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EXAMINING THE RELATIONSHIPS BETWEEN HOLOCENE CLIMATE CHANGE, HYDROLOGY, AND HUMAN SOCIETY IN IRELAND

PhD

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Dedicated in loving memory to Oma and to Raymond.

Declaration:

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Philip Stastney

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Abstract

This thesis explores human-environment interactions during the Mid-Late Holocene in raised bogs in central Ireland. The raised bogs of central Ireland are widely-recognised for their considerable palaeoenvironmental and archaeological resources: research over the past few decades has established the potential for such sites to preserve sensitive records of Holocene climatic variability expressed as changes in bog surface wetness (BSW); meanwhile archaeological investigations over the past century have uncovered hundreds of peatland archaeological features dating from the Neolithic through to the Post-Medieval period including wooden trackways, platforms, and deposits of high-status metalwork.

Previous studies have attempted to explore the relationship between records of past environmental change and the occurrence of peatland archaeological sites reaching varying conclusions. More recently, environmentally-deterministic models of human-environment interaction in Irish raised bogs at the regional scale have been explicitly tested leading to the conclusion that there is no relationship between BSW and past human activity. These relationships are examined in more detail on a site-by-site basis in this thesis. To that end, testate amoebae-derived BSW records from nine milled former raised bogs in central Ireland were produced from sites with known and dated archaeological records.

Relationships between BSW records and environmental conditions within the study area were explored through both the development of a new central Ireland testate amoebae transfer function and through comparisons between recent BSW records and instrumental weather data.

Compilation of BSW records from the nine fossil study sites show evidence both for climate forcing, particularly during 3200-2400 cal BP, as well as considerable inter-site variability. Considerable inter-site variability was also evident in the archaeological records of the same sites.

Whilst comparisons between BSW and archaeological records do not show a consistent linear relationship, examination of records on a site-by-site basis were shown to reveal interpretatively important contingent relationships. It is concluded therefore, that future research on human-environment interactions should focus on individual sites and should utilise theoretical approaches from the humanities in order to avoid the twin pitfalls of masking important local patterns of change, and of environmental determinism.

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Chapter 1: Introduction

Wetlands are of particular significance to many societies, both past and present (Strang 2008). The special ritual significance of wet landscape components to many societies, particularly those in later prehistory – the Bronze and Iron Ages, has long been recognised ((Coles and Coles 1989; Bradley 1998, 2000; O'Sullivan 2007a; Van de Noort and O'Sullivan 2007; Yates and Bradley 2010)). Until the relatively recent development of more systematic archaeological research in Ireland, spectacular ritual deposits in wetlands, of both metalwork and human remains, have, along with large field monuments, dominated our understanding of large sections of the human past. Indeed, the popular perception of Late Bronze Age and Iron Age archaeology in Ireland is still shaped by finds from the wetlands, peat bogs in particular: for example, the Dowris Hoard from the former, and Old Croghan Man and the Corlea Trackway from the latter. It is also evident that the wetland archaeological record need not necessarily be confined to ritual activities or expressions of power and status: systematic archaeological investigations ahead of industrial exploitation of peatlands have revealed thousands of trackways, brushwood paths, platforms and even occupation sites (Baillie and Brown 1996; Brindley and Lanting 1998; Brunning and McDermott 2013). One notable study has, with some justification, termed the peatland a 'vernacular landscape' (Gowen *et al* 2005). That peatlands may be considered to be vernacular in character is not surprising given their ubiquity in the Irish landscape; before large-scale drainage and reclamation, the extent of the peatlands would have been greater than that of today, and thus they would have been even more prominent in the landscape (Hammond 1981; Connolly and Holden 2009).

Today, the peatlands of Ireland have special significance not only for their economic uses and their heritage value, but also for their ecological value in providing habitats for a unique flora and fauna. In particular, legal obligations as a member of the European Union have prompted the creation of The Peatlands Council in April 2011 (National Parks and Wildlife Services 2011a). Concern for the conservation status of peatlands, raised bogs in particular, is not only limited to the direct effects of human activity (i.e. cutting and draining), but also to the effects of incipient climate change. The potential sensitivity of peatlands to present and future climate change is increasingly recognised (Dise 2009; Frolking *et al* 2011; Ferrat 2013) at least in part due to the existence of the body of 20th century research in the field of Quaternary science which established the role that ombrotrophic peatlands have as archives of past climatic variability (Aaby 1976; Barber 1981). Such work is integral to the body of research that has established the framework for recent climate variability during the Holocene at the global or hemispheric scale (e.g. Mayewski *et al* 2004). Methodological developments in peatland palaeoenvironmental research (Chambers *et al* 2012) allow for finer-resolution records to be developed, examining environmental change at a human scale. Furthermore, the close association of these archives of environmental change with records of human activity (i.e. the archaeological record) allow the network of relationships between climate, environment and human societies to be studied; in this area, environmental archaeology may be able to contribute meaningfully to current debates on the effects of present and future climate change (Van de Noort 2011).

Any study of the effects of environmental change in wetlands on past human society should begin with a consideration of the meaning and function of wetlands to those societies. Defining wetlands, or 'waterscapes' (Yates and Bradley 2010), as either ritual or vernacular, central or marginal, or any combination of these, is not an issue of semantics, nor is it irrelevant even to the most functional processualist approaches. Indeed, environmental functionalist and post-processual theoretical strands need not be in opposition in 'climate change archaeology' (Van de Noort 2011). Relatively minor changes in ritual landscapes may have far-reaching cultural implications; environmental change in vernacular landscapes can have profound and immediate effects on economic systems – which are amplified in socially central areas; and, the effects and perceptions of change in marginal regions may have implications for networks of communication and interaction. These processes are themselves interconnected. Human agency and environmental agency are contingent factors in all these processes. The interconnectedness of the natural and the human is underlined by those that challenge the viability of their separation, and who argue that they are mutually constituted (Head 2000). Scientific methods allow the reconstruction of particular environmental parameters of a site or region, but without considering the social and cultural parameters of wetlands, interpretations of human / environment interactions will be flawed and tend towards being hopelessly broad, simplistic or deterministic. It is, therefore, the overarching aim of this thesis to contribute to the reconstruction of both of these parameters, and thus to explore the network of relationships between past human society and the environment in Ireland.

1.1 Thesis structure

In the remainder of this introductory chapter the research aims and objectives of this thesis are outlined and the specific hypotheses that are tested are defined. In Chapter 2, the rationale and background to this thesis is expanded through a review of existing peatland palaeoenvironmental and archaeological literature. The study area and thirteen study sites (nine milled peatlands, and four intact raised bogs) investigated in this thesis are described in Chapter 3, with details of their archaeological records discussed in Chapter 4. The methods used to test the hypotheses described below are discussed in Chapter 5. Chapter 6 presents a new central Irish testate amoebae transfer function for palaeohydrological reconstruction which, in Chapter 7, is applied to Holocene fossil sequences from the nine milled study sites. Chapter 7 thus presents the main body of new palaeoenvironmental data collected during the course of the present study. The theoretical underpinning of the interpretation of such Holocene palaeohydrological records is explored in Chapter 8, where similar hydrological reconstructions from surface peats in intact raised bogs within the study area are compared with instrumental weather data. In Chapter 9 palaeohydrological datasets from the nine fossil sites are compared and combined in order to examine evidence for Holocene climate change. The resulting palaeoenvironmental records are then, in Chapter 10, compared with the archaeological records of the study sites in order to examine and synthesise evidence for Human-environment interactions in central Ireland. In Chapter 11 the hypotheses outlined below are evaluated against the evidence presented in the preceding chapters, leading to a set of final conclusions and a suggested framework for future research. A bibliography and appendices (including results of statistical analysis as well as a list of abbreviations used in the text) complete this thesis.

1.2 Aims

The overarching aims of this thesis are to:

Aim 1: Assess the driving mechanisms and consistency of peatland palaeoenvironmental records in central Ireland.

Aim 2: Assess evidence for interactions between records of past environmental change and past human activity.

Aim 3: Assess the suitability of existing theoretical frameworks for understanding human-environment interactions during the Holocene in central Ireland.

1.3 Objectives

In order to achieve the aims of this research, the following objectives were set:

1. To identify a means of creating sensitive and accurate records of past environmental change on raised bogs in central Ireland (*Aim 1*).
2. To produce multiple reconstructions of Holocene environmental change from sites within central Ireland (*Aims 2 and 3*).
3. To compare palaeoenvironmental records between the study sites (*Aim 1*).
4. To compile archaeological data from within the study area (*Aims 2 and 3*).
5. To compare the resulting palaeoenvironmental and archaeological records (*Aims 2 and 3*).

1.4 Hypotheses

Whilst the present state of knowledge and theoretical foundations leading to the formulation of these hypotheses are discussed at length in the next chapter, for clarity the specific hypotheses tested in this thesis are defined at the outset. In each case a null hypothesis (H_0), representing the default position to be tested against the evidence presented in this thesis, is given alongside a competing alternate hypothesis (H_1).

Hypothesis I: H_0 – Bog surface wetness (BSW) records from raised bogs in central Ireland *do not* preserve a record of Holocene climatic variability.

H_1 – BSW records from raised bogs in central Ireland *are sensitive* to Holocene climatic variability, and preserve a record of past changes.

Hypothesis II: H_0 – Subfossil testate amoebae recovered from peat cores from the study sites *do not* allow accurate and precise reconstruction of past BSW.

H_1 – Subfossil testate amoebae recovered from peat cores from the study sites *do* allow accurate and precise reconstruction of past BSW.

Hypothesis III: H_0 – Past human activity (as reflected in the construction of trackways) in raised bogs within the study area was *unaffected* by environmental conditions at those sites.

H_1 – Past human activity in raised bogs within the study area *was affected* by environmental conditions at those sites.

Hypothesis IV: H_0 – Records of past BSW and records of past human activity (i.e. the archaeological record) *cannot* be usefully compared.

H_1 – Records of past BSW and records of past human activity (i.e. the archaeological record) *can* be compared in an *interpretatively important* way.

Hypothesis V: H_0 – There is *no* predictable or consistent relationship between trackway construction and environmental conditions across the study area.

H_1 – There *is* a predictable and consistent relationship between trackway construction and environmental conditions across the study area.

1.5 Note on chronology

All ages are expressed on a calendrical timescale. Ages based on ^{14}C and AMS dates are given in years cal BP (years before present – set at AD 1950); uncalibrated dates are not referred to in the text, but are shown in tables for reference and are in years BP. To aid comparison with ^{14}C age determinations, ages derived from dendrochronology are converted to the equivalent age in cal BP, with the original date in BC or AD given in parentheses.

The principal chronological focus of this project is the Mid to Late Holocene. The date of the base of the Holocene Epoch has been dated to 11,650 BP by counting of annual layers (Walker *et al* 2009). It has been proposed that the Mid-Late Holocene boundary be set at 4200 BP (Walker *et al* 2012), and this is the definition used in this thesis.

Chapter 2: Literature Review

The aim of this thesis is to investigate the interactions between raised bogs in Ireland and the past societies which have lived on and around these wetlands; this project, therefore, builds upon a large body of existing research from a number of disciplines and seeks to integrate these varied approaches. This chapter reviews the existing literature covering the themes of peatland palaeoenvironmental and archaeological research in Ireland. To this end, this chapter is organised into two main sections.

The first section concerns the development of Irish raised bog palaeoenvironmental research: first the classification, extent and distribution of peatlands in Ireland is defined; following this, a brief overview of the development of Holocene palaeoclimate research is given which leads on to an account of the debates concerning the climatic sensitivity of ombrotrophic bogs; the development of the current 'toolkit' of palaeoenvironmental techniques is then reviewed in the light of these debates, with a particular focus on testate amoebae analysis; the first section is concluded with a review of the current foci of peatland palaeoclimate research.

The second section of this chapter discusses Irish peatland archaeological research, with a focus on raised bogs: a brief account of the development of this distinctive strand of Irish archaeological work is given, with particular reference to recent developer-funded fieldwork; the classification of site types is then discussed, with reference to parallels elsewhere in the British Isles and Europe; finally, following a brief critical account of environmental determinism, explanatory and interpretative frameworks for the construction and use of peatland structures are explored in relation to previous environmental archaeological work, and in relation to other models of human-environment interaction more heavily influenced by post-processualism.

The chapter concludes by defining the specific gaps in current research which this thesis aims to fill. The problem statement defined in this way is linked directly to the hypotheses outlined in Chapter 1 and informs the methods and theoretical approaches utilised throughout the remainder of this thesis.

2.1 Irish raised bogs and palaeoenvironmental research

2.1.1 Definition of wetland types

The Ramsar convention defines wetlands as "areas of marsh, fen, peatland or water... including areas of marine water the depth of which at low tide does not exceed six metres" (Ramsar 1971 Article 1.1). Such a broad definition includes a vast number of different environments, and the Ramsar classification system for wetland types defines 32 natural wetland types. The wetlands with which this thesis is concerned would, under this classification system, mostly be defined as category U – Non-forested peatlands, which includes open bogs, swamps and fens (Ramsar 2012). In English there is a wide, and potentially bewildering, range of terms to describe wetlands: bog, fen, marsh, mere, mire, moor, morass, peatland, quagmire and swamp have all been used to describe wetlands of one kind or another. Given the multiplicity of ecological and morphological environments, and of the terms to describe them, precise definitions of terminology used to describe wetlands has been recognised as an important objective (International Peat Society 2008).

Peat is formed from the accumulation of plant remains, where waterlogging has suppressed decomposition (Clymo 1983). Whilst the accumulation of organic sediments may be minimal in other types of wetlands, bogs and fens tend to be characterised by the accumulation of peat, and thus are often collectively referred to as 'peatlands' (Wells and Zoltai 1985, p.45). The term 'peatland' is often regarded as more or less synonymous with the term 'mire' (Gore 1983), although other researchers restrict the use of the former term to actively accumulating peatlands (Charman 2002; Montanarella *et al* 2006, p.1). Peatlands are often defined as having a specified minimum depth of peat (e.g. Wells and Zoltai 1985), although there is no general consensus on this definition (Montanarella *et al* 2006, p.1), and some definitions include any area covered with a surface layer of peat (Northern Ireland Environment Agency 2011).

The distinction between fens and bogs is principally based on hydrological status: fens receive groundwater and therefore tend to be minerotrophic (mesotrophic to eutrophic), whilst bogs are ombrotrophic (receive water principally from precipitation and therefore tend to be oligotrophic (Hammond 1981, p.8; Wells and Zoltai 1985, p.48). Moore (1984) provides a discussion of the classification of mires. Further distinctions between types of bog relate principally to form, with the distinction frequently being drawn between raised ('domed') bogs and blanket bogs. Sometimes further distinctions are made on the basis of vegetation communities; an example of this kind of hierarchical classification system is illustrated by Wells and Zoltai (Wells and Zoltai 1985) in Canada.

2.1.2 Classification and distribution of raised bogs in Ireland

Hammond (1981, p.7) defines the three principal natural peat formations which occur in Ireland, these are: fen peats, raised bogs, and blanket bogs. The distinction between the last two is based on morphology: raised bogs having a characteristic domed profile, blanket bogs often being shallower with surface topography following that of the underlying substrate. A further category of Irish bog are man-modified peatlands, which include milled bogs which have been drained and peat extracted for fuel – these milled sites are former raised and blanket bogs. The basic distinction between raised bogs and blanket bogs in Ireland was established by earlier work (Barry 1954, 1969), although it is notable that these earlier studies tended to ignore human-modified bogs.

Blanket and raised bogs have complimentary distributions in Ireland (Barry 1954, 1969; Moore 1962; Hammond 1981): raised bogs being concentrated in the Midlands and central lowlands of Ireland, and blanket bog confined to the Atlantic seaboard of western Ireland and upland areas (sometimes upland or 'high-level' bogs are considered a separate sub-group (e.g. Barry 1954)). The study area outlined in Chapter 3 is thus broadly coincident with the main distribution of raised bogs in the central lowlands area of Ireland. The earliest work defining these main types of bog noted that the boundaries between their distributions followed the 1000mm isohyet (Barry 1954, p.55). Moore (1962), building on this work defined the main floristic characteristics of these groups of bogs: blanket bogs tending to be more dominated by grasses and sedges e.g. *Schoenus nigricans*, *Molinia caerulea*, *Eriophorum* spp., and *Carex panicea* than Midland-type raised bogs which are characterised by *Sphagnum* spp., *Calluna vulgaris*, and *Vaccinium oxycoccos*, whilst transitional bogs share features of both types.

In the 1980s, Hammond estimated that peatlands covered 17.2% of the land surface of the Republic of Ireland (Hammond 1981, p.1), whilst more recent mapping suggests that peat soils are in fact even more extensive, covering 20% (over 1,400,000 ha) of the land surface (Connolly and Holden 2009).

2.1.3 Current uses and conservation

Hammond's (1981) detailed mapping showed that the vast majority (*c*. 74%) of areas of raised bog in Ireland have been modified by human activity. Cutting of turf by hand for use as fuel has been widespread since at least the 17th century (Clarke 2006), and only recently have measures been put in place by the Irish government and the European Union to stop the practice – with only limited success (McDonald 2012; Smyth 2012). In 1981, a total of 47,922 ha of peatlands were being industrially exploited, with the largest concentrations of milled bogs in counties Offaly, Longford and Mayo. The largest peat production company in Ireland, Bord na Móna plc. (BnM), own 77,000 ha of peatlands in the central lowlands of Ireland, of which 25,000 ha are being actively milled (Bord na Móna 2013).

In spite of the introduction of European legislation aimed at reducing carbon emissions, such as the Emissions Trading Scheme in 2005 (European Commission 2013), industrial-scale peat production in Ireland appears to be likely to continue for at least the next decade (Fitzgerald 2008). In the face of such widespread damage to raised bogs, early conservation efforts lead to the formation of the Irish Peatland Conservation Council in 1982 (O'Connell 2008), and the purchase and protection of a number of relatively intact raised bogs, notably Clara bog (protected in 1986). Schemes aimed at restoring damaged or milled peatlands have been initiated (Coilte 2013). Although a study in Estonia has demonstrated that conditions on milled peatlands are often not conducive to rapid re-vegetation, re-wetting milled bogs has shown some promise in restoring surface vegetation and as a potential means of carbon sequestration (Wilson *et al* 2013).

2.1.4 Chronology and development

Mitchell's (1986) popular account of the development of the Irish landscape is organised by broad chronological periods defined by both climate and human history (e.g. "Response to Warm Conditions: 10,000 to 5,100 years ago" and "The First Farmers: 5,700 to 1,650 years ago"); in this framework, the development of raised bogs is discussed as proceeding more or less uniformly in these phases. This framework echoes observations made earlier by Barry, who noted "the Common Factor" in Irish bogs, stating that "there can be no doubt that the profiles of the bogs of Ireland exhibit a definite and regular sequence of strata" (Barry 1954, p.51). Observations such as these have, from the outset, been intimately linked to Holocene climatostratigraphy (see section 2.1.5) and to debates about the relative roles of climate and natural succession in driving bog development which are discussed below in Section 2.1.6. Whilst more recent work has emphasised the relative heterogeneity of raised bog records in Ireland (Swindles *et al* 2013), and a more nuanced understanding of the variety of pathways of raised bog development (Hughes and Barber 2004), very general chronological patterns still largely hold true, albeit with significant variation from site to site.

In summary, the general pattern for raised bogs in central Ireland has been characterised as follows by Mitchell (1986): after the end of the last glaciation, the landscape of the central plains of Ireland were dominated by numerous shallow lakes which, over the course of the Early Holocene began to in-fill leading to the deposition of fen peats in these basins; as peat continued to form into the Mid to Late Holocene local conditions began to drive the development of ombrotrophic peat which thus continued to develop until the present. This general scheme thus broadly accords with the common raised bog sequence observed by Barry (1954, p.52): 1) fen peat; 2) a layer of 'forest peat'; 3) *Sphagnum*-dominated ombrotrophic peat, first a) highly-humified, and then, b) poorly humified. Developing these ideas, Barry (1969) then explicitly linked this generalised model of raised bog development to the Blytt-Sernander scheme of Holocene climatic development (discussed in the following section) combined with the radiocarbon chronology presented by Godwin (1956). More recent work has shown a wide range of dates for the initiation of ombrotrophic peat development in Irish raised bogs for example: 5450 cal BP at Mongan bog, Co. Offaly; *c*. 8000 cal BP at Abbeyknockmoy, Co. Galway (Barber *et al* 2003, pp.522–523); and *c*. 3265 cal BP at Derryville, Co. Tipperary (Gearey and Caseldine 2006).

2.1.5 Recognition of Holocene climatic variability

Although prior to the latter part of the 20th century, the climate of the Holocene was, when compared with the Pleistocene, presumed to have been relatively stable (Bond *et al* 1997, p.1257), the first widely-accepted scheme of Holocene climatic change was proposed in the late 19th century. Blytt (1876) proposed that alternating dark and light layers observed in peat exposures in Scandinavia were related to alternating dry and wet periods, and therefore proposed the subdivision of the post-glacial period into four phases: Boreal (dry), Atlantic (wet), Subboreal (dry), and Subatlantic (wet). This scheme was subsequently built upon by Sernander (1908), with chronology provided by comparison to the archaeological time scale, and through correlation with Swedish varve sequences (De Geer 1912). Pollen work by von Post (see von Post 1946 for a summary) further developed the Blytt-Sernander scheme by associating pollen assemblage zones with each phase, thus providing evidence for temperature variability through the Holocene. In parallel to the development of the Blytt-Sernander scheme based on Scandinavian peat bogs, by the late 19th century the notion of an early Holocene warm period was beginning to gain ground (e.g. Geikie 1891). In North America, Antevs (1931) proposed a tripartite subdivision of the Holocene into Anathermal, Altithermal (roughly analogous to the Atlantic period) and Medithermal periods.

Particularly in the first half of the 20th century, the peatlands of northern and western Europe were extensively studied to establish the main patterns of vegetation change, and thus by extension, climate. Following on from von Post's (1916) pioneering work in Scandinavia, similar vegetation history studies were carried out by Goodwin (1940) in England, and by Jessen (1949), and later Mitchell (1956) in Ireland.

As the 20th century progressed, mounting evidence suggested a more complicated series of climatic shifts during the Holocene. It was soon apparent that the Blytt-Sernander scheme represented a considerable over-simplification of peat stratigraphy in Scandinavia (von Post 1946, p.195); so-called 'recurrence surfaces' (Granlund 1932) observed in Swedish peat bogs appeared to show several shifts between Boreal and Atlantic-type conditions – these observations were germane to contemporary debates about the nature of bog development, discussed below. Further recognition of the complexity of climatic change particularly in the late Holocene was provided by the work of Lamb (Lamb *et al* 1966; 1977), based on a compilation both of existing proxy records and a wide range of documentary and other 'soft' data; several terms such as the Little Ice Age, Medieval Warm Period (now more usually known as the Medieval Climate Anomaly), and Dark Ages Cold Period have been popularised by Lamb's work, and are still often in use.

From the 1970s, however, the first tentative evidence for a series of abrupt climatic changes occurring over a millennial-scale pattern began to emerge: evidence from ^{14}C dated glacier termini indicated at least two phases of glacier expansion during the Holocene (Denton and Karlén 1973), whilst spectral analysis suggested changes in deep-sea sediments occurred over periodicities of 380, 1300 and 2600 years (Pisias *et al* 1973). Bond et al. (1997) found evidence for a series of abrupt climatic shifts during the course of the Holocene inferred from sedimentary evidence of ice-rafted debris in cores from the North Atlantic. These 'Bond events' occurred on a millennial-scale pattern, with a periodicity of 1470±500 years and was shown to relate to cycles in operation reached into the Pleistocene (Bond *et al* 1999). Strong correlations between these events and the production of cosmogenic nuclides suggested a possible solar forcing mechanism for these events (Bond *et al* 2001).

Mayewski et al. (2004) present a synthesis of over 50 high-resolution Holocene palaeoclimate records from both the northern and southern hemispheres. Mayewski et al. confirm that the climate has been highly variable over the course of the Holocene, and show at lease six episodes of global rapid climate change (RCC). Whilst these periods of RCC broadly agree with the timings of Bond events, the Mayewski et al. paper demonstrates the complexity and global nature of Holocene climatic variability. Building upon the recognition of the degree of variability and the periodicity of Holocene climate change, more recent research has focused on extending the range and geographical distribution of proxy records, in particular increasing the number of records from high-resolution terrestrial archives.

2.1.6 Climatic sensitivity of raised bogs

Although, as described above, the Blytt-Sernander climatostratgraphic scheme was based upon observations of the physical characteristics of the peat stratigraphy, for much of the 20th century peatland palaeoclimate research was largely restricted to pollen analysis (Chambers and Charman 2004). This can in part be explained by debates surrounding the driving forces behind peat accumulation. For much of the earlier part of the 20th century theories of cyclical peat development driven primarily by autogenic processes – exemplified by Osvald's (1923) 'regeneration complex' - were highly influential. This theory suggested that bog growth is primarily driven by a cyclical alternation of hummock and hollow microforms. Walker and Walker (1961) carried out detailed studies of peat faces in several raised bogs in Ireland, and found little evidence for cyclical regeneration; nevertheless, the autogenic model of raised bog development was not challenged until the late 1970s by the work of Aaby (1976) and was the more decisively falsified by Barber (1981). Barber reviews the extensive literature detailing the arguments for and against cyclical autogenic peat development, and demonstrates that most bogs exhibit horizontally-layered peat stratigraphy, more reminiscent of 'recurrence surfaces' than the lenticular stratigraphy of alternating hummocks and hollows typical of a 'regeneration complex'. Whilst little evidence was found to suggest that Granlund's (1932) 'recurrence surfaces' could be correlated between sites, Barber convincingly demonstrated that allogenic climate forcing drives hydrological change in raised bogs. Having established that raised bog hydrology is principally controlled by allogenic climate forcing, Quaternary scientists have shown renewed interest in raised bog climate studies, developing a range of analytical techniques (discussed in the next section).

As discussed below in section 2.1.9, the focus of much recent research is on calibration and correlation of the peatland palaeoclimate record (e.g. Charman *et al* 2012). This has given impetus not only to developing more sensitive and quantitative proxies (discussed in sections 2.1.7 and 2.1.8), but also to gaining a more detailed understanding of the links between external and internal processes controlling bog development. These considerations, coinciding with the drive to better understand global carbon cycles, have prompted studies modelling peatland development; such studies show that peat accumulation is sustained by a combination of both climatic and geomorphological factors (Belyea and Clymo 2001; Morris *et al* 2011). Utilising the Morris et al. (2011) model, Swindles et al. (2012) show that to a certain extent BSW may respond non-linearly to external climate forcing, leading some to argue that internal bog processes have been neglected by researchers in recent years (Bhattacharya 2012). Nevertheless, the increase in such studies has raised the profile of these potential complexities.

Recent compilations of proxy data from peatlands do confirm that the peatland archive contains a robust climatic signal (Mauquoy and Barber 2002; Charman *et al* 2006; Charman 2010; Swindles *et al* 2013), albeit often with considerable inter-site variability which may perhaps be at least partially explained by such non-climatic factors. Comparisons between BSW records from two sites (one in England, one in Estonia) and instrumental weather data have shown that BSW is most strongly correlated with summer precipitation, correlations with summer temperature were weaker, but may be more significant over longer timescales and in more continental settings (Charman *et al* 2004). These findings are confirmed by a subsequent study which shows that water balance (P-E) is the principal control on BSW, with precipitation more important than temperature, and that this is best reflected in estimated growing season deficit (Charman 2007). However, Barber and Langdon (2007) compared BSW records from bogs in northern England with a chironomid-inferred temperature record from a nearby lake, this study suggests that, over millennial timescales, summer temperature may indeed be important drivers of the peatland record.

Whilst in general there is a consensus that the peatland BSW record reflects summer water balance, there is some debate about the relative importance of precipitation and temperature; it has been suggested however that, for northern and western Europe, it is the strength of westerly airflow as opposed to temperature or precipitation in isolation which drives the record (Charman *et al* 2009). The notion that temperature becomes more important in more continental regions may perhaps be linked to the relative severity of the summer water deficit, which has been shown to have a profound effect on raised bog development (Hughes and Barber 2004, pp.75–76), and due to the fact that the westerlies are less important in eastern Europe (Charman *et al* 2009). Over long (e.g. millennial) timescales, far beyond the range of instrumental data, temperature and precipitation may be rather difficult to separate as in many regions these are likely to co-vary; thus studies aimed at examining links to specific forcing mechanisms, such as solar variability (e.g. Plunkett 2006; Swindles *et al* 2007a), and modelling studies may provide clarification.

Although by falsifying the 'regeneration complex' theory of bog development Barber (Barber 1981) has shown that hydrological changes are likely to occur in the same direction across a site, there remains some doubt over the relative sensitivity of different surface microforms (compare Barber *et al* 1998; and De Vleeschouwer *et al* 2010). Only one study, from a site in Estonia has addressed this issue directly (Niinemets *et al* 2011), finding that, as predicted by Barber, the direction of hydrological change is consistent across microforms, but that the magnitude of change varies. Further studies investigating this issue may be necessary since this is likely to affect the climatic sensitivity of records based on single cores.

2.1.7 Development of peatland palaeoenvironmental methods

As shown in the preceding sections, raised bog palaeoclimate investigations have a long history with recent work focusing on ever more sensitive reconstructions of BSW; these have been been facilitated by developments in the analytical methods available to researchers, this section gives a brief account of these developments, whilst the next section focuses specifically on testate amoebae analysis. Chambers et al. (2012) give a comprehensive review of peatland palaeoclimate proxies. A discussion of the rationale behind the selection of techniques used in this thesis is the focus of Chapter 5.

The earliest peatland investigations in the late 19th and early 20th centuries (described above) were based on the principle that the degree of decomposition (humification) of the peat matrix and the peat-forming floristic communities were controlled by moisture availability. These first principles therefore laid the foundations for contemporary methods of stratigraphic description, humification analysis, and plant macrofossil analysis.

Following the pioneering work of Blytt (1876) and Sernander (1908) in recognising the climatic significance of visible peat stratigraphy, von Post (1924) proposed a system of describing peat, including a ten-point scale of peat decomposition. Building upon these ideas, Troels-Smith (1955) developed a detailed scheme for the systematic description of peat composition, including a five-point humification scale. Such peat description methods, or variants thereof (e.g. Kershaw 1997), are still widely-used in peat stratigraphic studies.

Whilst visual estimation of humification using a ten- or five-point scale is still commonly used as a rapid means of assessing decomposition in the field, over the last few decades methods to measure humification more precisely have been developed. Colorimetric humification analysis was first proposed by Bahnson (1968), and was first used by Aaby and Tauber (1975), who demonstrated that humification changes were indeed linked to changes in surface moisture availability (and therefore climate). The methods of colorimetric analysis were then developed by Blackford and Chambers (1993), and subsequently revised by Chambers et al. (2010).; a fuller review of the method can be found in de Jong et al. (2010). Recent work has demonstrated that differential decomposition rates of different peat components can affect the humification signal (Yeloff and Mauquoy 2006); for this reason, humification is often used alongside other analytical techniques, although humification is useful for highly-decomposed peats (with few visible macrofossils) or sequences which show little change in floristic composition (e.g. blanket peats) (Chambers *et al* 2012). In spite of these concerns, a study by Plunkett (2006), showed good agreement between six tephra-dated humification records from Ireland from both raised and blanket bogs, suggesting a strong climatic signal in these data.

The acidic and waterlogged conditions in raised bogs are conducive to the preservation of the remains of plants growing on the bog surface which thus forms the basis of another long-established palaeoclimate technique: plant macrofossil analysis. Ecological work has established that plants growing on mires occupy distinct niches along the hydrological gradient. Quantification of the relative abundances of different *Sphagnum* mosses and other plants have been widely-used to reconstruct changes in BSW (e.g. Walker and Walker 1961; Aaby and Tauber 1975; Barber 1981). Methods used for quantifying the abundance of plant remains include assigning ordinal values (e.g. 1 = rare, 5 = abundant) to each component, which has been used in older studies (Walker and Walker 1961; Barber 1981), or alternatively to calculate the number of fragments per unit volume (Janssens 1983); intermediate between the two, the now widely-used Quadrat and Leaf Count method (Barber *et al* 2003) combines quantitative percentage estimates of major peat components with counts of minor components. Mauquoy et al. (2010) give a revised protocol for plant macrofossil analysis.

To facilitate comparisons between plant macrofossil data and other hydrological proxy data, it is often desirable to reduce the dataset to a single dimensional summary, this has been achieved either by using DCA axis 1 scores (Barber *et al* 1994a) or by using the Dupont hydrological index (Dupont 1986). These approaches are complicated by several factors:

rather than reflecting hydrological change, DCA axis 1 may, for example, reflect large assemblage changes not directly linked to hydrology, such as the replacement of *Sphagnum imbricatum* with *S. magellanicum* in the late Holocene (Chambers *et al* 2012, p.23); the Dupont index, meanwhile, is only semi-quantitative, based on rather subjective hydrological indicator values assigned to each component (Barber *et al* 2000, p.481). More recently, some attempts have been made to derive quantitative water table reconstructions based on local water table/surface vegetation modelling (Väliranta *et al* 2007), however, many plant taxa have wide tolerances and slow response times compared to other indicators such as testate amoebae (see below); nevertheless, using these quantitative approaches using multiple proxies has shown promise (Väliranta *et al* 2012).

Although less well-established than the other palaeohydrological proxies discussed in this section, testate amoebae analysis has a number of advantages over both humification and plant macrofossil analysis, and has therefore become one of the most widely-used peatland climate proxy techniques. As will be shown in the next section, testate amoebae are sensitive indicators of BSW, and have, over the last two decades, been used successfully to produce quantitative reconstructions of water table depth which facilitates comparisons between sites, and potentially with other proxies and instrumental weather records (see also section 2.1.9).

2.1.8 Testate amoebae analysis

Testate amoebae are a polyphyletic group (Bhattacharya *et al* 1995; Meisterfeld 2002; Nikolaev *et al* 2005; Lara *et al* 2008) of single-celled organisms which produce durable tests, and which inhabit a range of wet soil and peatland habitats. Although the fossil record of these organisms stretches back at least to the Carboniferous (Loeblich and Tappan 1964; cited in Mitchell *et al* 2008, p.2116), most attention is given to fossil testate amoebae found in Quaternary deposits, particularly those preserved in peats. Testate amoebae analysis has, over the past few decades, become one of the most widely-used peatland palaeoenvironmental techniques. The study of testate amoebae, however, has a history stretching back well over a century (Dujardin 1837; Leidy 1879; Cash 1891; Penard 1902; Cash *et al* 1905; Cash and Hopkinson 1909). The usefulness of testate amoebae as a climate proxy in peatland palaeoclimate research stems from the relationship between community composition and habitat moisture; this relationship has long been recognised (Harnisch 1925, 1927; Jung 1936; De Graaf 1956; Heal 1961, 1962; Meisterfeld 1977). Tolonen (1986) summarises the hydrological groupings suggested by these earlier authors, showing that many testate amoebae species have well-defined niches along the BSW gradient and thus illustrating their usefulness as palaeoenvironmental indicators.

Studies such as Aaby and Tauber (1975), Aaby (1976), and Barber (1981), examined fossil testate amoebae tests alongside other proxy indicators of BSW, however the usefulness of the method was limited due to inappropriate sample preparation techniques. The latter study in particular counted tests present on pollen slides, however this has been shown to severely reduce concentration and lead to the selective removal of certain taxa (Hendon and Charman 1997; Charman *et al* 2000). Preparation techniques based on disaggregating samples in water, first proposed by Grospietsch (1953), developed by Tolonen (1966, 1986), and subsequently by Hendon and Charman (1997), have now been more widely-adopted, and appear not to distort assemblages.

Whilst on the one hand recognition of appropriate sample preparation techniques was an important step in the development of testate amoebae analysis, the implementation of the transfer function approach has prompted the widespread use of the method. In Chapter 6 the transfer function approach is discussed more fully. Transfer functions, or calibration functions, were first developed by Imbrie and Kipp (1971). This approach allows for quantitative reconstruction of environmental variables from fossil assemblages. Based on a training set of modern data, including both testate amoebae taxon abundance and environmental data, the species-environment relationship is modelled, and this model is then used to infer past environmental conditions from fossil assemblages. Testate amoebae are suitable for quantitative reconstruction (Birks 1995) as:

1. Testate amoebae community composition has been shown to be related to BSW (e.g. Tolonen 1986), which therefore is potentially reconstructible.
2. Testate amoebae respond rapidly to changing conditions (Gilbert *et al* 1998a, 1998b).
3. They form a significant proportion of the microbial biomass in raised bogs (Mitchell *et al* 2003) and therefore produce abundant fossils, which are identifiable, often to species level, on the basis of the fossil tests (Charman *et al* 2000).

The first transfer function for reconstructing ombrotrophic bog hydrology from testate amoebae was proposed by Charman and Warner (1992), and implemented for peatlands in Ontario, Canada, by Warner and Charman (1994). The development of a transfer function for reconstructing hydrological variables allowed for the first time quantitative reconstructions of BSW from Holocene peats. Following this, further testate amoebae transfer functions have been developed for several regions: Newfoundland (Charman and Warner 1997), New Zealand (Charman 1997), Britain (Woodland *et al* 1998a), the Jura mountains (Mitchell *et al* 1999), Michigan (Booth 2002), north-western (Lamentowicz and Mitchell 2005) and western (Lamentowicz *et al* 2008) Poland, the Carpathian mountains (Schnitchen *et al* 2006), Europe (Charman *et al* 2007), Greece (Payne and Mitchell 2007), North America (Booth 2008), Turkey (Payne *et al* 2008), northern Ireland (Swindles *et al* 2009), Alaska (Payne *et al* 2006; Markel *et al* 2010), north-eastern Canada and Maine (Amesbury *et al* 2013a), northern England (Turner *et al* 2013), and Quebec (Lamarre *et al* In Press). These transfer functions cover a range of regions, varying from localised to supra-regional transfer functions.

Alongside the growing proliferation of testate amoebae transfer functions, some researchers have sounded notes of caution. Spatial autocorrelation is a property of many ecological datasets (Legendre and Fortin 1989); Telford and Birks (2005) discuss the potential problem of spatial autocorrelation, which may cause overly-optimistic estimates of model performance. Building upon this, and incorporating the controversial concept of 'neutral theory' (Bell 2000), Belyea (2007) argues for continuing critical examination of the assumptions behind transfer function reconstructions. Other statistical issues have also been highlighted, such as the effects of uneven sampling of environmental gradients (Telford and Birks 2011a), and highly-clustered datasets (Payne *et al* 2012). A recent transfer function from north-eastern Canada and Maine (Amesbury *et al* 2013a), developed specifically to take into account these concerns, appeared to show that many models are nevertheless likely to retain reasonable reconstructive power when less optimistic performance statistics are selected. Although many testate amoebae taxa appear to be cosmopolitan in their distribution (Cowling 1994; but see Mitchell *et al* 2008, pp.2119–2120 for a discussion), some studies have suggested that testate communities vary at the sub-continental scale (Booth and Zygmunt 2005). A recent study (Turner *et al* 2013) has, therefore, compared regional and supra-regional transfer functions in the British Isles; this study also suggests that testate amoebae transfer functions are generally robust.

Testate amoebae analysis has, through application of the transfer function approach, offered Quaternary scientists a method of deriving quantitative reconstructions of BSW from raised bogs. Such quantitative methods were quickly recognised as offering the opportunity to “convert subfossil peat data into more precise climatic data” (Blackford 2000, p.196).

Other methods such as humification analysis and plant macrofossil analysis (discussed in the previous section) are qualitative, or only semi-quantitative, and are not linearly related to BSW in the same way as the quantitative data generated by testate amoebae analysis (Charman *et al* 1999). For these principle reasons, testate amoebae analysis has been used in attempts to examine links with instrumental weather data to investigate driving mechanisms of the peatland record (discussed in section 2.1.6, above), attempts to calibrate the BSW record to reconstruct past climatic variables, and has also been used in studies which have aimed at comparing the BSW record between sites and regions. These studies which are the focus of much current research are discussed in more detail in the next section.

It is important to recognise, however, that there are a number of potential shortcomings to testate amoebae analysis. A number of studies have shown highly variable testate amoebae concentration and preservation, and the reasons for this variability are unclear (e.g. Amesbury *et al* 2008). In some highly humified peats, test concentration may be too low to count (Barber and Charman 2003), or tests may be entirely absent (e.g. Langdon and Barber 2001); in such cases hydrological reconstruction is impossible; in contrast, other methods (e.g. plant macrofossil or humification analysis) do not suffer from potentially fragmentary records in this way.

Whilst, as discussed above, the transfer function approach is generally considered to be robust, some taxa which are common in Mid-Holocene peats, such as *Difflugia pulex* are poorly represented in modern surface samples (Woodland *et al* 1998a; Charman *et al* 2007). The lack of good modern analogues for some taxa may suggest that reconstructions may be inaccurate or biased, particularly if the present ecological niche of those taxa have shifted or some ecological niches are no longer represented in existing intact bogs. Indeed Belyea (2007) has highlighted a number of concerns in reference to the development of “non-equilibrium ecology” which may challenge the assumption that species-environment relationships remain static through time, a crucial underlying assumption of the transfer function method (Birks 1995, p.168).

Assuming that the assumptions underpinning the transfer function approach remain valid, there are other factors which affect modern intact bogs which may bias modern testate amoebae communities. These factors may include human modification of bogs through cutting, and pollution, especially through increased nitrogen loading from burning fossil fuels and intensive agricultural activities (Payne *et al* 2013; Payne 2014).

2.1.9 Current peatland palaeoenvironmental research in the British Isles

Currently, much palaeoclimate research is focused on recognising and understanding global patterns of environmental change (e.g. Mayewski *et al* 2004)., and in integrating palaeoclimate data to reduce uncertainties in climate modelling (Jansen *et al* 2007). Developing this further, the PAGES 2k network has, for example, recently published a compilation of temperature reconstructions from across the globe (with the notable exception of Africa, where there are fewer records available) for the last 2000 years (PAGES 2k Consortium 2013); large-scale syntheses such as these respond to the need for more comprehensive data with which to compare climate models. A similar compilation of precipitation records is being planned (D. Fleitmann pers. comm.), and peatland BSW records may provide a useful source of such data.

It has been noted that peatland palaeoclimate research has received relatively little attention from the wider palaeoclimate research community (Chambers and Charman 2004, p.3); in order to realise the full potential of the peatland archive in this respect, data must be 'upscaled' to reflect regional climatic signals (Charman *et al* 2006, p.336) and, ideally, steps towards should be taken towards calibrating the BSW record to climatic variables. In this vein, much current and recent peatland palaeoenvironmental research in the British Isles has focused on quantitative palaeoclimate reconstruction (principally utilising testate amoebae analysis). In particular, much research has been focused on comparing and correlating BSW records between sites and regions (and this producing composite records) and on calibrating these records. To realise both aims, a rigorous understanding of the driving forces of the BSW record is required; this involves understanding both the external and the internal processes within raised bogs, as well as proxy-environment relationships, which are discussed above (sections 2.1.6, 2.1.7 and 2.1.8). As will be discussed in the second part of this chapter, peatland palaeoclimate data has the potential to be applied to improving understanding of the relationships between past environments and human societies.

Whilst chronological uncertainties associated with age vs. depth models from peat cores continue to pose challenges, evidence for teleconnections between BSW records has mounted in recent years (e.g. Barber *et al* 2000). To overcome the chronological problems associated with comparing multiple records, Charman et al. (2006) used the 'tuning and stacking' method in order to produce a composite BSW curve from ten sequences in northern Britain with the explicit goal of producing data more suited to comparisons with climate models. Following this study, a similar approach has been used to produce composite BSW records from both central (Blundell *et al* 2008) and northern (Swindles, Blundell, *et al* 2010) Ireland. Blaauw (2012) discusses the dangers associated with chronological tuning of records, in particular the danger of assuming that climate events are synchronous – the so-called "reinforcement syndrome" (Oldfield 2001) or "suck-in effect" (Baillie 1991) - and the circular reasoning that this can foster. Nevertheless, the tuning method employed in the three tuned BSW records from the British Isles avoid tuning dates beyond the uncertainties of the original age models as advocated by Blaauw (2012). Swindles et al. (2012) tested the uncertainties of this tuning method by comparing multiple alternative chronologies for the northern Irish record (Swindles, Blundell, *et al* 2010); whilst the resulting alternative records showed the approach to be robust, it was nonetheless concluded that "tuned peat-based proxy climate records cannot be used to assess the (a)synchroneity of events between sites" (Swindles, Blaauw, *et al* 2012, p.63). Both Charman et al. (2006) and Swindles et al. (2010) argue that their tuned and stacked records lend support to the hypothesis of solar forcing of the BSW record, however Bard and Delaygue (2008, p.302) argue that only un-tuned records should be used to infer any links to solar forcing so as to avoid the pitfalls of circular reasoning; whilst it may be true that such links cannot be proven outright using tuned chronologies, the posited mechanisms by which solar variability drive the BSW record remain highly plausible.

Whilst it is important that potential pitfalls of tuning and stacking are acknowledged, the method has been shown to be relatively robust. Both the northern British and northern Irish stacked records were recently compared to a high resolution record of BSW from Co. Longford (Langdon *et al* 2012); whilst the original article suggested a chronological offset between Irish and the northern British records, subsequent revision in fact indicated a large degree of agreement (Langdon *et al* 2013). The northern British stacked record has been used as an important component of Charman's (2010) recent review of evidence for mid-late Holocene climate change in Britain. An alternative approach has been utilised in a review of evidence for centennial-scale climate variability in Ireland (Swindles *et al* 2013): rather than tuning the chronologies of each individual record, the maximum likely uncertainties of each age vs depth model was calculated to give an estimation of the strength of correlation between records. Using this method, a high degree of inter-site variability was observed, although covariance between high-quality BSW records was found to be greater than to be expected by chance alone (see Blaauw *et al* 2010), furthermore, greater coherence between Irish and northern British records was observed at specific intervals – such as coherent wet shifts at *c*. 2700 cal BP (at the Subboreal to Subatlantic transition), *c*. 1400 cal BP (Dark Ages climate deterioration), and *c*. 500 cal BP (Little Ice Age).

The development of testate amoebae analysis as a quantitative proxy BSW (see section 2.1.8) has allowed direct comparisons with instrumental weather data to be made, whilst this has on the one hand improved understanding of the climate drivers of the peatland palaeoenvironmental record (see section 2.1.6), it has also opened up the possibility of attempting to calibrate the raised bog palaeoclimate record to climatic variables. Whilst this approach is relatively well-established in the field of dendroclimatology, usually to reconstruct summer temperature (e.g. Davi *et al* 2003; Zhu *et al* 2011; Gurskaya *et al* 2012), this approach has rarely been used for non-annually resolved proxies, such as peatland BSW. Charman et al. (2012) applied this methodology to reconstruct summer precipitation based on a high-resolution record from a raised bog in Co. Tipperary, Ireland. The calibration period used was 1958-1995, which was then used to reconstruct summer precipitation for the last 1000 years. Whilst the results of this reconstruction appeared to be successful, showing for example increased summer precipitation during the Little Ice Age - echoing the findings of Swindles et al. (2010), it is not certain if such reconstructions can be successfully applied over longer timescales.

Brown (2008, p.10) argues, it is unlikely that the effects of temperature and precipitation can ever be wholly disentangled in the BSW record. As Barber and Langdon (2007) show, the BSW record is a composite record, albeit one dominated by precipitation in oceanic areas such as Ireland (Charman *et al* 2009). As Brown points out, summer precipitation is correlated to winter North Atlantic Oscillation index (NAO) (Kettlewell *et al* 2003), which is thus linked to mean annual temperature. Booth (2010; Booth *et al* 2010) show strong links between BSW records and integrative hydroclimate measures such as the Palmer Drought Severity Index for sites in North America; whilst these sites undoubtedly have more continental settings than Ireland, and thus drivers of BSW may vary, such integrative measures are useful in that they can be directly related to impacts on human subsistence and economy. In any case, the calibration approach may offer insights not only into the modelling of present and future climate but also into how climatic variability has been experienced by past societies. The second part of this chapter will discuss the archaeological record of Ireland's raised bogs, and in sections 2.2.4 and 2.2.5, the relationships between past human societies, past activity on raised bogs, and environmental change will be discussed.

2.2 Irish raised bog archaeology

Wetland archaeology in Europe has, since the mid 19th century, provided some of the most spectacular and iconic insights into life in past societies (Coles 1985; Coles and Coles 1989). The special character of the wetland archaeological record is, above all, due to the unique preservation afforded by such environments which has allowed the recovery of organic elements of material culture which are rarely, if ever, preserved in dryland contexts (Coles 1988); indeed it has been widely acknowledged that for most past human societies (as well as many contemporary traditional societies) organic materials account for the vast bulk of material culture (Orme 1981). The focus of this project is specifically on lowland raised bogs in central Ireland, and this second part of this chapter discusses the literature covering the archaeological record of these wetlands. As will be shown below, archaeological investigations in these bogs has been dominated, above all, by the study of trackways – more trackways have been excavated in Ireland than anywhere else in Europe (Brunning and McDermott 2013, p.360); as a result, the discussion which follows below is principally focused on a discussion of trackways. Section 2.2.5 discusses the interpretation of this archaeological record, with a focus on debates surrounding the relationships between these structures and changing environmental conditions.

2.2.1 Development of Irish peatland archaeology

Investigations in Irish peatlands, compared to other wetlands in Ireland, have a relatively long history (Raftery 2003; cited in O'Sullivan 2007a, p.150). O'Sullivan (2007a, pp.150–154) and Brunning and McDermott (2013, pp.360–361) give synopses of the history of Irish peatland investigations. In general, archaeological discoveries have been made in the course of peat cutting, and more recently, industrial milling (see section 2.1.3). In the 19th and 20th century, stray finds including tools, ornaments and weapons, occasional organic remains such as wooden objects, pails of bog butter, and bog bodies, as well as some spectacular hoards of high-status metalwork were recovered in the course of cutting turf for fuel (Eogan 1983). At the same time numerous wooden structures were also recovered, and whilst these were usually recognised as trackways, very few received any attention from archaeologists (O'Sullivan 2007a, pp.150–151); exceptions to this (Macalister 1932; Price 1945; Prendergast 1946; Tohall *et al* 1955; Rynne 1961, 1964, 1965) tended to concentrate only on larger trackway structures (Stanley 2003).

From the mid 20th century onwards, industrial peat milling lead to a rapid increase in the destruction of raised bogs in the Midlands; by the 1980s, the realisation dawned that this was simultaneously causing the destruction of the unique archaeological record of these bogs. Raftery's (1996) excavations between 1985 and 1991 in the Mountdillon bogs, Co. Longford, marked a turning point, revealing over 60 peatland structures including the impressive, and unique, Corlea 1 Iron Age trackway. The sense of urgency was well-recognised amongst wetland archaeologists: "*there is some argument for saying that the Irish bogs still hold more information about the past than any wetland in Europe; but time is running out.*" (Coles and Coles 1989, p.159)

In 1991 the Irish Archaeological Wetland Unit (IAWU) was formed to carry out systematic survey and excavations on Bord na Móna's (BnM) production bogs. This lead to the discovery of thousands of peatland structures (IAWU 1993a, 1993b, 1995, 1997; McDermott 1998, 2007; Moore *et al* 2003). In 1999 Archaeological Development Services Ltd (ADS) took over the role as archaeological consultants to BnM (O'Carroll and Whitaker 1999).

2.2.2 The archaeological record of Irish raised bogs

The Sites and Monuments Register (SMR) for all counties of the Republic of Ireland contains over 2000 entries relating to peatland structures, of which more than 1700 are trackways of various type (National Monuments Service 2012), table 1 gives a breakdown of these figures. The classification of trackways is briefly discussed below, and is outlined in more detail in Chapter 4. Naturally, the distribution of these sites matches the distribution of peatlands in Ireland (see section 2.1.2), platforms and larger wooden trackways (class 1 and class 2 toghers) occur almost exclusively in the central lowlands of Ireland - matching the distribution of lowland raised bogs, and of the study sites for this project (see Chapter 3) - with comparatively few entries for sites on blanket bogs.

Table 1: Number of peatland structures in the Irish SMR (National Monuments Service 2012).

Classification	Number (all counties)
Road – class 1 togher	123
Road – class 2 togher	243
Road – class 3 togher	977
Road – unclassified togher	311

Classification	Number (all counties)	
Road – gravel/stone trackway – peatland	50	Total trackways – 1704
Platform – peatland	232	
Post row – peatland	61	
Structure – peatland	337	**Total – 2334**

Although the SMR gives an indication of the distribution of sites, many sites, particularly those which have been uncovered in the course of recent commercial excavations by ADS, are not likely to have been included. In total, it is estimated that over 3,500 peatland trackways have been excavated in Ireland to date (Brunning and McDermott 2013, p.361). Of these, over 350 have been dated (Chapple 2012), compared with only 112 in 1998 (Brindley and Lanting 1998), therefore around 10% of trackways discovered so far have been dated. Wooden trackways have been dated to virtually all periods from the Neolithic to the Medieval (see Table 2 for approximate dates of archaeological periods), with notable peaks in construction in the Late Bronze Age and Iron Age (Brunning and McDermott 2013, p.361). A degree of chronological patterning has been observed, with some periods of increased and decreased construction (Raftery 1996; Brindley and Lanting 1998; Plunkett *et al* 2013), this patterning has been the subject of considerable debate about the influence of environmental change which is discussed in section 2.2.5, below.

Table 2: Approximate dates of archaeological periods in Ireland (after Waddell 1998a, p.4).

Mesolithic	earlier	7000 – 5500 BC	8950 – 7450 cal BP
	later	5500 – 4000 BC	7450 – 5950 cal BP
Neolithic		4000 – 2400 BC	5950 – 4350 cal BP
Copper Age		2400 – 2200 BC	4350 – 4150 cal BP
Bronze Age	Early	2200 - 1500 BC	4150 – 3450 cal BP
	Middle	1500 – 1000 BC	3450 – 2950 cal BP
	Late	1000 – 600 BC	2950 – 2550 cal BP
Iron Age		600 BC – AD 400	2550 – 1550 cal BP
Early Christian		AD 400 – 800	1550 – 1150 cal BP
Medieval		AD 800 – 1500	1150 – 450 cal BP

Over 130 bog bodies have been recovered from Irish raised bogs (Bermingham 2006); although relatively few have been radiocarbon dated (Forde 2010), many appear to date to either the Iron Age or to the Medieval periods (Brindley and Lanting 1995). Recently, the phenomenon of Iron Age bog bodies has been the subject of both theoretical speculation (Kelly 2006) and to detailed palaeoenvironmental analysis (Plunkett *et al* 2009).

The deposition of both single objects and hoards of high-status metalwork are a notable feature of late prehistoric archaeology in Ireland which have received considerable attention (Hodges 1957; Eogan 1983, 1994; O'Flaherty 1995). Objects deposited include weapons, musical instruments, ornaments and tools. The majority of such deposits have been recovered from wetland contexts, including raised bogs – indeed over 50% of Late Bronze Age hoards have been recovered from raised bogs (Grogan 2005, p.172). The practice appears to have become particularly intense during the Late Bronze Age (O'Sullivan 2007a, p.183), and was also carried on during the Iron Age (Raftery 1998).

Whilst the construction of trackways and platforms, and the deposition of bog bodies and hoards are clear evidence for human activity on raised bogs, habitation sites on the bog surfaces are very rare. One example from Clonfinlough, Co. Offaly, dates to the Late Bronze Age and includes a number of roundhouses, platforms and artefactual evidence of occupation by pastoral farmers (McDermott 2001). A second example, from Ballykean, Co. Offaly, dates to the Early Christian period, and has been interpreted as a habitation, or possibly, as a hunting lodge (IAWU 2003).

2.2.2.1 Classification of trackways

Numerous terms have been used to describe different types of peatland structure in Ireland. Whilst wooden structures lacking any obvious orientation are usually termed 'platforms', a rather more complex terminology is in use to describe trackways. The term 'trackway' and the Irish word '*togher*' (derived from the Irish *tochar* = causeway) are often used interchangeably in the literature, in this thesis the term 'trackway' is used. Furthermore, Raftery (1996, pp.211–218) uses a variety of terms to describe different construction types, based loosely on Hayen's (1957) classification of German trackways: 'brushwood tracks' (constructed from longitudinally-lain brushwood), 'roundwood paths' (constructed from more substantial longitudinal roundwoods), 'hurdle tracks' (made up of woven wattle hurdles), 'plank paths' (constructed from longitudinal wooden planks) and 'corduroy roads' (large trackways constructed from transverse timbers). The Archaeological Survey of Ireland (undated) provides an official scheme for the classification peatland sites; wooden trackways are classified on the basis of length either as 'Class 1 togher' (trackways which originally would have traversed a bog), 'Class 2 togher' (over 15m long), and 'Class 3 togher' (less than 15m long), the 'Unclassified togher' category covers trackways where length is unknown, and a final category 'Road – gravel/stone trackway – peatland' includes trackways built mostly of stone or gravel. Raftery's trackway types and the official classification scheme imply a degree of functional differences between trackways of different construction or length (see section 2.2.5). See Chapter 4 for a more detailed discussion of site classifications used later in this thesis.

2.2.3 European parallels

Although more trackways have been found in Ireland than anywhere else, large numbers of examples are known from many other countries in northern Europe.

In the United Kingdom, fewer than 200 trackways have been recovered, mainly concentrated in the south-west of the country, with no examples from upland blanket bogs, and few from the raised bogs of the north-west (Brunning and McDermott 2013, p.361). These range in date from the Neolithic to the Iron Age. Possibly the best-known example from the UK is the Sweet Track, Somerset, which consisted of a raised plank walkway and dates to the early Neolithic (Coles and Coles 1989, p.156).

On the Continent, trackways have been excavated and studied in the large areas of raised bog in Lower Saxony (Hayen 1987), in northern Germany, and in adjoining parts of the Netherlands in the province of Drenthe (Casparie 1987). Numerous trackways have been excavated from these areas: over 300 in Germany, with a further 10 to 20 in the Netherlands; as in the British Isles, these trackways range in date from the Neolithic to the Iron Age (Brunning and McDermott 2013, p.363). Trackways have also, to a lesser extent, been found dating to similar periods in Denmark (Coles and Coles 1989, pp.161–164). Elsewhere in Scandinavia, a few examples are known from Norway, and these tend to be Medieval in date (Smedstad 2001).

The Irish trackways do, broadly, fit into a wider pattern of trackway construction throughout prehistory in areas where raised bogs forms a considerable component of the landscape. However, it has been noted that there are very few large trackways suitable for wheeled transport (Corlea 1 is one example) compared with Germany and the Netherlands, suggesting that wheeled transport was less important in Ireland than on the Continent (Brunning and McDermott 2013, p.364).

The deposition of bog bodies in the Iron Age appears to be a widespread phenomenon across northern Europe, with Irish examples having parallels in the UK, northern Germany and Denmark, although it has been argued that this practice has rather older origins in Denmark (Coles and Coles 1989, p.191). Similarly, the deposition of metalwork and other objects in raised bogs and other wetlands in Ireland fits in with wider patterns of the ritual importance of wetlands in the British Isles and continental Europe (Cooney and Grogan 1994; Bradley 1998).

2.2.4 Environmental determinism

Before progressing to the debates surrounding interpretation of the archaeology of Irish raised bogs, a brief discussion of environmental determinism may be useful, since many of these debates are framed in response or opposition to this position. Huntington's (1924; cited in Rosen 2007, p.1) *Civilization and Climate* is an influential example of classical environmental determinism which implies an environmental cause for the characteristics and behaviour of human societies. Following the Second World War, backlashes against eugenic theories made environmental determinism unfashionable (Frenkel 1994; cited in Coombes and Barber 2005, p.303), and critiques, especially those drawing on Marxist principles (e.g. Peet 1985), linked such theories with social Darwinism, racism, and the imperatives of late 19th and early 20th century imperialism.

Later in the 20th century, as recognition of climatic variability during the Holocene became more widespread, a worldwide synthesis recognised the broad synchroneity between the main shifts in Holocene climate and cultural periods (Wendland and Bryson 1974). A dramatic increase in the recognition of anthropogenic climate change since the 1990s (Chambers and Brain 2002) has renewed interest in human-environment interactions (Coombes and Barber 2005, p.304). In particular, interest has often focused on extreme events such as droughts (e.g. Butzer 1983; Rosen 2007), and other manifestations of climate in driving societal collapse (deMenocal 2001; Diamond 2011).

The renewed interest in human-climate relationships is not unproblematic, however, and several issues have been identified: whilst some authors have argued that improved chronological precision in both archaeological and palaeoenvironmental records would be sufficient to demonstrate causal links between climate and social change (e.g. Berglund 2003), Brown (2008), on the other hand, argues that only improved modelling of past demographics would facilitate convincing comparison between archaeological and climate data, others have, however, expressed scepticism about any such links at all (Coombes and Barber 2005). These suspicions are at least matched by many authors in mainstream humanities-based archaeology, particularly in the British Isles. Thomas (1990) argues that the positivist overtones of environmentally deterministic research, and of much environmental archaeological research generally, has been associated with the rather outdated concerns of the New Archaeology (a focus on sterile examination of systems, functionalist interpretation, and economic determinism); thus it has been seen as out of step with post-processualism and other more recent theoretical approaches. It has, however, been argued that deterministic models of interpretation remain popular in archaeological research in other regions, for example South America (Erickson 1999) and the Near East (Wright 1993). In response to such critiques, efforts have been made to integrate social and environmental archaeological approaches (e.g. Evans 2003; Morris and Maltby 2010).

2.2.5 Interpretation of human activity on Irish bogs

It has been noted that many wetland archaeologists have tended not to engage with wider theoretical debates within archaeology (Van de Noort and O'Sullivan 2007). Phenomenology provides an interesting case in point in this respect: this theoretical approach, first proposed and discussed in relation to archaeology by Tilley (1994), has been widely incorporated into the study of British (Brück 2005) and Irish (Cooney 2000) landscape archaeology. Tilley frequently discusses paths and formal routeways as ways in which experiences and identities are created; it is perhaps ironic, then, that given the positive abundance of paths and physical routeways (i.e. trackways) in the Irish raised bog archaeological record, such theoretical approaches have rarely, if ever, been applied to Irish bogs (Van de Noort and O'Sullivan 2007).

O'Sullivan gives a wide-ranging and comprehensive review of wetland archaeology in Ireland, highlighting the range of activities that may be represented by the archaeological record of raised bogs: hunting, fowling, the gathering of plants for medicine and crafts, grazing, preserving butter, seasoning wood, as well as religious and ritual practices (O'Sullivan 2007a, pp.175–176). Setting aside for a moment the interpretation of trackways, platform type structures clearly imply some form of activity within raised bogs requiring a stable surface - hunting or fowling, or even perhaps ritual activity of some kind. Some very notable concentrations of platforms have been noted, for example at Edercloon, Co. Longford (McDermott *et al* 2009); but the function of these structures remain elusive (Brunning and McDermott 2013, p.367).

The larger types of wooden trackway (e.g. Class 1 toghers) are often the focus of interpretations of human activity in Irish bogs, and therefore, as Stanley (2003, p.65) points out, many archaeologists have tended to over emphasise the notion that bogs represented obstacles, and therefore functional interpretations of trackways tend to predominate. In this vein, Raftery (1996) interpreted the trackways of the Mountdillon Bogs largely in utilitarian terms, albeit alongside a recognition that trackways could also project representations of prestige, power, and beliefs (especially in the case of the massive Corlea 1 trackway). The suite of wetland and dryland archaeological sites uncovered as part of the Lisheen Mine Archaeological Project (Gowen *et al* 2005) was interpreted as a "vernacular landscape. Neither an obstacle to be overcome nor a place of ceremony" (Cross May *et al* 2005a, p.363).

Evidence for ritual activity in Irish raised bogs consists principally of a range of votive deposits, including Bronze Age hoards (Eogan 1983) and the enigmatic bog bodies. Taken as a whole, these appear to be broadly in line with evidence from else where in the British Isles and Europe for the general ritual significance of wetlands, especially in later prehistory (Bradley 1998, 2000). Iron age bog bodies, for example, have been interpreted as being related to rituals connected to kingship and boundaries, physical, political, and spiritual (Kelly 2006). Although evidence directly linking trackways to ritual deposits is as yet rare, recent excavations of Iron Age trackways in Counties Longford (Moore 2008) and Tipperary (Taylor 2008) have uncovered assemblages of unused objects apparently deposited in these bogs.

Implicit, and often explicit, in most accounts of trackways and other peatland structures is the notion that construction is contingent on bog surface conditions in some way: that structures were either constructed to compensate for wet and treacherous surface conditions, or, that construction could only take place if the bog surface was not too wet and unstable, and sometimes both. In order to understand these relationships, several studies have been carried out which integrate the palaeoenvironmental techniques (outlined in section 2.1.7) with archaeological investigations, and these in particular are discussed below. The interpretation of the results of these investigations often intersect with the debates surrounding environmental determinism outlined in the previous section (2.2.4).

2.2.5.1 Trackway construction and environmental change

Raftery's study of the Mountdillon Bogs was the first major project to integrate both archaeological and palaeoenvironmental investigations; conclusions relating to the environmental or climatic context of trackway construction, however, were very tentative, although a “national pattern” of episodes of trackway construction was discerned (Raftery 1996, pp.411–413). This chronological clustering of trackways has in itself been interpreted, principally by Baillie and his colleagues, as evidence for social responses to environmental change, since these clusters appear to be related to growth-ring anomalies in Irish oaks; it has been suggested trackway construction may be a response either to wetter (Baillie 1993) or drier conditions (Baillie and Brown 2002). These studies have stimulated growing discourse about the role of climate in driving social change in Ireland (e.g. Turney *et al* 2006; Swindles and Plunkett 2010). Tensions between the intuitive notion that environmental conditions (e.g. BSW) are likely to have affected human behaviour (e.g. trackway construction), and the methodological (principally chronological) and conceptual difficulties (a general aversion to environmental determinism) associated with testing positivist hypotheses of human-environment interactions can be observed in the existing literature on Irish trackways.

Some studies have suggested chronological correlations between increased trackway construction and drier bog conditions (Brindley and Lanting 1998; Gearey and Caseldine 2006), although the palaeoenvironmental records with which the archaeological records have been compared in the former may be questionable: Brindley and Lanting make their assertion based on a degree of circular argument (that archaeological sites were preserved by a later rise in water tables, and thus are likely to have been built during a preceding dry interval), and potentially spurious links to dendroclimatological data and data from elsewhere in Europe. Gearey and Caseldine's (2006) work was based on combined archaeological and palaeoenvironmental investigations of a single site in Co. Tipperary, but elsewhere they have argued that the BSW records from this site was not climatically sensitive (Caseldine and Gearey 2005), thus implying that trackway construction was related to local bog conditions rather than climate *per se*.

Bermingham (2005), examining the archaeological and palaeoenvironmental record from a bog in Co. Offaly, also argues that trackway construction (and local wetness conditions), were not generally related to climate as such, but appeared to be related to periods of local, mostly autogenic hydrological change. It was therefore concluded that trackway construction was an "opportunistic venture" based on an unspecified combination between environmental conditions and cultural factors (Bermingham 2005, p.266).

Revisiting the apparent chronological structuring observed by Brindley and Lanting (1998) and Raftery (1996), Plunkett et al. (2013) critically examined the links between climate change and trackway construction in Ireland. The archaeological record (database of all published trackway dates) was compared with a composite palaeoclimate record based on six testate amoebae records from Ireland, explicitly excluding records which show evidence for autogenic processes or "considerable human impact" (Plunkett *et al* 2013, p.21). Based on this analysis, no consistent relationship between BSW and trackway construction was found, leading to the inevitable conclusion that trackway construction was governed by "wider cultural trends" (Plunkett *et al* 2013, p.29); meanwhile, apparent local trends observed by Bermingham, and Gearey and Caseldine in their respective studies were dismissed as being unable to explain the strong chronological clustering visible in the archaeological record as a whole. Although the Plunkett et al. (2013) study is a robust critical examination of a deterministic link between *climate* and trackway construction, the study does not directly address the question of relationships between *local* bog (i.e. not necessarily climate-driven) conditions and human activity. Earlier studies focusing on single sites (Bermingham 2005; Gearey and Caseldine 2006) did find correlations between human activity and BSW conditions, but the BSW records from these sites were themselves excluded from Plunkett's analysis. O'Sullivan (2007a, pp.170–171) discusses some of the activities which may have been associated with trackway construction: not only traversing bogs, but also other every-day economic, and ritual practices. These activities, clearly are "culturally-determined" (Plunkett *et al* 2013, p.28) whilst simultaneously being fundamentally linked to, and contingent upon, the raised bog environment – with it's distinctive flora, fauna, and physical characteristics. It is perhaps ironic, given that Plunkett et al. (2013, p.18) are so critical of "the limitations of even the most plausible climatically-determined theories", that they should point to functionalist theories of the impact of climate on agricultural output (Plunkett *et al* 2013, p.29) as a focus of future research; similarly, Plunkett et al. (2013, p.29) "draw attention to the potential pitfalls of interpreting cause-and-effect on the basis of close temporal proximity of cultural and climate changes", but offer no other means of conceptualising or testing the effects of climate other than chronological correlation between climate change and potential economic impact.

In recent years, there have been challenges to the dominance of functionalist and economically deterministic approaches in environmental archaeology; a good example is Evans' (2003) *Environmental Archaeology and the Social Order*. Head discusses the "trouble" that physical geographers (and palaeoecologists) are having with "culture" (Head 2000, p.3), and goes on to discuss ways in which approaches based on contingency, borrowed from the humanities, may offer better interpretive frameworks. Head argues that human society and the natural environment are mutually constituted (Head 2000, p.8), and thus goes on to even challenge the very concept of "humans impacts" on the environment (Head 2008). Adopting such an approach, the attempts of Plunkett et al. (2013) to separate human and climatic influence may be challenged. Indeed, it does not follow that the sites chosen to provide palaeoenvironmental records are free of human influence simply because archaeological sites have not been excavated there; all the sites are largely intact bogs (Plunkett *et al* 2004; Blundell *et al* 2008; Swindles *et al* 2009; Langdon *et al* 2012) and therefore any archaeology present in these sites will not have been uncovered.

Plunkett et al. (2013, p.22) state that their palaeoclimatic records show a great degree of variability, however the conceptual framework applied to their interpretation of the archaeological evidence ignores variability in favour of an overly-simplistic model: that trackway construction either is or is not driven by climate. This arguably reinforces simplistic or deterministic reasoning. A better model, based on the historically and locally contingent relationships between humans and the environment, would emphasise variable processes and circumstances, and would provide a more nuanced understanding (Head 2000, p.7). Environmentally deterministic models of human-environment relationships can be rejected on theoretical grounds (Thomas 1990; Coombes and Barber 2005), and, in the case of the Irish peatland archaeological record, are not supported by the data (Plunkett *et al* 2013);

nevertheless, natural places were clearly significant to past societies (Bradley 2000; O'Sullivan 2007a), and palaeoenvironmental work provides objective representations of past environments through which social relationships were explored (Evans 2003), thus adopting conceptual models emphasising contingent relationships can provide a more nuanced and useful understanding of the wetland archaeological record (Head 2000).

2.3 Conclusion

Quantitative palaeoenvironmental analysis from raised bogs, particularly utilising testate amoebae analysis, has been shown to have great potential to further our understanding both of mid to late Holocene climatic variability and of autogenic bog processes. Ireland is well-placed to examine the effects of changes in circulation patterns over the North Atlantic, typically lying in the path of the Westerlies. Recent work has focused on improving the coverage of proxy records with the aim of producing regional composite records; as such further work is required to validate our present understanding and to further explore apparent phases of disagreement between records. In spite of the widespread distribution of raised bogs in central Ireland, relatively few sites have been studied in detail.

Alongside the great potential of palaeoclimate studies, Irish raised bogs are also notable for their archaeological records; as such these sites provide a rare opportunity to examine well-dated archaeological evidence alongside palaeoenvironmental records derived from the same sites. The role of climate change in driving societal change generally, and human activity in wetlands more specifically has been the subject of considerable debate. Whilst efforts have been directed at examining the general patterns of archaeological activity in Irish raised bogs, relatively little work has has utilised environmental and archaeological data from the same sites. Where such investigations have taken place, results have been inconclusive.

This thesis, therefore aims to address these issues. In addition to improving understanding of the responses of testate amoebae to hydrological conditions (Chapter 6), and recent drivers of the BSW record in Ireland (Chapter 8), Palaeoenvironmental data from nine sites in central Ireland are presented (Chapter 7). These records can then be compared with each other and with existing records (Chapter 9). This study is unique in that archaeological data is available from all nine fossil study sites. The primary aim of this thesis, therefore, is to critically examine links between environmental change and human activity on Irish raised bogs (Chapter 10), and to test whether broad patterns observed in other studies hold true when examined on a site-by-site basis. Furthermore, this study will examine evidence for human-environment relationships in the light of more recent theoretical and interpretative frameworks to better illustrate the potential offered by such studies.

Chapter 3: Study sites

3.1 Study area – central Ireland

The study area for this thesis is central Ireland, see Figure 1. The raised bog, and former raised bog, sites analysed in this project are in Counties Roscommon, Longford, Meath, Offaly, Galway, Tipperary North and Laois. Archaeological evidence from adjoining parts of Counties Tipperary South, Kilkenny and Westmeath are also examined. The study area therefore covers much of the Midlands Region of Ireland (Counties Longford, Westmeath, Offaly and Laois), and some neighbouring portions of the Mid-East, Mid-West and West Regions. The regional capital of the Midlands is Athlone, Co. Westmeath, which is near the geographical centre of Ireland, and in the centre of the study area; other important settlements in the general study area include Mullingar, Co. Westmeath, Tullamore, Co. Offaly, Longford, Co. Longford, Ballinasloe, Co. Galway and Thurles, Co. Tipperary North. The Midlands region is relatively sparsely populated, with a population density of 34.6 persons per square km, compared with a population density of 65.3 persons per square km for Ireland generally. The most important industry in the Midlands is the peat industry, including both industrial peat harvesting, and peat-fired electricity generation (The Irish Regions Office 2012).

The region is characterised by generally flat or gently undulating topography dominated by the River Shannon (Whittow 1975), with mainly Dinantian (lower Carboniferous) limestone geology (Delaney 1997a), often with thick superficial till deposits (Delaney 1997b). Peatlands are a common feature across the region (Mitchell and Ryan 1997), with the area covered by this study broadly corresponding to the main concentrations of Midland-type raised bogs, and milled production bogs (Hammond 1981). Mean temperature is relatively homogeneous across the region at 9-10ºC (Met Éireann 2013a). Mean annual rainfall across the region is generally between 800 and 1000 mm, with the sites in Co. Galway having slightly higher rainfall (~1000 mm annually) lying near to the 1000 mm isohyet (Met Éireann 2013b), which largely corresponds to the division in distribution between the Midland and Transitional floristic sub-types of raised bogs (Moore 1962; Hammond 1981; Ward *et al* 2007).

