absence of taxa for that surface sample and illustrates a varied distribution across all SWBs. The tree taxa, *Abies* (fir)*, Pinus* and *Salix* (willow) are represented in all of the surface samples and only *Acer* is present in one. *Alnus* (birch)*, Betula pendula,* are not present in the SNP. Cyperaceae and Poaceae are present in all SWB samples, with the SNP having the highest percentage occurrence of 27.39%. The RBP has the highest percentage occurrence of Poaceae at 28.74% and *Phragmites* at 10.53% than the other SWBs. *Phragmites* is not recorded in P29. Asteraceae does not occur in the SNP but does in the other three, the highest in P8 at 4.29%. Brassicaceae (mustard family) and *Chenopodium* (goosefoot family) are evenly represented among all four surface sediment samples. *Epilobium* occurs in SNP and RBP at 0.87% and 0.13% respectively. *Lemna minor* occurs in very low percentage

(<3.91%) in all but P29 surface sample. There are some pollen taxa which only occur in one surface sediment sample. The taxa only recorded in the SNP are *Athyrium cf. filix-femina* (ladyfern) (1.30%)*, Potentilla rupestris* (rock cinquefoil) (0.43%)*, Schoenoplectus* (bulrush) (1.74%)*, Sparganium*-type (0.87%) and *Typha* (cattail) (1.30%). The taxa only recorded in the RBP are *Montia* (lettuce) (0.94%) and *Typha latifolia* (broadleaf cattail) (0.27%). Only the P8 records *Beta vulgaris*-type (beetroot) (1.13%), *Cardamine* (bittercress) (0.57%) *Lycospora* at 1.42% and *Typha minima* (dwarf bulrush) (0.28%). There are two crop taxa evident in the surface samples, *Secale cereale* (rye) and *Beta vulgaris*-type (only in P8). *Secale cereale* is evenly represented in all samples with the highest being in the SNP, RBP, P8 then P29. Indeterminable grains only occur in the SNP (3.04%) and RBP (1.62%).

6.1.2 Vegetation mapping 2014

The vegetation mapping displayed in Table 2 shows each mapping location and the percentage total of each location. Each of the four mapping locations within the same field has a different collection and percentage coverage of vegetation types. There are no tree or crop taxa recorded in the vegetation mapping as they were completed around the pollen trap locations at <4m. Within each mapping location the changes in vegetation coverage between 2m and 4m quadrats can be significantly large. VM3 had two quadrats recorded in the 4m concentric ring due to a very heterogeneous coverage. There is a collection of taxa which did not occur in the same two locations (VM1 and VM2) but did in the other two (VM3 and VM4) Caryophyllaceae, Ranunculaceae and Rosaceae (rose family) are not recorded in VM1 or VM2 but are in VM3 and VM4 at low coverage (<2.91%). *Leptodictyum riparium* occurs in the same pattern but has a substantially higher coverage in VM4 (10.53%) than VM3 (5.64%). Asteraceae is the highest abundance in VM2 at 22.01%, the next highest being only 8.13% in VM4. Cyperaceae is the highest in VM4 at 34.45% (predominantly from *Carex ortubae* at 31.58%) and VM1 at 22.12% (all from *Eleocharis*). There is a large difference between these two locations as VM2 does not have any and VM3 only has 1.09%. There is no *Schoenoplectus* recorded in any locations. Fabaceae is recorded in all locations but at various percentage coverages. VM4 at 36.84% is the highest followed by VM3 (17.82%), the VM2 (14.15%) and VM1 (3.10%). *Epilobium palustre* was not recorded in VM2 and was the highest in VM4 (1.44%). VM1 and

VM3 recorded very low percentage coverages of 0.44% and 1.9% respectively. Poaceae is high in VM1 (24.34%), VM2 (28.30%) and VM3 (37.09%) but very low in VM4 (2.87%). *Phragmites* contributes 0.18% to VM3 and 1.44% in VM4 and is not recorded in VM1 and VM2. *Lemna minor* only occurred in VM 3 at very low 0.18%. Ranunculaceae is only recorded in VM3 (2.91%) and (1.91%).

Table 1: Pollen surface samples of the SNP, RBP, 8 and P29 where the percentage of each grains in the first 1 cm layer of sediment is displayed with the palynological taxon name. The grey filled cells are the taxa which did not occur in the sediment sample and the names in bold are the taxa which can be compared with the vegetation mapping data.

Palynological taxon	SNP %	RBP %	P8 %	P29 %
Abies	0.43	0.54	0.28	0.99
Acer	1.30			
Alnus		1.21	3.40	1.48
Asteraceae		**0.13**	**4.39**	**0.99**
Athyrium cf. filix-femina	1.30			
Beta vulgaris-type			1.13	
Betula pendula		2.56	3.40	0.74
Brassicaceae undiff.	0.87	0.13	1.27	0.74
Cardamine			0.57	
Caryophyllaceae	**1.74**			**0.25**
Chenopodium	0.87	0.40	0.57	0.99
Cyperaceae undiff.	**27.39**	**8.91**	**7.37**	**3.69**
Epilobium	**0.87**	**0.13**		
Fabaceae				**0.99**
Lemna minor	**3.91**	**2.02**	**0.14**	
Lycospora			1.42	
Montia		0.94		
Poaceae	**3.91**	**28.74**	**6.09**	**6.16**
Phragmites	**5.65**	**10.53**	**1.27**	
Pinus	34.78	30.63	59.92	71.43
Plantago		**0.13**	**0.28**	
Potentilla rupestris	0.43			
Ranunculus				**0.25**
Rosaceae	**0.87**	**0.40**		
Rumex	**1.30**	**6.75**	**0.28**	
Salix	3.04	0.94	3.97	4.93
Schoenoplectus	**1.74**			
Secale cereale	2.61	1.75	1.13	0.99
Sparganium-type	0.87			
Typha	1.30			
Typha latifolia		0.27		
Typha minima			0.28	
Indeterminable	3.04	1.62		
Unknown	1.74	1.21	2.83	5.42

Table 2: Vegetation mapping 2014 data. The four vegetation mapping locations with the percentage total for each taxon in each quadrat are displayed. For comparison with the pollen surface samples, the total percentage of each family are displayed. Only the grey-filled cells are the families which also occur in the pollen surface samples.

Vegetation	Family	Vegetation mapping 1 — Low variety of vegetation taxa. Multiple storeys.				Vegetation mapping 2 — Same variety of species in Vegetation mapping 1.				Vegetation mapping 3 — Three sections of vegetation types. Half of VM3 was the same and two quarters were both different.					Vegetation mapping 4 — Glauca sedge dominant around the mapping location.			
		2m	4m	VM1 Total %	TOTAL Family %	2m	4m	VM2 Total %	TOTAL Family %	2m	4m Q1	4m Q2	VM3 Total %	TOTAL Family %	2m	4m	VM4 Total %	TOTAL Family %
Lemna	Araceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	0	0.00	
	Araceae				**0.00**				**0.00**					**0.18**				**0.00**
Jacobea	Asteraceae	10	0	4.42		5	0	1.57		1	0	0	0.18		9	0	4.31	
Cirsium arvense	Asteraceae	0	0	0.00		25	40	20.44		24	0	0	4.36		0	0	0.00	
Onopordum acanthium	Asteraceae	0	0	0.00		0	0	0.00		3	0	0	0.55		0	0	0.00	
Erigeron	Asteraceae	0	0	0.00		0	0	0.00		3	0	0	0.55		0	1	0.48	
Achillea	Asteraceae	0	0	0.00		0	0	0.00		1	0	0	0.18		2	1	1.44	
Taraxacum	Asteraceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	1	0.48	
Centaurea	Asteraceae	0	0	0.00		0	0	0.00		1	0	0	0.18		3	0	1.44	
	Asteraceae				**4.42**				**22.01**					**6.18**				**8.13**
Myosotis laxa	Borginaceae	0	0	0.00		0	0	0.00		3	0	0	0.55		0	0	0.00	
Myosotis scorpioides	Borginaceae	0	1	0.44		0	0	0.00		1	0	0	0.18		0	0	0.00	
	Borginaceae				**0.44**				**0.00**					**0.73**				**0.00**
Lychnis flos-cuculi	Caryophyllaceae	0	0	0.00		0	0	0.00		6	0	0	1.09		0	0	0.00	
Stellaria media	Caryophyllaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		1	0	0.48	
	Caryophyllaceae				**0.00**				**0.00**					**1.27**				**0.48**
Carex glauca	Cyperaceae	0	0	0.00		0	0	0.00		4	0	0	0.73		5	0	2.39	
Carex ortubae	Cyperaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	66	31.58	

Vegetation	Family	2m	4m	VM1 Total %	TOTAL Family %	2m	4m	VM2 Total %	TOTAL Family %	2m	4m Q1	4m Q2	VM3 Total %	TOTAL Family %	2m	4m	VM4 Total %	TOTAL Family %
Eleocharis	Cyperaceae	0	50	22.12		0	0	0.00		1	0	0	0.18		0	1	0.48	
	Cyperaceae				**22.12**				**0.00**					**1.09**				**34.45**
Equisetum arvense	Equisetaceae	50	0	22.12		20	30	15.72		1	0	0	0.18		1	0	0.48	
	Equisetaceae				**22.12**				**15.72**					**0.18**				**0.48**
Trifolium pratense	Fabaceae	0	0	0.00		0	0	0.00		0	0	0	0.00		10	0	4.78	
Trifolium repens	Fabaceae	5	0	2.21		0	0	0.00		1	1	0	0.36		0	0	0.00	
Trifolium	Fabaceae	0	0	0.00		8	15	7.23		1	38	0	7.09		0	3	1.44	
Trifolium campestre	Fabaceae	0	0	0.00		0	0	0.00		24	0	0	4.36		25	0	11.96	
Vicia	Fabaceae	0	0	0.00		12	0	3.77		1	0	0	0.18		0	0	0.00	
Vicia cracca	Fabaceae	1	1	0.88		0	0	0.00		1	0	0	0.18		0	0	0.00	
Lotus corniculatus	Fabaceae	0	0	0.00		10	0	3.14		31	0	0	5.64		1	38	18.66	
	Fabaceae				**3.10**				**14.15**					**17.82**				**36.84**
Cicendia filiformis	Gentianaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		1	0	0.48	
	Gentianaceae				0.00				0.00					0.18				0.48
Juncus effusus	Juncaceae	0	0	0.00		0	0	0.00		3	0	0	0.55		0	0	0.00	
Juncus inflexus	Juncaceae	0	0	0.00		0	0	0.00		64	0	37	18.36		0	1	0.48	
Juncus articulatus	Juncaceae	1	50	22.57		0	0	0.00		3	0	0	0.55		0	0	0.00	
Juncus conglomeratus	Juncaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	1	0.48	
	Juncaceae				**22.57**				**0.00**					**19.64**				**0.96**
Prunella	Lamiaceae	0	0	0.00		0	0	0.00		3	1	0	0.73		1	0	0.48	
Epilobium palustre	Lamiaceae	0	1	0.44		0	0	0.00		2	0	0	0.36		0	3	1.44	
	Lamiaceae				**0.44**				**0.00**					**1.09**				**1.91**
Euphrasia	Orobanchaeae	0	0	0.00		0	0	0.00		1	0	0	0.18		1	1	0.96	
Odontites vernus	Orobanchaeae	0	0	0.00		0	0	0.00		1	0	0	0.18		1	0	0.48	

Vegetation	Family	2m	4m	VM1 Total %	TOTAL Family %	2m	4m	VM2 Total %	Total Family %	2m	4m Q1	4m Q2	VM3 Total %	TOTAL Family %	2m	4m	VM4 Total %	TOTAL Family %
Rhinanthus minor	Orobanchaeae	1	0	0.44		0	0	0.00		1	0	0	0.18		0	0	0.00	
	Orobanchaeae				**0.44**				**0.00**						**0.55**				**1.44**
Plantago lanceolata	Plantaginaceae	0	0	0.00		25	30	17.30		6	16	0	4.00		0	1	0.48	
Veronica	Plantaginaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	1	0.48	
	Plantaginaceae				**0.00**				**17.30**						**4.18**				**0.96**
Holcus	Poaceae	50	0	22.12		20	10	9.43		3	0	37	7.27		2	0	0.96	
Poa	Poaceae	0	0	0.00		10	50	18.87		68	64	28	29.09		1	0	0.48	
Agrostis stolonifera	Poaceae	0	5	2.21		0	0	0.00		3	0	0	0.55		0	0	0.00	
Phragmites	Poaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	3	1.44	
	Poaceae				**24.34**				**28.30**						**37.09**				**2.87**
Rumex	Polygonaceae	0	0	0.00		3	5	2.52		4	0	0	0.73		0	0	0.00	
	Polygonaceae				**0.00**				**2.52**						**0.73**				**0.00**
Ranunculus	Ranunculaceae	0	0	0.00		0	0	0.00		3	12	0	2.73		0	3	1.44	
Ranunculus lingua	Ranunculaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	1	0.48	
	Ranunculaceae				**0.00**				**0.00**						**2.91**				**1.91**
Argentina anserina	Rosaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	1	0.48	
Filipendula ulmaria	Rosaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	0	0.00	
	Rosaceae				**0.00**				**0.00**						**0.36**				**0.48**
Galium palustre	Runiaceae	0	0	0.00		0	0	0.00		1	0	0	0.18		0	0	0.00	
	Runiaceae				**0.00**				**0.00**						**0.18**				**0.00**
Leptodictyum riparium	Moss	0	0	0.00		0	0	0.00		31	0	0	5.64		2	20	10.53	
	Moss				**0.00**				**0.00**						**5.64**				**10.53**

1.1.1.1 Comparison of the vegetation recorded in 2014 at the four mapping locations with the pollen surface samples.

With reference back to Figure 8 the pollen surface sample results do reflect the vegetation mapping locations. Cyperaceae percentages are high at VM1 and SNP which are the closest together on the field site. Similarly, Poaceae is present in all pollen surface samples and vegetation mapping locations. *Phragmites* highest presence is in the RBP pollen surface sample and only occurs in the two vegetation mapping locations (VM3 & VM4) closest to that SWB. *Ranunculus* is also only present in one location for the mapping and surface samples which is VM3 and P29 which are relatively close. The SNP pollen surface sample singularly records taxa more wet indicator taxa.

6.2 Vegetation assemblages from the constructed ponds

6.2.1 Macrophyte vegetation assemblage of the thirty constructed ponds

The following results are from the vegetation within all of the thirty constructed ponds. There are four zones in the graph for the thirty ponds (Figure 9**Error! Reference source not found.**), 1a, 2a, 3a, and 4a split by CONISS.

Zone 1a contains 1995-1999 where the aquatic habitat group percentages dominate. In 1995, the year in which the ponds were constructed, Filamentous algae (41.6%) and *Leptodictyum riparium* (54.8%) have the highest percentages. In 1996 *Callitriche* has its only occurrence in the record at 15.1%. In 1997 there is 35.8% of *Agrostis/Alopecurus* which appears as a peak in the whole record. Similarly peaking during the same year is *Myosotis spp., Rumex crispus* and *Ranunculus lingua* but none exceeding 10%. A peak in *Chara vulgaris* occurs in this zone during 1998 at 16%, its second highest in the assemblage and *Leptodictyum riparium* has its lowest percentage occurrence of <20%. *Juncus inflexus* and *Glyceria fluitans* illustrate an increase from 1998, and *Eleocharis palustris* from 1999. Between 1997 and 1999 in zone 1a, *Agrostis/Alopecurus* continues to decrease and a sharp increase in *Leptodictyum riparium* at 29.2%.

Zone 2a is a relatively small zone, covering 2000 and 2001 which is dominated by vegetation indicative of an aquatic habitat. *Agrostis/Alopecurus* exhibits <3% coverage while *Eleocharis palustris* has a constant coverage similar to *Juncus inflexus* and *Ranunculus aquatilis*. In 2000, *Chara vulgaris* and *Glyceria fluitans* has their highest peaks at 25.4% and 19.1% respectively.

Zone 3a, covering 2002-2011 is the largest zone. The percentages of *Agrostis/Alopecurus* fluctuate, with the highest percentages being in 2002 (17.6%) 2007 (19.2%) and 2010 (22.5%). Its lowest percentage during 2005 (7.8%) occurs with a peak in *Eleocharis palustris* (22.8%) and *Ranunculus aquatilis* (11.8%). There is no *Callitriche* sp. or *Chara vulgaris* present in this zone, which were present in the previous zone 2a. Filamentous algae peaks once at 2004. *Leptodictyum riparium* percentages remain relatively consistent.

Zone 4a contains 2012-2013 where there is a wide distribution of damp to aquatic habitat and aquatic habitat vegetation. *Agrostis/Alopecurus* has a very low percentage of 4.8%., Filamentous algae peaks in 2012 at 13.7% and *Leptodictyum riparium* percentages remain high at 54.2%.

6.2.2 Macrophyte vegetation assemblage of Pond 8

Figure 10 displays the vegetation assemblage of Pond 8. Zone 1 extends from 1995-2006 and illustrates more wet habitat vegetation such as *Callitriche, Chara vulgaris, Ranunculus aquatilis* and filamentous algae. There is damp to aquatic taxa present but only peaks in *Agrostis* and *Juncus articulatus*. Zone 2a illustrates a sharp increase in *Leptodictyum riparium* which has a constant presence throughout the whole zone, which spans 2006-2013. The presence of vegetation which prefer wet or dry habitats are more pronounced in the diagram but largely represent a similar patter as all of the ponds records represented as one (Figure 9).

6.2.3 Macrophyte vegetation assemblage of ponds close to P 8

Displaying only the vegetation close to P8 (Figure 11), highlights the small and sensitive changes in vegetation throughout the SWBs. The data within this diagram were taken from ponds close to P8 which were 5, 6, 7, 8, 9, 10 and 11. These are subject to being joined together via flood waters and therefore pollen grains are subject to water-borne transportation. Changes in the percentage coverage of all the vegetation are more noticeable in *Agrostis/Alopecurus, Eleocharis palustris, Schoenoplectus lacustris* and Filamentous algae. There are two main zones 1a and 2a which shows a shift from aquatic habitat species high percentage abundance in zone 1, to damp to aquatic habitat species in zone 2. Although most taxa remain a similar signal to that of Figure 9, the transition between habitat types (very wet during the colonising years to cyclic wet/dry years) can be identified clearer. There is not a considerable amount of change in percentages of different vegetation over the years. However, displaying the data from a selection of ponds within the thirty does highlight the specific changes in vegetation present, but no major changes.
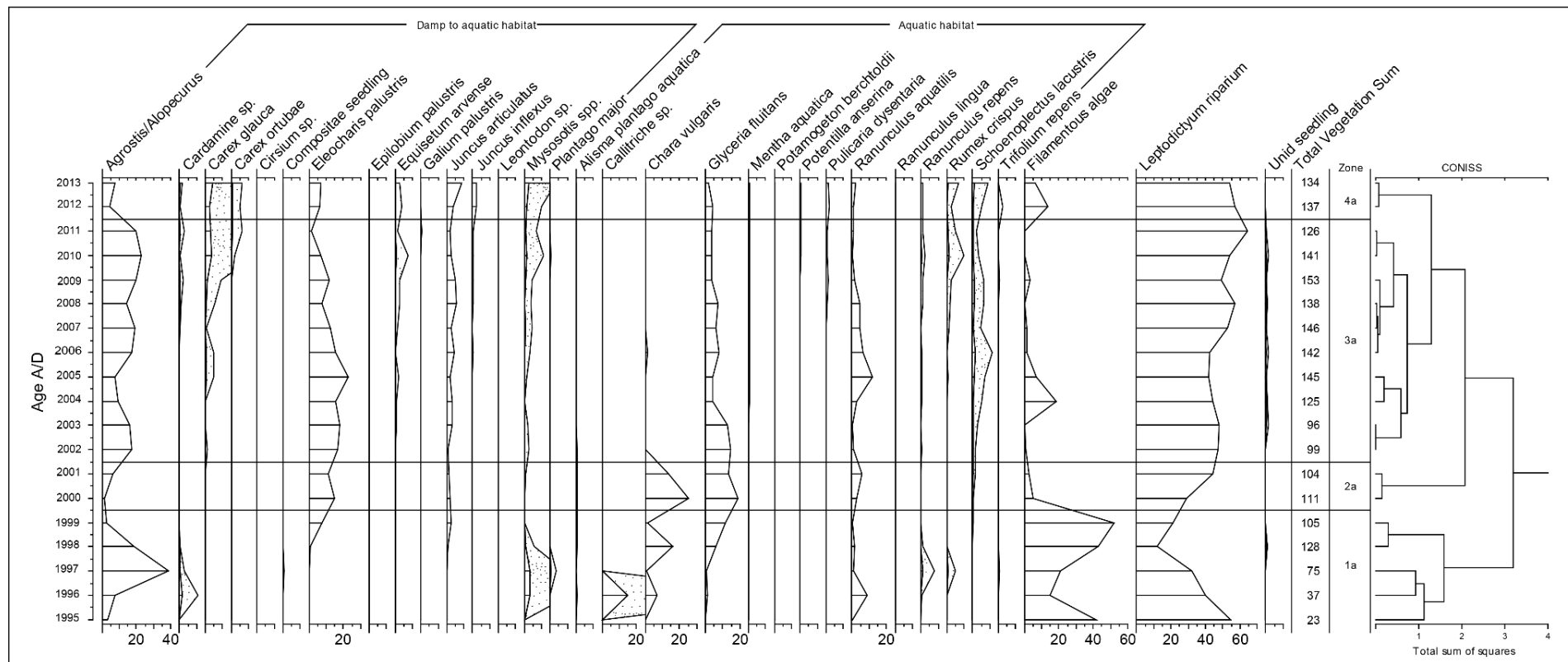
Figure 9: Macrophyte vegetation percentage diagram of the vegetation from all thirty constructed ponds within the field collected by Jeffries (2008). The yearly averages of the vegetation occurrence were calculated into percentages and plotted on this graph. *Cardamine, Carex glauca, Carex ortubae, Equisetum arvense, Mentha aquatic, Myosotis, Plantago major, Potentilla anserina, Pulicaria dysenterica, Ranunculus repens, Rumex crispus, Trifolium repens, Alisma plantago aquatic, Callitriche, Schoenoplectus lacustris,* and Unid. seedling was exaggerated by factor 8.
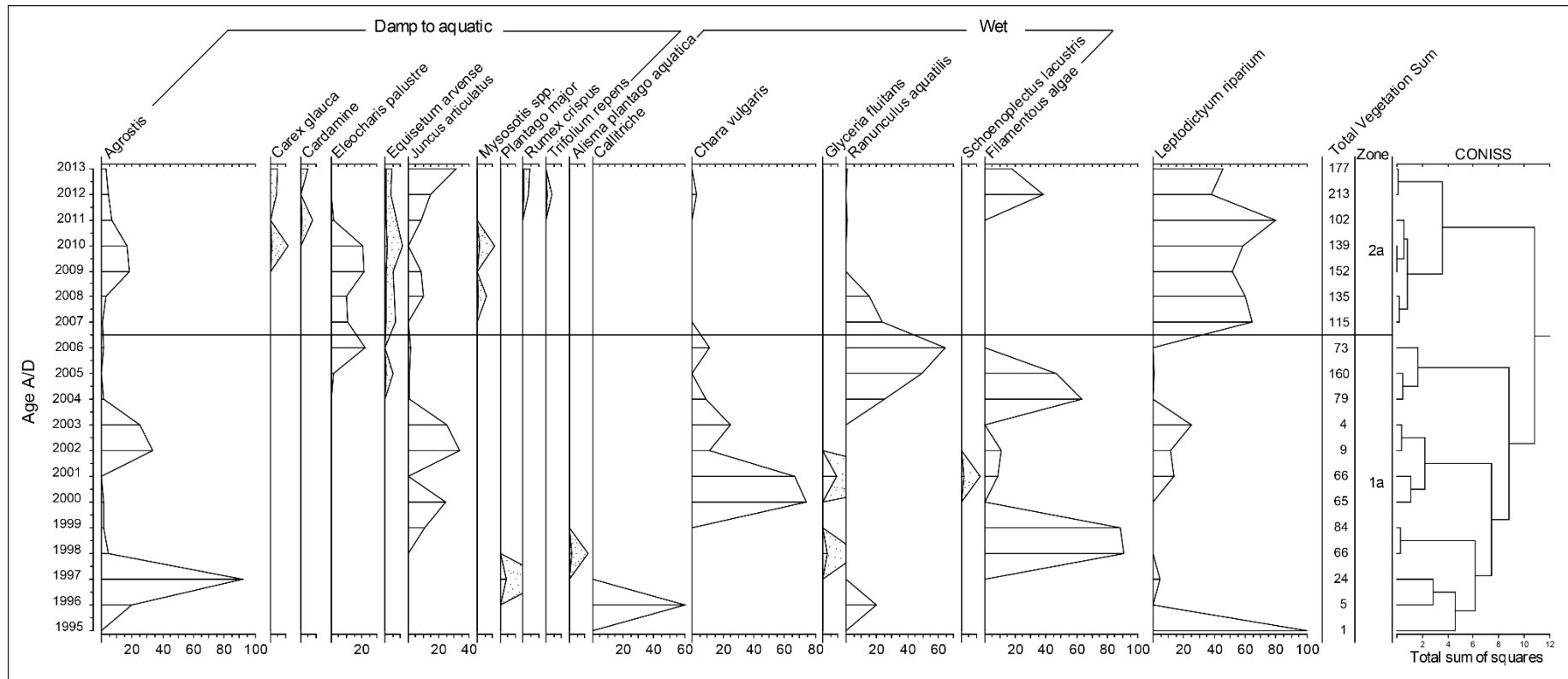
Figure 10: Percentage diagram for the vegetation assemblage from Pond 8 1995-2013 obtained from the same vegetation dataset collected by Jeffries (2008). *Carex glauca, Cardamine, Equisetum arvense, Myosotis spp., Plantago major, Rumex crispus, Glyceria fluitans* and *Schoenoplectus lacustris* are exaggerated by factor 8. The vegetation is grouped into damp to aquatic and wet habitat preferences. The two zones are split using CONISS.
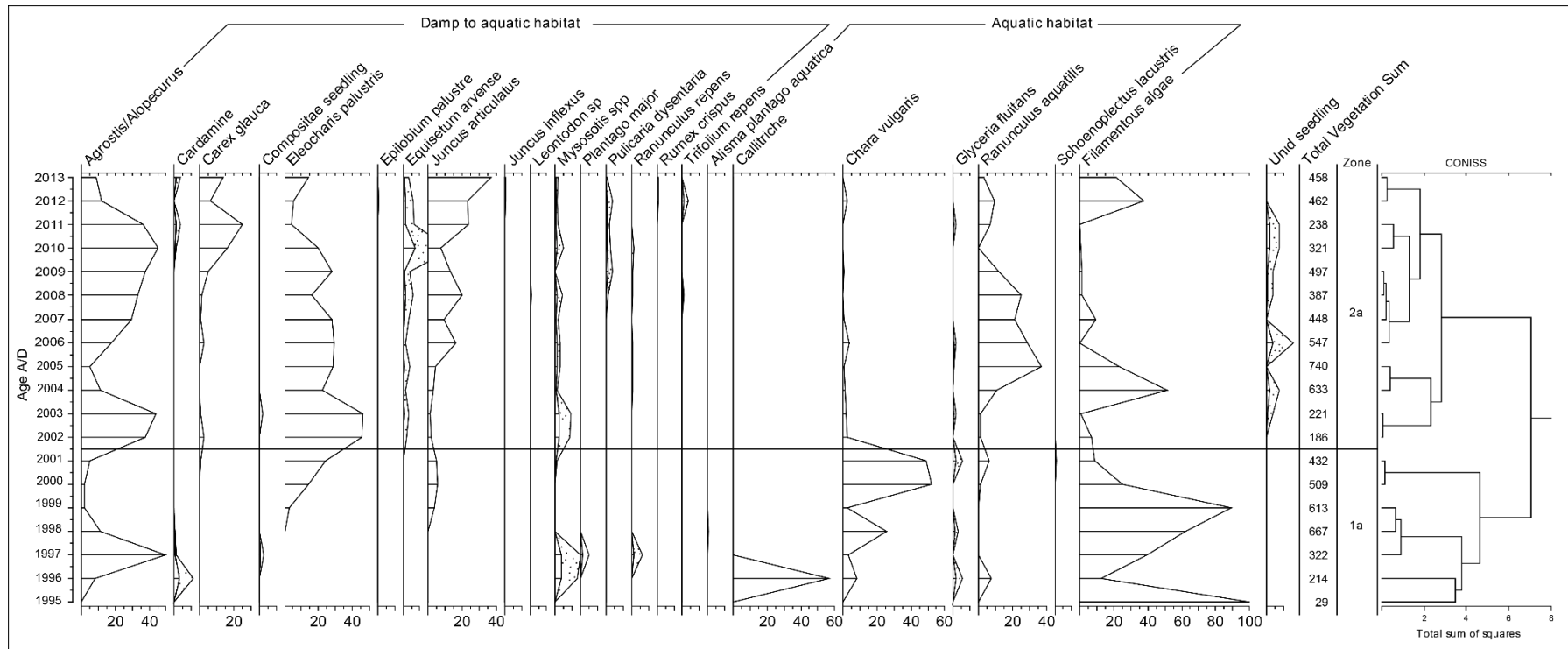
Figure 11: Percentage diagram for the vegetation close to Pond 8 obtained from the same vegetation dataset collected by Jeffries (2008). The ponds close to pond 8 are 5, 6, 7, 8, 9, 10 and 11 in which the yearly averages of the vegetation occurrence were calculated and plotted into this Tilia graph. *Cardamine, Equisetum arvense, Myosotis spp., Pulicaria dysenterica, Ranunculus repens, Rumex crispus, Trifolium repens, Alisma plantago aquatic, Glyceria fluitans, Schoenoplectus lacustris* and Unid. seedling was exaggerated by factor 4.

6.3   Rainfall record: Boulmer weather station

The precipitation data from Boulmer weather station (Figure 12) fluctuates between 499.3 mm (1996) and 949.4 mm (2012) per year which were the lowest and highest recorded rainfall. Between 1996 and 1998 there was a sharp increase in rainfall, similar to 2003 and 2005. After 2005 there was a sharp decrease, 938.7 mm to 587.9 mm, the most rapid annual decline over the 20-year period. From 2008 there was an annual cyclic decrease and increase in rainfall.
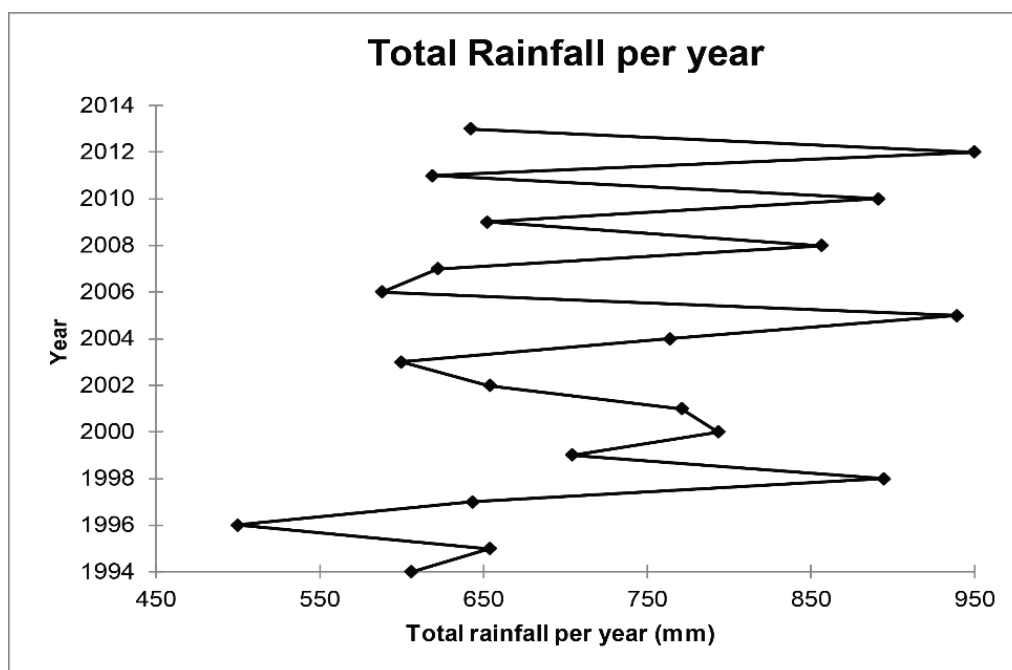
Figure 12: Total rainfall (mm) per year at Boulmer weather station, Alnmouth, 11 miles North of Low Hauxley (Met Office, 2015).

Also from the Met Office (2015) there are records from previous weather events (intermittent from 1990-2015), particularly of flooding and record temperatures in the UK. This is more of a general description of the weather in the UK, but there are some, which refer to the North East of England and can be used in conjunction with (Figure 12) to have a clearer understanding of the weather affecting the field site during certain years. During 2003 there were record temperatures in January and August and was generally a warm, dry and sunny year. In 2005 there was heavy rain and flooding across northern England. The following year in 2006, the UK had record temperatures and below average rainfall across England. The next heavy rainfall affecting the north east of the UK was in September 2008 and 2012. In 2011 and 2013, a persistent lack of rainfall and warm temperatures were recorded for England.

6.4   C/N ratios of SNP, RBP, P 8 and P 29

The C/N ratios (Figure 13) of SNP vary from the highest at 26.03 (19 cm) to 17.01 (16 cm). The sharpest increase occurs between 16 cm (17.01) and 12 cm (24.21). Between 11 cm and 5 cm the C/N ratios fluctuate between 22.25 and 22.71 respectively which is the least range through the whole core. Between 4 cm (20.65) and the surface of the core 1 cm (24.97) there are two sharp increases and decreases of C/N ratios. The RBP C/N ratios generally increase from the base of the core to the surface. Ratios do not fall below 18.02 (9.5 cm) and do not exceed 26.49 (1.5 cm). There is one sharp decrease at 4 cm to 22.97 from 24.50 to 24.65 but is still not a major change in C/N ratio. The base of P8 at 5.5 cm has the lowest value of 15.04 increasing to the highest value at 22.16 (4 cm.). Within the centre of the core there is a decrease from 22.16 (4 cm) to 17.36 (3 cm) increase (18.89 at 2.5 cm) and decrease to 16.78 (1.5 cm). P29 has a general increase with no major fluctuations possibly cause by low sampling resolution in the 6 cm core. There are no similarities in the trends illustrated between any of the SWBs regarding their C/N ratios, showing each SWB states over the years have been different. The consistently highest ratios (>20) are in the SNP followed by the RBP and the two constructed ponds are the lowest (P29 19.01).
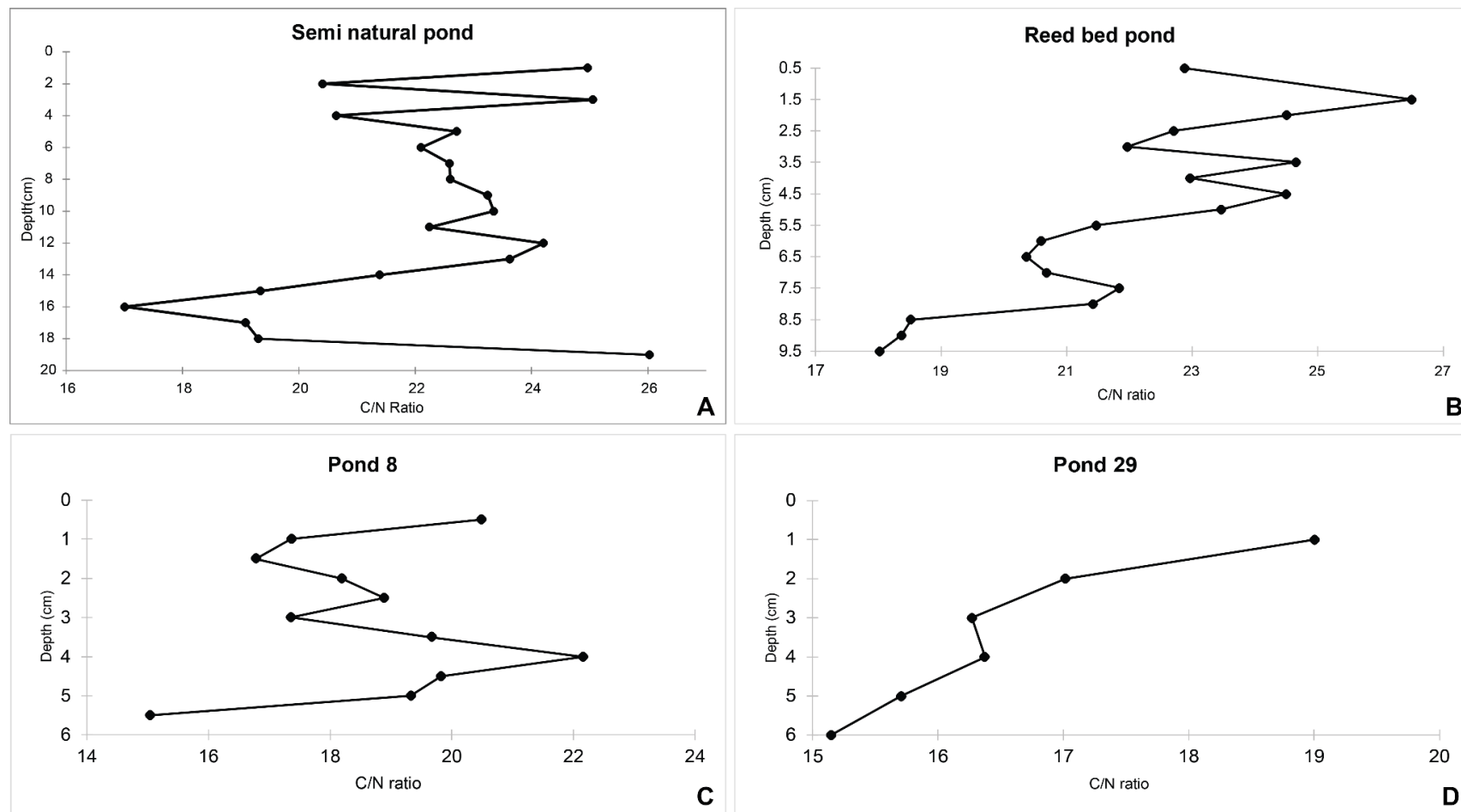
Figure 13: Carbon/Nitrogen ratios for each SWB plotted against the depth (cm). **A**: SNP at 1 cm intervals. **B**: RBP at 0.5 cm. **C**: P8 at 0.5 cm and **D**: P29 at 0.5 cm.

6.5 Sediment core testate amoebae assemblages

In this section the testate amoebae assemblages from SNP, RBP and P 8 are displayed. The descriptions of the lithology for each pond are described in the pollen assemblages section.