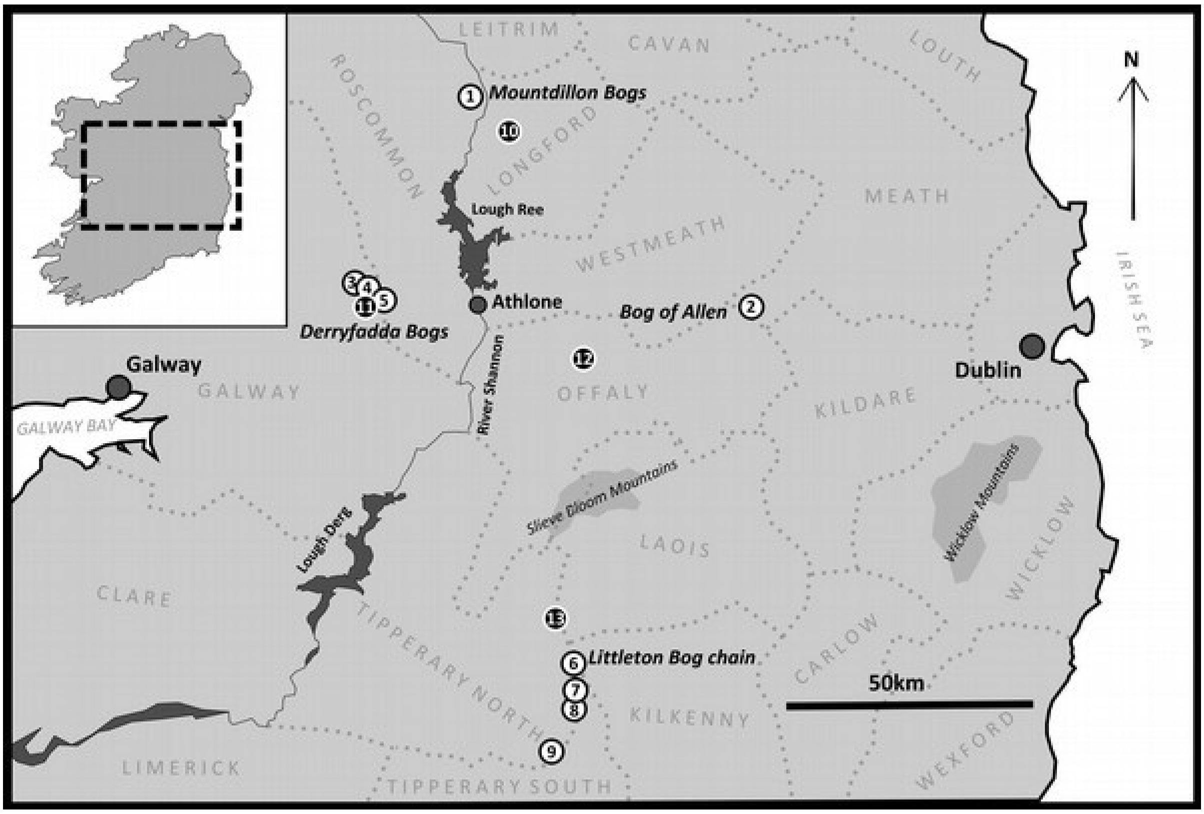

Figure 1: General map of the study area in central Ireland. White circles are milled bogs from which fossil sequences have been analysed, black circles are intact raised bogs sampled for the transfer function training set. 1 – Cloonshannagh; 2 – Kinnegad; 3 – Gowla; 4 – Killaderry; 5 – Castlegar; 6 – Inchirourke; 7 – Longfordpass; 8 – Littleton; 9 – Killeen; 10 – Brown bog; 11 – Annaghbeg; 12 – Clara East; 13 – Ballagharahin.

3.2 Fossil sequences – milled bogs

Fossil sequences from nine milled production bogs in central Ireland have been analysed. These are: Cloonshannagh bog, Co. Roscommon; Kinnegad bog, Co. Meath; Gowla, Killaderry and Castlegar bogs, Co. Galway; Inchirourke, Longfordpass, Littleton and Killeen bogs, Co. Tipperary. These sites therefore skirt the fringes of the central plain of Ireland. Bord na Móna PLC, who own and work all the study sites analysed here, are the largest peat production company in Ireland, owning around 7.5% of the peatlands of Ireland, with 25,000ha of peatland in production concentrated in the region covered by this study (Bord na Móna 2013). As mentioned above, all the fossil sequences analysed here come from milled production bogs. These sites are usually former raised bogs which have been drained, and milled flat. During the process of production, a series of parallel drainage ditches, 1.4m deep and 1.5m wide at the top, are cut across the bog at *c.*15m intervals. The partially dried surface of the bog is then milled and removed for use as fuel (Bord na Móna 2011). The surfaces of these bogs are therefore almost entirely unvegetaged, although some scattered *Calluna* and *Cladonia* do occur in areas which have not been recently disturbed, and *Phragmites* occasionally occurs in the base of some drainage ditches which have not been recently re-cut. Areas of abandoned cutover bog on the fringes of some of the study sites, which have often flooded occasionally show some signs of regeneration, with occasional patches of *Sphagnum* spp. and other bryophytes.

Study sites within the study area were selected on the basis of two main criteria: a) the availability of dated archaeological data; and, b) the presence of ombrotrophic peat strata that were likely to date to around the time of the dated archaeological features at the site. One potential study site, Mountdillon bog, Co. Roscommon, was rejected since, at the time of visiting in 2011, almost all of the ombrotrophic peat had been removed from the site by milling.

The nine study sites occur in four parts of the study area: in the north is Cloonshannagh bog, in the east is Kinnegad bog, to the west is the Derryfadda group of bogs (Gowla, Killaderry and Castlegar bogs) and in the south is another cluster of bogs, the Littleton chain of bogs (Inchirourke, Longfordpass, Littleton and Killeen bogs). This will therefore allow both north-south and east-west variation to be investigated. The specific characteristics of each of the four clusters and all the individual sites are detailed below.

3.2.1 Mountdillon bogs: Cloonshannagh bog, Co. Roscommon

Cloonshannagh bog is part of the Mountdillon group of Bord na Móna bogs. These peatlands are part of a broad belt *c.*20km wide from east to west on either side of the Shannon stretching for *c.*25km north from Lough Ree characterised by small scattered lakes and raised bogs. The underlying geology of this part of the Shannon valley is predominantly limestones of Carboniferous age, with hills formed by outcropping rocks of Ordovician age either side of the belt of wetlands beside the river which have formed in numerous depressions in the surface topography left by Pleistocene glacial action. At the nearby Mountdillon weather station mean annual rainfall of 1047.1mm and mean temperature of 9.6ºC have been recorded for the period 1981-2010 (Met Éireann 2012).

Cloonshannagh bog (53°46'37"N, 7°56'48"W) is located in eastern Co. Roscommon, at an altitude of 45m O.D., *c.*11km north west of Longford and *c.*3km west of Lough Forbes on the River Shannon, the Feerish River, a small tributary of the Shannon is just to the west, see

Figure 2. The site is mostly located within the Cloonshannagh townland, but the western part of the site lies within the Caul townland. The site is a roughly triangular area of milled Bord na Móna production bog measuring *c.*3.6km from east to west, and *c.*2km from north to south and is a former raised bog.

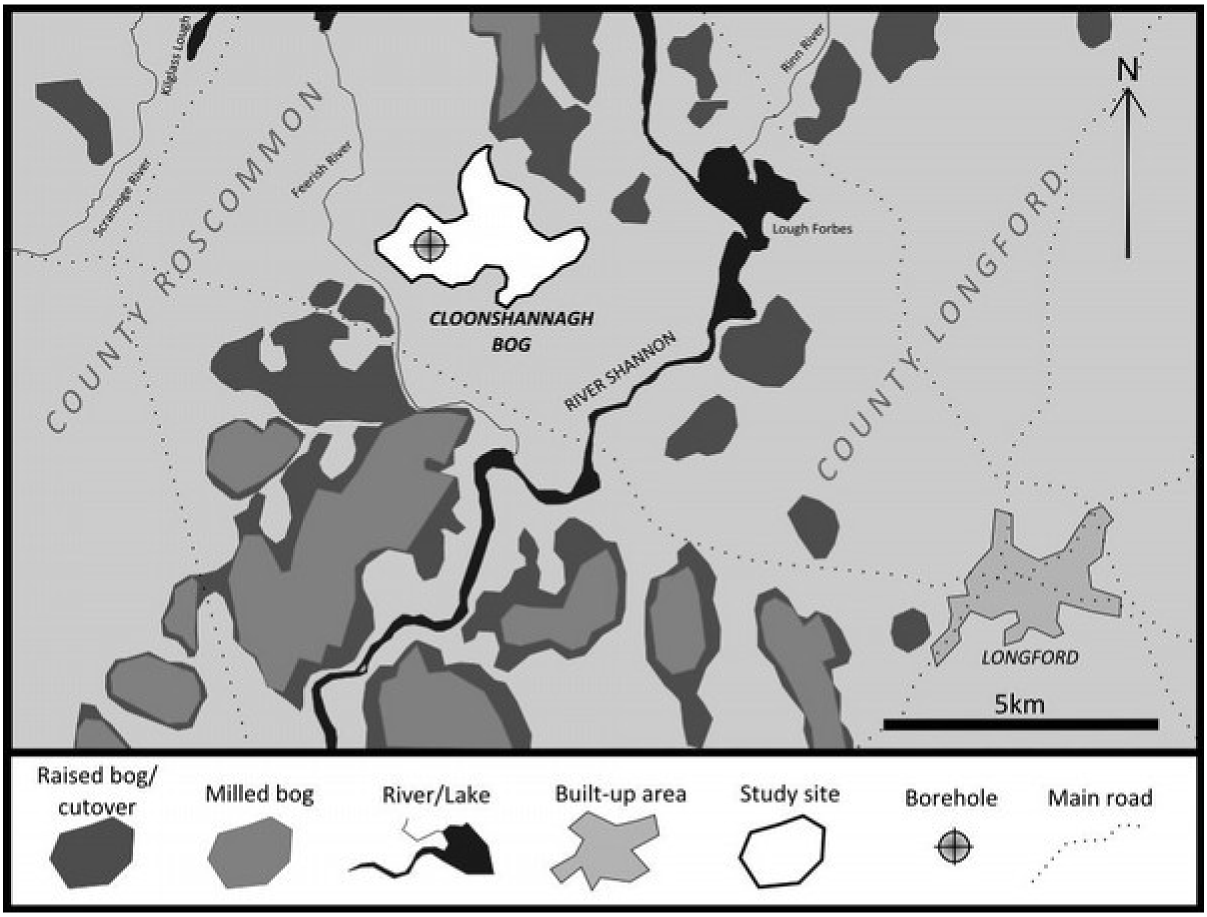

Figure 2: Location of Cloonshannagh bog, Co. Roscommon.

3.2.2 Bog of Allen: Kinnegad bog, Co. Meath

Kinnegad bog is one part of the Bog of Allen, the collective term for the extensive areas of raised bogs and milled production bogs which extend westwards from western Co. Meath, across Co. Offaly and into parts of Co. Westmeath and Co. Kildare (Hammond 1981). Kinnegad bog (53°26'7"N, 7°6'6"W), altitude 80m O.D., is located 1.2km south of the town of Kinnegad, near the western border of Co. Meath and close to the borders of Counties Westmeath to the north, Kildare to the south and Offaly to the west, see Figure 3. The Kinnegad River, a small tributary of the River Boyne, flows less than 1km north of the site. The underlying geology of the area is mainly composed of Pleistocene deposits, mainly limestone-derived tills (Pellicer 2010) overlying Carboniferous limestones (Coxon *et al* 1987). At the Mullingar weather station in County Westmeath, 18 km to the north west, mean annual rainfall of 970.9mm and a mean temperature of 9.3°C have been recorded for the period 1981-2010 (Met Éireann 2012).

The site, a former raised bog, is located in Rossan, Killaskillen and Moydrum townlands. Kinnegad bog measures 2.3km from east to west and 1.8 km from north to south, the vast majority of the site is in industrial production, although there are some small areas of hand-cut turbery along the eastern margins of the site.

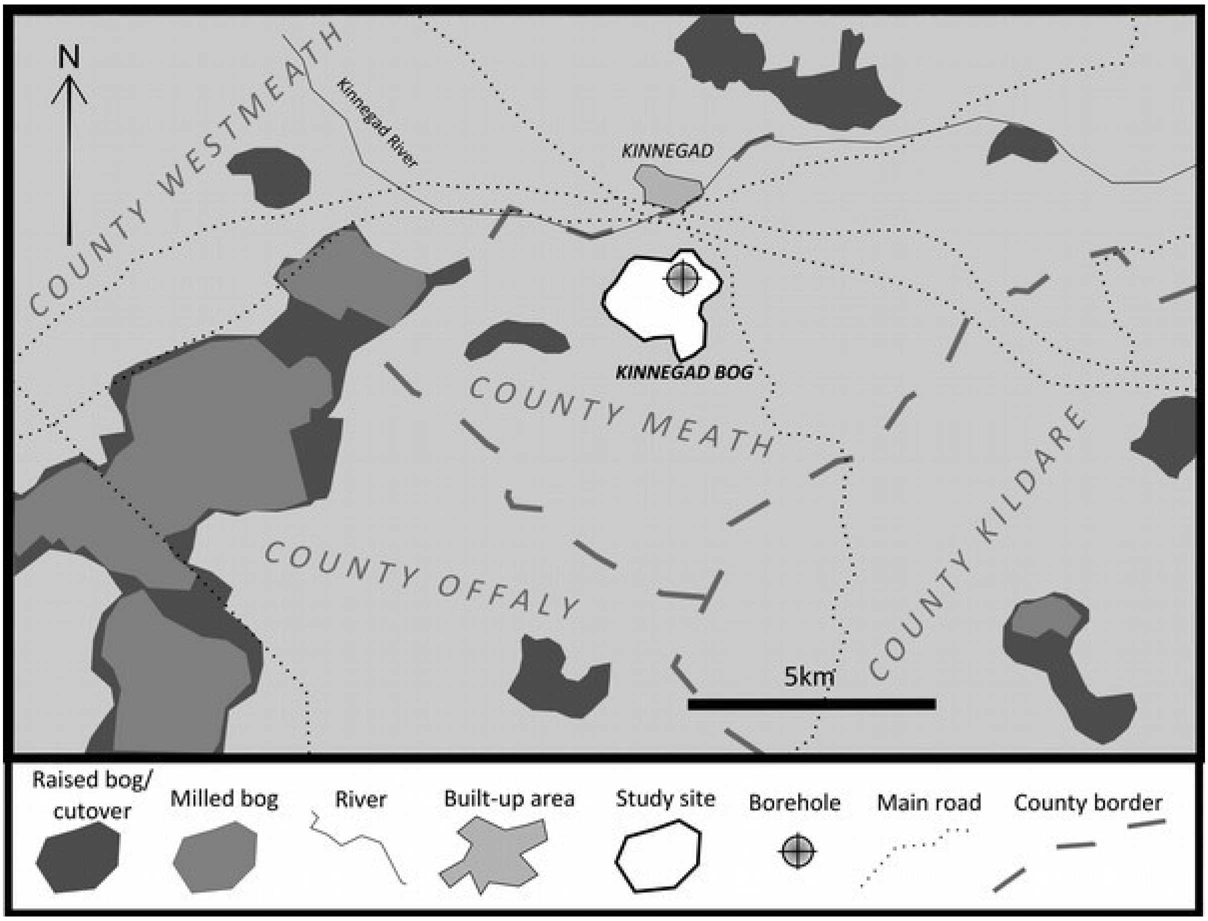

Figure 3: Location of Kinnegad bog, Co. Meath.

3.2.3 Derryfadda bogs: Gowla, Killaderry and Castlegar bogs, Co. Galway

The Derryfadda group of bogs lie 3-4km east of Ahascragh and *c*.10km north of Ballinasloe on the western bank of the middle reaches of the River Suck, which forms the eastern border of Co. Galway, see Figure 5. The Suck is one of the principal tributaries of the Shannon, and like the middle reaches of the Shannon (between Lough Ree in the north and

Lough Derg in the south), the middle and lower reaches of the river are flanked by seasonally-flooded grasslands known as callows. Both the Shannon and the Suck Callows are designated protected sites: proposed Natural Heritage Area 000216 and Natural Heritage Area 000222, respectively (National Parks and Wildlife Services 2012). The Derryfadda group of bogs are part of a complex of several raised bogs which have formed on either side of the River Suck amongst the callows. The areas on either side of the middle Shannon and the Suck therefore form near-continuous areas of wetlands, where ombrotrophic bogs have formed in the poorly-drained areas surrounding these low-energy river systems (Brown *et al* 2007). Work carried out on the sediments of the Little Brosna River valley (another tributary of the Shannon, *c.*18km south of the confluence of the Suck and Shannon) have shown that the Shannon River system was, during the early Holocene a large lacustrine system which in-filled to form the present-day river system surrounded by callows around 4300 – 4150 BP, and that this was associated with the formation of ombrotrophic bogs in the floodplains (Aalbersberg 1994). In common with most of the entire study area, the underlying geology is predominantly Carboniferous limestones covered by glacial till.

Figure 4: Gowla bog. Note the parallel drainage ditches and the pile of harvested peat on the left hand side. Photograph by the author.

Monthly and annual weather data have been recorded form two weather stations near to the Derryfadda group of bogs. At Athenry, Co. Galway, 33km west of the Derryfadda bogs, the period 1981-2010 has seen mean annual rainfall of 1192.2 mm and a mean temperature of 10ºC; at Gurteen, Co. Offaly, 40 km south east of the bogs, mean annual rainfall was 948.2mm and mean temperature 9.8ºC over the same period (Met Éireann 2012). These sites therefore lie close to the 1000mm isohyet; as a result intact raised bogs in the area include those with both true Midland-type and Transitional-type bog flora (Moore 1962).

Three bogs in the Derryfadda group have been analysed, from north to south these are: Gowla bog, Killaderry bog and Castlegar bog. All three sites are former raised bogs currently in industrial peat production.

Gowla bog (53°26'33"N, 8°18'57"W), altitude 50m O.D., is located 4.6 km north of Ahascragh, Co. Galway, and *c.*3 km from the west bank of the River Suck. Gowla bog is partially within the Gowla, Killaderry and Cloonshee townlands. The site itself measures 1.4km from north to south and 1km from east to west, and is part of a continuous area of milled peatland joining on to Killaderry bog to the south, and other production bogs to the north.

Killaderry bog (53°25'37"N, 8°16'30"W), altitude 45m O.D., is located 4.4km north-east of Ahascragh and is *c.*200m from the River Suck, and lies within the Killaderry, Cloonshee and Acre East townlands. Killaderry bog measures 2km north west to south east and 1.1km from north east to south west.

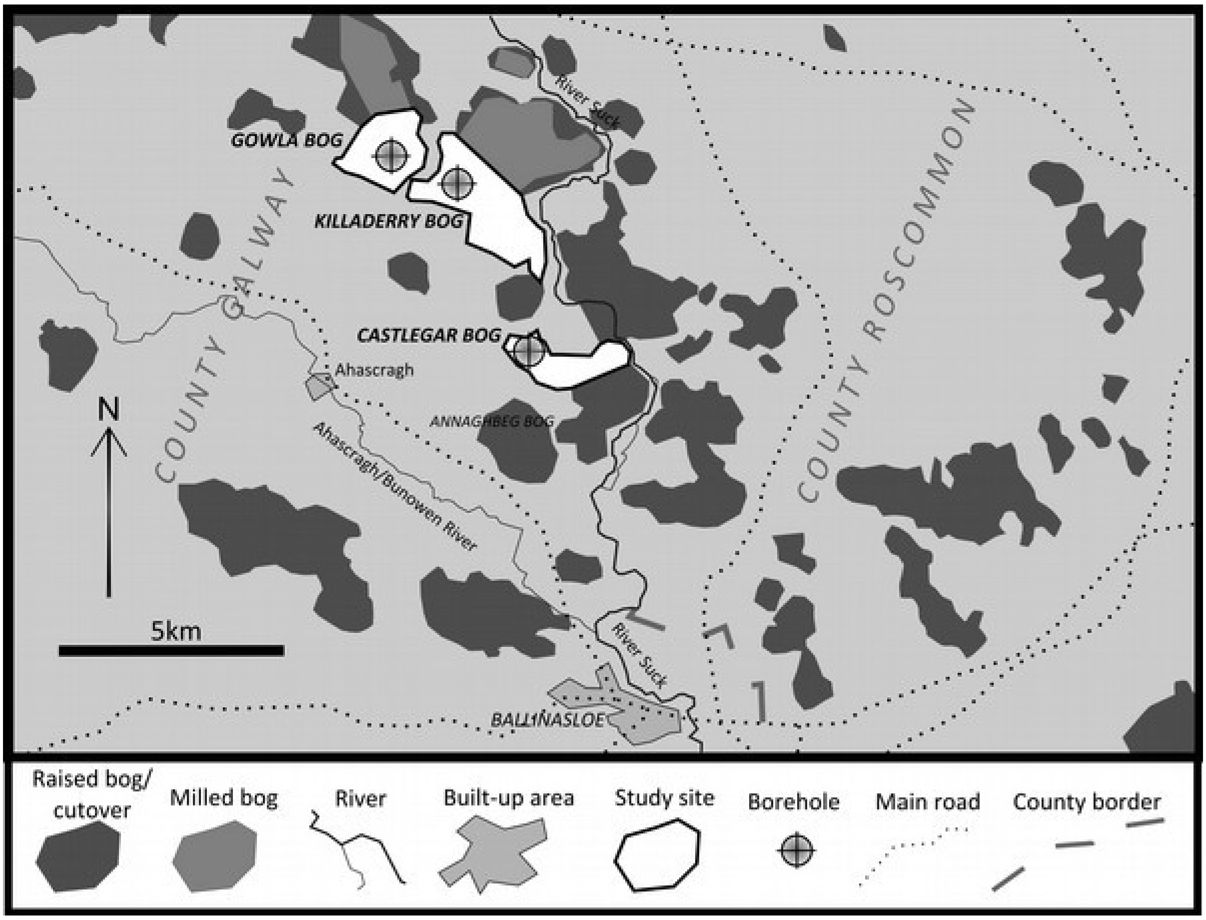

Figure 5: Location map showing the Derryfadda group of bogs.

Castlegar bog (53°24'4"N, 8°14'56"W), 45m O.D., is 3.8km east of Ahascragh and continues up to the western bank of the River Suck. The site is overlooked by the ruins of Eglish Abbey which is situated on a hill of glacial till 1km to the south west. Castlegar bog is located in the Knockaunroe, Eglish and Kilcrin townlands. The site is 2.6km long from east to west, and 1km wide from north to south. This site is separated from the other study sites in this group of bogs by a small island of dry land formed by a small mound of glacial till to the north west.

3.2.4 Littleton chain: Inchirourke, Longfordpass, Littleton and Killeen bogs, Co. Tipperary

Extending some 40km running roughly north to south from near the Slieve Bloom mountains towards the Slieveardagh Hills and Cashel in the south, the Littleton chain of bogs is a near-continuous series of raised bogs, and former raised bogs *c.*10km east of Thurles, Co. Tipperary, and the River Suir, see Figure 6. Two streams which flow westwards into the Suir, the Black River and Clover River drain the western edges of the Littleton chain of bogs. The underlying geology of the area is Carboniferous limestone capped with Glacial till and these bogs may have formed in a glacial valley or tongue basin (Casparie and Gowen 2005). with elevations generally around 100 to 120m O.D. 5 to 10km to the south east of the chain of bogs, running from the north east to the south west is a ridge formed of Carboniferous shale (including coal-bearing deposits) and sandstone, reaching up to *c.*300m O.D, whilst 15km west of Thurles, Devonian and Silurian sandstones form another ridge of hills, reaching up to *c.*400m O.D. The Littleton chain of bogs form the eastern boundary between Tipperary North and Counties Laois, Kilkenny, and Tipperary South.

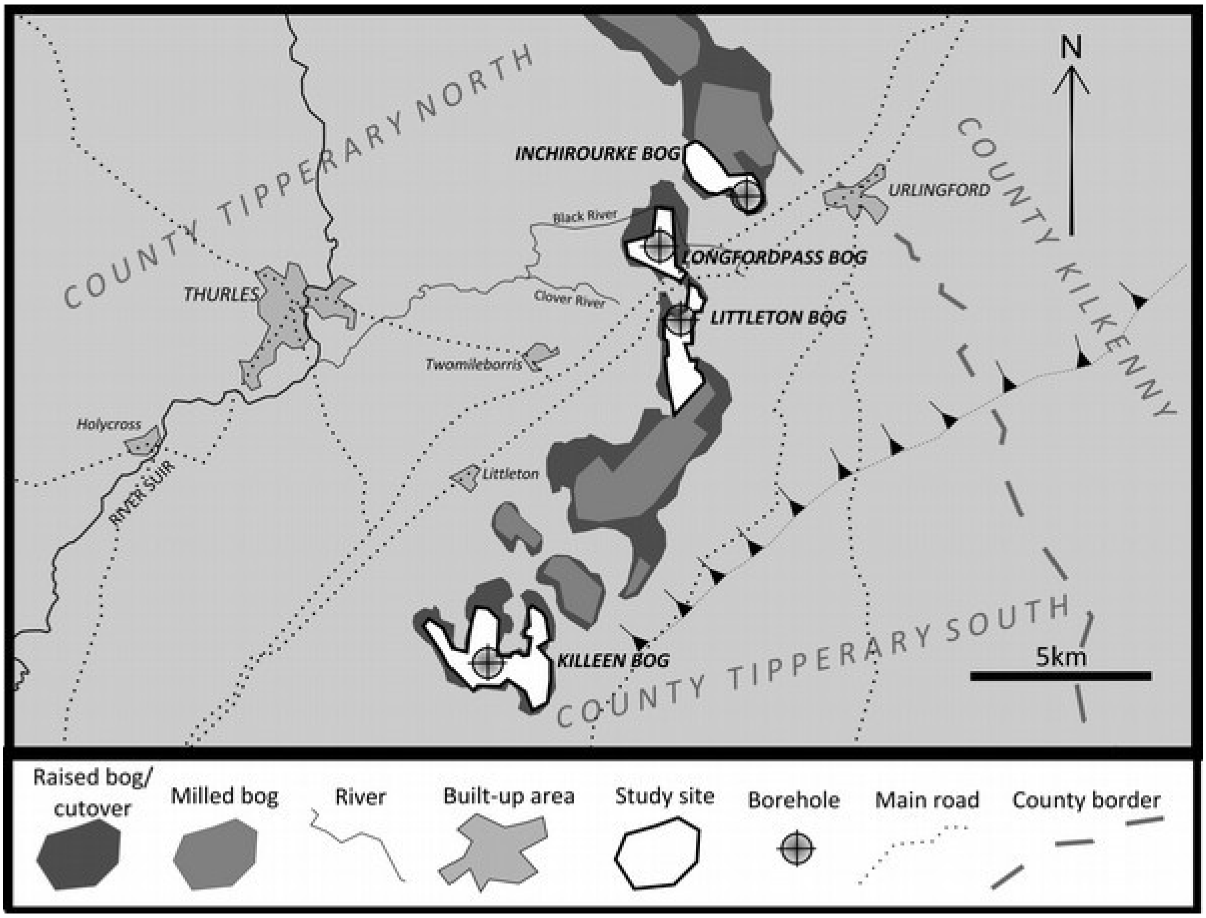

Figure 6: Location map showing the Littleton chain of bogs, note that the chain of bogs continues further to the north. Hachures show the edge of the shale ridge south east of the bogs.

At Gurteen weather station, Co. Offaly, 46km north of the Littleton chain of bogs, mean annual rainfall was 948.2mm and mean temperature was 9.8ºC for the period 1981-2010 (Met Éireann 2012).

The Littleton complex is notable for previous work carried out by Mitchell (1956, 1965) which defined the main phases of Holocene vegetation history in Ireland, and thus functions as the type site for the Holocene – referred to as the 'Littletonian' in older Irish literature (Mitchell 1981).

Four milled bogs in the southern part of the Littleton chain of bogs have been analysed; from north to south these are: Inchirourke, Longfordpass, Littleton and, at the southern end of the chain of bogs, Killeen bog.

Inchirourke bog (52°42'57"N, 7°37'59"W), altitude 125m O.D., is located 2.8 km west of the town of Urlingford, Co. Kilkenny, and 11 km north east of Thurles, Co. Tipperary. The Black River flows 1.3km south of the site. Inchirourke bog is located almost entirely within the Inchirourke townland. The bog itself consists of two lobes, a lobe in the north west measuring c.800m in diameter joined on to a larger area of bog in the south east measuring 1 km north to south and 800m east to west, sampling was carried out on the larger area in the south and east.

Longfordpass bog (52°41'56"N, 7°39'40"W), altitude 125m O.D., is 5.4km south west of Urlingford, Co. Kilkenny, 4km north east of Twomileborris, and 9km east of Thurles, Co. Tipperary. The site is located partially in the Kilmakill and the Longfordpass North townlands. The bog measures *c.*2km from north to south and *c.*1km from east to west, with small areas of tree plantation on both the northern and southern ends of the site. The M8 motorway runs immediately to the south of the site, separating it from Littleton bog just to the south.

Littleton bog (52°40'50"N, 7°39'19"W), altitude 130m O.D., is 3km east of Twomileborris and 8.3km east of Thurles, Co. Tipperary. Littleton bog is located at the boundaries of Leigh, Longford pass North and Longfordpass South townlands. The site itself measures 3km from north to south and 700m from east to west, with samples taken from the northern part of the bog.

Killeen bog (52°35'60"N, 7°43'47"W), altitude 130m O.D., is 7km south of Twomileborris, and 9km south east of Thurles, Co. Tipperary. The site straddles the administrative boundary between Tipperary North and Tipperary South, and is located in the townlands of Lurgoe, Derricknew, Ballintogher, Cooldine and Killeen. Killeen bog is an irregularly-shaped area of milled bog measuring 3.5km east to west and 2km from north to south, likely to consist of several smaller basins.

3.3 Transfer function and recent sequences – uncut bogs

Four uncut raised bogs in central Ireland have been analysed in this project to provide surface samples for the construction of the new central Ireland testate amoebae transfer function. These sites fall within the general study area outlined above. The uncut bogs analysed in this study are, from north to south: Brown Bog, Co. Longford; Annaghbeg bog, Co. Galway; Clara bog, Co. Offaly; and Ballagharahin bog, Co. Laois.

Few, if any, raised bogs remain completely undisturbed by peat cutting in Ireland. Peat cutting has been a major source of fuel in Ireland for several centuries; by the 18th century turf was the main domestic fuel in use (Clarke 2006), and today, alongside industrialised peat production as carried out by Bord na Móna on the milled production bogs, turf cutting is still widely practised on the fringes of many smaller bogs in spite of increasing efforts by the Irish and EU governments to curb the practice, especially on the growing number of protected sites (McDonald 2011; Smyth 2012). Although referred to as 'uncut' the study sites described below have all been cut or disturbed in some way, but crucially they all still possess an intact acrotelm, and retain floristic assemblages and features such as hummock-lawn-hollow complexes, pools, soaks and flush systems which are indicative of intact or relatively intact raised bogs.

Details of each site are given below.

3.3.1 Brown Bog, Co. Longford

Brown bog (53º43'53"N, 7º51'13"W), at an altitude of 48m O.D., is located 3.2km west north west of Longford, Co. Longford, immediately north of the N5 road from Longford towards the west coast, *c.*5km from the east bank of the River Shannon and the Mountdillon group of bogs, see Figure 7. The site is located in the Tully, Lissanurlan and Cartonlebagh townlands. Brown bog is situated in a small depression in the limestone-derived Glacial till which overlies the Carboniferous limestone which underlies much of the area around the site. At the Mountdillon weather station, *c.*10km west of Brown bog, mean annual rainfall of 1047.1mm and mean temperature of 9.6ºC have been recorded for the period 1981-2010 (Met Éireann 2012).

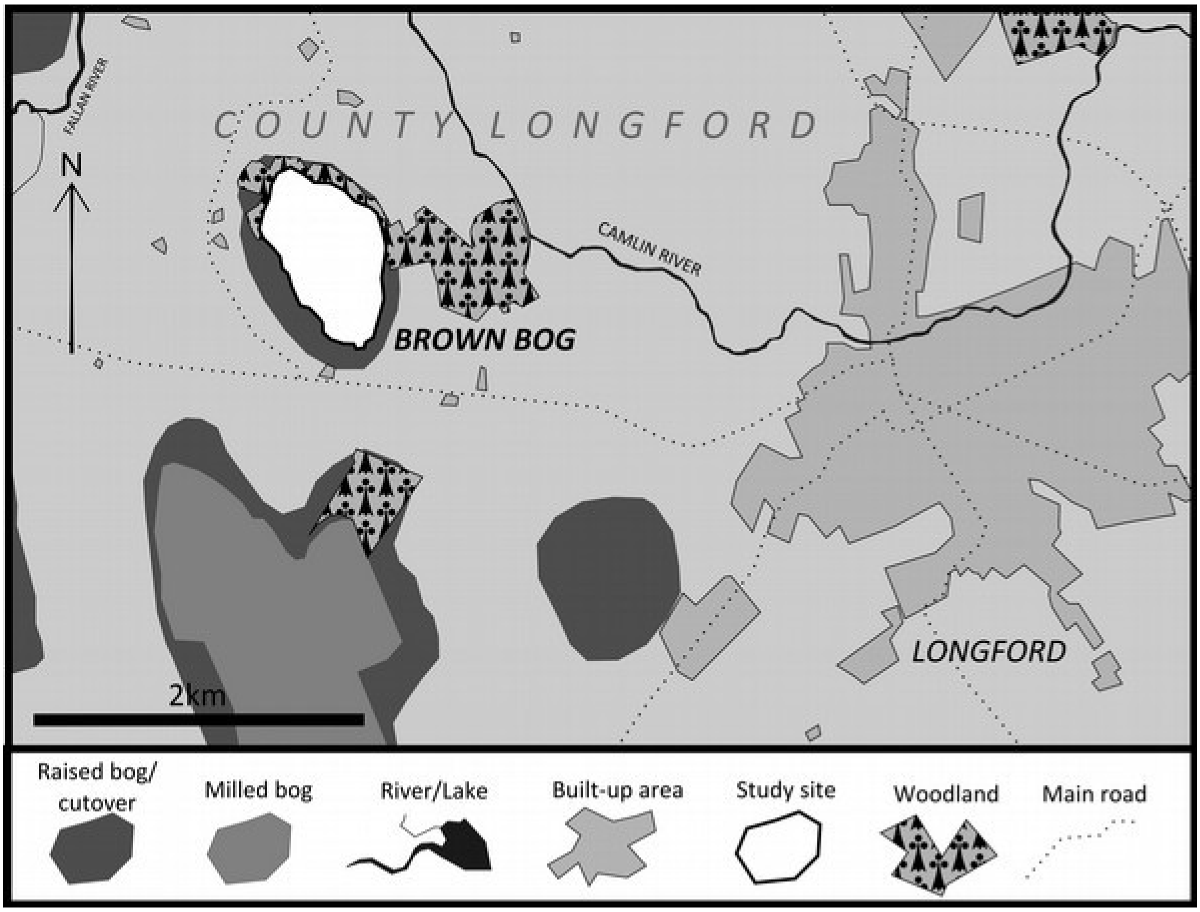

Figure 7: Location of Brown bog, Co. Longford.

Brown Bog is designated a special area of conservation (SAC002346) and is a proposed natural heritage area (NHA000442). Brown bog is a small, roughly oval-shaped raised mire measuring 1100m from north to south and 750m at its widest from east to west. The bog is surrounded on all sides by pasture, and there is a small plantation of pine trees on the eastern margins of the site, and remnants of old deciduous woodland to the north west. The dome of Brown bog is almost entirely intact, most of the edges of the bog are covered with damp, scrubby *Betula* wooded areas on abandoned cutover bog, although there is a small amount of turbery at the southern end of the site (National Parks and Wildlife Services 2011b). The vegetation of the site is typical of a Midland-type raised bog, and Brown Bog is one of the most intact examples of this kind of bog in Ireland. The centre of the bog is extremely wet, with several large (>2m long) and deep (>1.5m) pools. Flowing northwards from the central part of the dome, there is a flush system (see Figure 8). In the wet central part of the bog there is a wide variety of *Sphagnum* mosses, including the relatively rare *S. imbricatum*, with hummocks of *S.* sect. Acutifolia spp, and lawns and hollows containing *S. papillosum* and *S. magallenicum*, and pools containing *S. cuspidatum*. In the flush, in the northern part of the bog, vegetation indicative of slightly enriched conditions occur including *Sphagnum* sect. Subsecunda. Other species present on the wetter parts of the bog include *Rynchospora* spp. and *Drosera* spp. and abundant *Menyanthes trifoliata* in the pools and wetter hollows; whilst *Cladonia* spp. and *Calluna vulgaris* occurring on top of the larger hummocks. The southern parts of the bog, perhaps due to more recent (albeit limited) peat cutting, are somewhat drier and may be classified as degraded raised bog; vegetation here is more dominated by *Calluna vulgaris*, *Erica tetralix*, *Eriophorum vaginatum* with some *Sphagnum*, mainly *S.* sect. Acutifolia spp. Occasional to rare *Myrica gale*, *Vaccinium oxycoccos* and *Andromeda polifolia* also occur on Brown Bog.

Figure 8: View of the flush on Brown bog. Photograph by the author.

3.3.2 Annaghbeg bog, Co. Galway

Annaghbeg bog (53º22'58"N, 8º16'12"W), altitude 52m O.D., is located 5km north of Ballinasloe, and 3.6km south east of Ahascragh, Co. Galway, and is 1.5km west of the River Suck, in eastern Co. Galway, see Figure 10. Annaghbeg bog is located within the Derryfadda group of bogs, and is mostly owned by Bord na Móna. The site is within the Addergoole

West, Addergoole North, Gortbrackmoor and Annaghbeg townlands. Annaghbeg bog occurs in a depression in the undulating surface of glacial limestone-derived tills which overlie the local Carboniferous limestone; this bog was formerly part of a larger system of raised bogs which have now been milled, including Castlegar bog (see above) which is *c.*500m north of Annaghbeg. These bogs, the Derryfadda group of bogs (see above), have formed in the floodplain of the River Suck, which is flanked by seasonally-flooded grasslands, known as the Suck Callows. Monthly and annual weather data have been recorded form two weather stations near to Annaghbeg bog; at Athenry, Co. Galway, 32km west of the site, the period 1981-2010 has seen mean annual rainfall of 1192.2 mm and a mean temperature of 10ºC; at Gurteen, Co. Offaly, 38km to the south east, mean annual rainfall was 948.2mm and mean temperature 9.8ºC over the same period (Met Éireann 2012). Annaghbeg therefore lies close to the 1000mm isohyet; as a result intact raised bogs in the area include those with both true Midland-type and Transitional-type bog flora (Moore 1962), and Annaghbeg has features of both floristic assemblages.

Figure 9: Blocked drainage ditch on Annaghbeg bog. Photograph by the author.

Annaghbeg bog is designated a Natural Heritage Area (NHA002344) (National Parks and Wildlife Services 2003). The site is a small roughly oval-shaped raised bog, measuring 1.5km from north to south, and 1.4km from east to west. Although Annaghbeg is mostly owned by Bord na Móna, the site has not been developed for industrial peat production, unlike the other sites in the Derryfadda group; some initial drainage ditches were cut across the bog in the 1980s to prepare the site for milling (E. McDonagh, *pers. comm.*), these have since been abandoned and blocked and are now filled with floating mats of *Sphagnum cuspidatum* (see Figure 9). Although the site has not been subjected to peat milling, all the margins of the bog have been affected by peat cutting, and, in spite of a government ban on turf cutting on protected bogs coming into force in 2011 (McDonald 2012), turf cutting was still being practised at the site during summer 2012.

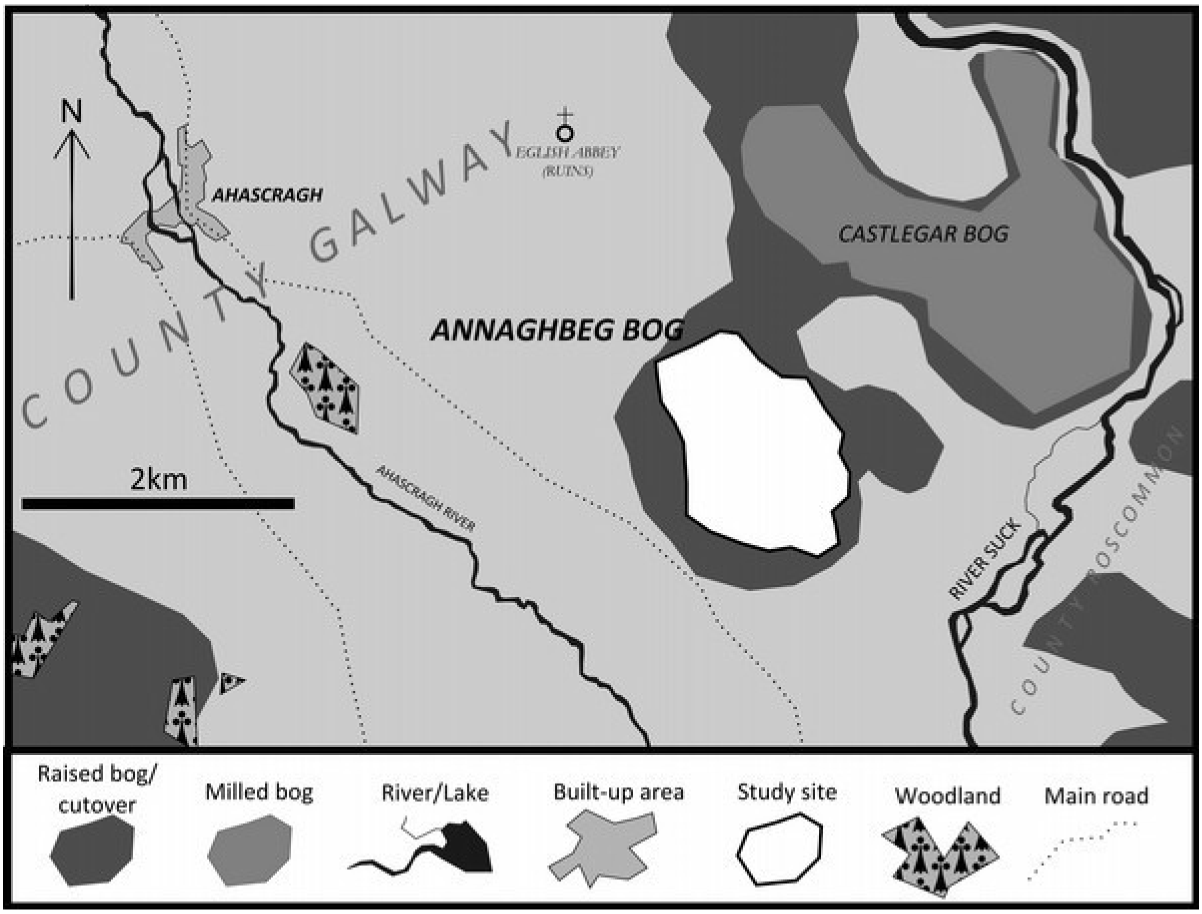

Figure 10: Location of Annaghbeg bog, Co. Galway.

The dome of Annaghbeg bog is still largely intact, with an area in the centre of the bog which features some well-developed hummock-lawn-hollow-pool microtopography. In the northern part of the bog is the remnant of a soak (natural internal drainage system), which appears to have been partially modified by human activity by running several (now blocked) small drainage ditches off from the natural drainage channels. Large areas of the bogs are covered with high bog vegetation with features of both Midland-type raised bogs – *Calluna vulgaris*, *Scirpus cespitosus*, *Narthesium ossifragum* and *Eriophorum vaginatum*, as well as Western-type raised bog flora – *Carex panicea* and *Rynchospora alba*. *Vaccinium oxycoccos* and *Andromeda polifolia* also occur across much of the bog, alongside abundant *Cladonia rangifera* across the drier, heath-like areas of much of the high bog. In the wetter part of the dome of the bog there is more extensive *Sphagnum* moss cover featuring hummocks of *Sphagnum* sect. Acutifolia, *S. magallenicum* and *S. papillosum* in the lawns and hollows, and *S. cuspidatum* in the wetter hollows, pools and infilling blocked drainage ditches. In this area of the bog, *Calluna vulgaris* and *Cladonia* spp. occur on the tops of the hummocks, with

Rynchospora spp. and *Drosera* spp. throughout the lawn and hummock areas, and *Menyanthes trifoliata* in the pools. In the remnant soak area towards the northern part of the bog is a large area dominated by *Myrica gale*, with other non-*Sphagnum* bryophytes and grasses including *Molinia caerulea* indicating slightly more enriched conditions; this area is however, presumably due to human activities at the site, rather dry.

3.3.3 Clara bog East, Co. Offaly

Clara bog East (53°19'13"N, 7°36'53"W), altitude 56m O.D., is located 1.5km south of the town of Clara, Co. Offaly, see Figure 12. The River Brosna flows *c.*1km to the north of the site, and the Silver River, a small tributary of the Brosna, flows *c.* 600m to the south. The site is located mostly in the Erry and the Doory townlands. The Erry Mill road runs roughly north to south across the centre of Clara bog, dividing the site into eastern and western halves, samples have been collected from the eastern part of this site. Clara bog occupies a depression in the undulating surface of 'clayey gravel till' and 'sandy gravel till' deposited during the last glaciation between the mainly east-west trending eskers which are a feature of the area, these overlie Carboniferous limestone bedrock (Smyth 1997). Connolly (1997) has studied the development and vegetation history of the site – peat formation began at around 10,000 BP, with a transitional phase between 8,400 and 6,300 BP, with the final shift to ombrotrophic conditions occurring at around 6,300 BP; in this respect, Clara bog follows the broad model of raised bog formation proposed by Mitchell and Ryan (1997). At Gurteen weather station, Co. Offaly, 33km south west of Clara bog, mean annual rainfall was 948.2mm and mean temperature was 9.8ºC for the period 1981-2010; at Mullingar, 30km to the north east, mean annual rainfall of 970.9mm and a mean temperature of 9.3ºC have been recorded for the same period (Met Éireann 2012).

Figure 11: General view of Clara bog East. Note the large pool with floating mats of Sphagnum cuspidatum. Photograph by the author.

Clara bog measures roughly 4.5km from east to west and is up to 2km wide from north to south; the eastern part of the site has an area of intact raised bog measuring 1.5km east to west, and 1.8km north to south. Clara bog is currently mostly under state ownership. The site has been a protected site (Special Area of Conservation) since 1987 (SAC000572) and in 1988 was designated a Ramsar site (Ramsar number 415). Clara bog is now the largest area of intact raised bog left in Ireland. Although the site is currently protected, some areas along the southern margins of the site are in private ownership, and some recent turf cutting has taken place; also, prior to the acquisition of the site by the Irish government in the 1980s and its subsequent protection, the site was mostly owned by Bord na Móna, and some shallow drains (which have since been blocked) were cut into the eastern half of the bog in preparation for peat harvesting (Connolly 1997).

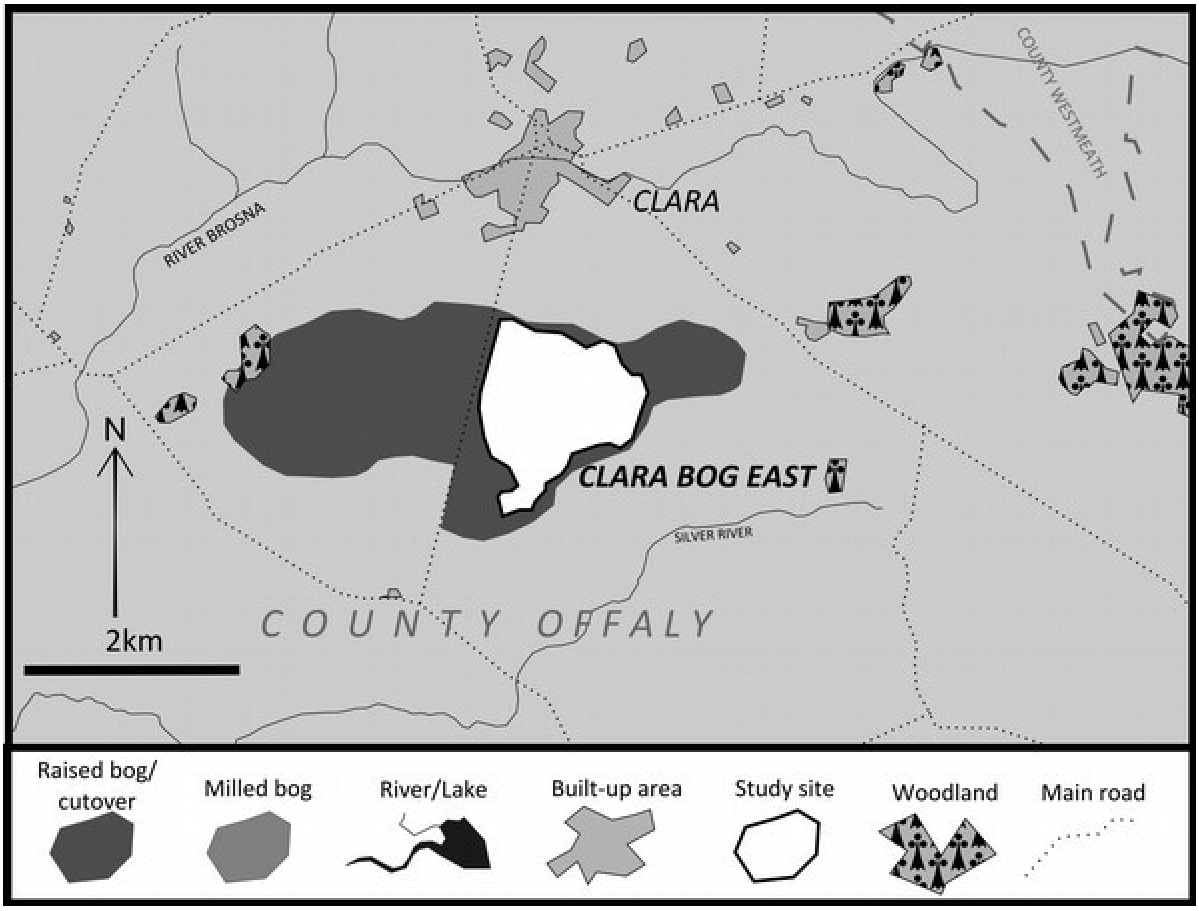

Figure 12: Location of Clara bog East, Co. Offaly.

Kelly (1993) has studied the vegetation of Clara bog and gives a full and detailed account of the site. The site features vegetation typical of a Midland raised bog including a range of *Sphagnum* mosses and *Narthecium ossifragum*, with *Menyanthes trifoliata* in the wetter hollows and pools and *Calluna vulgaris* on the drier microtopographic situations. There is a well-developed soak system on Clara bog, with two lakes, Lough Roe and Lough Beag, situated in the eastern half of the site, in some areas associated with these features, vegetation is more typical of mesotrophic environments including *Betula pubescens* and *Molinia caerulea*.

3.3.4 Ballagharahin bog, Co. Laois

Ballagharahin bog (52º50'9"N, 7º40'30"W), altitude 127m O.D., is located 2km south of the village of Errill, Co. Laois, and is 15km south east of Roscrea, Co. Tipperary North, see Figure 13. A small stream, the Erkina River, a tributary of the River Nore flows eastwards 1.5km north of the site. Ballagharahin bog is at the very northern end of the Littleton chain of bogs (see above), which are likely to have formed in glacial tongue basin running *c.* 40km from north to south (Casparie and Gowen 2005). At Gurteen weather station, Co. Offaly, 32km north west of Ballagharahin bog, mean annual rainfall was 948.2mm and mean temperature was 9.8ºC for the period 1981-2010 (Met Éireann 2012).

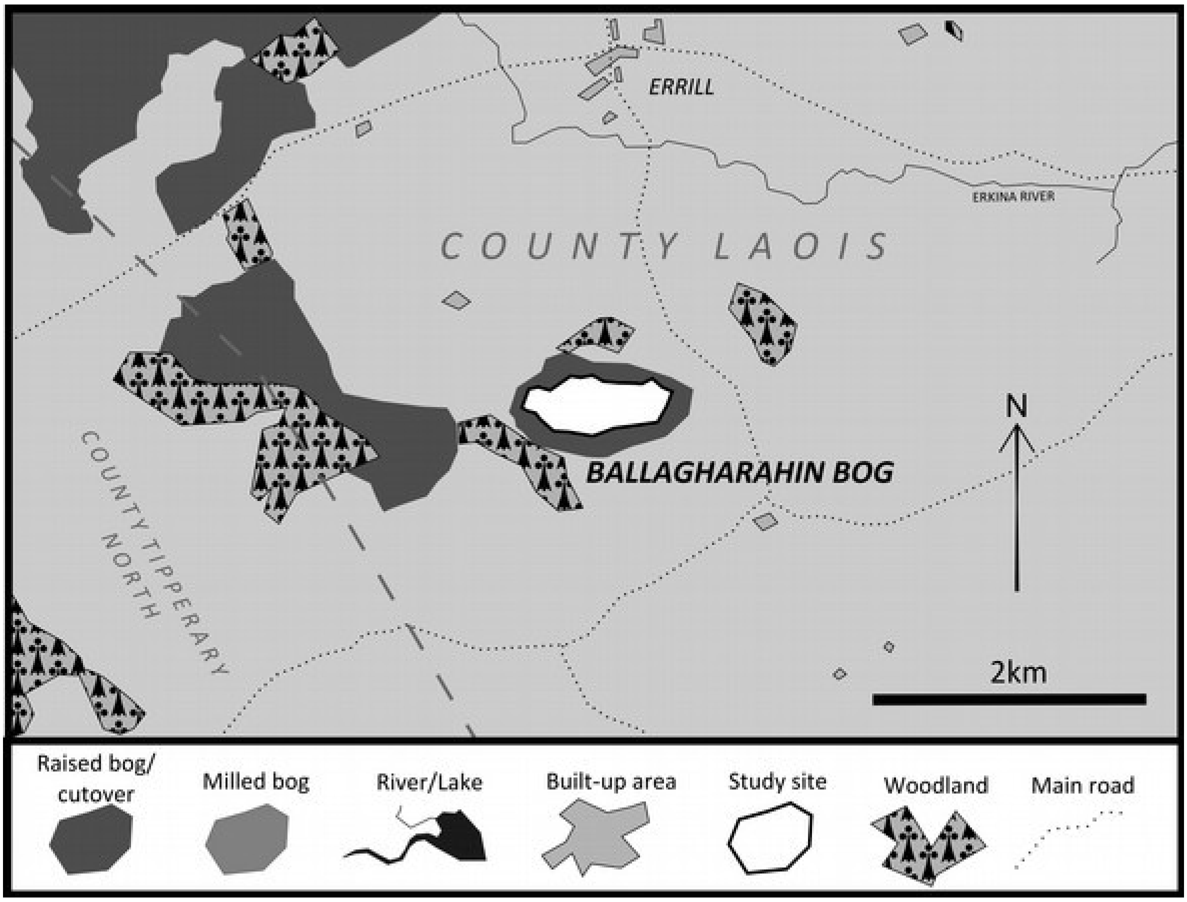

Figure 13: Location of Ballagharahin bog, Co. Laois.

Ballagharahin bog is a relatively small raised bog measuring 1km from east to west and *c.* 500m from north to south, prior to human interference, the area of intact high bog would have previously been somewhat larger. The site is mostly located in the Ballagharahin and Lisduff townlands. Although the central portion of the bog is intact, there has been extensive turf cutting around all the margins of the site, and there are some small areas of pine plantation in the cutover areas around the site. In spite of the small size of this bog, and the considerable human interference, there is still some hummock-lawn-hollow microtopography evident and good cover of *Sphagnum* mosses – mostly *S.* sect. Acutifolia spp., but with some *S. papillosum* and *S. cuspidatum* in the small pools. There is abundant *Calluna vulgaris* growing on the site, along with some *Erica tetralix. S*cattered in places on the high bog, evidence of the partial degradation of the site, are some stunted *Pinus* and *Betula* saplings, with some *Myrica gale* growing in the immediate vicinity of these trees (see Figure 14).

Figure 14: View towards Ballagharahin bog. Note the cutting on the margins of the bog, and the trees growing on the bog surface. Photograph by the author.

Chapter 4: Catalogue of Archaeology

This chapter contains descriptions of the archaeology recovered from each of the milled study sites, described in Chapter 3. The first section gives details of the identifiers assigned to each feature. The second section defines the various categories of archaeological feature. The main body of this chapter is organised by site, in the same order as in the previous chapter. For each site a brief summary is given of the archaeological survey and excavations carried out by Archaeological Development Services Ltd (ADS), this is followed by a list of each feature excavated with brief descriptions. Following this, for each site, or group of sites, a summary of the surrounding dryland and wetland archaeology is then given – based on a search of the Sites and Monuments Register (SMR) in a 5km radius.

In total, survey on the nine study sites has identified 308 archaeological features, 87 of these have been dated (28%). Following survey, a sample of sites, including those thought to be most at risk from milling, have been excavated, in total 86 features have been excavated (not that not all features excavated have been dated).

4.1 Feature identifiers

Archaeological features excavated at each site are assigned three separate identifiers: site code, license number, and feature ID.

In advance of excavation, each site was subject to survey. The objective of this survey was to identify features, and to identify which features to prioritise for excavation before being destroyed by peat milling. In the course of this survey, features visible either in the faces of drainage ditches or on the milling surface were assigned a unique site code. An example site code is 'RO-CLS001': the first two letters identify the County (in this case: RO for Roscommon), the second three letters identify the bog (CLS = Cloonshannagh), and finally a three digit number to identify the particular feature. Occasionally lower-case letters follow the site code to indicate multiple sightings which can be definitively assigned to the same feature before excavation (e.g. RO-CLS001a and RO-CLS001b would be two sightings of the same feature). Following excavation, it may become evident that a single feature has been assigned more than one site code, for example when what are thought to be several platforms are in fact found to be one larger trackway.

In Ireland, licenses are required to carry out excavations on archaeological features;

therefore each feature will be associated with one or more excavation license number. Whilst separate licenses are issued for each feature identified before excavation, in practice a single license number may be used for more than one feature if excavation subsequently reveals more than one structure in a single excavation cutting, conversely excavation may reveal that several features originally assigned separate license numbers (and site codes) may be part of a single larger feature. An example excavation license number is '10E0250': the first two digits indicate the year of issue of the license.

For the purposes of the analysis in this thesis, and for the sake of simplicity, each feature is assigned a unique feature ID. Only excavated or dated features are assigned a feature ID. This identifier is used in subsequent discussion in the text. An example feature ID is 'CLS-CT-1': the first three letters identify the bog (e.g. CLS = Cloonshannagh), this is followed by two letters indicating the type of feature (e.g. CT = corduroy trackway, see below), and finally a number, with all features at each site numbered in a single series.

4.2 Classification

Feature classification generally utilises elements of the official classification used in the Irish SMR (Archaeological Survey of Ireland undated), with some modifications detailed below. Terms used in the text are given below in italics, with the two-letter abbreviations used in the feature ID given in parenthesis.

4.2.1 Trackways

For the purposes of this thesis, the term 'trackway' is used as an umbrella term to describe all trackways and toghers irrespective of length or construction. The term 'trackway' therefore is applied to the following official classifications: 'Road – class 1 togher', 'Road – class 2 togher', 'Road – class 3 togher', 'Road – gravel/stone trackway – peatland', and 'Road – unclassified togher'. Trackways referred to as 'short' would broadly correspond to the official classification 'Road – class 3 togher', and may refer to a trackway constructed to span a small obstacle – sometimes referred to as a 'puddle togher'. Terminology following that of Raftery (1996, pp.211–218) to describe different types of trackway construction is used:

Figure 15: Brushwood trackway (Middle Bronze Age) GLA-BT-1. Photograph by the author.

Brushwood trackway (BT) - a trackway constructed entirely, or mostly, from small brushwood, usually laid longitudinally. Brushwood may be laid in neat bundles secured with pegs, or may be rather amorphous and quickly constructed.

Roundwood path (RP) - a trackway where the upper surface is entirely, or mostly, formed by lengths of roundwood laid longitudinally. The roundwoods used are more substantial than brushwood, but have usually been only minimally dressed or prepared before use.

Hurdle trackway (HT) - a trackway where the upper surface is constructed from sections of woven wattle hurdles.

Figure 16: Plank path (Early Bronze Age) LTN-PP-2. Photograph courtesy of ADS Ltd.

Plank path (PP) - a trackway where the walking surface is constructed using cleft timber planks or split timbers laid longitudinally, and often set above an underlying layer of wood and/or secured with wooden pegs.

Figure 17: Corduroy trackway (Iron Age – Early Christian) CGR-CT-2. Photograph courtesy of ADS Ltd.

Figure 18: Corduroy trackway (Middle – Late Bronze Age) LTN-CT-1. Photograph courtesy of ADS Ltd.

Corduroy trackway (CT) - a trackway consisting of substantial transverse timbers, which may either be roundwoods, planks, split timbers, or a combination of these; this surface is usually set on a substructure of longitudinal runners, or sometimes smaller roundwoods or brushwood, secured with wooden pegs.

Figure 19: Gravel trackway (Medieval) at Edera bog, Co. Longford. Photograph by the author.

Gravel trackway (GT) - a trackway constructed entirely, or mostly from stones and gravel, sometimes incorporating some minor wooden elements.

4.2.2 Other feature types

Platform (PF) - this feature type corresponds to the official classification 'Platform – peatland', and consists of a non-linear structure, usually composed mostly of roundwoods and brushwood, which serves as an artificially-raised area on the bog surface.

Archaeological wood (AW) - this feature type is defined as any deposit of wood which has been deliberately processed and deposited, but which cannot be described as either a trackway or platform. Some features listed in the SMR as 'Structure – peatland' with no further qualification may correspond to this feature type. These deposits may be the result of *in-situ* woodworking on the bog surface, perhaps related to nearby construction of trackways or platforms, or alternatively may be the poorly-preserved or heavily-truncated remains of platforms or trackways.

4.2.3 Chronology

Following survey and excavation of sites, selected archaeological features were dated using either AMS ^{14}C dating or by dendrochronology. Dates obtained for features are given in tables. Table 3 outlines the approximate dates of archaeological periods in Ireland used in subsequent discussion in the text. Laboratory codes for each ^{14}C date are provided in the tables below: codes prefixed 'BETA' have been analysed by Beta Analytic, Miami, Florida, USA; codes prefixed 'UBA' have been analysed by 14CHRONO, Queen's University, Belfast, UK.

Table 3: Approximate dates of archaeological periods in Ireland (after Waddell 1998, 4).

Mesolithic	earlier	7000 – 5500 BC	8950 – 7450 cal BP
	later	5500 – 4000 BC	7450 – 5950 cal BP
Neolithic		4000 – 2400 BC	5950 – 4350 cal BP
Copper Age		2400 – 2200 BC	4350 – 4150 cal BP
Bronze Age	Early	2200 - 1500 BC	4150 – 3450 cal BP
	Middle	1500 – 1000 BC	3450 – 2950 cal BP
	Late	1000 – 600 BC	2950 – 2550 cal BP
Iron Age		600 BC – AD 400	2550 – 1550 cal BP
Early Christian		AD 400 – 800	1550 – 1150 cal BP
Medieval		AD 800 – 1500	1150 – 450 cal BP

4.3 Mountdillon bogs, Co. Roscommon

4.3.1 Survey and excavations at Cloonshannagh bog

Cloonshannagh bog was surveyed between July and August 2008 by ADS. A total of 88 features or possible features were identified at Cloonshannagh, this included 11 trackways, 54 platforms, one possible trackway, three possible platforms and 19 sightings of archaeological wood (Ó Maoldúin 2008; Rohan 2009). Following this, excavations of 31 features were carried out by ADS between July and September 2010 (ADS 2012a). In total, the 2010 excavation recorded five corduroy trackways, four hurdle trackways, one roundwood path, 18 platforms, and three deposits of archaeological wood. Of these 31 features, seven have been dated; details of the ^{14}C dates obtained for each site are given in Table 4. Nine other features identified during the 2008 survey were dated, including six platforms, two deposits of archaeological wood and one short corduroy trackway, details of these dates are given in Table 5.

4.3.1.1 Excavated features

Table 4: ^{14}C dates of excavated archaeological features at Cloonshannagh bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	License no.	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
RO-CLS005	10E0250	**CLS-CT-1**	UBA-11305	2065±18	**2110-1950**
RO-CLS006	10E0251	**CLS-HT-2**	UBA-11306	1919±20	**1920-1820**
RO-CLS016	10E0254	**CLS-CT-5**	UBA-11308	2491±18	**2710-2490**
RO-CLS045	10E0263	**CLS-CT-16**	UBA-11313	343±16	**480-320**
RO-CLS055	10E0267	**CLS-AW-19**	UBA-11314	976±19	**930-800**
RO-CLS077	10E0272	**CLS-PF-23**	UBA-11318	2130±19	**2290-2010**
RO-CLS082	10E0275	**CLS-PF-27**	UBA-11319	781±18	**730-680**

CLS-CT-1 (license number 10E0250, site codes CLS001 and CLS005) - this Iron Age (2110-1950 cal BP) corduroy trackway was constructed from transversely-lain split timbers and roundwoods, secured in places with square-cut mortices and wooden pegs and set over longitudinal supports; in places sand was incorporated into the substructure. This trackway has at least two successive phases of use and repair, and in one section was found to have three phases of construction. In each case the method of construction was the same. No peat accumulation was noted between the successive trackway surfaces suggesting that there was little or no gap in between phases. It is not clear from which layer the ^{14}C dated sample was taken, although the sample was collected during the 2008 survey, and therefore may possibly relate to the uppermost phase. This trackway may, therefore, have been in use for a relatively long period, and would have been considered important enough to warrant the significant effort required to partially reconstruct the trackway at least twice. Artefacts recovered from this trackway include a crude anthropomorphic wooden figure, a wooden lid, a fragment of a wooden vessel, and some wooden fragments thought to be part of a cart. CLS-CT-1 is potentially synchronous, or near-synchronous to the Corlea 1 trackway, which was of similar construction type, and where similar artefacts have been recovered.

CLS-HT-2 (license number 10E0251, site code CLS006) - this feature consists of the heavily-truncated remains of an Iron Age (1920-1820 cal BP) hurdle trackway, consisting of one wattle hurdle with underlying longitudinal supports.

CLS-HT-3 (license number 10E0252, site code CLS007) - this undated feature was a wide trackway constructed from wattle hurdles.

CLS-PF-4 (license number 10E0253, site code CLS013) - an undated platform constructed from brushwood and roundwoods, up to 4.2m across.

CLS-CT-5 (license number 10E0254, site code CLS016) - a Late Bronze Age or very early Iron Age (2710-2490 cal BP) trackway consisting of an upper surface of transverse roundwoods overlying longitudinal supports which in turn, overlie a layer of sand and brushwood in places.

CLS-CT-6 (license numbers: 10E0255, 10E0271, 10E0278, 10E0262; site codes: CLS017, CLS075, CLS087, CLS088) - an undated corduroy trackway, originally thought to be a number of separate platforms. The trackway was constructed with transverse roundwoods and split timbers overlying longitudinal supports. Two wooden anthropomorphic figures were found in the substructure of this feature.

CLS-PF-7 (license number 10E0256, site code CLS023) - an undated platform constructed from roundwood and brushwood elements, apparently partially over a bog pool.

CLS-PF-8 (license number 10E0257, site code CLS026) - an undated platform constructed from brushwoods, apparently replacing an earlier platform (CLS-PF-9).

CLS-PF-9 (license number 10E0257, site code CLS027) - an undated brushwood platform, apparently replaced by CLS-PF-8 after a hiatus (there was some peat accumulation between the two structures).

CLS-PF-10 (license number 10E0258, site code CLS029) - undated roundwood and brushwood platform, contemporary with neighbouring platform CLS-PF-12.

CLS-AW-11 (license number 10E0259, site code CLS030) - small undated deposit of longitudinally-laid roundwoods.

CLS-PF-12 (license number 10E0260, site code CLS032) - undated platform contemporary with CLS-PF-10.

CLS-PF-13 and CLS-PF-14 (license number 10E0261, site code CLS035) - two contemporary but undated platforms.

CLS-PF-15 (license number 10E0262, site code CLS036) - undated platform, thought to be broadly contemporary with CLS-PF-13 and CLS-PF-14, but underlying part of CLS-CT-6, and therefore earlier than this trackway. This platform showed two phases of construction, suggesting a degree of continuity of use.

CLS-CT-16 (license number 10E0263, site code CLS045) - heavily-truncated remains of a late Medieval (480-320 cal BP) corduroy trackway.

CLS-AW-17 (license number 10E0264, site code CLS050) - undated archaeological wood.

CLS-RP-18 (license numbers 10E0265, 10E0266; site codes CLS051, CLS052) - heavily-truncated remains of an undated roundwood path, consisting of longitudinal roundwoods supported by transverse brushwood.

CLS-AW-19 (license number 10E0267, site code CLS055) - deposit of archaeological wood dating to the Medieval period (930-800 cal BP).

CLS-PF-20 (license number 10E0268, site code CLS057) - undated platform.

CLS-PF-21 (license number 10E0269, site code CLS069) - undated platform.

CLS-HT-22 (license number 10E0270, site code CLS072) - short undated hurdle trackway.

CLS-PF-23 (license number 10E0272, site code CLS077) - Iron Age (2290-2010 cal BP) platform constructed from roundwoods and brushwood. A wooden mallet was found amongst the timbers.

CLS-PF-24 and CLS-PF-25 (both license number 10E0273, site code CLS080 and CLS081) - two contemporary undated platforms overlying CLS-HT-26.

CLS-HT-26 (license 10E0273, no site code) - undated short hurdle trackway overlain by platform CLS-PF-24.

CLS-PF-27 (license 10E0275, site code CLS082) - Medieval (730-680 cal BP) platform.

CLS-PF-28 and CLS-PF-29 (license 10E0276, site code CLS083) - two undated but contemporary platforms.

CLS-PF-29 (license 10E0277, site code CLS084) - undated platform.

CLS-CT-31 (license 10E0280, site code CLS089) - heavily-truncated remains of an undated corduroy trackway.

4.3.1.2 Dated unexcavated features

Table 5: ^{14}C dates of surveyed archaeological features which have not been excavated at Cloonshannagh bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
RO-CLS003	**CLS-PF-32**	UBA-11304	3980±22	**4520-4420**
RO-CLS015	**CLS-PF-33**	UBA-11307	2649±23	**2790-2740**
RO-CLS018	**CLS-PF-34**	UBA-11309	2446±19	**2700-2360**
RO-CLS022	**CLS-AW-35**	UBA-11310	647±25	**670-560**
RO-CLS033	**CLS-AW-36**	UBA-11311	2150±19	**2300-2060**
RO-CLS037	**CLS-AW-37**	UBA-11312	607±18	**650-550**
RO-CLS059	**CLS-CT-38**	UBA-11315	748±17	**720-670**
RO-CLS073	**CLS-PF-39**	UBA-11316	1606±18	**1540-1420**
RO-CLS076	**CLS-PF-40**	UBA-11317	2080±20	**2120-2000**

4.3.2 SMR entries around Cloonshannagh bog

The SMR contains a total of 212 entries within a 5km radius of Cloonshannagh bog (National Monuments Service 2012). A large number of these entries are ringforts, thought to be mostly of early Medieval date, which are scattered across the dryland areas mainly to the west of the site. A possible crannog is listed under 1km to the east. Just to the south of Cloonshannagh bog is the traditional location of an ecclesiastical site associated with the 6th century St Barry. Several other SMR entries relate to a number of peatland structures in neighbouring bogs, and, although not within 5km of Cloonshannagh, Corlea Iron Age trackway is located less then 15km to the south. There are no entries in the SMR which relate to dryland sites specifically associated with the Iron Age or Bronze Age such as *fulachtaí fia*. A Neolithic megalithic wedge tomb is located 2km to the north-east, across the River Shannon.

4.3.3 Cloonshannagh summary

Archaeological features at Cloonshannagh bog date to the later Neolithic, Late Bronze Age, Iron Age and the Medieval period. Although only 16 features have been dated, activity appears to be more intensive during the Iron Age and Medieval periods. The best-represented feature type excavated at Cloonshannagh are platforms. Although only eight examples have been dated, there are several examples of more than one platform being in use at broadly the same time, and examples of platforms being re-built on the same locations or repaired, clearly suggesting some degree of continuity in use. Platforms have been dated mostly to the

Iron Age (CLS-PF-23, CLS-PF-34, CLS-PF-40), the Early Christian period (CLS-PF-39) and to the Medieval period (CLS-PF-27), although two examples are earlier: CLS-PF-33 dating to the Late Bronze Age, and CLS-PF-32 dating to the end of the Neolithic. The majority of trackways excavated at Cloonshannagh are of the corduroy trackway type, which are rather substantial structures capable of carrying mounted and wheeled traffic; evidence for this is provided by the remains of a cart associated with CLS-CT-1. CLS-CT-1 appears to be broadly contemporary with hurdle trackway CLS-HT-2, and may have been part of a larger Iron Age communication network; CLS-CT-1 also has several parallels with the Corlea 1 trackway (Raftery 1996) in that it is broadly contemporary, is similar in construction type, and also contains similar artefactual evidence (anthropomorphic figures and wooden vessels). CLS-CT-1 may therefore reflect the same pattern of Iron Age human activity (importance of communication routes, and ability to organise the construction and maintenance of such substantial structures etc.) reflected at Corlea. Medieval activity on the bog, may have been associated with linking the ecclesiastical enclosure to the south with the drier lands north and west of Cloonshannagh (e.g. CLS-CT-16, and CLS-CT-38).

4.4 Bog of Allen, Co. Meath

4.4.1 Survey and excavations at Kinnegad bog

Kinnegad bog was surveyed during the 2005 Peatland Survey, when a total of 19 features were identified (Whitaker 2006a, p.13). Following this excavations were carried out between May and July 2007 on eight features, including two plank pathways, two brushwood trackways, three platforms and a deposit of archaeological wood (Rohan 2008). Four of these excavated features were ^{14}C dated (details in Table 6), and one feature was dated using dendrochronology (Table 7). In addition, three sites identified in the survey, but not subsequently excavated, have been dated (details in Table 8); note that laboratory codes for six of the dates were not available from Beta Analytic due to the latter's commercial confidentiality policy.

4.4.1.1 Excavated features

Table 6: ^{14}C dates of excavated archaeological features at Kinnegad bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	License no.	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
ME-KND001	07E0496	**KND-PP-1**	???	3310±70	**3690-3390**
ME-KND011	07E0499	**KND-PF-4**	???	2990±70	**3360-2980**
ME-KND012	07E0500	**KND-PF-5**	UBA-11360	2997±20	**3320-3080**
ME-KND015	07E0501	**KND-PF-7**	UBA-11362	2863±20	**3070-2890**
ME-KND016	07E0501	**KND-BT-8**	???	3120±60	**3480-3160**

Table 7: Dendrochronological date of plank path KND-PP-3, from Kinnegad bog. For comparison with ^{14}C dated features, the equivalent age in cal BP is given.

Code	License no.	Feature ID	Felling date	Age cal BP
ME-KND002	07E0497	**KND-PP-3**	1569±9 BC	**3519±9**

KND-PP-1 (license number 07E0496, site code KND001) - Early or Middle Bronze Age (3690-3390 cal BP) plank path constructed from either one or two longitudinally-laid split planks secured with mortices and wooden pegs, overlying roundwood transverse supports. Overlies KND-AW-2

KND-AW-2 (license number 07E0496, site code KND003) - although not directly dated, this deposit of archaeological wood is overlain by KND-PP-1, suggesting this feature dates to the Early Bronze Age. Composed of roundwoods and brushwoods with upright roundwood posts. Overlying poorly-humified *Sphagnum* and *Menyanthes* peat, suggesting this may have served as a stable surface in a wet area of bog.

KND-PP-3 (license number 07E0497, site code KND002) - Early Bronze Age (3528-3510 cal BP) plank path composed of longitudinal planks overlying transverse roundwoods, secured with wooden pegs on either side.

KND-PF-4 (license number 07E0499, site code KND011) - Middle Bronze Age (3360-2980 cal BP) platform constructed from roundwoods and brushwood.

KND-PF-5 (license number 07E0500, site codes KND012 and KND013) - Middle Bronze Age (3320-3080 cal BP) broadly contemporary with the nearby KND-PF-4.

KND-BT-6 (license number 07E0501, site code KND014) - undated brushwood trackway.

KND-PF-7 (license number 07E0501, site code KND015) - Middle to Late Bronze Age (3070-2890 cal BP) platform constructed from brushwood, with larger roundwoods around each edge, built over poorly-humified peat. Overlies KND-BT-8.

KND-BT-8 (license number 07E0501, site code KND016) - Middle Bronze Age (3480-3160 cal BP) trackway constructed from tightly-packed brushwood with occasional longitudinal roundwoods. Overlain by, and therefore definitely earlier than KND-PF-7.

4.4.1.2 Unexcavated features

Table 8: ^{14}C dates of surveyed archaeological features which have not been excavated at Kinnegad bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
ME-KND004	**KND-AW-9**	???	1490±60	**1520-1300**
ME-KND006	**KND-PF-10**	???	3200±60	**3570-3270**
ME-KND010	**KND-PF-11**	???	3220±70	**3630-3270**

4.4.2 SMR entries around Kinnegad bog

113 SMR entries are located within a 5km radius of Kinnegad bog (National Monuments Service 2012). A hilltop enclosure of possible prehistoric date is located just under 5km to the south. A single *fulacht fia* is situated *c.*2.5km to the east. Perhaps most prominent in the local SMR is the concentration of Medieval castles of various types located north-west, north-east and south of Kinnegad bog.

4.4.3 Kinnegad summary

The peatland archaeological structures at Kinnegad bog show a concentration of activity in the Early and Middle Bronze Age. The earliest structures are two plank paths (KND-PP-1 and KND-PP-3). This is followed in the Middle Bronze Age by brushwood trackway KND-BT-8, which seems likely to be associated with a number of brushwood platforms. Whilst there is relatively little clear evidence of Bronze Age occupation around Kinnegad bog in the SMR, excavations in 2002 in advance of the construction of the M6 motorway immediately to the north of the site revealed evidence for Middle Bronze Age settlement in the form of a number of pits (license number 02E0866 – see www.archaeology.nra.ie for details).

The only feature dating to later periods in Kinnegad is KND-AW-9, dating to the Early Christian period, which was composed of a single plank, which may be all that remains of a trackway. It may be that activity later than the Bronze Age at Kinnegad has simply been truncated by milling, since the Early Bronze Age features were located near to the milled surface of the bog.

4.5 Derryfadda bogs, Co Galway

4.5.1 Survey and excavations at Gowla bog

Gowla bog was surveyed by ADS in 2007, when a total of 33 features were identified, including 16 trackways, eight platforms and nine deposits of archaeological wood (Rohan 2009, p.90). Following this, in summer 2011 one brushwood trackway was excavated (D. Young pers. comm.), the date of this trackway is given in Table 9. A further seven sites identified in the survey, but not excavated in 2011, were dated, including three platforms, three brushwood trackways, and one plank path; details of these dates are given in Table 10.

4.5.1.1 Excavated feature

Table 9: ^{14}C dates of excavated archaeological features at Gowla bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	License no.	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
GA-GLA016	11E0191	**GLA-BT-1**	UBA-11342	3171±22	**3440-3360**

GLA-BT-1 (license number 11E0191, site code GLA016) - Middle Bronze Age (3440-3360 cal BP) brushwood trackway. Composed of densely-packed brushwood, interspersed with occasional larger roundwoods. See Figure 15.

4.5.1.2 Unexcavated features

Table 10: ^{14}C dates of surveyed archaeological features which have not been excavated at Gowla bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
GA-GLA001	**GLA-PF-2**	UBA-11340	3099±20	**3380-3260**
GA-GLA007	**GLA-BT-3**	UBA-11341	3113±20	**3380-3270**
GA-GLA021	**GLA-PF-4**	UBA-11343	2118±20	**2150-2010**
GA-GLA024	**GLA-PP-5**	UBA-11344	1301±21	**1290-1180**
GA-GLA025	**GLA-PF-6**	UBA-11345	1475±20	**1400-1310**
GA-GLA026	**GLA-BT-7**	UBA-11346	1802±20	**1820-1640**
GA-GLA033	**GLA-BT-8**	UBA-11347	2102±20	**2130-2000**

4.5.2 Gowla summary

The first phase of activity at Gowla bog is in the Middle Bronze Age, where GLA-BT1, GLA-BT-3 and GLA-PF-2 may be potentially contemporary. The second main phase of activity is during the Iron Age, where brushwood trackway GLA-BT-8 and platform GLA-PF-4 may be more or less contemporary. A second Iron Age trackway GLA-BT-7 was constructed later on in the Iron Age, perhaps a successor to GLA-BT-8. There are a large number of as yet undated and unexcavated brushwood trackways (15 in total, including the four dated examples) of similar construction and similar (east-west) alignment, which may suggest frequent replacement of these structures and perhaps a greater degree of continuity than is suggested by the dated sample of features. The more substantial plank path-type trackway GLA-PP-5 was constructed in the Early Christian period.

4.5.3 Survey and excavations at Killaderry bog

Killaderry bog was surveyed by ADS as part of the 2007 Peatland Survey (Rohan 2007a, 2009). A total of 61 features were identified in the course of the survey, including a total of 27 trackways of various types. Following this, in June and July 2011 a total of 24 features were excavated under 13 separate excavation licenses (ADS 2012b); these include two corduroy trackways, four brushwood trackways, 11 platforms, one gravel and plank trackway, and five deposits of archaeological wood. Seven of the 23 features have been dated, details of the ^{14}C determinations are given in Table 11 below. Ten other features identified during the 2007 survey were dated, including one roundwood path, two platforms, three brushwood trackways, one deposit of archaeological wood and three plank paths; details are given in Table 12.

4.5.3.1 Excavated features

Table 11: ^{14}C dates of excavated archaeological features at Killaderry bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	License no.	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
GA-KDY003a	11E0175	**KDY-CT-1**	UBA-11323	2722±26	**2860-2770**
GA-KDY005	11E0176	**KDY-GT-5**	UBA-11324	1309±18	**1290-1180**
GA-KDY013	11E0183	**KDY-BT-2**	UBA-11326	3021±20	**3330-3160**
GA-KDY030	11E0183	**KDY-AW-11**	UBA-11331	1016±25	**970-830**
GA-KDY031b	11E0184	**KDY-CT-18**	UBA-11332	1101±19	**1060-960**
GA-KDY035a	11E0186	**KDY-BT-20**	UBA-11333	386±23	**510-330**
GA-KDY044	11E0187	**KDY-BT-22**	UBA-11334	748±18	**720-670**

KDY-CT-1 (license numbers: 11E0175, 11E0182, 11E0184; site codes: KDY003, KDY027, KDY031a) - this is a Late Bronze Age (2860-2770 cal BP) corduroy trackway constructed from transverse split planks and roundwoods, secured with wooden pegs in mortice holes, and overlying longitudinal supports. This trackway extends across Killaderry bog running north-west to south-east.

KDY-BT-2 (license numbers: 11E0179, 11E0183; site codes: KDY004, KDY013) - a brushwood trackway, with roundwood 'kerbing' on either side, traced for at least 280m in length (and most likely traversing the entire bog). This is of Middle Bronze Age date (3330-3160 cal BP), and in places it underlies the Late Bronze Age corduroy trackway KDY-CT-1.

KDY-PF-3 (license number 11E0175, no site code) - this is an undated platform, which post-dates the Late Bronze Age trackway KDY-CT-1.

KDY-PF-4 (license number 11E0175, no site code) - undated brushwood and split plank platform.

KDY-GT-5 (license number 11E0176, site code KDY005) - this is a trackway constructed from transverse split timber planks with deposits of clay and gravel above and below the timber structure. This feature dates to 1290-1180 cal BP in the Early Christian period. This trackway traverses the entire bog from north-west to south-east, and crosses over KDY-CT-1 in two places.

KDY-BT-6 (license number 11E0177 and 11E0178, site code KDY008) - undated brushwood trackway.

KDY-AW-7 (license number 11E0178, site code KDY009) - undated deposit of archaeological wood.

KDY-PF-8 and KDY-PF-9 (license number 11E0180, site codes KDY016a and KDY016b, respectively) - two undated platforms.

KDY-AW-10 (license number 11E0181, site code KDY024) - single undated plank.

KDY-AW-11 (license number 11E0183, site code KDY030) - a deposit of archaeological wood, likely to be the heavily-truncated remains of a trackway, dated to the Medieval period (970-830 cal BP).

KDY-PF-12 (license number 11E0183, no site code) - undated platform.

KDY-PF-13 (license number 11E0183, no site code) - platform structure. Although not directly dated, appears to be associated with the Middle Bronze Age trackway KDY-BT-2.

KDY-PF-14 (license number 11E0183, no site code) - platform structure. Not directly dated, but Middle Bronze Age or a little later: built directly on top of part of the Middle Bronze Age trackway KDY-BT-2, when the trackway was still exposed. This may, potentially, be an *ad hoc* repair to KDY-BT-2, or be related to some kind of activity associated with this trackway.

KDY-AW-15 (license number 11E0183, no site code) - undated archaeological wood – two split planks.

KDY-PF-16 (license number 11E0183, no site code) - platform structure. Although not directly dated, appears to be associated with the Middle Bronze Age trackway KDY-BT-2.

KDY-PF-17 (license number 11E0183, no site code) - platform structure, not dated but Middle Bronze Age or older: underlies KDY-BT-2.

KDY-CT-18 (license number 11E0184, site code KDY031b) - a 4m wide trackway, constructed from transverse split planks overlying longitudinal supports and secured with pegs. Medieval in date (1060-960 cal BP).

KDY-PF-19 (license number 11E0185, site code KDY34c) - brushwood and roundwood platform. A rough-out for a wooden bowl with a handle was recovered from the timbers.

KDY-BT-20 (license number 11E0186, site code KDY035a) - late Medieval to Post-Medieval brushwood trackway (dated to 510-330 cal BP).

KDY-PF-21 (license number 11E0186, site code KDY035e) - undated platform.

KDY-BT-22 (license number 11E0187, site code KDY044) - Medieval (720-670 cal BP) brushwood trackway.

KDY-AW-23 (license number 11E0187, site code KDY044) - deposit of archaeological wood, including possible spade artefact. Located close to KDY-BT-22, this platform may potentially be associated with that trackway.

4.5.3.2 Dated unexcavated features

Table 12: ^{14}C dates of surveyed archaeological features which have not been excavated at Killaderry bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
GA-KDY006	**KDY-RP-24**	UBA-11325	636±21	**660-560**
GA-KDY014	**KDY-PF-25**	UBA-11327	2762±23	**2920-2780**
GA-KDY021	**KDY-BT-26**	UBA-11328	2403±20	**2650-2350**
GA-KDY023	**KDY-BT-27**	UBA-11329	2840±20	**3000-2870**
GA-KDY026	**KDY-AW-28**	UBA-11330	2015±21	**2030-1900**
GA-KDY049	**KDY-PF-29**	UBA-11335	1460±28	**1390-1300**
GA-KDY053	**KDY-BT-30**	UBA-11336	342±18	**480-320**
GA-KDY054	**KDY-PP-31**	UBA-11337	4897±27	**5660-5590**
GA-KDY058	**KDY-PP-32**	UBA-11338	3641±21	**4070-3890**
GA-KDY059	**KDY-PP-33**	UBA-11339	3605±20	**3970-3850**

4.5.4 Killaderry summary

Peatland archaeological features at Killaderry bog suggest concentrations of activity during the Early, Middle and Late Bronze Age and then in the Early Christian and Medieval periods. Only one, unexcavated, feature – brushwood trackway KDY-BT-26 – may possibly date to the Iron Age Three unexcavated plank pathways are the earliest evidence of human activity at Killaderry, including one Neolithic example (KDY-PP-31), and two Early Bronze Age trackways (KDY-PP-32, and KDY-PP-33); it is unclear if these structures traversed the entire bog, but this seems plausible considering their relatively complex construction (using split timber planks). Large trackways traversing the bog date to the Middle Bronze Age (KDY-BT-2), the Late Bronze Age (KDY-CT-1), the Early Christian period (KDY-GT-5), and the Medieval period (KDY-CT-18 and possibly also KDY-AW-11). The Middle Bronze Age trackway in particular appears to be closely associated chronologically with several of the platform structures (KDY-PF-13, KDY-PF-14, KDY-PF-16, and KDY-PF-17), suggesting intensive human activity during this time concentrated on the southern margins of the bog. Although undated, the unfinished wooden bowl found at KDY-PF-19 – possible evidence for woodworking – is tantalising evidence of the kinds of everyday activities perhaps carried out on Killaderry bog.

4.5.5 Survey and excavations at Castlegar bog

Castlegar bog was surveyed during the 2007 Peatland Survey, which identified 56 features (including 14 trackways and 14 platforms) all concentrated in the eastern portion of the bog, between the higher ground to the west, and a dryland 'island' to the east (Rohan 2007b, 2009). Excavation of three trackways, of which two were dated (see Table 13) were carried out in July 2011 by ADS (Whitaker 2012). In addition, a further 13 features identified in the 2007 survey, but not excavated in 2011, were dated - see Table 14; these included two deposits of archaeological wood, two brushwood trackways, four roundwood paths, four platforms, and one plank path.

4.5.5.1 Excavated features

Table 13: ^{14}C dates of excavated archaeological features at Castlegar bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	License no.	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
GA-CGR001	11E0193	**CGR-CT-1**	UBA-11286	511±21	**550-510**
GA-CGR050b	11E0194	**CGR-CT-2**	UBA-11301	1670±38	**1690-1420**

CGR-CT-1 (license number 11E0193, site code CGR001) - a Medieval (550-510 cal BP) corduroy trackway constructed from densely-packed transverse roundwoods; this trackway traversed the northern section of Castlegar bog.

CGR-CT-2 (license number 11E0194, site code CGR050) - a late Iron Age to Early Christian (1690-1420 cal BP) corduroy trackway, constructed from radially- and half-split timbers overlying a brushwood substructure. A wooden mallet-like artefact was recovered from the substructure; similar artefacts have been found at other Iron Age trackways (Raftery 1996, p.273; Buckley *et al* 2005, p.315). See Figure 17.

CGR-BT-3 (license number 11E0195, site code CGR051) - an undated trackway, constructed mostly from randomly-lain brushwood, overlying a substructure constructed from roundwoods and radially-split planks. On similar alignment to CGR-CT-1 and CGR-CT-2.

4.5.5.2 Dated unexcavated features

Table 14: ^{14}C dates of surveyed archaeological features which have not been excavated at Castlegar bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
GA-CGR006	**CGR-AW-4**	UBA-11287	679±30	**680-560**
GA-CGR008	**CGR-BT-5**	UBA-11288	2535±29	**2744-2500**
GA-CGR011	**CGR-BT-6**	UBA-11289	2288±31	**2350-2160**
GA-CGR014	**CGR-RP-7**	UBA-11290	2709±28	**2860-2760**
GA-CGR015	**CGR-PF-8**	UBA-11291	2300±29	**2350-2180**
GA-CGR017	**CGR-AW-9**	UBA-11292	2115±29	**2290-2000**
GA-CGR022	**CGR-AW-10**	UBA-11293	482±26	**540-500**
GA-CGR029	**CGR-RP-11**	UBA-11295	2086±19	**2960-2860**
GA-CGR031	**CGR-PF-12**	UBA-11296	2496±20	**2720-2490**
GA-CGR034	**CGR-RP-13**	UBA-11297	2011±19	**2000-1900**
GA-CGR037	**CGR-PP-14**	UBA-11298	1083±30	**1060-930**
GA-CGR044	**CGR-PF-15**	UBA-11299	2559±26	**2750-2510**
GA-CGR047	**CGR-PF-16**	UBA-11300	2141±34	**2000-2300**
GA-CGR058	**CGR-RP-17**	UBA-11302	2438±28	**2700-2360**

4.5.6 Castlegar summary

The earliest recorded features at Castlegar bog are all as yet unexcavated and date to the Late Bronze Age; these are three roundwood paths (CGR-RP-7, CGR-RP-11, and CGR-RP-17 – the last site may date to the earliest part of the Iron Age), one brushwood trackway (CGR-BT-5) and one platform (CGR-PF-15). There is abundant evidence for activity on the bog during the Iron Age, including three trackways, three platforms and one deposit of archaeological wood, some features dating to the latest part of the Iron Age, or possibly the Early Christian period. This activity shows apparent continuity into the Medieval period. The excavated Medieval (CGR-CT-1) and late Iron Age/Early Christian (CGR-CT-2) trackways are both substantial corduroy trackways, both traversing the northern part of Castlegar, connecting the higher ground on the west to Dalysgrove dryland island which is situated between Castlegar bog and the River Suck. An enclosure listed on the SMR is situated on Dalysgrove, whilst immediately to the west of Castlegar bog is Eglish Abbey; CGR-CT-1 is potentially contemporary with the first mention of Eglish Abbey (see below).

4.5.7 SMR entries around the Derryfadda bogs

The SMR contains 418 entries within a 5km radius of the Derryfadda group of bogs (National Monuments Service 2012). A large number of these entries (67) are enclosures, with no other details supplied, these may potentially date to any period from prehistory onwards. Firm evidence for prehistoric activity in the area is provided by the presence of a mound barrow 4km to the east, on the edge of the dryland on the far side of the callows on the east bank of the River Suck, this is likely to date to either the Iron or Bronze Age (Archaeological Survey of Ireland undated). Stray finds of a socketed bronze spearhead, and a bronze sword, both dating to the Bronze Age, have also been recorded near to the Derryfadda bogs (Rohan 2009, p.13). Two *fulachtaí fia*, most likely of Bronze Age in date, are located on the edge of the higher ground immediately to the west of the Derryfadda bogs. There is abundant evidence for Early Christian and early Medieval activity, with 86 ringforts in the SMR, mostly concentrated on the area of higher ground to the west of the Derryfadda bogs. Eglish Abbey, first recorded in AD 1436 (514 cal BP) (Alcock *et al* 1999), is located on this area of higher ground to the west, overlooking Castlegar bog to the east.

4.5.8 Summary: Derryfadda bogs

In total, 40 features from study sites in the Derryfadda group have been dated. These appear to date to all main archaeological periods. Neolithic (KDY-PP-31), and Early Bronze Age (KDY-PP-32, and KDY-PP-33) plank paths at Killaderry are the earliest peatland features in this area. A range of features are represented in the Middle and Late Bronze Ages, but the Iron Age is the best-represented period in the Derryfadda bogs; being characterised by numerous brushwood and roundwood structures, mostly of fairly simple construction. In the Early Christian and into the Medieval period there is another increase in activity, mostly dominated by substantial trackways such as the gravel and plank trackway KDY-GT-5, corduroy trackways KDY-CT-18 and CGR-CT-1 and the plank path CGR-PP-14; these probably formed important routeways, including links to the Medieval Eglish Abbey which overlooks this group of bogs.

4.6 Littleton chain, Co. Tipperary

4.6.1 Survey and excavations at Inchirourke bog

Inchirourke bog was surveyed during the 2006 Peatland survey, revealing a plank path and a deposit of archaeological wood (Whitaker 2006b). This oak plank path was subsequently dated using dendrochronology to the Early Bronze Age (see Table 15), and was excavated in August 2010 (Whitaker 2011).

Table 15: Dendrochronological date of plank path IRK-PP-1, from Inchirourke bog. Dendrochronological analysis undertaken by D. Brown, Queen's University, Belfast. For comparison with ^{14}C dated features, the equivalent age in cal BP is given.

Code	Feature ID	Felling date	Age cal BP
TN-IRK001	**IRK-PP-1**	After 1607 BC	**After 3557**

IRK-PP-1 (site code IRK001) - Early Bronze Age (3557 cal BP or later) plank path. Constructed from either a single, or two parallel, longitudinally-laid split oak planks, sometimes with narrow half split timbers on either side, supported by radially-clef upright posts and overlying occasional transverse roundwoods. Wood chips encountered during excavation are evidence for some light in-situ woodworking. Several similar trackways, also of similar Early Bronze Age date are known from Ireland and Germany (Raftery 1996, pp.215–217; Cross May *et al* 2005b, p.223,233; Whitaker 2009, pp.20–25), and also from Littleton bog to the south (LTN-PP-2).

4.6.2 Survey and excavations at Longfordpass bog

The 2006 peatland survey on Longfordpass bog identified a total of six features including one large corduroy trackway, two plank paths, one roundwood path, a structure thought to be an animal trap, and a deposit of archaeological wood (Whitaker 2006c). The corduroy trackway, and both plank paths were excavated in 2010 (J. Whitaker pers. comm.). Following the 2006 survey, the four trackways were all dated using dendrochronology (see Table 16), whilst the possible animal trap was dated by AMS ^{14}C.

Table 16: Dendrochronological dates of trackways from Longfordpass bog. For comparison with ^{14}C dated features, the equivalent age in cal BP is given.

Code	License no.	Feature ID	Felling date	Age cal BP
TN-LFP001	10E0330	**LFP-CT-1**	After 986 BC	**After 2936**
TN-LFP002	10E0333	**LFP-PP-2**	After 1004 BC	**After 2954**
TN-LFP003	Not excavated	**LFP-RP-3**	After 1035 BC	**After 2985**
TN-LFP005	10E0332	**LFP-PP-5**	1559±9 BC	**3509±9**

Table 17: ^{14}C date of possible animal trap feature at Longfordpass bog. 95% confidence interval calibrated age range is given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
TN-LFP004	**LFP-AW-4**	BETA-222648	2360±50	**2700-2210**

LFP-CT-1 (license number 10E0330, site code LFP001) - Middle or Late Bronze Age (after 2936 cal BP) corduroy trackway constructed from transverse split planks, with roundwood and gravel substructure.

LFP-PP-2 (license number 10E0333, site code LFP002) - Middle or Late Bronze Age (after 2954 cal BP) plank path constructed from longitudinally-laid split oak timbers.

LFP-PP-5 (license number 10E0332, site code LFP005) - Early Bronze Age (3518-3500 cal BP) plank path constructed from longitudinal split planks.

4.6.3 Longfordpass summary

The features recorded at Longfordpass mostly date to the Bronze Age. The Early Bronze Age plank path LFP-PP-5 appears to be part of a wider communication network of similar trackways (at Derryville, Inchirourke and Littleton) of very similar date crossing this part of the Littleton bog chain. A second phase of activity occurs at the end of the Middle or beginning of the Late Bronze age, including a large corduroy trackway (LFP-CT-1), and smaller trackways (LFP-PP-2 and LFP-RP-3), again these may potentially be part of another regional communication network along with LTN-CT-1 (and possibly also Cooleeny 31 at Derryville (see Cross May *et al* 2005c, p.358)) which is also of similar construction and date. Due to the plateau in the radiocarbon calibration curve between 2600 and 2400 cal BP, the chronological precision of the date of the animal trap is poor, however, this feature is further evidence for day-to-day human activity on Longfordpass bog.

4.6.4 Survey and excavations at Littleton bog

Littleton bog was surveyed in 2006 by ADS, when 33 features were identified; these included 21 trackways of various type, four platforms, and eight deposits of archaeological wood (Whitaker 2006d). Between May and July 2008 12 features of these were excavated, including two corduroy trackways, one plank path, one brushwood trackway, five platforms, and three deposits of archaeological wood (Turrell 2008); of these excavated features, six have 14C dates (see Table 18), and one has been dated using dendrochronology (see Table 19). In addition, a further 6 features identified in the 2006 survey, but not excavated in 2008, have been dated: one plank path, four brushwood trackways, and one platform; details of these dates are given in Table 20.

4.6.4.1 Excavated features

Table 18: ^{14}C dates of excavated archaeological features at Littleton bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	License no.	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
TN-LTN001	08E0399	**LTN-CT-1**	BETA-222649	2860±50	**3160-2860**
TN-LTN010	08E0401	**LTN-BT-3**	BETA-222653	2100±70	**2310-1900**
TN-LTN017	08E0407	**LTN-PF-8**	UBA-11363	1880±21	**1880-1740**
TN-LTN024	08E0410	**LTN-PF-10**	UBA-11364	1814±18	**1820-1710**
“ “	“ “	**“ “**	BETA-222654	1740±60	**1810-1540**
TN-LTN025	08E0411	**LTN-PF-11**	UBA-11365	1865±19	**1870-1730**
TN-LTN030	08E0412	**LTN-PF-12**	UBA-11366	2001±32	**2040-1880**

Table 19: Dendrochronological date of plank path LTN-PP-2, from Littleton bog. Dendrochronological analysis undertaken by D. Brown, Queen's University, Belfast. For comparison with ^{14}C dated features, the equivalent age in cal BP is given. Note that three separate samples from the same structure were analysed.

Code	License no.	Feature ID	Felling date	Age cal BP
TN-LTN006e	08E0400	**LTN-PP-2**	1571±9 BC	**3521±9**
TN-LTN006g	“ “	**“ “**	1502±9 BC	**3452±9**
TN-LTN006k		**“ “**	1522±9 BC	**3472±9**

LTN-CT-1 (license number 08E0399, site code LTN001) - Middle or Late Bronze Age (3160-2860 cal BP) wide corduroy trackway constructed from transverse split timber planks secured with wooden pegs and overlying a substructure consisting of longitudinal roundwoods and, in places, deposits of stones and gravel. In places this trackway shows at least two phases, suggesting repair and renewal of the structure indicating that it may have been in use for some time. A bronze leaf-shaped sword was recovered from amongst the timbers of this trackway in 1990 – the only metalwork ever found in direct association with a trackway in Ireland (Turrell 2008). This sword was apparently deposited during the second phase of construction. See Figure 18.

LTN-PP-2 (license number 08E0400, site code LTN006) - Early Bronze Age (3530-3440 cal BP) plank path constructed from single longitudinally-laid planks secured with wooden pegs and supported by transverse planks and roundwoods, with additional brushwood where the trackway crossed over bog pools. Several small stones, probably manuports, were recovered from beside this trackway in one cutting. See Figure 16.

LTN-BT-3 (license number 08E0401, site code LTN010) - Iron Age (2310-1900 cal BP) roughly-constructed brushwood trackway, apparently allowing access into the bog, rather than traversing it.

LTN-AW-4 (license number 08E0402, site code LTN012) - undated deposit of archaeological wood.

LTN-CT-5 (license number 08E0404, site code LTN014) - undated corduroy trackway constructed from transverse roundwoods and occasional planks secured with pegs.

LTN-AW-6 (license number 08E0405, site code LTN015) - undated deposit of archaeological wood.

LTN-AW-7 (license number 08E0406, site code LTN016) - undated deposit of archaeological wood.

LTN-PF-8 (license number 08E0407, site code LTN017) - Iron Age (1880-1740 cal BP) platform constructed from two layers of brushwood and roundwoods. A wooden trough-like vessel with a handle on one end was found immediately beside this platform.

LTN-PF-9 (license number 08E0408, site code LTN020) - undated platform.

LTN-PF-10 (license number 08E0410, site code LTN024) - Iron Age (1810-1540 cal BP) platform constructed from roundwoods and brushwood.

LTN-PF-11 (license number 08E0411, site code LTN025) - Iron Age (1870-1730 cal BP) square platform constructed from small roundwoods and brushwood secured with pegs.

LTN-PF-12 (license number 08E0412, site code LTN030) - Iron Age (2040-1880 cal BP) rectangular brushwood platform. A thin layer of peat followed by a second layer of brushwood overlies this platform, suggesting maintenance or renewal of this structure over a period of time.

4.6.4.2 Dated unexcavated features

Table 20: ^{14}C dates of surveyed archaeological features which have not been excavated at Littleton bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
TN-LTN002	**LTN-PP-13**	BETA-222650	3300±70	**3690-3390**
TN-LTN004	**LTN-BT-14**	BETA-222651	2040±60	**2150-1870**
TN-LTN009	**LTN-BT-15**	BETA-222652	2220±50	**2340-2130**
TN-LTN028	**LTN-BT-16**	BETA-222655	2170±70	**2330-2000**
TN-LTN029	**LTN-BT-17**	BETA-222656	2180±70	**2340-2010**
TN-LTN031	**LTN-PF-18**	BETA-222657	2010±60	**2120-1830**

4.6.5 Littleton summary

The earliest human activity recorded at Littleton bog is the construction of two Early Bronze Age plank pathways (LTN-PP-2 and LTN-PP-13). Trackways of similar date and construction type have been found at Inchirourke (IRK-PP-1) and also at Derryville (Cross

May *et al* 2005b) to the north. In the Middle or Late Bronze Age, a large corduroy trackway was constructed (LTN-CT-1), again with a parallel at Derryville bog: Cooleeny 31 (Cross May *et al* 2005c, p.358). The best-represented period at Littleton is the middle Iron Age, when five brushwood trackways and four platforms were constructed, which may be potentially all be near-contemporary.

4.6.6 Survey and excavations at Killeen bog

Survey in 2006 identified ten features in the central portion of Killeen bog including two trackways, four platforms, and four deposits of archaeological wood (Whitaker 2006e). The corduroy trackway, roundwood path and one platform were excavated in June and July 2010 (Rohan and Whitaker 2011), the dates of these trackways are detailed in Table 21.

Table 21: ^{14}C dates of excavated archaeological features at Killeen bog. 95% confidence interval calibrated age ranges are given in cal BP, calibrated using the Clam software package (Blaauw 2010), and using the IntCal09 calibration curve (Reimer et al 2009).

Code	License no.	Feature ID	Lab code	^{14}C date (BP)	Calibrated range 2σ (cal BP)
TN-KLN002	10E0210	**KLN-CT-1**	BETA-222645	1720±60	**1810-1520**
TN-KLN004	10E0211	**KLN-PF-2**	BETA-222646	2550±70	**2770-2370**
TN-KLN007	10E0212	**KLN-RP-3**	BETA-222647	1290±60	**1300-1080**

KLN-CT-1 (license number 10E0210, site code KLN002) - later Iron Age (1810-1520 cal BP) narrow (*c*.1.5m wide) corduroy trackway, consisting of densely-packed transverse roundwoods and rare split timbers overlying parallel longitudinal roundwoods.

KLN-PF-2 (license number 10E0211, site code KLN004) - Late Bronze Age or earlier Iron Age (2770-2370 cal BP) platform, constructed from substantial roundwoods, brushwood and occasional split timbers.

KLN-RP-3 (license number 10E0212, site code KLN007) - Early Christian to Medieval (1300-1080 cal BP) roundwood path, constructed from longitudinal roundwoods supported by occasional transverse roundwoods. In some cuttings a second later roundwood path was found directly overlying this trackway, separated by a thin layer of peat, suggesting continuity of use, most likely into the Medieval period, probably related to the ecclesiastical foundation on Derrynaflan dryland island to which this trackway leads.

4.6.7 Killeen summary

Evidence for late prehistoric activity on Killeen bog is provided by the Late Bronze Age or very early Iron Age platform KLN-PF-2. Trackways from the latter part of the Iron Age (KLN-CT-1) and Early Christian period (KLN-RP-3) both connect the drylands to the north-east of Killeen bog to Derrynaflan dryland island to the south-west. KLN-RP-3 is potentially contemporary with the foundation of Derrynaflan monastery, or with the Derrynaflan hoard, and the replacement of this roundwood path suggests the continued importance of this routeway, suggesting Derrynaflan was considered a significant place from later prehistory on into the Medieval period.

4.6.8 SMR entries around the Littleton chain of bogs

796 entries on the SMR are located within a 5km radius of the Littleton chain of bogs. Three megalithic structures, of possible Neolithic date, are located on the area of higher ground to the east. The SMR contains references to seven late prehistoric (Bronze Age or Iron Age) barrows, which are mostly located on either side of the chain of the bogs, and one being sited on Derrynaflan dryland island (see below). 32 *fulachtaí fia* have been identified, with a large concentration of entries just to the north-west of the study sites along the edges of Derryville bog, where large-scale excavations in advance of the construction the Lisheen Mine uncovered several of these features on the peatland fringes. A large number of peatland structures, trackways and platforms are recorded on the SMR from this area, dominated by sites identified in the Lisheen Mine Archaeological Project (Gowen *et al* 2005). A standing stone, and a stone circle, which may also be of prehistoric in date are located *c*.3 km to the south. Over 100 ringforts, thought to be mainly Early Christian and Medieval in date are scattered around the Littleton bogs. The Early Christian Derrynaflan monastery, founded in the 6th century, is situated on a dryland island (known locally as Goban Saor's island) almost entirely surrounded by Killeen bog. The well-known 8th or 9th century Derrynaflan hoard was found in 1980 on this dryland island (Ryan 1980, 1997).

4.6.9 Summary: Littleton chain of bogs

The most obvious parallels to the peatland structures encountered in the Littleton bogs are those uncovered during the Lisheen Mines Archaeological Project (Gowen *et al* 2005), but archaeological investigations of trackways have a relatively long history in this area, including some of the earliest systematic peatland excavations carried out in Ireland on trackways on Littleton bog itself: Rynne (1965) carried out the first investigations on the large Late Bronze Age corduroy trackway LTN-CT-1.

The Early Bronze Age plank paths at Inchirourke (IRK-PP-1), Longfordpass (LFP-PP-5) and Littleton (LTN-PP-2 and LTN-PP-13) have direct parallels with similar plank paths Cooleeny 22 and Derryfadda 23 which were excavated only 2-3km to the north (Cross May *et al* 2005b, pp.223, 233); these trackways all are likely to date to the last century of the Early Bronze Age, and appear to converge on the same area of dryland west of the Littleton chain of bogs, where evidence for a Bronze Age settlement has been found (Cross May *et al* 2005d, pp.288–292).

A second phase of activity on the Littleton chain of bogs occurs in the Late Bronze Age, with LFP-RP-3, LFP-PP-2, and the large corduroy trackways LFP-CT-1 and LTN-CT-1 all potentially contemporary, and all possibly part of the same regional communication network. This may be a successor to the Early Bronze Age system of trackways, but the corduroy trackways in particular are much larger than the Early Bronze Age paths. It has been suggested that LTN-CT-1 might have been a replacement for Cooleeny 31 at Derryville bog, which was destroyed by a bog burst soon after construction (Cross May *et al* 2005c, p.358); this is plausible since the trackways at Longfordpass and Littleton appear to be slightly later. As well as the seemingly obvious role as a means of communication, LTN-CT-1 also shows some evidence of ritualistic activity, with the apparently votive deposition of a bronze sword. Whilst votive deposition of high status metalwork in bogs (and other wet places) is well-known in Ireland, this is the only example of such deposition in direct association with a trackway. Whilst votive deposits in Irish bogs generally tend to be of ornamental metalwork rather than weapons (O'Sullivan 2007b), the deposition of weaponry in bogs appears to be a regional peculiarity in northern Munster (Grogan 2005).

Iron Age activity in the study sites appears to be largely confined to Littleton bog, with a number of brushwood trackways and platforms being constructed at this time, again potentially concentrated in one or two phases, or alternatively representing the gradual replacement of individual sites. There is no evidence for repair on these Iron Age brushwood trackways, although LTN-PF-12 does show evidence of re-use after a hiatus, perhaps suggesting relatively short-lived episodic activity. It may be possible that similar brushwood trackways and platforms at the other sites may date to this part of the Iron Age, but have merely not been dated – apart from at Littleton bog, there is a bias towards dating larger corduroy trackways and plank paths.

The latest phase of activity in the study sites in the Littleton chain is during the Early Christian, and possibly into the Medieval, period; this activity is concentrated in Killeen bog, and appears to be directly associated with the monastic foundation (and possibly pre-Christian enclosure and barrow) on the Derrynaflan dryland island, which would formerly have been encircled by wetlands. Although KLN-CT-1 and KLN-RP-3 clearly serve as a means of getting from the surrounding drylands to the 'island', the setting of Derrynaflan, surrounded by raised bog, seems likely to have played a part in making this a significant and appropriate place for a monastery.

Chapter 5: Methodology

This chapter outlines the general methods applied to fossil peat sequences. Methods employed in collecting and analysing modern surface moss and short cores vary slightly from the methods outlined in this chapter, and details are presented in Chapter 6 for the transfer function training set, and Chapter 8 for the short core study. This chapter is separated into the following sub-sections: field methods (Section5.1), sediment description (5.2), humification analysis (5.3), testate amoebae analysis (5.4), chronology (5.5), and statistical methods (5.6).

As outlined in Chapter 1, a principal objective of this research was to carry out palaeohydrological reconstructions from each of the nine milled study sites (described in Chapter 3) in order to compare the resulting records with the archaeological records of these sites. To complete this objective, the following were required:

1. A core sequence capable of recording the main shifts in environmental conditions at each study site.
2. Selection of appropriate methods to reconstruct past bog hydrology at an appropriate chronological resolution (i.e. decadal to centennial).
3. Adequate chronological control of the palaeohydrological reconstructions to allow these records to be compared to the archaeological record.
4. Selection of appropriate statistical methods to characterise the structure within the palaeoenvironmental data.

To this end, the methodological strategy outlined in detail below was formulated.

5.1 Field Methods

Field sampling of the fossil peat sequences from the milled bogs was typically carried out over a period of 3-5 days for each site. For each site, fieldwork consisted of three distinct phases: a rapid coring survey to characterise the shape of the underlying basin and the depth of the peat sequence; survey of the coring locations using dGPS; and finally, a location for the master-sequence core was selected and core samples were obtained for further analysis.

5.1.1 Single core analysis and sampling locations

Although the analysis of multiple cores from a single site has been explored in some past studies (Barber *et al* 1998; Charman *et al* 1999), this is, in practice, usually difficult, largely due to the very considerable commitment in terms of both time involved in laboratory analysis, and in terms of cost in producing robust chronologies for multiple sequences. However, past studies have suggested that a single sequence is likely to provide a representative record of the main changes in bog surface wetness across a site (Barber 1981; Barber *et al* 1994a). Whilst some studies, which have focused on analysis from a single site have utilised a multi-sequence approach (e.g. Bermingham 2005; Gowen *et al* 2005; Gearey and Caseldine 2006), the majority of recent peatland investigations tend to use a single master sequence core from each site for palaeoenvironmental analysis (e.g. Blundell *et al* 2008; Swindles, Patterson, *et al* 2012). The single core, master-sequence, approach is appropriate for this study as the aims of this research are to examine palaeohydrological and archaeological records from a number of sites across the study area and thereby assess potential regional trends, rather than to focus on analysis of only one site. Furthermore, theoretically, the tuning and stacking method of producing regional palaeoclimate records (Charman *et al* 2006) offers a potential means of differentiating between local hydrological variability and regional palaeoclimate signals (see Chapter 9).

Since a single master-sequence was taken from each site, it was important that the sampling location provided the best and most representative sequence possible. Some studies have suggested that particular micro-topographic locations in raised bogs may be more sensitive than others, although there is no clear consensus in the literature. Barber *et al.* (1998) suggest that, ideally, the master-sequence should contains the most switches between *Sphagnum cuspidatum* pool peat and lawn peat i.e. be from an intermediate microtopographic location. The rationale of this is partly based on the assumption that cores from hummocks, which tend to be persistent features, “will record a 'complacent' climatic signal” (Barber *et al* 1998, p.527) on the notion that hummocks and hollows tend to persist on the same location, and that, on this basis, the interfaces between these features are likely to be most sensitive to small variations in climatic forcing. Since the surface microtopography and vegetation on the sites examined for palaeoenvironmental analysis in this research have been obliterated by draining and milling, however, the micro-topographic location of each sampling location was almost impossible to ascertain. Despite this, sampling locations were chosen to provide the longest possible sequence from near to the centre of each site, where it was thought likely that the dome would formerly have been located.

5.1.2 Basin characterisation

An understanding of the general morphology of the underlying basin at each sampling site was required in order to select a sampling location for the master-sequence (see below). In order to do this, at a minimum, a rapid survey of the depth of the peat sequence was carried out at each site. Where time was more plentiful, a transect of cores, at 100 – 200m spacing, was carried out, using an Eijkelkamp D-section “Russian” peat corer (Belokopytov and Beresnevich 1955; Jowsey 1966) with the peat stratigraphy described in the field, but no samples retained. However, study sites are often in excess of 1km across, and thus require more than 10 cores to be extracted and described in the field to produce a transect at 100m resolution; this work could often take up to 2-3 days fieldwork. Therefore, particularly for large sites, where time was a major constraint on fieldwork, a far more rapid survey using an Eijkelkamp narrow-diameter (3cm) gouge auger.

Initial survey of the basin proceeded as follows:

1. A 'walk-over' survey was carried out at each site to ascertain: the former extent of the bog; the location of the excavated portions of the archaeological structures, and any further sightings of these structures.
2. Based on step 1, the position of the transect across the bog was chosen. The position was chosen to:
   a) Cross over the approximate centre of the bog.
   b) Avoid, where possible, any of the archaeological structures.
3. a) If the transect is to be a rapid gouge survey, a narrow-diameter gouge auger would simply be pushed into the peat, with additional rods attached until the underlying mineral sediments were reached, and the depth of the peat sequence was noted.

   b) If sufficient time was available, a “Russian” corer would be used, following the same procedures outlined below (see section on master-sequence coring), with the exception that core samples were not recovered. Instead, as each 50cm length of core was retrieved the peat stratigraphy was immediately described in the field. Description of the stratigraphy would proceed using the same modified version of the Troels-Smith system of sediment description (described in Section 5.2), with the exception that a hand lens, as opposed to a low-powered binocular microscope was used to identify very small, or poorly-preserved plant remains. In this way, a composite cross-section of the bog could be produced showing the main stratigraphic units present across the site.

5.1.3 DGPS survey

The coring locations were recorded using a Leica dGPS, which allows three-dimensional accuracy up to *c.*2-3cm. Coring locations were recorded in latitude/longitude, using the WGS86 system. Depths recorded in the rapid coring survey were corrected for differences in elevation recorded using the dGPS, and a general profile of the basin was compiled.

5.1.4 Master-sequence coring

A single sampling location from each study site was selected to provide core samples for further analysis. The location of the master-sequence was chosen based on the following criteria (in descending order of importance):

1. The sampling location should be representative of the bog as a whole and sensitive to changes, although the destruction of the surface layers of the bog due to milling meant that it was impossible to discern the micro-topographic situation, e.g. hummock, or hollow, of the sampling location (c.f. De Vleeschouwer *et al* 2010).
2. The sequence should include the maximum possible depth of ombrotrophic peat, which is likely to contain deposits contemporary with the archaeology being excavated on the site (i.e. the elevation of the top of the core should, generally, not be below the elevation of the archaeology).
3. The sampling location should not have been subject to excessive anthropogenic disturbance, and should be at least 100m away from any archaeological structures.

Master sequence coring was carried out using a D-section "Russian" peat corer (Belokopytov and Beresnevich 1955; Jowsey 1966), with a 50cm long hemi-cylindrical chamber (internal diameter: 6cm). To avoid disruption of the stratigraphy caused by the 10cm long conical nose section of the coring device, samples would be retrieved from two parallel boreholes (labelled A and B), located a maximum of 50cm apart, at overlapping intervals (see Table 22). The location was recorded using dGPS (see above), coring proceeded as follows:

1. A sufficient number of clean, 50cm long, longitudinally split sections of plastic drain pipe (6 cm diameter), were labelled with: site code, sampling date, borehole number,

duplicate set number, sample depth, and the top and base clearly marked.

2. The corer was pushed vertically into the peat until the top of the chamber was level with the surface.
3. To capture the sample, the coring device was rotated clockwise 180º by turning the handles.
4. The coring device was pulled upwards out of the peat.
5. The sampling chamber was laid horizontally onto a clean working area, and the sampling chamber was carefully opened.
6. A clean 50cm long section of longitudinally-split plastic drain pipe was carefully placed over the sample.
7. To transfer the sample to the length of plastic pipe, the blade of the coring device was carefully turned, whilst firmly holding the split pipe in place.
8. The sample was carefully wrapped with cling-film, secured with brown packing tape, and re-labelled.
9. Coring then proceeded in a parallel borehole, maximum 50cm away, at overlapping depths (see Table 22 below for example coring depths).
10. Steps 2 – 8 were repeated, alternating between boreholes A and B, until the base of the peat sequence was reached.
11. Core samples were then carefully transported and were stored in refrigerators at *c*.5ºC pending further analysis.

Table 22: Example coring depths using parallel boreholes to allow a 10cm overlap between cores to avoid disruption cased by the 10cm long nose section of the coring device (table adapted from De Vleeschouwer et al 2010, p.5).

Borehole A	Borehole B
0 – 50cm	*40 – 90cm*
80 – 130cm	*120 – 170cm*
160 – 210cm	*200 – 250cm*
240 – 290cm	*280 – 330cm*
Etc...	

At each sampling location, typically 3 – 4 duplicate sets of cores would be recovered.

Additional sets of cores would be recovered in the same way, and labelled "Set 1", "Set 2" etc. Duplicate cores were recovered no more than 50cm away from the original coring location. Although further laboratory analysis was carried out, wherever possible, from a single set of cores, additional cores provide additional material for future analyses and for archival purposes. In order to identify any discrepancy between the sequences, all sets of cores were described in the laboratory (see section below).

Figure 20: The author and Dan Young coring at Inchirourke bog.

5.1.5 Field methods summary

1. A 'walk-over' survey of each study site was carried out to locate any archaeological sites visible and to define the likely former extent of the bog.
2. A transect of boreholes was be carried out across each site to characterise the shape of the underlying basin.
3. Based on the transect of boreholes, a sampling location for the master-sequence was selected.

4. Locations of all boreholes, including the sampling location, were recorded using dGPS.
5. A D-section “Russian” peat corer was used to extract 3 – 4 duplicate sets of core samples (all analyses were carried out on the same set).
6. Samples were carefully wrapped and labelled in the field.
7. Core samples were transported to Reading, and stored at *c.*5ºC prior to further analysis.

5.2 Sediment description

Once returned to the laboratory, all cores were carefully described prior to sub-sampling for further analysis. Description of the peat stratigraphy utilised a modified version of the Troels-Smith (1955) method of describing unconsolidated sediments outlined in Birks and Birks (1980, pp.37–44). This method of sediment description is widely-used in peatland studies and has the chief advantage over other popular schemes of sediment description that it is able to distinguish between a wide variety of organic components (Kershaw 1997, p.63). The method is relatively straightforward, and thus was also used in the field to describe core samples not retained for further analysis (see Section 5.1, above).

The modified system of sediment description outlined below records five principal characteristics of each unit: the depth of the unit, colour, composition, the level of humification, and the characteristics of the upper boundary.

The overall colour of each stratigraphic unit was recorded using a Munsell Soil Color Chart (Munsell Color 1992), noting the hue, value and chroma as well as a description of the colour (e.g. “10YR 3/3 dark brown”).

Each sedimentary component is represented by two-letter symbols, abbreviated from Latin terms. Kershaw (1997) criticised the use of Latin terminology, and suggested that this makes this system less accessible and more difficult to use; however, these terms are widely understood and widely used within palaeoenvironmental studies. The components (represented by two letter symbols, outlined in Table 23 below) of each stratigraphic unit were recorded on a five point scale of relative abundance (4 = ~100%, 3 = ~75%, 2 = ~50%, 1 = ~25%, + = trace). In addition to the relative abundance of the components of each unit, an assessment of the degree of humification of each individual component was recorded (for Tb, Tl, Th, Dl, Dh, and Ld only) on a five point scale (noted in superscript after the symbol) from

0 – totally unhumified, to 4 – completely disintegrated. Thus “Tb(sphag)^{3}2 Th^{3}1 Sh+” denotes a peat composed mostly (~75%) of well-humified in-situ *Sphagnum* moss, with some (~25%) well-humified herbaceous rootlets and a trace of completely humified organic matter.

The overall level of humification of each stratigraphic unit was also estimated on a five-point scale from Humo 0 (completely unhumified) to Humo 4 (totally disintegrated). This was not recorded for units containing no organic material. Thus the example unit description above might be written: “Tb(sphag)^{3}2 Th^{3}1 Sh+ Humo 3” denoting that the unit is generally well-humified.

The upper boundary of each stratigraphic unit was recorded as either “grading” (transition between units over >10mm), “diffuse” (transition between units over 2 – 10mm) or “sharp” (transition between units over <2mm), or “top” where the unit is at the top of the core sequence.

Table 23: Classes of sediment component identified in sediment description (after Troels-Smith 1955).

Symbol	Description
Tb$^{0-4}$	*“Turfa bryophytica” - in-situ leaves, branches and stems of mosses. Most commonly Sphagnum, often labelled Tb(sphag).*
Tl$^{0-4}$	*“Turfa lignosa” - in-situ roots and other attached parts of trees and shrubs.*
Th$^{0-4}$	*“Turfa herbacea” - in-situ roots and attached leaves and stems of herbaceous plants. Remains of Eriophorum vaginatum are often very distinctive and may be labelled Th(vagi.)*
Sh	*“Substantia humosa” - completely disintegrated organic substances and plant remains, and precipitated humic acids.*
Dl$^{0-4}$	*“Detritus lignosus” - fragments of trees and shrubs >2mm.*
Dh$^{0-4}$	*“Detritus herbosus” - fragments of herbaceous plants >2mm.*
Dg	*“Detritus granosus” - fragments of plants <2mm.*
Ld$^{0-4}$	*“Limus detrituosus” - organic lake sediment composed of humified plant remains and microplankton (i.e. gyttja)*
Ls	*“Limus siliceous” - siliceous skeletons of diatom, sponges, etc., or fragments of these.*
Lc	*“Limus calcareus” - calcium carbonate, or marl.*
Lf	*“Limus ferrugineus” - iron oxides.*

As	*"Argilla steatodes" - mineral particles <0.002mm (i.e. clay)*
Ag	*"Argilla granosa" - mineral particles 0.002 – 0.2mm (i.e. silt)*
Ga	*"Grana arenosa" - mineral particles 0.2 – 0.6mm (i.e. fine sand)*
Gs	*"Grana saburralia" - 0.6 – 2mm (i.e. coarse sand)*
Gg(min)	*"Grana glareosa" - mineral particles 2 – 6mm (i.e. granule sized particles)*
Gg(maj)	*"Grana glareosa (majora)" - mineral particles >6mm (i.e. gravel)*

Based on the descriptions produced using the conventions outlined above, graphical representations of each core were produced using the Inkscape (ver. 0.48.4) open-source graphics editor package, and using the graphical conventions outlined in Troels-Smith (1955).

Three to four duplicate sets of cores were taken from each master-sequence sampling location (see field methods, above); the peat stratigraphy of each duplicate set of cores was described in the laboratory in order to ensure that there were no serious discrepancies between sets. Where possible all other analyses (detailed below) were carried out on the same set of cores.

5.2.1 Summary

1. Core samples were unwrapped in the laboratory, and the exposed face was carefully cleaned with a clean scalpel.
2. The boundaries between each stratigraphic unit were defined and noted.
3. For each stratigraphic unit, the overall colour was recorded using a Munsell Soil Color Chart (Munsell Color 1992).
4. The components of each unit were noted utilising the modified Troels-Smith (1955) scheme outlined above.
5. The upper boundary of each unit was described.
6. Graphical stratigraphic logs were produced using Inkscape (ver. 0.48.4).

5.3 Humification analysis

Humification analysis is a very well-established proxy for bog surface wetness (Chambers *et al* 2012). The method is based on the assumption that variations in surface moisture in the acrotelm will affect the rate of decomposition of plants growing on the surface of the bog. Prior to the introduction of colorimetric determination of peat humification, first used by Aaby and Tauber (1975), early studies (e.g. Walker and Walker 1961) typically estimated humification based on visual examination of the peat, using either a five point scale (Troels-Smith 1955), or using the ten point scale of von Post and Granlund (von Post and Granlund 1926).

In spite of being so well-established, important criticisms of the method exist: Yeloff and Mauquoy (2006) have shown that the botanical composition of peat can have a large effect on the humification signal, furthermore Charman *et al.* (1999, p.452) suggest that humification data are likely to be non-linear in its scaling to bog wetness, a complication which does not apply to other proxies available (e.g. testate amoebae, see below).

Humification analysis does have some important advantages, however:

1. Colorimetric analysis can be utilised as a good compliment to the visual assessment of humification carried out during description of the stratigraphy (see above).
2. The method is relatively quick, allowing *c.*30-40 samples to be prepared and processed in *c.*2-3 days.
3. The method is operator independent, providing the methodology is closely followed (Chambers *et al* 2012).

As such, humification analysis was selected as a useful compliment to testate amoebae analysis, which was selected as the main analytical method (see below).

Methods for peat humification analysis broadly follow those outlined in Blackford and Chambers (1993), and more recently in Chambers *et al.* (2010). Due to the relatively large volumes of peat required, humification determinations were usually carried out at relatively low resolution (typically a sample from a 1cm thick horizon, every 8cm down the length of the core) when compared to the resolution used for testate amoebae analysis (see below).

1. Core samples were unwrapped in the laboratory; and the exposed face carefully cleaned using a scalpel. Samples of 4cm^3 were extracted from the cores using a clean small spatula and a volumetric sampling device. Samples of 4cm3 were generally thought to provide sufficient material for analysis; however, in some rare occasions, where a visual inspection of the peat suggested that the bulk density was very low

(i.e. in very fresh *Sphagnum* peat), larger samples were extracted – up to 6cm^3.

2. Sub-samples were placed in marked foil dishes, and were then placed in an oven at 60ºC overnight to dry. The dry sub-samples were then ground in an agate pestle and mortar. The pestle and mortar were cleaned between samples using dry paper.
3. Typically 20 samples were processed together as a single batch. Before beginning colorimetric analysis, sufficient 8% NaOH solution was prepared for each batch of analyses, two litres for a batch of 20 samples.
4. A large hotplate was heated to *c.*90ºC.
5. 200mg of each dried and ground sub-sample was carefully weighed out, using a fine (up to three decimal places) balance, into a 200ml pyrex beaker.
6. 100Ml of 8% NaOH, measured using a measuring cylinder, was added to each beaker, the time was noted – analysis must be completed within 2 hours to avoid fading of the solution (Blackford and Chambers 1993).
7. The beakers were placed onto the hotplate and allowed to simmer for one hour.
8. After one hour the hotplate was turned off, and the beakers removed from the hotplate.
9. 100ml of deionised water was added to each beaker, and the samples were stirred vigorously, but carefully, using clean class stirring rods.
10. The Sherwood CHROMA model 2600 colorimeter, with 540nm filter, was turned on to stabilise.
11. A 100ml plastic skirted centrifuge tube was marked for each sample. Retort stands were set up, holding a glass funnel containing a folded piece of Whatman No. 1 grade filter paper (size: 30cm diameter) set above a clamp to hold a 100ml skirted centrifuge tube.
12. Samples were poured into the funnels, the first few drops of filtrate were discarded, and 50ml of filtrate was collected in each skirted centrifuge tube.
13. 50ml deionised water was added to each tube, the lid was replaced, and the samples were shaken vigorously for 5 seconds.
14. The colorimeter was zeroed using a cuvette containing deionised water.
15. A small amount of each sample was poured into a clean plastic cuvette, and the

cuvette was placed into the colorimeter. The % absorbance was noted.

16. The cuvette was emptied, and re-filled with more of the same sample, and the measurement was repeated, and the % absorbance noted.
17. The two readings obtained for each sample were averaged, and the data recorded in a spreadsheet.

5.4 Testate amoebae analysis

Testate amoebae analysis is now one of the most commonly-used proxies of bog surface wetness (BSW) in palaeoecological work (Charman 2001; e.g. Chambers *et al* 2012), and is often thought to be more robust than other methods (Swindles *et al* 2013, p.14), as quantitative reconstructions can be produced using transfer functions based on modern ecological data (Imbrie and Kipp 1971; Birks 1995; Woodland *et al* 1998a; Charman *et al* 2007; Turner *et al* 2013). Furthermore, the interpretation of these data is not complicated by a non-linear relationship with environmental conditions as is the case with humification analysis or plant macrofossil DCA axis scores (Charman *et al* 1999, p.452). Testate amoebae are thought to respond rapidly to environmental change and many taxa appear to be cosmopolitan in their distribution (Mitchell *et al* 2008), and so therefore make ideal indicators of environmental conditions. Sample sizes for testate amoebae analysis can also be rather smaller then other methods such as humification analysis (see above) and plant macrofossil analysis (Amesbury *et al* 2011). Whilst testate amoebae clearly have great potential as sensitive and precise proxy indicators, it must be borne in mind that the reliability of these results rests to a large extent on the precision and accuracy of the identification of taxa, and that taxonomy must be applied consistently (Payne *et al* 2011). For the reasons outlined above, testate amoebae analysis was selected as the primary analytical technique for reconstructing past bog surface wetness in this research.

Methods for testate amoebae analysis generally follow closely those outlined in Charman *et al.* (2000). The methods discussed and outlined below were carried out following description of the peat stratigraphy. Analysis was restricted to the ombrotrophic part of the sequence, as changes in hydrology in these parts of the sequences were thought to reflect allogenic forcing more accurately.

Most sequences were analysed in two stages: first, low-resolution analysis (samples at 8cm spacing down core) was carried out over the whole of the ombrotrophic sequence;

secondly, after initial 'rangefinder' dates had been obtained for each sequence (see section on chronology, below), sections of the sequences were re-sampled (sampling resolution at 2cm spacing) to increase resolution around (in order of importance): a) periods of archaeological site construction on the bog (based on initial age vs. depth models), and b) major shifts in testate amoebae assemblages, reflecting hydrological changes.

5.4.1 Sub-sampling

Core samples were unwrapped in the laboratory, and the exposed face carefully cleaned using a scalpel. Samples of $1cm^3$ were extracted from the cores using a small metal spatula and a volumetric sampling device. All equipment was carefully rinsed with deionised water between samples. Charman *et al.* (2000) recommend sub-samples of $1\text{-}2cm^3$; whilst several studies have used the larger $2cm^3$ sample size (e.g. Blundell *et al* 2008), others have successfully used the smaller $1cm^3$ sample size (e.g. Caseldine *et al* 2005), and many published studies do not specify the exact sample size used (Swindles *et al* 2007b; e.g. Plunkett *et al* 2009). Amesbury *et al.* (2011) demonstrate that the use of the smaller sub-sample size does not affect the quality, reliability or replicability of the results. Sample preparation then followed a modified version of standard procedures outlined in Charman *et al.* (2000).

Sub-samples were transferred to labelled 50ml pyrex beakers along with *c.*30ml deionised water. A single tablet containing a known quantity of *Lycopodium* spores was added to each beaker to allow quantitative testate amoebae analysis (Stockmarr 1971). Each beaker was agitated for 10 seconds using a clean disposable wooden stick and covered tightly with aluminium foil. Beakers were then transferred to a hotplate and simmered for *c.*10 minutes until the peat was thoroughly disaggregated and the *Lycopodium* tablet had dissolved fully. Sub-samples were left unstained.

5.4.2 Sieving

Each sample was rinsed through a 250µm sieved set over a 10µm mesh using deionised water. Payne (2009) criticises the use of the smaller sieve (micro-sieving), suggesting that, although the clarity of slides is improved by discarding the very fine fraction, this may lead to the selective loss of some small taxa such as *Corythion* spp. and *Trinema* spp., which may sometimes be in the dominant group of testates in certain samples. However, since micro-sieving was used for the training sets in the central Irish transfer function (Chapter 6) and in Charman *et al.* (2007), the use in fossil samples in this research should not affect the robustness of the hydrological reconstructions. Sieves were carefully rinsed clean using deionised water between sub-samples. The 10µm mesh was discarded and replaced every five sub-samples as the mesh may become clogged with microscopic particles which are invisible to the naked eye. The 10 – 250µm fraction was retained and washed into labelled plastic 15ml centrifuge tubes. The centrifuge tubes were loaded into a Jouan G4.22 centrifuge and centrifuged at 3000rpm for 5 minutes (acceleration = 9, brake = 9) and the supernatant was poured away.

5.4.3 Slide mounting

Small aliquots of each sub-sample was placed onto a glass microscopy slide. A few drops of deionised water were pipetted onto the slide and mixed with the sample using a clean disposable wooden stick. A coverslip was gently placed over the suspended aliquot of sample. Slides were prepared immediately before counting and were counted rapidly before the sample dried out. The use of deionised water as a mounting medium is recommended in Charman *et al.* (2000) as having superior optical qualities to other mounting media, furthermore, multiple slides from a single sample could be quickly and easily prepared where test concentration was low.

5.4.4 Counting

Slides prepared as described above were analysed using a Leica DM EP microscope at 200x magnification for general counting and higher magnifications (400x – 1000x) for examining finer features of fossil tests where identification was not immediately clear.

Following procedures outlined in Charman *et al.* (2000) a total count of 150 tests was aimed for. Whilst it has been suggested that higher counts may be required to identify all the taxa present in a sample counts of 50-100 tests have been shown often to be sufficient (Payne and Mitchell 2008) and where test concentration was low lower counts have been used. Other studies have shown that the cumulative number of taxa counted in each sample reaches a plateau after counts of 60-100 tests per sample (Warner, B. G. 1990; Woodland *et al* 1998a; Mitchell *et al* 2000). Samples that yielded fewer than 50 tests, however, were excluded from further analysis, in line with other recent studies (Swindles *et al* 2007a; Amesbury *et al* 2008;

e.g. Charman *et al* 2012).

5.4.5 Taxonomy

Identification was principally carried out using the dichotomous key presented in Charman *et al.* (2000) with occasional reference to other texts including SEM images in Ogden and Hedley (1981), images in older texts such as Leidy (1879), Cash *et al.* (1905) and Corbet (1973).

Taxonomy generally followed that used in Charman *et al.* (2000) with the following exceptions: *Hyalosphenia minuta* Cash 1891 was identified in several samples in the transfer function training set. *Difflugia globula* Ehrenberg 1848 (Cash and Hopkinson 1909) has been separated from other taxa included within *Cyclopyxis arcelloides* Penard 1902 (Deflandre 1929) by Charman *et al.* (2000) on the basis of the larger size of the former. These two taxa are briefly described below:

Difflugia globula Ehrenberg 1848 (Cash and Hopkinson 1909)

N.B. Specific term originally referred to *globulus*, but changed to agree with generic term.

Dimensions: generally 100 – 150µm in diameter.

Test outline: ±spherical – sub-spherical.

Colour: colourless – yellowish brown.

Test material: mineral particles and frequent diatom frustules bound in organic cement.

Aperture: large, ~50µm, often slightly irregular in outline.

Hyalosphenia minuta Cash 1891

Dimensions: *c.* 15µm long.

Test outline: Slightly pyriform in broad lateral view, straight sides tapering uniformly to aperture.

Colour: colourless.

Test material: proteinaceous.

Aperture: terminal, small, straight.

5.4.6 Data handling

Testate amoebae counts were entered into a spreadsheet using the OpenOffice Calc package, and were converted into percentages of total tests counts. Percentages were calculated using the following equation:

$$\%taxonA=\left(\frac{C}{T}\right)100$$

Where C = number of individuals of taxon A counted, and T = total test count.

Test concentration, expressed as tests/cm^3 were calculated for each sample using the following equation:

$$tests/cm3=\left(\frac{T}{\left(\frac{N}{L}\right)100}\right)100$$

Where T = total test count, N = *Lycopodium* spores counted, and L = number of *Lycopodium* spores per tablet.

Percentage testate amoebae data was then entered into the C2 software package (Juggins 2011) to produce testate amoebae diagrams. To produce quantitative reconstructions of Depth to Water Table (DWT), the ACCROTELM European testate amoebae transfer function (Charman *et al* 2007) and the new central Irish transfer function (presented in this thesis, Chapter 6) were then applied to the percentage testate amoebae data with sample-specific errors derived from 1000 bootstrap cycles (Birks 1995). The data were then also entered into C2, and plotted as the reconstructed DWT curve alongside the percentage data. Statistical analyses were then applied to the testate amoebae data (see section 5.6)

5.4.7 Testate amoebae analysis method summary

1. 1cm^3 sub-samples of peat were extracted from the core samples.
2. Sub-samples were boiled in *c*.30ml deionised water with one *Lycopodium* tablet for

10 minutes.

3. Samples were sieved though 250µm and 10µm sieves.
4. The 10-250µm fraction was transferred to plastic centrifuge tubes and centrifuged at 3000rpm for 5 minutes, supernatant removed.
5. Samples were mounted in deionised water on glass slides, and tests counted under light microscopy at 200x magnification.
6. Taxonomy broadly followed Charman *et al.* (2000).
7. Counts of 50-150 tests were achieved for each sample.
8. Counts were entered onto a spreadsheet, and percentage diagrams produced using C2 software package (Juggins 2011).
9. DWT reconstructions were carried out using central Irish (this study) or European transfer function (Charman *et al* 2007).

5.5 Chronology

Chronological control of the palaeoenvironmental sequences was provided principally through AMS ^{14}C dating, with tephra providing additional chronological control for the sequence from Kinnegad bog; these two methods are the amongst the most commonly used methods to date peat sequences.

The advent of AMS ^{14}C dating (Elmore and Phillips 1987; also see Taylor 2000) has allowed high-precision (when compared with conventional radiocarbon dates on bulk peat) dates to be obtained from small plant macrofossils, potentially allowing a sequence of dates to be obtained at closely-spaced intervals down core, assuming suitable above-ground macrofossils are present, and given sufficient financial resources. Even high-quality AMS ^{14}C dates may produce calibrated date ranges (at the 95% confidence interval) of *c.* 100-300 years. Improved age-modelling software, incorporating Bayesian statistical approaches, when combined with high-resolution ^{14}C dating, do however provide opportunities to improve precision. Much higher-precision dates may be obtained using wiggle-match ^{14}C dates (Van Geel and Mook 1989): this approach utilises the shape of the radiocarbon calibration curve itself, and fitting radiocarbon dates from several closely-spaced horizons in a stratigraphic sequence to the 'wiggles' in this curve. This involves a potentially large number of horizons to be dated (~5-10) from a portion of a sequence, and may therefore be prohibitively expensive;

and whilst this approach does offer potentially very high precision dates (~ decadal) (Turetsky *et al* 2004), errors may occur where dates may fit to several very similar 'wiggles' in the calibration curve. Ombrotrophic peat sequences generally provide abundant material for ^{14}C dating, especially in well-preserved *Sphagnum*-rich peats where easily identifiable above-ground macrofossils can be readily picked for dating; very well-humified peats, however, may pose difficulties in finding suitable material for dating (Piotrowska *et al* 2010, p.3).

Tephrochronology provides an alternative means of constraining age vs. depth models with very high precision dating, and is particularly useful as a means of correlating palaeoenvironmental sequences between sites (Pilcher *et al* 1995, 1996; Swindles, De Vleeschouwer, *et al* 2010). Previous work has shown the great potential of identifying several Icelandic tephras from the Holocene in Ireland (Plunkett *et al* 2004; Matthews 2009), and these isochrons have been successfully used to correlate palaeohydrological reconstructions between sites (e.g. Plunkett 2006). Where tephra horizons do occur, there are few disadvantages to this method of dating, and, when combined with appropriate geochemical analysis of the tephra, there is relatively little likelihood of significant error; researchers are, however, obviously restricted to being able to date particular horizons using this method.

5.5.1 Sampling for AMS ^{14}C dating

Horizons selected for AMS ^{14}C dating were selected on the following criteria, utilising a two-stage dating strategy (as recommended in Piotrowska *et al* 2010, p.10):

1. Following description of the peat stratigraphy in each master-sequence core sample, and concurrent with initial sub-sampling for humification and testate amoebae analysis, two samples to provide 'rangefinder' dates were selected from as near to the top and the base of the ombrotrophic (i.e. not fen peat) part of the core sequence. Care was taken to ensure that samples were not taken from any disturbed deposits of re-deposited peat that frequently occur on drained and milled sites.
2. Following completion of the palaeoenvironmental analysis, additional samples for dating were taken from horizons which:
   a) related to marked changes in testate amoebae assemblages, indicating hydrological shifts.
   b) appeared, based on initial linear age models (see section below), to date to within

a few centuries of the main phases of archaeological site construction on each site.

In-situ, above-ground plant macrofossils from short-lived specimens provide the best samples for AMS ^{14}C dating with the fewest potential complications (Piotrowska *et al* 2010): material which has been re-worked will give a date which can be very much older than the horizon sampled, although such material should be very rare in normal ombrotrophic peats, and should be easily identified; roots and other below-ground parts of plants are, for obvious reasons, intrusive, and so are likely to give misleadingly young dates which do not relate to the horizon sampled. Fortunately, the ombrotrophic peats analysed in this research often contain abundant suitable material for dating. Specimens picked for AMS ^{14}C dating must be carefully examined for any signs of contamination, especially fungal hyphae (which would contaminate the sample with younger carbon).

Sampling for AMS ^{14}C dating proceeded as follows:

1. Core samples were unwrapped in the laboratory, and the exposed face carefully cleaned using a scalpel.
2. A small glass vial was labelled with the site code, borehole number, and the sample depth, and rinsed with deionised water.
3. Using a clean scalpel and small metal spatula, a small amount (*c.* 1cm^3) of peat from the horizon selected for dating was removed from the core and transferred into a clean Petri dish containing a few drops of deionised water.
4. The sample was examined using a low-powered binocular microscope, and identifiable, above-ground plant macrofossils (ideally whole branches or stems of *Sphagnum* (Nilsson *et al* 2001)) were picked and transferred to a second Petri dish using a pair of foil tweezers.
5. The picked macrofossils were carefully examined at x10 magnification for evidence of contamination either by very small rootlets or fungal hyphae.
6. Clean macrofossils were transferred to the labelled glass vial and a small drop of deionised water was added to facilitate transfer of the macrofossils from the tweezers.
7. Steps 3-6 were repeated until ample material (minimum 20mg, but ideally *c.* 50mg or more) was collected from the sampling horizon.
8. The glass vial was seal with a stopper, and stored at 5ºC in a refrigerator until the samples were sent away for analysis (to either: BETA Analytic Inc., Florida;

14CHRONO Centre, Belfast; or, SUERC, East Kilbride).

5.5.2 Tephrochronology

An overview of the use of tephrochronology in dating peat profiles is given in Swindles *et al.* (2010), and the method is well-established in Ireland (Pilcher *et al* 1995, 1996; Plunkett *et al* 2004; Plunkett 2006; Rea *et al* 2012). Tephrochronological analysis was of the core sequence from Kinnegad bog, was carried out by Dr Ian Matthews, Royal Holloway, University of London (Matthews 2009).

5.5.3 Calibration of radiocarbon dates and age vs. depth modelling

Following the recommendations of Bartlein *et al.* (1995, p.422) all radiocarbon ages are presented in tables showing both uncalibrated and calibrated ages. Radiocarbon dates were calibrated using the IntCal09 radiocarbon calibration curve (Reimer *et al* 2009) using software packages such as OxCal v.4.2 (Bronk Ramsey 1995, 2001; Bronk Ramsey *et al* 2010), Bpeat (Blaauw and Christen 2005), CLAM v.2.1 (Blaauw 2010), or Bacon (Blaauw and Christen 2011); these software packages were also used to construct age vs. depth models for each core sequence (see below). Calibration of ^{14}C dates produces a non-normally distributed, and often multimodal, probability density function, for this reason selection of a single point estimate of a radiocarbon age can be complicated: Telford *et al.* (2004) show that the intercept (of a radiocarbon date against the calibration curve), which is a commonly-used point estimate, is highly unstable, sensitive to minor changes in the calibration curve, and may fall outside of the 95% confidence range when dates are adjusted using Bayesian age modelling techniques. Therefore, the 95% confidence interval, rather than any single point estimate, of ^{14}C dates are referred to in the this text.

5.5.3.1 Non-Bayesian Linear age vs. depth models

Age vs. depth modelling was carried out to estimate the ages of undated levels in each peat core. Perhaps still the most common form of age model used in palaeoenvironmental studies is linear interpolation - i.e. point estimates are made for each dated level and a straight line is drawn, joining the dated point estimates (Blaauw and Christen 2005, p.806). Such an approach to age modelling has several deficiencies:

1. There are difficulties associated with selecting a single point estimate from a ^{14}C age (see above).

2. Such age vs. depth models may show abrupt changes in deposition rate at each date (Bennett 1994, p.339), which is likely to be unrealistic (Piotrowska *et al* 2010, p.7).
3. Such models assume that all ^{14}C measurements are correct, i.e. there are no outliers (Bronk Ramsey 2009a).

Linear models, although crude, are easy to implement, and are frequently thought to provide a reasonable estimate of ages (Bennett 1994, p.339). Such models are still useful, and indeed widely used, where only a small number of levels are dated as more advanced Bayesian techniques (discussed below) may be unlikely to improve models (Blaauw 2010, p.516). A recently developed software package, CLAM (Blaauw 2010), has been developed with the specific goal of producing “classical” linear age models in a more “systematic, transparent, [and] documented [way]” (Blaauw 2010, p.512). This software package, which operates in the R statistical environment (R Core Team 2013), allows a number of different models (as defined in Bennett 1994, pp.339–340) to be rapidly assessed: linear interpolation, spline interpolation and polynomial line-fitting. Unlike other approaches to linear age vs. depth modelling, a probability sampling (Monte Carlo sampling) approach is utilised to take into account the complex probability distribution of calibrated ^{14}C ages. Repeated (1000 iterations) Monte Carlo sampling of the calibrated age distributions, and drawing and re-drawing of the resulting age vs. depth models, results in an equal number of age estimates for each undated level, which are then used to estimate 95% confidence intervals of the modelled age ranges. A weighted mean of these confidence intervals provide a relatively robust point estimate for each level.

The CLAM v.2.1 (Blaauw 2010) package was used to produce initial age models for each of the core sequences after the first stage of ^{14}C dating (see above) to provide chronologies for the first stage of palaeoenvironmental analysis. Where sequences were dated at low resolution (e.g. 4 dates over a sequence *c.*3m long), final age vs. depth models were also produced using this approach (see Chapter 7 for the age vs. depth models generated for each sequence). Smooth spline models were selected as being most likely to represent realistic representations of peat accumulation; this model assumes relatively consistent accumulation rates with gradual changes, which appears to be a reasonable assumption over long time scales (Belyea and Clymo 2001).