6.5.1 Key for testate amoebae

The identification key for the testate amoebae (Figure 14) shows the images of the testate amoebae found in this study and were then identified using a selection of reference material from Corbet, (1973); Jax, (1985); Charman et al., (2000); Montoya et al., (2010) and Glime, (2013). Also shown in the key is the teeth from Chironominae (subfamily of Chironomidae), tardigrade eggs, a non-identified non-pollen palynomorph and the reworked *Lycospora* spore.
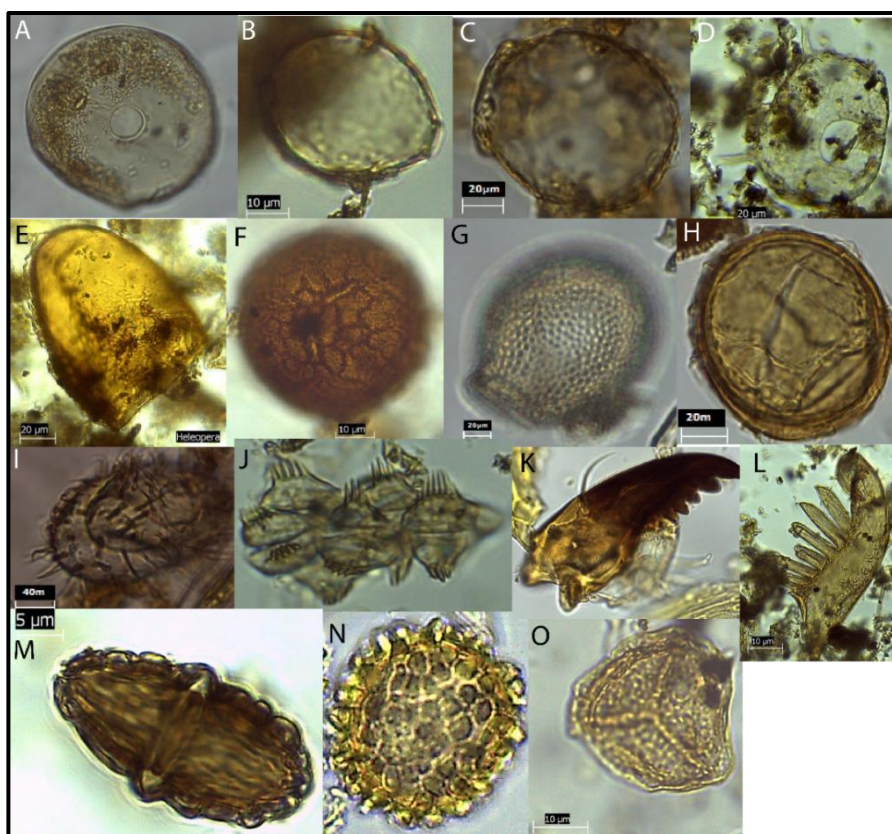
Figure 14: **A-I** Light Microscope illustrations of testate amoebae in the SWB sediments. **A**: *Arcella*. **B**: *Assulina*. **C**: *Nebela*. **D**: *Centropyxis*. **E***: Hyalosphenia* **F**: *Bullinaria* **G**: *Euglypha* **H**: *Pyxidicula*. **I**: *Placocista*. **J-N**: Non-Pollen Palynomorphs present throughout the sediment cores of all ponds. **J**: Unknown**. K & L**: Teeth from insect in the Chironominae, indicative of a fishless environment (Smol, 2002) **M**: Non-identified (also in Montoya et al., 2010). **N:** Possibly Tardigrada egg morphotypes as found in Montoya et al., (2010). **O**: *Lycospora* from reworked from the Carboniferous as the site is on a previous open cast coal mine.

Arcella: Associated with very wet conditions, most often with standing water (Charman et al., 2000). Identified in three different habitats; in aquatic sediment, in aquatic macrophytes and in plankton (Alves et al., 2010)

Assulina: Dry to damp conditions. *A. muscorum* is regarded as cosmopolitan and exists in greater numbers in dry conditions whereas *A. seminulum* is hygrophilous (growing in damp conditions) also occurring in bog hummocks (Charman et al., 2000).

Bullinaria: Regarded by most authors as extreme xerophile (extremely dry conditions). Indicator of a dry habitat (Charman et al., 2000).

Centropyxis: Most taxa within this genus are typical of hygrophilous environments in submerged and wet mosses and tolerate planktonic, aquatic macrophytes and aquatic sediment habitats (Charman et al., 2000; Alves et al., 2010).

Euglypha: Moderately wet preferable to standing water (Charman et al., 2000).

Hyalosphenia: Unable to identify down to species level due to limited literature descriptions. Most species within the genus prefer damp to wet conditions (Charman et al., 2000). Identified in aquatic macrophytes and not in any other habitats (Alves et al., 2010).

Nebela: Unable to identify down to species level due to limited literature descriptions. Most species within the genus prefer damp to wet conditions (Charman et al., 2000).

Placocista: *P. spinosa* type is typical of bog pools and/or very wet conditions (Charman et al., 2000).

Pyxidicula operculata: There is little information on the ecology of this species but it is reported to be most common on aquatic vegetation in ponds and lakes (Jax, 1985).

6.5.2 Semi-natural pond testate amoebae assemblage

The three zones in the SNP testate amoebae assemblage (Figure 15), zones, 1a, 2a and 2b are spilt by CONISS. Zone 1a has a wide distribution of taxa habiting dry, wet and aquatic vegetation habitats. Zone 2a illustrates the highest percentage of *Pyxidicula operculata* with only 12 cm having the coexisting presence of *Centropyxis*. There is an increasing amount of dry indicator species towards the upper part of the zone at 7 cm. Zone 2b has a high occurrence of *Centropyxis* at 6 cm rapidly decreasing as *Pyxidicula operculata* increases. *Placocista*, indicative of wet environments, shares the same pattern as *Centropyxis* in zone 2b. Dry species of *Assulina* and Trigonopyxidae occur together at 7 cm and 4 cm, near lithology changes. *Bullinaria* occurs at 5 cm between the presence of *Assulina* and Trigonopyxidae.

6.5.3 Reed bed pond testate amoebae assemblage

The RBP testate amoebae assemblage (Figure 16) shows two prominent zones, 1a and 2a split by CONISS at 4.75 cm. Zone 1a has a low presence of dry testate amoebae with only *Heleopera* from 8.5-7.5 cm. There are no semi aquatic indicators. *Arcella* is the most prominent test indicating wet conditions and as *Arcella* decreases, *Placocista* occurs. *Centropyxis* has a steady occurrence from 8.5-5.5 cm. Zone 2a illustrates a sharp increase in *Centropyxis* at 4 cm with no presence of *Arcella*. The highest peak of *Arcella* (2.5 cm) is accompanied by a low presence of *Centropyxis*. *Pyxidicula operculata* only occurs twice (6.5 cm and 8 cm) at <20% and occurs with *Centropyxis, Placocista, Arcella* and *Heleopera* at 12 cm. Dry species of *Heleopera*, Trigonopyxidea and *Trinema* are present with wet and aquatic vegetation indicators.

6.5.4 Constructed pond 8 testate amoebae assemblage

P8 testate amoebae (Figure 17) zone 1a is the smallest zone having mostly aquatic vegetation tests. Zone 1b illustrates an increase in *Heleopera*, dry indicator, as *Pyxidicula operculata* decreases. Within Zone 2a *Arcella,* a wet indicator, increases gradually peaking at 0.5 cm. *Centropyxis* and *Pyxidicula operculata* occur simultaneously but not at their highest presence when together. *Heleopera* peaks at 1.5 cm with very low occurrence of any other testate amoebae.
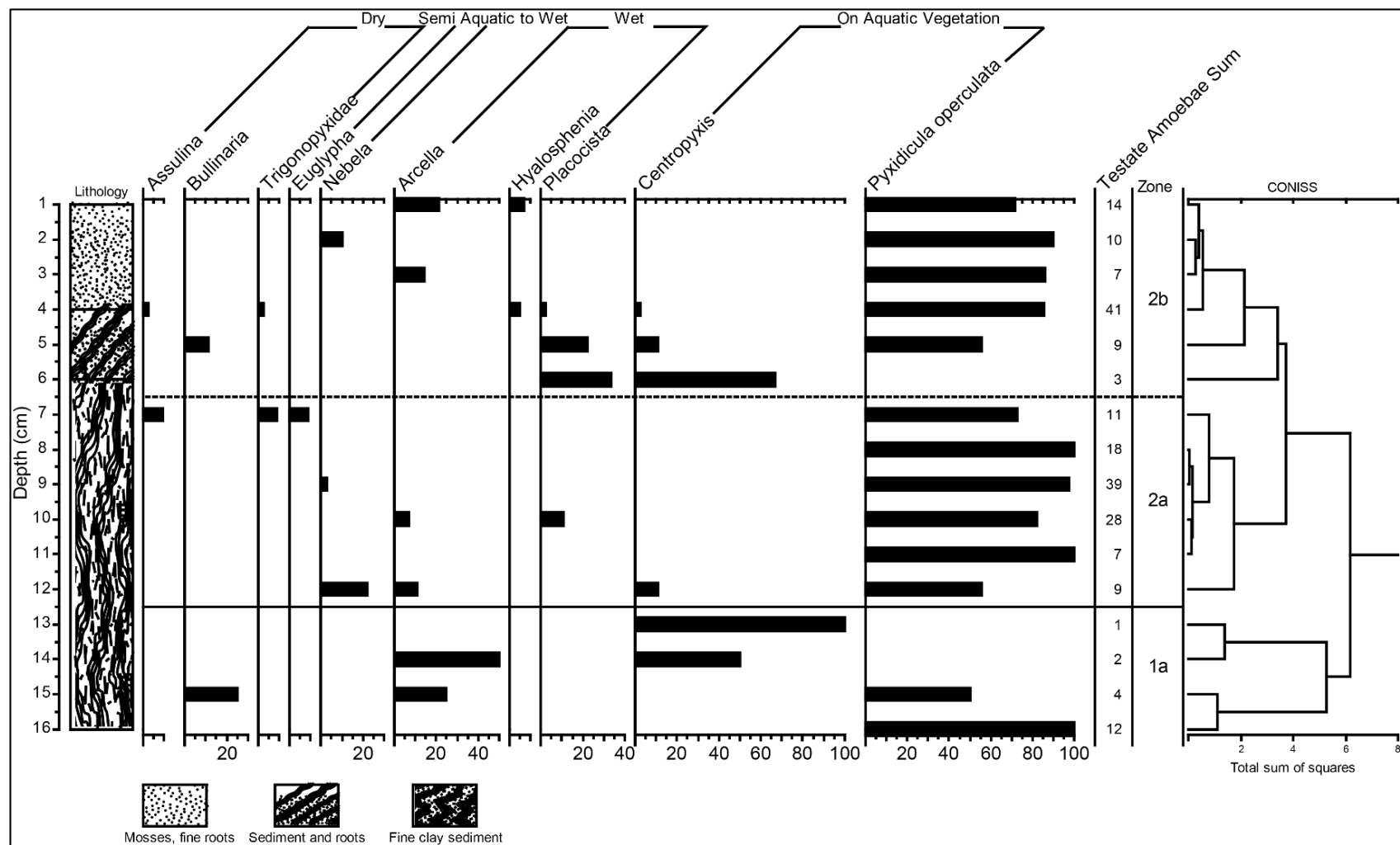
Figure 15: Testate amoebae percentage diagram of SNP, taken from the same core as the pollen for SNP. There are three zones, 1a, 2a and 2b as suggested by CONISS. There are four groups for the testate amoebae, dry, semi aquatic-wet, wet and on aquatic vegetation.
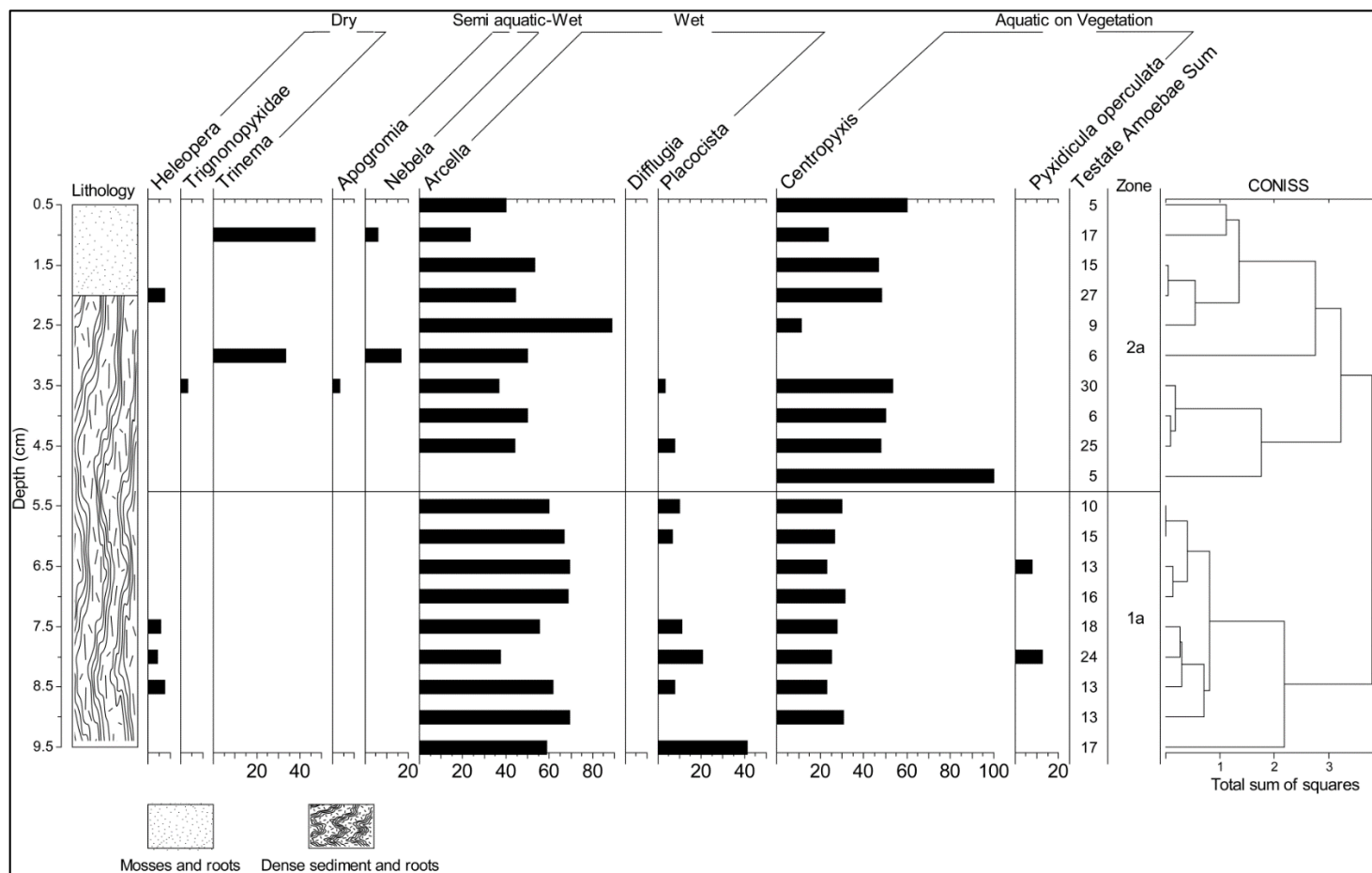
Figure 16: RBP Testate amoebae percentage diagram of taken from the same core as the pollen for RBP. The testate amoebae sum is the total sum of all the testate amoebae. There are two zones, 1a and 1b as suggested by CONISS. There are four groups for the testate amoebae, dry, semi aquatic-wet, wet and on aquatic vegetation.
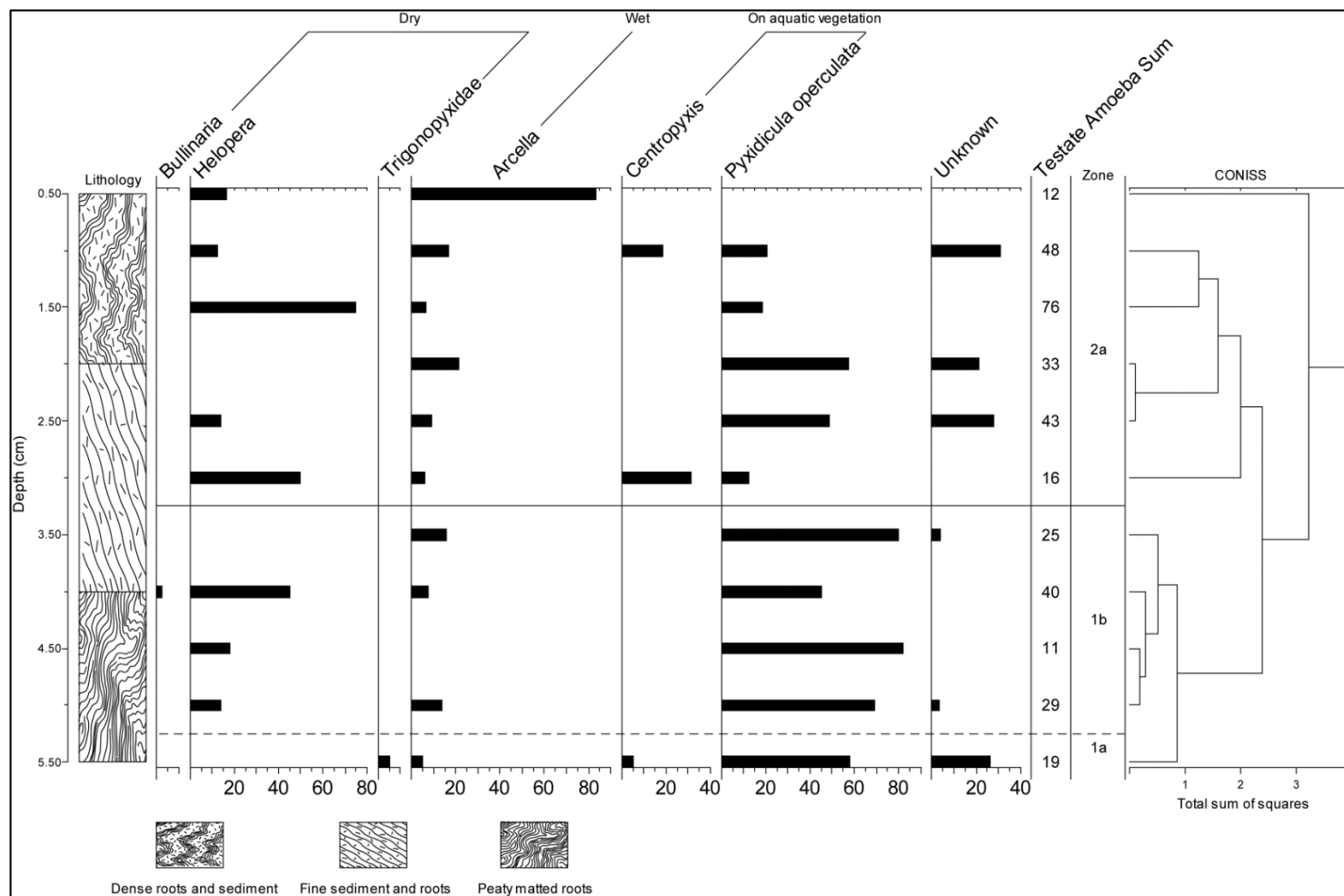
Figure 17: P8 Testate amoebae percentage diagram taken from the same core as the pollen for P8. There are three zones split by CONISS, 1a, 1b and 2a. There are three groups for the testate amoebae on this graph, dry, wet and on aquatic vegetation.

6.6 Sediment core pollen assemblages

6.6.1 SNP pollen assemblage

The SNP lithology section illustrates four changes (Figure 18). The top depth (1-4 cm) is made up of organic matter, mosses and grasses at a Munsell colour of 2.5y 3/1, dark brown. From 4-17 cm the core progresses into a dense root system mixed with a fine clay sediment texture (Munsell colour 2.5y 4/1, dark reddish brown). The bottom depth from 17- 19 cm changes very quickly in texture from the section above and is a very thick, dense clay texture (Munsell colour 2.5y 5/1, mud brown). There are 41 different pollen taxa in the assemblage excluding *Lycospora.*

The record can be subdivided into four zones, 1a, 1b, 2a and 2b. Zone 1a has peaks of taxa from different groups, which is at the very base of the core. Zone 1a has a peak of *Pinus* and Cyperaceae undiff. at the change in lithology at 17 cm. Poaceae undiff. slightly increases as Cyperaceae undiff. decreases at 15 cm in zone 1b. Brassicaceae and *Secale cereale* increase in percentage in zone 1a and ends at 16 cm in zone 1b. *Lemna minor* in the aquatics group peaks with *Phragmites* with the absence of *Schoenoplectus* at 16 cm. Zone 2a has an increase of *Pinus* peaking at 9 cm with Cyperaceae undiff. Within the herbs group, *Epilobium* has its highest percentage abundance between 12-8 cm. The Brassicaceae and *Zea mays* peak at 8 cm in the crops group and *Avena*-type peaks twice at 13 cm and 2 cm. Brassicaceae undiff. was put into the crops group in all percentage pollen diagrams, as *Brassica* was recorded in the crop record and could potentially represent that record. Progressing into zone 2b there is a decrease in *Pinus* at 4 cm (change in lithology). The aquatics group continue to fluctuate, and *Lemna minor* and *Phragmites* are present when *Schoenoplectus* is absent at 5 cm, similar to 16 cm.

There are peaks in *Lycospora* at 17 cm, 15-12 cm, 10 cm and 6 cm. At 17 cm there is the first peak of *Lemna minor* and a further three at 12 cm, 10-7 cm and 5 cm. These three peaks occur after the four *Lycospora* peaks. There are *Pinus* and Cyperaceae undiff. peaks at 9cm and fluctuate in a similar pattern throughout the core. The pollen concentration peaks three times at 12 cm, 8 cm and 5 cm which coincide with low *Pinus*.
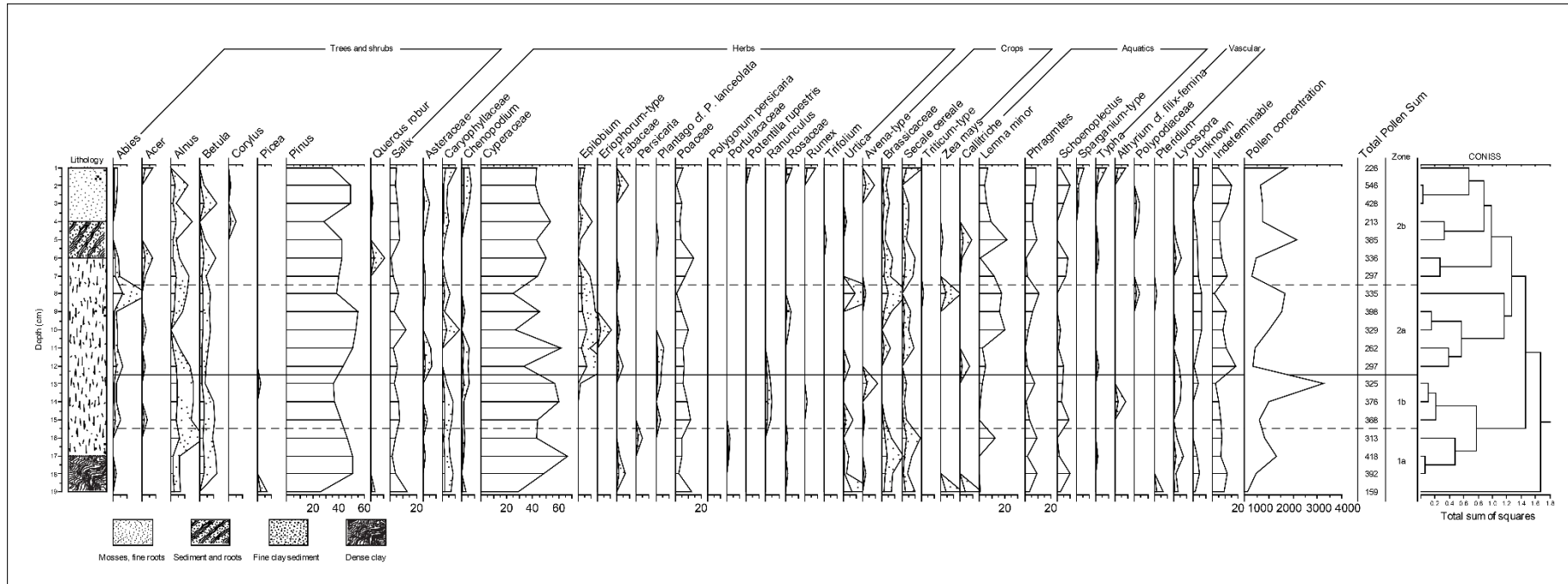
Figure 18: SNP: percentage pollen diagram with pollen zones based on CONISS. Depth (cm), lithology, pollen percentage data, pollen concentration and pollen sum are displayed and the dotted shading indicates x4 exaggeration for taxa with low abundance.

6.6.2 Reed bed pond pollen assemblage

The lithology of the RBP has two main sections of lithology. The largest section (9.5-2 cm) constitutes of dense sediment and roots which changes to mosses and roots in the top section of sediment (2-0.5 cm). There are six zones, 1a, 2a, 2b, 2c, 3a and 3b in the RBP pollen assemblage (Figure 19). There are 30 different pollen taxa in the assemblage excluding *Lycospora*.

Within Zone 1a the least present are the aquatics within only *Typha latifolia* present. Zone 2b illustrates a peak in *Pinus* and Cyperaceae undiff. at 6.50 cm. There is a continuous presence of all tree taxa throughout this zone. Herbaceous taxa have a varied distribution. In the crops group, Brassicaceae undiff. and *Avena*-type peak at 9 cm and 8.5 cm respectively, and *Brassica* has a continuous presence. Zone 2b is one of the smallest, signified by peaks in *Pinus*, *Eleocharis*, Poaceae undiff., *Urtica, Avena, Secale cereale* and *Typha latifolia.* Zone 2a has lower tree percentages than the other zones, especially *Pinus*. In Zone 3a Poaceae undiff. has sharp fluctuations, of particular note at 2 cm where it decreases at the change in lithology. *Lemna minor* peaks at 3 cm in this zone with the third appearance of *Phragmites. Phragmites* peaks at 2 cm with no other aquatic taxa. Brassicaceae undiff. has its second peak at 3 cm and Brassica has very low percentages compared to zone 1a and 1b. Zone 3b is the smallest zone in the RBP pollen assemblage and CONISS splits the very upper sample (0.5 cm) on its own. Pollen concentration peaks, *Phragmites* and *Lemna minor* decreases and Poaceae undiff. increases.

There are three *Lycospora* peaks at 9 cm, 7.5 cm and 4.5 cm. *Pinus* and Cyperaceae undiff. share their largest peak at 6.5 cm. *Phragmites* does not enter the pollen record until a small peak at 8 cm and 7 cm and occurs in low numbers until after 3 cm, peaking at 2 cm where the lithology changes.
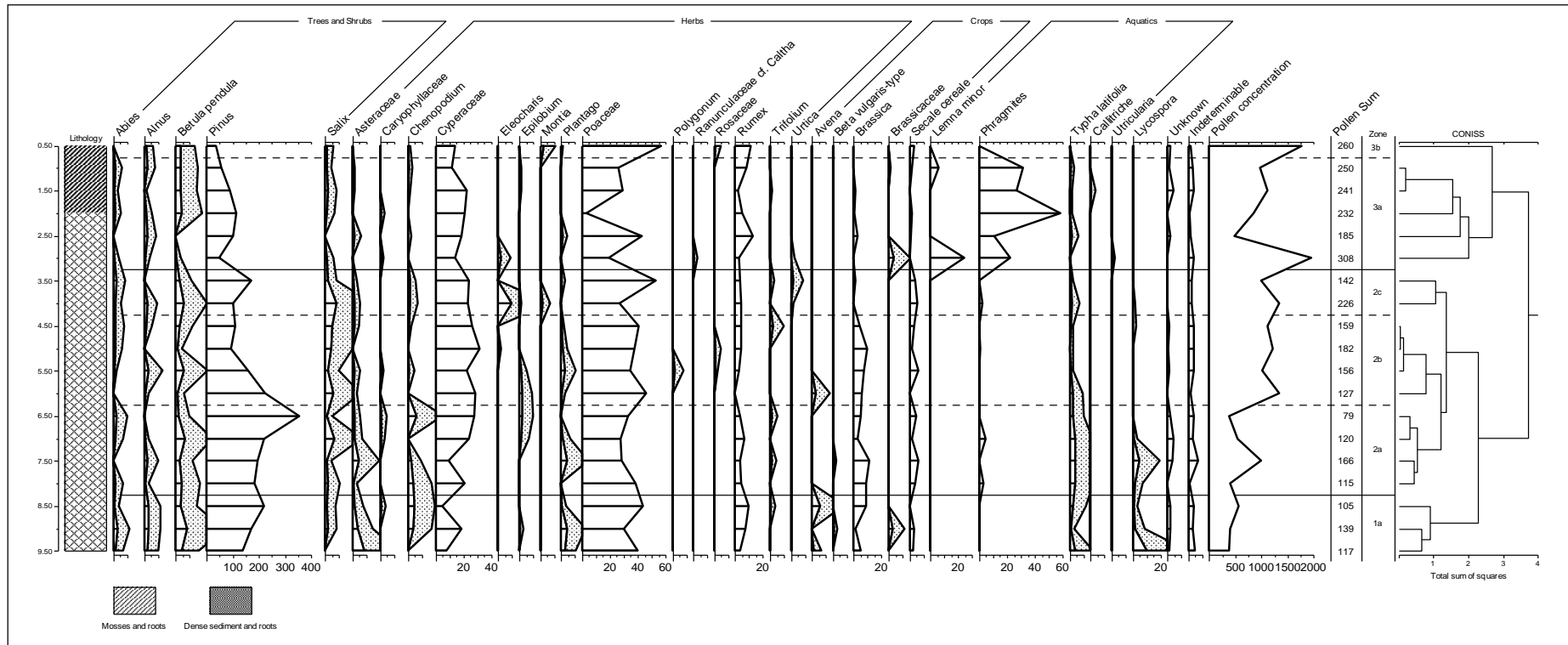
Figure 19: RBP: percentage pollen diagram with pollen zones based on CONISS. Depth (cm), lithology, pollen percentage data, pollen concentration and pollen sum are displayed and the dotted shading indicates x4 exaggeration for taxa with low abundance.

6.6.3 Constructed pond 8 pollen assemblage

There are three main changes in lithology in P8. The uppermost section from 0.5-2.0 cm is dense roots and sediments progressing into fine sediment and roots 2.0-3 cm. From 3 cm to the base at 5.50 cm there are peaty matted roots. There are 19 different pollen and spore taxa in the assemblage excluding *Lycospora*.

The pollen percentage diagram for P8 is split into zones 1a, 1b, 2a and 2b (Figure 20). Between zones 1a and 1b there is one major fluctuation of *Abies* and *Pinus* at 4 cm (change in lithology) which coincides with a Cyperaceae peak and a trough in Poaceae undiff. and *Lemna minor*. In zone 1a, *Lemna minor* singularly peaks at 4-5.5 cm. Zone 2a and 2b has a significant increase in *Salix* and slight fluctuations in *Pinus* but no major changes similar to zone 1. There is a slight increase in the amount of herbaceous taxa. All crop taxa (*Beta vulgaris*-type, Brassicaceae undiff. and *Secale cereale*) peak in zone 2b, similar to zone 1b. The aquatics group do not share any similarity in presence. *Lycospora* has a continuous presence throughout the core after peaking at 4 cm. *Pinus* and Cyperaceae fluctuate in the same way. P8 records the least amount of crop pollen grains giving a signal of *Beta vulgaris-type*, Brassicaceae undiff. and *Secale cereale.*

6.6.4 Constructed pond 29 pollen assemblage

P29 was the first of the constructed ponds in this study to be sampled and was sub-sampled to 1 cm (Figure 21). There are 20 different pollen taxa in the assemblage excluding *Lycospora.* The pollen profile displays small fluctuations, especially in the *Pinus* and Poaceae undiff. There are no changes in lithology for P29 sediment core which has a make-up of fine sediment and roots from 6-1 cm.

There are two zones, 1a (6-4.5 cm) and 2a (4.5-1 cm). Zone 1a displays a gradual increase in pollen concentration but does not reach its highest concentration in this zone. There is low percentage presence of the majority of the pollen taxa within this zone and there are no crops present. A gradual decrease in *Lycospora* from the base of the core can be identified. Zone 2a has the highest peak in pollen concentration at 4 cm and displays a general increase in presence of most pollen taxa. *Pinus* and *Abies* peak at 3 cm with a reflected decrease of Poaceae undiff. at the same level. *Lycospora* continues a very low presence from 4-2 cm and appears to be non-existent at 1 cm.
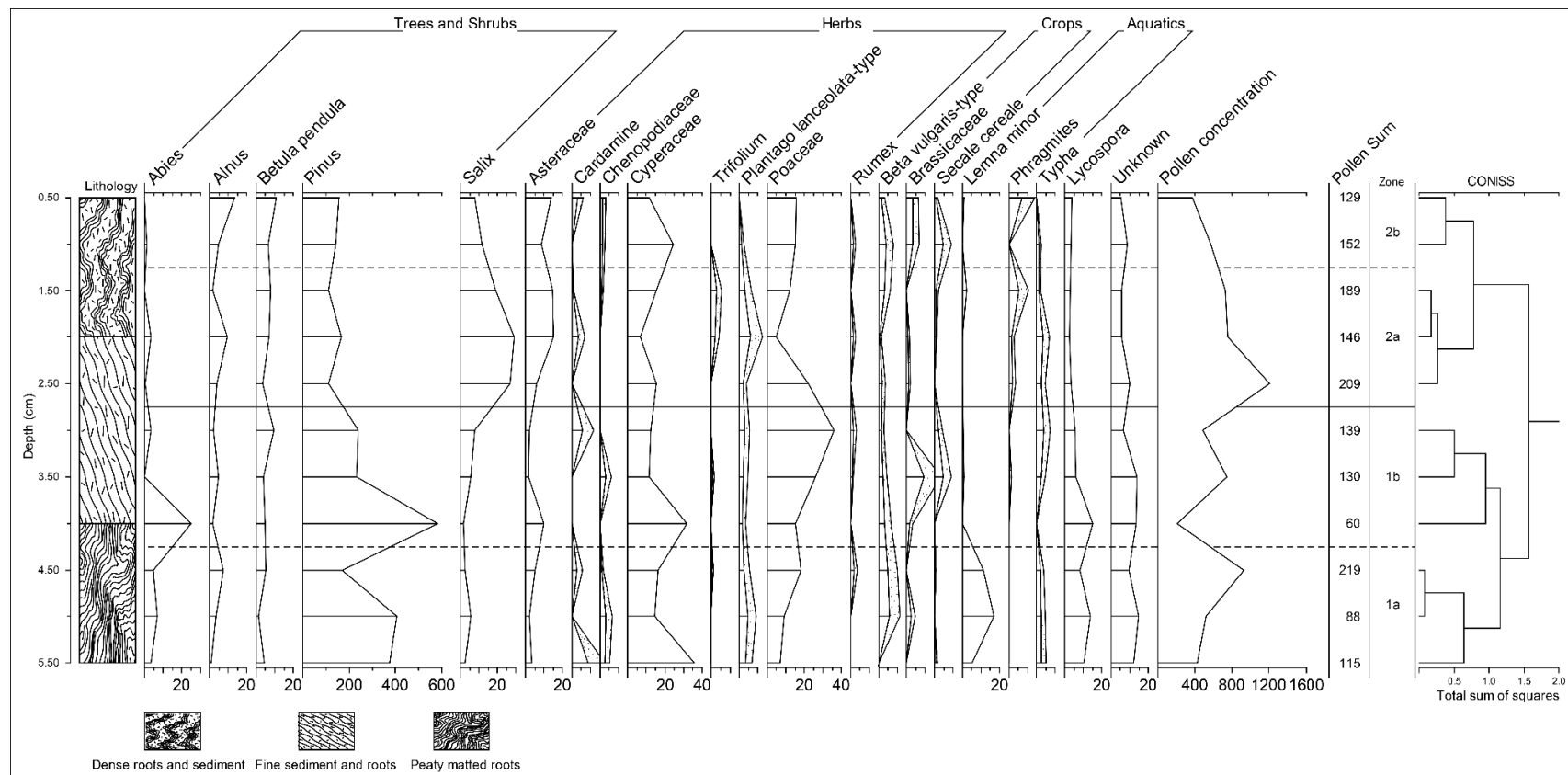
Figure 20: Constructed Pond 8 percentage pollen diagram with pollen zones based on CONISS. Depth (cm), lithology, pollen percentage data, pollen concentration and pollen sum are displayed and the dotted shading indicates x4 exaggeration for taxa with low abundance.
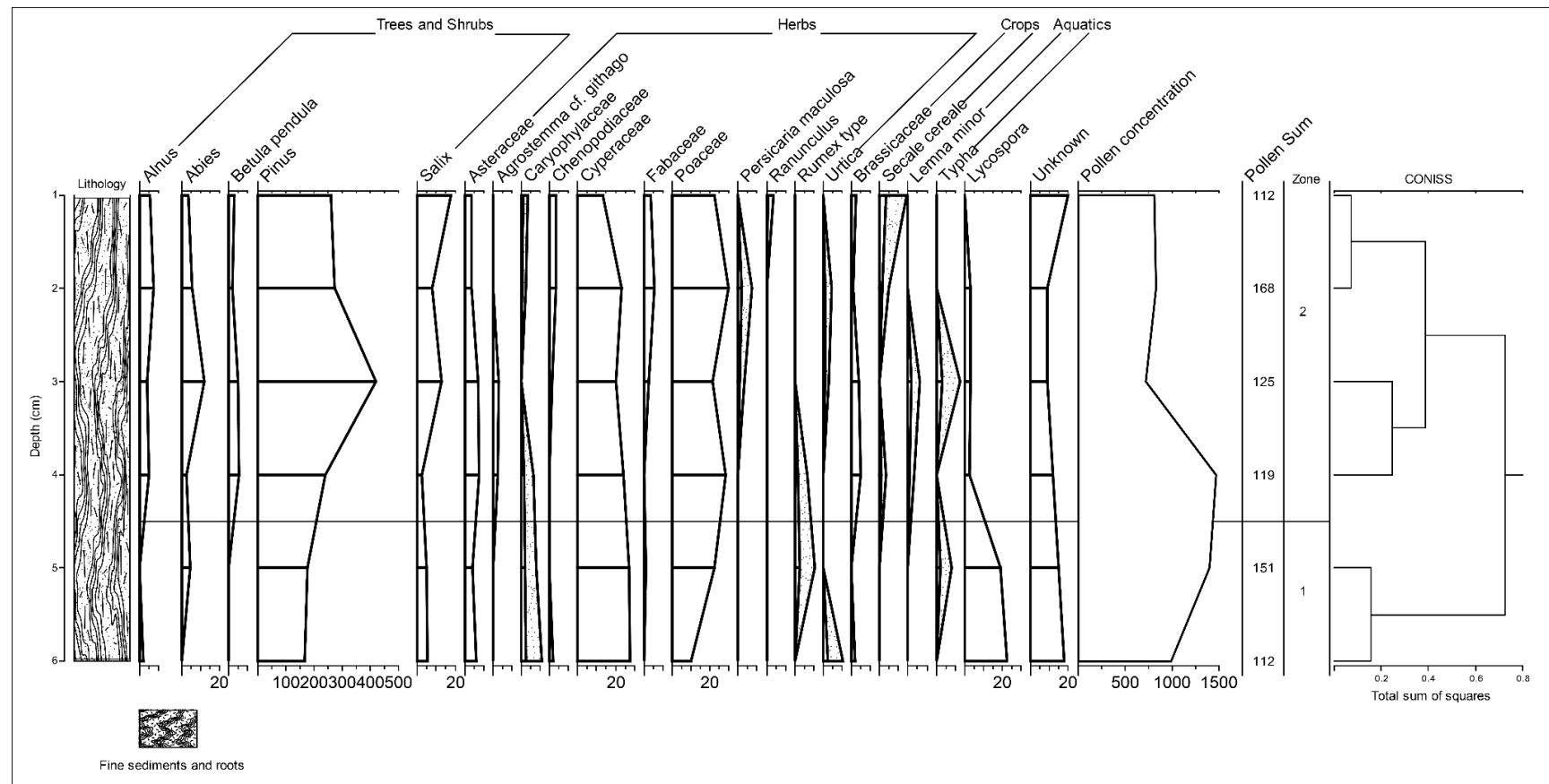
Figure 21: Constructed pond 29 percentage pollen diagram. Caryophyllaceae, *Persicaria maculosa, Urtica, Secale cereale, Lemna minor* and *Typha* are exaggerated by factor 4. CONISS (Grimm, 1987) splits the graph into two zones, zone 1 (4.5 cm – 6 cm) and zone 2 (1 cm – 4.5 cm).