5.5.3.2 Bayesian age vs. depth models

In recent years a number of other approaches to age vs. depth modelling have been developed, most notably incorporating Bayesian statistical techniques (Blaauw and Christen 2005; Bronk Ramsey 2008, 2009b). Bayesian statistical approaches allow *prior* assumptions and knowledge to be incorporated when calculating a *posterior* probability distribution. In the case of age vs. depth modelling, prior assumptions would include (amongst others, see below) the assumption that age increases with depth (i.e. that there are no inversions in the stratigraphic sequence – such disruption of the sequence would normally be obvious when examining cores of ombrotrophic peat). These age vs. depth model generally offer greater flexibility than the linear models described above.

A number of software packages exist which are capable of implementing Bayesian age vs. depth modelling techniques. Perhaps the most widely used software package is OxCal (Bronk Ramsey 1995, 2001; Bronk Ramsey *et al* 2010), which offers a variety of deposition models including the P (Poisson) sequence (Bronk Ramsey 2008). In this model, deposition is assumed to be driven by a series of small random increments (the size of which are defined by the *k* parameter) and is approximately proportional to depth, thus allowing a large degree of flexibility; there are, however, no clear guidelines about how to determine *k* (Haslett and Parnell 2008, p.412).

A software package designed specifically for age vs. depth modelling of peat deposits, Bpeat (Blaauw and Christen 2005), utilises a Bayesian wiggle match approach, using a set of prior assumptions based on palaeoecological knowledge of raised bogs. These are:

1. Age increases with depth.
2. Peat accumulation proceeds linearly with occasional hiatuses or changes in accumulation rate (i.e. piecewise linear accumulation).
3. Hiatuses or changes in deposition rate may occur at any depth.
4. Peat accumulation rates are usually 10 – 20yr/cm.
5. There is a weak relationship between accumulation rates of neighbouring sections (i.e. 'memory').
6. Short hiatuses are more likely than longer hiatuses.
7. Any ^{14}C date may be an outlier.
8. (from Blaauw, Bakker, *et al* 2007, p.358)

Priors for the peat accumulation rate and the hiatus length are given as gamma distributions and are constrained to be positive. Age estimates for each depth are derived from age estimates resulting from large numbers of Markov Chain Monte Carlo (MCMC) iterations. Bpeat thus allows this knowledge about the deposition environment of raised bogs to be incorporated into age vs. depth models. However where these assumption begin to break down, wiggle matching of the ages will be less successful and more flexible models will be more appropriate (Blockley *et al* 2007, pp.1924–1925) Similarly for cores where there are few dates, the approach used can be too restrictive unless a large number of sections are used (Blaauw and Christen 2011, p.458).

Bacon (Blaauw and Christen 2011) combines the prior information incorporated into age vs. depth models in Bpeat with greater flexibility; this builds upon improvements (proposed by Haslett and Parnell 2008) of the piecewise-wise linear approach discussed above, whilst still retaining the ability to input prior information on accumulation rates based on palaeoecological knowledge. The resulting model performs well for cores that are densely dated, as well as providing good estimates for less densely dated sequences (Blaauw and Christen 2011, p.459).

The Bacon package was therefore used to produce age vs. depth models for each core once the results of all radiocarbon age determinations had been obtained.

5.5.4 Summary of chronological methods

1. Following description of the peat stratigraphy (see above), horizons for 'rangefinder' ^{14}C dates were selected from close to the top and the base of the ombrotrophic part of the sequence.
2. Above-ground plant macrofossils (preferably *Sphagnum* stems or branches) were picked from the selected (1cm thick) horizons.
3. Samples were washed using deionised water, transferred to stoppered glass vials using clean tweezers, and sent to the laboratory for AMS ^{14}C dating.
4. Initial (linear) age vs. depth models for each sequence were produced in the CLAM v.2.1 (Blaauw 2010) software package, using the IntCal09 (Reimer *et al* 2009) radiocarbon calibration curve.
5. Following completion of humification (Section 5.3) and testate amoebae (Section 5.4) analyses, additional samples for 14C dating were taken to date horizons which relate to hydrological events identified in the proxy analyses.

6. Steps 2. and 3. were repeated.
7. Age vs. depth models were produced using the Bacon (Blaauw and Christen 2011) software package, and age vs. depth plots were produced.

5.6 Statistical methods

This section gives details of statistical methods that were routinely applied to all testate amoebae data (see Section 5.4). The aims of these analyses were to: a) provide additional information about the community structure represented by the fossil testate assemblages; and b) to assess the main gradients within the data. These aims were achieved through the generation and interpretation of diversity indices, and the application of Detrended Correspondence Analysis (DCA), respectively.

5.6.1 Diversity indices

Diversity indices were calculated as part of a basic examination of the structure of all the testate amoebae assemblages assessed in this study. Diversity indices can provide information, for example, about stress in an ecological community (Magurran 1988), or may be related to selective preservation in fossil assemblages (Swindles and Roe 2007).

There are a variety of diversity indices that are used in ecology and palaeoecology, perhaps the simplest of which is the species richness (*R*). Species richness is simply the number of taxa observed in any given assemblage, which in itself can often be highly informative (Shaw 2003).

Alongside measures of the richness of communities, other methods such as the Shannon (or Shannon-Weiner) and the Simpson diversity indices give an indication of the evenness of the distribution of taxa in a community. The Shannon diversity index (H') is one of the most popular indices in ecology (Magurran 1988, p.34), but it assumes that all of the species in an assemblage are present in a sample (Peet 1974). H' values usually fall between 1.5 and 3.5 (Magurran 1988, p.35), with values between 2.5 and 3.5 indicating healthy environments and values significantly below this are thought to indicate stressed environments (Turner *et al* 2013, p.398). The Shannon diversity index is calculated as follows:

$$H' = -\sum_{i=1}^{R} \left(\frac{X_i}{N_i}\right) x \ln \left(\frac{X_i}{N_i}\right)$$

Where R is the species richness, X_i is the abundance of each taxon in a sample and N_i is the total abundance of the sample.

Unlike the Shannon diversity index, which provides a measure of the species richness, Simpson's index (Simpson 1949) is a measure of dominance of the commonest taxa in a sample. Simpson's index is a measure of the probability that any two individuals from a sample will be of different species. The Simpson index (D) is calculated as follows:

$$D=\sum_{i=1}^{R} p_i^2$$

Where R is the species richness and p_i is the proportion of individuals in the ith species.

Testate amoebae count data were entered into the PAST v.2.17 statistics package, and R, H' and D were calculated using the diversity indices function.

5.6.2 Detrended Correspondence Analysis (DCA)

Texts such as Kovach (1995) and Shaw (2003) provide useful introductions to various commonly used multivariate data analysis techniques used in Quaternary science. DCA is an indirect ordination technique that is commonly used by ecologists and palaeoecologists to analyse gradients within datasets, which is likely, for example, be related to environmental conditions (Hill 1979). In DCA, datapoints are plotted along a number of orthogonal ordination axes, each associated with an eigenvalue. DCA is an improvement upon reciprocal averaging (more commonly known as correspondence analysis (CA)). The main faults in CA, which are corrected in DCA are the 'arch effect' and compression of the ends of the gradient, and so, in DCA the arch effect is removed by detrending, and the end effects removed by nonlinear rescaling (Hill and Gauch 1980).

Biplots showing both species and sample scores, typically along the first two axes, can then be plotted; axis 1 is often interpreted as the main environmental gradient controlling community composition.

DCA makes few underlying assumptions, however the most important is that of a Gaussian unimodal response of species to environmental conditions (ter Braak 1995), although some work has suggested that DCA may still be able to extract a meaningful environmental gradient when this assumption is violated (Ejrnæs 2000). DCA may be used to estimate the length of the gradient of variation within the data, expressed as standard deviation (SD) units of biological turnover (Hill and Gauch 1980); where axis scores range over four SD units or more (as is the case for the datasets presented in this thesis) this represents a complete turnover in community composition, suggesting that unimodal statistical methods may be used (Birks 1995, p.174).

DCA is often used on plant macrofossil data from raised bogs, and axis 1 scores are frequently interpreted as a measure of BSW (Barber *et al* 1994a; Chambers *et al* 2012). Similarly, DCA has been used on testate amoebae, where a good correlation between DCA axis 1 scores and DWT values increase confidence in the reconstruction (e.g. Wilmshurst *et al* 2003; Amesbury *et al* 2008, p.91).

DCA was carried out on percentage testate amoebae data from each core sequence using the PAST v.2.17 (Hammer *et al* 2001) statistics package. Rare taxa (fewer than 5 occurrences) were removed, and values were converted to percentage of the row (sample) sum. Sample and species scores for the first three axes were saved and biplots were produced.

5.6.3 Summary of statistical methods

1. Spreadsheets containing raw testate amoebae counts (species in rows, samples in columns) from each core sequence were loaded into PAST.
2. R, H', and D were calculated using the diversity indices function, and the results were copied and tabulated.
3. Spreadsheets containing percentage testate amoebae data (samples in rows, species in columns) from each core sequence were loaded into PAST.
4. Taxa with fewer than five occurrences were removed from the dataset.
5. DCA was carried out on the dataset.
6. Species and samples scores for the first three axes, and their respective eigenvalues were extracted and saved.
7. A biplot (axis 1 vs. axis 2) was produced for each sequence.

Chapter 6: Transfer function

In this chapter, a new central Irish transfer function for reconstructing past BSW from fossil testate amoebae is presented. This chapter is organised as follows: first, a brief introduction to the transfer function approach is presented, with a focus on previous applications of the approach to testate amoebae analysis; second, the sites and methods utilised in developing the training set for the new transfer function are presented; this is followed by an analysis of the training set data; the development of the transfer function model is then discussed; finally, the model is tested and the resulting reconstructions compared to existing published transfer functions.

6.1 Introduction

Transfer functions, (also known as calibration functions) allow quantitative reconstruction of environmental variables from fossil assemblages. The approach was first introduced by Imbrie and Kipp (1971), where marine foraminifera assemblages were used to reconstruct past sea surface temperatures. Since then, transfer functions have been used widely in Quaternary palaeoecology. Birks (1995) gives an overview of the method, and outlines seven basic requirements for this approach to be applicable:

1. *The biological system to be studied produces abundant, identifiable fossils and is responsive and sensitive to the environmental variables of interest.*
2. *A training set of modern samples and environmental data.*
3. *Fossil data used for reconstruction must follow the same nomenclature, and be from the same sedimentary environment as the training set.*
4. *Good chronological control to permit comparisons between fossil data sets.*
5. *Robust statistical methods to model the relationships between taxa and their environment.*
6. *Reliable statistical estimates of errors of prediction.*
7. *Critical evaluations of the reconstructions.*
8. (adapted from Birks 1995, pp.169–170.)

Testate amoebae meet the first of these requirements since they form a large component of the microbial biomass in ombrotrophic bogs (Gilbert *et al* 1998a; Mitchell *et al* 2003), their tests are readily preserved in peat (e.g. Warner 1988, p.251), and past ecological work has shown that testate communities are responsive to bog surface wetness (e.g. Tolonen 1986). The third requirement is met in this study as both modern and fossil samples were prepared using very similar methodologies, and the same nomenclature (as outlined in Chapter 5). Comparisons between fossil data sets (requirement 4) is the subject of later chapters in this thesis, and are not discussed in this chapter. The development of the modern training set (requirement 2), the selection of appropriate statistical methods to model taxa-environment relationships (requirement 5) and errors of prediction (requirement 6), and critical evaluation of the resulting reconstructions (requirement 7) are the focus of the main body of this chapter. It is important to bear in mind however, that recent developments in ecological theory may challenge some of these assumptions (Belyea 2007).

Since first being proposed by Charman and Warner (1992), and implemented by Warner and Charman (1994), in Canada, the transfer function approach has been applied to testate amoebae from a number of regions since the 1990s including Alaska (Payne *et al* 2006), New Zealand (Charman 1997), and Greece (Payne and Mitchell 2007). In the British Isles, the first testate amoebae transfer function was published by Woodland et al. (Woodland *et al* 1998a). Recently, a widely-used supra-regional European transfer function has been published by Charman et al. (2007), this transfer function includes samples from one site in central Ireland (Ballyduff bog, Co. Tipperary). Regional transfer functions have been developed for smaller areas of the British Isles including Northern Ireland (Swindles *et al* 2009), and Northern England (Turner *et al* 2013). The latter study explored the relationships between reconstructions based on regional and supra-regional transfer functions, and found the transfer function method to be generally robust, but stressed the importance of avoiding using transfer functions from other regions, and comparing multiple reconstructions (Turner *et al* 2013). In the same vein, the regional transfer function for central Ireland is presented and tested below. Alongside the proliferation of transfer functions, recent research on the underlying statistics of the method have sounded notes of caution, including problems associated with spatial autocorrelation (Telford and Birks 2005), the need to sample environmental gradients evenly in training sets (Telford and Birks 2011b), and the effects of highly-clustered datasets (Payne *et al* 2012). The new central Irish transfer function presented below will allow investigation of the ecological relationships between hydrology and testate amoebae communities in the specific study area set out in this thesis. This will then be compared to existing the existing supra-regional transfer function as well as other transfer functions from other parts of the British Isles.

6.2 Sites and methods

Modern surface samples from four intact raised bogs in central Ireland were collected in April 2011 (Annaghbeg bog, Co. Galway) and March 2012 (Brown bog, Co. Longford; Annaghbeg bog, Co. Galway; Clara bog East, Co. Offaly; and, Ballagharahin bog, Co. Laois) - see Chapter 3.2 for detailed descriptions of these sites and their locations. These sites were selected to capture the range of variation in lowland raised bogs within the study region and to be distributed as closely as possible to the nine milled sites from which fossil testate amoebae sequences (see Chapter 7) and archaeological data (Chapter 4) have been analysed. Although generally smaller than the milled study sites, these intact sites were selected to give good modern analogues for past conditions prior to drainage and industrial peat extraction.

According to recently developed maps of nitrogen deposition in Ireland, three of the sites (Annaghbeg, Clara east, and Ballagharahin) receive 10-15kg/ha of total nitrogen, whilst Brown bog is located within an area mapped as receiving 15-20kg/ha; at all sites, 80-90% of this deposition was reduced nitrogen (Henry and Aherne 2014), and therefore most likely to comprise the products of intensive agriculture (Payne 2014, p.1). Given that excessive exposure to nitrogen pollution has been shown to have a significant effect on microbial biomass in ombrotrophic peatlands (Payne *et al* 2013), the effect of the differential nitrogen loading on the four study sites is a potentially important factor that has not been considered here, but should be the focus of further work.

6.2.1 Field methods

The aim of field sampling at each intact site was to collect a representative training set of samples of surface moss to develop a transfer function to reconstruct past BSW from fossil testate amoebae assemblages. The samples were collected to cover as wide a range of microhabitats and hydrological conditions as possible to cover the full range of past BSW conditions to be encountered in the fossil sequences. To this end, the following sampling strategy was devised:

1. At each site, four to six sampling locales were selected; these were widely dispersed across each bog, and were selected to cover the range of broad vegetation types present on each site; in addition, each location ideally displayed good variation in microtopography.

2. At each locale, four to twelve sampling locations were selected within a *c.* 5m radius to cover the range of microtopographic features at each locale (e.g. hummock top, hummock edge, lawn etc.). Sampling locations were kept clear of equipment, and care was taken to keep disruption of the surface to a minimum.
3. A digital photograph was taken, and a note was made of the vegetation cover at each sampling location.
4. Using a clean serrated carving knife, a section of surface moss (measuring 10×10×10 cm) was carefully removed, the upper 5 cm of green moss was removed using scissors. Samples were placed into labelled plastic (Tupperware type) tubs.
5. The sampling locations were marked with canes, and after allowing the water table to equilibrate for 1-2 hours, the depth from the surface of the vegetation to the water table was measured and noted.
6. Samples were transported back to Reading for laboratory analysis.

6.2.2 Laboratory methods

In the laboratory, samples were divided in half. Half of each sample was used to determine moisture content using the following method:

1. Clean foil boats were labelled and weighed.
2. Samples were transferred to the foil boats, and weighed.
3. The foil boats were placed in an oven set to 105ºC and allowed to dry over night.
4. Samples were removed from the oven and re-weighed.
5. Percentage moisture content was calculated using the following equation:

$$\%Moisture = \left(\frac{(w-d)}{w} \right) * 100$$

where *w* is the wet sample weight (wet weight minus boat weight) and *d* is the dry sample weight (dry weight minus boat weight).

The other half of each sample was prepared for testate amoebae analysis. Methods followed those outlined in Chapter 5.4 with the exception that samples were not of a set volume, and so test concentration per cm^3 was not calculated; *Lycopodium* was still added to samples to check that tests had not been poured away along with the supernatant after centrifuging.

6.3 Analysis of training set

The complete training set obtained from the four sampling sites consists of a total of 116 samples, of these 116 samples 24 were collected from Annaghbeg bog, 40 from Brown bog, 24 from Clara East, and 28 from Ballagharahin bog. Table 24 gives a summary of the characteristics of each sampling site. A total of 60 taxa were present in the training set, of which 43 taxa had maximum relative abundances of greater than 2%. Before proceeding to develop a transfer function to reconstruct hydrological variables from this training set, a number of analyses have been carried out. Firstly the evenness of sampling of the hydrological gradient is examined. Then the ecological structure of the assemblages is analysed, including an examination of diversity indices, and cluster analysis of the data to characterise the main groupings of species assemblages. The final stage of data analysis involves assessing the suitability of this dataset for use in developing a transfer function, to this end two ordination techniques are used: detrended correspondence analysis (DCA) is employed to examine differences between sampling sites in the training set, to determine the length of the environmental gradients, and to check for trends in the species data; finally, canonical correspondence analysis (CCA) is used to elucidate the relationships between hydrological variables and the testate amoebae assemblages.

Table 24: Summary of sites in training set.

Site	Mean annual rainfall (mm)	Mean annual temperature (ºC)	Number of samples (n)	DWT (cm)	Moisture content (%)
Annaghbeg	1190 – 950 [1,2]	10 – 9.8 [1,2]	24	-3 to 56	86.1 to 98.5
Ballagharahin	950 [2]	9.8 [2]	28	0 to 26	90.8 to 98.9
Brown	1050 [3]	9.6 [3]	40	-20 to 20	92.6 to 98.3
Clara	970 – 950 [4,2]	9.3 – 9.8 [2,4]	24	-2 to 30	90.7 to 98.3

Weather stations (indicated by number in superscript): 1 – Athenry, Co. Galway; 2 – Gurteen, Co. Offaly; 3 – Mountdillon, Co. Longford; 4 - Mullingar, Co. Westmeath. Mean values are for the period 1981 – 2010 (Met Éireann 2012).

6.3.1 Evenness of sampling of gradient

Telford and Birks (2011b) have shown that transfer functions based on unevenly sampled gradients may bias estimates of the root mean square error of prediction (RMSEP).

For the purposes of this discussion DWT values will be used to represent the hydrological gradient. Figure shows the sampling evenness across the DWT gradient in the central Irish training set. As shown in this histogram, the gradient is unevenly sampled – this is likely to lead to overly-optimistic estimations of RMSEP at the less-densely sampled part of the gradient, and possibly to pessimistic estimations of RMSEP in the central part of the wetness gradient (Telford and Birks 2011b, pp.105–106).

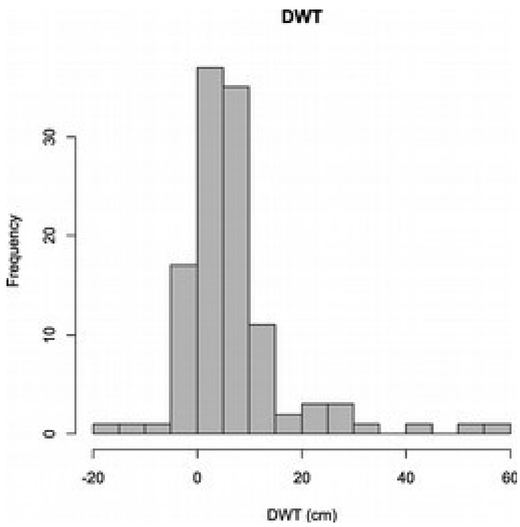

Figure 21: Evenness of sampling of the DWT gradient in the central Irish training set.

Table 25 shows the summary statistics for measured DWT values of samples in the training set, divided by site, and also for the whole dataset, generated in GenStat ver.15. DWT values observed in the training set range from -20 to 56 cm. Observed DWT values have a positively-skewed distribution, reflecting that there are more extreme values towards the drier end of the sampled gradient – i.e. more very dry hummocks were sampled than very deep pools; this result is to be expected since intact raised bogs in central Ireland are typically rather 'hummocky' (Barber *et al* 1998, p.516). The distribution of DWT values are also rather leptokurtic – that is that the probability of extreme values is greater than the normal distribution, again, this finding is intuitive since all the sites, to varying extents, show pronounced hummock-lawn-hollow microtopography. These statistics reveal some differences between sites: Brown bog is the only site where DWT values are negatively skewed, reflecting the fact that this sites was the wettest of the four bogs. Annaghbeg and Ballagharahin both have platykurtic distributions, with fewer extreme values than expected in the normal distribution - this is thought to reflect the fact that these sites appear to have been more heavily effected by drainage and marginal peat cutting, resulting in less pronounced microtopography compared to Brown and Clara which shows less damage.

Table 25: Summary statistics of measured DWT values in central Irish training set.

Site	Mean	Median	Minimum	Maximum	S.D.	Skewness	Kurtosis
Annaghbeg	13.58	8	-9	56	17.43	1.14	0.34
Ballagharahin	7.21	6	0	26	6.27	1.02	0.98
Brown	4.25	4.5	-20	20	6.36	-1.23	4.47
Clara	6.33	5	-2	30	7.03	1.91	3.96
FULL DATASET	7.33	5.25	-20	56	10.26	2.12	7.33

The training set presented here, therefore, spans the range of types of intact lowland raised bog in central Ireland, including both very wet and relatively dry bogs. The measured DWT values cover the range of values likely to be encountered in fossil data, from deep pools (DWT = -20 cm) to very dry hummocks (DWT = 56 cm). The distributions of the observed DWT values appear to reflect observations made in the field, and therefore appear to be a representative sample.

Although representative of the range of DWT values observed at the sampling sites, the gradient is not evenly sampled, and as mentioned above, this is likely to cause bias in the estimation of RMSEP. One hypothetical alternative, where the gradient is evenly sampled, would involve very unrepresentative sampling of the sites, with an inordinately large number of samples from the extremes of the gradient; this however is potentially impractical since extremely wet and extremely dry locations on bogs are less common, and could potentially exacerbate problems associated with highly clustered datasets (Payne *et al* 2012). Another alternative would be to reduce the number of samples in the over-sampled part of the gradient; this approach was attempted by Ginn et al. (2007) and lead to worsening of the RMSEP. Clearly both alternatives are undesirable, the choice of model used for the transfer function (discussed below) can to a certain extent mitigate against the effect of an unevenly sampled gradient (Telford and Birks 2011b), and evaluations of the performance of reconstructions must allow for the possibility that the RMSEP is likely to be overly-optimistic for very wet or very dry samples.

6.3.2 Diversity

Table 26 shows the summary statistics of some common measures of diversity carried out on the training set data from central Ireland. Diversity was measured using the PAST v. 2.17 software package (Hammer *et al* 2001). The measures of diversity reported here are the species richness (*R*), the Shannon diversity index (*H'*) and Simpson's index (*D*).

Table 26: Summary of measures of diversity of central Irish testate amoebae training set.

	N	Minimum	Maximum	Mean	Median	SD
Species richness (*R*)	116	9	29	17.81	18	3.89
Shannon index (*H'*)	116	1.04	2.84	2.19	2.23	0.38
Simpson's index (*D*)	116	0.46	0.93	0.82	0.85	0.09

One of the simplest, and sometimes most informative, measures of diversity is species richness (*R*) - i.e. the number of taxa observed in a given sample (Shaw 2003). *R* in the central Irish training set ranges between 9 and 29 (mean value 17.81), which is typical for testate amoebae samples (Woodland *et al* 1998a, p.262). Figure 22 shows scatter plots of *R* against DWT and moisture content. There is no clear relationship between these hydrological variables and the species richness, values are close to the mean across the hydrological gradient, with a large amount of variation in the most densely-sampled section of the gradient (DWT -2 to 12 cm, and 94 to 99% moisture content).

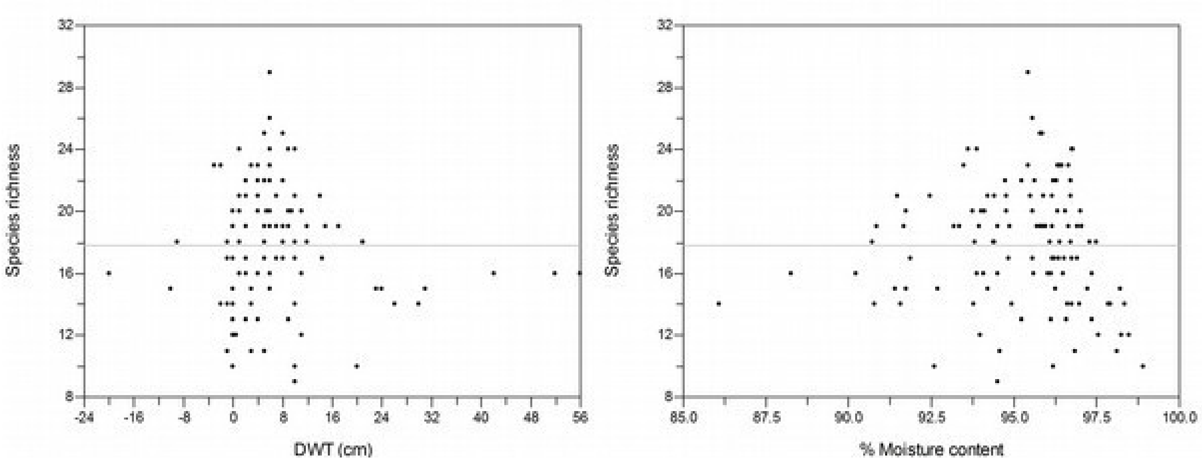

Figure 22: Species richness of samples in central Irish testate amoebae training set plotted against hydrological variables. Left – against DWT; Right – against % Moisture content. Horizontal grey line shows mean species richness value (17.81).

H' values range between 1.04 and 2.84, with a mean value of 2.19. These values therefore are towards the lower end of the typical range of *H'* values, which usually fall between 1.5 and 3.5 (Margalef 1972), although the mean value observed in this dataset falls in the middle of this range. Shannon diversity index values from this dataset are similar to the values observed in a similar study of testate amoebae ecology in Northern Ireland (Swindles *et al* 2009, p.127). Figure 23 shows scatter plots of *H'* values against DWT and moisture content; no clear trends are visible, suggesting that there is no clear relationship between diversity habitat wetness. Across the sampled hydrological gradient *H'* values tend to be close to the mean, with greatest variation in the most densely-sampled part of the gradient (DWT -2 to 12 cm, and 94 to 99% moisture content).

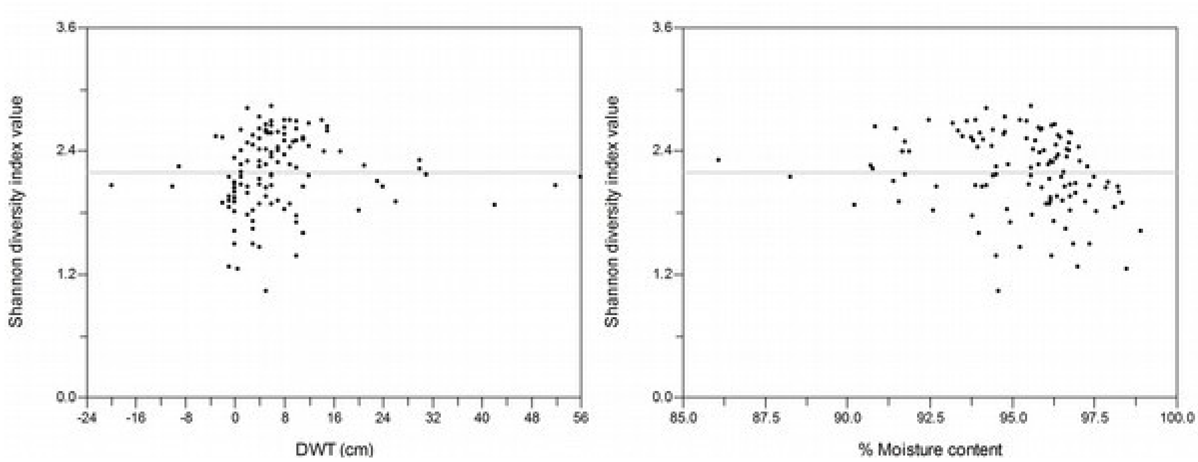

Figure 23: Shannon diversity index values of samples in central Irish testate amoebae training set plotted against hydrological variables. Left – against DWT; Right – against % Moisture content. Horizontal grey line shows mean Shannon index value (2.19).

D values range between 0.46 and 0.93, with a mean value of 0.82. As is the case with *R* and *H'*, Figure 24 shows that there is no clear relationship between hydrological variables and *D* values, with greatest variability in the most densely-sampled section of the gradient. This plot does, however, highlight three outliers – these are ANNA9, ANNA20 and BROW35 which all have especially low *D* values which is a result of the overwhelming dominance of *Amphitrema flavum* in each of these samples. Figure 25 shows *D* plotted against species richness; the same three samples are again identifiable as outliers.

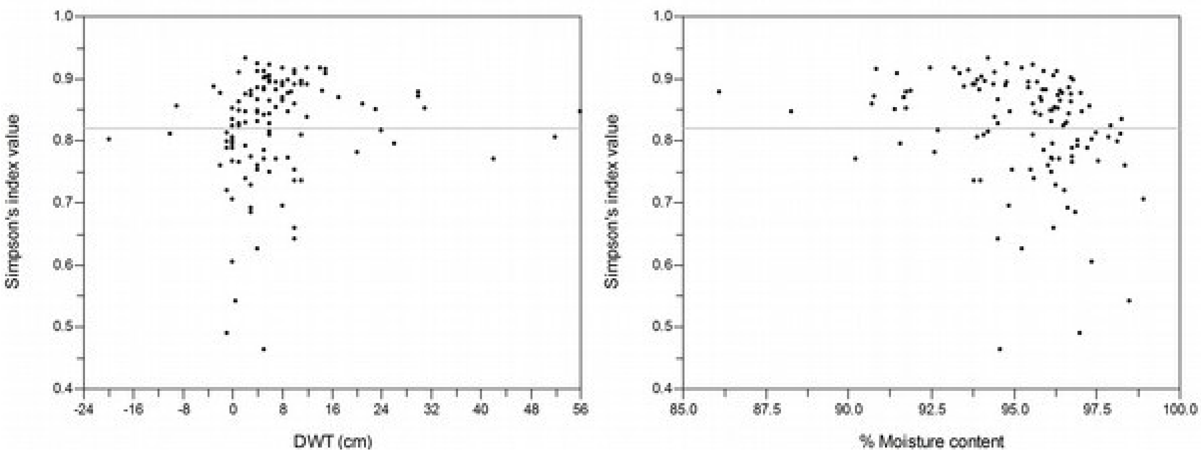

Figure 24: Simpson's index values of samples in central Irish testate amoebae training set plotted against hydrological variables. Left – against DWT; Right – against % Moisture content. Horizontal grey line shows mean Simpson's index value (0.85).

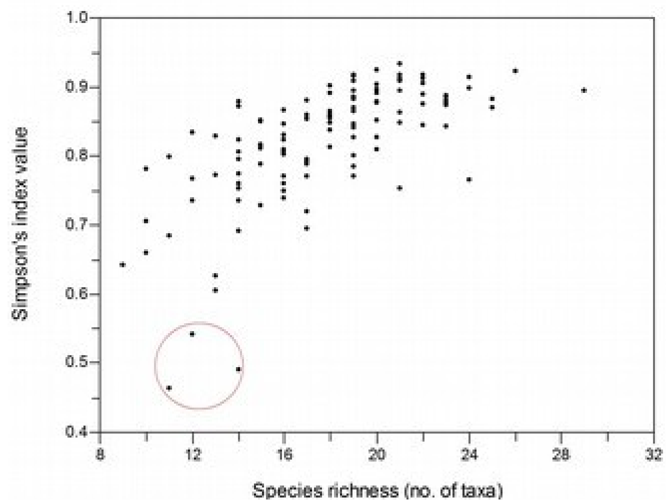

Figure 25: Scatter plot showing Simpson's index values plotted against species richness of central Irish testate amoebae training set. Outlying samples with low Simpson's index values are indicated with the red circle.

6.3.3 Cluster Analysis

In order to characterise the main taxa assemblage groups in the training set, cluster analysis has been carried out. Analysis was carried out using PAST v. 2.17 (Hammer *et al* 2001) using Ward's method and Euclidean distance. Figure 26 shows the resulting dendrogram, with samples grouped into eight clusters for further discussion below. Figure 27 shows the relative abundances of all taxa with maximum occurrences over 2% of all samples in the central Irish training set presented in dendrogram order, with cluster groups shown with dashed lines.

The figures presented below use the following abbreviations for taxon names, these are: AMPFLA – *Amphitrema flavum*, AMPSTE – *Amphitrema stenostoma*, AMPWRI – *Amphitrema wrightianum*, ARCCAT – *Arcella catinus*, ARCDIC – *Arcella discoides*, ARCGIB – *Arcella gibbosa*, ASSMUS – *Assulina muscorum*, ASSSEM – *Assulina seminulum*, BULIND – *Bulinularia indica*, CENACU – *Centropyxis aculeata*, CORTYP – *Corythion-Trinema* type, CRYOVI – *Cryptodifflugia oviformis*, CRYSAC – *Cryptodifflugia sacculus*, CYCARC – *Cyclopyxis arcelloides*, DIFBACarum – *Difflugia bacillariarum*, DIFBACfera – *Difflugia bacillifera*, DIFGLO – *Difflugia globula*, DIFLEI – *Difflugia leidyi*, DIFOBL – *Difflugia oblonga*, DIFPRI – *Difflugia pristis*, DIFPUL – *Difflugia pulex*, DIFRUB – *Difflugia rubescens*, EUGCIL – *Euglypha cilliata*, EUGCOM – *Euglypha* *compressa*, EUGROT – *Euglypha rotunda*, EUGSTR – *Euglypha strigosa*, EUGTUB – *Euglypha tuberculata*, HELPET – Heleopera *petricola*, HELROS – *Heleopera rosea*, HELSPH – *Heleopera sphagni*, HELSYL – *Heleopera sylvatica*, HYAELE – *Hyalosphenia elegans*, HYAMIN – *Hyalosphenia minuta*, HYAPAP – *Hyalosphenia papilio*, HYASUB – *Hyalosphenia subflava*, NEBCAR – *Nebela carinata*, NEBFLA – *Nebela flabellulum*, NEBGRI – *Nebela griseola*, NEBMAR – *Nebela marginata*, NEBMIL – *Nebela militaris*, NEBPAR – *Nebela parvula*, NEBTIN – *Nebela tincta*, PLASPI – *Placocista spinosa*, PSEFUL – *Pseudodifflugia fulva*, TRIARC – *Trigonopyxis arcula*, TRILIN – *Trinema lineare*.

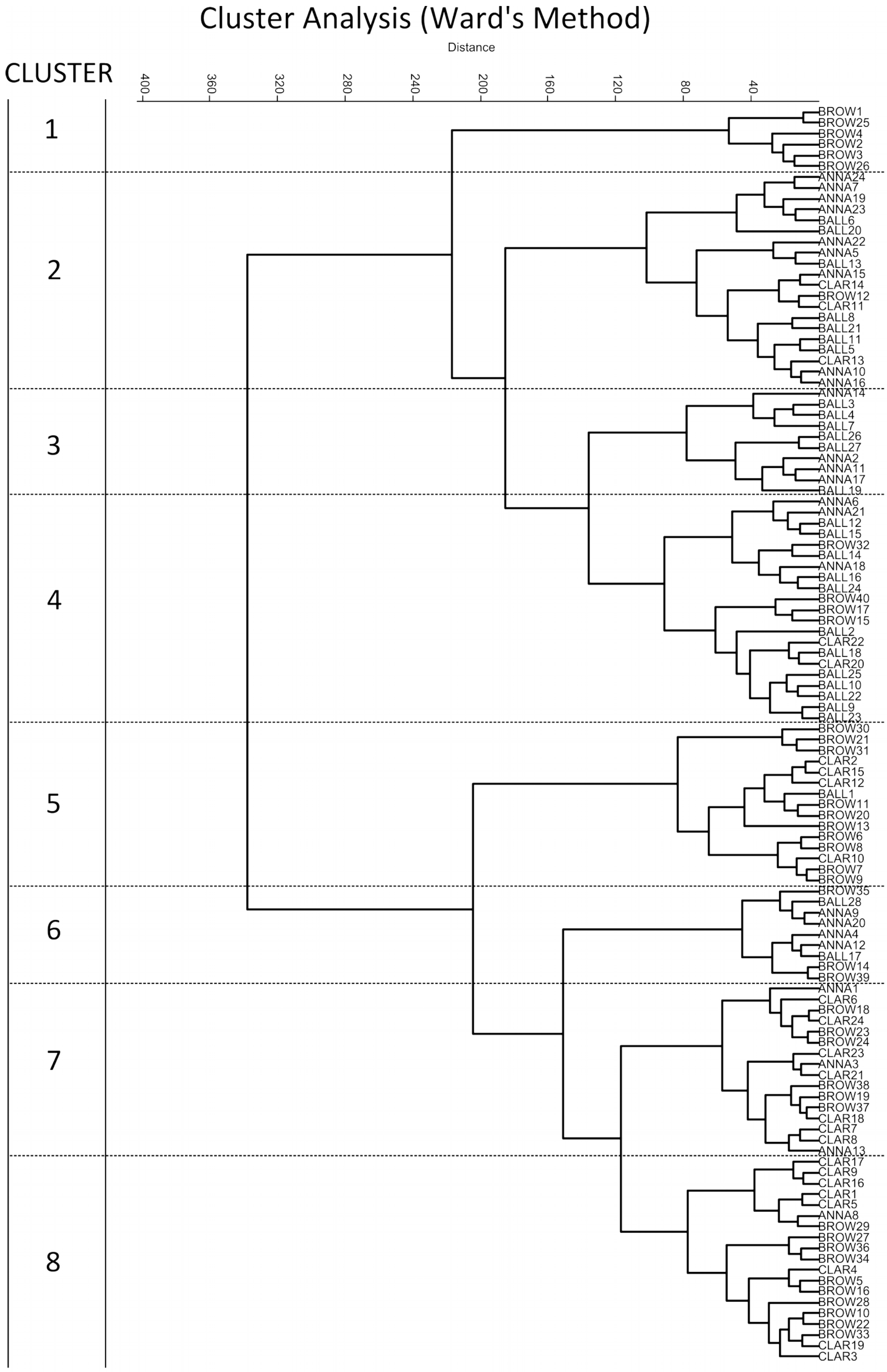

Figure 26: Dendrogram produced by performing cluster analysis on the central Irish testate amoebae training set, using Euclidean distance and Ward's method.

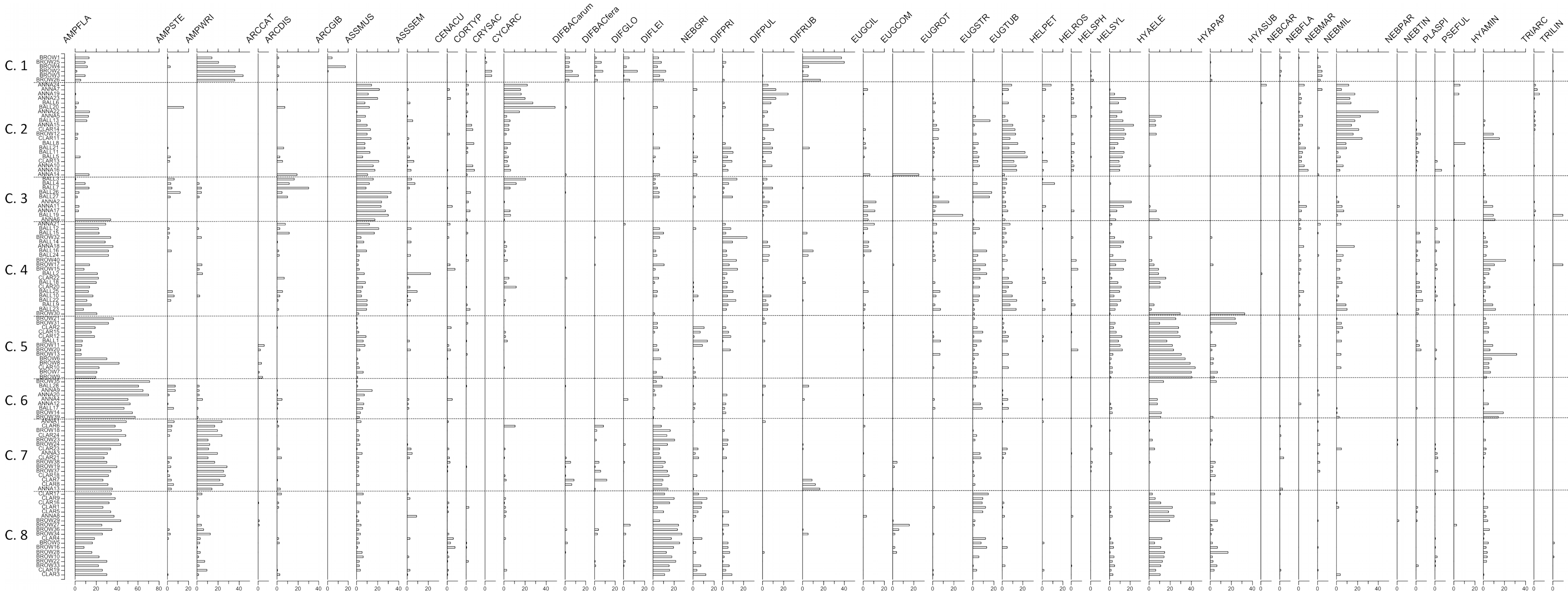

Figure 27: Percentage testate amoebae diagram of samples in the central Irish testate amoebae training set. Samples are presented in dendrogram order, and dashed lines define clusters. Only taxa with maximum occurrences over 2% are shown.

Below, the main taxa in each cluster are detailed:

Cluster 1 – *Amphitrema wrightianum* – *Amphitrema flavum – Difflugia leidyi*

This group is dominated by *Amphitrema wrightianum*, with smaller proportions of *Amphitrema flavum*, *Difflugia leidyi*, *Difflugia rubescens*, *Difflugia bacillifera*, *Difflugia bacilliariarum*, *Difflugia globula* and *Nebela marginata*. The only occurrences of *Arcella gibbosa* are also in this group. All of these samples are from pool microforms (DWT -20 cm to 0 cm; Moisture content 97.35% to 98.33%), and all of these samples are from Brown bog only.

Cluster 2 – *Assulina muscorum – Cyclopyxis arcelloides* type *– Heleopera sylvatica*

This group is composed of similar proportions of *Assulina muscorum*, *Cyclopyxis arcelloides* type, *Nebela militaris*, *Euglypha tuberculata*, *Difflugia pulex* and *Heleopera sylvatica*. Most of these samples are from hummock microforms, but some are from a range of other microhabitats; DWT values range widely from -30 cm to 42 cm, as do moisture content percentages (from 86.08% to 98.9%).

Cluster 3 – *Assulina muscorum* – *Euglypha – Difflugia pulex*

This group is heavily dominated by *Assulina muscorum* with smaller and more variable proportions of *Euglypha* spp., *Difflugia pulex* and sometimes *Arcella discoides* type. These samples come from a range of microforms including both pools and hummocks. DWT values vary widely between -9 cm and 56 cm, moisture content 88.28% to 97.91%. These samples only come from Ballagharahin and Annaghbeg bogs.

Cluster 4 – *Amphitrema flavum* – *Assulina muscorum – Heleopera sylvatica*

This group is characterised by moderate to high proportions of *Amphitrema flavum* with smaller and variable proportions of *Assulina muscorum*, *Difflugia pristis* type, *Euglypha* spp., *Heleopera sylvatica* and *Hyalosphenia minuta*. These samples are mostly from lawn or hummock microforms (DWT values between 1 cm and 52 cm; moisture content 92.47% to 97.04%).

Cluster 5 – *Hyalosphenia elegans* – *Amphitrema flavum – Hyalosphenia minuta*

This group is dominated by *Hyalosphenia elegans* with smaller proportions of *Amphitrema flavum* and *Hyalosphenia minuta*. These samples are mostly from drier lawns and hummocks (DWT values from 5 cm to 20 cm, moisture content from 93.98% to 96.36%).

Cluster 6 – *Amphitrema flavum* – *Assulina muscorum – Amphitrema wrightianum*

This group is characterised by very high proportions of *Amphitrema flavum* with much lower proportions of *Assulina muscorum*, *Amphitrema wrightianum* and *Amphitrema stenostoma*. These samples are mostly from wetter lawn microforms (DWT values from -1 cm to 10 cm; moisture content from 95.25% to 97.35%).

Cluster 7 – *Amphitrema flavum* – *Amphitrema wrightianum – Difflugia leidyi*

This group is dominated by *Amphitrema flavum*, with *Amphitrema wrightianum* and *Difflugia leidyi*. These samples are from the edges of pools and wetter lawn microforms (DWT values from -1 cm to 6 cm; moisture content from 95.59% to 98.26%).

Cluster 8 – *Amphitrema flavum* – *Difflugia leidyi – Hyalosphenia elegans*

This group is mainly composed of *Amphitrema flavum* with *Difflugia leidyi*, *Nebela griseola*, *Euglypha strigosa, Hyalosphenia elegans* and *Hyalosphenia papilio* occurring in varying proportions. These samples are mostly from pools and wet lawn microforms (DWT values from -2 cm to 9 cm; moisture content from 94.22% to 96.93%).

6.3.4 Detrended Correspondence Analysis (DCA)

DCA was carried out on the modern dataset following procedures outlined in Chapter 5. Figure 28 shows the resulting sample and species ordinations. Axis 1 (eigenvalue = 0.51) appears to reflect the hydrological gradient, samples with the lowest DWT values have the highest Axis 1 scores, whilst those with the highest DWT values occur at the lower end of Axis 1 (see Figure 28, A). The species ordination (Figure 28, B) shows species thought to be indicative of bog pools such as *Amphitrema wrightianum*, *Difflugia bacillariarum*, *D. bacillifera* and *D. rubescens* (Corbet 1973; Tolonen 1986) with the highest Axis 1 scores, and dry indicators such as *Trigonopyxis arcula* and *Hyalosphenia subflava* (Tolonen 1986) at the opposite end of the axis. Axis 2 (eigenvalue = 0.23) is a less significant secondary axis which is difficult to interpret, but may potentially be at least partially related to disturbance, with samples with low Axis 2 scores coming mostly from Brown and Clara bogs, in particular samples from cluster 5 (see above) have the lowest Axis 2 scores; samples from Annaghbeg and Ballagharahin, which are more damaged by drainage, tend to have higher Axis 2 scores, especially samples identified in cluster 3 which are dominated by *Assulina muscorum* and *Euglypha* spp..

The sample ordination (Figure 28, A) is grouped by site, for illustrative purposes samples from each site are surrounded by polygons – this shows that there is considerable overlap between sites and therefore generally similar testate amoebae communities at all sites. DCA was also used to estimate the length of the gradient of variation in the testate amoebae data (Hill and Gauch 1980). Axis 1 sample scores range over 4 standard deviation (SD) units, representing a complete turnover in community composition from one end of the axis to the other, suggesting that unimodal statistical methods are most appropriate for developing the transfer function (Birks 1995, p.174).

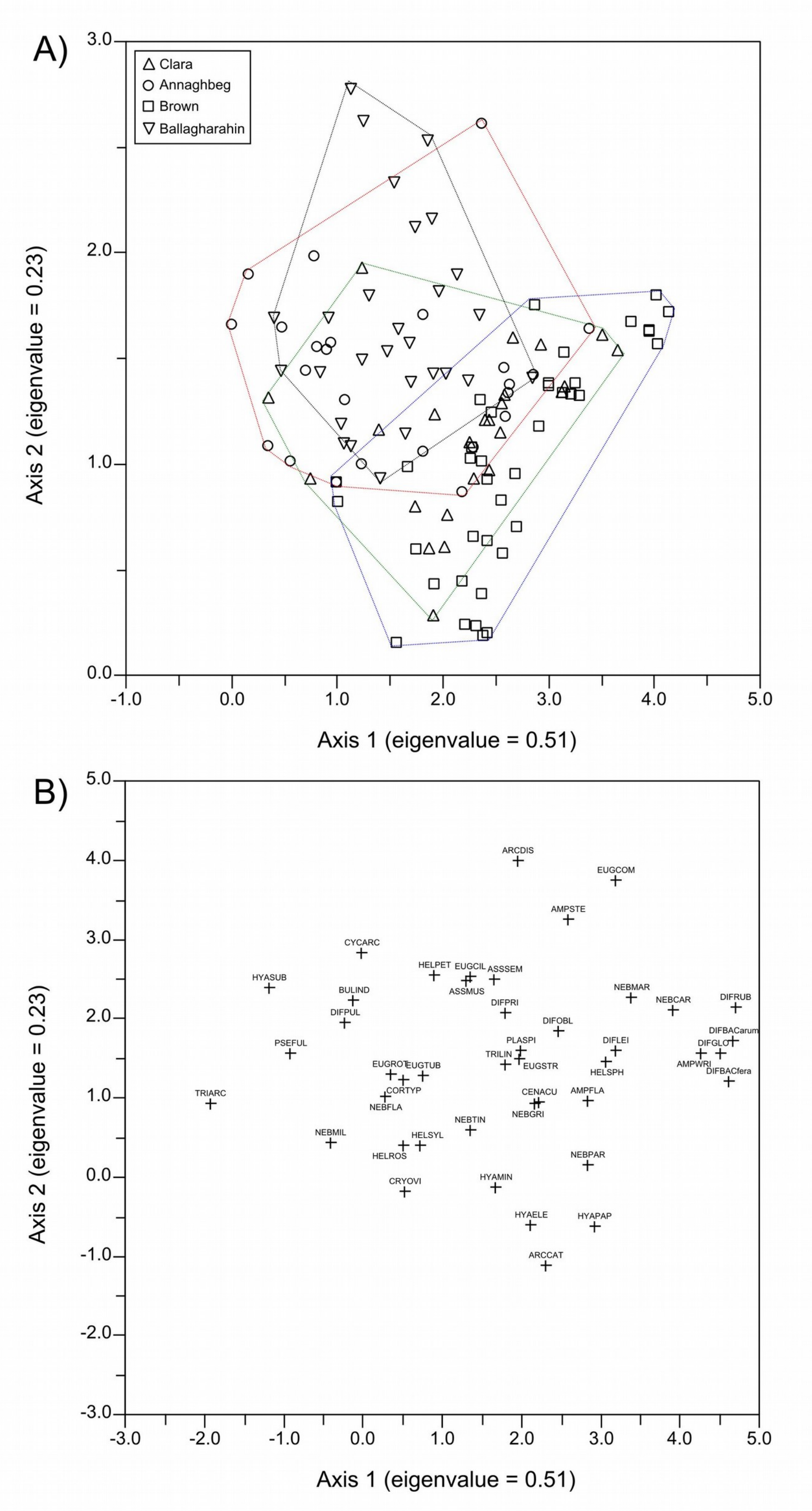

Figure 28: Ordination from DCA of the central Irish testate amoebae training set. A) Sample ordination, with polygons grouping samples by site illustrating relationships. B) Species ordination. See text for taxon abbreviations.

6.3.5 Canonical Correspondence Analysis (CCA)

CCA was carried out on the modern dataset using the vegan v. 2.0-7 package (Oksanen *et al* 2013) which operates in the R statistical environment (R Core Team 2013). Table 25 shows a summary of the results, whilst Figure 29 shows sample and species ordinations. The main axis of variation, Axis1 (eigenvalue = 0.33), appears to be strongly related to hydrology, with DWT and percentage moisture content occurring at opposite ends of this axis; both variables are strongly correlated with Axis1 ($r = 0.7$, $p = 0.001$ for DWT, and $r = -0.8$, $p = 0.001$ for percentage moisture content). Monte Carlo permutation tests (1000 random permutations) show that Axis1 is significant ($p < 0.005$), as are DWT and percentage moisture content (both $p < 0.01$). Axis 2 is less significant ($p = 0.075$), DWT is weakly correlated to Axis 2 ($r = 0.26$, $p = 0.003$), whilst moisture content is not significantly correlated to this axis. Together, both variables explain 13.2% of the variance in the species data. Partial CCAs performed on DWT (see Table 28) and percentage moisture content (Table 29) alone show that alone these variables explain 8.7% and 11.8% of the variability, respectively.

*Table 27: Summary of CCA results of central Irish training set. (*** p<0.001, ** p<0.01, * p<0.1)*

	Axis1**	Axis2*	Total Inertia
Eigenvalue	0.3287	0.0346	2.7547
Species-environment correlation	0.8318***	0.4751***	
Cumulative percentage of variance			
of species data	11.93	13.19	
of species-environment relation	90.49	100	
DWT correlation coefficient	0.6977***	0.2587**	
Moisture content correlation coefficient	0.8268***	0.0519	

*Table 28: Summary of results of partial CCA performed on DWT only. (*** p<0.001)*

	Axis1	Total Inertia
Eigenvalue	*0.2415*	*2.7547*
Species-environment correlation	*0.7320****	
Percentage of variance of species data	*8.77*	

*Table 29: Summary of results of partial CCA performed on percentage moisture content only. (*** p<0.001)*

	Axis1	**Total Inertia**
Eigenvalue	0.3251	2.7547
Species-environment correlation	0.8260***	
Percentage of variance of species data	11.80	

CCA has shown, therefore that the testate amoebae data show strong relationships between both DWT and percentage moisture content, and that these relationships are both potentially reconstructible. DWT and moisture content are strongly correlated (r = -0.77, p < 0.001). Previously-published testate amoebae transfer functions tend to concentrate on reconstruction of DWT rather than moisture content (e.g. Charman *et al* 2007; Swindles *et al* 2009); moisture content may be more difficult to measure accurately (e.g. due to evaporative loss between sampling and laboratory analysis (Charman *et al* 2007, p.211)) than DWT, and is may therefore be considered to be a less reliable indicator. The data presented here support this assertion. For example, sample BROW1, which was taken from a deep pool (DWT = -20, moisture content = 97.35%) but has a lower moisture content than the neighbouring sample, BROW2 (DWT = -10, moisture content = 98.2%), both samples consisted of *Sphagnum cuspidatum* - the only way to account for this difference is evaporative loss, and the difficulties associated with accurately measuring the moisture content of totally saturated moss. The relationship between DWT and moisture content similarly appears to be very unclear where DWT values are very low, and the otherwise monotonic relationship between DWT and moisture content appears to break down; this is illustrated by samples ANNA2 (DWT = 56, moisture content = 96.61%), ANNA18 (DWT = 52, moisture content = 93.9%), ANNA 22 (DWT = 42, moisture content = 90.21%) and ANNA24 (DWT = 30, moisture content = 86.01%). All of these samples come from more heavily drained areas of Annaghbeg bog, and this disturbance may be the cause of these unusual characteristics. For this reason, transfer function model development concentrated on reconstructing DWT only.

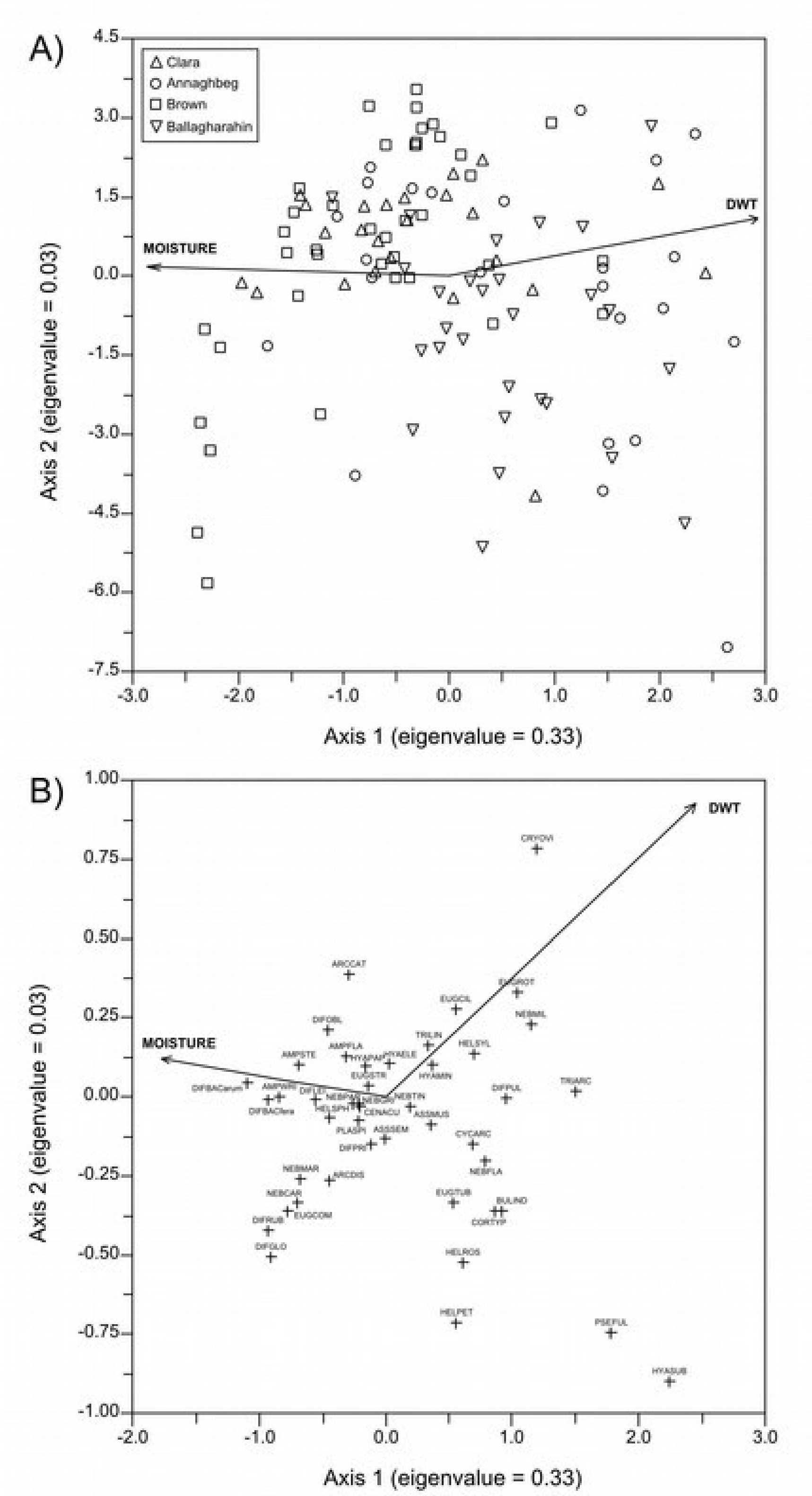

Figure 29: Constrained ordination from CCA of central Irish testate amoebae training set. A) sample ordination grouped by site. B) species-environment biplot. See text for taxon abbreviations.

6.4 Transfer function development

DCA showed that gradients in the testate amoebae data are longer than 2 SD units, therefore unimodal methods are appropriate for reconstructing species-environment relationships (Birks 1995), furthermore these techniques have been shown to be more robust to the effects of spatial autocorrelation (Telford and Birks 2005). Calibration techniques based on weighted averaging (WA) (ter Braak 1987) have been widely used (and Woodland *et al* 1998a; e.g. Swindles *et al* 2009), and have been shown to perform well with "noisy, species-rich compositional data including many taxa that may be absent from many of the sites" (Birks 1995, p.199). Weighted averaging partial least squares regression (WA-PLS) (ter Braak and Juggins 1993), incorporating partial least squares regression into WA, has the advantage that it incorporates residual correlations in the biological data into models (Birks 1995, p.200); WA-PLS has also been implemented in previous testate amoebae transfer functions (e.g. Charman *et al* 2007).

Transfer function models were therefore developed in the C2 software package (Juggins 2011), using a number of methods based on WA and WA-PLS to reconstruct DWT. The models evaluated are: weighted averaging with inverse (WA Inv) and classical deshrinking (WA Cla), weighted averaging tolerance downweighted with inverse (WA-Tol Inv) and classical deshrinking (WA-Tol Cla), and weighted averaging partial least squares (WA-PLS). Models were cross-validated using the 'jack-knifing' or leave-one-out method; jack-knifing is used to estimate the squared correlation between inferred and observed DWT values (r^2_{jack}), the average bias in residuals ($Ave\ bias_{\ jack}$), the maximum bias in residuals ($Max\ bias_{\ jack}$), and the root mean square error of prediction ($RMSEP_{\ jack}$). Performance statistics for these models based on the full training set are shown in Table 30, showing the first three components in WA-PLS.

Based on the full training set, the best performing models were WA-Tol Inv ($RMSEP_{\ jack}$ =7.04 cm, $r^2_{\ jack}$ = 0.53) and WA-PLS component 2 ($RMSEP_{\ jack}$ = 7.43 cm, $r^2_{\ jack}$ = 0.49). Whilst $RMSEP_{\ jack}$ was lower for WA-Tol Inv, WA-PLS gives lower average and maximum bias. Comparison between observed DWT with model-predicted DWT from the WA-Tol Inv model (Figure 30) showed that the model performed poorly for some samples with very high and very low DWT values. Based on this, samples with residuals higher than 20% of the total range of DWT values (15.2 cm) were identified as outliers; these samples were ANNA7 (observed DWT = -3 cm), ANNA22 (observed DWT = 42 cm), ANNA18 (observed DWT = 52 cm), and ANNA2 (observed DWT = 56 cm). All of these samples come from Annaghbeg bog, and may have anomalous testate amoebae assemblages due to the damage (due to cutting and drainage) evident in some parts of this bog. It was noted above that the monotonic relationship between DWT and moisture content appears to break down at the drier end of the hydrological gradient, suggesting that water tables may not have reached equilibrium at time of measurement for these samples. To check whether all samples from Annaghbeg were anomalous, the WA-Tol Inv model was re-run without any Annaghbeg samples. Without removing the outlier samples there was a fairly weak correlation between model-predicted and observed DWT (r^2 = 0.44), this improves to a strong correlation if the outlier samples are disregarded (r^2 = 0.63), suggesting that, with the exception of these outliers, samples from Annaghbeg did not distort the model.

Table 30: Performance of transfer function models based on full training set (n=116).

Model	r^2_{jack}	Ave bias $_{jack}$	Max bias $_{jack}$	RMSEP $_{jack}$
WA Inv	0.44	0.08	38.42	7.68
WA Cla	0.44	0.15	31.75	10.31
WA-Tol Inv	0.53	0.31	38.11	7.04
WA-Tol Cla	0.53	0.46	33.34	8.19
WA-PLS 1	0.44	0.8	38.42	7.68
WA-PLS 2	0.49	0.2	35.33	7.43
WA-PLS 3	0.43	0.31	33.5	8.19

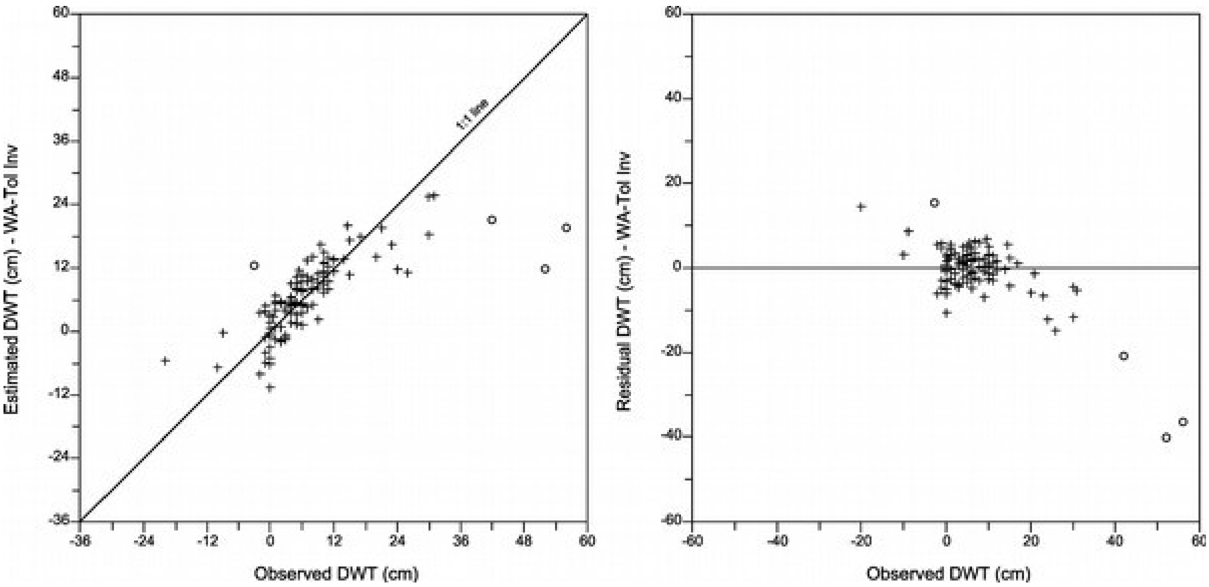

Figure 30: WA-Tol Inv model based on full training set. Left: observed vs. model-predicted DWT. Right: residual DWT. Samples identified as outliers are indicated by open circles.

Transfer function models were re-run with the four outliers removed. This resulted in improvements in the performance statistics for all models, shown in Table 31. The best performing model is WA-Tol Inv, $RMSEP_{jack}$ improved to 4.46 cm, and r^2_{jack} to 0.65. Comparison between observed and model-predicted DWT of the transfer function based on the screened training set are shown in figure 31.

Table 31: Performance of transfer function models based on screened training set (n=112).

Model	r^2_{jack}	Ave bias $_{jack}$	Max bias $_{jack}$	RMSEP $_{jack}$
WA Inv	0.54	0.07	15.15	5.12
WA Cla	0.55	0.09	9.84	6.22
WA-Tol Inv	0.65	0.18	15.27	4.46
WA-Tol Cla	0.65	0.22	11.6	4.84
WA-PLS 1	0.54	0.07	15.15	5.12
WA-PLS 2	0.54	0.16	20.02	5.17
WA-PLS 3	0.5	0.25	19.1	5.66

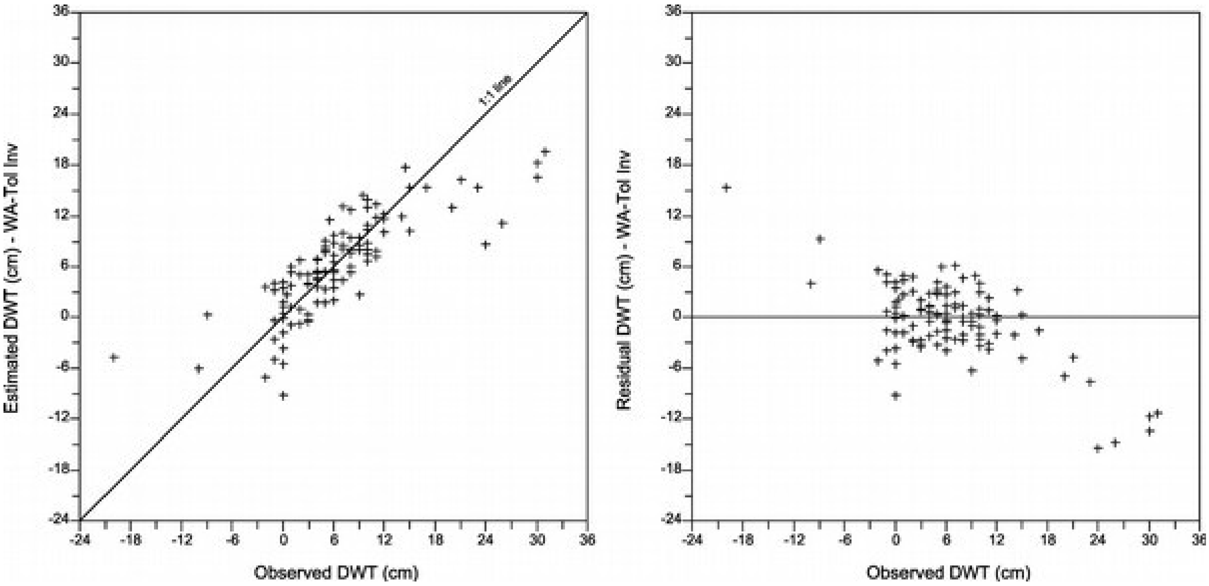

Figure 31: WA-Tol Inv model based on screened training set, with outliers removed. Left: observed vs. model-predicted DWT. Right: residual DWT.

6.4.1 Species DWT optima and tolerances

Figure 32 shows the jack-knifed DWT optima and tolerances of taxa in the central Irish testate amoebae training set based on the WA model. These optima are generally similar to those reported in other studies (Woodland *et al* 1998a; Charman *et al* 2007; Swindles *et al* 2009; Turner *et al* 2013) e.g. *Amphitrema wrightianum* towards the wetter end, and *Trigonopyxis arcula* towards the drier end of the gradient. There are, however some notable exceptions: *Bullinularia indica*, for example, is usually at the very driest end of the hydrological gradient, but in this study several other taxa have drier optima. The optimum and tolerances of this taxon may not be very well modelled, however, as it has few occurrences in the central Irish training set (n=6). Despite differences in rank position along the hydrological gradient, *Bullinularia indica* is still a dry indicator (Optimum $_{\text{jack}}$ = 9.38 cm), and is broadly similar to the optimum published in Woodland et al (1998b): 10.31 cm.

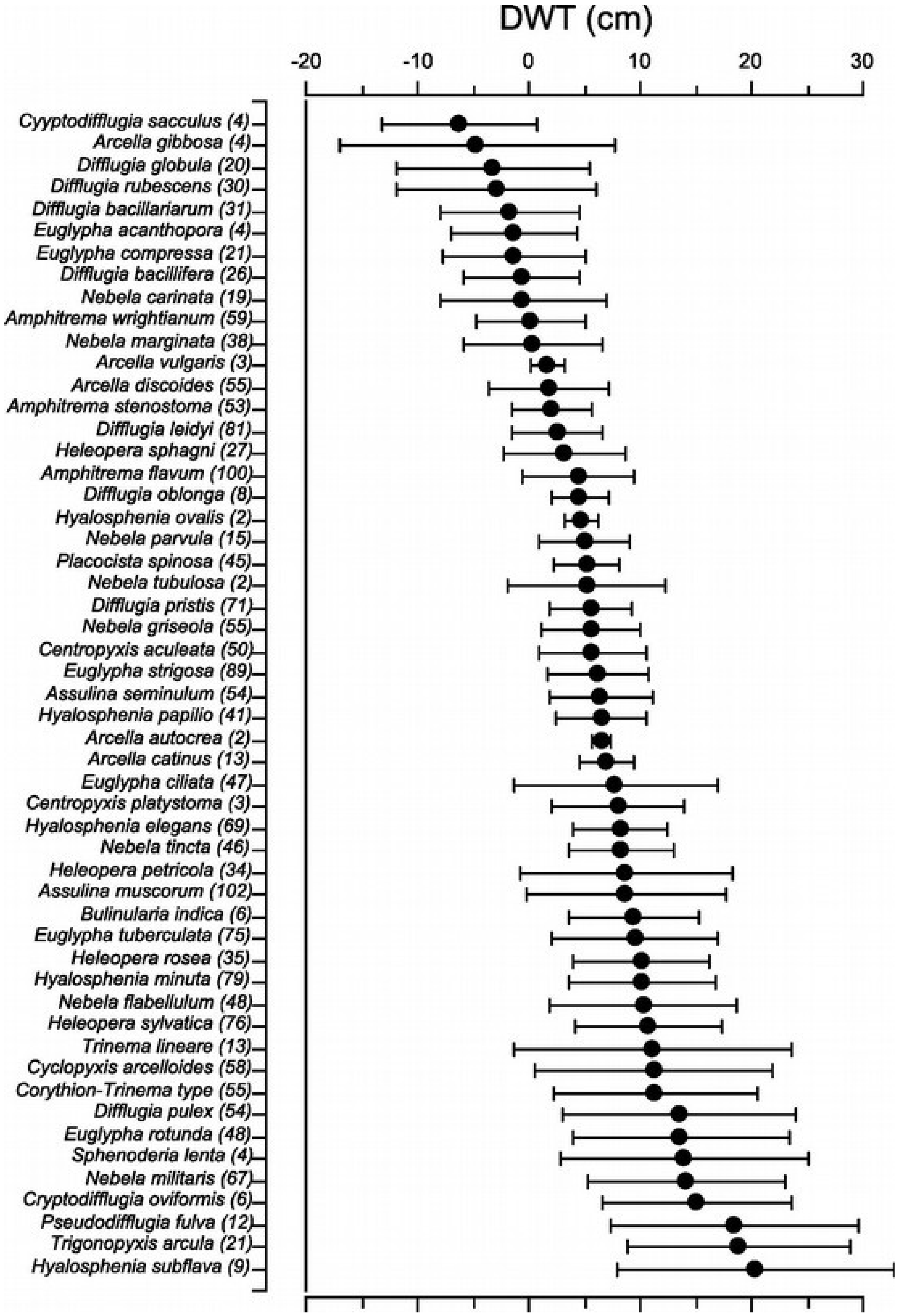

Figure 32: Optima and tolerances of taxa in the central Irish training set. Numbers in brackets show number of occurrences in the training set.

Other taxa with fewer than ten occurrences in the central Irish training set are: *Hyalosphenia ovalis* (n=2), *Nebela tubulosa* (n=2), *Arcella autocrea* (n=2), *Arcella vulgaris* (n=3), *Centropyxis platystoma* (n=3), *Arcella gibbosa* (n=4), *Cryptodifflugia sacculus* (n=4), *Euglypha acanthopora* (n=4), *Sphenoderia lenta* (n=4), *Cyptodifflugia oviformis* (n=6), *Difflugia oblonga* (n=8) and *Hyalosphenia subflava* (n=9); due to their relatively low number of occurrences, the optima and tolerances of these taxa may not be accurately modelled. Arguably, these taxa could have been filtered from the dataset before model development, an approach adopted by Payne et al. (2006).

Difflugia pulex, a taxon which is absent from the Woodland et al. (1998b) transfer function, but which is a very common taxon in some fossil sequences, appears at the drier end of the hydrological gradient in the central Irish training set (Optimum $_{jack}$ = 13.5 cm), and therefore has a drier optimum than found by other studies (Charman *et al* 2007; Swindles *et al* 2009), although Turner et al. (2013) also found *D. pulex* to be a dry indicator.

Difflugia globula is a taxon which is included within *Cyclopyxis arcelloides* type by Charman et al. (2000) but has been separated in this study. This separation is important since *C. arcelloides* is a dry indicator in this (Optimum $_{jack}$ = 11.23 cm) and other studies, but *D. globula* is indicative of very wet conditions (Optimum $_{jack}$ = -3.26 cm). Turner et al. (2013) also separated *D. globula* from *C. arcelloides* type and found a similar optimum for this taxon (Optimum $_{jack}$ = -3.9 cm).