6.7 Crop records from surrounding fields

The crop records were collected from the local farmer who owned the fields surrounding the study site (Table 3). There were five years which did not have any records and were labelled as Unknown, but the remaining years indicate what pollen signal could be expected from the local area. *Brassica rapa* and *Secale cereale* were the two most planted crops over the nineteen years and there was only one year, 2001 which had records of two crops, *Brassica rapa* and *Zea mays*.

Table 3: The crop records (1996-2014) of the surrounding fields to the study site, sourced from the local farmer owning the fields.

Date	Crop record
2014	Unknown
2013	Unknown
2012	Unknown
2011	*Secale cereale*
2010	*Avena sativa*
2009	*Triticum aestivum*
2008	*Brassica rapa*
2007	Unknown
2006	*Secale cereale*
2005	*Solanum tuberosum*
2004	*Brassica rapa*
2003	*Solanum tuberosum*
2002	*Secale cereale*
2001	*Brassica rapa and Zea mays*
2000	*Zea mays*
1999	Unknown
1998	*Secale cereale*
1997	*Solanum tuberosum*
1996	*Brassica rapa*

6.8 PCA analysis of pollen, testate amoebae and vegetation data

The PCA analysis of pollen assemblages from SNP, RBP and P 8 are illustrated as scatter plots and explained.

6.8.1 PCA of macrophyte vegetation from all thirty constructed ponds

The PCA of the vegetation dataset (Figure 22), has a percentage variance of 30.94% on PC1 and 19.12% variance on PC2. Component 1 represents the dry

to wet scale, positioning the majority of wet habitat species on the negative end. The colonising and aquatic flora of *Callitriche, Chara Vulgaris, Ranunculus aquatilis, Alisma plantago aquatic, Glyceria fluitans* and Filamentous Algae are closely grouped at the negative end of component 1. *Eleocharis palustris,* and *Cardamine* are also near this group. Component 2 denotes the occurrence of vegetation over the years with the least occurring positioned on the top positive section of the axis and most prevalent on the negative end. The 95% ellipses do not group any taxa. However, on the either side of PC1 the taxa are split into two groups.

6.8.2 PCA of SNP pollen and testate amoebae

The SNP PCA (Figure 23) component 1 explains 13.82% variance and does not illustrate any strong groupings of the pollen and testate amoebae sub-samples. Component 1 appears to represent wet to dry, with wet on the left moving along to a drier environment to the right. The group of taxa on the far right of component 1 are indicative of a drier habitat, associated the closest with 1 cm depth and appears the most defined group which is separated the greatest distance in the PCA plot. The testate amoebae and pollen taxa comprising of this group are *Hyalosphenia* (wet) shown in the lower right group with *Sparganium -type, Rumex, Potentilla rupestris, Typha,* and Rosaceae. No other sample depths are associated closely with these taxa. Cyperaceae undiff. and *Centropyxis* (wet, aquatic vegetation) are plotted closely with each other on the scatter graph at the negative end of component 2. These are closest to sample depths of 6 cm, 13 cm and 14 cm, similar to that of *Lycospora*, Poaceae, *Ranunculus* and *Schoenoplectus.* On the opposite side of component 2 to this group is *Lemna minor*, *Phragmites* and *Pyxidicula* operculata (wet, aquatic vegetation) which are close together near the sample depth 9 and 10 cm.

6.8.3 PCA of RBP pollen and testate amoebae

Component 1 explains 18.15% of the variance between the pollen and testate amoebae (Figure 24). Component 2 (13.90% variance) shows separation between the sample depths illustrating the upper half of the core (0.5 cm-5 cm) is on the opposing side to the lower half (5 cm-9.5 cm). Sample depth 3 cm is an outlier and is closest to *Nebela* (damp-wet), Brassicaceae*, Ranunculus cf. Caltha* and *Utricularia* at the negative end of component 1. *Centropyxis* (wet, aquatic vegetation) and Cyperaceae are at the negative section of component 2 but are

not in the same area as *Lycospora*. *Pyxidicula operculata* (wet, aquatic vegetation) is closely associated with *Epilobium*, Poaceae, *Secale cereale, Trifolium* and *Polygonum*.

6.8.4 PCA of P8 pollen and testate amoebae

The PCA of P 8 sub-samples (Figure 25), pollen and testate amoebae showed a broad distribution of all taxa and sample depths. Component 1 explained a relatively large proportion of variance at 26.25% which appears to represent the age of the samples, with the younger at the negative end of the scale (0.5-3.0 cm) to the older at the positive end (3.5-5.5 cm). Component 2 explains 16.02% of the variance and does not indicate any strong representation of environmental variances. *Heleopera*, *Arcella* and *Centropyxis* are associated with these samples. *Lycospora*, *Pinus*, *Abies,* Cyperaceae and *Bullinaria* testate amoebae (dry) are closely associated with each other in the lower left of the graph. *Lemna minor* and *Pyxidicula operculata* (wet, aquatic vegetation) show similar relationships to the SNP PCA. *Centropyxis* and Cyperaceae have been closely related in the PCA for the SNP and RBP but there is no association in the P8 PCA. The results of the P8 PCA are similar to the RBP PCA, in that the upper depths of P8 (0.5 cm-3 cm) are associated to the opposite side of the PCA than the lower half (3.5 cm-5.5 cm).
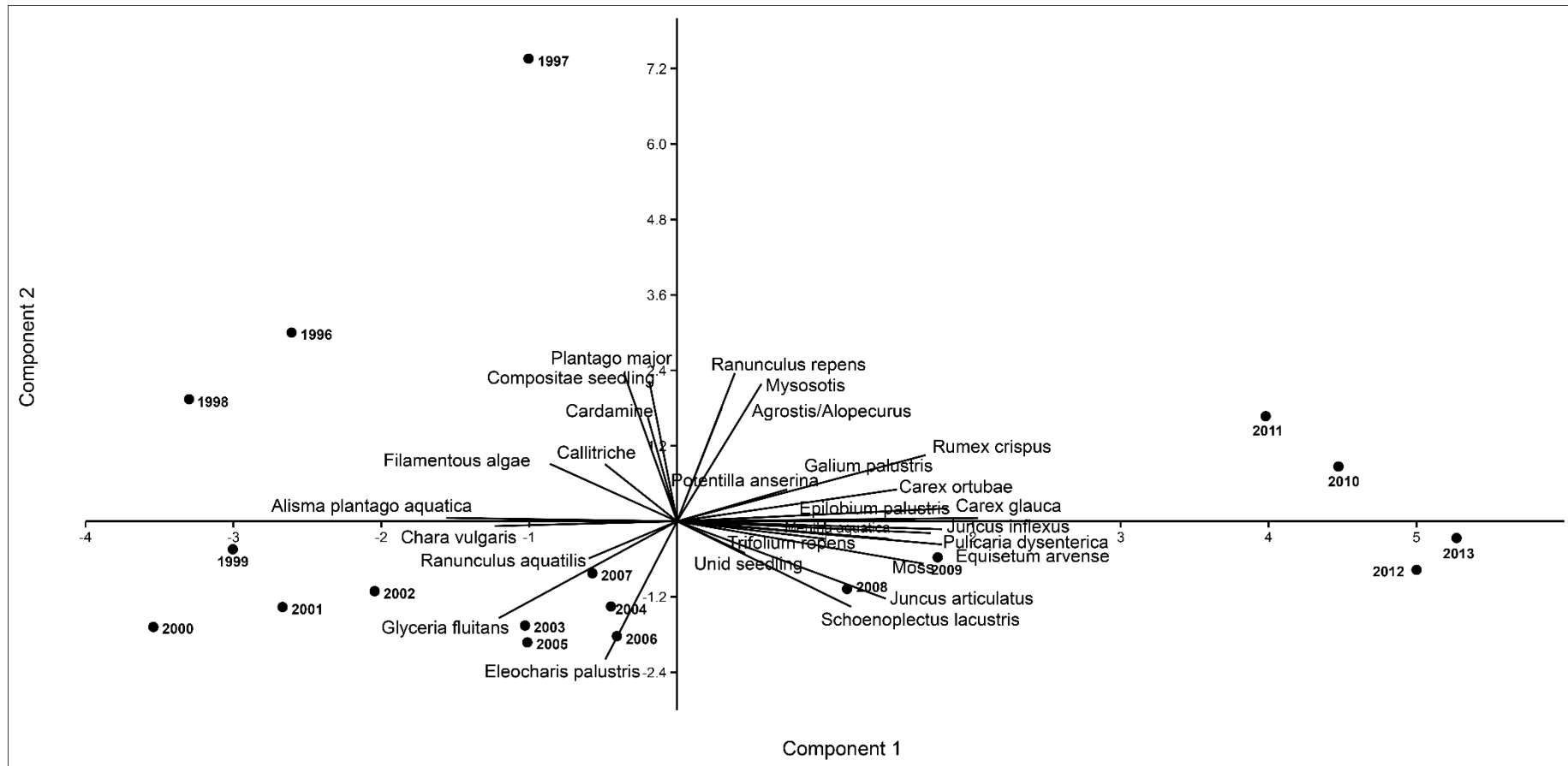
Figure 22: PCA plot of the vegetation from all 30 ponds dataset computed on normalised percentage data and displaying component 1 and component 2.
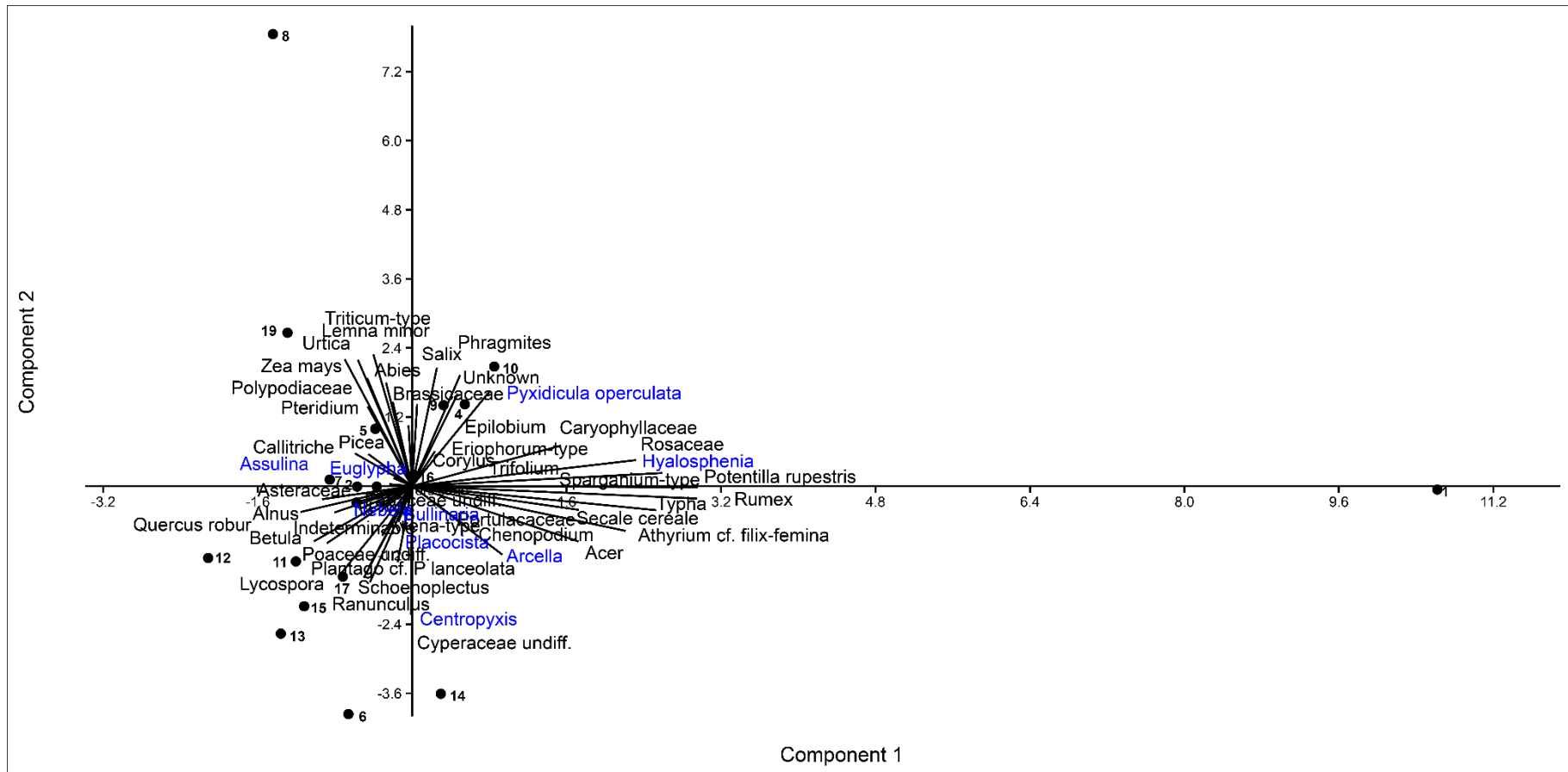
Figure 23: PCA plot of the SNP pollen and testate amoebae dataset computed on normalised percentage data and displaying component 1 and component 2. The pollen names are in black and the testate amoebae are in blue.

Figure 24: PCA plot of the RBP pollen and testate amoebae dataset computed on normalised percentage data and displaying component 1 and component 2. The pollen names are in black and the testate amoebae are in blue.
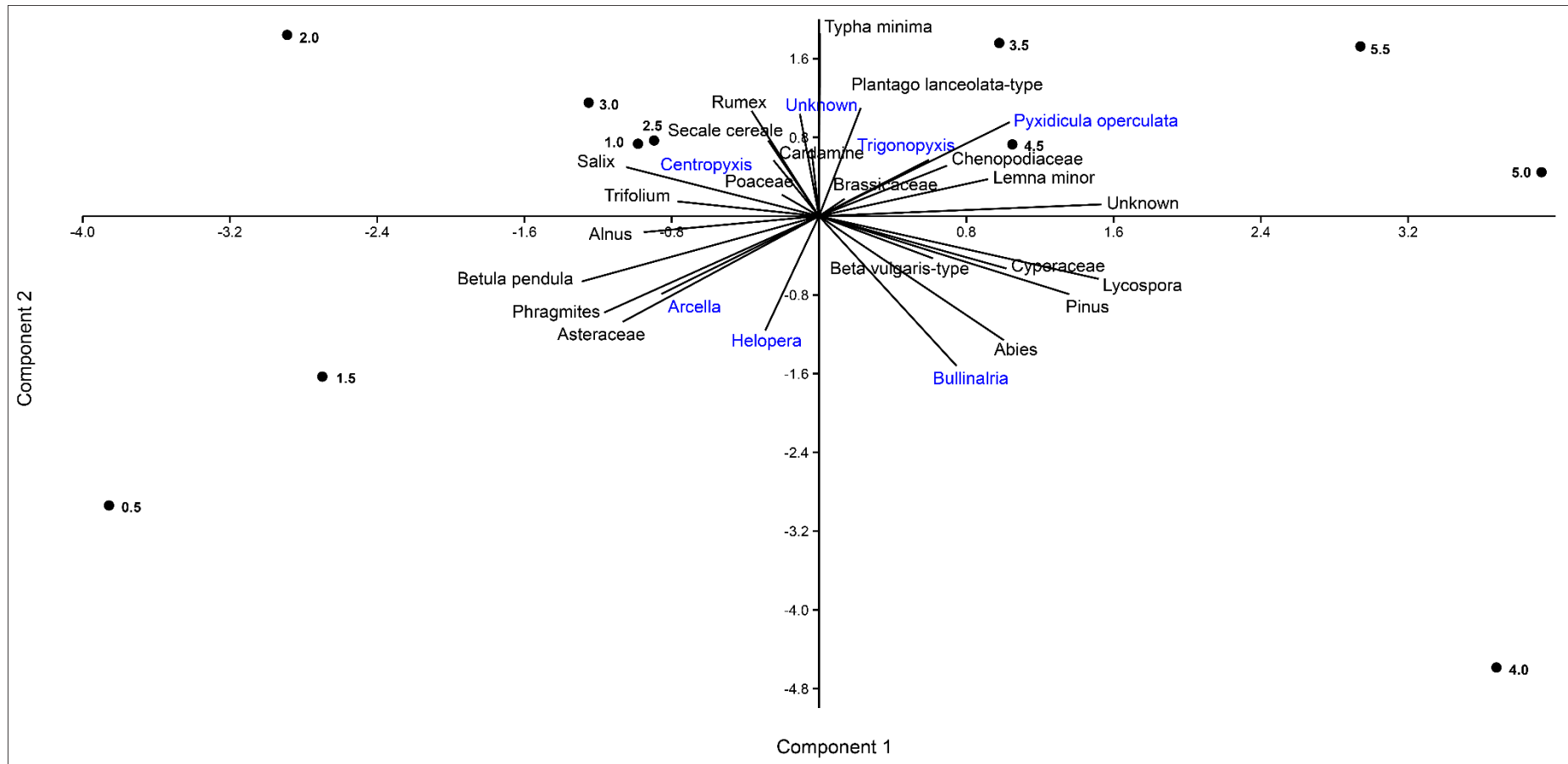
Figure 25: PCA plot of Pond 8 pollen and testate amoebae dataset computed on normalised percentage data and displaying component 1 and component 2. The pollen names are in black and the testate amoebae are in blue.

6.8.5 Comparison of the PCA results from the vegetation and pollen records

Figure 26 displays the vegetation, SNP, RBP and P8 PCA plots on one page to allow easier visual comparison. The PCA of the macrophyte vegetation from all thirty ponds do show a broad grouping of the wet and dry taxa but cannot be identified in any of the pollen PCAs. The similarity between Cyperaceae undiff. and *Centropyxis* on the SNP and RBP PCA, indicate a useful link which can be used to see if their habitat and environmental preferences are similar. The RBP and P8 illustrate that the upper and lower halves of their sediment cores are being affected by different variables. However, there are no similarities between their pollen taxa or testate amoebae and cannot be used for comparison.

Figure 26: PCA plots. **A**: PCA of the vegetation dataset computed on normalised percentage data and displaying component 1 and component 2. **B**: SNP PCA of pollen and testate amoebae computed on normalised percentage data and displaying component 1 and component 2. **C**: RBP PCA of pollen and testate amoebae computed on normalised percentage data and displaying component 1 and component 2. **D**: P8 PCA of pollen and testate amoebae computed on normalised percentage data and displaying component 1 and component 2. For Figures B, C and D the pollen names are in black and the testate amoebae are in blue.

7 Discussion

The following sections will discuss the approaches taken to achieve absolute dates for the SNP and relative dates for the RBP and P8, and the mechanisms that have affected this dating technique. In the first section the modern pollen rain and vegetation mapping will explore pollen representation and how this can be used to interpret the pollen records in sediment cores. There are two separate dating sections, absolute and relative. The absolute dating section compares existing dates and events in the vegetation (Jeffries, 2008), rainfall (Met Office, 2015) and crop record, with the testate amoebae and pollen assemblages to identify potential dates for sections of the SWB sediment cores. The different types of reworking which affected the pollen and testate amoebae signal, and how this was beneficial in supporting dating interpretations will be discussed. The relative dating section compares all of the SWB's pollen records and discusses them in relation to findings from the pollen representation of the modern samples and vegetation. The limitations in some approaches used for dating, such as reworking, pollen representation in different size and type of SWBs and observational records will be discussed in the relevant sections. To conclude this section, a discussion of how palynology can be used as a tool for aiding calculations of sedimentation rates and carbon burial is presented.

7.1 Modern pollen surface sample and vegetation mapping

Modern pollen and vegetation mapping have been widely used to assist the interpretations of fossil records (Giesecke et al., 2010; Bunting & Middleton, 2005; Wilmshurst & McGlone, 2005). However, pollen assemblages in the modern samples have been shown to be highly influenced by the pollen production of the surrounding vegetation, transport medium and distances as well as methods of deposition (Lisitsyna et al., 2012; Goring et al., 2013). The problems of wildlife and contamination, which occurred in this study as indicated by the pollen traps, are not uncommon (Sjogren et al., 2015). Statistical analyses were therefore limited and more of a qualitative approach was taken in comparing the pollen-vegetation relationships.

In the modern pollen surface sediment samples, tree taxa occurred in all four SWB surface samples, apart from *Acer* occurring only in SNP and *Betula pendula* occurring in RBP, P8 and P29. This was unlike the majority of low-growing plants, which only occurred in one or two surface samples. This was also evident in modern pollen samples collected by Ranta et al., (2008). Tree pollen, released from height and transported by anemophily, is reflective of local and regional sources (Ranta et al., 2014). All four pollen surface samples had >30% *Pinus* reflected the particularly high pollen production of Pine trees and widespread dispersal capacity of their pollen grains due to grain morphology (Zanni & Ravazzi, 2006).

The pollen signal represented the vegetation of the surrounding fields as shown by the presence of crop pollen. *Zea mays, Avena* and *Secale cereale* were known to have been growing nearby the site (<1000 m). Cultivated grass pollen is typically larger than the wild grass pollen, and has particularly defining features such as annulus diameter (sometimes protruding with a sharp outer boundary), surface sculpturing and grain shape (Tweddle et al., 2005). However, the dispersal ability of these large grains is known to be poor and long distance transport is unlikely (Tweddle et al., 2005). *Secale cereale* (>40 μm) is a large cultivated pollen grain which is present in all of the pollen surface samples. *Beta vulgaris*-type was the only other possible crop signal identified in the surface samples.

When comparing the modern pollen surface sample and vegetation mapping location, Cyperaceae and Poaceae were present in all vegetation mapping locations (apart from Cyperaceae in VM2) and pollen surface sediment samples. This is because Cyperaceae and Poaceae are two of the most abundant sources of pollen (McGlone & Moar, 1997). Poaceae and Cyperaceae contain many species, each with their own unique characteristics in relation to pollen, which contribute to uncertainties in pollen and vegetation correlations (Sjöfren et al., 2015). The dispersal properties of pollen from low-growing vegetation, especially anemophilous pollen taxa are different than trees and can limit pollen dispersal to very short distances, therefore primarily coming from local sources (McGlone & Moar, 1997; Ranta et al., 2014; Sjöfren et al., 2015).

Three of the four vegetation mapping locations recorded Cyperaceae, (VM1 22.12%, VM4 34.45% and VM3 1.09%) and all four surface sediment samples recorded Cyperaceae pollen (highest in SNP 27.39%). VM1 and SNP are the closest in distance (Figure 8) and shows that pollen representation is affected by the distance of the vegetation source. The RBP was the closest to VM4 which recorded the highest Cyperaceae (34.45%, 31.58% from *Carex ortubae*) but was not strongly reflected in the surface sediment sample (8.91%). The RBP was on a raised bed above the VM4 location and also had *Phragmites* growing in the SWB. These two factors coupled with the fact that Cyperaceae, particularly *Carex ortubae* is low growing (Swan, 1993), and its pollen dispersal being limited, explains why there were less Cyperaceae pollen in the RBP surface sediment sample despite records of high abundances nearby. On the other hand, there was moderate representation of Cyperaceae in the SNP pollen surface sample (27.39%) which was closest to the second highest vegetation mapping (22.12%). *Eleocharis* was the only contributing plant to the vegetation mapping record and is of lower pollen frequency but good representation (Randall, et al., 1986). The pollen vegetation relationship of Cyperaceae appears to represent the dispersal characteristics.

Waller et al. (2012) found that the pollen from the vegetation directly above the site of deposition should be strongly represented in the pollen assemblage. *Phragmites* was known to be growing in the RBP during the later years, after 1995 (Jeffries, unpublished data). *Phragmites* is strongly represented in the pollen surface sample located closer to the source, with the highest presence being in the RBP pollen surface sample (10.53%). There is very little information about the pollen dispersal of *Phragmites australis,* apart from observed distance of tens of metres over the landscape (Fér & Hroudová, 2009).

The pollen source area of smaller lakes is less than larger ones (Seppa and Bennett, 2003), and the extensive pollen modelling completed on small lakes, shows that pollen taxa diversity is known to be low (Fyfe, 2005; Sugita, 2007a). The diversity of pollen taxa in the surface samples of the two semi-natural SWBs (SNP and RBP) is higher than the two smaller constructed ponds (P8 and P29). The pollen percentages of the majority of taxa in the SNP and RBP, particularly *Epilobium, Lemna minor, Phragmites,* Rosacaceae and *Rumex* are very similar, but are very low or non-existent in P8 and P29. The effect of distance from the

pollen source to deposition is also potentially illustrated by the occurrence of *Ranunculus*, as it is present in one vegetation mapping location (VM3), and only in one pollen surface sediment sample (P29).

Epilobium pollen dispersal can be by entomophily (insect) or autogamy (self). Low pollen production has been identified in *Epilobium* due to developments in their biotic pollination systems shifting to autogamy (Randall et al., 1986; Daghlian et al., 2012). Coupled with this shift to autogamy, some species of *Epilobium* have been recorded to have viscid pollen threads (Waser & Price, 1982) which would also result in low distribution, and a weak representation in surface sediment samples and sediment pollen assemblages. Pollen grain morphology within the genus of *Epilobium* can range from 56.3 μm - 120.8 μm thus being poorly dispersed, transported and consequently not strongly represented in the pollen record.

In summary, the modern pollen surface samples and vegetation mapping indicate that the location of vegetation to the pollen sink is important. Pollen grain morphology and dispersal techniques for different taxa all show an effect on the representation in the surface sample, particularly shown by *Carex ortubae*, *Eleocharis* and *Epilobium*. Site-specific factors, such as *Phragmites* growing only in the RBP SWB, show the unique effect that vegetation growth location has on the pollen signal. These interpretations from the modern pollen section can be utilised to interpret the pollen vegetation relationship in the SWB sediment cores and vegetation monitoring record.

7.2 Compilation of datasets for absolute dating

7.2.1 Vegetation monitoring record comparison with rainfall record

The vegetation monitoring data (Jeffries, 2008) was compared with the rainfall data to identify if the record showed wet and/or dry years (Met Office, 2015). Figure 27 displays the vegetation monitoring data with the high and low rainfall years explicitly indicated. There are four wet years (>890 mm per year) in 1998, 2005, 2010 and 2012, and three dry years (<600 mm per year) in 1996, 2003 and 2006. There were no consistent vegetation occurrences suggestive of wet or dry environments in these years. This vegetation data collected by Jeffries (2008) was recorded once a year, which could have been during a dry month and would therefore not reflect the average high rainfall of that year. Therefore, the vegetation in this dataset cannot be entirely expected to reflect high rainfall years. This interpretation of the vegetation and rainfall records was intended to be use for identifying possible trends in the pollen assemblages of the SWBs. There were no taxa indicative of a wet or dry year in the vegetation monitoring record which could be identified in the RBP, P8 or P29 pollen record and comparison of these two records could not be taken any further. However, the SNP pollen record did illustrate some similarities with the vegetation monitoring record and is discussed in section 7.2.5.
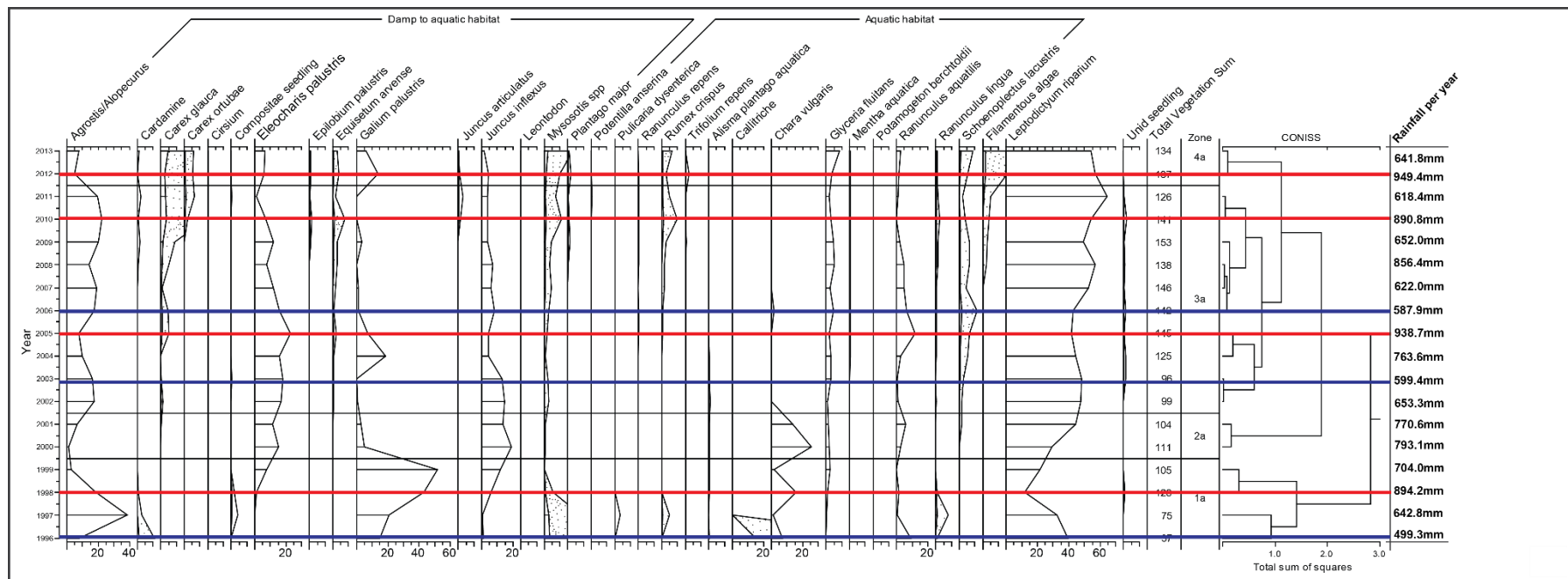
Figure 27: Vegetation record from thirty constructed ponds (Jeffries, 2008) with rainfall record per year (mm) (Met Office, 2015). Red lines indicate the wettest years (>890 mm per year) in 1998, 2005, 2010 and 2012, and blue lines indicate the driest years (<600 mm per year) in 1996, 2003 and 2006.

Discussion

7.2.2 Reworking of sediment in the SWBs

Reworking was identified in the sediment cores as a result of bioturbation or during significantly wet periods (possible flood events) indicated by the signal of a reworked (Carboniferous) spore, *Lycospora.* Bioturbation was visible at the base of all SWB sediment cores where the roots of the colonising vegetation were establishing themselves in the sediment. The sediment in this benthic environment would also be mixed by birds, particularly Ardeidae (herons), Laridae (gulls) and *Phasianus* (pheasants). The SNP and P8 illustrated changes in the lithology at the base 19-17 cm and 5.5-4 cm respectively, but no change in the RBP lithology was evident. This mixing of sediment was evident in the base of the pollen profiles, predominantly by the increased presence of *Lycospora*, which coincided with the SNP and P8 change in lithology. *Lycospora* is an abundant miospore known to be common in the Carboniferous period, primarily Pennsylvanian (Bek, 2012). The constructed ponds were dug into the infill material from an open cast coal mine, indicating this as the most probable source of *Lycospora,* since this was the only location in the field where the infill material was exposed.

Percentages of *Lycospora* spore illustrated an increase during significantly wet periods (potential flooding of the field-site) in the SNP from 0% to <2.0%. The field site is known to flood and join SWBs together (Jeffries, 2008), particularly the two constructed ponds and the SNP (Figure 8), which means that pollen grains can be transported with the flow of water between the SWBs. Consequently, when *Lycospora* appears in the record of the SNP, it could have been flooded in from the constructed ponds. A change in lithology 6-4 cm in the SNP was visible which was after a peak in *Lycospora*. The RBP was on a raised bed and thus was not flooded with the other SWBs. These two types of re-working naturally altered the pollen record of all the SWBs which was taken into account when interpreting the results.

7.2.3 Testate amoebae records indicative of wet periods

The sensitivities of testate amoebae to hydrological changes (Mitchel et al., 2000) and their individual preferences to different aquatic habitats such as aquatic sediments, macrophytes and mosses (e.g. *Sphagnum*), as well as rivers, lakes and reservoirs (Alves et al., 2010), can indicate and support interpretations of substantial habitat changes within SWB sediment cores. The comparison

between the testate amoebae and observational rainfall records identified potential wet years (two in the SNP at 13 cm reflecting 1997 and 6 cm reflecting 2005 or 2010 or 2012 and one in the RBP at 5 cm reflecting 1997 or 2005). These depths however, could not be matched to any of the four specific wet years and suggestions were made based on the approximate known date of construction (1995). It must be stressed that the dashed red lines on Figure 28 purely indicate the possible years for each depth and are not a certain conclusion with the testate amoebae results. The C/N ratios at the same depths of the identified wet period did not largely reflect any particular environmental changes, but were >20 suggesting terrestrial input of organic matter. This input of terrestrial organic matter could have been a result of high rainfall. Figure 28 illustrates the testate amoebae assemblages for the SNP and RBP with the rainfall record and also the C/N ratios for both SWBs. The homogeneity of P8 testate amoebae assemblage did not illustrate any specific wet or dry events. The results from the PCA between the pollen and testate amoebae assemblages (Figure 26, B, C & D) identified significant ecological and environmental similarities between taxa, which contribute to understanding why the testate amoebae records of the SNP and RBP illustrated wet years.

The four wet years marked on Figure 28 D could not be directly matched in the SNP (Figure 28 A) or the RBP (Figure 28 B) but estimations were made to assign possible ages. Estimations were primarily based on the association and ecological characteristics of the testate amoebae *Centropyxis* and *Pyxidicula operculata* and their occurrence in the SNP and RBP. Inferences of habitat preferences of each testate amoebae and known associations with vegetation types were collected from literature (Jax, 1985; MacArthur & Wilson, 1967; Corbet, 1973; Holcova, 2007; Pchelin, 2011; Glime, 2013; Swindles et al., 2014). These approximations, of what years the two depths in the SNP and one depth in the RBP could be, were marked on Figure 28 by red dashed lines.

The PCA was completed to identify environmental groupings within the pollen and testate amoebae assemblages of each SWB (Figure 26, B, C & D), and to see if these could be correlated with the wet/dry phases in the climate record to support dating interpretations. The results from the PCA of pollen and testate amoebae for the SNP, RBP and P8 did not consistently identify any similarities between the pollen and testate amoebae, but a correlation between Cyperaceae

undiff. pollen and *Centropyxis* testate amoebae in the SNP and RBP was evident, which demonstrated they inhabited the same environment.

The testate amoebae *Centropyxis* lives on sediment and aquatic macrophytes but the exact plant families it favours are unknown (Charman et al., 2000; Mattheeussen et al., 2005; Alves et al., 2010). Peaks in *Centropyxis* was closely associated with high abundances of Cyperaceae on all PCAs. Along with water levels, lakeside vegetation has been identified to control testate amoebae distribution (Holcova, 2007), which appeared to be the interaction with Cyperaceae undiff. and *Centropyxis*. The PCA particularly showed separation between *Pyxidicula operculata* and *Centropyxis,* in which their characteristics and habitat preferences will be explained in detail in the following sections. Swindles et al., (2014) also identified that *Pyxidicula operculata* and species within *Centropyxis* were not closely associated. The ecology may be complex, since this relationship was found in tropical studies (Swindles et al., 2014) and also observed in this northern hemisphere SWB study.

The PCA of P8 did not show any results which were similar to the SNP or RBP and are not discussed any further.

Within the SNP, *Pyxidicula operculata* had the consistently highest populations throughout the whole core with only two, 13 cm and 6 cm, where it was not recorded. *Pyxidicula operculata* is known to be a pioneer species which has the ability to colonise new habitats quickly but does not maintain high populations under competition (Jax, 1985). High population growth rates in relatively young habitats, which remain relatively unchanged have also been observed by Jax (1985), showing that high oscillations and no equilibrium level for *Pyxidicula operculata* populations were shown. *Centropyxis* has an opportunistic nature (Holcova, 2007) and shows peaks in abundance at 13 cm and 6 cm in the SNP which coincide with the absence of *Pyxidicula operculata*. *Pyxidicula operculata* has been shown to tend towards r-strategy, which is part of R and K selection that was introduced by MacArthur & Wilson in 1967. This concept of R and K selection distinguishes between species which are weak competitors and therefore have high populations and colonise new habitats quickly, and species which are good competitors and consequently have low populations and utilise resources effectively on a long-term basis (Jax, 1985). The young SWBs (<20

years) are known to have been temporarily flooded during times of high rainfall (Jeffries, unpublished data). The competition between *Pyxidicula operculata* and *Centropyxis* in the SNP is suggestive of wet periods at 13 cm and 6 cm, but with only two depths and four wet rainfall years, a certain match cannot be concluded. The C/N ratios for the SNP depths at 13 cm and 6 cm (Figure 28 C) were 23.63 and 22.10 respectively, and did not reflect wet periods.

In the RBP *Arcella* and *Centropyxis* are the most predominant taxa. The abundance of *Arcella* in the sediment core of RBP could be due to their ability to form new shells, where the new shell is filled by the organism (exuviation) or cast off empty (Pchelin, 2011). *Arcella* communities are more typically associated with standing water (Glime, 2013). It was noted by Patterson et al., (2002) that strains of *Centropyxis* and *Arcella* (in particular *Centropyxis aculeate* and *Arcella vulgaris*) dominate marginal environments where the majority of other testate amoebae are not found. This characteristic is evident in the RBP testate amoebae assemblage. The competition and ability of *Centropyxis* to cope under stressed conditions (Patterson et al., 2002; Holcova, 2007) are visible at 5 cm where no other testate amoebae occurred. This assemblage may represent a wetter environment, but attempting to match it to a date with certainty via the rainfall record was unsuccessful. Similar to the C/N ratios of the SNP, the RBP C/N ratio was 23.46 at 5 cm also did not indicate particularly wet periods.

One of the most recent studies on testate amoebae by Swindles et al., (2014) suggested that a large proportion of variance between testate amoebae data remained unexplained possibly due to inter-connectivity between unmeasured environmental and geochemical factors such as water, nutrient status, light and temperature. It has also been suggested that short term environmental variability may be an important factor in the community dynamics of testate amoebae (Woodland et al., 1998; Swindles et al., 2014). The distribution and occurrence of the other testate amoebae in the SNP and RBP sediment cores do not have any similarities. Corbet (1973) highlighted that there are many different factors such as, size, test construction, microclimate, temperature, moisture, pH, distribution patterns, light, oxygen and food, that affect the occurrence of testate amoebae species. The very low percentage abundance and stochastic distribution of *Assulina, Bullinaria,* Trignonopyxidae. *Euglypha, Nebela, Hyalosphenia* in the SNP and *Heleopera,* Trignonopyxidae*, Trinema, Apogromia,*

Nebela and *Difflugia* in the RBP, did not indicate to any other specific wet or dry conditions.