Placocista spinosa is a taxon which has not been included in the previously published European (Charman *et al* 2007) and Northern Ireland (Swindles *et al* 2009) transfer functions, but which has been included in the recently-published northern England (Turner *et al* 2013) transfer function. In the northern England study, the optimum of this taxon was found to be much drier (Optimum = 11.6 cm, Tolerance = 14.9 cm) than in this study (Optimum $_{jack}$ = 5.2 cm, Tolerance $_{jack}$ = 2.86 cm). It is difficult to account for the difference between these datasets and may reflect biogeographical differences in the ecological niche of this taxon; however, this species has more occurrences in the central Irish transfer function (n = 45) than in the northern English study (n = 19), and so the optimum of this taxon may be better modelled in the present study, since this optimum is within the tolerance range found in the northern England study.

Hyalosphenia minuta is a rare taxon, which has been included in few contemporary training sets with the exception of Payne et al. (2006) in Alaska and Amesbury et al. (2013b) in Canada. This taxon appears to be a moderately dry indicator (Optimum $_{jack}$ = 10.17 cm). *H. minuta* appears to be relatively common in surface samples in central Ireland (n=79, maximum 32% of total tests), but appears to be extremely rare in fossil assemblages.

In common with the findings of other similar studies (Charman *et al* 2007; Swindles *et al* 2009; Turner *et al* 2013), *Euglypha* spp. are far more diverse and abundant in surface samples from central Ireland than they are in fossil assemblages (see also Mitchell *et al* 2007). This taxon appears to be particularly susceptible to decay, particularly in dry conditions (Swindles and Roe 2007), Swindles et al. (Swindles *et al* 2009) experimented with excluding *Euglypha* spp. from their training set and found that reconstructions were not affected by the inclusion of these taxa.

6.5 Testing the central Irish transfer function

The central Irish testate amoebae transfer function has been tested in two ways: by applying the transfer function to a fossil dataset from Daingean bog, Co. Offaly (Stastney 2010); and secondly by testing the transfer function on a spatially independent dataset from northern England (Turner *et al* 2013). Overall, based on model cross-validation, the central Irish transfer function appears to have comparable predictive power to existing transfer functions from Europe (Charman *et al* 2007), Northern Ireland (Swindles *et al* 2009), and northern England (Turner *et al* 2013), see Table 32.

Table 32: Comparison of performance statistics of central Irish and previously-published transfer function.

	Model	*n*	r^2	*RMSEP*
Central Ireland	WA-Tol Inv	112	0.65	4.46
Northern Ireland	WA-Tol Inv	81	0.83	4.99
Northern England	WA-Tol Inv	116	0.71	7.36
Europe	WA-PLS 2	119	0.71	5.63

6.5.1 Applying the transfer function to fossil data

The central Irish (CI) transfer function has been applied to fossil testate amoebae data from a core sequence taken from Daingean bog, Co. Offaly; this dataset was originally produced as part of an unpublished MSc thesis (Stastney 2010), and further details are published in Stastney (2013). Daingean bog is a milled production bog, similar to the study sites investigated in this thesis. Two AMS ^{14}C dates obtained for this sequence suggest that the sequence spans the period between *c.* 4200 and 2800 cal BP. For comparison, the ACCROTELM European transfer function (EUR) and the northern England (NE) transfer function were also applied to the data. Sample specific errors for each model were generated using 1000 bootstrap cycles. Figure 33 shows the summary testate amoebae diagram from Daingean bog alongside reconstructed DWT produced by the CI, EUR and NE transfer functions.

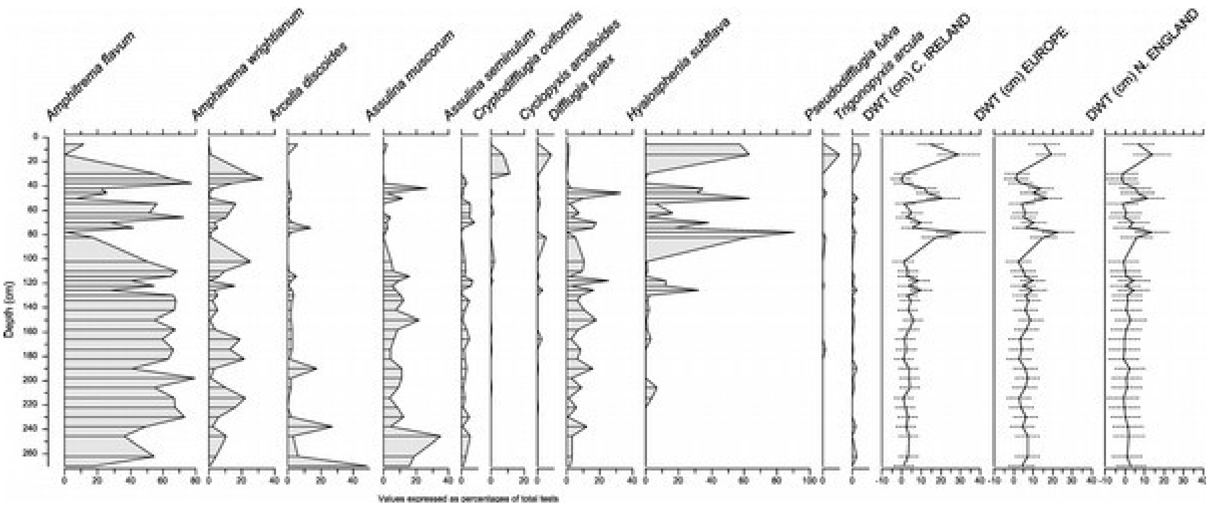

Figure 33: Summary testate amoebae diagram from Daingean bog, Co. Offaly showing reconstructed DWT values based on central Irish, European, and northern England transfer functions.

Testate amoebae assemblages from Daingean are mostly dominated by *Amphitrema flavum* and *A. wrightianum* indicating fairly wet conditions, the upper part of the sequence is characterised by drastic switches to assemblages dominated by the dry indicator *Hyalosphenia subflava*. Reconstructed DWT values from all three transfer functions are generally very similar (Figure 34), and consistently show shifts in the same direction of change, although CI shows slightly greater magnitude of change than the other two models. Reconstructed DWT values from all three models are strongly correlated with each other: the CI model is strongly correlated to the EUR model (r = 0.97, p < 0.01) and NE (r = 0.97, p < 0.01), and the results of EUR and NE are also strongly correlated (r = 0.95, p < 0.01). DWT values from the NE model are generally wetter (mean = 2.34 cm) than those generated by the CI (mean = 6.28) and EUR (mean = 7.4 cm) models, this is largely due to the wetter optimum for *Amphitrema* (*Archerella*) *flavum* in the NE model. The similarity between all three transfer function models indicates that the reconstructions are generally robust.

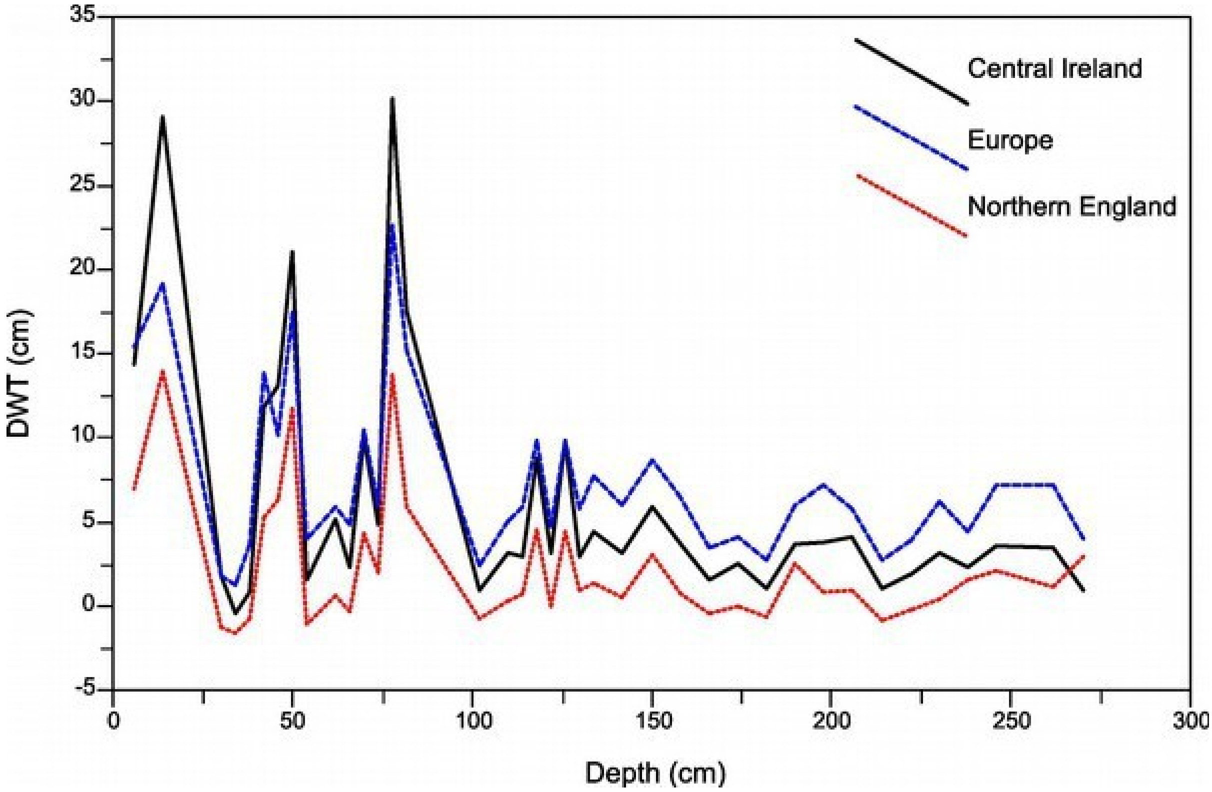

Figure 34: Comparison of reconstructed DWT values from Daingean fossil sequence, based on central Ireland (solid black line), European (dashed blue line) and northern England (dotted red line) transfer functions. For clarity, sample-specific errors are omitted.

6.5.2 Spatially independent cross-validation

Telford and Birks (2005) showed that spatial autocorrelation within ecological training sets may cause estimates of model performance to be overly-optimistic. Although the WA-based models used to develop this transfer function tend to be more robust to autocorrelation, the model was tested against a spatially independent dataset. If the cross-validated model performance is over-estimated due to spatial autocorrelation, the RMSEP would be expected to drop significantly when the model is applied to spatially independent data. The dataset used for this purpose is the northern England (NE) contemporary testate amoebae training set from Turner et al. (2013). When applied to the NE contemporary data, the central Irish (CI) transfer function performed rather poorly: although CI model-predicted DWT values were correlated to observed values in the NE dataset ($r = 0.53$, $p < 0.001$), only 24% of observed values fell within the standard errors of reconstruction, 13% of predicted values were too dry, whilst 63% were too wet, with a mean error of 11.93 cm (compared with a cross-validated *RMSEP* $_{jack}$ of 4.46 cm). Conversely, the NE transfer function performed relatively well at predicting DWT values of the CI training set: the correlation coefficient was higher (r =0.66, $p < 0.001$), 85.3% of observed values fell within standard errors of the model, and the mean error of prediction was 2.88 cm. The far wider range of variability sampled in the NE dataset may partially explain the differences between these models. Differences in sampling season may also play a role in explaining some differences – samples for the CI dataset were sampled during the spring when water tables are likely to have been high, but the time of sampling for the NE dataset in unclear. The poor performance of the CI model on spatially independent data may indicate that problems with spatial autocorrelation may lead to an artificially low *RMSEP* for the CI transfer function (Telford and Birks 2005), and so sample-specific errors should be regarded as conservative. Furthermore, this indicates that the CI transfer function cannot be reliably applied to other regions, echoing the findings of Charman et al. (Charman *et al* 2007) when comparing the European transfer function to the British transfer function of Woodland et al. (1998a), reinforcing the notion that testate assemblages vary at the sub-continental scale (Charman and Warner 1997; Booth and Zygmunt 2005).

6.6 Conclusions

- A testate amoebae training set has been developed for lowland raised bogs in central Ireland.
- A transfer function to reconstruct DWT from fossil testate amoebae assemblages has been developed. In line with other published testate amoebae transfer functions, the best-performing model was WA-Tol Inv, cross-validation using jack-knifing resulted in r^2 of 0.65, and *RMSEP* 4.46 cm.
- Most taxa occupy similar relative positions along the hydrological gradient to those observed in other studies in the British Isles and Europe.
- Some taxa in the central Irish dataset, e.g. *Placocista spinosa* appear to have very different optima and tolerances to those observed in the northern English dataset. *Hyalosphenia minuta*, a taxon not included in other datasets from the British Isles, has also been found to be relatively common in surface samples from central Ireland. This may suggest that whilst most taxa are cosmopolitan in distribution, there may be significant differences in testate amoebae communities at the sub-continental scale.

- Spatially independent cross validation of the model using a contemporary dataset from northern England, however suggests that this model performs less well when applied to datasets from other regions and may indicate that performance statistics are somewhat over optimistic.
- When applied to fossil data from the same region (central Ireland), the transfer function produces very similar results to the regional European and the northern English transfer functions, suggesting that reconstructions are generally robust.
- Investigation of the effect of nitrogen loading on testate amoebae communities in these intact bogs needs to be considered in future work.

Chapter 7: Palaeohydrological investigations

7.1 Cloonshannagh bog, Co. Roscommon

7.1.1 Stratigraphy

A transect of nine boreholes, running for *c*. 2km north-east to south-west, was carried out using a Russian peat corer across the central portion of Cloonshannagh bog. Peat deposits thin towards the south-west, and deepen towards the north-east, with a maximum thickness of peat deposits of 5.5m. The general sequence of sedimentary units at Cloonshannagh was as follows: mineral sediments, mostly sands and gravels were encountered in the base of each borehole, overlain in most places by organic lake sediments. These sediments were overlain by 1 to 4m of fen peat, including frequent woody (*Alnus* and *Betula*) and herbaceous (*Phragmites*) macrofossils. Ombrotrophic peat, dominated by *Sphagnum* and *Eriophorum vaginatum* overlaid the fen peat in the northern half of the transect, but was absent in the southern part of the transect, possibly due to more intensive milling in this part of the site. Borehole 1, near the centre of the transect, had the deepest deposits of ombrotrophic peat, and was therefore selected for further sampling. Further details of the stratigraphic transect are given in Young et al. (2011a).

Table 33: Stratigraphic log, BH1 Cloonshannagh, Co. Roscommon.

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact	Notes
---	0	1	---	VOID	---	---	
16	1	9	7.5YR 2.5/1	Sh3 $Th^3$1	4	sharp	
15	6	24	7.5YR 3/3	$Th^3$3 Sh1 Tb+	3	diffuse	
14	24	48	7.5YR 3/3	$Th^3$3 Sh1 Tl+	3	diffuse	
13	48	76	7.5YR 3/3	$Tb^3$3 $Th^2$1	3	diffuse	
12	76	139	7.5YR 3/3	$Th^2$4 Tl+ Tb+	2	diffuse	
11	139	198	7.5YR 3/2	$Th^3$4	3	diffuse	
10	198	216	7.5YR 3/2	Th(vagi)^{2}4 Tl+	2	diffuse	*E. vaginatum*
9	216	244	7.5YR 3/2	$Th^2$4 Sh+	2	diffuse	
8	244	259	7.5YR 3/3	$Th^3$4 Sh+ Tl+	3	diffuse	
7	259	282	7.5YR 3/2	$Tl^2$3 Sh1 Th+	3	diffuse	
6	282	300	7.5YR 2.5/2	$Th^4$3 Sh1 Tl+	4	diffuse	
5	300	309	10YR 2/1	Sh2 $Th^3$2 Tl+	3	diffuse	
4	309	314	10YR 2/2	Sh4 Tl+ Gg(min)+	4	diffuse	
3	314	321	10YR 2/2	Sh3 $Tl^3$1	4	diffuse	
2	321	328	10YR 4/2	$Ld^4$3 Ga1 Dl+	4	sharp	
1	328	330	10YR 5/3	Ga3 As1 Gg(min)+	---	---	

Core samples from the location of BH1 were recovered, the samples were wrapped and the sediments were described in the laboratory. Figure 35 shows the stratigraphy of BH1, the full Troels-Smith sediment log is shown in Table 33. The peat sequence from BH1, Cloonshannagh bog, was 330cm deep, and follows the general pattern of sedimentary units outlined above. The base of the sequence was composed of unsorted mineral sediments – probably Glacial till (unit 1). Overlying this was 3cm of organic lake sediments (unit 2). The lacustrine sediments were overlain by *c.* 60cm of highly humified wood fen peat, composed of totally humified organic material (Sh) and occasional fragments of wood (units 3-6). This is overlain by *c.* 180cm of herbaceous peat (units 7 – 12) - mostly *Eriophorum vaginatum* - of varying humification (Humo 2 – 4). The transition to ombrotrophic conditions, based on the floristic composition of the peat, appears to have occurred in this herbaceous peat, at *c.* 244 cm depth. Above this, was a 28cm thick deposit of moderately-humified *Sphagnum* peat (unit 13). The upper part of the sequence was composed of *c.* 30cm of moderately-humified herbaceous peat (units 14 and 15), overlain by 9cm of highly-humified herbaceous peat (unit 16).

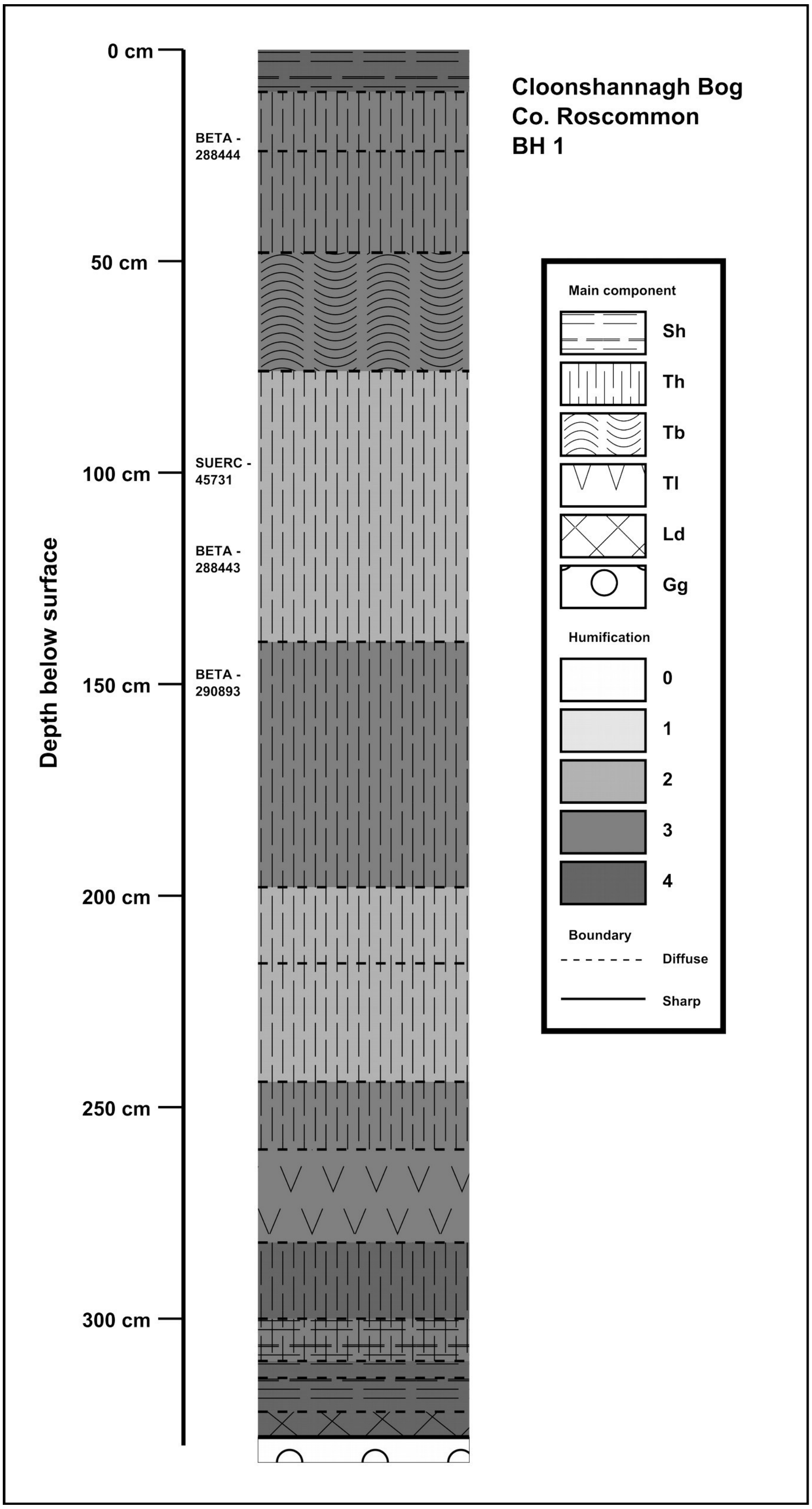

Figure 35: Peat stratigraphy of BH1, Cloonshannagh bog, Co. Roscommon.

7.1.2 Chronology

Four samples of picked and cleaned above-ground plant macrofossils from the ombrotrophic part of BH1 (above 244cm depth) were submitted for AMS ^{14}C dating. BETA-288443, BETA-288444, and BETA-290893 were analysed in Miami, Florida, USA, by Beta Analytic Inc., whilst SUERC-45731 was prepared to graphite at the NERC radiocarbon facility, East Kilbride, and was analysed at the SUERC AMS Laboratory. Details of these dates are given in Table 34. Whilst the uppermost (BETA-288444) and lowest (BETA-290893) dates show a clear increase in age with depth, there is an inversion in the dates, where BETA-288443 returned an earlier date than SUERC-45731, despite being 22cm lower. Both these samples were taken from the same unit of poorly-humified herbaceous peat, and visual examination of the peat sequence did not reveal any evidence for disruption or inversion of the stratigraphy. It appears therefore more likely that one of these dates may be an outlier.

Table 34: AMS ^{14}C dates obtained from BH1, Cloonshannagh bog, Co. Roscommon. Dates were calibrated using the IntCal09 calibration curve (Reimer et al 2009)*, and 95% confidence (2σ) intervals were generated using the Clam software package (Blaauw 2010).*

Lab code	Depth (cm)	Material dated	$^{13}C/^{12}C$ ratio	^{14}C date (BP)	Calibrated range 2σ (cal BP)
BETA-288444	21.5	Plant macrofossils	N/a	450±40	540-340
SUERC-45731	98.5	Plant macrofossils	-27.3	1576±35	1540-1390
BETA-288443	120.5	Plant macrofossils	-28.2	1300±40	1300-1150
BETA-290893	148.5	Wood (Ericaceae)	-29.9	2030±30	2100-1900

The dates from BH1 suggest that the ombrotrophic peat at Cloonshannagh dates to the Late Holocene, and that the upper 148cm covers most of the last *c.* 2000 years. Based on the midpoints of the calibrated 95% confidence ranges of the uppermost and lowest dates (BETA-288444 and BETA-290893, respectively), the sequence shows a mean accumulation rate of *c.* 12 years/cm.

Age vs depth modelling for the sequence from Cloonshannagh bog was carried out using both Clam (Blaauw 2010) and Bacon (Blaauw and Christen 2011) software packages.

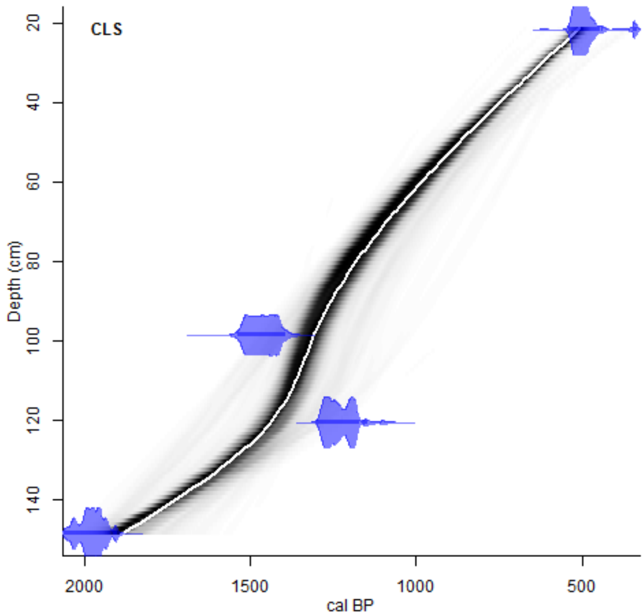

Figure 36: Smooth spline age vs depth model for BH1 Cloonshannagh.

Clam was used to provide an initial, 'classical', age model. All models available in this package (linear interpolation, linear and polynomial regression, and cubic and smooth spline models) did not satisfactorily deal with the inversion in radiocarbon dates; due to this inversion, most models produced significant reversals in the relationship between age and depth. The most plausible age vs depth model was produced using the smooth spline model, which assumes that changes in accumulation rate are smooth, rather than abrupt. Figure 36_ shows the smooth spline age vs depth model for BH1. This model did not produce significant reversals in the age vs depth relationship, but showed large uncertainties for much of the core, and produced a poor overall fit with the ^{14}C dates.

The more flexible Bayesian approach utilised in the Bacon package has been shown to be robust to the presence of outliers (Blaauw and Christen 2011, pp.461–462). The age vs depth model produced for Cloonshannagh, shown in Figure 37, appears to identify BETA-288443 as an outlier, effectively bypassing this date, and producing an otherwise apparently linear model, with a relatively constant accumulation rate, mostly close to the mean of around 12 years/cm. Uncertainties are highest in the relatively long section between 21.5 and 98.5cm depth, where there are no dates. The relatively constant accumulation rate suggested by this model appears to be plausible, since the stratigraphy shows relatively few major changes, but arguably further dating of the shift to *Sphagnum* dominated peat between 48 and 76cm depth may be useful to demonstrate this conclusively. This age vs depth model has been used for all further analysis and discussion, with point age estimates (prefixed with '*c.*') using the *maximum a posteriori* (MAP) date estimate generated by the software based on several million MCMC runs.

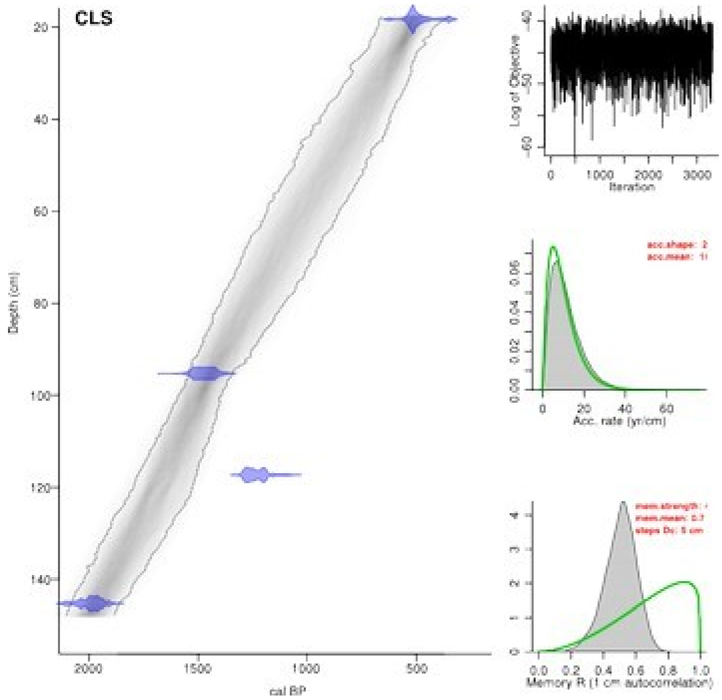

Figure 37: Age vs depth model for BH1, Cloonshannagh, produced using Bacon. 95% confidence intervals of the age model are shown by dotted lines.

7.1.3 Humification

41 samples, at 4cm spacing between 12 and 196cm depth, were analysed from BH1 from Cloonshannagh bog. The humification data, shown in Figure 38 shows a significant amount of variation between samples. A LOWESS smooth line (span 0.2) shows a trend towards increasing humification (i.e. drier conditions) between 196 and 148cm, followed by a brief decrease at 132cm, and further increases in humification up to *c.* 100cm depth, thereafter, there is a trend towards decreasing humification values (wetter conditions), to the top of the sequence, with a step-change to lower humification values above 60cm depth.

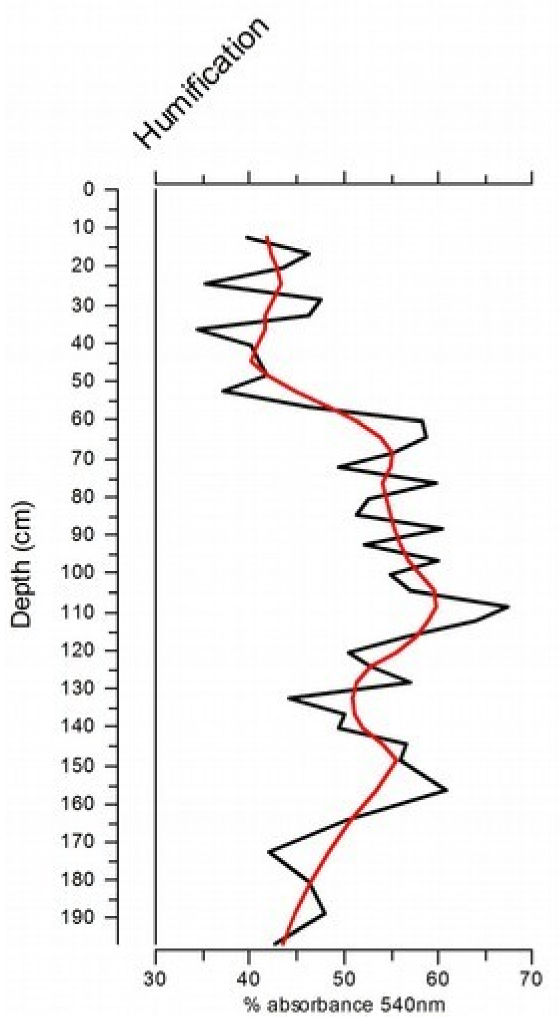

Figure 38: Humification curve (black line) from BH1, Cloonshannagh, red line shows a LOWESS smooth line (span 0.2).

7.1.4 Testate amoebae analysis

Samples for testate amoebae analysis were taken from BH1 initially every 8cm between 8cm and 320cm depth. No samples below 248cm depth yielded counts of over 50 tests, suggesting that test preservation and concentration is poor in the minerotrophic fen peats in the bottom *c.* 90cm of BH1. Following analysis of the initial samples, sampling resolution was increased to 2cm spacing between 66cm and 118cm depth. In total, 35 samples yielded counts of at least 50 tests, of which 27 yielded counts of 100 tests or more. Samples yielding fewer than 50 tests were excluded from further analysis. Samples consistently yielded usable counts from c. 118cm upwards. Test concentration in Cloonshannagh BH1 was highly variable, with no clear relationship between lithostratigraphy and test concentration.

Figure 39 shows the full testate amoebae diagram from BH1, Cloonshannagh bog. Values of testate taxa are expressed as percentages of the total test count. Reconstructed Depth to Water Table (DWT) values in cm are shown on the right hand side of the diagram, reconstructions were carried out using the central Irish transfer function developed as part of this project (see Chapter 6). DCA Axis 1 (eigenvalue 0.2554) and DCA Axis 2 (eigenvalue 0.08087) scores are also plotted on the right hand side of Figure 39, DCA ordinations are shown in Appendix 1. Generally these is close agreement between DWT values and DCA Axis 1 values, and the two are highly correlated (r = 0.86), increasing confidence that hydrology is the principal control on testate communities at Cloonshannagh. Only towards the base of the sequence at 192cm, do DWT and DCA Axis 1 values not follow each other, suggesting that this sample is anomalous. DWT values range between 0.58 and 11.73cm (mean DWT = 5cm). For convenience in the discussion of these results, the testate amoebae diagram has been divided into zones based on visual assessment, these are shown in the diagram as dashed lines. A total of 37 taxa are present in the assemblages from BH1, *Amphitrema flavum* is generally the dominant taxon. Species richness (R) ranges between 7 and 15 taxa, Shannon diversity index (H') values range from 1.195 to 2.152, and Simpson's index (D) ranges from 0.5 to 0.8.

CLS-1 (***Amphitrema flavum* –** *A. wrightianum – Assulina muscorum*) - below *c.* 208cm (before 2100 cal BP): this zone is represented by only three samples. This zone is dominated by *Amphitrema flavum* with values between 38 and 68%, with smaller amounts of *Amphitrema wrightianum* (max. 19%) and *Assulina muscorum* (max. 17%). Other taxa present with low values include *Amphitrema stenostoma*, *Centropyxis aculeata, Difflugia pulex* and *Hyalosphenia subflava*. DWT values range from 2.5cm and 6.2cm indicating moderate to moderately wet conditions. The sample at the base of this group at 248cm has notably low diversity index scores (H' = 1.24, D = 0.5), this may be due to problems with preservation of tests in this part of BH1.

CLS-2 (***Assulina muscorum* –** *Amphitrema flavum – Trigonopyxis arcula*) - *c.*208 – 184cm (before *c.* 2100 cal BP): this zone consists of only one sample which yielded a count of over 50 tests, at 192cm. *Assulina muscorum* and *Trigonopyxis arcula* both reach their highest values in this zone (38% and 7% respectively). DWT for this sample is 6.29cm, indicating moderate conditions. This zone is unusual in displaying high diversity (R = 15, H' = 2.114, D = 0.8). The unusual nature of this sample is also reflected in DCA, plotting much higher on Axis 2 than all other samples from Cloonshannagh; Axis 2 may possible reflect another, non-hydrological gradient in the data – possibly nutrient status or pH – suggesting perhaps that this zone may not reflect fully ombrotrophic conditions.

CLS-3 (***Amphitrema flavum –*** *A. wrightianum – Assulina muscorum*) - *c.* 184 – 126cm (from before 2100 to *c.* 1550 cal BP): this zone is very similar to CLS-1, except that *Arcella discoides* is present in small amounts (max. 8.9%). DWT values are around 2cm in this zone indicating wet conditions.

CLS-4 (*Amphitrema flavum – Difflugia pulex – Hyalosphenia subflava)* - 126 – 96cm (*c.* 1550 to *c.* 1380 cal BP): this zone is characterised by high values of *Amphitrema flavum*, *Difflugia pulex*, and *Hyalosphenia subflava* (around 20 – 35% for all three taxa); *H. subflava* declines throughout this zone. Other taxa present include *Amphitrema stenostoma, A. wrightianum* (which increases throughout this zone), *Assulina muscorum*, *A. seminulum*, *Centropyxis aculeata,* and *Difflugia pristis.* DWT values at the base of this zone are high – around 11cm – indicating dry conditions, but fall towards the top of this zone to *c.*3cm indicating moderately wet conditions. Indices show high diversity in this zone (H' = ~2, D = up to 0.8).

CLS-5 (*Amphitrema flavum – Amphitrema wrightianum – Difflugia pulex*) - 96 – 61cm (*c.* 1380 to *c.* 1020 cal BP): this zone is dominated by *Amphitrema flavum, A. wrightianum* and *Difflugia pulex* but relative proportions of these taxa are highly variable in this zone. As a result of these fluctuation, DWT values also vary widely in this zone from a maximum of 9.17cm to a minimum of 0.59cm, indicating fluctuating water table levels.

CLS-6 (*Amphitrema flavum – A. wrightianum – Assulina muscorum*) - 61cm to top (*c.* 1020 to after 500 cal BP): this zone is characterised by high levels of *Amphitrema flavum* (up to 57%) and significant amounts of *A. wrightianum* (*c.* 15%) and *Assulina muscorum* (*c.* 20%). DWT values are relatively constant in this zone, indicating wet conditions (DWT = ~1.5cm). Diversity in this zone is relatively low due to the dominance of *Amphitrema flavum*.

7.1.5 Summary

The testate amoebae record begins at the transition to poorly humified peat at *c.*244 cm depth. Humification data shows a wet shift at 144cm (*c.* 1840 cal BP), the testate amoebae record also suggests wet conditions, but test preservation is inconsistent in this part of the sequence. Both proxies show dry conditions from around 118cm depth (*c.* 1510 cal BP) and then a trend towards variable but mostly increasingly wet conditions. Testate amoebae indicate a wet shift at 94cm (*c.* 1370 cal BP), followed by another shift towards drier conditions and another wet shift at 68cm depth (*c.* 1060 cal BP); soon after this second wet shift, the peat stratigraphy becomes dominated by *Sphagnum* and this results in a step-change in the humification record towards lower values. Both proxies then indicate wet conditions to the top of the sequence (after 500 cal BP).

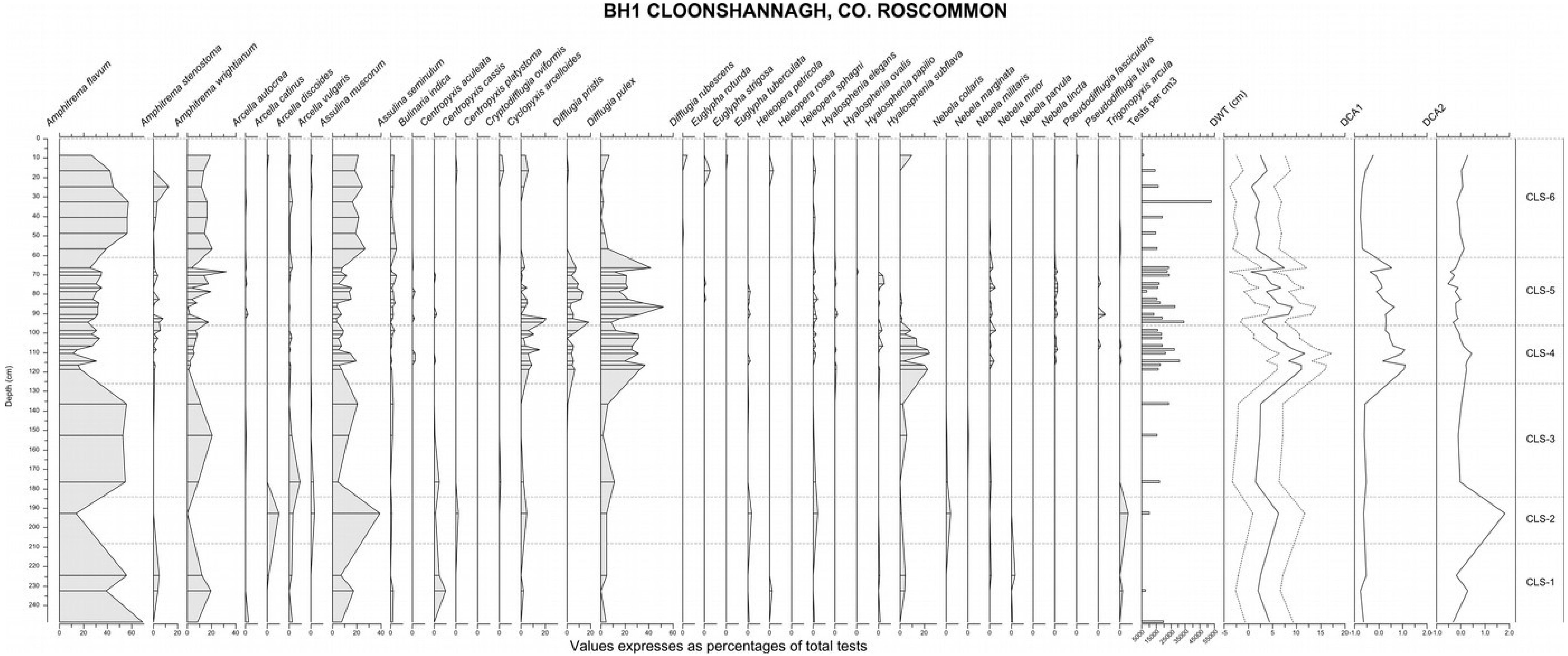

Figure 39: Full testate amoebae diagram from BH1, Cloonshannagh bog, Co. Roscommon. Values are presented as percentages of the total test count. Reconstructed DWT was calculated using the central Irish transfer function.

7.2 Kinnegad bog, Co. Meath

Fieldwork on Kinnegad bog was carried out during summer 2007. Results of initial analyses on BH3 (not including testate amoebae analysis) are given in Young et al. (2009).

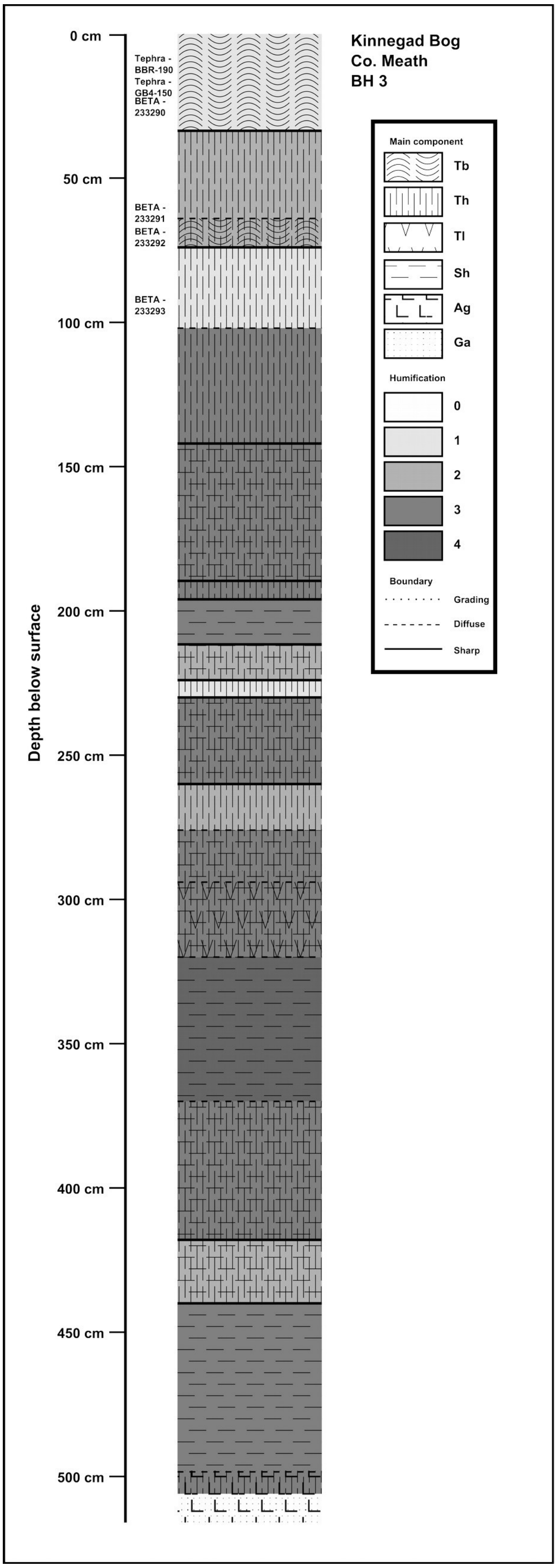

Figure 40: Peat stratigraphy of BH3, Kinnegad bag, Co. Meath.

7.2.1 Stratigraphy

A stratigraphic transect of boreholes carried out by Young et al. (2009), revealed a single concave basin underlying the peat deposits at Kinnegad bog, with a maximum depth of peat of 520cm. At the base of these sequences were mineral sediments, overlain in places with lacustrine deposits, overlain in turn by deposits of fen peat (generally 300-400cm thick). The present milled surface of Kinnegad bog is underlain by up to *c.* 100-250cm of ombrotrophic peat. The location for the master sequence BH3 was selected as it was located near to a relatively deep sequence of ombrotrophic peats, and *c.* 150m from excavated archaeological structures at Kinnegad.

The sequence recovered from BH3 (see Figure 40) was a total of 515cm deep. The bottom 18cm (Units 1 and 2) were composed of mineral sediments which graded into 267cm of generally well-humified fen peats (Units 3-10: mostly herbaceous, some traces of woody remains). This was overlain by 230cm of moderately- to poorly-humified ombrotrophic peat (Units 11-20), mostly dominated by herbaceous remains, but with significant amounts of poorly-humified *Sphagnum* remains in the top 74cm (Units 18-20). The full Troels-Smith sedimentary log from BH3 is reproduced in Table 35.

Table 35: Troels-Smith stratigraphic log, BH3 Kinnegad Bog, Co. Meath.

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact
20	0	35	5YR 2.5/2	$Tb^1 3$ $Th^2 1$	1	sharp
19	35	64	5YR 2.5/1	$Th^2 3$ Sh1	2	diffuse
18	64	74	5YR 2.5/2	$Th^2 2$ $Tb^2 2$	2	sharp
17	74	101	5YR 2.5/1	$Th^1 3$ $Tl^1 1$	1	diffuse
16	101	141	5YR 2.5/1	$Th^3 3$ Sh1	3	sharp
15	141	189	5YR 2.5/1	$Th^3 2$ Sh2 Tl+	3	sharp
14	189	195	5YR 2.5/2	$Th^2 3$ Sh1	2	sharp
13	195	212	5YR 2.5/1	Sh3 $Th^3 1$ Tl+	3	sharp
12	212	224	5YR 2.5/1	Sh2 $Th^2 2$	2	sharp
11	224	230	5YR 3/2	$Th^1 3$ Sh1 Tl+	1	sharp
10	230	261	5YR 2.5/1	$Th^3 2$ Sh2	3	sharp

9	261	277	5YR 2.5/1	$Th^3 2\ Tl^1 2$	2	diffuse
8	277	290	5YR 2.5/1	$Th^3 2$ Sh2	3	diffuse
7	290	320	5YR 2.5/1	$Th^3 2$ Sh2 Tl+	3	diffuse
6	320	370	5YR 2.5/1	Sh3 $Th^3 1$	4	diffuse
5	370	418	5YR 2.5/1	Sh2 $Th^3 2$	3	sharp
4	418	440	5YR 2.5/1	$Th^2 2$ Sh2	2	sharp
3	440	497	5YR 2.5/1	Sh3 $Th^3 1$	3	diffuse
2	497	506	7.5YR 4/1	Ag2 $Th^3 1$ Ga1 Gs+	3	diffuse
1	506	515	7.5YR 5/1	Ag2 Ga1 Gs1 Th+	3	---

7.2.2 Chronology

Four samples of picked and cleaned above-ground plant macrofossils from the ombrotrophic part of BH3 were submitted for AMS ^{14}C dating. These samples were analysed in Miami, Florida, USA, by Beta Analytic Inc. Details of these dates are given in Table 36. These samples generally show a clear increase in age with depth. BETA-233291 and BETA-233292 may potentially show an inversion, however there is considerable overlap in the calibrated 95% confidence ranges of these dates.

Table 36: AMS ^{14}C dates obtained from BH3, Kinnegad bog, Co. Meath. Dates were calibrated using the IntCal09 calibration curve (Reimer et al. 2009), and 95% confidence (2σ) intervals were generated using the Clam software package (Blaauw 2010).

Lab code	Depth (cm)	Material dated	$^{13}C/^{12}C$ ratio	^{14}C date (BP)	Calibrated range 2σ (cal BP)
BETA-233290	20.5	Peat	-24.4	2740±40	2920-2760
BETA-233291	60.5	Peat	-26	3130±40	3440-3260
BETA-233292	68.5	Peat	-27.2	3010±40	3340-3080
BETA-233293	92.5	Peat	-26.2	3350±40	3690-3480

In addition to AMS ^{14}C dating, additional chronological control has been provided by the identification of two tephra layers, which have been matched, based on geochemical characteristics, with dated Icelandic tephras found elsewhere in Ireland. Dates of these layers are given in Table 37. This work was undertaken by Ian Matthews, Royal Holloway, University of London.

Table 37: Tephra layers identified in BH3, Kinnegad bog. Tephra analysis was carried out by Ian Matthews, Royal Holloway, University of London. Date ranges of the identified layers are those given in Plunkett et al. (2004), uncalibrated dates are given in parenthesis.

Tephra	Depth (cm)	Date range	Reference
BMR-190	10	2655-2535 cal BP (2493±25 BP)	(Plunkett *et al* 2004)
GB4-150	18	2750-2708 cal BP (2660±50 BP)	(Larsen *et al* 2001; Plunkett *et al* 2004)

The ^{14}C and tephra dates from BH3, Kinnegad bog, suggest that the upper 92cm spans the earlier part of the Late Holocene. Based on these dates, the mean accumulation rate was *c.* 12 years/cm in this part of the sequence. Age vs depth models were generated using the Clam (Blaauw 2010) and Bacon (Blaauw and Christen 2011) software packages.

Non-Bayesian, 'classical' age vs depth models for the sequence were produced using Clam. All of these models showed significant reversals in the age vs depth relationship between 68 and 60cm depth. Figure 41 shows the smooth spline age vs depth model for BH3.

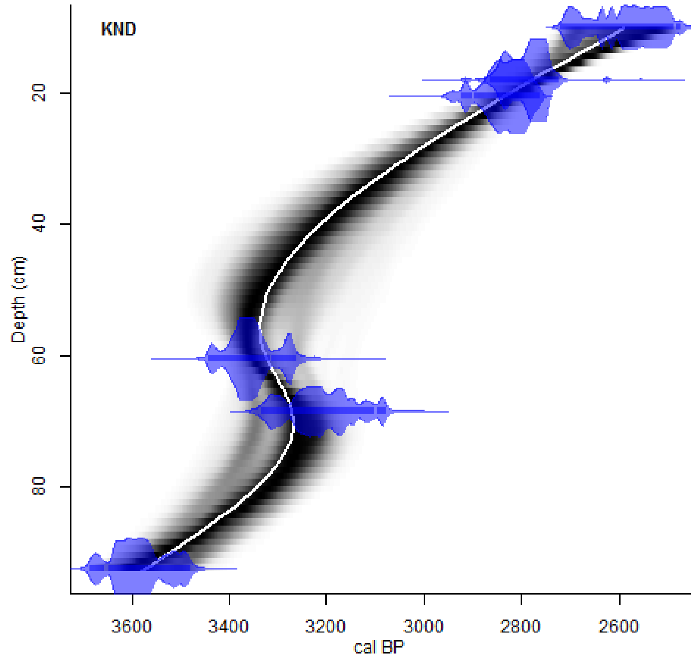

Figure 41: Smooth spline age vs depth model for BH3, Kinnegad.

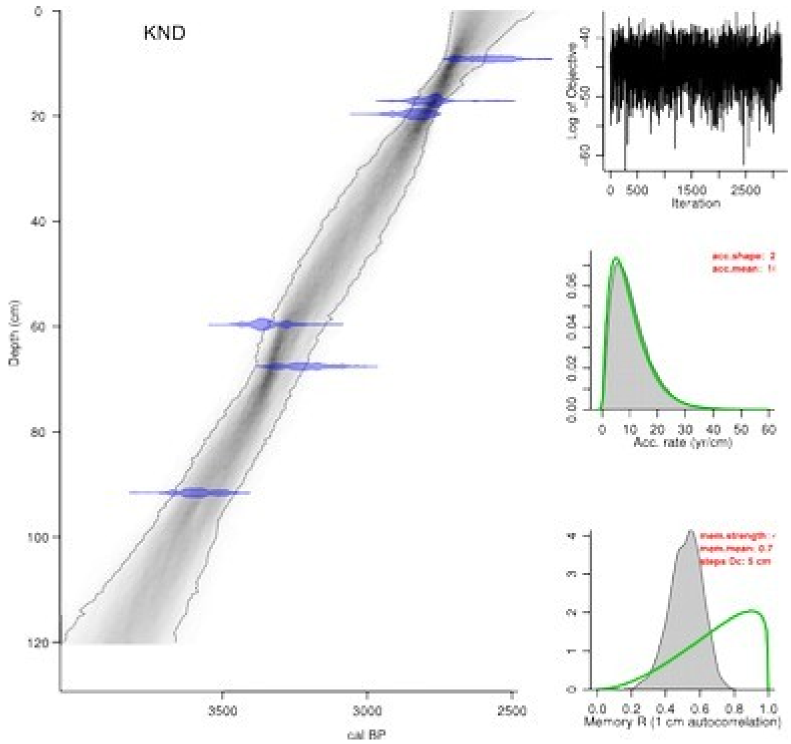

Figure 42: Age vs depth model for BH3, Kinnegad, produced using Bacon. Dotted lines indicate 95% confidence intervals of the age vs depth model.

More flexible age vs depth models were produced using Bacon, this model is illustrated in Figure 42. The Bayesian approach utilised by Bacon was able to produce age vs depth models without the significant reversal shown in the smooth spline age vs depth model. The age vs depth model produced using Bacon has been used for all further analysis and discussion, with point age estimates (prefixed with '*c.*') using the *maximum a posteriori* (MAP) date estimate generated by the software based on several million MCMC runs.

7.2.3 Humification

Humification analysis on BH3 was carried out by Young et al. (2009); for comparison with the testate amoebae data these results are briefly discussed here. Figure 43 shows the humification curve from Kinnegad BH3. Samples for humification analysis were taken at 8cm spacing down BH3. In total 65 samples were analysed. For brevity only samples down to 116cm are presented here (15 samples). Humification values ranged between 40% and 81% (mean humification = 61%). There is general trend towards decreasing humification values towards the top of BH3, with notable dips in humification values (possibly indicating wet shifts) at 68cm and 20cm depth (at *c.* 3310 and *c.* 2790 cal BP).

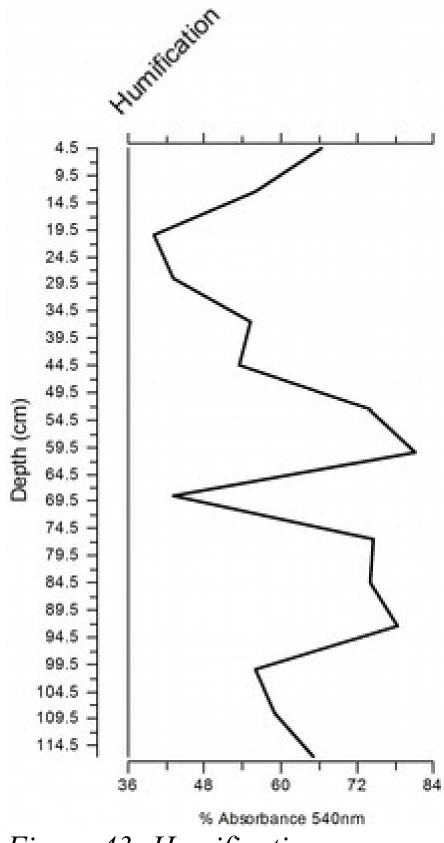

Figure 43: Humification curve from BH3, Kinnegad.

7.2.4 Testate amoebae analysis

Samples for testate amoebae analysis were taken every 2cm between 1cm and 119cm depth. In total 60 samples were analysed, of which all yielded counts of over 50 tests and all but seven samples yielded counts of 150 tests or more. Test concentration was generally good, but variable throughout the sequence although there was no clear correlation between concentration and lithostratigraphy.

Figure 45 shows the full testate amoebae diagram from BH3, Kinnegad bog. Values are expressed as percentages of the total test count. In addition to the total test count, loricae of the Bdelloid rotifer *Habrotrocha angusticollis* and fragments of Cladoceran carapace were also counted, estimated minimum numbers of individuals (estimated using an exotic *Lycopodium* spore spike) are presented as bars in the diagram. DWT values (reconstructed using the central Irish transfer function and with sample-specific errors generated through 1000 bootstrap cycles shown in dotted lines, see Chapter 6) are shown on the right hand side of the diagram, beside DCA Axis 1 (eigenvalue 0.1456) scores. See Appendix 1 for DCA ordinations. DWT values and DCA Axis 1 scores are highly correlated (r = 0.86), suggesting that the main axis of variation in the species data from Kinnegad is related to hydrology. DWT values range between -2cm and 6cm (mean DWT = 2.25cm), indicating very wet to intermediate conditions.

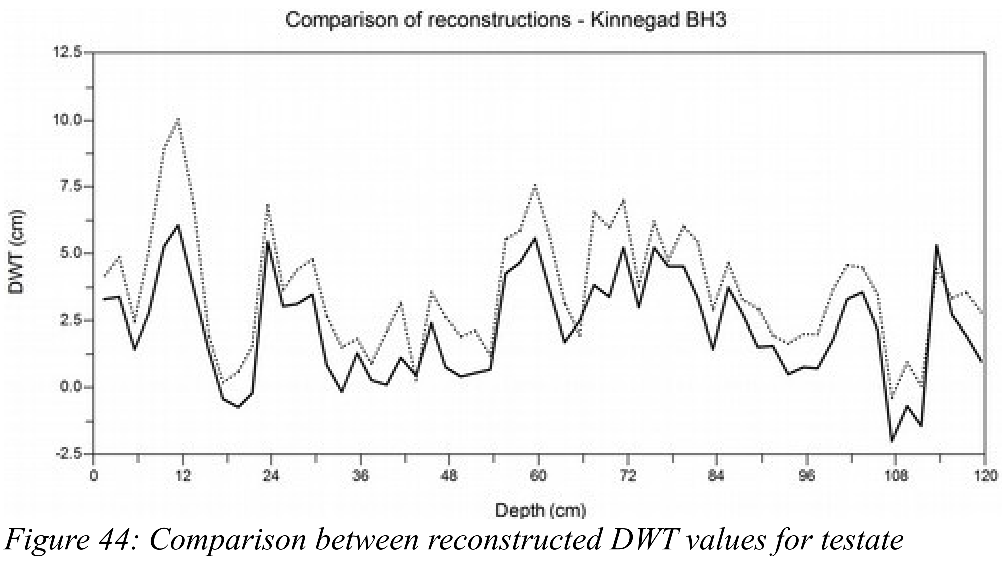

Figure 44: Comparison between reconstructed DWT values for testate amoebae data from BH3, Kinnegad, using the central Irish (solid line) and ACCROTELM (dotted) transfer functions.

In addition to the central Irish transfer function, the ACCROTELM European supra-regional transfer function (Charman *et al* 2007) was also applied to the testate amoebae data from BH3. Figure 44 shows both DWT curves from BH3; for clarity sample-specific errors are not shown. Both transfer functions produced very similar results and the two reconstructions were strongly correlated ($r = 0.93$), although the central Irish transfer function consistently produced lower DWT (wetter) values with a mean value of 2.3cm compared with 3.6cm for the ACCROTELM transfer function. The similarity of the two reconstructions suggests that these are both generally robust. The reconstruction from the central Irish transfer function has been used in the discussion below.

To facilitate discussion of the results, the testate amoebae diagram has been divided into assemblage zones based on a visual assessment of the data. A total of 29 taxa are present in this sequence; assemblages are generally dominated by *Amphitrema* spp., with varying amounts of *Difflugia pulex* and *Assulina muscorum*. Diversity indices show some variation throughout the sequence, *R* values range between 6 and 15 taxa per sample (mean $R = 9.6$), H' values range between 0.56 and 1.88 (mean $H' = 1.36$), and *D* ranges between 0.25 and 0.8 (mean $D = 0.6$).

KND-1 (*Amphitrema flavum – Difflugia pulex – Amphitrema wrightianum*) - 120 to 112cm depth (*c.* 3670 to *c.* 3630 cal BP): this zone is dominated by *Amphitrema flavum* with abundances up to a maximum of 55%. *Difflugia pulex* is also present, and peaks at the top of this zone at 35%. *Amphitrema wrightianum, Assulina muscorum* and *Assulina seminulum* are also present throughout this zone (max. 22%, 11% and 3%, respectively). DWT values rise from 1cm to 5.3cm in KND-1.

KND-2 (*Amphitrema wrightianum – Amphitrema flavum*) - 112 to 106cm depth (*c.* 3630 to *c.* 3590 cal BP): this zone is characterised by a sharp rise in *Amphitrema wrightianum* (max. 51%) with a concomitant drop in *Difflugia pulex* and to a lesser extent *Amphitrema flavum.* This zone also features a notable peak in Cladoceran remains. DWT values drop to -2cm in this zone, indicating a wet shift with the water table at or above the bog surface.

KND-3 (*Amphitrema flavum – Difflugia pulex – Amphitrema wrightianum*) - 106 to 52cm depth (*c.* 3590 to *c.* 3200 cal BP): assemblages in this zone are very similar to those in KND-1, except that low values of *Difflugia pristis* and *Centropyxis aculeata* (~5%) are present in the lower half of this zone, but give way to increasing dominance of *Difflugia pulex* in the upper half of this zone, up to a maximum of 35%. DWT values are generally higher (drier) than in KND-2, representing a return to more moderate conditions, and show a trend to slightly increasing DWT throughout the zone, up to a maximum of 5.6cm at the top of this zone.

KND-4 (*Amphitrema flavum – Amphitrema wrightianum – Difflugia pulex*) - 52 to 22cm depth (*c.* 3200 to *c.* 2810 cal BP): assemblages in this zone are again similar to KND-1 and KND-3. *Amphitrema wrightianum* is generally abundant in this zone (~30-40%), whilst values of *Difflugia pulex* are initially lower in this zone than in the previous zone, but values steadily rise to 29% at the top of the zone. DWT values initially drop again to 0.6cm (very wet), but rise towards the top of this zone to a maximum of 5.45cm (moderately-wet).

KND-5 (*Amphitrema wrightianum – Amphitrema flavum*) - 22 to 14cm depth (*c.* 2810 to *c.* 2730 cal BP): again *Amphitrema wrightianum* peaks in this zone, with a concomitant drop in both *Difflugia pulex, Amphitrema flavum,* and *Assulina muscorum*; *A. flavum* quickly recovers to 55% at the top of this zone. DWT values indicate a shift to very wet conditions (DWT = -0.4cm) in this zone.

KND-6 (*Amphitrema* spp. - *Assulina muscorum – Hyalosphenia subflava*) - 14cm depth to top (*c.* 2730 to *c.* 2630 cal BP): *Amphitrema flavum* rises to 86% at the base of this zone before dropping to 45% as a result of a rise in *Amphitrema wrightianum* (max. 25%) and *Hyalosphenia subflava* (max. 20%) near the top of this sequence. *Assulina muscorum* is present throughout this zone, with abundances ranging from 6% to 18%. DWT values are variable in this zone, but generally show a drop in water tables to 6cm below the surface, followed by some fluctuation (minimum DWT = 1.6cm in this zone).

7.2.5 Summary

The sequence from BH3, Kinnegad bog is of a relatively high resolution, covering a relatively short time-span between *c.* 3670 and *c.* 2630 cal BP. Testate amoebae-derived reconstructed water tables show generally moderately-wet bog surface conditions, with two notably wet intervals at *c.* 3630 cal BP and another, well-dated wet shift at *c.* 2810 cal BP; the latter event being reflected by notably low humification values at 20cm depth (*c.* 2790 cal BP). Both wet shifts appear to be relatively short-lived events, lasting for around 40 years, before water tables returned to more moderate levels. Throughout the rest of the sequence, DWT values indicate moderately-wet conditions, with a slight trend towards increasing DWT, with a possible minor increase in moisture availability at *c.* 3200 cal BP. The shift to lower humification at 68cm depth is not reflected in testate amoebae data, but may instead be as a result of a shift in peat composition to *Sphagnum*-dominated peat between 74 and 64cm depth (i.e. a 'species effect' (Yeloff and Mauquoy 2006) rather than reflecting BSW).

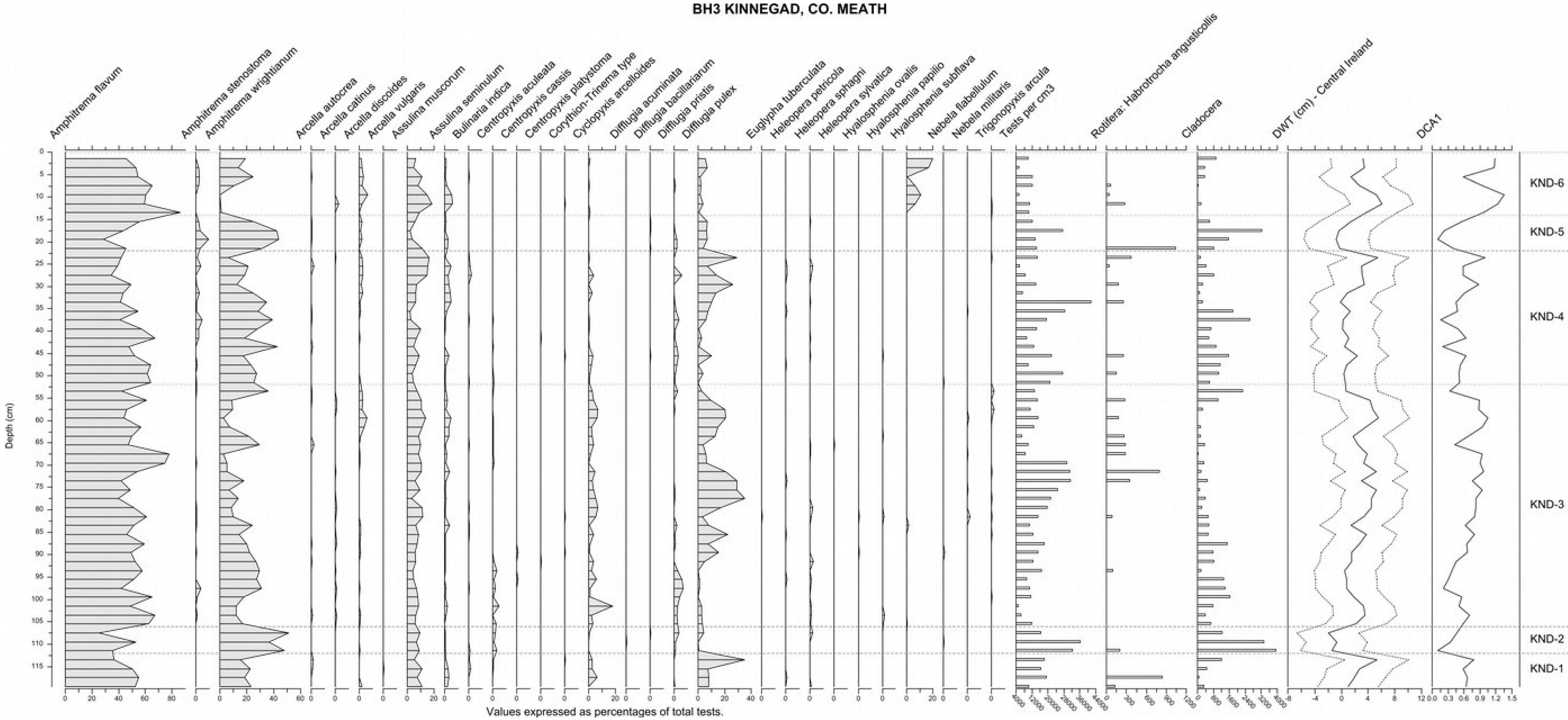

Figure 45: Full testate amoebae diagram from BH3, Kinnegad bog, Co. Meath. Values are presented as percentages of the total test count. Reconstructed DWT was calculated using the central Irish transfer function.

7.3 Gowla bog, Co. Galway

Fieldwork on Gowla bog, Co. Galway was carried out during summer 2011. Results of preliminary analyses are given in Young et al. (2012).

7.3.1 Stratigraphy

A transect of 12 peat depth soundings was undertaken, using a gouge auger, running for *c.* 1,200m from west to east across Gowla bog. This transect revealed the undulating surface of the underlying mineral sediments, with the surface topography of the drained and milled bog, broadly following the morphology of the underlying sediments. Peat deposits at Gowla bog ranged from 1.6 to 4.4m in depth, a low ridge of mineral sediments occurred in the middle of the transect, with deeper peat deposits occurring in the eastern half of the transect. The location of the master sequence, BH1, was selected in this eastern half of the transect where peat deposits were deepest, and *c.* 150m from the nearest sightings of archaeological structures.

Table 38: Peat stratigraphic log, BH1 Gowla Bog, Co. Galway.

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact	Notes
12	0	31	7.5YR 2.5/1	Sh2 $Th^3$1 $Tb^3$1 Tl+	3	diffuse	
11	31	34	7.5YR 3/2	$Th^2$4 Sh+	2	diffuse	*E. vaginatum*
10	34	59	7.5YR 3/2	$Tb^2$4 Th+ Sh+	3	diffuse	*Sphagnum*
9	59	78	7.5YR 3/1	$Tb^3$2 $Th^3$1 Sh1 Tl+	3	diffuse	
8	78	86	7.5YR 3/1	$Th^3$3 Sh1 Tl+	3	diffuse	*E. vaginatum*
7	86	103	7.5YR 3/3	$Th^2$3 Sh1 Tl+	3	diffuse	*Menyanthes*
6	103	130	7.5YR 2.5/1	Sh3 $Tl^3$1 Th+	4	diffuse	
5	130	166	7.5YR 2.5/1	Sh2 $Tl^2$1 $Th^3$1	3	sharp	Fen/bog transition
4	166	169	7.5YR 2.5/2	$Tl^1$2 $Th^3$2 Sh+	3	sharp	
3	169	173	7.5YR	$Th^1$4	1	sharp	single fragment

			2.5/2				of *Alnus*?
2	173	357	7.5YR 2.5/1	$Th^2$3 Sh1 Tl+	3	diffuse	fen peat
1	357	370	7.5YR 2.5/1	$Th^3$3 Sh1 As+	4	---	

Core samples from BH1 were wrapped, transported to Reading, and the peat stratigraphy was described in the laboratory. Figure 46 shows the peat stratigraphy of BH1, whilst full Troels-Smith lithostratigraphic logs are given in Table 38. A sequence of peat deposits 370cm deep was recovered from BH1. Mineral sediments were not sampled at BH1 as the coring device could not penetrate any deeper; the basal sediments in BH1 were composed of *c.* 13cm of highly-humified herbaceous peat (Unit 1), with a trace of mineral material discernible suggesting that this deposit lay just above mineral sediment. This deposit was overlain by almost 200cm of fen peat (Units 2-4) composed of completely disintegrated organic material, humified herbaceous remains and frequent woody remains, including a large piece of *Alnus* at 173-169cm depth (Unit 3). At 166cm there was a sharp transition to well-humified peat (Unit 5) containing remains of both herbaceous and Ericaceous plants, this boundary may mark the fen/bog transition; these well-humified deposits (Units 5 and 6) were 63cm thick and were overlain at 103cm depth by a 17cm thick deposit of herbaceous peat (Unit 7), containing remains of *Menyanthes*, in turn this was overlain by *Eriophorum* peat (Unit 8). From 78cm to 34cm depth (Units 8-10), *Sphagnum* moss became increasingly dominant, this deposit was overlain by a band of poorly-humified *Eriophorum* peat (Unit 11). From 31cm to the top of the sequence was a deposit of well-humified herbaceous and moss peat, with traces of Ericaceous remains (Unit 12).

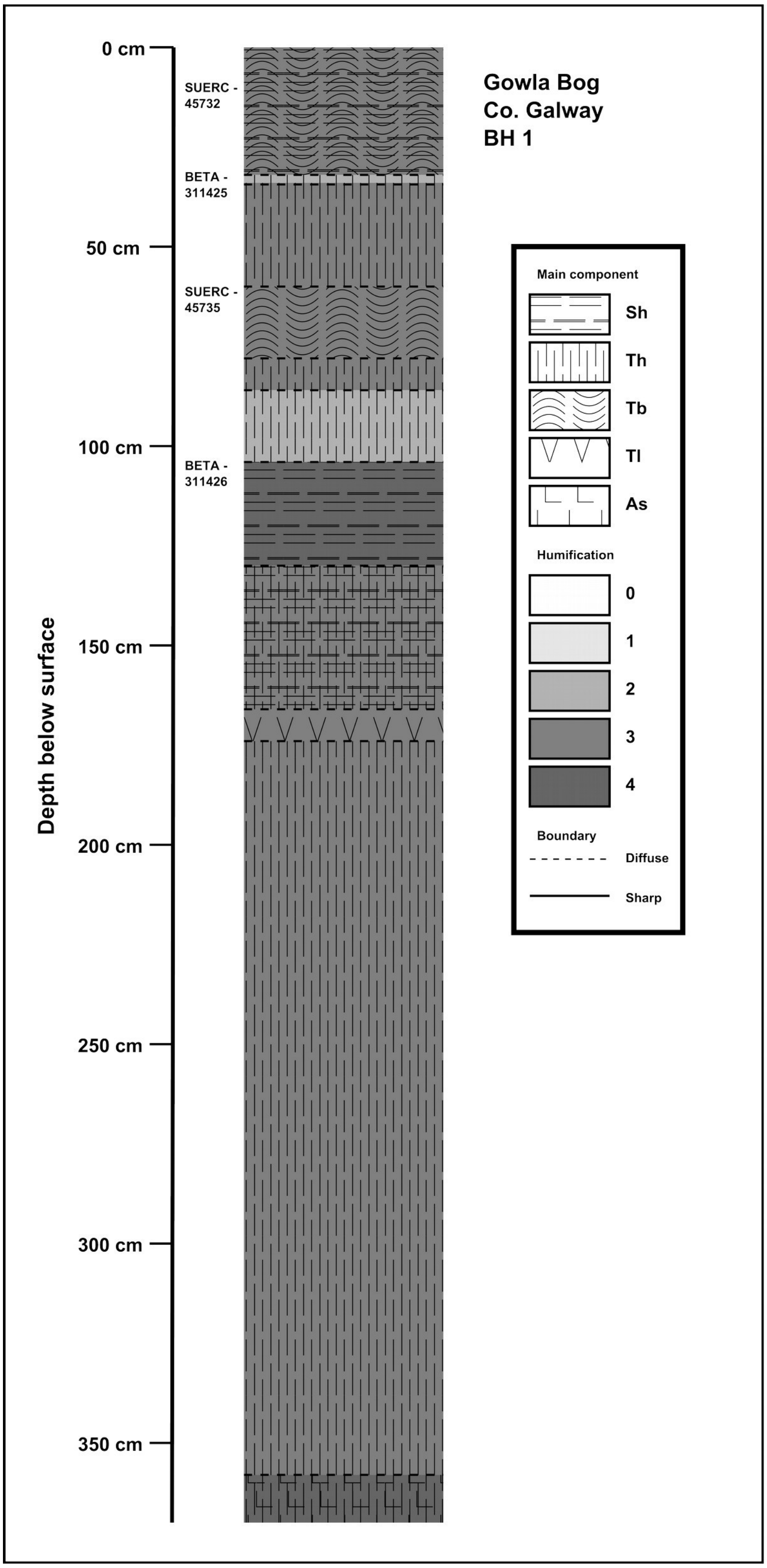

Figure 46: Peat stratigraphy of BH1, Gowla bog, Co, Galway.

7.3.2 Chronology

Four samples of picked and cleaned above-ground plant macrofossils from the ombrotrophic part of BH1 were submitted for AMS ^{14}C dating. BETA-311425, and BETA-311426 were analysed in Miami, Florida, USA, by Beta Analytic Inc., whilst SUERC-45732, and SUERC-45735 were prepared to graphite at the NERC radiocarbon facility, East Kilbride, and analysed at the SUERC AMS Laboratory. Details of these dates are given in Table 39. These samples show a clear increase in age with depth in BH1, Gowla bog.

Table 39: AMS ^{14}C dates obtained from BH1, Gowla bog, Co. Galway. Dates were calibrated using the IntCal09 calibration curve (Reimer et al. 2009), and 95% confidence (2σ) intervals were generated using the Clam software package (Blaauw 2010).