The testate amoebae assemblages of *Arcella*, *Centropyxis* and *Pyxidicula operculata* of the SNP and RBP indicated wet periods within the sediment cores. These wet periods and the known associations of testate amoebae with pollen taxa could be used in conjunction with the pollen assemblages to support the implication of dates to sections of the SNP and RBP sediment cores.

Figure 28: Testate amoebae record of the SNP and RBP (**A** and **B** respectively) with red lines highlighting the wetter conditions within the SWB sediment cores. The C/N ratios for SNP and RBP (**C** and **E** respectively) have a red circle marking on the corresponding depth at which the wet testate amoebae signal was identified. **D**: Total rainfall per year (mm) (Met Office, 2015) with the four wettest years (1997, 2005, 2010 and 2012) circled in red. The dashed red lines from each sediment core (**A** and **B)** to the rainfall graph (**D**) represent the possible year that depth could be.

7.2.4 Pollen and testate amoebae as indicators for wet periods and possible flood events

In the SNP the presence of *Lycospora* and peak in *Lemna minor* are suggested to be indicative of very wet environmental conditions, possibly flooding, which could be correlated with the rainfall record (Figure 29). It was assumed that *Lycospora* had entered the SWB's sediment from the exposed infill material in the constructed ponds (see reworking section) when the SWBs were flooded (Jeffries, 2008). *Lycospora* peaked at 17 cm, 14-12 cm, and 6 cm followed by high proportions of *Lemna minor* at 16 cm, 10-7 cm and 5 cm. When the flood event occurred *Lycospora* would enter the SNP and settle to the bottom of the SNP while it was full of water. *Lemna minor* would then grow and the pollen grains would be transported through the water column to settle on the sediment. *Lemna minor* lives in wet communities and requires open water surfaces to exist (Cox, 1985). The C/N ratios at each depth where *Lemna minor* occurred suggested terrestrial input for the organic matter source as the ratios ranged between 22.59 and 23.35. This does not discount the possibility that these were flooded years, as the *Lycospora* in-wash events would transport terrestrial matter.

The indication that these depths were representative of a wet environment comes partly from the correlation with the rainfall records and is supported by results from the testate amoebae record but there is no definitive match. The presence of *Centropyxis* at 13 cm and 6 cm were suggestive of very wet environments (see section 7.2.2) coinciding with two of the three *Lycospora* peaks. The four peaks in rainfall occurred in 1997, 2005, 2010 and 2012 (Figure 28 D). The previous weather events explained the years of 2005 and 2012 experienced particularly heavy rain and flooding in the North East of England, which is also reflected in the average annual rainfall (Met Office, 2015). It is suggested that the first peak in rainfall in 1997 is reflected in the SNP sediment core by the presence of *Lemna minor*, *Lycospora* and *Centropyxis* between 14-12 cm. The second peak however could not be determined to be any of the three dates (2005, 2010 or 2012). The *Lycospora* peak at 17 cm was suggested to be reflective of the bioturbation reworking of sediments during the establishment of the SWB since the other SWBs also illustrated this *Lycospora* signal at the base of the sediment cores.
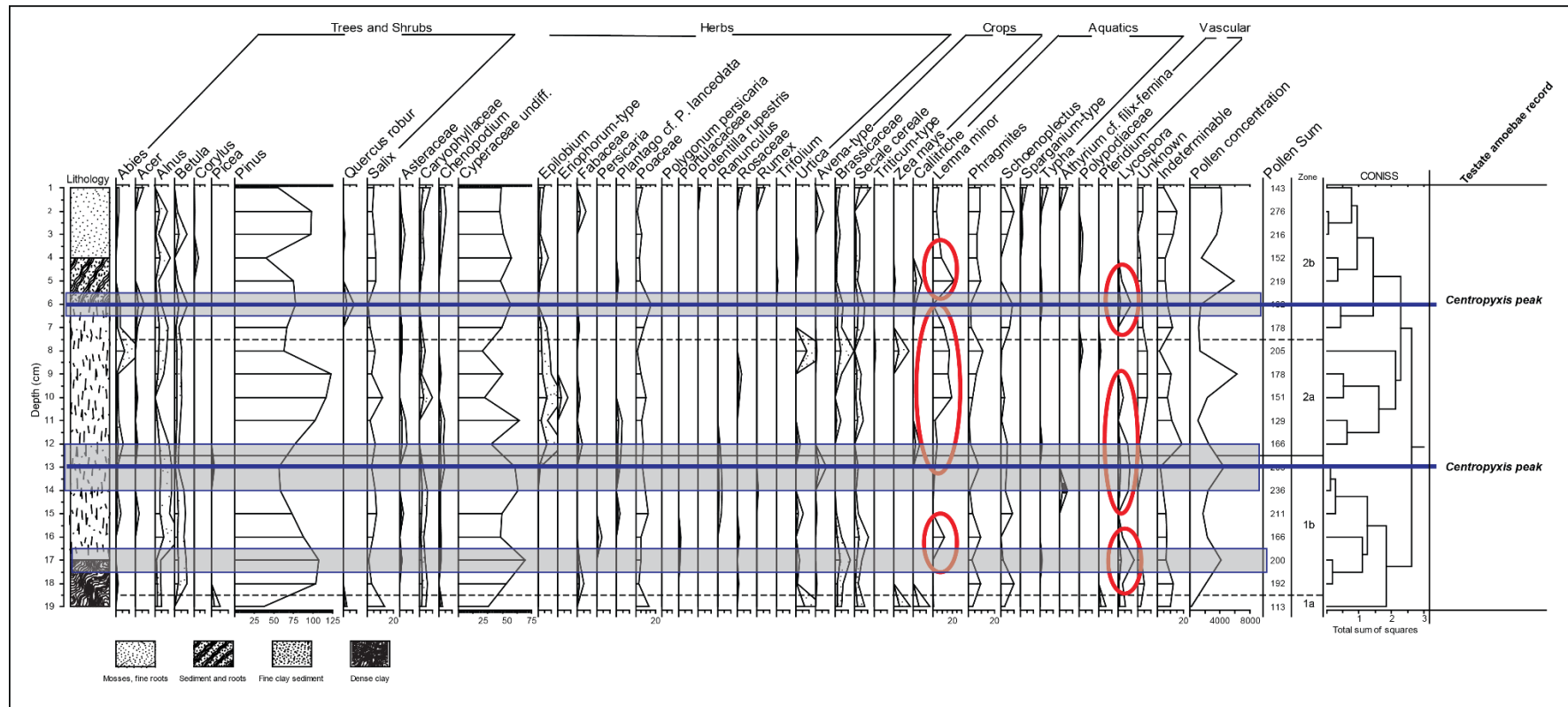
Figure 29: SNP pollen percentage diagram illustrating the *Lycospora* and *Lemna minor* peaks with red circles. The sections highlighted in grey are the suggested wet environmental conditions (indicated by *Lycospora*) which illustrate the subsequent rise in *Lemna minor*. The first at 17 cm was during SWB establishment and bioturbation reworking of sediments. The second two *Lycospora* peaks at 13 cm and 6 cm correlated with the peaks in *Centropyxis* (marked by blue lines) and high rainfall years, suggested to be 1997 and 2005 respectively.

7.2.5 Vegetation monitoring in the sediment pollen record

This section will discuss the matches between the sedimentary pollen record of the SNP and the vegetation monitoring record. Table 4 presents the depths in the SNP sediment core where the pollen assemblage potentially reflected part of the vegetation record (Jeffries, 2008) and observational record (Jeffries, unpublished data). The RBP and P8 pollen assemblages did not have any pollen taxa occurrence which could be matched with the vegetation records.

There were no similarities between the PCA results of the vegetation monitoring record (Jeffries, 2008) and pollen records (Figure 26, A, B, C, & D) but fluctuations in the SNP pollen assemblage (Figure 18) could be identified (Table 4). The vegetation monitoring record and observational data column briefly explain the most significant fluctuations in plant occurrences with the corresponding date for that year (Table 4) which will be discussed in the following sections. These were entered on the same row, establishing potential dates for that section of the sediment core. These pollen-vegetation matches were supported by justifications of individual pollen characteristics, detailed in the modern pollen section (7.1).

The first pollen-vegetation match was identified at 15 cm in the SNP pollen assemblage with the presence of Poaceae undiff. and *Ranunculus*, which broadly matched with the occurrence of *Agrostis/Alopecurus* and *Ranunculus lingua* in the vegetation monitoring record (1997). *Agrostis/Alopecurus* are two different genera in the Poaceae family. The results from the modern pollen and vegetation mapping (*Ranunculus* mapped close to the site of deposition) coupled with Ranunculaceae growing low to the ground (Swan, 1993) and pollen dispersal being local indicates that this pollen signal likely reflects 1997.

Not only individual peaks but also short intervals could be matched between the pollen assemblage and vegetation monitoring in the SNP sediment core. Between 9 cm and 7 cm, Poaceae undiff. showed one of its lowest percentages in the whole sediment core. This was also evident in the vegetation record from 1999 and 2001 shown by low abundance of *Agrostis/Alopecurus* and a peak of *Chara vulgaris* in 2000 and increase in *Ranunculus aquatilis* and *Leptodictyum riparium* in 2001 as the latter three all inhabit aquatic environments (Swan, 1993). The rainfall record shows an increase in the average annual rainfall between

1999 (704.0 mm) and 2001 (770.6 mm). Throughout this time period, Poaceae, indicative of a drier environment (Tweddle et al., 2005) decreased in the vegetation record. The increases of taxa indicative of a wetter environment between 1999 and 2001 in the vegetation record and the increase in rainfall during the same time period suggests wetter conditions prevailed during these years. Therefore, the results from the pollen assemblage, vegetation and rainfall record suggests that 9-7 cm reflects 1999-2000.

Another match between the presence of *Agrostis/Alopecurus* in the vegetation and Poaceae undiff. pollen was identified between 2002 and 2003 at 7-6 cm in the sediment core, where both increased in abundance. Similar to 1997 at 15 cm, where *Agrostis/Alopecurus* peaked and *Ranunculus aquatilis* decreased, this also occurred between 2002 and 2003 and was reflected in the sediment core at 7-6 cm. In 2005 this was shown again, as *Agrostis/Alopecurus* decreased and *Ranunculus aquatilis* peaked in the vegetation record. A similar pollen assemblage was identified at 6-5 cm as shown by slightly lower proportions of Poaceae undiff..

Lastly, the abundance of *Epilobium* (4-0 cm) could be linked with the observational data (Table 4). *Epilobium* was known to be in high abundance around the SNP from 2009 (Jeffries, unpublished data). However, this observational data was not methodically collected but gives information on changes and events observed by the field scientist, such as recent *Epilobium* and *Phragmites* occurrence in the field. *Phragmites* was known to have entered the RBP in the later years of the pond's life but an indication to which year were not provided. The *Phragmites* pollen signal in the SNP pollen assemblage was in constant abundance from 4 cm to the top of the core, similar to *Epilobium*, confirming these depths were reflecting the later years. Knowing that the vegetation record is reflected in the SNP pollen assemblage, this can be used to match the pollen assemblages of the RBP and P8 sediment cores, relative to each other (discussed in section 7.3).

Given that these pollen vegetation matches do not indicate substantial similarities between the two records, it can be concluded that the SNP pollen record does partially reflect the vegetation record but cannot singularly be used for substantial dating.

Table 4: The vegetation monitoring record (Jeffries, 2008) and observational data (Jeffries, unpublished data), which describes the vegetation composition during that year is presented in the two left columns. The two right columns show the SNP pollen record and depth (cm) where there is a possibility that the pollen taxa in the sediment record reflect the vegetation monitoring record. The greyed-out cells do not have any possible matching information between the vegetation and pollen record.

Date	Vegetation monitoring (Jeffries, 2008) and observational data (Jeffries, unpublished data)	Depth (cm)	SNP pollen record
2013	Observational data of *Epilobium* in high abundance around the SNP SWB (Jeffries, unpublished data).		
2012	*Eleocharis palustris, Carex glauca* and *Carex ortubae* present simultaneously. *Epilobium palustre* present. *Schoenoplectus lacustris* and Filamentous algae present.		
2011	Vegetation monitoring does not record *Epilobium palustre* and there is a decrease in *Eleocharis palustris*. Small peak in *Leptodictyum riparium*.		*Epilobium* continues to be present from 4 cm to the top of the core.
2010	Observational data of *Epilobium palustre* in high abundance around the SNP SWB (Jeffries, unpublished data) and also recorded in the vegetation record. *Eleocharis palustris* present with a small increase in *Carex glauca*.		
2009	Observational data of *Epilobium* in high abundance around the SNP SWB (Jeffries, unpublished data) and also present in the vegetation dataset. Small increase in *Eleocharis palustris* and *Carex glauca*.		
2008	Slight dip in *Agrostis/Alopecurus* and *Eleocharis palustris*. Increase in *Leptodictyum riparium*.		
2007	Slight increase in *Agrostis/Alopecurus*.		
2006	Slight increase in *Agrostis/Alopecurus* and presence of *Carex glauca*. Decrease in *Eleocharis palustris* and small peak in *Chara vulgaris* and *Glyceria fluitans*.		
2005	Decrease in *Agrostis/Alopecurus*, peak in *Eleocharis palustris* and *Ranunculus aquatilis* peaks at its highest. Increasing *Schoenoplectus lacustris*.	6 - 5	Slight decrease in Poaceae undiff.. *Lemna minor* and *Phragmites* both have high presence at this depth.
2004	Decreasing *Agrostis/Alopecurus*, Peak in *Ranunculus aquatilis*.		
2003	High presence of *Agrostis/Alopecurus, Eleocharis palustris*. A decreased presence of *Ranunculus aquatilis*.	7 - 6	Increase in Poaceae undiff..

2002	Increase in *Agrostis/Alopecurus*, presence of *Carex glauca*. No *Chara vulgaris.*		
2001	Increase in *Leptodictyum riparium* and *Ranunculus aquatilis.* Decrease in *Chara vulgaris.*	9 -7	Poaceae undiff. very low presence, one of the lowest in whole sediment core.
2000	*Chara vulgaris* peaks at its highest in all the years. *Agrostis/Alopecurus* very low presence.		
1999	Beginning of *Eleocharis palustris* which continues to the top of the core. *Agrostis/Alopecurus* very low presence.		
1998	*Chara vulgaris* peaks at its second highest. Lowest amount of moss *(Leptodictyum riparium)* over all years.		
1997	*Agrostis/Alopecurus,* Compositae seedling, *Pulicaria dysenterica, Rumex crispus* and *Ranunculus lingua* peak.	15	Poaceae undiff. second highest presence in whole core. *Ranunculus* present.
1996	Pond just created. *Callitriche's* only presence. *Chara vulgaris* and *Ranunculus aquatilis* presence.		

7.2.6 Crop record identified in the sediment pollen record

The following section discusses the identification of crop records (Table 3) in the SNP pollen assemblage, which is illustrated in Figure 30. The pollen signal of different SWB types within the same field show that despite the SWBs being near the same vegetation, some pollen taxa are recorded differently. The list of crops which were sourced from the farmer owning the fields surrounding the study site (Table 3), were compared with the crops groups in all of the SWB pollen assemblages, but only four possible similarities were identified in the SNP pollen assemblage.

In 2000 and 2001 *Zea mays* and *Avena sativa* in 2010 are known to have been growing nearby the site (<1000 m) but this pollen record was only visible in the SNP and no other SWB studied. These large grains' dispersal ability is known to be poor and the chance of long distance transport is very low (Tweddle et al., 2005) (see section 7.1.) and partly explains why these grains were only recorded in the SNP pollen assemblage. Another reason for this pollen signal only being present in the SNP could be due to the type and size of the SWB. The constructed pond P8 is 1m^2 in size, which is a limited area to catch pollen grains therefore ponds of that size are estimated to record less pollen taxa than larger lakes, since their PSA is lower than that of larger lakes (Sugita, 1994). Coupled with the poor dispersal ability of the crop grains, the chances of dispersal into that pond are very low.

In 2001 *Brassica rapa* and *Zea mays* was planted in the fields nearby. In the SNP a peak in Brassicaceae and *Zea mays* is observed at 8 cm, suggesting that this layer corresponds to the year 2001 (Figure 30). This is supported by the presence of *Secale cereale* at 11-9 cm and 6 cm which was recorded in 2002 and 1998. However, there were some uncertainties involved as the match in pollen record to *Brassica rapa* was made with Brassicaceae undiff. During pollen identification, especially with the SNP sediment samples, a number of Brassicaceae grains were damaged on the exine which limited identification below family level. The corrosion of pollen grains might have also been an artefact of oxidation or reworking at times when the sediment was not fully submerged in water (e.g. during a dry year). The timescale of this deterioration of pollen grains in the sediment through oxidation is unknown and could be 1-2 years of exposure or several tens of years (Lowe, 1982; Bunting, 2008). This interpretation of *Brassica*

rapa and *Zea mays* in 2001 being represented in the SNP at 8 cm was substantiated by the presence of *Secale cereale* above (6 cm) and below (11-9 cm) the pollen signal can probably be correlated to 2002 and 1998, respectively, in the crop record (Table 3). In 1996, the date of pond construction, there was *Brassica rapa* recorded in the crop record. At the base of the SNP sediment core, there was Brassicaceae present between 19-16 cm which was the only presence before the Brassicaeceae peak at 8 cm to 2001.

The four years 1996, 1998, 2001 and 2002, that have been assigned to pollen assemblages in the SNP sediment core match the years from the comparison of vegetation monitoring record and pollen assemblage. The first match at 11-9 cm represents 1998, and was in-between two identified vegetation monitoring records and pollen assemblage matches at 15 cm (1997) and 9-7 cm (1999-2001). The years 1999-2000 were identified by low proportions of Poaceae in both the pollen (9-7 cm) and vegetation record (Table 4). Therefore, the presence of Brassicaceae undiff. and *Zea mays* pollen in the pollen assemblage and crop record of *Brassica rapa* and *Zea mays* at 1998 fits in with the implication that 9-7 cm represents 1999-2001. The final date implied from the pollen assemblage at 6 cm reflecting the crop record in 2002 did match the inferred date from the vegetation and pollen record (7-6 cm 2002-2003).
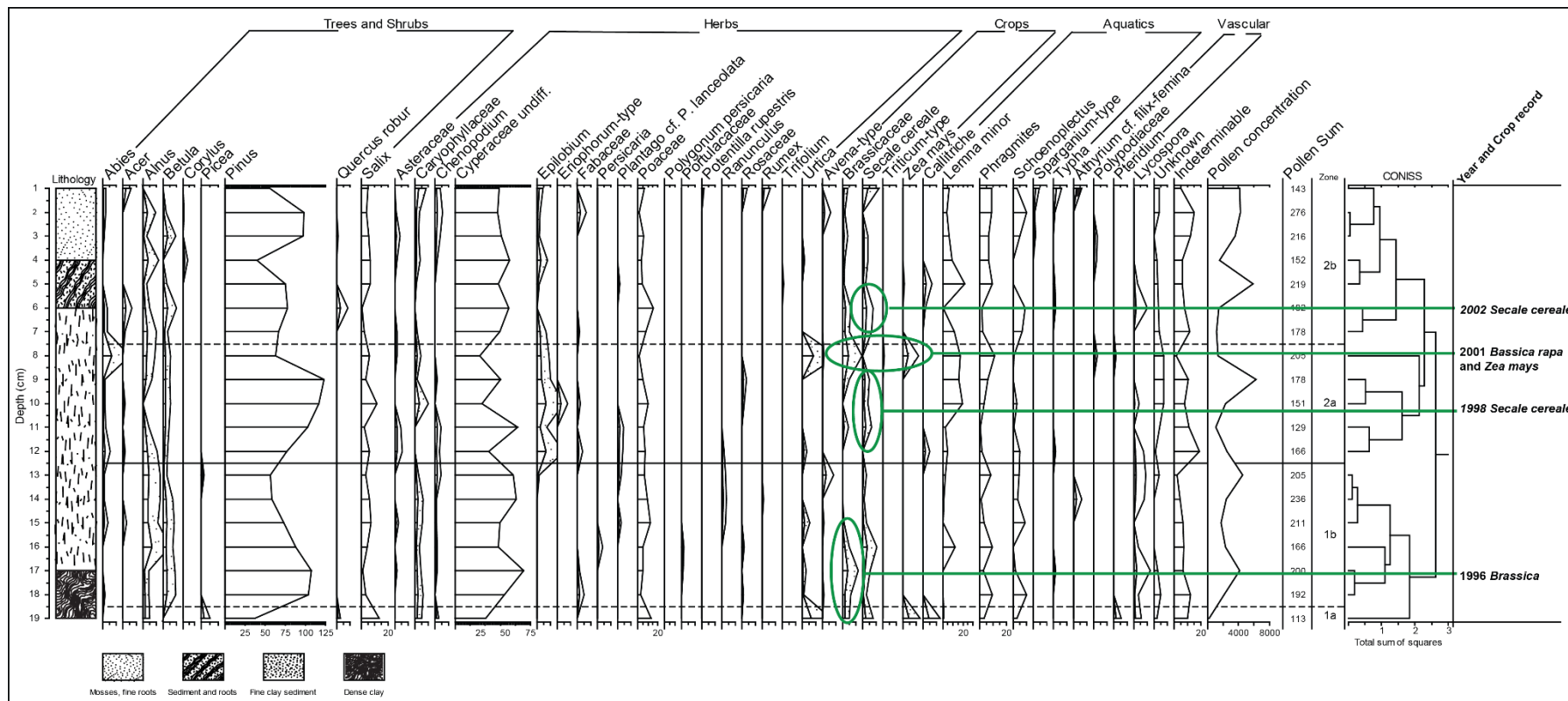
Figure 30: SNP percentage pollen diagram illustrated with green circles around the pollen taxa in the crops group, which could potentially reflect the crop and year on the right-hand side of the diagram.