Lab code	Depth (cm)	Material dated	$^{13}C/^{12}C$ ratio	^{14}C date (BP)	Calibrated range 2σ (cal BP)
SUERC-45732	10.5	*Sphagnum* macrofossils	-25.8	1760±35	1810-1570
BETA-311425	33.5	Plant macrofossils	-24.6	2150±30	2300-2010
SUERC-45735	61.5	*Sphagnum* macrofossils	-25.3	2880±37	3160-2880
BETA-311426	105.5	Plant macrofossils	N/a	3510±30	3860-3700

The AMS ^{14}C dates suggest that the sequence of ombrotrophic peat at Gowla bog dates to the Late Holocene, with a mean accumulation rate of *c.* 22 years/cm. Age vs depth models for BH1 were created using the Clam (Blaauw 2010) and Bacon (Blaauw and Christen 2011) software packages.

Most 'classical' and linear age vs depth models created in Clam produced very similar results with no reversals in the relationship between age and depth. The smooth spline model was selected as the most plausible age vs depth model as it assumes gradual changes in deposition rate between dated levels, this model produced a good fit with the dated levels; the smooth spline age vs depth model is shown in Figure 47.

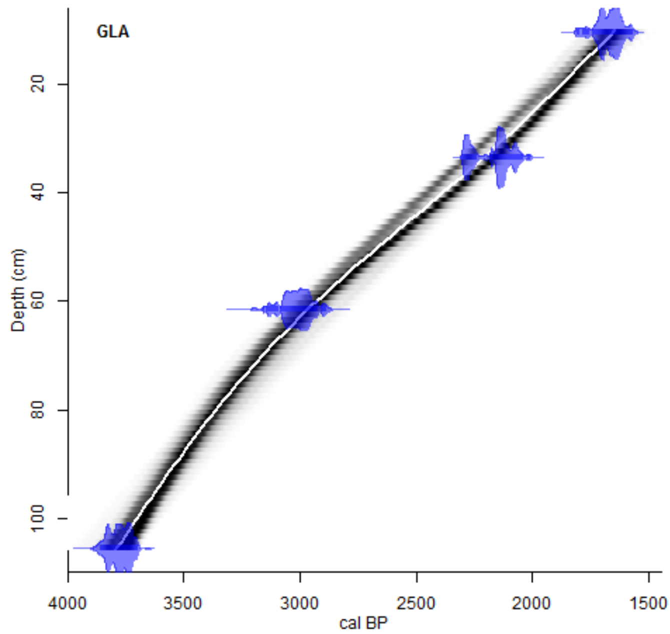

Figure 47: Smooth spline age vs depth model, BH1 Gowla.

Bacon was used to produce a more robust age vs depth model utilising a Bayesian approach, with prior information about the mean accumulation rate (set to 20 years/cm, curve shape 2) incorporated into the age model; the resulting plot is shown in Figure 48. This age vs depth model is generally very similar to the smooth spline model, suggesting these models are generally robust; the Bacon model does, however give larger (and probably more realistic) error margins at the 95% confidence interval in undated sections of the core than the smooth spline model, suggesting that the latter may be somewhat over-optimistic. The age vs depth model produced using Bacon has been used for all further analysis, with point age estimates (prefixed with '*c.*') using the *maximum a posteriori* (MAP) date estimate generated by the software based on several million MCMC runs.

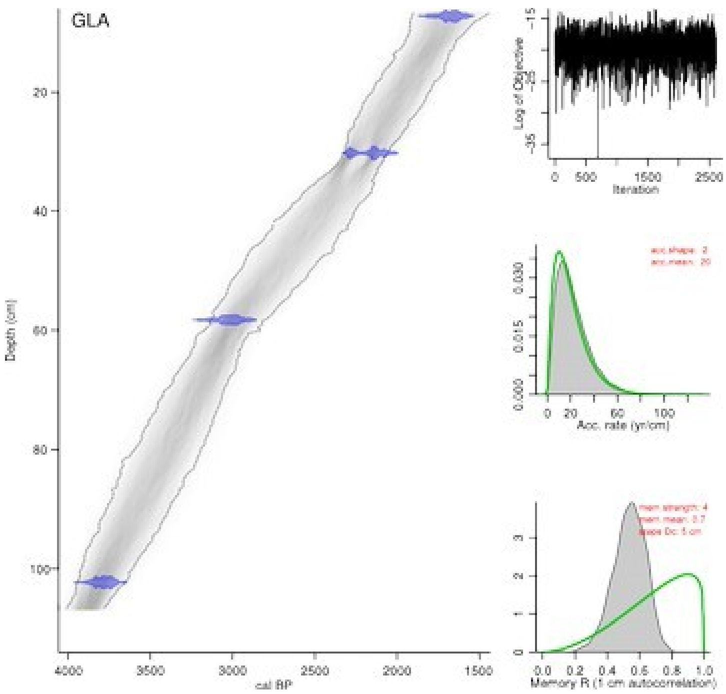

Figure 48: Age vs depth model for BH1 Gowla, produced using Bacon. Dotted lines indicate the 95% confidence intervals of the age model.

7.3.3 Humification

20 samples, at 8cm spacing between 1 and 153cm depth, were analysed from BH1, Gowla bog. The humification data, shown in Figure 49, shows a large amount of variability (absorbance between 29% and 81%). A LOWESS smooth line (span 0.2) shows a general trend towards increasing humification (indicating increasingly dry conditions) up-core throughout the ombrotrophic part of the sequence.

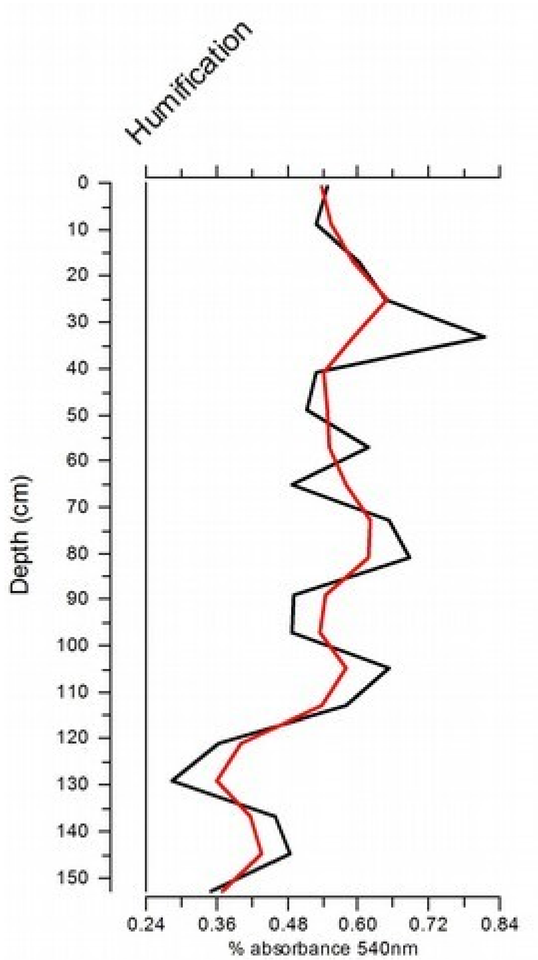

Figure 49: Humification curve (black line) from BH1 Gowla, red line is a LOWESS smooth line (span 0.2).

7.3.4 Testate amoebae analysis

Samples for testate amoebae analysis were initially taken every 8cm along BH1. No samples below 137cm depth yielded counts of 50 tests or more, indicating poor preservation or test concentration in the minerotrophic fen peats; samples above 89cm depth consistently produced usable counts. Following initial analysis at 8cm resolution, sampling was increased to 2cm resolution between 9cm and 89cm depth. In total, 42 samples produced counts of 50 tests or more, of which 35 yielded counts of more than 100 tests. Samples with fewer than 50 tests were excluded from further analysis. Test concentration was variable, but appeared to be highest in the moderately- and poorly-humified herbaceous and *Sphagnum*-rich peats between 86cm and 31cm depth.

Figure 50 shows the full testate amoebae diagram from BH1, Gowla bog. Values are expressed as percentages of the total test count. DWT values (using the central Irish transfer function, see Chapter 6) in cm are shown on the right hand side of the diagram, beside DCA Axis 1 (eigenvalue 0.356) scores. See Appendix 1 for DCA ordinations. DWT values and DCA Axis 1 scores are highly correlated ($r = 0.9$), suggesting that the main axis of variation in the species data from Gowla is related to hydrology. DWT values range between -1cm and 25cm (mean DWT = 7cm), therefore displaying a wide range of hydrological conditions. To facilitate discussion of the results, the testate amoebae diagram has been divided into assemblage zones based on a visual assessment of the data. A total of 25 taxa are present in this sequence; assemblages from BH1, Gowla, are generally characterised by switches in dominance between *Amphitrema* spp. and *Difflugia pulex*, indicating wetter and drier periods respectively. Diversity indices show some variation throughout the sequence, R values range between 5 and 13 taxa per sample (mean $R = 9.6$), H' values range between 1.06 and 1.76 (mean $H' = 1.5$), and D ranges between 0.58 and 0.78 (mean $D = 0.7$). Diversity is generally near to or above mean values above *c.* 89cm depth, but is generally below the mean in the lower part of the sequence - this may reflect the poorer preservation of tests in the lower part of the core sequence rather than stressed ecological communities.

GLA-1 (***Amphitrema flavum*** – *Difflugia pulex – Assulina muscorum – Cyclopyxis arcelloides*) - below *c.* 97cm (before *c.* 3820 to *c.* 3560 cal BP): this zone is represented by only three samples, preservation is very variable in this zone, and test concentration is generally low. Assemblages are dominated by *Amphitrema flavum* (increasing towards the top of the zone, max. 51%), *Difflugia pulex* (max. 45%, declining towards top of the zone), and stable levels *Assulina muscorum* (*c.* 15%). *Nebela militaris* also occurs in low numbers in this zone. DWT values range between 14.5 and 7cm indicating moderate to dry conditions, with a trend towards wetter conditions towards the top of the zone.

GLA-2 (*Amphitrema flavum – Difflugia pulex – Cyclopyxis arcelloides*) - *c.* 97 to 75cm depth (*c.* 3560 to 3220 cal BP): this zone is characterised by a switch from *Amphitrema flavum* – falling dramatically from 89 to 4% in this zone – to *Difflugia pulex* and *Cyclopyxis arcelloides* dominance (rising from 0% to 45% and 0% to 24%, respectively). DWT values accordingly fall from 3.6cm to 14.2cm, indicating a shift towards drier conditions.

GLA-3 (*Amphitrema flavum – Amphitrema wrightianum*) - *c.* 75 to 47cm depth (*c.* 3220 to 2700 cal BP): high values of *Amphitrema flavum* (max. 67%) and *Amphitrema wrightianum* (max. 44%) characterise this zone, with *Assulina muscorum*, *Difflugia pristis*, and *Heleopera sphagni* also present. DWT values are around 0 to 1cm, indicating wet conditions throughout this zone.

GLA-4 (***Difflugia pulex*** *– Amphitrema flavum*) - *c.* 47 to 25cm depth (*c.* 2700 to *c.* 2090 cal BP): values of *Difflugia pulex* are high (increasing from 56 to 66%), values of *Amphitrema flavum* are also relatively high, but falling (from 45% to 9%), *Amphitrema wrightianum* also falls in this zone from 17% to 0%. *Assulina muscorum* and *Difflugia pristis* are also present. DWT values rise from 3.6cm to 12.8cm indicating a shift towards dry conditions throughout this zone.

GLA-5 (***Difflugia pulex*** *– Hyalosphenia subflava*) - *c.* 25cm to 17cm depth (*c.* 2090 to *c.* 1900 cal BP): this zone is characterised by high values of *Difflugia pulex* (around 60%) and a notable peak in *Hyalosphenia subflava* – the only occurrence of this taxon in this sequence – reaching up to 35%. DWT values are high in this zone, peaking at 24.6cm, indicating dry conditions.

GLA-6 (*Difflugia pulex – Amphitrema flavum*) - *c.* 17cm depth to top (*c.* 1900 cal BP to after 1700 cal BP): values of *Difflugia pulex* fall from 63% to 14.6%, whilst values of *Amphitrema flavum* rise from 24% to 50%. *Amphitrema wrightianum* also rises to a maximum of 17% in this zone. DWT values fall from 8.5cm to 2.8cm, indicating a shift from moderately dry to wet conditions in this zone.

7.3.5 Summary

Although hampered by poor preservation, the testate amoebae record suggests relatively wet conditions prior to *c.* 3300 cal BP, an inference broadly supported by the humification data. The humification data shows a high degree of variability, and is of low sampling resolution, and only broadly accords with the testate amoebae-derived DWT record in showing gradually drier conditions until *c.* 2280 cal BP. The DWT record shows a distinct dry shift between *c.* 3280 and *c.* 3220 cal BP, followed by a period of wet conditions until *c.* 2700 cal BP. Water tables then fall, reaching the driest phase between *c.* 2090 and *c.* 1900 cal BP after which conditions become increasingly wet until after *c.* 1700 cal BP.

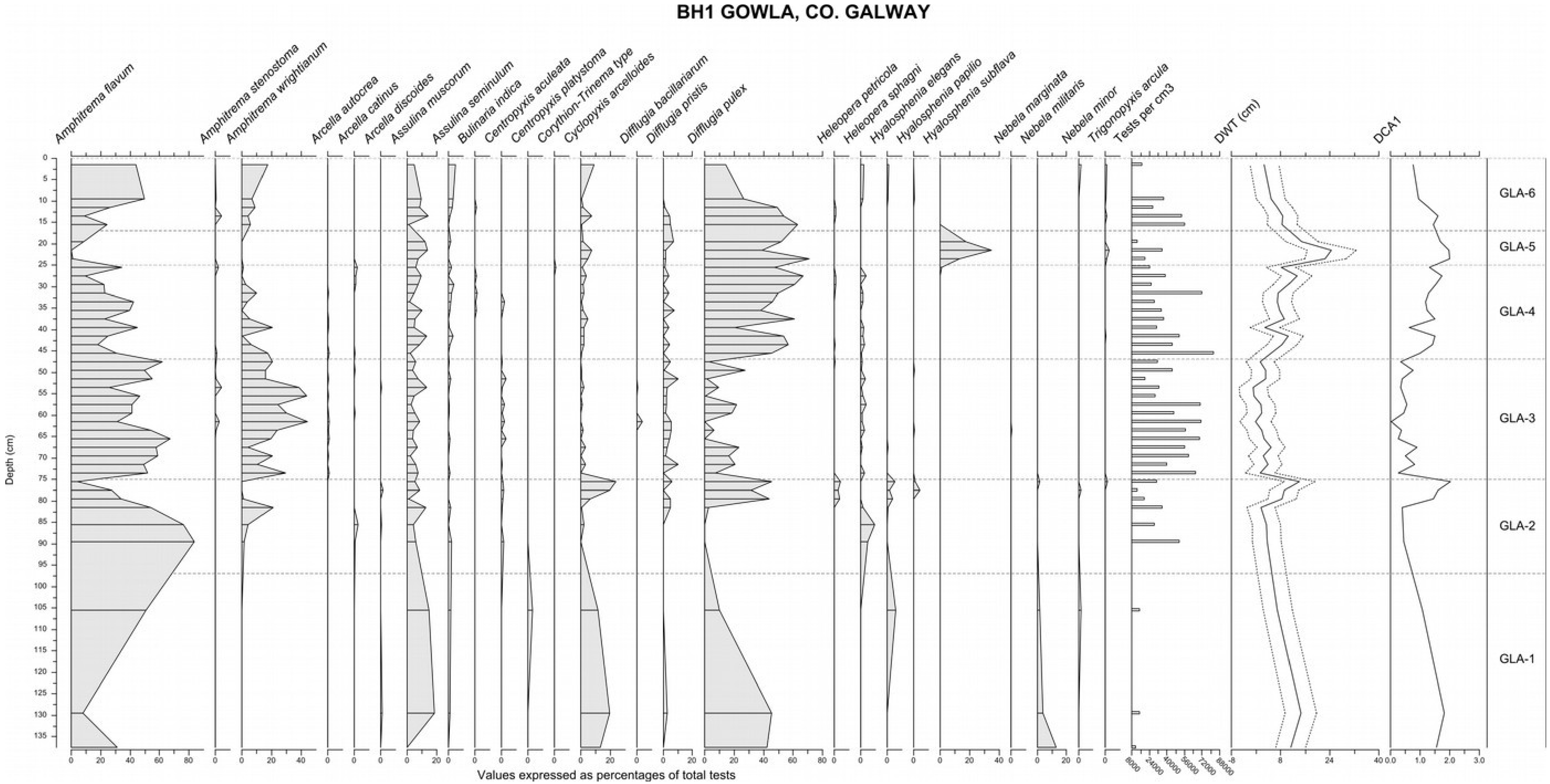

Figure 50: Full testate amoebae diagram from BH1, Gowla bog, Co. Galway. Values are presented as percentages of the total test count. Reconstructed DWT was calculated using the central Irish transfer function
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7.4 *Killaderry bog, Co. Galway*

Fieldwork on Killaderry bog was carried out during Summer 2011. Preliminary results from Cloonshannagh bog were also reported in Young et al. (2012a).

7.4.1 Stratigraphy

To characterise the shape of the underlying basin, a grid *(c.* 50m spacing) of 24 depth soundings was carried out using a gouge auger across the area of Killaderry bog where the main concentration of archaeological features was sited. Peat deposits ranged in thickness from *c.* 170cm to *c.* 450cm. This survey revealed that the underlying mineral sediments formed a shallow basin oriented east – west, with peat deposits thinning to the north and south. The master sequence, BH25, was situated in the central portion of this basin, where peat deposits were relatively thick, and *c.* 100m to the east of the archaeological structures excavated at Killaderry.

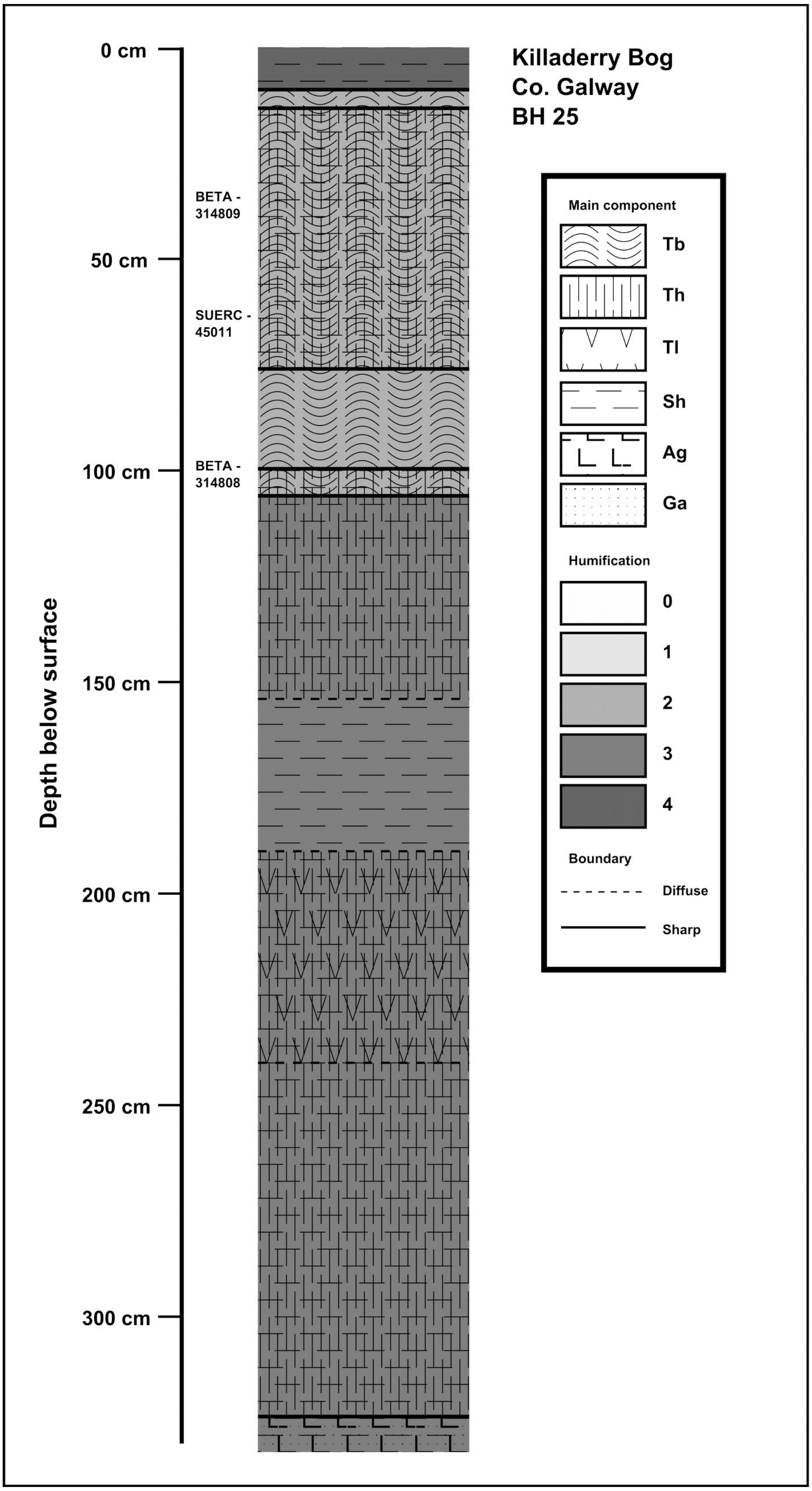

Figure 51: Peat stratigraphy of BH25, Killaderry bog, Co. Galway.

Figure 51 shows the stratigraphic log from BH25, whilst full Troels-Smith sediment descriptions are given in Table 40. BH25 revealed a peat sequence 330cm deep. At the base of the sequence was 5cm of mineral sediments mixed with well-humified detrital organic material, probably lacustrine in origin (Unit 1). Above this was a deposit of well-humified *Phragmites* fen peat *c.* 85cm thick (Unit 2), which in turn was overlain by 51cm of well-humified wood fen peat, containing both herbaceous and woody remains (Unit 3). Above the fen peat deposits was 84cm of generally well-humified herbaceous peat (Units 4 and 5). This was overlain by 95cm of mostly poorly- or moderately-humified peat composed of varying proportions of *Sphagnum* and herbaceous remains (Units 6-1). The top 10cm of the sequence consisted of well-humified herbaceous peat (Unit 12).

Table 40: Peat stratigraphic log, BH25 Killaderry Bog, Co. Galway.

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact	Notes
12	0	10	2.5YR 2.5/1	Sh3 $Th^3$1	4	sharp	
11	10	13	2.5YR 2.5/2	$Tb^2$3 Sh1	2	sharp	
10	13	27	2.5YR 2.5/1	Sh2 $Th^1$1 $Tb^2$1	2	diffuse	
9	27	48	2.5YR 2.5/1	Sh2 $Th^1$1 $Tb^2$1	2	sharp	
8	48	76	2.5YR 2.5/1	Sh2 $Th^2$1 $Tb^2$1	2	sharp	
7	76	100	2.5YR 2.5/2	$Tb^1$2 Sh1 $Th^2$1	2	sharp	
6	100	105	2.5Y 3/3	Sh2 $Th^2$1 $Tb^1$1	2	sharp	
5	105	154	2.5YR 2.5/1	Sh2 $Th^2$2	3	diffuse	
4	154	189	2.5YR 2.5/1	Sh3 $Th^3$1	3	diffuse	
3	189	240	2.5YR 2.5/1	Sh2 $Th^3$1 $Tl^2$1	3	diffuse	
2	240	325	2.5YR 2.5/1	Sh2 $Th^2$2	3	sharp	Phragmites
1	325	330	2.5Y 2.5/1	Sh1 Ga1 Ag1 Dh1	3	---	

7.4.2 Chronology

Three samples of picked and cleaned above-ground plant macrofossils from the ombrotrophic part of BH25 were submitted for AMS ^{14}C dating. BETA-314809, and BETA-314808 were analysed in Miami, Florida, USA, by Beta Analytic Inc., whilst SUERC-45011 was prepared to graphite at the NERC radiocarbon facility, East Kilbride, and analysed at the

SUERC AMS Laboratory. Details of these dates are given in Table 41. These dates show a clear increase in age with depth.

Table 41: AMS ^{14}C dates obtained from BH25, Killaderry bog, Co. Galway. Dates were calibrated using the IntCal09 calibration curve (Reimer et al. 2009), and 95% confidence (2σ) intervals were generated using the Clam software package (Blaauw 2010).

Lab code	Depth (cm)	Material dated	$^{13}C/^{12}C$ ratio	^{14}C date (BP)	Calibrated range 2σ (cal BP)
BETA-314809	35.5	Plant macrofossils	-22.6	2070±30	2120-1950
SUERC-45011	64.5	*Sphagnum* macrofossils	-25.7	3128±37	3440-3260
BETA-314808	99.5	Plant macrofossils	-23.9	3450±30	3830-3640

The AMS ^{14}C dates suggest that the sequence of ombrotrophic peat at Killaderry bog spans the Late Holocene, with a mean accumulation rate of *c.* 26 years/cm. Age vs depth models for BH1 were created using the Clam (Blaauw 2010) and Bacon (Blaauw and Christen 2011) software packages.

Since only three ^{14}C dates were obtained from BH25, only linear age vs depth models could be generated using Clam. Figure 52 shows the age vs depth model for BH25 based on linear interpolation between dated levels. This model shows an abrupt change in accumulation rate at 64cm depth.

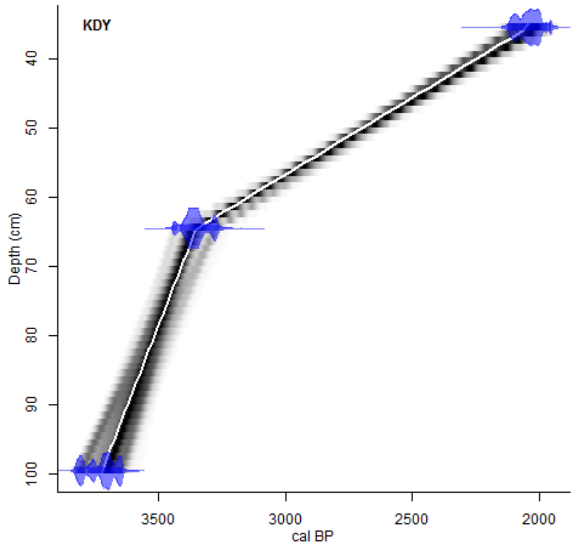

Figure 52: Age vs depth model for BH25, Killaderry, produced in Clam using linear interpolation.

Bacon was used to generate a more flexible age vs depth model, shown in Figure 53. This model is similar to the linear age vs depth model, but shows increased (and more realistic) uncertainty between dated levels, and a less abrupt (probably more plausible) change in accumulation rate. The age vs depth model produced using Bacon has been used for all further analysis and discussion, with point age estimates (prefixed with '*c.*') using the *maximum a posteriori* (MAP) date estimate generated by the software based on several million MCMC runs.

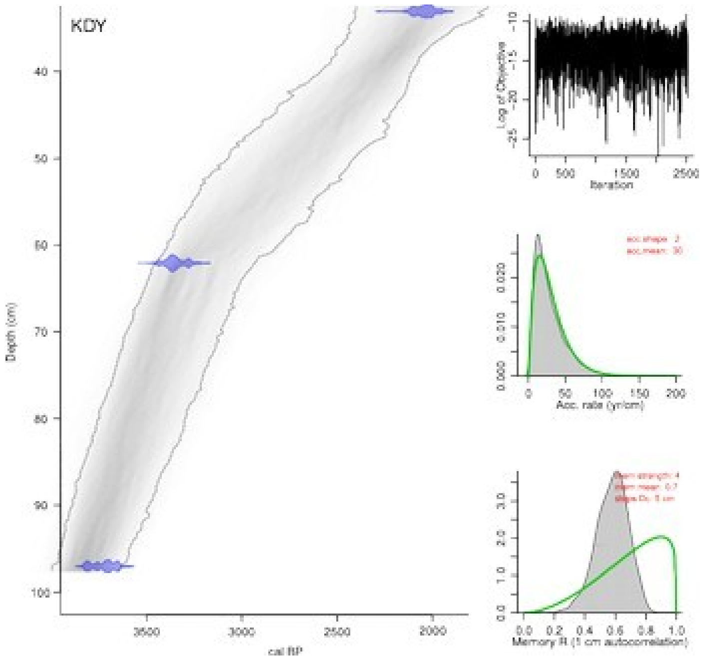

Figure 53: Age vs depth model for BH25, Killaderry, produced using Bacon. Dotted lines indicate the 95% confidence intervals of the age model.

7.4.3 Humification

21 samples, at 8cm spacing between 10 and 170cm depth, were analysed from BH25, Killaderry bog. The humification data, shown in Figure 54, shows a large amount of variability (absorbance between 32% and 79%, mean = 56%). A LOWESS smooth line (span 0.2) shows a general trend towards decreasing humification up-core throughout the ombrotrophic part of the sequence - suggesting gradually increased moisture availability during the Late Holocene.

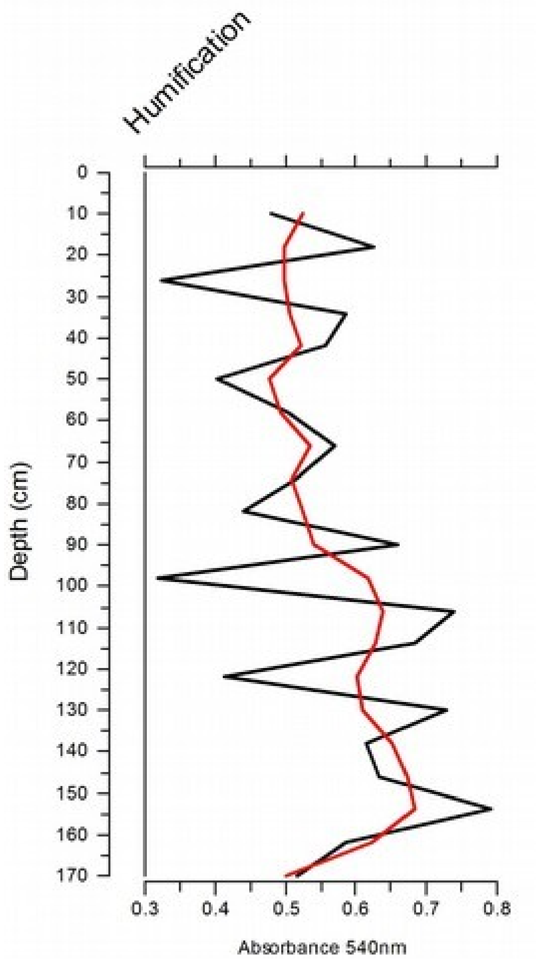

Figure 54: Humification curve (black line) from BH25, Killaderry, red line shows a LOWESS smooth line (span 0.2).

7.4.4 Testate amoebae analysis

Samples for testate amoebae analysis were initially taken every 8cm along BH25. No samples below 162cm depth yielded counts of 50 tests or more, indicating poor preservation or test concentration in the minerotrophic fen peats; samples above 162cm depth consistently produced usable counts. Following initial analysis at 8cm resolution, sampling was increased to 2cm resolution between 34cm and 98cm depth. In total, 43 samples produced counts of 50 tests or more, of which 36 yielded counts of more than 100 tests. Samples with fewer than 50 tests were excluded from further analysis. Test concentration was variable throughout, with no clear correlation between concentration and lithostratigraphy.

Figure 55 shows the full testate amoebae diagram from BH25, Killaderry bog. Values are expressed as percentages of the total test count. DWT values (using the central Irish transfer function, see Chapter 6) in cm are shown on the right hand side of the diagram, beside DCA Axis 1 (eigenvalue 0.303) scores. See Appendix 1 for DCA ordinations. DWT values and DCA Axis 1 scores are highly correlated ($r = 0.9$), suggesting that the main axis of variation in the species data from Gowla is related to hydrology. DWT value range between -0.2cm and 23cm (mean DWT = 7.4cm), therefore displaying a wide range of hydrological conditions. To facilitate discussion of the results, the testate amoebae diagram has been divided into assemblage zones based on a visual assessment of the data. A total of 27 taxa are present in this sequence; assemblages from BH25, Killaderry, are generally characterised by switches in dominance between *Amphitrema* spp. on the one hand and *Difflugia pulex* and *Assulina muscorum* on the other, indicating wetter and drier periods respectively. Diversity indices show considerable variation throughout the sequence, R values range between 4 and 12 taxa per sample (mean $R = 7.9$), H' values range between 0.47 and 2.07 (mean $H' = 1.3$), and D ranges between 0.19 and 0.85 (mean $D = 0.63$). Diversity is generally lower towards the base of the sequence suggesting that preservation may be having a slight effect on assemblage structure, all diversity indices show particularly low values in the sample at 60cm depth, where DWT is at it's highest (22cm) which may possibly indicate ecological stress caused by the dry conditions.

KDY-1 (*Difflugia pulex – Amphitrema flavum – Assulina muscorum*) - 162 to 134cm depth (before *c.* 3870 cal BP): *Difflugia pulex* increases in this zone to a maximum of 60%, with a concomitant decrease in *Amphitrema flavum* (decreasing from 69% to 0%). *Assulina muscorum* is also present (up to 30%). The DWT curve shows increasingly dry conditions with values rising from 4.6cm to 19cm in this zone.

KDY-2 (*Amphitrema flavum – Difflugia pulex*) - 134 to 102cm depth (before *c.* 3870 cal BP): this zone is characterised by an increase and subsequent decline in *Amphitrema flavum* – up to a maximum of 90% in the middle of this zone at 122cm depth. *Difflugia pulex* declines early in this zone, before increasing to a maximum of 62% at the top of this zone. *Assulina muscorum* is also present and declines and increases concurrently with *Difflugia pulex*. DWT values fall from 19cm to a minimum of 3.8cm in the middle of this zone (122cm depth) before rising again to 17cm, indicating a shift to wet conditions followed by a return to dry bog surface conditions.

KDY-3 (*Amphitrema flavum – Difflugia pulex – Amphitrema wrightianum*) - 102 to 77cm depth (before *c.* 3870 to *c.* 3570 cal BP): this zone is characterised by high values of

Amphitrema flavum throughout (generally *c.* 40-50%). *Amphitrema wrightianum* appears for the first time in BH25 in this zone, and values fluctuate between 3.5% and 45%; these fluctuations are in anti-phase with fluctuations in *Difflugia pulex* which vary from 0% to 52%. These fluctuations account for the highly variable DWT values in this zone, values range from -0.2cm (indicating a water table at or just above the bog surface) to 8cm (indicating moderately dry conditions). *Assulina muscorum*, *Difflugia pristis*, and *Cyclopyxis arcelloides* are also present in small amounts through this zone.

KDY-4 (*Difflugia pulex – Amphitrema flavum – Difflugia pristis*) - 77 to 59cm depth (*c.* 3570 to *c.* 3180 cal BP): *Difflugia pulex* dominates this zone with a maximum abundance of 86%. *Amphitrema flavum* is also present in variable amounts (max. 45%), as are *Difflugia pristis* (max. 21%) and *Assulina muscorum* (max. 20%). Low values (max. ~5%) of *Cyclopyxis arcelloides* are present throughout this zone. DWT values are variable but generally indicate dry to moderately dry conditions (~5 to 10cm), with a trend to increasingly dry conditions through this zone, reaching a peak at the top of this zone (DWT = 22.9cm) indicating very dry bog conditions.

KDY-5 (*Assulina muscorum – Difflugia pulex – Amphitrema flavum*) - 59 to 45cm depth (*c.* 3180 to *c.* 2400 cal BP): the lower part of this zone is characterised by high levels of *Assulina muscorum* (max. 57cm) and *Difflugia pulex*. Both taxa decline at the top of this zone with a concomitant rise in *Amphitrema flavum* (increasing from ~10% to a maximum of 40%). The DWT curve initially shows dry conditions in this zone (max. DWT = 14cm) which drop throughout this zone to a minimum of 2cm, suggesting a steady increase in BSW in this zone.

KDY-6 (*Difflugia pulex*) - 45 to 37cm depth (*c.* 2400 to *c.* 2050 cal BP): this zone is characterised by high levels of *Difflugia pulex* (max. 71%) with lower abundances of *Amphitrema flavum*, *Assulina muscorum*, and *Difflugia pristis*. DWT values range from 8cm to 12cm in this zone indicating moderately dry to dry conditions.

KDY-7 (*Difflugia pulex – Amphitrema flavum*) - 37cm depth to top (*c.* 2050 to after *c.* 2000 cal BP): this zone begins with a peak in *Amphitrema flavum* values (40%) which subsequently decline to 22%. *Difflugia pulex* increases from 10% to 51%. *Hyalosphenia subflava* is present at the very top of this zone (20%) as is *Cyclopyxis arcelloides* (21%). DWT values show wet conditions at the base of this zone (DWT = 3cm) with values increasing to 9cm towards the top of the sequence, indicating moderately dry conditions.

7.4.5 Summary

Prior to *c.*3870 cal BP both testate amoebae-derived DWT and humification indicate fluctuating BSW at Killaderry bog including a significant wet shift at around 130cm depth. Bog surface conditions were generally wet, but variable between *c.* 3870 and *c.* 3570 cal BP. Between *c.* 3570 and *c.* 3240 cal BP there is a general trend towards drier conditions, albeit with considerable variation, with the lowest DWT value recorded at Killaderry at *c.* 3580 cal BP. Following a wet shift at *c.* 3240 water tables rose steadily until a sharp drop in water tables at *c.* 2340 cal BP. Surface conditions are then dry until a further wet shift at *c.* 2020 cal BP, after which moderate BSW conditions prevail to the top of the sequence.

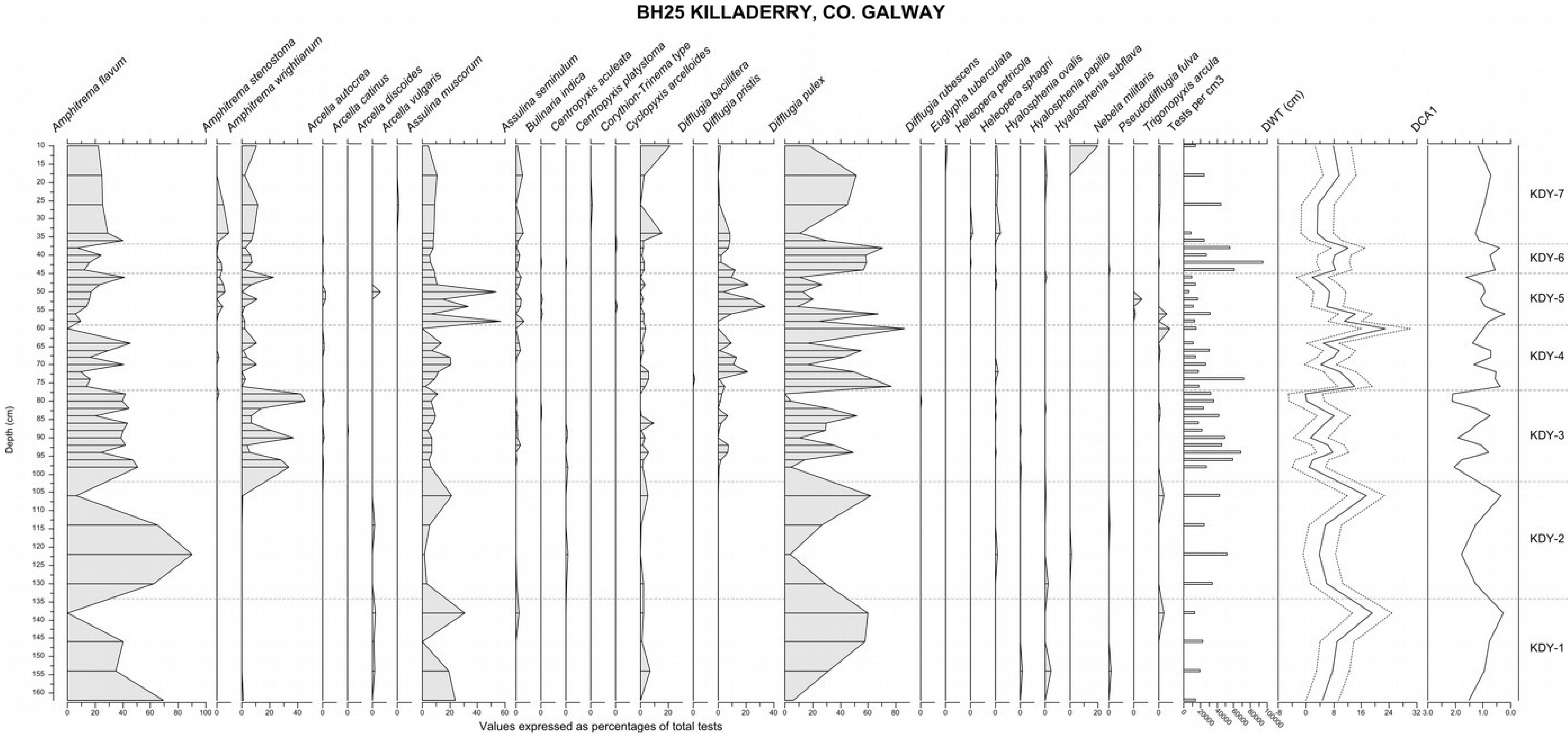

Figure 55: Full testate amoebae diagram from BH25, Killaderry bog, Co. Galway. Values are presented as percentages of the total test count. Reconstructed DWT was calculated using the central Irish transfer function.

7.5 Castlegar bog, Co. Galway

Fieldwork on Castlegar bog, Co. Galway, was carried out during summer 2011. Results of preliminary analyses are discussed in Young et al. (2012b).

7.5.1 Stratigraphy

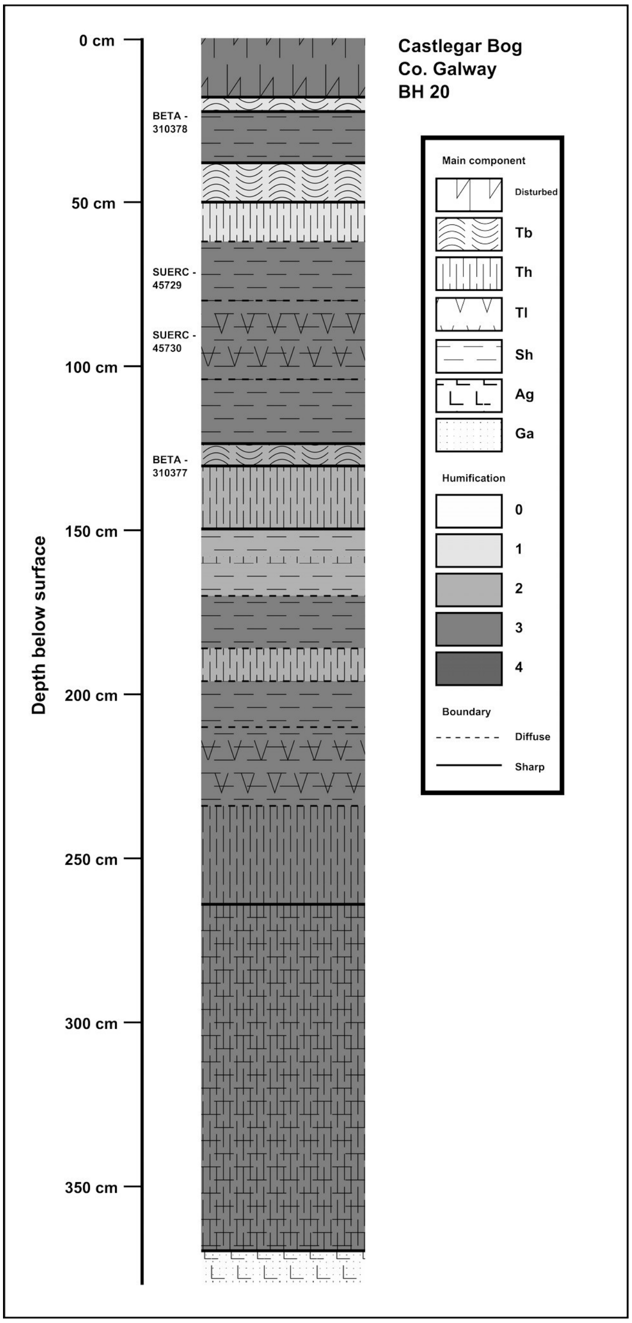

Figure 56: Peat stratigraphy BH20, Castlegar bog, Co. Galway.

A transect of 19 peat depth soundings, running for *c.* 1200m from north-west to south-east, was carried out using a gouge auger. This survey revealed an undulating surface of mineral sediments overlain by peat deposits of varying thickness (max. 775cm), and suggested the presence of a small basin in the north-west and a larger basin to the south-east. Although shallower than the larger expanse of peatland towards the south-east of the transect, sampling of the master sequence, BH20, was carried out in the north-western basin, as the archaeological structures uncovered at the site were located in this area; the location of BH20 was selected for being the deepest sequence from this basin, and as it was *c.* 150m from the nearest archaeological structures.

Table 42: Peat stratigraphic log, BH20 Castlegar Bog, Co. Galway.

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact	Notes
20	0	18	2.5YR 2.5/1	Sh3 $Th^2$1 Tl+	3	sharp	Disturbed
19	18	21	2.5YR 2.5/1	$Tb^1$2 $Th^2$1 $Tl^2$1	1	sharp	
18	21	38	2.5YR 2.5/1	Sh3 $Th^2$1	3	sharp	
17	38	50	2.5YR 2.5/1	$Tb^1$3 $Th^2$1 Sh+	1	sharp	
16	50	62	10YR 2/2	$Th^1$3 Sh1	2	diffuse	
15	62	80	10YR 2/2	Sh3 $Th^2$1 Tl+	3	diffuse	
14	80	105	2.5YR 2.5/1	Sh2 $Th^2$1 $Tl^2$1	3	diffuse	
13	105	123	10YR 2/2	Sh3 $Th^3$1	3	sharp	pool?
12	123	130	2.5YR 2.5/1	$Tb^1$2 Sh1 $Th^2$1	2	sharp	
11	130	150	2.5YR 2.5/1	$Th^2$2 Sh2	2	sharp	
10	150	158	2.5YR 2.5/1	Sh2 $Th^2$1 $Tb^2$1	2	sharp	
9	158	160	2.5YR 2.5/2	$Th^1$3 Sh1	2	sharp	
8	160	170	2.5YR 2.5/2	Sh2 $Tb^2$1 $Th^3$1	2	diffuse	
7	170	186	10YR 2/1	Sh3 $Th^2$1	3	diffuse	

6	186	196	10YR 2/1	$Th^1 3$ Sh1	2	diffuse	
5	196	210	10YR 2/1	Sh2 $Th^2 2$	3	diffuse	
4	210	234	10YR 2/1	Sh2 $Tl^2 1$ $Th^2 1$	3	diffuse	Fen/bog transition?
3	234	265	10YR 2/1	$Th^2 3$ Sh1	3	sharp	
2	265	370	10YR 2/1	Sh2 $Th^2 2$ Tl+	3	sharp	
1	370	380	2.5Y 4/2	As2 Ga1 Gg1	---	---	

Figure 56 shows the stratigraphic log from BH20, whilst full Troels-Smith sediment descriptions are given in Table 42. The sequence from BH20 was 380cm deep. The base of the sequence consisted of 10cm of mineral clay with sands and traces of gravel (Unit 1), representing the top of the underlying deposits of Glacial till. This was overlain by 160cm of moderately- to well-humified herbaceous peats with occasional wood remains (Units 2-4) - this probably represents the minerotrophic fen phase of the development of this site. Above the sharp upper boundary of the fen peat was 40cm of herbaceous peat of varying humification (Units 5-7), which was in turn overlain by 47cm of mostly poorly-humified herbaceous and *Sphagnum* peat (Units 8-12). Above this was a layer 18cm of humified algal mud with traces of *Menyanthes* (Unit 13), possibly representing a deposit of pool peat, which was then overlain by 55cm of moderately-humified herbaceous peat with some Ericaceous remains (Units 14-16). Above this was 12cm of poorly-humified *Sphagnum* peat (Unit 17), overlain by 17cm of well-humified peat (Unit 18), in turn overlain by another band of poorly-humified *Sphagnum*-dominated peat (Unit 19). The top 18cm of the sequence was composed of well-humified mixed peat (Unit 20), which appeared to be re-deposited milled peat lying on the surface of the site.

7.5.2 Chronology

Four samples of picked and cleaned above-ground plant macrofossils from the ombrotrophic part of BH20 were submitted for AMS ^{14}C dating. BETA-310378, and BETA-310377 were analysed in Miami, Florida, USA, by Beta Analytic Inc., whilst SUERC-45729 and SUERC-45730 were prepared to graphite at the NERC radiocarbon facility, East Kilbride, and analysed at the SUERC AMS Laboratory. Details of these dates are given in Table 43. These dates show a clear increase in age with depth.

Table 43: AMS ^{14}C dates obtained from BH20, Castlegar bog, Co. Galway. Dates were calibrated using the IntCal09 calibration curve (Reimer et al. 2009), and 95% confidence (2σ) intervals were generated using the Clam software package (Blaauw 2010).

Lab code	Depth (cm)	Material dated	$^{13}C/^{12}C$ ratio	^{14}C date (BP)	Calibrated range 2σ (cal BP)
BETA-310378	26.5	Plant macrofossils	-28.7	1270±30	1290-1100
SUERC-45729	73.5	*Sphagnum* macrofossils	-27.5	2119±37	2300-1990
SUERC-45730	91.5	Plant macrofossils	-27.8	2428±37	2700-2350
BETA-310377	130.5	Plant macrofossils	-26.6	3210±40	3550-3360

The ^{14}C dates from Castlegar bog show that the ombrotrophic part of the sequence spans a large part of the Late Holocene, from before *c.* 3400 cal BP to after *c.* 1250 cal BP. These dates suggest a mean peat accumulation rate of *c.* 20 years/cm. Age vs depth models were generated for BH20 using Clam (Blaauw 2010) and Bacon (Blaauw and Christen 2011) software packages.

The smooth spline age vs depth model was selected as being the most plausible of the various 'classical' models implemented in Clam, as it assumes that changes in accumulation rate are likely to have been smooth, rather than abrupt; a plot of this age vs depth model is shown in Figure 57. The 95% confidence intervals of the four AMS ^{14}C dates from BH20 show an approximately linear relationship between age and depth, and this is reflected in the output from this model.

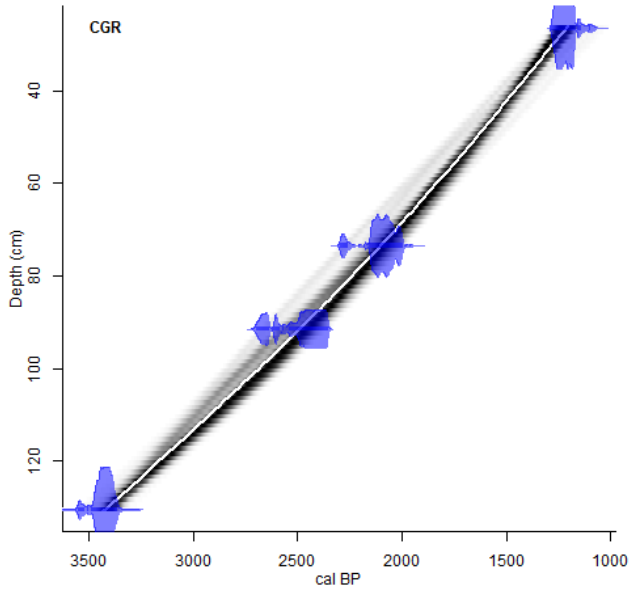

Figure 57: Smooth spline age vs depth model for BH20, Castlegar.

For comparison, a more flexible age vs depth model was developed using Bacon. The output of this model is shown in Figure 58. The results of this model are very similar to those obtained from the smooth spline model discussed above, showing that these models appear to be generally robust. The age vs depth model produced using Bacon has been used for all further analysis, with point age estimates (prefixed with '*c.*') using the *maximum a posteriori* (MAP) date estimate generated by the software based on several million MCMC runs.

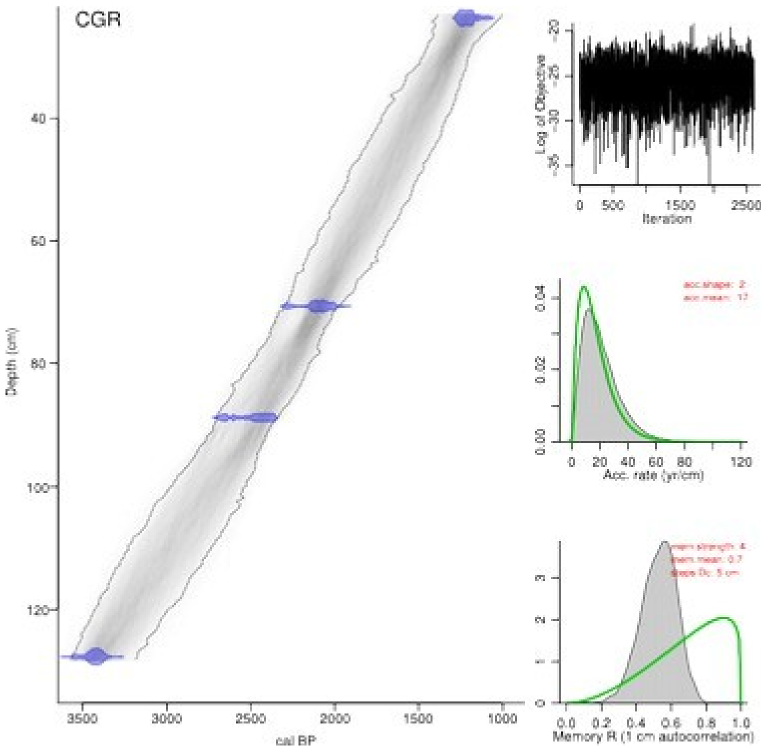

Figure 58: Age vs depth model fro BH20, Castlegar, produced using Bacon. Dotted lines indicate the 95% confidence intervals of the age model.

7.5.3 Humification

25 samples, at 8cm spacing between 1 and 193cm depth, were analysed from BH20, Castlegar bog. The humification data, shown in Figure 59, shows considerable of variability (absorbance between 39% and 79%, mean = 62%). A LOWESS smooth line (span 0.2) shows a general trend towards decreasing humification up-core throughout the ombrotrophic part of the sequence - suggesting gradually increased moisture availability during the Late Holocene, with a notable dip in absorbance values (suggesting a wet shift) at 81cm depth (*c.* 2260 cal BP).

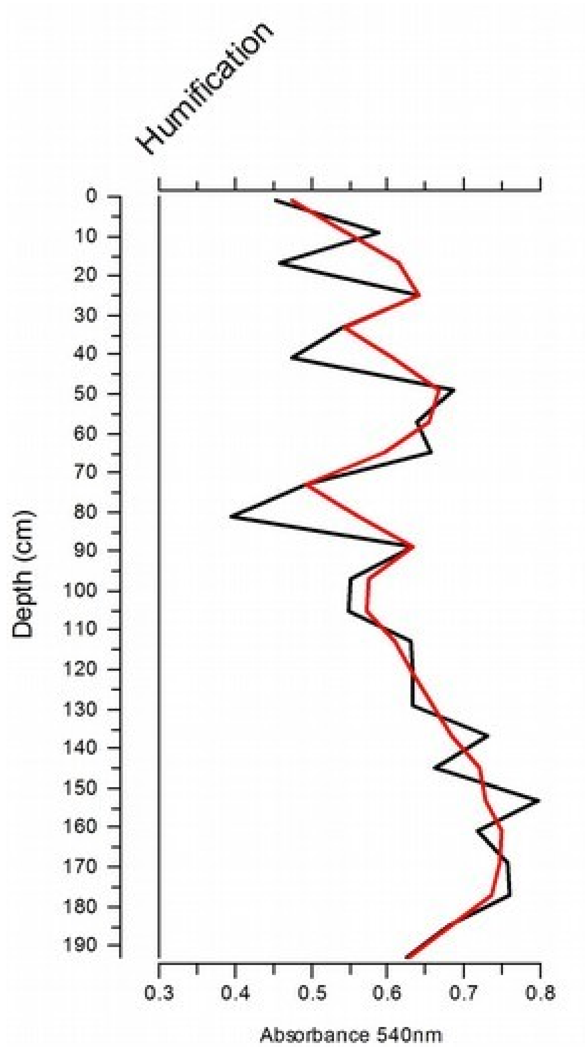

Figure 59: Humification curve (black line) from BH20, Castlegar, red line is a LOWESS smooth line (span 0.2).

7.5.4 Testate amoebae analysis

Samples for testate amoebae analysis were initially taken every 8cm along BH20. No samples below 217cm yielded counts of 50 tests or more, indicating poor preservation or test concentration in the minerotrophic fen peats. Following initial analysis at 8cm resolution, sampling was increased to 2cm spacing between 19 and 177cm depth. Samples above 18cm depth were excluded from further analysis since these appeared to have been disturbed by milling. In total 51 samples yielded counts of 50 tests or more, of which 39 produced counts of over 100 tests. Samples with fewer than 50 tests were excluded from further analysis. Test concentration was variable throughout the analysed section of the sequence, with no clear relationship between lithostratigraphy and concentration, other than the poor preservation of tests in the fen.

Figure 60 shows the full testate amoebae diagram fro BH20, Castlegar bog. Values are expressed as percentages of the total test count. DWT values in cm (reconstructed using the central Irish transfer function, see Chapter 6, with sample-specific errors generated through 1000 bootstrap cycles) are shown on the right hand side of the diagram, along with DCA Axis 1 (eigenvalue 0.2987) sample scores. See Appendix 1 for DCA ordination diagrams. DWT values and DCA Axis 1 scores are highly correlated ($r = 0.84$), suggesting that the main axis of variation in the species data is strongly related hydrology. DWT values range from -0.1cm to 20cm (mean DWT = 8.6cm), representing a wide range of hydrological conditions. For the purposes of the following discussion of results, the testate amoebae diagram has been divided into assemblage zones based on a visual assessment of the data. A total of 25 taxa are present in this sequence, although most samples are dominated either by *Difflugia pulex* or *Amphitrema flavum*. Diversity indices show variability throughout the sequence, R values range between 4 and 13 (mean $R = 8$ species per sample), H' values range between 0.8 and 1.9 (mean $H' = 1.31$), and D ranges between 0.36 and 0.82 (mean $D = 0.6$). D appears to be negatively correlated with DWT ($r = -0.62$), showing that samples showing high DWT (e.g. dry conditions) tend to be more dominated by fewer taxa - reflecting the overwhelming dominance of *Difflugia pulex* in some samples from BH20 which have high DWT values, but with more even communities where DWT values are lower (wetter).

CGR-1 (*Amphitrema flavum – Difflugia pulex*) 217 to 173cm depth (before *c.* 3400 cal BP): this zone is characterised by a decline in *Amphitrema flavum* from 75% to 39% and a concomitant increase in *Difflugia pulex* up to a maximum of 49%. Low values of *Heleopera sphagni* are present throughout this zone. DWT increases slightly in this zone from 4.8 to 8.8cm indicating moderately wet conditions giving way to moderately dry conditions.

CGR-2 (*Amphitrema flavum – Difflugia pulex – Amphitrema wrightianum*) 173 to 141cm depth (before *c.* 3400 cal BP): this zone is characterised by another decline in *Amphitrema flavum* from a maximum of 59% at the base of this zone to 17% at the top. *Difflugia pulex* initially falls to to 13% before increasing up to a maximum of 70%. *Amphitrema wrightianum* increases to 20% in the lower part of this zone before declining as *D. pulex* increases. DWT initially drops to 1.7cm before rising again to 10cm indicating a wet shift followed by a change to moderately dry conditions.

CGR-3 (*Amphitrema flavum – Difflugia pulex – Assulina muscorum*) 141 to *c.*103m depth (before c. 3400 to *c.* 2700 cal BP): *Amphitrema flavum* and *A. wrightianum* are more abundant at the base of this zone, and decline (from 57% to 9%, and from 33% to 4%, respectively). Meanwhile *Difflugia pulex* and *Assulina muscorum* increase through this zone to maxima of 63% and 20%, respectively. DWT increases in this zone from 1.5 to 12cm indicating wet conditions giving way to dry conditions.

CGR-4 (*Difflugia pulex – Assulina muscorum – Difflugia pristis*) *c.*103 to 82cm depth (*c.* 2700 to *c.* 2270 cal BP)*: Assulina muscorum* and *Difflugia pristis* both decline from maxima of 36% and 39%, respectively, whilst *Difflugia pulex* increases considerably through this zone to a maximum of 71%. *Amphitrema flavum* is present throughout, but with relatively low (and decreasing) values (34% to 5%). DWT increases from 4.9cm to 15cm indicating a shift towards drier conditions.

CGR-5 (*Difflugia pulex – Amphitrema flavum – Amphitrema wrightianum*) 82 to 72cm depth (*c.* 2270 to *c.* 2130 cal BP): *Difflugia pulex* declines sharply to 19% whilst *Amphitrema* spp. increase sharply. DWT values fall sharply to -0.1cm at the top of this zone indicating a shift to very wet conditions.

CGR-6 (*Difflugia pulex*) 72 to 56cm depth (*c.* 2130 to *c.*1880 cal BP): *Difflugia pulex* increases (with considerable variation) to a maximum of 73%. *Hyalosphenia subflava* also is present and increasing towards the top of this zone. DWT values rise accordingly (to 17cm), indicating a shift towards dry bog surface conditions.

CGR-7 (*Amphitrema flavum*) 56 to 48cm depth (*c.* 1880 to *c.* 1730 cal BP): *Amphitrema flavum* increases in this zone to a maximum of 42%, DWT values show a return to moderate BSW conditions (DWT = ~5cm).

CGR-8 (*Difflugia pulex*) 48 to 40cm depth (*c.* 1730 to *c.* 1530 cal BP): *Difflugia pulex* dominates this zone (~60%). DWT values are around 10-12cm, indicating dry conditions.

CGR-9 (*Amphitrema flavum – Difflugia pulex – Assulina muscorum*) 40 to 28cm depth (*c.* 1730 to *c.* 1290 cal BP): *Amphitrema flavum* dominates the base of this zone (max. 60%) and then falls sharply. As *A. flavum* falls, *Assulina muscorum* briefly increases to 36% before declining, as *Difflugia pulex* again increases to 80% at the top of this zone. This zone begins with a shift to moderately-wet conditions (DWT = 5cm), and then an increase in DWT to 20cm – indicating dry conditions.

CGR-10 (*Difflugia pulex – Amphitrema flavum – Assulina muscorum*) 28 to 19cm depth (*c.* 1290 to after *c.* 1250 cal BP): *Difflugia pulex* generally dominates this zone (max. 78%), but fluctuates with *Amphitrema flavum* and *Assulina muscorum*. DWT values are highly variable in this zone mostly around 10-16cm (moderately-dry to dry), but falls to 4cm at the very top of this zone.

7.5.5 Summary

The sequence from BH20, Castlegar, Co. Galway, is mainly characterised by fluctuations in the taxon *Difflugia pulex* which dominates most of the testate amoebae assemblages. A number of wet shifts, mostly indicated by increases in *Amphitrema* spp. punctuate the generally moderately dry conditions on this bog. These wet shifts occur at around 161cm, 137cm (both prior to *c.* 3400 cal BP), 49cm (*c.* 1760 cal BP), and most notably at 79cm (*c.* 2230 cal BP), this event is also reflected in the humification record with a sharp decrease in absorbance at 81cm.

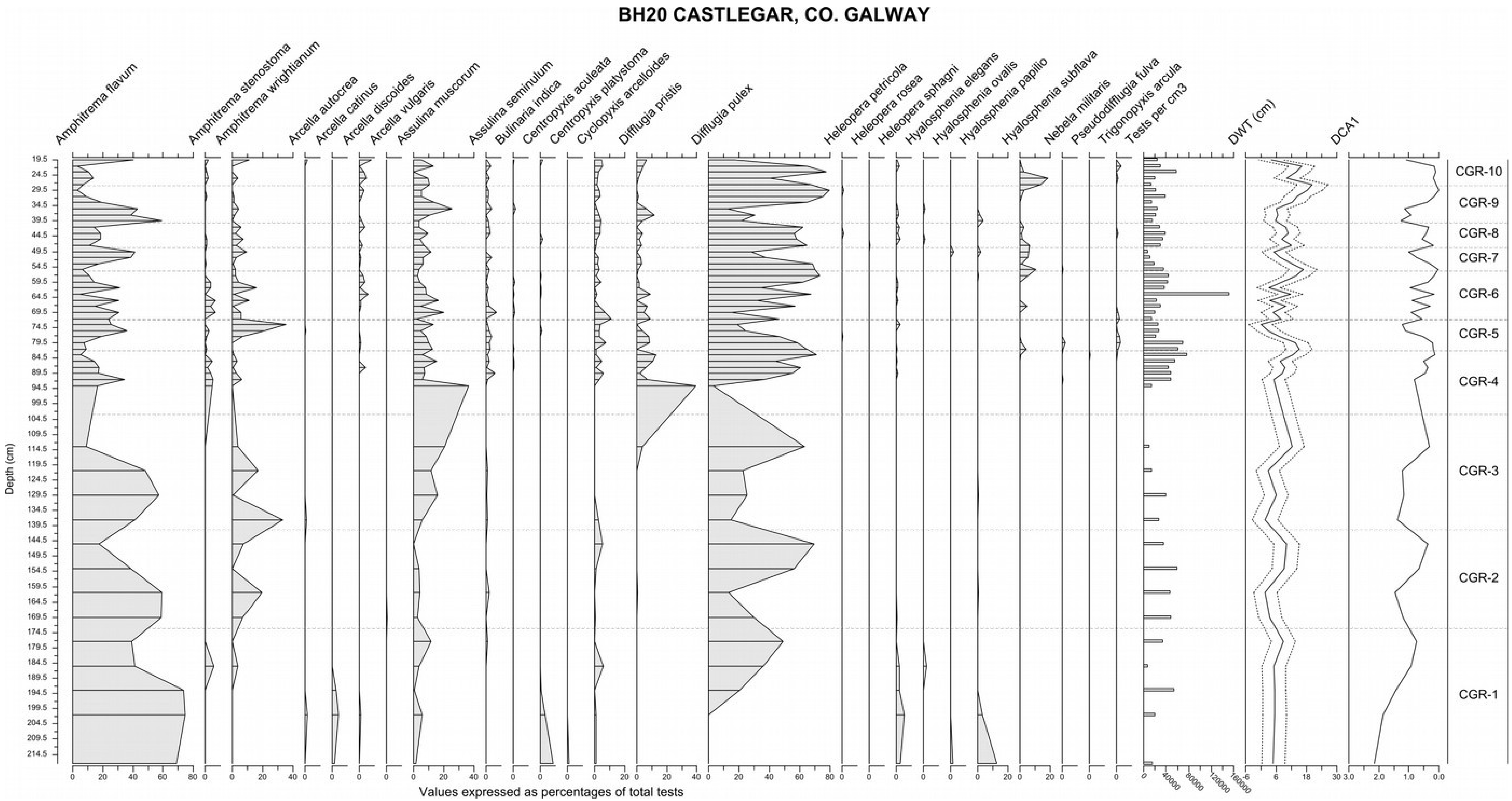

Figure 60: Full testate amoebae diagram from BH20, Castlegar bog, Co. Galway. Values are presented as percentages of the total test count. Reconstructed DWT was calculated using the central Irish transfer function.

7.6 Inchirourke bog, Co. Tipperary

7.6.1 Stratigraphy

A transect of 9 peat depth soundings was carried out using a gouge auger along the length of a single milling bay (c.1000m) running across the area of milled bog in which trackway IRK-PP-1 was excavated. This transect, combined with dGPS survey revealed the form of the basin in which peat had formed at Inchirourke. The maximum depth of peat deposits was *c.* 470cm. The location of BH4 was selected as it contained the deepest peat sequence and was situated *c.* 150m from the trackway.

Table 44: Stratigraphic log BH4, Inchirourke Bog, Co. Tipperary.

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact	Notes
15	0	89	5YR 3/1	$Tb^3 2$ $Th^3 1$ $Tl^3 1$ Sh+	3	sharp	Disturbed
14	89	103	7.5YR 2.5/2	$Th^2 3$ $Tl^2 1$ Tb+ Sh+	3	diffuse	
13	103	116	7.5YR 3/2	$Tb^2 3$ $Tl^2 1$ Th+ Sh+	3	diffuse	
12	116	119	7.5YR 3/3	$Tb^2 3$ $Th^2 1$	2	diffuse	
11	119	179	7.5YR 3/2	$Tb^2 3$ $Th^2 1$ Tl+ Sh+	2	diffuse	
10	179	188	7.5YR 3/2	$Th^2 3$ $Tb^2 1$ Sh+	2	diffuse	
9	188	220	7.5YR 3/1	$Tb^3 4$ Sh+ Tl+	3	diffuse	
8	220	262	7.5YR 2.5/1	$Th^3 2$ $Tb^3 1$ Sh1 Tl+	4	sharp	Fen/bog transition
7	262	271	10YR 3/2	$Th^2 4$ Sh+	3	diffuse	
6	271	440	10YR 2/1	$Th^3 3$ Sh1	4	grading	
5	440	456	10YR 2/1	$Th^3 2$ Sh2 Tl+	4	sharp	
4	456	463	10YR 3/2	$Th^2 3$ Sh1	3	diffuse	*Phragmites*
3	463	466	10YR 4/2	$Th^3 1$ Sh1 Ld1 Lc1	3	grading	Molluscs
2	466	480	10YR 6/2	Ld1 Lc3	---	diffuse	
1	480	490	10YR 7/2	Lc4	---	---	Fine laminae

Figure 61 shows the stratigraphic log from BH4, whilst full Troels-Smith sediment descriptions are given in Table 44. The sequence obtained from BH4 was 490cm deep. The bottom 27cm was composed of laminated calcareous lake sediments, including frequent mollusc inclusions (Units 1-3). The lacustrine sediments graded upwards into a unit of *Phragmites* peat 7cm thick (Unit 4). Unit 4 was overlain by 194cm of generally well-humified fen peat including both herbaceous and woody plant remains (Units 5-7). At 262cm depth was a sharp transition (possibly the fen-bog transition) to a 42cm thick unit of well-humified *Sphagnum-Eriophorum* peat with occasional Ericaceous remains (Unit 8); Unit 8 was overlain by 32cm of moderately-humified *Sphagnum* peat (Unit 9). Above this was 72cm of poorly-humified peat of varying composition (Units 10-12), being initially dominated by herbaceous plants (Unit 10), with increasing *Sphagnum* content from 179cm depth upwards (Units 11 and 12). At 116cm was a transition to a 13cm thick layer of moderately-humified *Sphagnum-Calluna* peat (Unit 13), above which was 15cm of moderately-humified *Eriophorum-Calluna-Sphagnum* peat (Unit 14). The top 89cm of the sequence (Unit 15) was found to consist of re-deposited milled peat, having a very mixed macrofossil content, a loose crumbly texture and a very sharply-defined contact with the *in-situ* peat deposits below. It was subsequently established that this milling bay had previously been covered with a stockpile of milled peat which had recently been removed.

7.6.2 Chronology

Four samples of picked and cleaned above-ground plant macrofossils from the ombrotrophic part of BH4 (262cm to 0cm depth) were submitted for AMS ^{14}C dating. BETA-327615, and BETA-327616 were analysed in Miami, Florida, USA, by Beta Analytic Inc., SUERC-45736 was prepared to graphite at the NERC radiocarbon facility, East Kilbride, and analysed at the SUERC AMS Laboratory, CAMS-164333 was analysed at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, California, USA. Details of these dates are given in Table 45. These dates show a clear increase in age with depth.

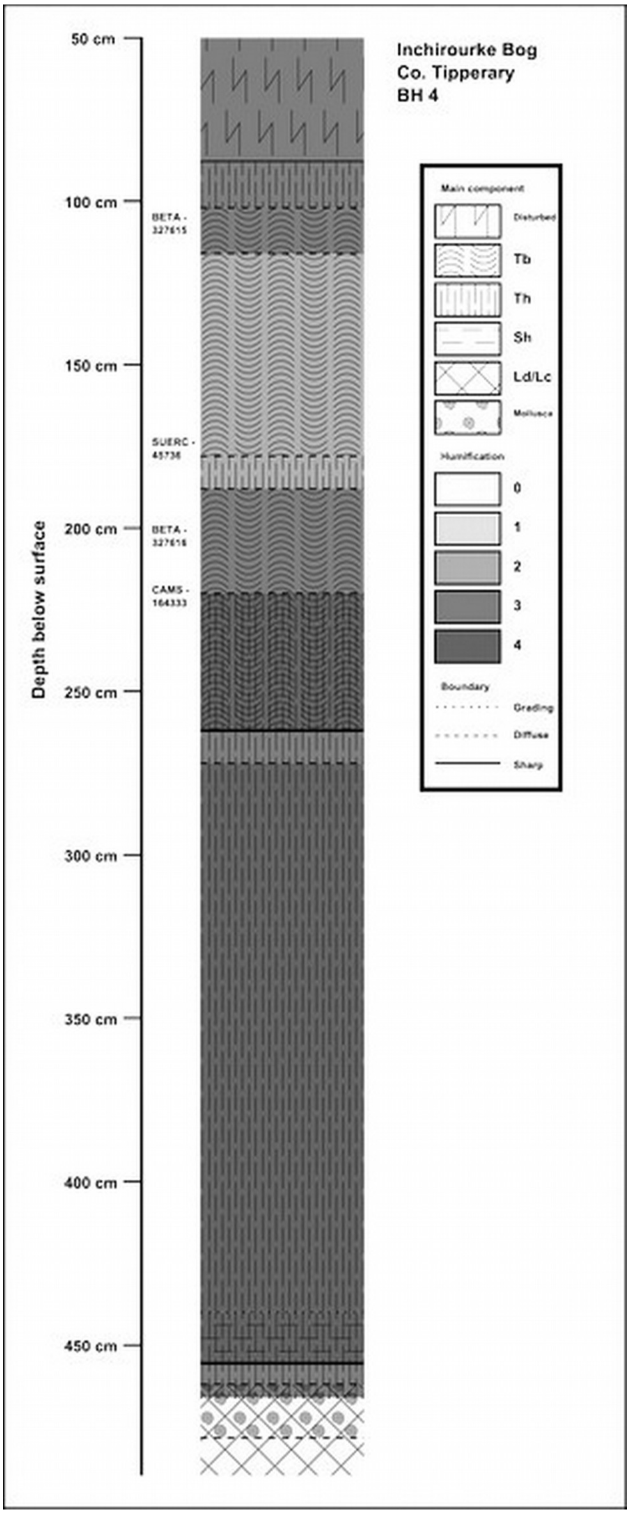

Figure 61: Peat stratigraphy BH4 Inchirourke bog, Co. Tipperary.

Table 45: AMS ^{14}C dates obtained from BH4, Inchirourke bog, Co. Tipperary. Dates were calibrated using the IntCal09 calibration curve (Reimer et al. 2009), and 95% confidence (2σ) intervals were generated using the Clam software package (Blaauw 2010).