7.3 Comparison of pollen records between all SWBs for relative dating

The comparisons between the pollen records of the different SWBs show that there were some similarities in the occurrence of taxa which were used for relative dating. Figure 31 shows three pollen percentage diagrams from SNP, RBP and P8, which illustrate similarities in *Pinus, Epilobium, Lycospora* and *Phragmites*. P29 could not be used for comparison as the sampling resolution of 1 cm for 6 cm of sediment is not high enough. Figure 31 illustrates the four similarities identified between the pollen assemblages of the SNP, RBP and P8. There was a high amount of reworking in the constructed ponds from annual sampling by Jeffries (2008) and bioturbation (section 7.2.2) which could be seen in the pollen assemblage of P8 but still illustrated some similarities with the SNP and RBP pollen assemblages (Figure 31).

There were similar fluctuations in the pollen percentages of *Pinus* in all of the SWBs. *Pinus* pollen grains are large, easily transported over long distances due to their grain morphology, are highly abundant (Zanni & Ravazzi, 2006), and therefore have a higher opportunity to enter the sedimentary record. High pollen percentages of Cyperaceae undiff. were identified at the same depths as the peaks in *Pinus* pollen but due to their consistent presence in all SWB sediment cores, no specific comparable peaks could be identified. Cyperaceae is one of the largest flowering plant families (Wichelen et al., 1999), occurring widespread in the margin of ponds and wet lowlands (Swan, 1993) and are an indicator of wet conditions (Anupama et al., 2014). They appeared to enter the pollen record successfully and as prolific as *Pinus,* explaining why these two pollen signals were comparable between SWB types. Cyperaceae pollen grains were also well represented in SWB surface sediment samples which were close to the vegetation mapping locations but not registered in the mapping locations. Therefore, the source of Cyperaceae through the whole sediment profiles of the SWBs must be originating from the same source which was not covered during mapping.

Similarities in *Epilobium* were identified in the SNP and RBP pollen assemblages but did not occur in P8. The dispersal ability of *Epilobium*, (section 7.1) and PSA of P8 being small explains why it did not enter the sedimentary record. *Epilobium*

occurred in the SNP 12-8 cm and in the RBP 7-5.5 cm which were near the centre of both sediment cores. A *Pinus* peak in the centre of all SWB pollen assemblages coincided with the *Epilobium* peak in the SNP and RBP demonstrating the ability to relatively date the sediment cores. Inferring an approximate date to the *Epilobium* and *Pinus* peaks in the SNP, RBP and P8 sediment cores could not be concluded from the observational data by Jeffries (unpublished data) because *Epilobium* was recorded in high abundance during 2009, 2010 and 2013.

The presence of *Lycospora* (see section 7.2.2) can be identified at the base of the SNP (19-17 cm), RBP (9.5-7 cm) and P8 (5.5-3.5 cm), which is highly likely to be due to reworking of the sediments during the early stages of their formation.

The *Phragmites* were known to have entered the RBP in the later years of the SWB's life by field observations (Jeffries, unpublished data), but an exact date is not known. The increased abundance of *Phragmites* pollen in the RBP pollen assemblage (3-0.5 cm) suggests that this signal is from the *Phragmites* growing in the RBP, which is also identified in the modern pollen samples. The SNP and P8 show an increased presence of *Phragmites* at the top of the core (5-1 cm and 3-0.5 cm respectively) which also suggests that this pollen signal was being contributed to from the RBP's *Phragmites*. The pollen signal of *Lemna minor* occurred at the beginning of this *Phragmites* peak, which suggested to reflect three possible years of 2005, 2010 or 2012 (see section 7.2.4).

The different SWBs' pollen assemblages from the SNP, RBP and P8 had illustrated that relative dating is possible. The blue lines indicated on Figure 31 A correspond to the absolute dates obtained for the SNP pollen assemblages. Utilising these dates in relation to the relative matches of the pollen records between SWBs, can approximate ages for the RBP and P8. The presence of *Phragmites* at the top of the sediment cores was suggested to be 2002/2005. Derived from the testate amoebae assemblage for the RBP, 5 cm is suggested to be either 1997 or 2005; relative dating using the crop record indicates that 5 cm in the RBP is more reflective of 2005 than 1997. The matches between pollen and vegetation monitoring, crop record and pollen, testate amoebae, rainfall and *Lycospora*/*Lemna minor* indicate that 6-5 cm was reflective of 2002 or 2005. However, the inability to correlate the testate amoebae records and

Lycospora/Lemna minor peaks with specific years of high rainfall, especially 2005, 2010 or 2012, concludes that a definitive date cannot be inferred. The presence of *Lycospora* at the base of the RBP and P8 sediment cores correlate to 1997 in the SNP. *Epilobium* presence in the RBP at 7-5.5 cm suggests a correlation to 1998. From the *Pinus* peaks in all three SWBs it can be inferred that 5 cm in P8 corresponds to 1998.

1: *Pinus* peaks between SNP, RBP and P8 at similar depth to *Epilobium*

2: *Epilobium* peaks between SNP and RBP but not in P8

3: *Lycospora* present at the base of SNP, RBP and P8-possible bioturbation

4: *Phragmites* and *Lemna minor* similar presence between SNP, RBP and P8
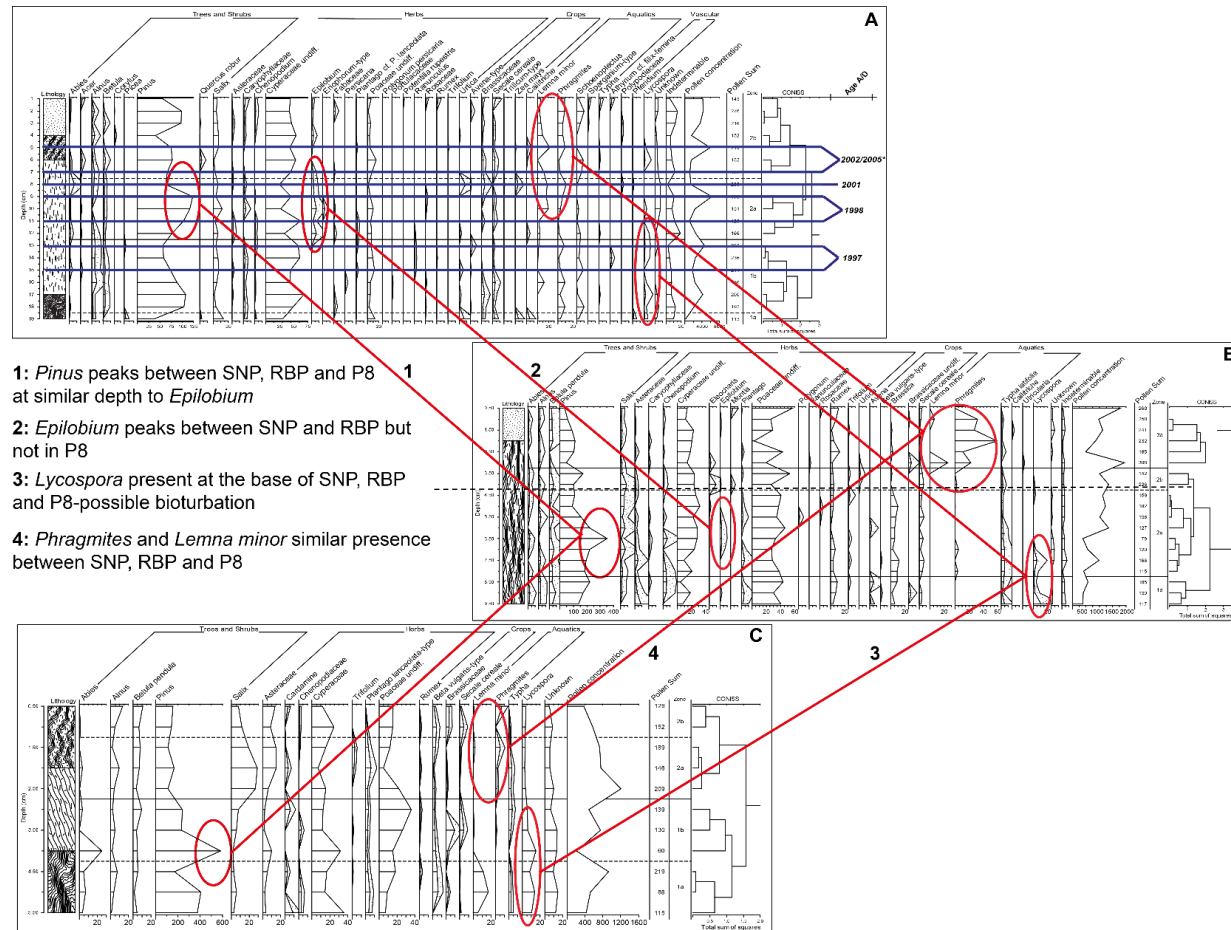
Figure 31: **A**: SNP Pollen assemblage with the inferred absolute dates, indicated with the blue lines, **B**: RBP Pollen assemblage and **C**: P8 pollen assemblage. Points **1-4** refer to the pollen taxa with a similar occurrence (circled in red) in each SWB pollen assemblage and are connected by red lines.

Discussion

7.4 Concluding argument for dating the SNP

The pollen and testate amoebae assemblages from the SNP sediment core matched with some results from the vegetation monitoring, crop and rainfall records. The arguments supporting each of these individual interpretations collectively support the assignment of certain sections of the sediment core to specific years.

Table 5 presents the inferred dates for the sections of the SNP sediment core. It is suggested with moderate certainty that the reworking within these SWBs are responsible for the pollen and testate amoebae signal to be mixed over a few centimetres. Wet periods derived from the testate amoebae depths in the SNP and RBP could be matched to the rainfall record but the C/N ratios did not substantially indicate wetter environmental conditions. However, using the habitat information for testate amoebae together with the pollen record, allows the identification of wetter conditions. The two significantly wet periods in 2010 and 2012 which could not be identified could be due to two main factors, Firstly, the very recent age of the sediment core and secondly, that the palynological signal was not recorded in the sedimentary record as a consequence of reworking.

Table 5: Table illustrating the inferred dates for sections of the SNP sediment core. The depth (cm) shown in relation to the date inferred from each dataset which was supported by the other records. **Veg-Pol**: Vegetation monitoring record compared with the pollen assemblage. **Crop-Pol**: The crop record compared with the pollen assemblage. **TA-RF**: Testate amoeba compared with the rainfall and **Lyc-Lem** is the *Lycospora* and *Lemna minor* indicating high rainfall. ** Refers to the remaining two dates which were unaccounted for and therefore that inferred date was more uncertain. **Age A/D** is the concluding ages inferred for depths of the SNP sediment core.

Depth (cm)	Veg-Pol	Crop-Pol	TA-RF	Lyc-Lem	Age/AD
0					
1					
2					
3					
4					
5					
6	2005	2002	2005 **	2005 **	**2002-2005**
7					
8	1999-2001	2001			**2001**
9					
10		1998			**1998**
11					
12					
13			1997	1997	
14					**1997**
15	1997				
16					
17		1996			**1996**
18					
19					

7.5 Palynology as a tool for reconstructing carbon burial rates

7.5.1 Estimations of the sedimentation rate for the SNP

The sedimentation rate of a lake or pond is important factor to know when calculating the store of carbon, as an uneven input of sediment and reworking can affect burial (Mackay et al., 2012). Figure 32 illustrates an increase in sedimentation over the past 20 years, where five possible age points were identified for the SNP, 1996, 1997, 1998, 2001 and 2002-2005, the latter with a higher uncertainty. The identified reworking in the SNP pollen and testate amoebae assemblages resulted in slightly different depths for what was acknowledged to be the same time period (1997 and 1998). The uncertainties surrounding each date inferred for the SNP must be taken into account when attempting to use the sedimentation rates for carbon sequestration estimations. The accuracy of dating the RBP and P8 were limited to relative dating and could not be used to estimate sedimentation rates.

The calculation of carbon burial rates is affected by compaction during sediment sampling (Pitmann et al., 2013). The sampling method used to extract the sediment cores in this study accounted for compaction. Consequently, the sampling method and the proxies used to obtain dates was a successful combination to work as a tool in obtaining dates for short sub recent SWB sediment cores.

The estimations of the sedimentation rate in these SWBs are not affected by the typical problems encountered for larger lakes such as sediment focusing (fine-grained sediments settling in deeper sections of the lake) or wind-induced currents which are major changing factors to carbon burial rate calculations (Mackay et al., 2014). The rate of sediment accumulation and the subsequent calculation of carbon burial within that sediment can affect the estimations for the whole SWB. Therefore, these inferred dates achieved for the SNP and the estimations of the sedimentation rate could be used to estimate carbon burial rates in the SWB but must be used as estimations only, since the chronology is not entirely robust.
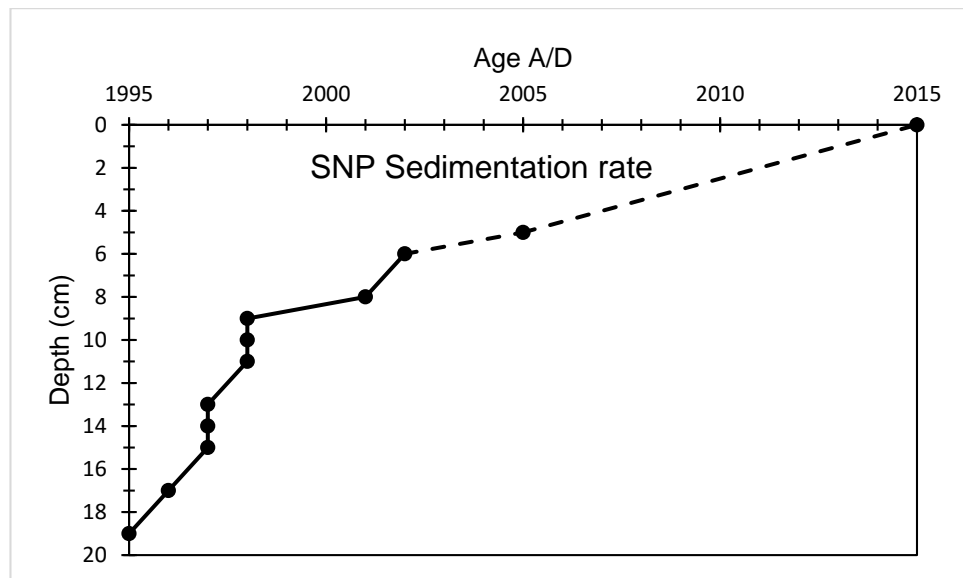
Figure 32: Estimations of the sedimentation rate for the SNP SWB sediment core based on the absolute dating interpretations inferred from results of the pollen, testate amoebae, vegetation, crop and rainfall records.

8 Conclusions

This thesis has demonstrated an application of high resolution pollen analysis on short sub-recent (<20 years) SWB sediment cores. The main findings are:

- Success in dating the SNP SWB to an arguable level of certainty for each date inferred which were 1996 at 17 cm, 1997 at 15-13 cm, 1998 at 11-9 cm, 2001 at 8 cm, and 2002-2005 at 6-5 cm.

- It is evident from the modern pollen surface samples and vegetation mapping that the location of vegetation to the pollen sink is important and the type of vegetation (low growing vegetation) and pollen grain morphology affects dispersal and pollen representation.

- The vegetation monitoring record did not consistently identify wet or dry periods, as a possible consequence of data collection, and there were no similarities identified between the vegetation record and pollen assemblages of the RBP, P8 or P29 SWB sediment pollen record.

- The SNP pollen record did partially reflect the vegetation record and the inferred dates correlated with the testate amoebae, crop and rainfall records.

- The comparison of the SNP pollen assemblage with the crop record revealed four possible dates 1996, 1998, 2001 and 2002 at 17 cm, 11-9 cm, 8 cm and 6 cm respectively. These dates correlated with the inferred dates from the comparison between the vegetation monitoring record and pollen assemblage, testate amoebae and rainfall record and *Lycospora-Lemna minor* reworking observation.

- Wetter environmental conditions were inferred due to the testate amoebae assemblages in the SNP and RBP, which also correlated, within 1 cm of sediment, with the pollen signal of *Lycospora* and *Lemna minor*.

- The interpreted reworking of sediment in the SNP, indicated by *Lycospora*, and subsequent rise in *Lemna minor* pollen, and *Centropyxis* testate amoebae signal correlated with the rainfall record. It was suggested 13 cm reflected 1997 but a definitive match at 6 cm to either 2005, 2010 and 2012 could not be made.

- The C/N ratios suggested terrestrial input during peaks in *Lemna minor* supported the inference of wetter environmental conditions/possible flooded periods

- The similarities between the SWBs revealed that relative dating for the RBP and P8 could be achieved by using the dates obtained for the SNP sediment core.

- The 1m^2 constructed SWBs were not suitable for the calculation of sedimentation rates, and consequently carbon burial rates as there is a minimum size required.

- The estimations of the sedimentation rate in the SNP could be used to estimate carbon burial rates in the SWB but must be used as estimations only, since the chronology is not entirely robust.

- The results from this research has shown the ability to obtain dates for recent sediments in SWBs which can be applied to other SWBs around the world, and can be used to investigate carbon cycling and asses their impact on the carbon budget.

8.1 Further research

It is suggested that investigations using a similar methodological approach to obtain dates as used in this study, should not use sediment cores <19 cm from SWBs which have a high amount of vegetation growing within the pond or be the same size or smaller than 1m^2. The effects of pollen grain morphology, dispersal and the size and type of SWB limits the use of palynology for the reconstruction of absolute dates. It is proposed that future research focuses on coring short sub-recent (<20 years) sediment cores in SWBs similar to the SNP using a similar methodology, to test if dates can be reconstructed in another SWB.

9 References

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