Lab code	**Depth (cm)**	**Material dated**	**$^{13}C/^{12}C$ ratio**	**^{14}C date (BP)**	**Calibrated range 2σ (cal BP)**
BETA-327615	105.5	Plant macrofossils	-24.9	1180±30	1180-990
SUERC-45736	174.5	*Sphagnum* macrofossils	-25.8	2491±35	2730-2370
BETA-327616	201.5	Plant macrofossils	-26.3	3110±30	3390-3260
CAMS-164333	218.5	*Sphagnum* macrofossils	-25	3345±40	3690-3450

The four dates from Inchirourke show that the ombrotrophic peat sequence from BH4 covers a large portion of the Late Holocene, with an average accumulation rate of just over 20 years/cm. For comparison multiple age vs depth models from this sequence were created using the Clam (Blaauw 2010) and Bacon (Blaauw and Christen 2011) software packages.

Both linear interpolation and smooth spline 'classical' age vs depth models produced using the Clam software package produced similar results since the distribution of the four dates suggested approximately linear accumulation. The smooth spline age vs depth model (smoothing = 0.3) is shown in Figure 62.

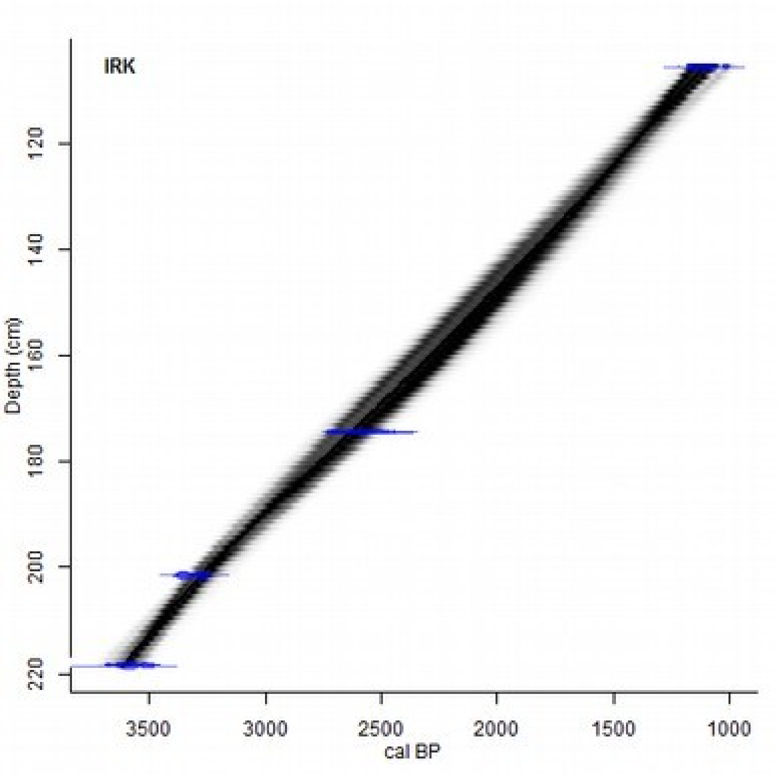

Figure 62: Age vs depth model, based on smooth spline interpolation, from BH4 Inchirourke.

A more flexible age vs depth model was created using Bacon, shown in Figure 63. The resulting model is generally very similar to the linear model, except that it shows greater (and probably more realistic) uncertainty in age in the *c.* 70cm undated section of core between BETA-327615 and SUERC-45736. The age vs depth model produced using Bacon has been used for all further analysis, with point age estimates (prefixed with '*c.*') using the *maximum a posteriori* (MAP) date estimate generated by the software based on several million MCMC runs.

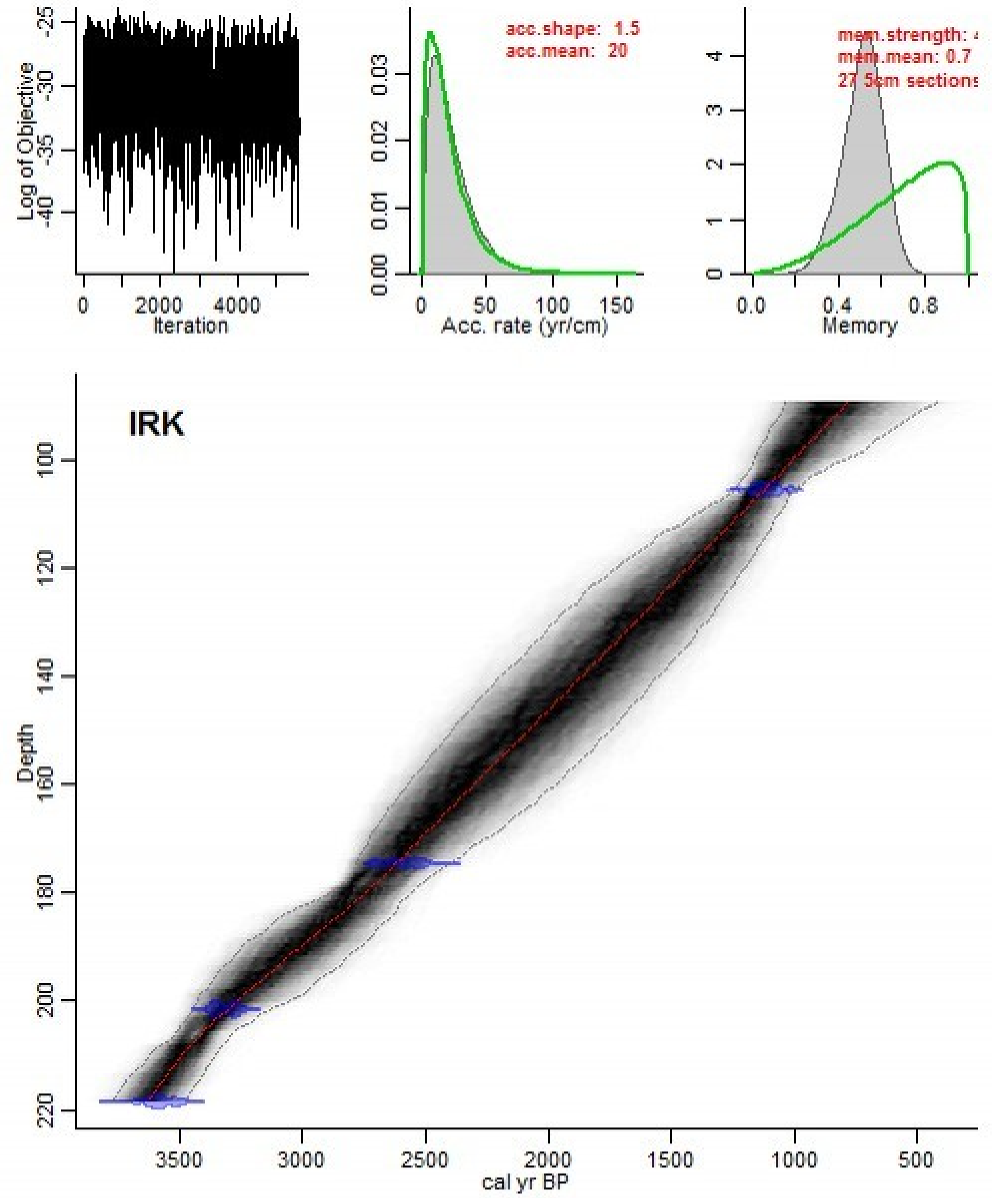

Figure 63: Age vs depth model for BH4 Inchirourke, produced using Bacon. Black dotted lines indicate the 95% confidence intervals of the age vs depth model, red dotted line indicates maximum a posteriori age.

7.6.3 Testate amoebae analysis

Samples for testate amoebae analysis were initially taken every 8cm along BH4. No samples below 257cm yielded counts of 50 tests or more, indicating poor preservation or test concentration in the minerotrophic fen peats. Following initial analysis at 8cm resolution, sampling was increased to 2cm spacing between 161 and 227cm depth. Samples above 89cm depth were excluded from further analysis since these appeared to have been disturbed by milling. In total 47 samples yielded counts of 50 tests or more, of which 40 produced counts of over 100 tests. Samples with fewer than 50 tests were excluded from further analysis. Test concentration was variable throughout the analysed section of the sequence, with no clear relationship between lithostratigraphy and concentration, other than the poor preservation of tests in the fen.

Figure 64 shows the full testate amoebae diagram fro BH4, Inchirourke bog. Values are expressed as percentages of the total test count. In addition to the total test, loricae of the Bdelloid rotifer *Habrotrocha angusticollis* and fragments of Cladoceran carapace were also counted, estimated minimum numbers of individuals (estimated using exotic *Lycopodium* spore spike) are presented as bars in the diagram. DWT values in cm (reconstructed using the central Irish transfer function, see Chapter 6, with sample-specific errors generated through 1000 bootstrap cycles) are shown on the right hand side of the diagram, along with DCA Axis 1 (eigenvalue 0.1753) sample scores. See Appendix 1 for DCA ordination diagrams. DWT values and DCA Axis 1 scores are highly correlated ($r = 0.89$), suggesting that the main axis of variation in the species data is strongly related hydrology. DWT values range from 1.9cm to 20cm (mean DWT = 10cm), representing a wide range of hydrological conditions. For the purposes of the following discussion of results, the testate amoebae diagram has been divided into assemblage zones based on a visual assessment of the data. A total of 22 testate amoebae taxa are present in this sequence, most samples being dominated by *Difflugia pulex*. Diversity indices show variability throughout the sequence, R values range between 4 and 11 (mean $R = 8.5$ species per sample), H' values range between 0.8 and 1.9 (mean $H' = 1.4$), and D ranges between 0.32 and 0.82 (mean $D = 0.65$).

IRK-1 (*Difflugia pulex – Amphitrema flavum*) 257 to 220cm depth (before *c.* 3630 cal BP): this zone is characterised by generally high levels of *Difflugia pulex* (~50%), whilst *Amphitrema flavum* generally declines from *c.* 50% to *c.* 5%. Other taxa present include *Hyalosphenia subflava* which increases throughout this zone to a maximum of 19%, *Assulina muscorum* (max. 19%) and *Arcella discoides* (max. 14%). DWT values generally rise through this zone from 2cm (wet conditions) to 14cm (dry) at the top of this zone, interrupted by a slight shift towards moister conditions at 225cm depth.

IRK-2 (*Amphitrema flavum – Amphitrema wrightianum*) 220 to 216cm depth (from before *c.* 3630 cal BP to *c.* 3590 cal BP): *Amphitrema flavum* and *A. wrightianum* peak sharply in this zone (max. 82% and 14%, respectively), whilst abundances of *Difflugia pulex* and *Hyalosphenia subflava* drop. DWT values fall to 3.8cm in this zone, indicating a shift to moderately wet conditions.

IRK-3 (*Difflugia pulex – Hyalosphenia subflava*) 216 to 198cm depth (from *c.* 3590 to *c.* 3230 cal BP): *Difflugia pulex* dominated this zone (max. 66%), but falls slightly throughout this zone (to *c.* 40%). *Hyalosphenia subflava* is present throughout this zone and peaks in the middle of this zone with maximum abundance of 40%. *Difflugia pristis, Assulina* spp., *Arcella discoides,* and *Amphitrema wrightianum* are all present throughout this zone, but in low abundances (less than 10%). *Amphitrema flavum* is present throughout this zone in variable abundances (between 3% and 32%). DWT values are variable, but generally around 7cm to 12cm – indicating moderately-dry or dry conditions, with water tables falling to a maximum of 20cm below the surface in the centre of this zone. The Bdelloid rotifer, *Habrotrocha angusticollis* peaks in abundance in this zone, supporting the interpretation of moderately dry conditions in this zone.

IRK-4 (*Amphitrema flavum – Difflugia pulex – Hyalosphenia subflava*) 198 to 190cm depth (*c.* 3230 to *c.* 3020 cal BP): *Amphitrema flavum* increases to a maximum of 42% in this zone, *A. wrightianum* is present in low abundances but also increases in this zone (up to 10%). *Difflugia pulex* drops to a minimum of 23%, abundances of *Hyalosphenia subflava* are constant at *c.* 15%. The DWT curve shows a rise in water tables to 6cm in this zone – indicating a return to moderate or moderately wet conditions.

IRK-5 (*Difflugia pulex – Hyalosphenia subflava*) 190 to 182cm depth (*c.* 3020 to *c.* 2810 cal BP): the dry indicators *Difflugia pulex* and *Hyalosphenia subflava* return to dominance in this zone (max. 62% and 23%, respectively), but drop sharply at the top of this zone, *Assulina muscorum* (indicative of moderate conditions) briefly increases, then decreases and is replaced by the moderately wet indicator *Difflugia pristis* (which peaks at 10%). DWT reaches 14cm in the middle of this zone, indicating dry conditions, but drops sharply at the top of this zone to 6cm indicating a brief shift to moderately wet conditions. This wet shift is accompanied by a sharp peak in the abundances of cladoceran remains.

IRK-6 (*Difflugia pulex – Amphitrema flavum – Assulina muscorum – Arcella discoides*) 182 to 170cm depth (*c.* 2810 to *c.* 2530 cal BP): *Difflugia pulex* rises sharply up to 75% in the middle of this zone, before falling again to 38% at the top of this zone, replaced partly by an increase in *Amphitrema flavum* (max. 30%). *Assulina muscorum* and *Arcella discoides* are both present in abundances of 10-15%. DWT rises again to *c.* 13cm (a return to dry conditions) before falling again to 6cm at the top of this zone.

IRK-7 (*Difflugia pulex – Amphitrema flavum – Hyalosphenia subflava*) 170 to 125cm depth (*c.* 2530 to *c.* 1500 cal BP): abundances of *Difflugia pulex* rise again to a maximum of *c.* 60%, and *Hyalosphenia subflava* rapidly returns to abundances of *c.* 15-20%. *Amphitrema flavum* declines slightly to around 20%. DWT rises at the base of this zone to remain relatively stable at around 14cm, suggesting a return to dry or moderately dry conditions.

IRK-8 (*Difflugia pulex – Amphitrema flavum*) 125 to 89cm (*c.* 1500 to *c.* 780 cal BP): *Amphitrema flavum* rises sharply to 46% at the base of this zone before steadily declining; following an initial drop in abundance, *Difflugia pulex* rises to over 60%. The DWT curve shows a drop of DWT to 2cm at the base of this sequence, indicating a wet shift, this is followed by a gradual and steady rise in DWT to 16cm – indicating a gradual return to dry conditions to the top of this sequence.

7.6.4 Summary

Reconstructed water tables from BH4 Inchirourke show mostly dry or moderately dry conditions punctuated by occasional shifts to wet or moderately wet conditions, indicated by declines in the dry indicators *Difflugia pulex* and *Hyalosphenia subflava* in favour of increases in *Amphitrema* spp. and, to a lesser extent, *Arcella discoides.* These shifts to increased moisture availability occur at *c.* 3630 cal BP, *c.* 3230 cal BP, *c.* 2810 cal BP, *c.* 2600 cal BP, and at *c.* 1450 cal BP.

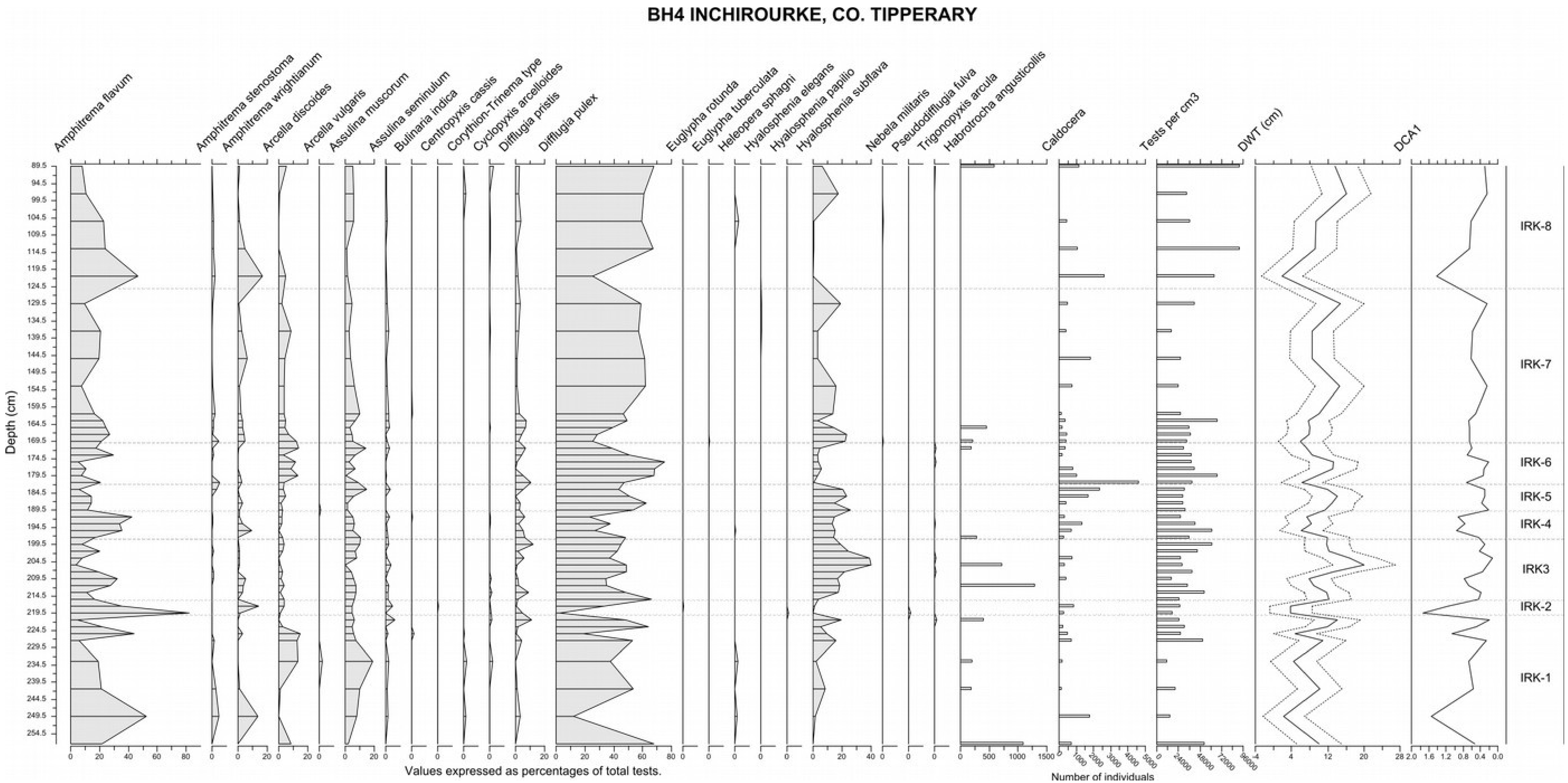

Figure 64: Full testate amoebae diagram from BH4, Inchirourke bog, Co. Tipperary. Values are presented as percentages of the total test count. Reconstructed DWT was calculated using the central Irish transfer function.

7.7 Longfordpass bog, Co. Tipperary

Fieldwork on Longfordpass bog was carried out in summer 2010. Results of preliminary analyses are given in Young et al. (2011b).

7.7.1 Stratigraphy

Due to the extent of drainage and compression in much of the milled area of Longfordpass, few boreholes could be extracted to the base of the peat sequence, therefore a full stratigraphic transect could not be carried out. The location for the master sequence (BH2) was therefore selected on the basis of being close to the apparent centre of the bog and between 100 and 200m of any known archaeological structures.

Table 46: Peat stratigraphic log BH2, Longfordpass, Co. Tipperary.

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact	Notes
–-	0	9	---	VOID	---	---	
31	9	62	7.5YR 2.5/2	$Tb^3$3 Sh1 Th+	3	sharp	Disturbed
30	62	67	10YR 4/6	$Tb^0$4	0	diffuse	*Sphagnum*
29	67	72	7.5YR 3/3	$Tb^2$4 Th+ Sh+	2	diffuse	
28	72	91	7.5YR 2.5/3	$Tb^2$3 $Th^2$1 Sh+	2	diffuse	
27	91	113	7.5YR 3/4	$Tb^1$4 Th+ Tl+	1	diffuse	
26	113	124	7.5YR 2.5/1	$Tb^3$1 $Th^1$2 Sh1 Tl+	3	diffuse	
25	124	138	7.5YR 3/4	$Tb^1$4 Sh+ Tl+	1	diffuse	
24	138	147	7.5YR 2.5/1	$Th^2$1 $Tb^3$2 Sh1 Tl+	3	diffuse	
23	147	168	7.5YR 2.5/3	$Tb^2$3 $Tl^2$1	2	diffuse	
22	168	194	7.5YR 2.5/2	Sh1 $Tb^2$3 Tl+	2	diffuse	
21	194	198	7.5YR 2.5/2	$Th^1$4 Sh+	1	diffuse	E. vaginatum
20	198	213	7.5YR 2.5/3	Sh1 $Tb^3$1 $Th^2$2	2	diffuse	

19	213	253	7.5YR 2.5/3	$Tb^3$2 $Th^2$1 $Tl^2$1 Sh+	3	diffuse	
18	253	266	7.5YR 2.5/1	$Tb^2$1 $Th^3$2 Sh1	3	diffuse	
17	266	280	7.5YR 2.5/2	Sh1 $Th^3$3 Tl+	3	diffuse	
16	280	289	7.5YR 2.5/3	Sh1 $Tb^3$1 $Th^2$2	3	diffuse	
15	289	297	10YR 2/1	Sh2 $Th^3$2 Tl+	3	diffuse	
14	297	304	7.5YR 2.5/3	$Tl^2$1 $Th^1$3	2	diffuse	
13	304	322	10YR 2/1	$Tl^2$1 $Th^2$3	2	diffuse	
12	322	332	7.5YR 3/3	$Tl^2$1 $Th^2$2 $Tb^3$1 Sh+	2	diffuse	
11	332	350	10YR 2/1	$Th^2$4 Sh+	2	diffuse	
10	350	360	10YR 2/1	Sh3 $Th^3$1 Tl+	4	diffuse	
9	360	366	7.5YR 2.5/2	$Tb^3$1 $Th^3$1 Sh2 Tl+	3	diffuse	
8	366	387	10YR 2/1	$Th^3$2 $Tl^2$1 Sh1	3	diffuse	
7	387	400	10YR 2/1	$Th^4$2 Sh2	4	diffuse	
6	400	408	7.5YR 2.5/3	$Tb^2$3 Sh1	2	diffuse	NOT *Sphagnum*
5	408	419	10YR 2/2	$Th^3$3 Sh1	3	diffuse	
4	419	435	10YR 2/1	Sh3 $Th^4$1	4	diffuse	
3	435	438	10YR 3/2	$Ld^2$2 $Th^4$1 Sh1	3	diffuse	Molluscs
2	438	442	2.5Y 5/3	Lc2 $Ld^1$1 $Th^1$1	1	diffuse	Molluscs, fine laminae
1	442	450	2.5Y 6/3	Lc3 $Ld^1$1 As+	---	---	

The sequence from BH2 (see Figure 65), Longfordpass bog, was 459cm deep. The full peat stratigraphic log is given in Table 46. The bottom 15cm of the sequence consisted of 15cm of laminated calcareous lake sediments (Units 1, 2 and 3). The lacustrine sediments had a diffuse boundary to the organic sediments above; these consisted of 27cm of well-humified herbaceous peat Units 4 and 5). These were overlain by an 8cm thick band of (non-*Sphagnum*) moss peat (Unit 6), which in turn was overlain by another 13cm of well-humified herbaceous fen peat (Unit 7). Above this was 21cm of humified herbaceous peat with woody remains (Unit 8). This was in turn overlain by 168cm of peat of variable humification (mostly well-humified) composed mainly of herbaceous remains, with some *Sphagnum* and some

Ericaceous material (Units 9-20). At 198cm a 4cm thick band of poorly-humified *Eriophorum vaginatum* peat (Unit 21) gave way to a succession of deposits of generally poorly-humified *Sphagnum*-rich peat up to the top of the sequence at 62cm depth (Units 22-30), of which the upper 5cm were of very fresh *Sphagnum* with fully articulated branches and stems (Unit 30). Above 62cm depth was peat of mixed composition (Unit 31), with a very friable texture indicating that this was re-deposited milled peat.

The post AD 1950 date obtained from 63.5cm depth (see next section) suggests that the sequence from BH2, Longfordpass has in fact not been significantly truncated. The large amount of re-deposited peat overlying the *in-situ* peat deposits are due to the fact that a milled peat stockpile had only recently been removed from the milling bay in which coring had been carried out; these stockpiles can often be in place for several years, and may have been in place since Longfordpass went into peat production in the last 20 years. This may account both for the compression which prevented the stratigraphic transect being carried out, and for the apparent lack of truncation of the peat sequence from BH2.

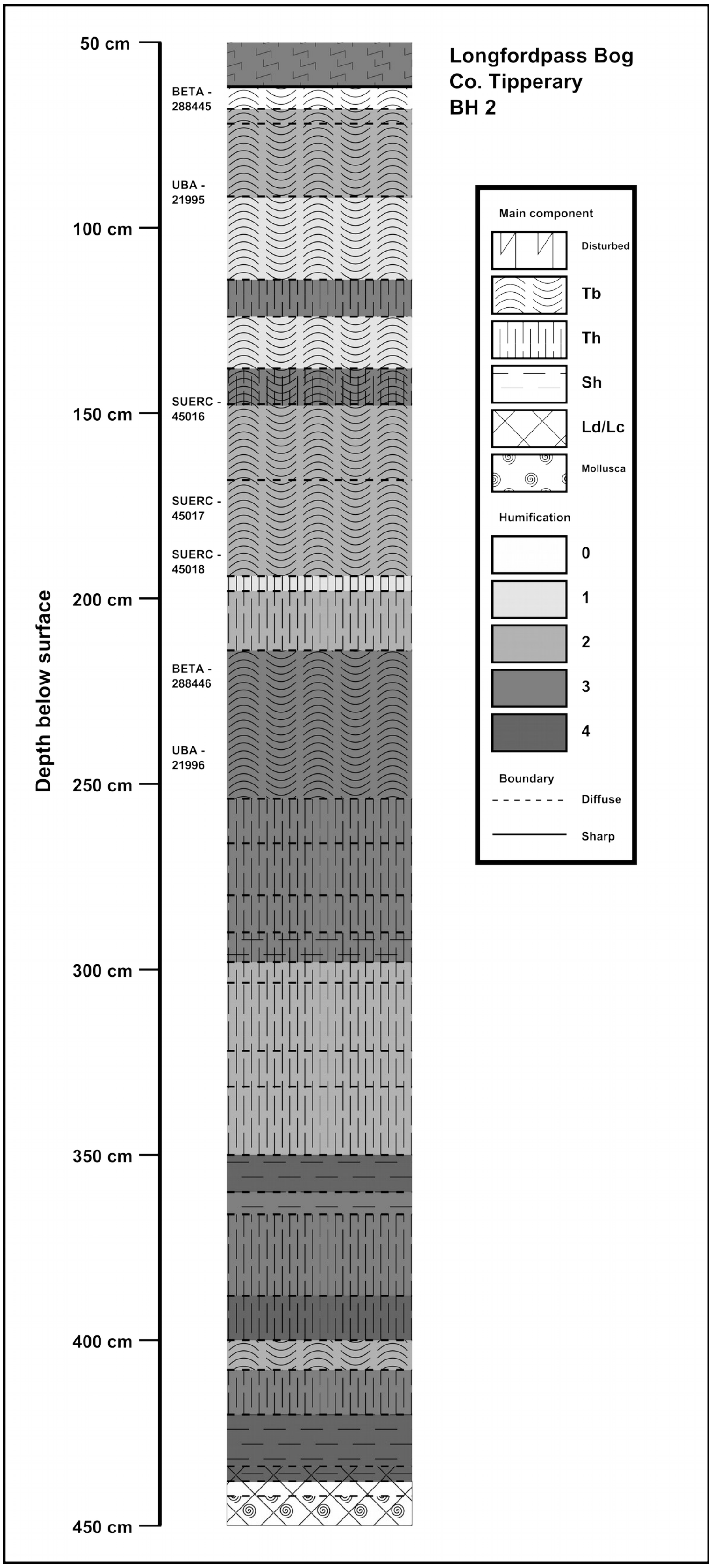

Figure 65: Peat stratigraphy BH2 Longfordpass bog, Co. Tipperary.

7.7.2 Chronology

Seven samples of picked and cleaned above-ground plant macrofossils (all *Sphagnum* leaves and branches) from the ombrotrophic part of BH2 were submitted for AMS ^{14}C dating. BETA-288445, and BETA-288446 were analysed in Miami, Florida, USA, by Beta Analytic Inc., SUERC-45016, SUERC-45017, and SUERC-45018 were prepared to graphite at the NERC radiocarbon facility, East Kilbride, and analysed at the SUERC AMS Laboratory, whilst UBA-21995 and UBA-21996 were analysed at the 14CHRONO centre, Belfast. Details of these dates are given in Table 47. These dates generally show a clear increase in age with depth, except that SUERC-45016 and SUERC-45017 are statistically indistinguishable; this is likely to be due to the presence of a significant plateau in the radiocarbon calibration curve at around 2450 BP. BETA-288445 is reported in the table below in F14C notation as it return a 'post-modern' date, this was calibrated using the NH1 post-bomb calibration curve (Hua and Barbetti 2004).

Table 47: AMS ^{14}C dates obtained from BH2, Longfordpass bog, Co. Tipperary. Dates were calibrated using the IntCal09 calibration curve (Reimer et al. 2009) and the NH1 post-bomb calibration curve (Hua and Barbetti 2004), and 95% confidence (2σ) intervals were generated using the Clam software package (Blaauw 2010).

Lab code	Depth (cm)	Material dated	$^{13}C/^{12}C$ ratio	^{14}C date (BP)	Calibrated range 2σ (cal BP)
BETA-288445	63.5	Plant macrofossils	-27.1	1.267±0.005 F14C*	-10 – 30 (AD 1959-1982)
UBA-21995	88.5	*Sphagnum* macrofossils	-25.9	1115±37	1170-940
SUERC-45016	147.5	*Sphagnum* macrofossils	-26.5	2471±35	2710-2370
SUERC-45017	175.5	*Sphagnum* macrofossils	-27.2	2469±35	2710-2360
SUERC-45018	188.5	*Sphagnum* macrofossils	-26.2	2965±35	3250-3010
BETA-288446	219.5	Plant macrofossils	-28.6	3730±40	4230-3940
UBA-21996	240.5	*Sphagnum* macrofossils	-25.6	3923±39	4510-4240

The ^{14}C dates from Longfordpass show that the ombrotrophic peat sequence from BH2 spans most, if not all of the Late Holocene up to the modern era, with an average accumulation rate of *c.* 25 years/cm. For comparison multiple age vs depth models from this sequence were created using the Clam (Blaauw 2010) and Bacon (Blaauw & Christen 2011) software packages.

'Classical' age vs depth models for the BH2 sequence were generated using Clam. Linear models performed poorly in dealing with the similarity of SUERC-45016 and SUERC-45017, and often produced inversions in the age vs depth relationship. The smooth spline model, was however found to give acceptable results. This model is illustrated in Figure 66. This model assumes that changes in accumulation rate would be gradual and smooth, and as such shows an increase in accumulation rate from *c.* 175cm to *c.* 120cm depth, which is plausible since the sedimentary logs (see above) show a change to poorly-humified *Sphagnum* peat between 168 and 124cm depth.

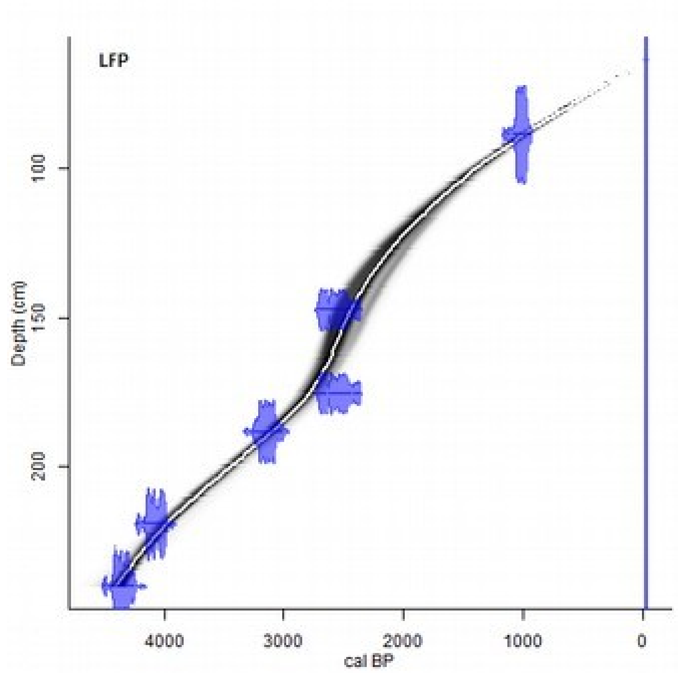

Figure 66: Smooth spline age vs depth model for BH2, Longfordpass bog.

For comparison, age vs depth models were created using Bacon, which employs a more flexible Bayesian approach. This model is shown in Figure 67. This model did indeed give similar results to the smooth spline model, illustrating that this model is more or less robust. However, the Bacon model presents a number of improvements: whilst uncertainties at the 95% confidence interval were larger (and probably more realistic) in less-densely dated sections of the sequence (e.g. between 147 and 88cm), the Bayesian approach utilised by Bacon allowed for greatly reduced uncertainties between *c.* 140 and 170cm depth where the gap between dated levels was smaller; in addition, this part of the sequence was analysed in greater detail since this was thought to relate chronologically to the archaeological remains at Longfordpass, thus reduced chronological uncertainty is highly desirable. The age vs depth model produced using Bacon has been used for all further analysis, with point age estimates (prefixed with '*c.*') using the *maximum a posteriori* (MAP) date estimate generated by the software based on several million MCMC runs.

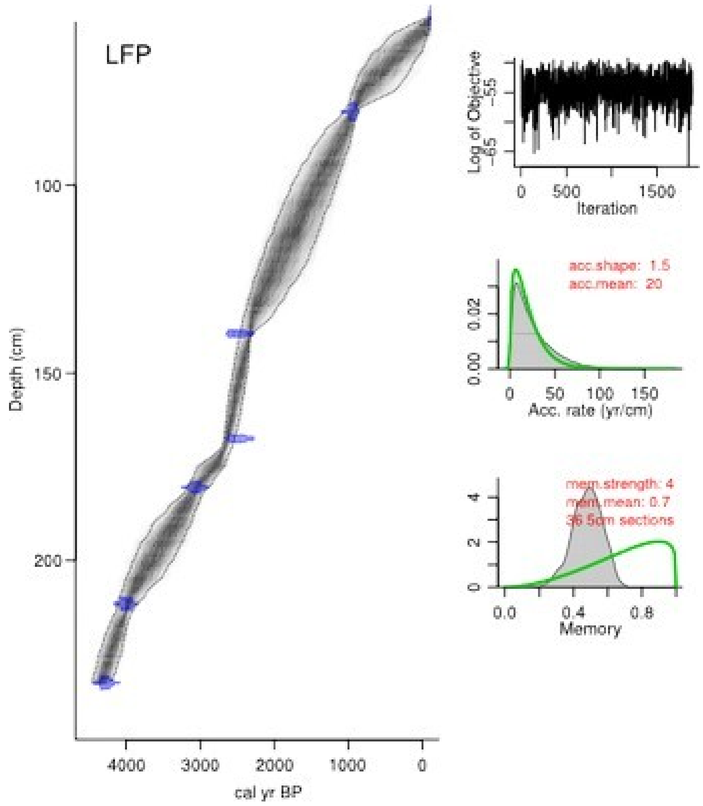

Figure 67: Age vs depth model for BH2 Longfordpass, produced using Bacon. Dotted lines indicate the 95% confidence intervals of the age vs depth model.

7.7.3 Humification

30 samples, at 8cm spacing between 64 and 296cm depth, were analysed from BH2, Longfordpass. The humification data, shown in Figure 68, shows considerable of variability (absorbance between 33% and 67%, mean = 52%). A LOWESS smooth line (span 0.2) shows a general trend towards decreasing humification up-core throughout the ombrotrophic part of the sequence - suggesting gradually increased moisture availability during the Late Holocene, with a notable dip in absorbance values (suggesting a wet shift) at *c.* 240cm depth (*c.* 4400 cal BP), and at *c.* 168cm depth (*c.* 2570 cal BP), with a step change to decreased humification

from 104cm depth *(c.* 1400 cal BP).

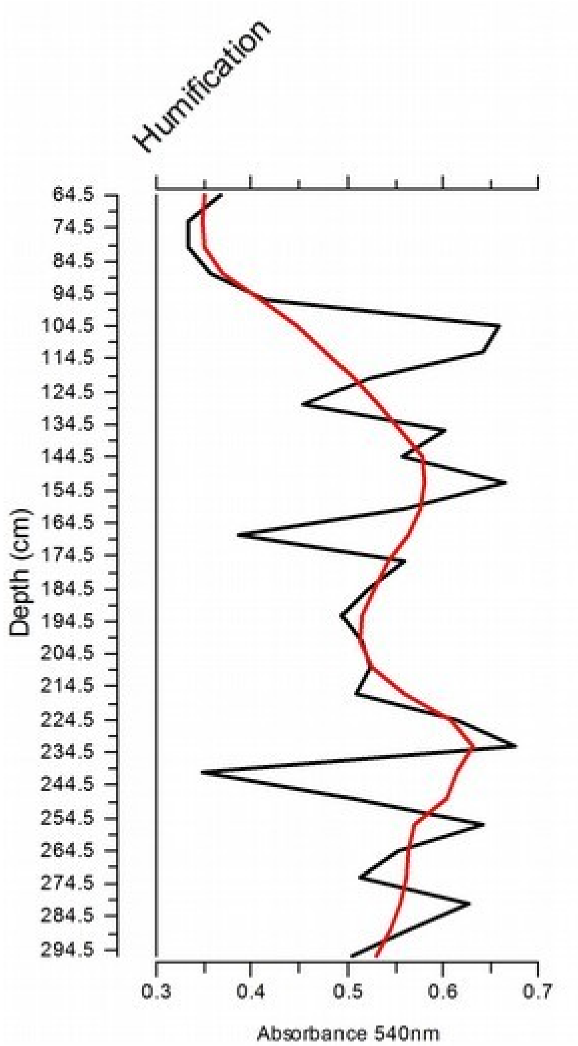

Figure 68: Humification curve (black line) from BH2 Longfordpass, red line shows a LOWESS smooth line (span 0.2).

7.7.4 Testate amoebae analysis

Samples for testate amoebae analysis were initially taken every 8cm along BH4. No samples below 296cm depth yielded counts of 50 tests or more, indicating poor preservation of tests in the minerotrophic fen peats. After initial analysis at 8cm resolution, sample spacing was increased to 2cm between 200cm and 136cm depth. Samples above 62cm depth were excluded from analysis since these were taken from re-worked peat deposits. In total, 53 samples yielded counts of 50 tests or more, of which 39 samples yielded counts of 150 tests or more. Samples with fewer than 50 tests were excluded from further analysis. Test concentration was generally variable, with no obvious correlation between concentration and lithostratigraphy.

Figure 69 shows the full testate amoebae diagram from BH2, Longfordpass bog. Values are expressed as percentages of the total test count. DWT values in cm (reconstructed using the central Irish transfer function, see Chapter 6), are shown on the right hand side of the diagram. Sample-specific errors (generated using 1000 bootstrap cycles) are shown in dotted lines. Also on the right hand side of the diagram are DCA Axis 1 (eigenvalue 0.3745) sample scores, ordination diagrams are given in Appendix 1. DCA Axis 1 scores are strongly correlated with DWT values ($r = 0.94$), showing that the main axis of variation in the species data from Longfordpass is strongly related to hydrology. DWT values range from -1cm to 14cm (mean DWT = 5.6cm). The testate amoebae diagram has been divided into assemblage zones on the basis of visual examination. A total of 29 testate amoebae taxa are present in the samples from BH2, with assemblages generally dominated by either *Amphitrema* spp. or *Difflugia pulex*. Diversity indices vary throughout the sequence, R ranges from 4 to 14 (mean $R = 8$ taxa), H' ranges from 0.3 to 2.1 (mean $H' = 1.3$), and D ranged from 0.15 to 0.84 (mean $D = 0.62$). All diversity indices show decreased diversity towards the base of the sequence, and markedly increased diversity at the top (72cm to 64cm depth).

LFP-1 (***Amphitrema flavum*** **–** *Difflugia pulex – Assulina muscorum*) 296 to 236cm depth (from before *c.* 4400 to *c.* 4350 cal BP): this zone is overwhelmingly dominated by *Amphitrema flavum* (min. 55%, max. 92%). *Difflugia pulex* is present in variable amounts (max. 25%), as is *Assulina muscorum* (max. 17%). *Heleopera petricola* and *Arcella catinus* have their only occurrences at the base of this zone. DWT values indicate generally moderate conditions throughout this zone (max. 6.6cm, min. 3.6cm).

LFP-2 (*Amphitrema flavum – Assulina muscorum – Amphitrema wrightianum*) 236 to 195cm depth (from *c.* 4350 to *c.* 3350 cal BP): values of *Amphitrema flavum* remain high in this zone (max. 75%), whilst *Assulina muscorum* increases to a maximum of 30% at the base of this zone, declining to 5%. Values of *Difflugia pulex* are low in this zone (max. 5%). *Amphitrema wrightianum* rises to a maximum of 27% in this zone. DWT values are relatively constant throughout this zone with a general trend towards wetter conditions reaching a minimum of 0.7cm at the top of the zone.

LFP-3 (*Amphitrema flavum – Assulina muscorum – Difflugia pulex – Difflugia pristis*) 195 to 179cm depth (*c.* 3350 to *c.* 2790 cal BP): *Difflugia pulex* and *Assulina muscorum* initially dominate (maximum 38 and 46%, respectively) this zone, but decline and are replaced by *Difflugia pristis* (max. 29%). *Amphitrema flavum* is present in variable amounts throughout this zone (max. 64%). *Amphitrema wrightianum* increases to 17% near the top of this zone. DWT values initially rise to ~7cm (moderate to moderately-dry), before falling to ~3cm at 186cm depth (*c.* 3050 cal BP), marking a shift to wet conditions.

LFP-4 (***Difflugia pulex*** – *Amphitrema flavum – Assulina muscorum*) 179 to 141cm depth (*c.* 2790 to *c.* 2300 cal BP): this zone is characterised by high values of *Difflugia pulex* (max. 72%), with variable levels of *Amphitrema flavum* (max. 60%, but generally ~25-30%). *Assulina muscorum*, *Difflugia pristis,* and *Arcella discoides* are present throughout this zone. DWT values show marked variability in this zone, but are generally above the mean (max. 14cm), indicating dry (but variable) conditions, there is a shift to wetter conditions between 176 and 168cm depth (*c.* 2720 to *c.* 2640 cal BP).

LFP-5 (*Amphitrema flavum – Amphitrema wrightianum*) 141 to 132cm depth (*c.* 2300 to *c.* 2080 cal BP): this zone is characterised by a marked increase in *Amphitrema flavum* (max. 69%) and *Amphitrema wrightianum* (max. 18%). *Difflugia pulex* declines steeply in this zone, as do *Assulina muscorum* and *Difflugia pristis*. DWT values drop sharply to 1cm, indicating a shift to wet conditions.

LFP-6 (*Difflugia pulex - Amphitrema flavum - Assulina muscorum - Amphitrema wrightianum*) 132 to 108cm depth (*c.* 2080 to *c.* 1530 cal BP): *Difflugia pulex* initially increases to 41% before declining in this zone. *Amphitrema flavum* values are initially low, but increase to 54%. *Amphitrema wrightianum* and *Assulina muscorum* are present throughout this zone (both taxa reaching a maximum of 16%). DWT values initially indicate moderate conditions (DWT = ~6cm), but gradually fall through this zone to 1.6cm, indicating a steady increase in BSW.

LFP-7 (*Amphitrema flavum – Amphitrema wrightianum*) 108 to 64cm depth (*c.* 1530 to *c.* -6 cal BP): *Amphitrema flavum* and *Amphitrema wrightianum* dominate this zone (max. 77% and 38%, respectively). *Difflugia pulex* and *Assulina muscorum* are present in low values throughout this zone. DWT values are generally around 1cm, indicating consistently wet conditions in this zone.

7.7.5 Summary

Testate amoebae-derived DWT values indicate generally moderately to moderately-wet conditions throughout the sequence at Longfordpass, with only a few large sudden changes in

BSW. These rare, potentially abrupt, shifts towards wet conditions occur at 186cm, 176cm, and 136cm depth – at *c.* 3050 cal BP, *c.* 2720 cal BP, and at *c.* 2180 cal BP. The two later wet shifts are also reflected in the humification data, possibly showing a slightly lagged response, although this is difficult to demonstrate given the low sampling resolution of the humification analysis. Following soon after the wet shift at *c.* 2720 cal BP, the peat stratigraphic record shows a switch to greater dominance of *Sphagnum* moss, which in turn appears to be associated with an increase in peat accumulation rate, at this time DWT values increase, indicating drier conditions. It may be that this increase in DWT is a result of the increased peat accumulation rate rather than allogenic climate forcing *per se*, although this increase in accumulation rate appears to be a consequence of a sharp increase in BSW. Swindles et al. (2012) describe just such a scenario in a series of modelling experiments.

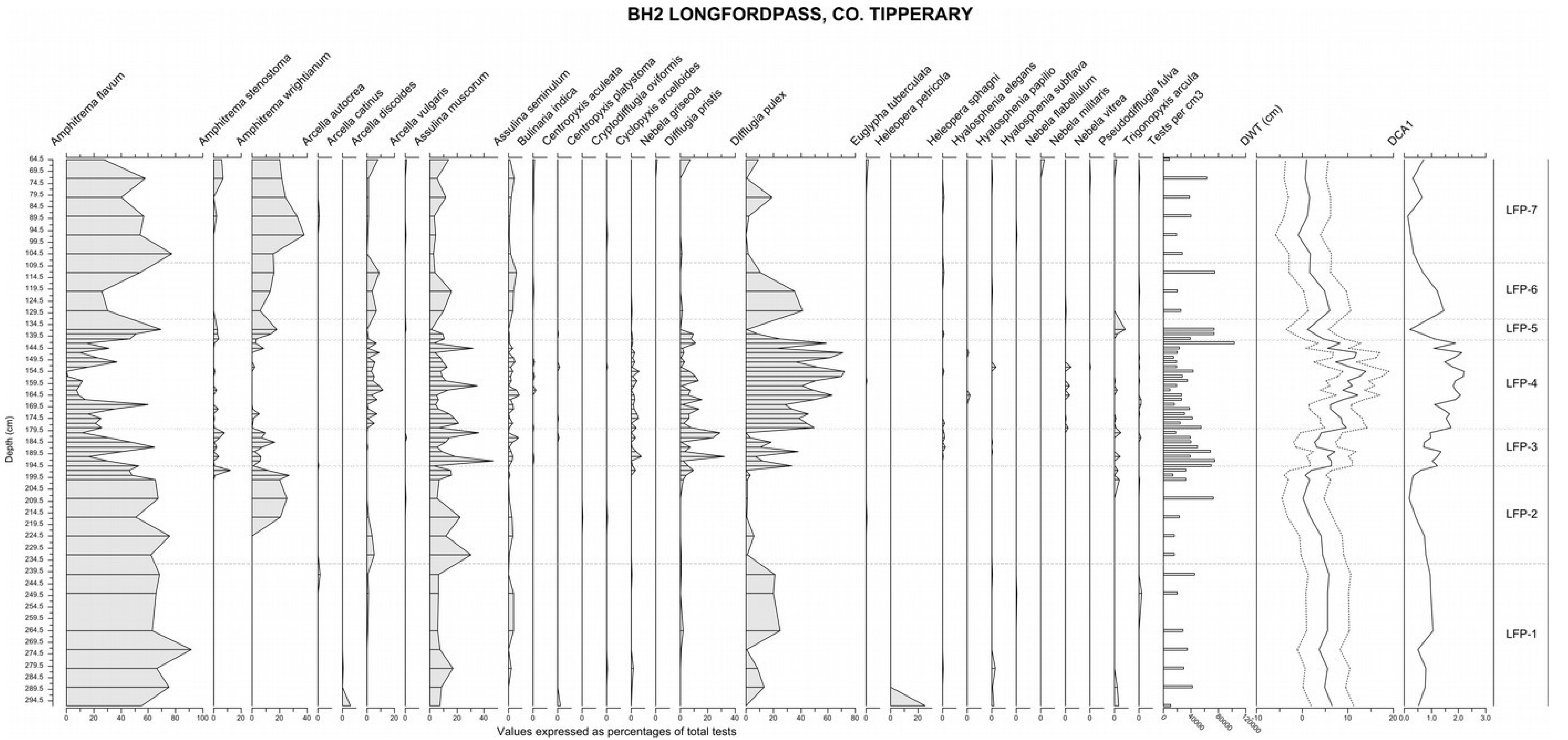

Figure 69: Full testate amoebae diagram from BH2, Longfordpass bog, Co. Tipperary. Values are presented as percentages of the total test count. Reconstructed DWT was calculated using the central Irish transfer function.

7.8 Littleton bog, Co. Tipperary

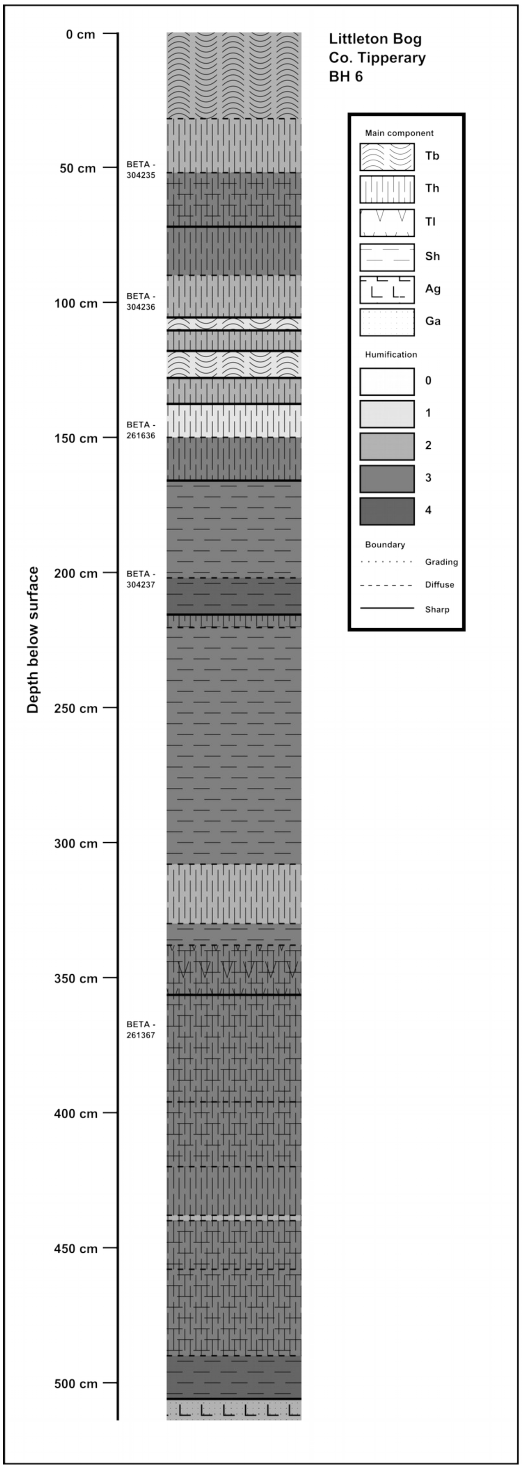

Figure 70: Peat stratigraphy BH6 Littleton Bog, Co Tipperary.

Fieldwork at Littleton bog was carried out in 2008. The results of plant macrofossil, pollen, and coleopteran analyses from other borehole sequences are given in Branch et al. (2009). The sequence analysed here, BH6, was first described and analysed (plant macrofossils and humification analysis) by McCarroll (2009).

7.8.1 Stratigraphy

The core sequence from BH6 was described by McCarroll (2009), therefore only a brief synopsis is given here. The full Troels-Smith sedimentary log is reproduced in Table 48.

Table 48: Stratigraphic log BH6 Littleton Bog, Co. Tipperary, after McCarroll (2009).

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact	Notes
26	0	32	2.5YR 2.5/1	$Tb^2 3$ $Th^3 1$	2	diffuse	
25	32	52	2.5YR 2.5/1	$Th^2 2$ $Tb^2 1$ $Tl^2 1$	2	diffuse	
24	52	72	2.5YR 2.5/1	$Th^3 2$ Sh2	3	sharp	
23	72	90	2.5YR 3/1	$Th^3 3$ Sh1	3	diffuse	
22	90	106	2.5YR 2.5/1	$Th^2 3$ Sh1	2	sharp	
21	106	109	2.5YR 2.5/2	$Tb^1 3$ $Th^1 1$	1	sharp	
20	109	118	2.5YR 2.5/1	$Th^2 3$ Sh1	2	sharp	
19	118	127	2.5YR 2.5/2	$Tb^1 3$ $Th^1 1$	1	sharp	
18	127	137	2.5YR 3/1	$Th^2 3$ Sh1	2	sharp	
17	137	150	2.5YR 2.5/1	$Th^1 4$ Sh+	1	diffuse	
16	150	166	2.5YR 2.5/1	$Th^3 3$ $Tb^2 1$	3	sharp	
15	166	202	2.5YR 2.5/1	Sh3 $Th^3 1$ $Tl^1 +$	3	diffuse	
14	202	215	2.5YR 2.5/1	Sh4 Th+	4	sharp	
13	215	220	2.5YR 2.5/3	$Th^3 3$ Sh1	3	diffuse	
12	220	309	2.5YR 2.5/1	Sh3 $Th^3 1$	3	diffuse	
11	309	330	2.5YR 2.5/1	$Th^2 3$ Sh1	2	diffuse	
10	330	338	2.5YR 2.5/1	Sh3 $Th^3 1$ $Tl^1 +$	3	diffuse	
9	338	355	2.5YR 2.5/1	Sh2 $Th^3 1$ $Tl^2 1$	3	sharp	
8	355	395	2.5YR 2.5/1	$Th^2 2$ Sh2 $Tl^2 +$	3	diffuse	
7	395	420	2.5YR 2.5/1	$Th^1 2$ Sh2	3	diffuse	
6	420	438	2.5YR 2.5/1	$Th^3 3$ Sh1	3	diffuse	
5	438	440	2.5YR 2.5/2	$Th^2 2$ $Tl^3 1$ Sh1	2	diffuse	

4	440	457	2.5YR 2.5/1	Th^32 Sh2	3	diffuse
3	457	490	2.5YR 2.5/1	Th^22 Sh2	3	diffuse
2	490	506	2.5YR 2.5/1	Sh3 Th^31 Tl^3+	4	sharp
1	506	513	GLEY1 3/10Y	Ga2 As1 Ag1 Dh^2+	2	---

Figure 70 shows a representation of the sedimentary sequence from BH6. The sedimentary sequence obtained from BH6 was a total of 513cm deep. At the base was mineral sediments with herbaceous detritus (Unit 1). Overlying this was 176cm of generally well-humified fen peats containing both herbaceous and woody remains (Units 2-10). This was overlain by a 21cm thick deposit of relatively poorly-humified herbaceous peat (Unit 11). Overlying Unit 11 was 143cm of generally well-humified herbaceous peat (Units 12-15). *Sphagnum* moss became more common and deposits were generally less humified from 166cm depth to the top of the sequence (Units 16-26).

7.8.2 Chronology

Five samples of picked and cleaned above-ground plant macrofossils from the ombrotrophic part of BH6 (i.e. from 0cm to 309cm depth) were submitted for to Beta Analytic, Miami, Florida, for AMS ^{14}C dating (laboratory codes prefixed "BETA"); a further two samples consisting of picked *Sphagnum* macrofossils were submitted to the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, California (CAMS-164206 and CAMS-164207). Details of these seven dates are given in Table 49. These dates generally show an increase in age with depth except that BETA-304237 and CAMS-164207 display an inversion in the age vs depth relationship.

Table 49: AMS ^{14}C dates obtained from BH6, Littleton bog, Co. Tipperary. Dates were calibrated using the IntCal09 calibration curve (Reimer et al. 2009), and 95% confidence (2σ) intervals were generated using the Clam software package (Blaauw 2010).

Lab code	**Depth (cm)**	**Material dated**	**$^{13}C/^{12}C$ ratio**	**^{14}C date (BP)**	**Calibrated range 2σ (cal BP)**
BETA-304235	50.5	Plant macrofossils	-24.3	820±30	780-690
BETA-304236	98.5	Plant macrofossils	-25.1	1070±30	1050-930
BETA-261636	146.5	Plant macrofossils	-24.6	2370±40	2690-2330
CAMS-164206	167.5	*Sphagnum* macrofossils	-25	2400±60	2700-2340
BETA-304237	202.5	Plant macrofossils	-26.9	4670±40	5580-5310
CAMS-164207	240.5	*Sphagnum* macrofossils	-25	3625±30	4070-3850
BETA-261637	369.5	Plant macrofossils	-26.6	6520±40	7550-7330

The ^{14}C dates from BH6 suggest that this sequence spans most of the Middle and Late Holocene. Taking the midpoints of the calibrated 95% confidence intervals of the uppermost and lowermost dates, the average accumulation rate of BH6 is *c.* 21 years/cm. Bayesian age vs depth modelling suggests, however, significant changes in accumulation rate in this sequence.

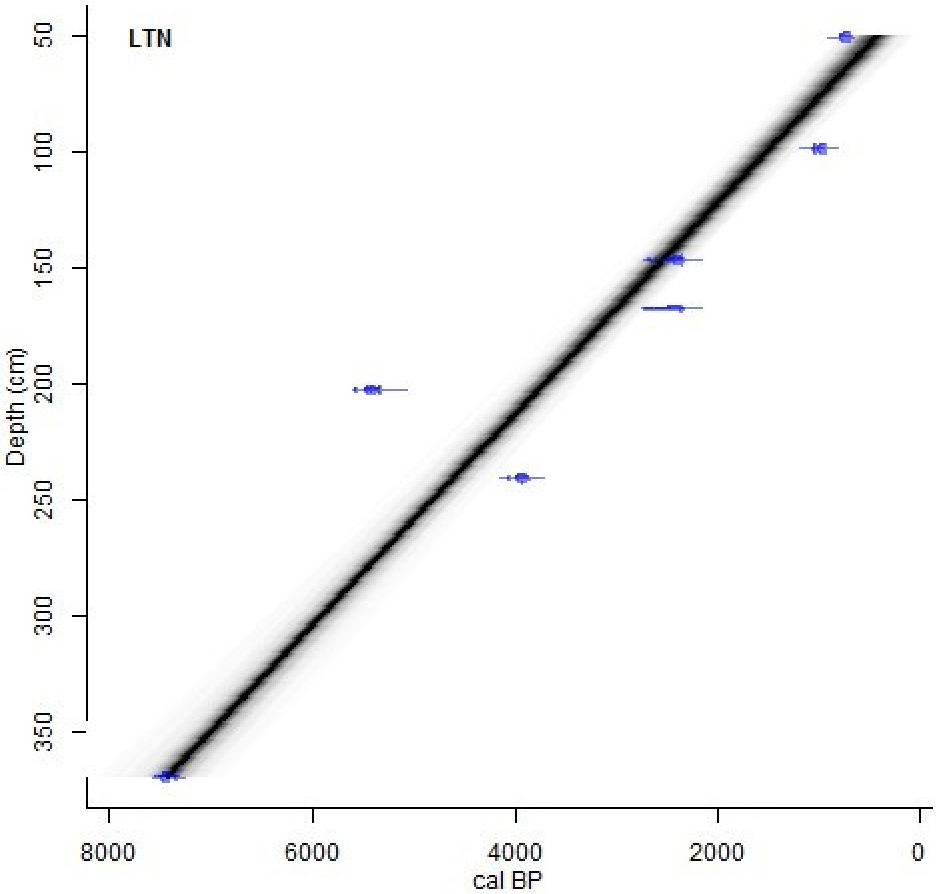

Figure 71: Linear regression age vsdepth model, Littleton BH6.

'Classical' age models were generated for the BH6 sequence using the Clam software package (Blaauw 2010). Linear interpolation resulted in age vs depth models with very abrupt changes in accumulation rate with reversals in the age vs depth relationship, these models were thus considered to be unrealistic. Other models including the smooth spline model were similarly sensitive to the inverted ^{14}C dates in the sequence and were therefore rejected. An age model produced using linear regression, illustrated in Figure 71, was selected as representing a reasonable approximation of the age vs depth relationship as this model is insensitive to the inversion in dates. However, the overall goodness of fit with individual dates was relatively poor, and the model produced was, by definition, linear, and therefore at odds with the apparent increase in accumulation rate above *c.* 150cm depth shown by the 14C dates seemingly concomitant with the generally reduced humification and increased presence of *Sphagnum* shown in the sedimentary log (see above).

Bacon (Blaauw and Christen 2011) was used to produce more flexible Bayesian age vs depth models for BH6, shown in Figure 72. This model identifies BETA-304237 as an outlier. Uncertainties in the age vs depth model are large below 150cm depth. The difficulty in producing a stable model of the accumulation of BH6 below 150cm depth, is likely to be exacerbated by the relatively low density of ^{14}C dates in the this part of the sequence. With the obvious caveat that there a re large uncertainties below 150cm, the age vs depth model produced using Bacon has been used for all further analysis, with point age estimates (prefixed with '*c.*') using the *maximum a posteriori* (MAP) date estimate generated by the software based on several million MCMC runs.

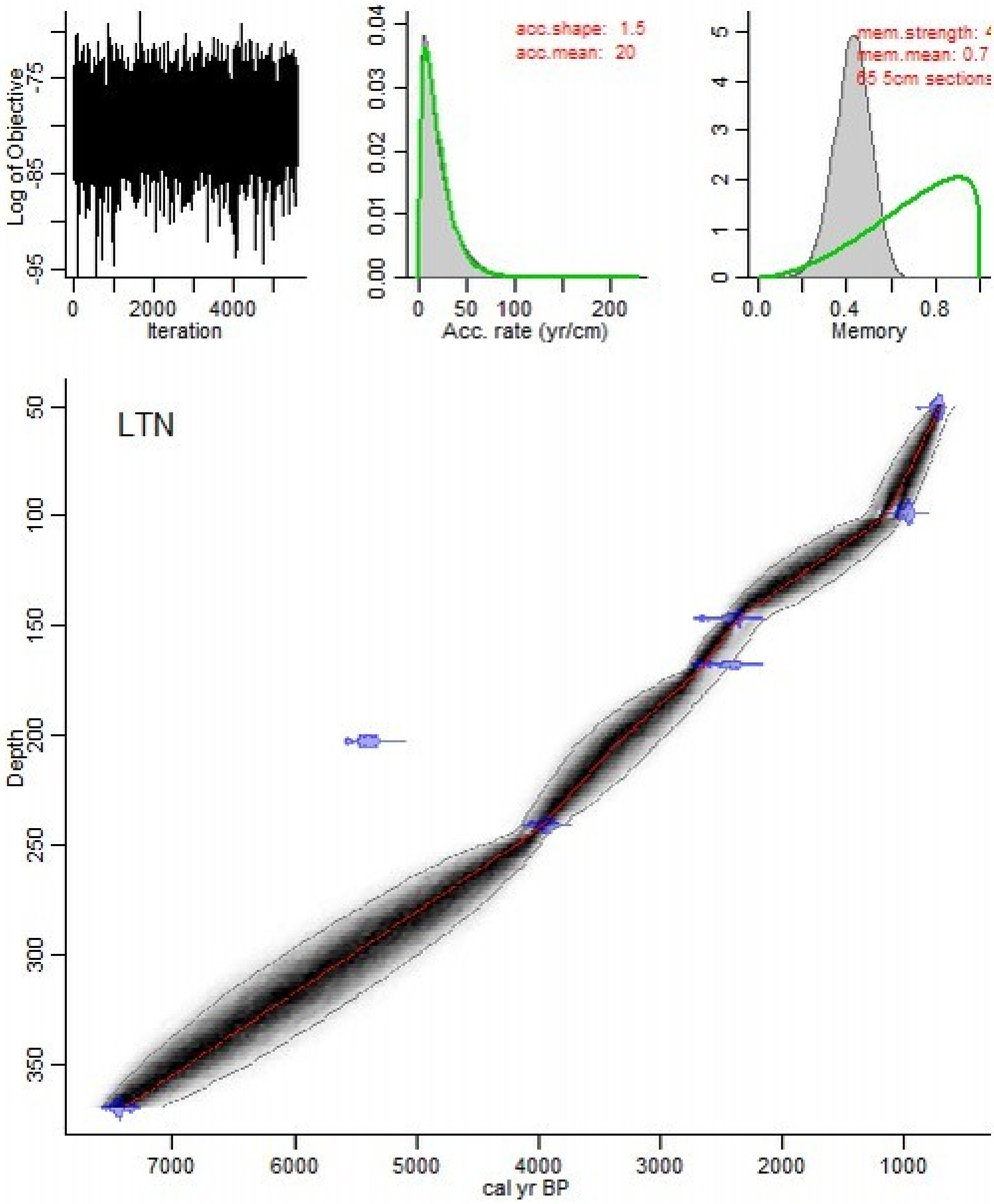

Figure 72: Age vs depth model for BH6 Littleton, produced in Bacon. Black dotted lines indicate the 95% confidence intervals of the age vs depth model, red dotted line indicates maximum a posteriori (MAP).

7.8.3 Humification

Humification analysis was undertaken using the same methodology outlined in Chapter 5 by McCarroll (2009). For comparison with the results of the testate amoebae analysis, the results are briefly described. 30 samples for humification were taken from BH6, at 8cm spacing between 18 and 250cm depth. Results are shown in Figure 73. A LOWESS smooth line (span 0.2) shows a general trend towards decreasing humification up-core throughout the ombrotrophic part of the sequence - suggesting gradually increased moisture availability during the Late Holocene, with a notable step-change to decreased humification values above 98cm depth (from *c.* 1140 cal BP onwards).

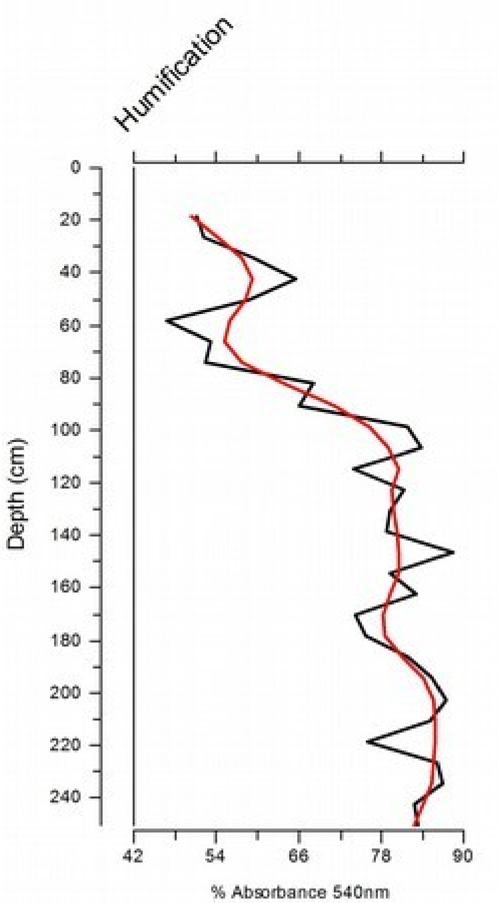

Figure 73: Humification curve (black line) BH6 Littleton, red line shows a LOWESS smooth line (span 0.2).

7.8.4 Testate amoebae analysis

Samples for testate amoebae analysis were initially taken every 4cm along BH6 between 2cm and 250cm depth. No samples below 234cm depth yielded counts of 50 tests or more. After initial analysis at 4cm resolution, sample spacing was increased to 2cm between 186cm and 90cm depth. In total, 81 samples yielded counts of 50 tests or more, of which 71 samples yielded counts of 100 tests or more. Samples with fewer than 50 tests were excluded from further analysis. Test concentration was generally variable, with no obvious correlation between concentration and lithostratigraphy.

Figure 74 shows the full testate amoebae diagram from BH6, Littleton bog. Values are expressed as percentages of the total test count. DWT values in cm (reconstructed using the central Irish transfer function, see Chapter 6), are shown on the right hand side of the diagram. Sample-specific errors (generated using 1000 bootstrap cycles) are shown in dotted lines. Also on the right hand side of the diagram are DCA Axis 1 (eigenvalue 0.439) sample scores, ordination diagrams are given in Appendix 1. DCA Axis 1 scores are strongly correlated with DWT values ($r = 0.84$), showing that the main axis of variation in the species data from Longfordpass is strongly related to hydrology. DWT values range from -1.6cm to 38cm (mean DWT = 4.6cm). The testate amoebae diagram has been divided into assemblage zones on the basis of visual examination. A total of 33 testate amoebae taxa are present in these samples, with most assemblages dominated by either *Amphitrema* spp. or *Hyalosphenia subflava,* whilst in some samples *Assulina muscorum, Difflugia pulex* or *Cyclopyxis arcelloides* are the dominant taxa. Diversity indices vary throughout the sequence, R ranges from 3 to 20 (mean $R = 9$ taxa), H' ranges from 0.1 to 2.4 (mean $H' = 1.45$), and D ranged from 0.03 to 0.86 (mean $D = 0.65$). All diversity indices show lowest diversity index scores in the lowermost sample in the sequence, and greatest diversity at the top, suggesting that the lowest sample (LTN234.5) may have been affected by selective preservation of certain taxa. Test concentration (tests per cm^3) does not appear to be particularly poor in this sample, however.

LTN-1 (***Hyalosphenia subflava*** **–** *Amphitrema flavum*) 234 to 224cm depth (from *c.* 3870 to *c.* 3700 cal BP): this zone is overwhelmingly dominated by *Hyalosphenia subflava* (max. 98%). Other taxa present in this zone are *Amphitrema flavum*, *Amphitrema wrightianum*, and *Assulina muscorum*. These samples have the amongst the lowest diversity index scores, indicating either ecological stress, or poor preservation in the lower part of the sequence. Test concentration does not appear to be unusually low in this zone, however, so the former explanation seems plausible, especially considering the unusually high DWT values in this zone. DWT values fluctuate widely from extremely dry (DWT = 38cm) to moderate conditions (DWT = 5cm). Reconstructed water tables in this zone must be viewed with caution since there are no modern analogues for communities dominated so heavily by *Hyalosphenia subflava* in the central Irish modern training set. This caveat also applies to other *H. subflava* dominated assemblages in this sequence.

LTN-2 (*Amphitrema flavum – Amphitrema wrightianum – Assulina muscorum*) 224 to 194cm depth (*c.* 3700 to *c.* 3170 cal BP): *Amphitrema* spp. are the dominant taxa throughout this zone, usually *A. flavum* is dominant (max. 62%), but *A. wrightianum* increases to a maximum of 45% at 214cm depth before declining again. DWT values indicate wet conditions (min. = -1.6cm, max. = 1cm) in this zone.

LTN-3 (*Assulina muscorum – Hyalosphenia subflava – Amphitrema stenostoma*) 194 to 181cm depth (*c.* 3170 to *c.* 2900 cal BP): *Hyalosphenia subflava* initially dominates this zone (max. 29%) before falling and being replaced by *Assulina muscorum* which reaches a peak abundance of 53% at 186cm, and *Amphitrema stenostoma* which peaks at 19%, also at 186cm. DWT values initially indicate moderately-dry conditions (DWT = 7cm) before dropping to 0cm, indicating wet conditions.

LTN-4 (*Amphitrema flavum – Amphitrema wrightianum – Assulina muscorum*) 181 to 157cm depth (*c.* 2900 to *c.* 2500 cal BP): this zone is characterised by a return to *Amphitrema* spp. and *Assulina muscorum* dominance, with DWT values are generally 2 to 4cm, indicating wet to moderately-wet conditions.

LTN-5 (*Hyalosphenia subflava – Assulina muscorum – Amphitrema flavum*) 157 to 149cm depth (*c.* 2500 to *c.* 2400 cal BP): *Amphitrema* spp. decline sharply, replaced by a rapid increase in *Hyalosphenia subflava* (max. 40%), and, to a lesser extent, *Assulina muscorum* (max. 36%). DWT values rise sharply throughout this zone to a maximum of 16cm – indicating a shift to dry conditions.

LTN-6 (*Amphitrema flavum – Assulina muscorum*) 149 to 137cm depth (*c.* 2400 to *c.* 2130 cal BP): this zone is dominated by *Amphitrema flavum* (53% increasing to 83%), whilst *Assulina muscorum* is also present (max. 20%). DWT values are around 4cm in this zone, indicating moderately-wet conditions.

LTN-7 (*Amphitrema flavum – Amphitrema wrightianum – Assulina muscorum*) 137 to 121cm depth (*c.* 2130 to *c.* 1710 cal BP): assemblages in this zone are similar to LTN-6, except that *Amphitrema wrightianum* shows a marked increase to 28%; accordingly, DWT values drop to around 0cm, indicating a wet shift with water tables at the surface. At the top of this zone is a brief peak in *Hyalosphenia subflava* up to 23%, resulting in a rapid drop in water tables to 6.4cm below the surface.

LTN-8 (*Amphitrema flavum – Amphitrema wrightianum – Arcella discoides*) 121 to 109cm depth (*c.* 1710 to *c.* 1400 cal BP): this zone is characterised by a return to the dominance of *Amphitrema* spp.. *Arcella discoides* also increases in this zone to 20%. DWT values are around 3cm below the surface, indicating wet conditions.

LTN-9 (*Hyalosphenia subflava – Assulina muscorum*) 109 to 95cm depth (*c.* 1400 to 1110 cal BP): this zone is dominated by a sharp increase in *Hyalosphenia subflava* (max. 68%), followed by a decline. *Assulina muscorum* is present throughout (~15%). DWT values indicate a shift to dry conditions, with the water table 19cm below the surface, before rising to 11cm below the surface.

LTN-10 (*Amphitrema flavum – Assulina muscorum – Amphitrema wrightianum*) 95 to 48cm depth (*c.* 1110 to after *c.* 670 cal BP): this zone is characterised by a return to *Amphitrema* and *Assulina* spp. dominance, with DWT values around 2cm below the surface, indicating wet conditions throughout.

LTN-11 (*Amphitrema flavum – Difflugia pulex – Assulina muscorum*) 48 to 32cm depth (after *c.* 670 cal BP): *Amphitrema wrightianum* declines in this zone, and is replace by an increase in *Difflugia pulex* to a maximum of 23%. DWT values increase slightly to 4 to 5cm below the surface, indicating moderately wet conditions.

LTN-12 (*Cyclopyxis arcelloides – Heleopera sphagni – Trigonopyxis arcula*) 32 to 16cm depth (after *c.* 670 cal BP): this zone is characterised by a marked increase in *Cyclopyxis arcelloides* and *Trigonopyxis arcula* (to 36 and 21%, respectively), and a concomitant decrease in *Amphitrema flavum* (max. 16% in this zone). DWT values indicate a shift to drier conditions, with water tables falling to 12cm below the surface, followed by a return to wet conditions (DWT = 0.6cm) at the top of this zone, as *Heleopera sphagni* increases to 23%.

LTN-13 (*Amphitrema flavum – Amphitrema wrightianum*) 16cm to top (after *c.* 670 cal BP): this zone is dominated by *Amphitrema* spp., with a slight increase in *Hyalosphenia subflava* towards the top of the zone. DWT values fluctuate between 4cm and 0cm below the surface, indicating wet conditions.

7.8.5 Summary and discussion

The peat sequence from BH6, Littleton bog, appears to span a large portion of the Mid-and Late-Holocene, with the onset of ombrotrophic conditions by *c.* 4900 cal BP. The testate amoebae-derived DWT curve indicates generally wet conditions throughout the sequence, with DWT values remaining close to the mean (4.62cm) throughout. Conditions are particularly wet between *c.* 3870 and *c.* 3250 cal BP (222 to 198cm depth); another wet shift where DWT values are significantly below the mean occurs between *c.* 2160 and *c.* 1790 cal BP (138 to 124cm depth). The older of these wet shifts is clearly reflected in the humification data, with a dip in humification evident at 218cm depth (*c.* 3610 cal BP).

The generally wet conditions at Littleton bog indicated by the testate amoebae data are punctuated by a series of sharp drops in the water table. These shifts to dry conditions are indicated by rapid switches to *Hyalosphenia subflava* dominance. These dry shifts occur at *c.* 3100 cal BP (190cm depth), *c.* 2470 cal BP (154cm depth), and at *c.* 1420 cal BP (110cm depth). Although the transfer function indicates some very low water tables (DWT >15cm), these values must be taken with caution since the central Irish training set does not have any good analogues for communities with such high abundances of *H. subflava* (maximum in training set = 5.8%, maximum in fossil data = 98%). Nevertheless, *H. subflava* is consistently considered to be a dry indicator (Charman *et al* 2000, p.117), often associated only with soils and drained peatlands (Tolonen 1986; Warner, B. G. 1990; cited in Charman *et al* 2000, p.117). A possible explanation for these drastic drops in water table may be that these represent bog bursts.

Bog bursts

Bog bursts are defined as a flow failure in a raised bog, resulting in a catastrophic loss of water, a fall in the level of the cupola of the bog, and localised rupturing of the bog surface (Dykes and Warburton 2007). At Derryville bog, 5km north of Littleton, a series of very similar sudden dry shifts associated with drops in the level of the bog surface were recorded (Casparie 2001; Caseldine and Gearey 2005). These bog bursts were lettered A to E, dates of these events are: A at *c.* 4150 cal BP; B at *c.* 3200 cal BP; C at *c.* 2770 cal BP; D at *c.* 2550 cal BP; and E at *c.* 2050 cal BP; with additional possible bog bursts at *c.* 2350 cal BP and *c.* 1400 cal BP.

The similarity of the events at Derryville to the dry shifts observed at Littleton (e.g. dominance of *Hyalosphenia subflava*, sudden sharp increase in DWT), support the idea that the dry shifts at Littleton do represent bog bursts. At Derryville drops in the level of the bog surface could be inferred from a large number of archaeological and non-archaeological dendrochronological dates from levelled deposits; whilst drops in the level of the bog surface cannot be observed from the single core from Littleton, the low accumulation rate of peat below *c.* 100cm depth in BH6 may possibly support the idea of bog growth being interrupted by a series of hiatuses and setbacks.

It has been proposed that bog bursts, and other mass movements in peatlands, may ultimately be driven by hydrology. Although the precise mechanisms remain unclear, it appears that bog bursts may be associated with an excess of water, leading to a failure either in response to heavy precipitation, or increased precipitation after a prolonged period of dry conditions (Warburton *et al* 2004; Feldmeyer-Christe *et al* 2011). Indeed, climatic changes at around 2800 cal BP have recently been implicated as the cause of a bog burst at a bog in the Netherlands (Van Geel *et al* 2014).

In spite of the likely linkages between extreme weather conditions and bog bursts, Derryville bog has been generally considered not to be climatically sensitive (sensu Barber *et al* 1994b) due to the presence of the bog bursts (Caseldine and Gearey 2005, p.598; Caseldine *et al* 2005, p.105; Plunkett *et al* 2013; Swindles *et al* 2013). The same conclusion must also be reached for the sequence at Littleton bog. Whilst some of the smaller-scale hydrological fluctuations visible in the testate amoebae data may very likely be due to allogenic forcing (discussed further in Chapter 9), the most obvious features visible in these data are the drops in water table caused by the series of bog bursts, and it is likely impossible to disentangle the effects of these from variations in effective precipitation. Nevertheless, even if water tables appear not to be responding linearly to allogenic forcing due to these autogenic bog bursts it is intriguing to note the close chronological correspondence between these events at Littleton and at nearby Derryville.

Table 50: Comparisons between dates of possible bog bursts at Littleton and Derryville bogs. The 95% confidence range, and point estimate (MAP - 'maximum a posteriori') are derived from the output of the age vs depth model generated using Bacon.

Possible bog bursts at Littleton BH6			**Bog bursts at Derryville (Caseldine and Gearey 2005)**
Depth	**95% confidence range cal BP**	**MAP cal BP**	
190cm	4250-3080	3100	Bog burst B – c. 3200 cal BP
154cm	2970-2410	2473	Bog burst D – c. 2550 cal BP and possibly also c.2350 cal BP
110cm	1802-1202	1420	Possible bog burst – 1400 cal BP

Although chronological control is relatively poor in parts of this sequence, the events at Littleton are potentially closely synchronous with bog bursts identified at Derryville as shown in Table 50. This may support the tentative hypothesis that these bogs, which are morphologically similar and part of the same system of wetlands, burst at similar times as a response to some kind of allogenic forcing, possibly a sudden increase in rainfall (as suggested by Van Geel *et al* 2014). Although attractive, this hypothesis is difficult to demonstrate conclusively since by their nature bog bursts are difficult to date precisely: bog bursts cause erosion and disruption of stratigraphy in localised parts of bogs, and probably cause significant changes in accumulation rate or hiatuses across the bog as a whole. Furthermore, even if a positive link between bog bursts and weather conditions is accepted, the precise mechanisms of individual bog bursts are undoubtedly modulated by other internal bog processes, the morphology of individual basins, and other contingent factors (e.g. vegetation patterns, weather conditions prior to the event, and human activity). Whilst the presence of these events may hamper quantitative palaeoclimate reconstructions, bog bursts are likely to have represented a tangible consequence of environmental change to the communities living on and around Littleton.

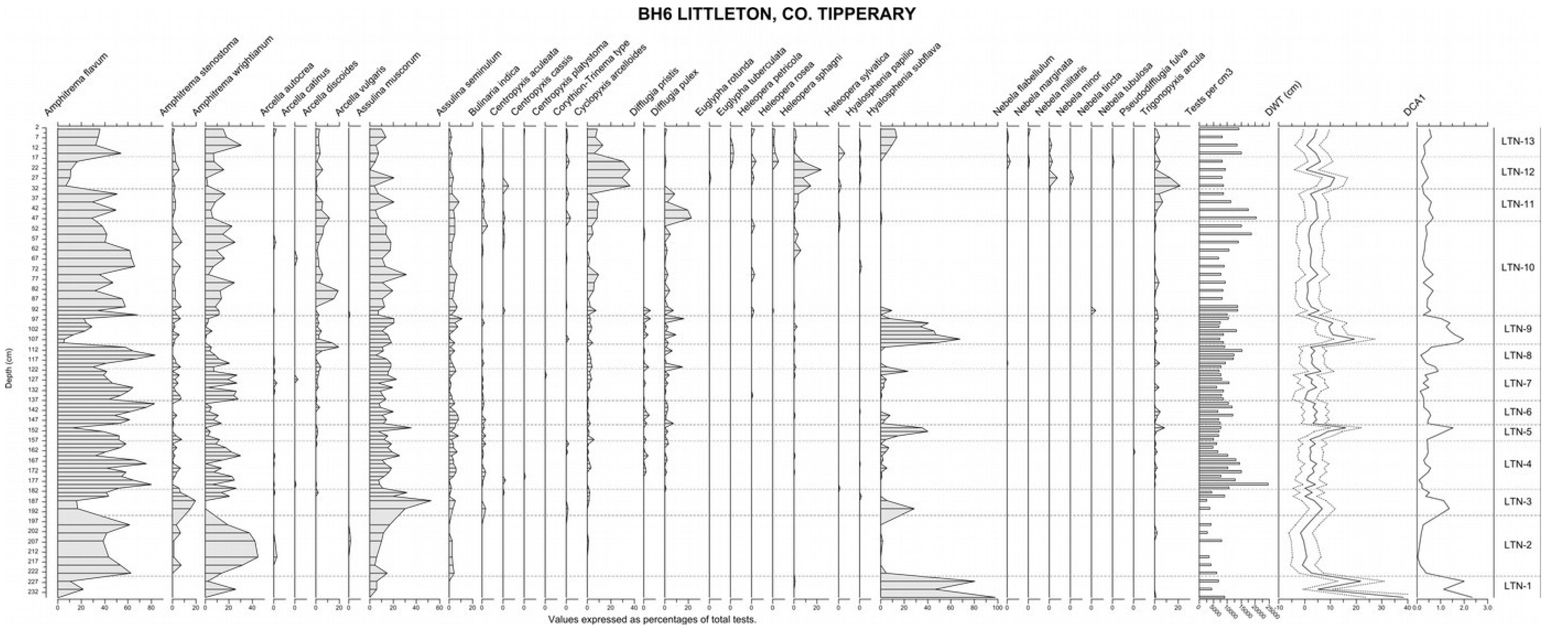

Figure 74: Full testate amoebae diagram from BH6, Littleton bog, Co. Tipperary. Values are presented as percentages of the total test count. Reconstructed DWT was calculated using the central Irish transfer function.

7.9 Killeen bog, Co. Tipperary

7.9.1 Stratigraphy

Due to the severe desiccation of the milled surface of Killeen bog during the fieldwork season, a full transect of boreholes could not be carried out to characterise the basin (Young *et al* 2011c). The location for the master sequence (BH1) was selected because it was: a) near to the centre of the area of former raised bog in which archaeological investigations were taking place, and b) it was located *c.* 150m from the nearest sighting of any archaeological feature.

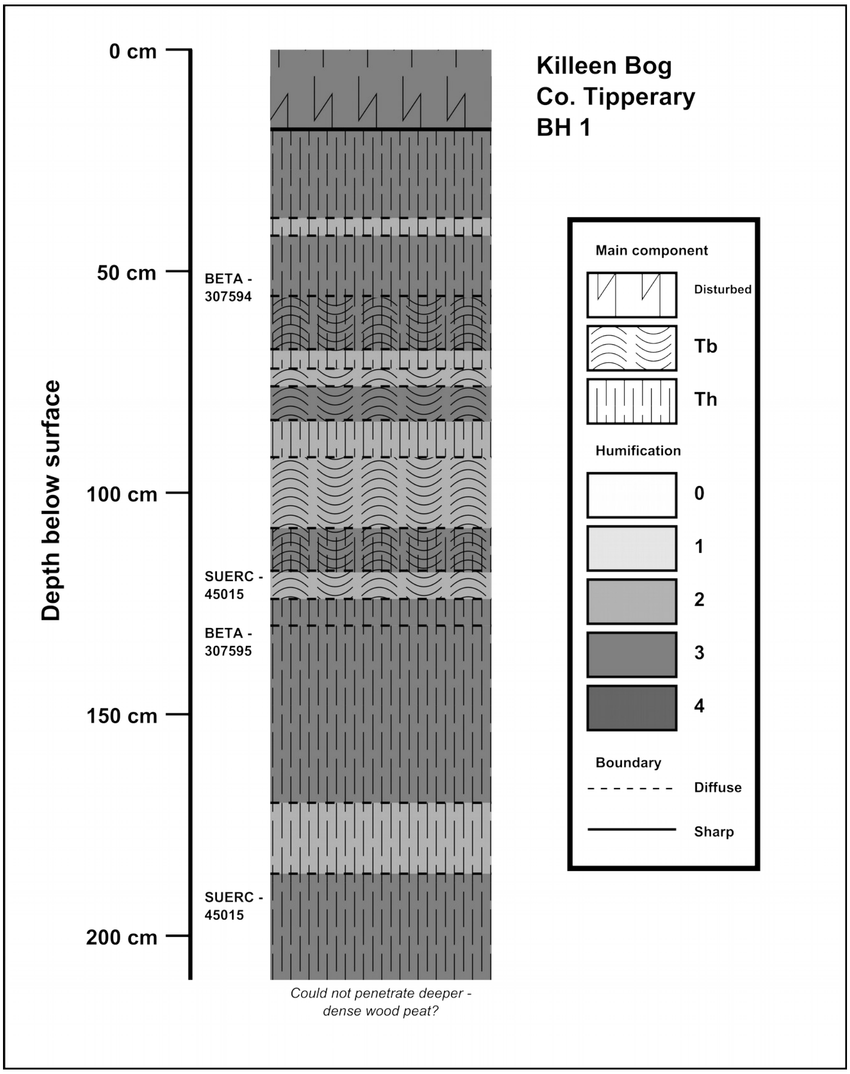

Figure 75: Peat stratigraphy, BH1 Killeen bog, Co. Tipperary.

The sequence recovered from BH1 (illustrated in Figure 75) was a total of 210cm deep. Mineral sediments were not reached and the sequence was not bottomed due to the extensive recent drainage at Killeen. The base of the sequence as recovered consisted of 80cm of generally moderately-humified herbaceous (including *Phragmites* remains) peat with traces of woody remains (Units 1-3); it is possible that the underlying deposits contained more wood fragments, thus impeding further coring. The upper boundary of these deposits was thought to mark the fen-bog transition, and was overlain by 39cm of *Sphagnum-Eriophorum* peat of varying humification (Units 4-.7) Overlying this was an 8cm thick band of humified *Eriophorum* peat (Unit 8), which was in turn overlain by 27cm of generally *Sphagnum*-rich peat (Units 9-12). The upper 56cm were composed of generally moderate to well-humified herbaceous peat (Units 13-16), of which the upper 20cm (Unit 16) appeared to be composed of re-deposited or disturbed milled peat. The full stratigraphic log of BH1 is given in Table 51.

Table 51: Stratigraphic log BH1 Killeen Bog, Co. Tipperary.

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact	Notes
16	0	20	10YR 2/1	Sh2 $Th^3$1 $Tl^2$1	3	sharp	Disturbed?
15	20	39	10YR 2/2	Sh1 $Tl^2$1 $Th^2$2 Tb+	3	diffuse	
14	39	41	10YR 3/3	$Th^2$4 Sh+ Tl+	2	diffuse	
13	41	56	10YR 2/1	$Th^3$3 Sh1 Tl+	3	diffuse	
12	56	68	7.5YR 3/2	$Th^3$2 $Tb^3$1 Sh1	3	diffuse	
11	68	72	7.5YR 3/2	$Th^2$3 $Tb^3$1	2	diffuse	*E. vaginatum*
10	72	76	7.5YR 3/2	$Tb^2$3 $Th^2$1	2	diffuse	*Sphagnum*
9	76	83	7.5YR 2.5/2	$Tb^3$3 $Th^3$1 Sh+	3	diffuse	*Sphagnum*
8	83	91	10YR 2/1	$Th^2$2 Sh2 Tl+	3	diffuse	*E. vaginatum*
7	91	107	7.5YR 3/4	$Th^2$1 $Tb^2$3 Tl+	2	diffuse	*Sphagnum*
6	107	118	7.5YR 2.5/2	$Th^2$2 $Tb^3$2 Sh+	3	diffuse	
5	118	123	7.5YR 3/2	$Tb^2$3 $Th^2$1	2	diffuse	*Sphagnum*
4	123	130	7.5YR 2.5/1	$Tb^3$1 $Th^3$1 Sh2	3	diffuse	
3	130	167	7.5YR 2.5/1	$Th^3$3 Sh1 Tl+	3	diffuse	fen/bog transition
2	167	186	10YR 3/2	$Th^2$3 Sh1 Tl+	2	diffuse	*Phragmites*?
1	186	210	10YR 2/1	$Th^3$3 Sh1 Tl+	3	End of BH	

7.9.2 Chronology

Four samples of picked and cleaned above-ground plant macrofossils from BH1 were submitted for AMS ^{14}C dating. BETA-307594, and BETA-307595 were analysed in Miami, Florida, USA, by Beta Analytic Inc., whilst SUERC-45012 and SUERC-45015 were prepared to graphite at the NERC radiocarbon facility, East Kilbride, and analysed at the SUERC AMS Laboratory. Details of these dates are given in Table 52. These dates show a clear increase in age with depth.

Table 52: AMS ^{14}C dates obtained from BH1, Killeen bog, Co. Tipperary. Dates were calibrated using the IntCal09 calibration curve (Reimer et al. 2009), and 95% confidence (2σ) intervals were generated using the Clam software package (Blaauw 2010).

Lab code	Depth (cm)	Material dated	$^{13}C/^{12}C$ ratio	^{14}C date (BP)	Calibrated range 2σ (cal BP)
BETA-307594	52.5	Plant macrofossils	-24.1	200±30	300-0
SUERC-45012	119.5	*Sphagnum* macrofossils	-25.4	1124±37	1170-960
BETA-307595	132.5	Plant macrofossils	-24.1	1310±30	1290-1180
SUERC-45015	192.5	*Sphagnum* macrofossils	-32.9	2523±37	2740-2490

The ^{14}C dates from BH1 suggest that this sequence spans the latter part of the Late Holocene. Taking the midpoints of the calibrated 95% confidence intervals of the uppermost and lowermost dates, the average accumulation rate of BH1 is *c.* 16 years/cm.

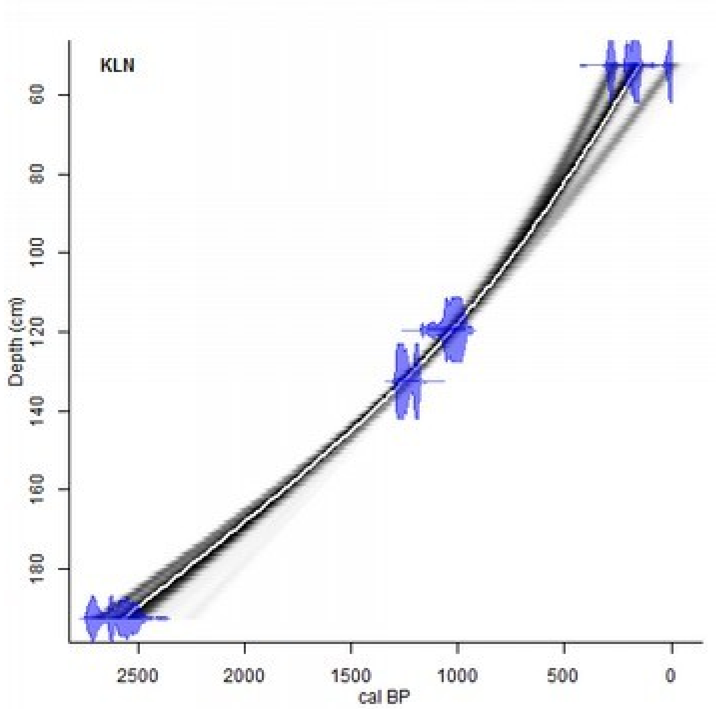

Figure 76: Smooth spline age vs depth model, BH1 Killeen.

'Classical' age models were generated for the BH1 sequence using the Clam software package (Blaauw 2010). The smooth spline model, illustrated in Figure 76, was selected as it assumes gradual changes in accumulation rate. This model shows a relatively constant accumulation rate between 192 and 52cm depth, with a possible slight increase in accumulation above *c.* 120cm depth to the top.

Bacon (Blaauw & Christen 2011) was also used to produce more flexible Bayesian age vs depth models for BH1. This model is illustrated in Figure 77. The resulting model is very similar to the smooth spline age vs depth model, suggesting that both models are relatively robust. The age vs depth model produced using Bacon has been used for all further analysis, with point age estimates (prefixed with '*c.*') using the *maximum a posteriori* (MAP) date estimate generated by the software based on several million MCMC runs.

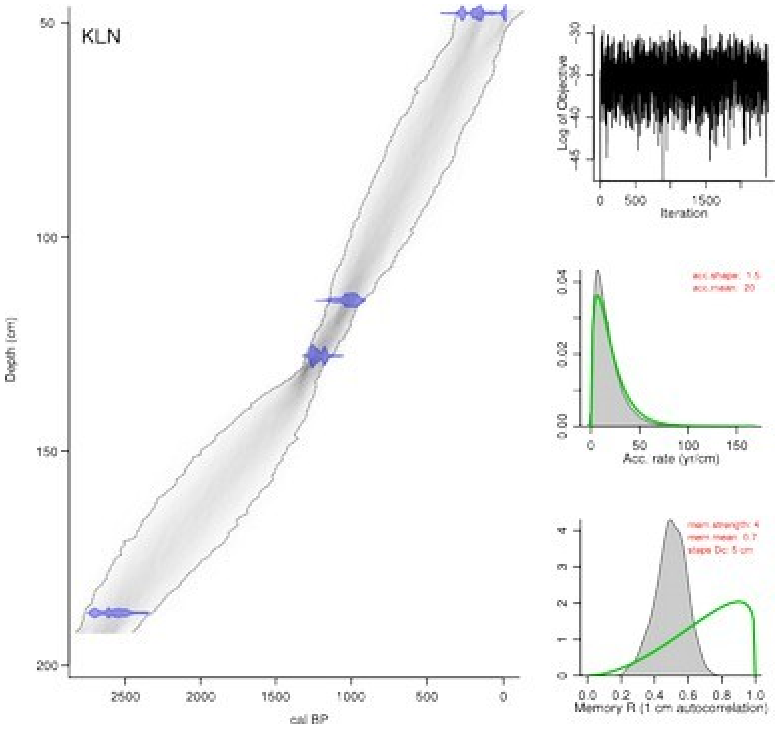

Figure 77: Age vs depth model for BH1, Killeen, produced in Bacon. Dotted lines indicate the 95% confidence intervals of the age vs depth model.

7.9.3 Humification

Sub-samples for humification analysis were taken at 8cm intervals between 5cm and 205cm along BH1, in total 26 samples were analysed. Humification values range between 29% and 64% (mean humification = 46%). Figure 78 shows the resulting curve plotted against depth. A LOWESS smooth line (span = 0.2) shows a drop from initially high humification values from 189cm depth, and then moderate but variable humification to the top of the sequence.

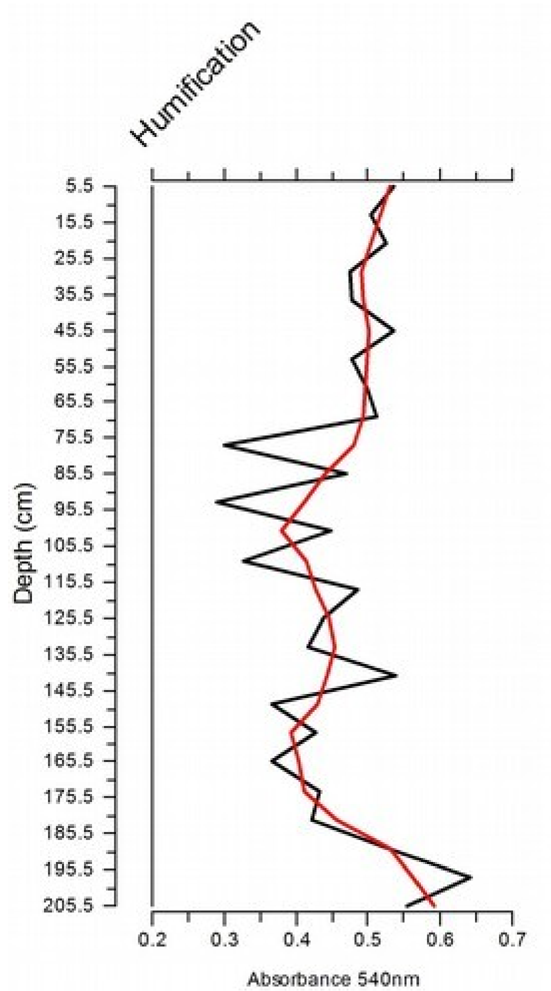

Figure 78: Humification curve (black line) from BH1 Killeen, red line shows LOWESS smooth line (span 0.2).

7.9.4 Testate amoebae analysis

Samples for testate amoebae analysis were initially taken every 8cm along BH1 between 5cm and 205cm depth. No samples below 188cm depth yielded counts of 50 tests or more. After initial analysis at 8cm resolution, sample spacing was increased to 2cm between 134cm and 194cm depth. Samples above 20cm depth were excluded as these peat deposits appeared to be disturbed or re-deposited. In total, 24 samples yielded counts of 50 tests or more, of which 18 samples yielded counts of 100 tests or more. Samples with fewer than 50 tests were excluded from further analysis. Test concentration was generally variable but poor, especially below 144cm depth.

Figure 79 shows the full testate amoebae diagram from BH1, Killeen bog. Values are expressed as percentages of the total test count. DWT values in cm (reconstructed using the central Irish transfer function, see Chapter 6), are shown on the right hand side of the diagram. Sample-specific errors (generated using 1000 bootstrap cycles) are shown in dotted lines. Also on the right hand side of the diagram are DCA Axis 1 (eigenvalue 0.43) sample scores, ordination diagrams are given in Appendix 1. DCA Axis 1 scores are strongly correlated with DWT values (r = 0.94), showing that the main axis of variation in the species data from Longfordpass is strongly related to hydrology. DWT values range from -1.3cm to 18cm (mean DWT = 4.1cm). The testate amoebae diagram has been divided into assemblage zones on the basis of visual examination. A total of 34 testate amoebae taxa are present in these samples, with most assemblages dominated by either *Amphitrema* spp. or *Difflugia pulex.* Diversity indices vary throughout the sequence but generally show a very clear trend towards markedly decreased diversity down the core, R ranges from 7 to 15 (mean R = 10 taxa), H' ranges from 0.97 to 2.2 (mean H' = 1.35), and D ranged from 0.51 to 0.85 (mean D = 0.64). All diversity indices show lowest diversity index scores at the base of the sequence, and greatest diversity at the top. H' and D in particular are both negatively correlated with depth (r = -0.86 and -0.97, respectively); this could suggest that the poor preservation of tests which approximately increases with depth could be causing selective destruction of tests of certain taxa in the lower part of the core.

KLN-1 (*Amphitrema flavum – Amphitrema wrightianum*) 188 to 143cm depth (from *c.* 2480 to *c.* 1410 cal BP): this zone is dominated by *Amphitrema flavum* (max. 75%) and *A. wrightianum* (max. 28%). DWT values range between 2 and 5cm, indicating moderate to wet conditions in this zone.

KLN-2 (*Difflugia pulex – Amphitrema flavum – Assulina muscorum*) 143 to 133cm depth (*c.* 1410 to *c.* 1200 cal BP): this zone is characterised by a sharp increase in *Difflugia pulex* (max. 33%), and a concomitant drop in *Amphitrema flavum* (down to a minimum of 9%). *Amphitrema wrightianum* is absent. In the middle of this zone, at 138cm depth is a brief peat in *Trigonopyxis arcula* and *Cyclopyxis arcelloides* (to 24% and 16%, respectively). *Assulina muscorum* is present throughout this zone (~10%) and is present thereafter throughout this sequence. DWT values rise sharply, as water tables drop to 16.5cm below the surface indicating a sharp shift to dry conditions.

KLN-3 (*Amphitrema* spp. - *Assulina muscorum – Difflugia pulex*) 133 to 48cm depth (*c.* 1410 to after *c.* 280 cal BP): *Amphitrema* spp. return to dominance in this zone (up to *c.* 80% of total tests), alongside *Assulina muscorum* and *Difflugia pulex* (max. 40% and 22%, respectively). This zone is similar to KLN-1, but with greater species diversity. DWT values fall again to between 1cm and 5cm below the surface indicating generally moderate to wet conditions, albeit with some minor variation.

KLN-4 (*Difflugia pulex – Cyclopyxis arcelloides – Assulina muscorum*) 48 to top (after *c.* 280 cal BP): *Difflugia pulex* and other moderate to dry indicators increase in this zone and dominate assemblages. Species diversity is highest in this zone. Although undated this zone may represent very recent or modern peat accumulation prior to milling of the surface. DWT values rise to a maximum of 18cm below the surface indicating dry conditions.

7.9.5 Summary

The short sequence from Killeen bog, Co. Tipperary, dates to the latter part of the Late Holocene, and shows few major hydrological shifts. Testate amoebae preservation is generally poor throughout the sequence, except in the upper 144cm of peat. A sharp dry shift occurs at *c.* 1430 cal BP. Moderately-wet conditions return by *c.* 1190 cal BP, at the same time the peat stratigraphy shows a switch to *Sphagnum* as the dominant peat component. Moderately-wet conditions persist until some time after *c.* 280 cal BP, when another dry shift occurs. It is difficult to relate these shifts in testate amoebae-derived DWT conclusively with the humification data, which is generally variable with few major trends. It is possible that these sudden dry shifts may be related to some form of disturbance, or perhaps bog bursts similar to those at Littleton bog, which is 9km north-east of Killeen. It is possible that the earlier dry event at Killeen (at 144cm depth) and the latest possible bog burst at Littleton (see above) may be broadly contemporary. The data from Killeen bog are, however, relatively sparse and it is difficult to draw firm conclusions.

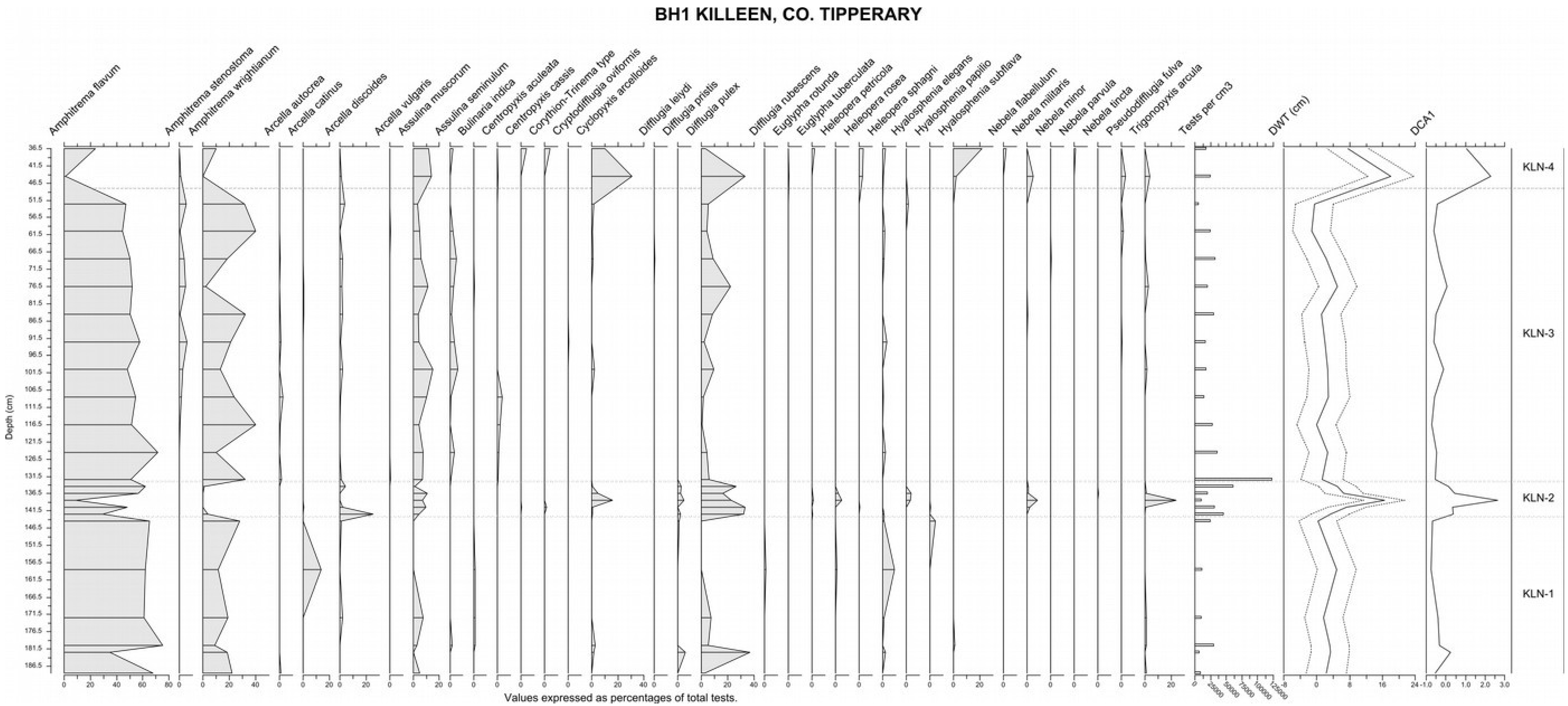

Figure 79: Full testate amoebae diagram from BH1, Killeen bog, Co. Tipperary. Values are presented as percentages of the total test count. Reconstructed DWT was calculated using the central Irish transfer function.

Chapter 8: Recent climate drivers of BSW and intra-site variability

In this chapter the results of a study examining the recent climatic drivers of BSW in a raised bog in central Ireland are presented. A series of short cores were taken from an intact raised bog, Annaghbeg, Co. Galway, and DWT reconstructions based on high-resolution testate amoebae analysis, supported by chronologies provided by ^{210}Pb, were compared with instrumental weather data. Instrumental weather data time series for Ireland extend back to the late 18th century (Butler *et al* 2005). Three replicate cores from Annaghbeg were analysed and the resulting records compared with instrumental climate data to examine the climatic sensitivity of these records, and to assess the intra-site consistency of the BSW record.

8.1 Rationale

The falsification (Barber 1981) of the autogenic 'regeneration complex' (Osvald 1923) model of bog development, based on the cyclical alternation of hummocks and hollows, has underpinned developments in peatland palaeoclimatology over the last few decades (Blackford 2000; Chambers and Charman 2004). As discussed in Chapter 2, previous studies (e.g. Charman *et al* 2004, 2009; Schoning *et al* 2005; Barber and Langdon 2007; Charman 2007; Lamentowicz *et al* 2010; Amesbury *et al* 2012) have, through comparisons between proxy records and instrumental climate data, examined the question of exactly which variables of climate drive the BSW record. These studies have shown that a combination of precipitation and temperature drive this record, possibly varying in relative importance between more oceanic or continental regions.

However, fewer studies have directly assessed the response of different bog surface microforms to climate forcing (an exception is Niinemets *et al* 2011). Building on the observation that hummocks and hollows tend to be persistent features, authors have suggested that particular microtopographic locations may be likely to yield more climatically-sensitive sequences (Barber *et al* 1998, p.527; De Vleeschouwer *et al* 2010, p.2). The focus of this research is to examine human-environment relationships by reconstructing past environmental change through the analysis of cores from former raised bogs truncated by milling. The process of milling obliterates all former surface microtopography, and so the selection of sensitive sampling locations based on surface morphology is impossible. Therefore, it is important to understand the likely effects of microtopography on the climatic sensitivity of peatland records in order to fully understand the uncertainties of palaeoenvironmental reconstructions. Furthermore, understanding the magnitude and nature of environmental change is directly relevant to understanding the effects and perception of these on past human societies (Stehr and von Storch 1995; Head 2000).

8.2 Study site and methods

Short cores of recent peat were taken from Annaghbeg bog, Co. Galway; see Chapter 3 for a full description of the site and its location. A series of eight 90cm deep cores were taken from a single transect (shown in Figure 80) across the dome of the intact raised bog using a large diameter Russian peat corer; locations of each borehole were recorded using a Leica dGPS. Utilising a simplified variant of the quadrat method (Cox 1990), the taxa present within a 20cm radius of each sampling location were recorded, using Smith (1978) to identify *Sphagnum* mosses to section and Clapham *et al.* (1959) to identify vascular plants. After removing each core, the depth to water table (DWT) in cm was measured and noted. The total length of the transect was 213m. Boreholes were not evenly spaced along this transect; in the centre of the transect, six boreholes (B to G) were placed across a single hummock - lawn - hollow - hummock sequence at spacings of *c.*1.5 to 6m.

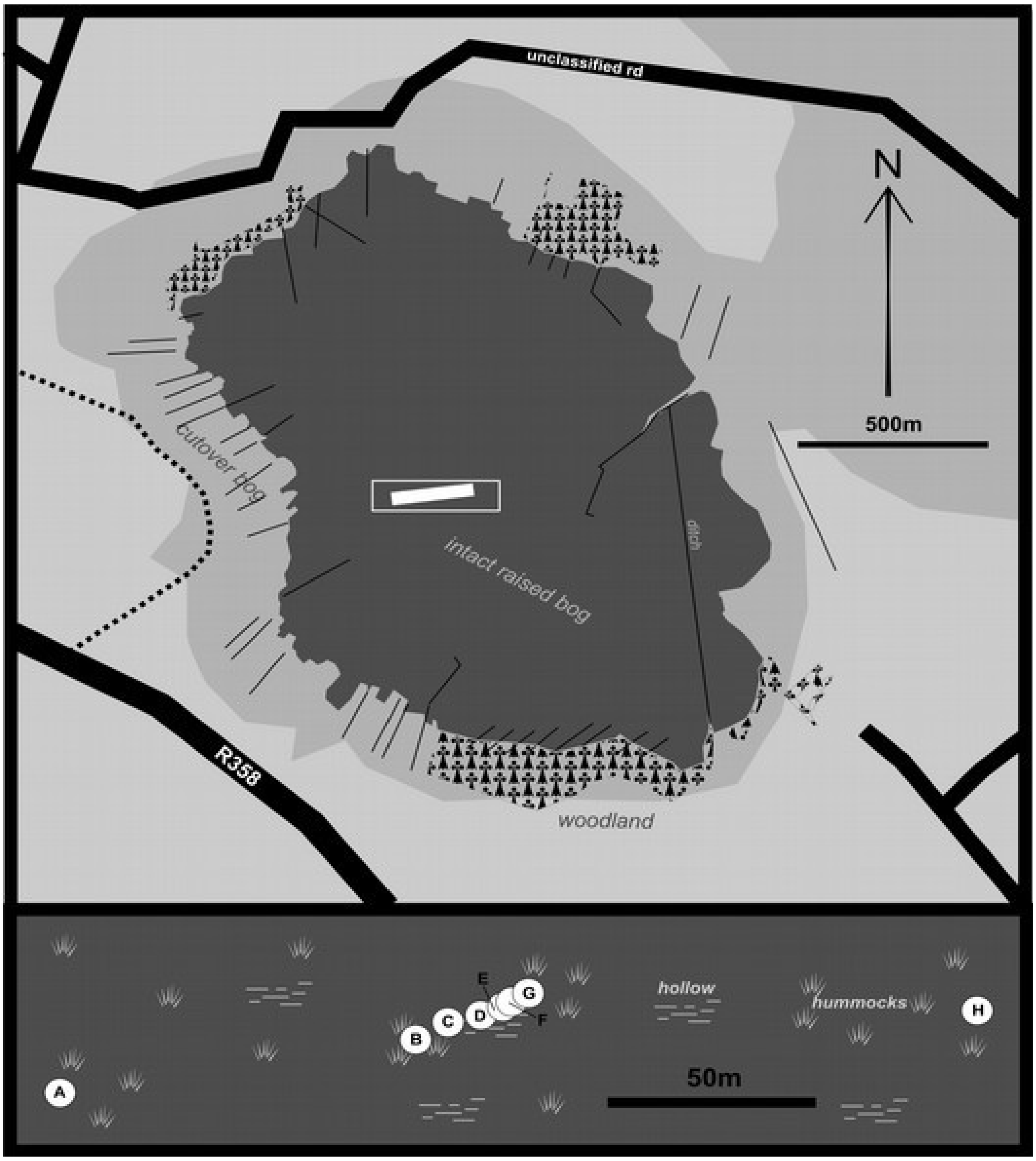

Figure 80: Coring locations, Annaghbeg bog, Co. Galway. Upper panel: the location of the transect of cores is shown by the bold white line. Lower panel: detail showing location of cores A – H.

All cores were described using the modified Troels-Smith methodology outlined in Chapter 5. ^{210}Pb dating and testate amoebae analysis was carried out on cores B – D.

Chronologies for the upper 50cm of cores B, C, and D were constructed using ^{210}Pb, dating, measured using gamma spectrometry. ^{210}Pb dating was first proposed by Goldberg (1963), however the implementation of the method is generally attributed to Krishnaswami *et al.* (1971), who used the method to date recent lacustrine sediments. Methods for sample preparation followed those summarised in Appleby (2002), and Le Roux and Marshall (2011).

Each core was divided in half lengthways, and contiguous 1cm thick slices of peat were carefully extracted. Samples were weighed, air-dried at 50ºC overnight, re-weighed, and homogenised using a pestle and mortar. Cumulative dry density (g/cm^3) was calculated to allow the Constant Rate of Supply (CRS) model (Appleby and Oldfield 1978) to be applied. The homogenised samples were then packed into small plastic Petri dishes and sealed with adhesive tape. Samples were then left for at least 21 days to allow ^{222}Rn-^{214}Pb-^{226}Ra equilibration before being analysed. In addition, the fall-out radionuclide ^{137}Cs was also measured to cross validate resulting age models (Le Roux and Marshall 2011).

The upper 50cm of cores B, C, and D were sampled for testate amoebae analysis following standard methods outlined in Chapter 5. The only deviation from standard methods was that samples from core D were 2cm^3 in volume, and samples from cores B and C were 50% of the volume of the sample (generally *c.*1-3cm^3) since some parts of these cores contained relatively little material due to compression; for this reason estimates of tests concentration are not given for cores B and C. Samples were then mounted on glass slides using deionised water as a medium; counting and analysis continued as described in Chapter 5. Reconstructed DWT values were calculating using the central Irish transfer function (see Chapter 6), with sample-specific errors generate through 1000 bootstrap cycles (Line *et al* 1994).

Instrumental weather data (temperature and precipitation) from six sites were analysed: Armagh Observatory, Co. Armagh, available at www.arm.ac.uk (Butler *et al* 1998, 2005); Galway (Athenry), and Ahascragh (Clonbrock), Co. Galway; Taughmaconnell, Co. Roscommon; Birr Castle/Gurteen Agricultural College, Co. Offaly; and Dublin (Phoenix Park), Co. Dublin, all available at www.eca.knmi.nl (Klein Tank *et al* 2002). Locations of these weather stations relative to Annaghbeg are shown in Figure 81. Alongside these, a decadal dataset from the IPCC (available at www.ipcc-data.org), interpolated from a network of stations for the grid square in which Annaghbeg is located was also analysed. Station-based seasonal North Atlantic Oscillation index (NAO) data, stretching back to 1865 were also analysed. These data are regularly updated and is provided by the Climate Analysis Section, NCAR, Boulder, USA, Hurrell (1995).

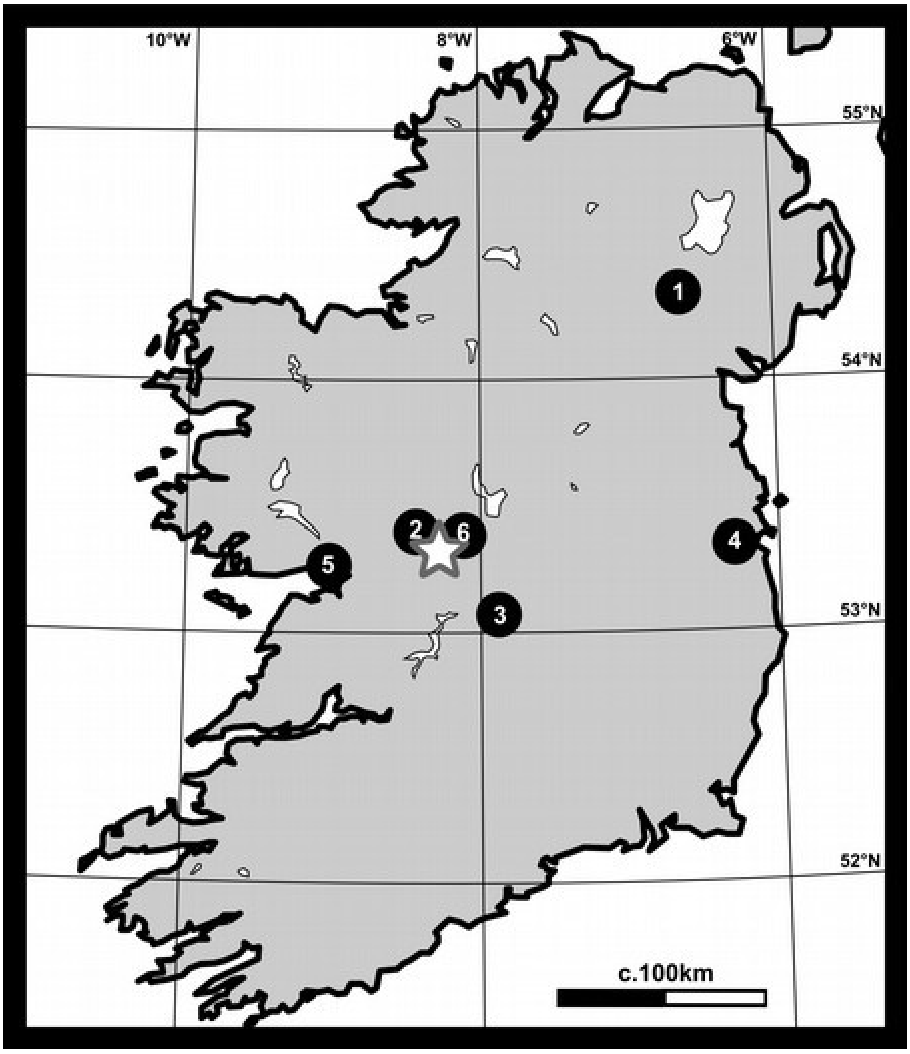

Figure 81: Location of weather stations from which instrumental data have been analysed: 1) Armagh observatory; 2) Ahascragh; 3) Birr Castle/Gurteen Agricultural College; 4) Phoenix Park, Dublin; 5) Galway/Athenry; 6) Taughmaconnell. The location of Annaghbeg bog is indicated by the grey star.

8.3 Analysis of short cores

8.3.1 Surface morphology and peat stratigraphy

At each coring location, a 90cm deep core was extracted. Coring locations were placed along a transect and selected to cover a range of bog surface microforms. The surface characteristics and depth to water table (DWT) of each core is given in Table 53, the central portion of the transect is illustrated in Figure 82.

Table 53: Surface characteristics and depth to water table of short cores form Annaghbeg bog, Co. Galway.

Core	Microform	Main plant taxa	Elevation (relative to top of Core B)	Depth to Water Table (DWT)
A	Dry lawn / Low hummock	*Sphagnum* sect. *Acutifolia, Sphagnum* sec. *Sphagnum, Erica tetralix*	-28cm	6cm
B	Hummock	*Calluna*, *Sphagnum* sect. *Acutifolia, Rynchospora*	0	18cm
C	Hummock edge / dry lawn	*Sphagnum* sect. *Acutifolia*, *Calluna, Erica tetralix, Menyanthes*	-17cm	10cm
D	Hollow	*Sphagnum papillosum*, *Menyanthes, Drosera*	-23cm	3cm
E	Hollow	*Sphagnum papillosum, Sphagnum cuspidatum, Menyanthes, Drosera, Rynchospora*	-23cm	2cm
F	Lawn	*Sphagnum papillosum, Sphagnum cuspidatum, Menyanthes, Drosera*	-21cm	6cm
G	Hummock	*Sphagnum* sect. *Acutifolia*, *Calluna, Erica tetralix, Cladonia*	-4cm	30cm
H	Hummock	*Calluna*, *Sphagnum* sect. *Acutifolia, Eriophorum*	-35cm	27cm

The peat stratigraphy of each short core was described in the laboratory – stratigraphic logs are given in Table 54. Since cores did not reach the base of the peat sequence, units are numbered from the top.

Table 54: Troels-Smith peat stratigraphic logs from short cores A to H, Annaghbeg, Co. Galway.

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact
Core A						
1	0	7.5	7.5YR 3/4	Tb(Sphag.)^{0}3 Tl(Ericaceae)^{0}1 Th^0+	0	Sharp
2	7.5	18	7.5YR 3/2	Th^{2}2 Sh2	3	Grading
3	18	25.5	7.5YR 3/3	Th^{2}2 Tb^{3}1 Sh1	3	Grading
4	25.5	32	7.5YR 3/2	Th^{2}2 Sh2	3	Diffuse

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact
5	32	46	7.5YR 3/4	$Tb^1 3$ $Tl^2 1$ $Th^1 +$	1	Diffuse
6	46	50.5	7.5YR 3/2	$Th^3 3$ Sh1	3	Grading
7	50.5	90	7.5YR 2.5/2	Th(Eriophorum)^{3}4 Tl+ Sh+	3	---
Core B						
1	0	10	7.5YR 2.5/2	Tl(Ericaceae)^{1}3 $Th^0 1$ Tb+ Sh+	1	Sharp
2	10	24.5	7.5YR 4/4	Tb(Sphag.)^{1}4 Tl+ Th+	1	Diffuse
3	24.5	32	7.5YR 3/3	$Th^2 3$ $Tb^3 1$ Sh+	2	Grading
4	32	41	7.5YR 3/2	$Th^3 3$ $Tl^2 1$ Tb+ Sh+	3	Diffuse
5	41	45.5	7.5YR 3/4	$Tb^2 2$ $Th^2 2$ Tl+ Sh+	2	Diffuse
6	45.5	53.5	7.5YR 3/3	$Tb^3 2$ $Th^2 2$ Tl+ Sh+	3	Sharp
7	53.5	59.5	7.5YR 3/4	$Tb^2 4$ Tl+ Th+	2	Diffuse
8	59.5	90	7.5YR 2.5/3	$Th^2 3$ $Tb^3 1$ Sh+ Tl+	3	---
Core C						
1	0	20	5YR 3/2	$Tb^3 3$ $Tl^2 1$ Sh+ Th+	3	Diffuse
2	20	34	7.5YR 3/3	$Tb^2 3$ $Th^2 1$ Tl+	2	Diffuse
3	34	52.5	7.5YR 4/3	$Tb^1 3$ $Th^2 1$ Tl+	1	Diffuse
4	52.5	60.5	7.5YR 4/3	Tb(S. Cusp.) ^{1}3 Th(Menyanthes)^{1}1	1	Sharp
5	60.5	90	7.5YR 3/2	$Th^3 3$ Sh1 Tb+ Tl+	3	---
Core D						
1	0	5.5	10YR 8/8	Tb(Sphag)^{0}3 Th(Menyanthes)^{0}1	0	Diffuse
2	5.5	58	10YR 3/4	$Tb^1 2$ $Th^1 2$ Sh+	1	Diffuse
3	58	90	7.5YR 3/2	$Tb^3 1$ $Th^2 3$ Sh+	2	---
Core E						
1	0	10	7.5YR 4/4	Tb(Sphag)^{0}3 $Th^0 1$	0	Grading
2	10	90	7.5YR 4/4	$Tb^1 2$ Th(Menyanthes)^{1}2	1	---
Core F						
1	0	6	7.5YR 3/3	$Tb^1 2$ $Th^1 2$	1	Diffuse
2	6	34	7.5YR 3/2	$Th^3 3$ $Tb^3 1$	3	Diffuse
3	34	39	7.5YR 3/3	$Tb^2 3$ $Th^2 1$	2	Diffuse
4	39	90	7.5YR 3/3	$Th^2 3$ $Tb^2 1$ Tl(Ericaceae)+	2	---
Core G						
1	0	1.5	10YR 8/8	Tb(S. acutifolia)^{0}4	0	Sharp
2	1.5	11.5	7.5YR 2.5/1	$Th^3 1$ $Tl^3 1$ Sh2	4	Diffuse
3	11.5	33	7.5YR 3/2	$Th^2 3$ Sh1 Tl+	3	Diffuse

Unit	Top (cm)	Base (cm)	Colour	Composition	Hum.	Contact
4	33	61.5	7.5YR 3/4	$Tb^2 3$ $Th^2 1$ Tl+ Sh+	2	Diffuse
5	61.5	90	7.5YR 2.5/1	$Th^3 1$ $Tb^3 2$ Sh1 Tl+	3	---
Core H						
1	0	15	7.5YR 2.5/2	$Th^1 3$ $Tl^1 1$ Sh+	1	Diffuse
2	15	37.5	7.5YR 2.5/3	$Th^3 3$ Sh1 Tl+	4	Diffuse
3	37.5	48	7.5YR 2.5/3	$Th^3 2$ $Tb^3 2$ Sh+ Tl+	3	Diffuse
4	48	69.5	7.5YR 3/3	$Tb^2 3$ $Th^2 1$ Sh+	3	Sharp
5	69.5	90	7.5YR 2.5/1	$Th^3 2$ Sh1 $Tl^3 1$ Tb+	4	---

The peat stratigraphy from these cores appear to indicate that surface microforms are generally persistent features, and correlation of horizontal stratigraphic units across cores is difficult. Cores D and E in particular show little variation in the floristic composition of the peat in the upper 90cm. Cores A and H appear to show the greatest variability, showing marked changes in humification. Cores B and G from adjacent hummocks also show variability in peat composition in the upper 90cm, both featuring units of poorly-humified *Sphagnum* rich peat at 41cm depth (unit 5, core B) and 33cm depth (unit 4, core G), respectively.

Based on an examination of the peat stratigraphy, cores B, C and D were selected for testate amoebae analysis and dating, as these appear to be representative of the range of variability of near-surface peats at Annaghbeg.

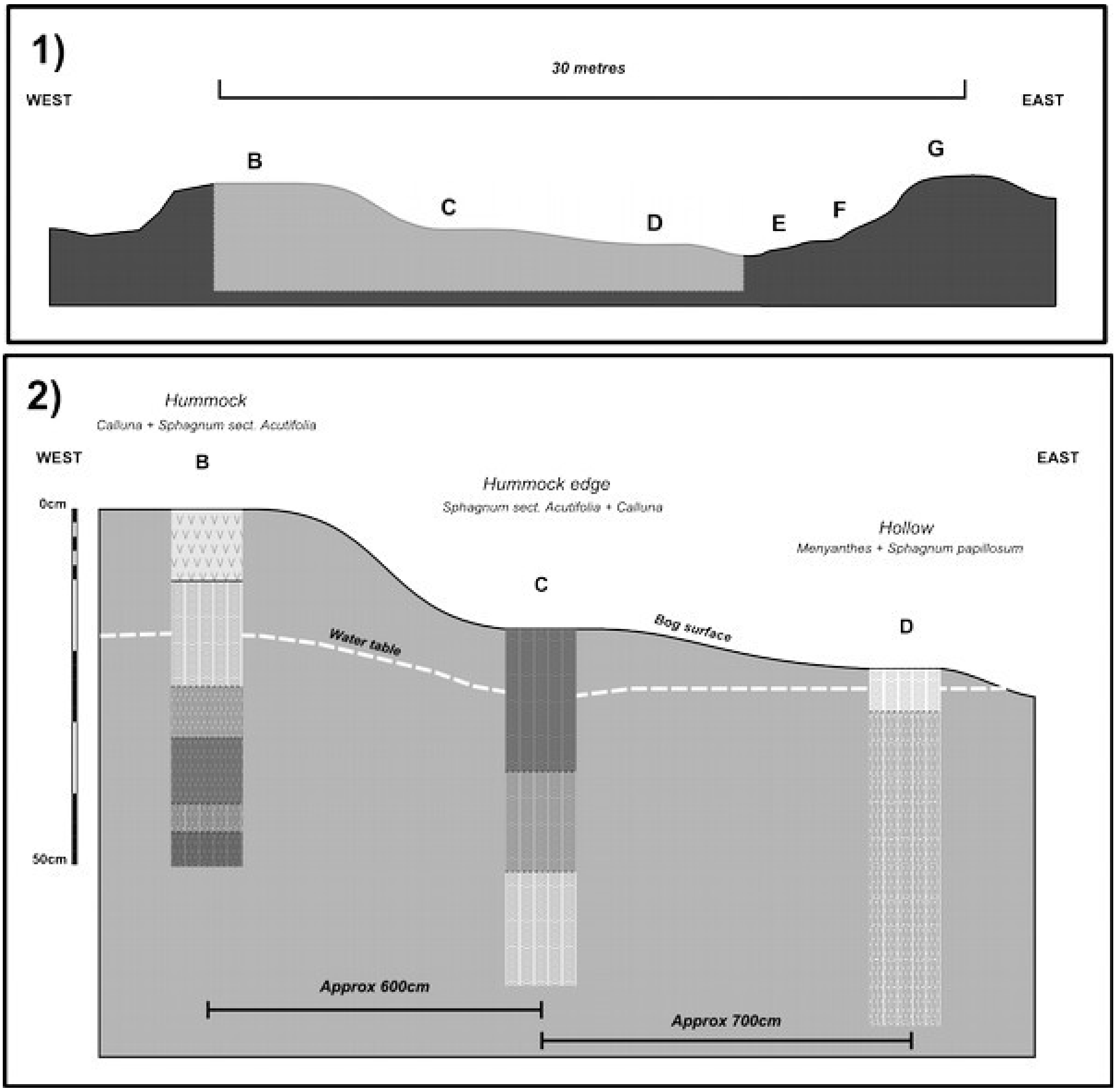

Figure 82: 1) High-resolution transect of cores (B – G) across a single hummock – hollow – hummock microtopographic sequence at Annaghbeg. Not to scale. 2) Detailed view of cores B, C, and D. Vertical scale is shown on the left hand side, not to scale horizontally.

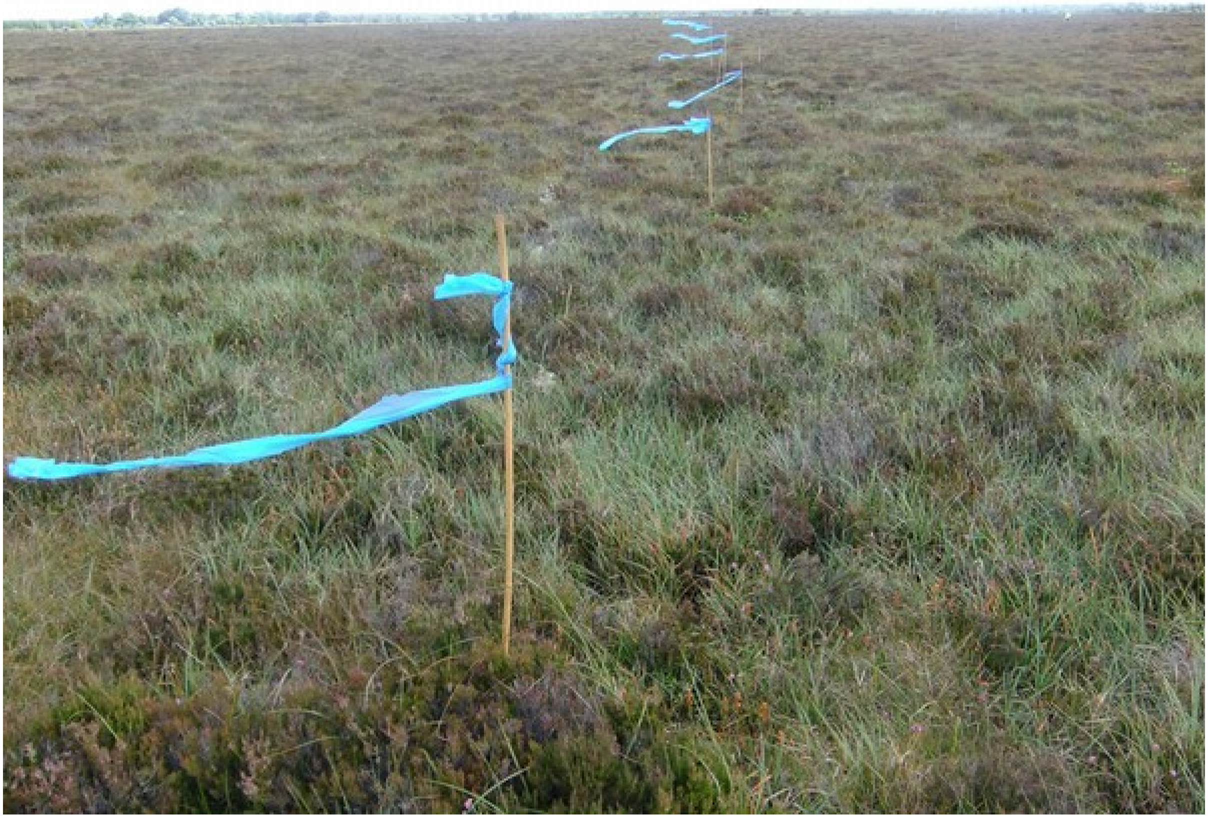

Figure 83: Location of shortcores B - G (marked by canes with blue tape). View towards east.

8.3.2 Chronology

To provide a chronological framework for the testate amoebae analysis, samples from cores B, C, and D were prepared for dating using ^{210}Pb; in addition, samples from core A were also prepared to compare the accumulation rate of this more marginal part of Annaghbeg with the other cores obtained from nearer to the dome of the bog. As a means of cross-validating the chronologies based on ^{210}Pb. $^{210}Pb_{excess}$ and ^{137}Cs inventories for cores B, C and D are shown in Figure 84.

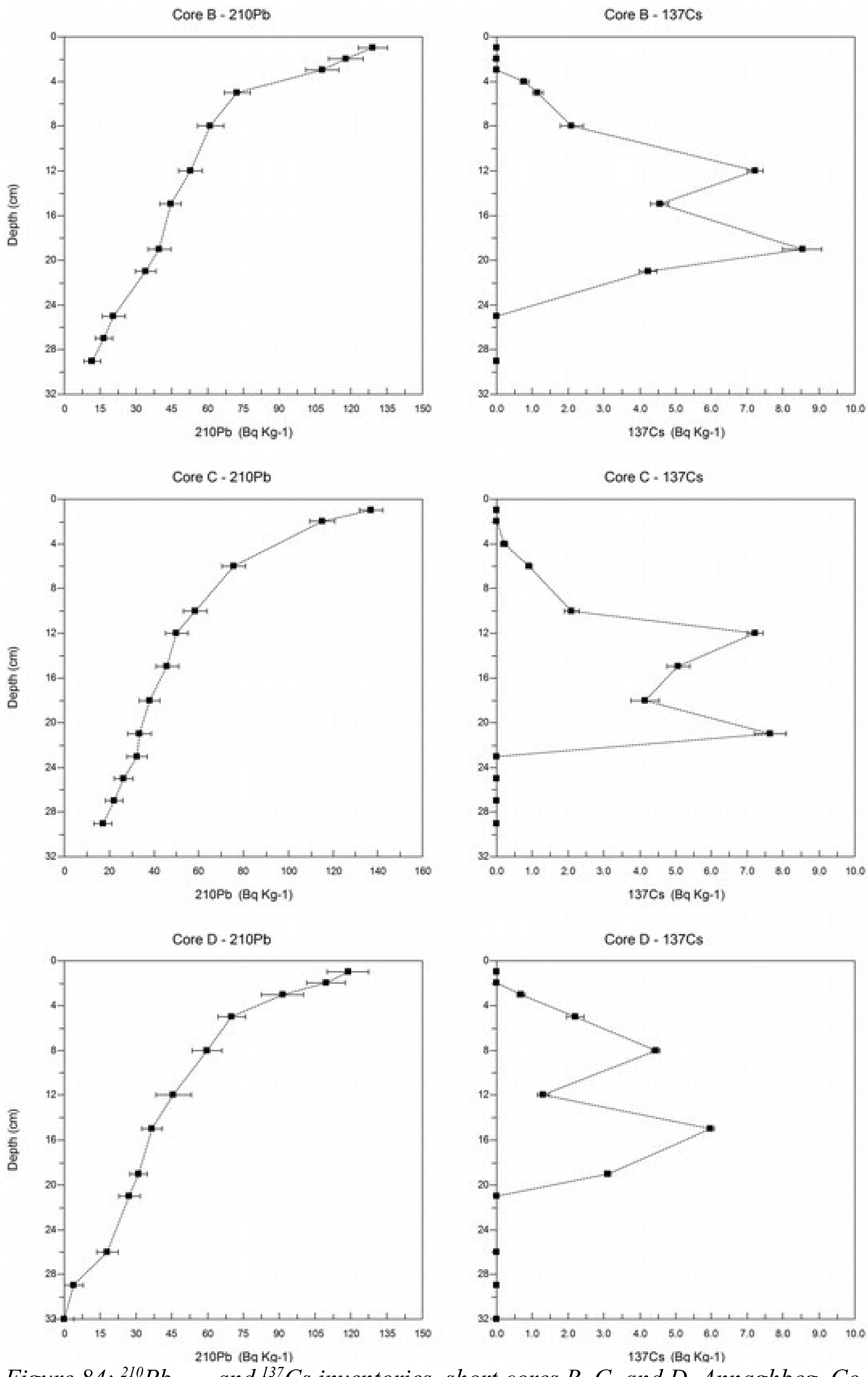

Figure 84: $^{210}Pb_{excess}$ and ^{137}Cs inventories, short cores B, C, and D, Annaghbeg, Co. Galway.

Based on these data and measurements of peat bulk density, the Constant Rate of Supply (CRS) model was applied, with resulting age vs depth model is shown in Figure 85.

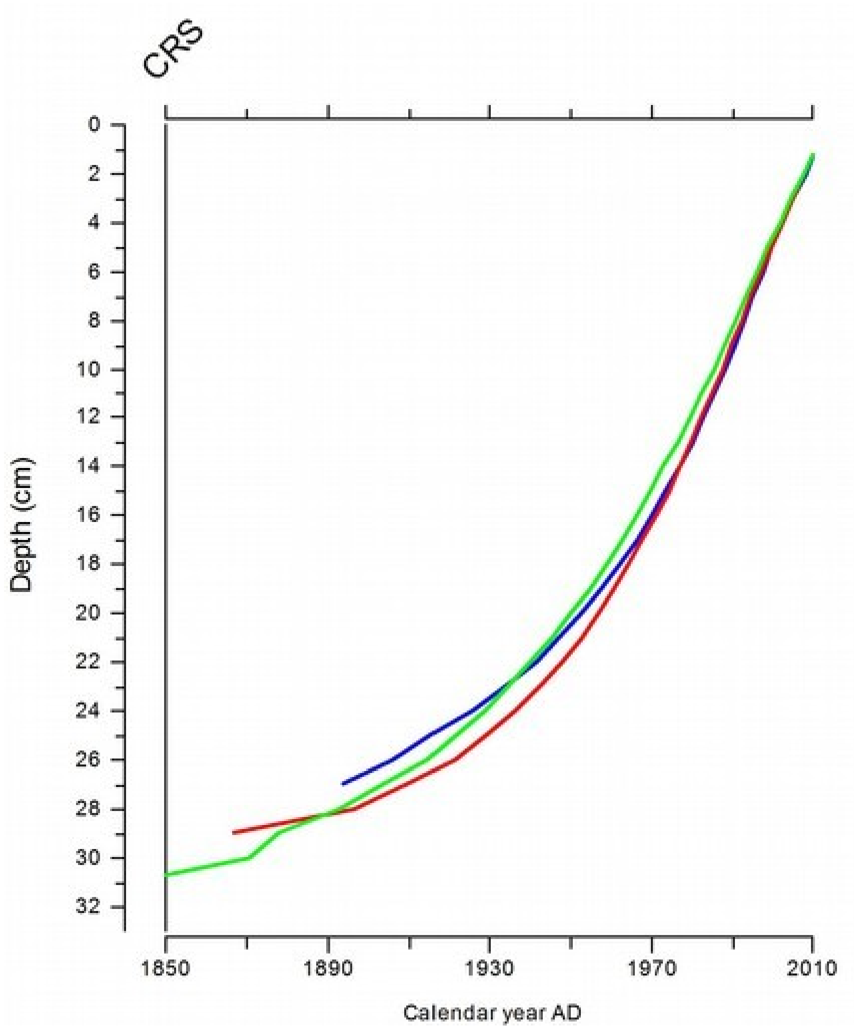

Figure 85: Age vs depth model for short cores B, C, and D, Annaghbeg bog, Co. Galway. Blue line – core B, red line – C, green line – D. Age vs depth models are based on the CRS model.

The CRS model (Appleby and Oldfield 1978) is the most commonly used model for ages from ^{210}Pb measurements, and is often thought to produce robust results (Le Roux and Marshall 2011, p.6). As illustrated in Figure 84, this model appears to show very similar accumulation rates for cores B, C, and D. Accumulation rates in the late 19th century appear to be around 10-15 years per cm, increasing to rates of up to *c.* 2 years per cm. At least part of this decrease in accumulation rate with depth may be attributed to compression of lower peats due to the weight of the overlying deposits (Belyea and Clymo 2001).

This model appears to be relatively robust when compared with the ^{137}Cs data. In the

Northern hemisphere, ^{137}Cs deposition histories show two peaks – a large peak at around 1963 as a result of atmospheric nuclear weapons tests, and a smaller peak relating to the explosion at Chernobyl in 1986 (Monna *et al* 2009). ^{137}Cs inventories from all three cores show two distinct peaks, the earlier being larger. When the CRS age vs depth model was applied, the 210Pb dates of lower peak were estimated at 1958, 1953, and 1970 in cores B, C, and D, respectively. The upper peak was dated to 1983, 1983, and 1980, respectively. This suggests that some age estimates of the ^{210}Pb age models may tend to be slightly too old, but that errors of the age estimates are in the region of around 10 years for the 20th century. In the process of producing the composite water table curve these chronologies were tuned, see section 8.3.4 below.

8.3.3 Testate amoebae analysis

A total of 24 samples each from cores B and C, and 50 samples from core D were analysed. All but 7 samples from core B, six samples from core C, and ten samples from core D yielded counts of 150 tests or more; the remaining samples all produced counts of at least 110 tests.

8.3.3.1 Core B

The percentage testate amoebae diagram from core B is shown in Figure 86. A total of 33 taxa were present in the upper 48cm of core B. Assemblages were generally dominated by *Difflugia pulex* and *Nebela militaris*. Between 48cm and 36cm depth, *N. militaris* dominates (up to 38%) alongside *D. pulex* (maximum 32%). From 36cm depth to 20cm depth, *N. militaris* declines to *c.* 10%, and *D. pulex* increases, reaching a maximum of 54% at 26cm depth. From 20cm depth to the top of the sequence *D. pulex* generally declines, with a concomitant increase in *N. militaris*. *Hyalosphenia minuta* is present from 18cm depth, and reaches a maximum of 27% at 12cm depth, before declining. *Trigonopyxis arcula* was present in the upper 10cm of the sequence, increasing to a maximum of 16% at 4cm depth. *Amphitrema flavum* was only present intermittently, reaching peaks at 48cm (19%), 34cm (15%), and at 20cm (14%). *Assulina muscorum*, *Cyclopyxis arcelloides*, and *Difflugia pristis* are present in abundances of *c.* 10-20% throughout the sequence.

Depth to water table (DWT) reconstructions produced using the central Irish transfer function indicate generally dry conditions throughout the sequence, with a mean DWT of 13.6cm. DWT values indicate dry conditions at 48cm depth, water tables then rise with DWT values reaching a minimum at 32cm depth (DWT = 8.4cm). Thereafter DWT values generally indicate increasingly dry conditions, increasing to a maximum of 19.7cm at 12cm depth, but punctuated by a slightly wetter interval at 20cm depth (DWT = 9.8cm).

8.3.3.2 Core C

The percentage testate amoebae diagram from core C is shown in Figure 87. A total of 37 taxa were present in the upper 46cm of core C. Assemblages were generally characterised by a gradual shift from co-dominance of *Amphitrema* spp. and *Difflugia* pulex, to communities dominated by *D. pulex*. *Assulina* muscorum, *Difflugia pristis*, *Cyclopyxis arcelloides*, and *Nebela militaris* were present throughout. *Arcella* spp. were more abundant lower in the sequence, and decline towards the top.

DWT values generally increase throughout the upper 50cm of core C, indicating a general trend towards drier conditions. The wettest value (DWT = -0.7cm) was at the base of the sequence (at 46cm depth), indicating saturated surface conditions. Following this, water tables fall steadily, reaching a maximum at 3cm depth (DWT = 14cm). Generally falling water tables were punctuated by a brief shift to moister conditions (DWT = 6cm) at 14cm depth.

8.3.3.3 Core D

The percentage testate diagram from core D is shown in Figure 88. A total of 43 taxa are represented in assemblages from the upper 50cm of core D. Assemblages are dominated by *Amphitrema flavum* and *Amphitrema wrightianum*. The relative proportions of these taxa fluctuated, with *A. wrightianum* reaching peaks at 46cm depth (52%) and 16cm depth (59.5%). From 44cm depth, *Heleopera sphagni* increased from 0% to a peak of 27% at 34cm before declining again. *Assulina muscorum* was present in low concentrations throughout the sequence, but reaches a peak of 29% at 14c depth. *Difflugia rubescens* was present from 50cm to 25cm depth, and was also present in the upper part of the sequence reaching a peak of 17% at 8cm depth. From 13cm depth to the top of the sequence, *Difflugia leidyi* increased up to a maximum of 20%.

DWT values show persistent wet conditions, with a mean value of -0.7cm – indicating saturated or submerged surface conditions. DWT values reach maximum values of 2.4cm at the top of the sequence. Small drops in the water table are indicated at 27cm depth (DWT = 2.2cm) and 13cm depth (DWT = 1.3cm). Wetter shifts occurred at 46cm depth (DWT =

-4.5cm), 16cm depth (DWT = -3cm), and 9cm depth (DWT = -3.2cm), indicating periods of standing water.

8.3.3.4 Discussion

Analysis on cores B, C, and D, has shown that testate amoebae assemblages vary considerably between microtopes. Assemblages from the top of a hummock (core B) were generally characterised by *Difflugia pulex – Nebela militaris* communities, whilst assemblages from the adjacent hollow (core D) were dominated *Amphitrema* spp., and assemblages from an intermediate location (core C) share features of both communities. The persistence of these associations lends support to the suggestion that, at least whilst the upper *c.* 50cm of peat has been accumulating, surface microforms have been long-lived persistent features.

Reconstructed DWT values from the three cores vary both in absolute values and in magnitudes of variability. DWT values from core D have a mean value of -0.7cm, and range from a minimum of -4.5cm to a maximum of 2.4cm. DWT values from core B have a mean value of 13.6cm, and range from a minimum of 8.4cm to a maximum of 19.7cm. Core C is intermediate between these two, with a mean DWT of 7.7cm. Core C shows the greatest range of DWT values, with a minimum of -0.7cm and a maximum of 14.6cm – a range of water table variability of 15.3cm.

In spite of these important differences between cores, DWT curves from all three cores show common features (see also section 8.3.4): all three DWT curves show a trend towards increasing (drier) values towards the top of the core, this is especially evident in cores B and C. This trend towards drier conditions is punctuated be wetter intervals in all three cores at similar depths, particularly clear is the wet shift recorded in core B at 20cm, 14cm in core C, and 16cm in core D. This suggests that the hydrology of all three locations appear to be responding to a common forcing.

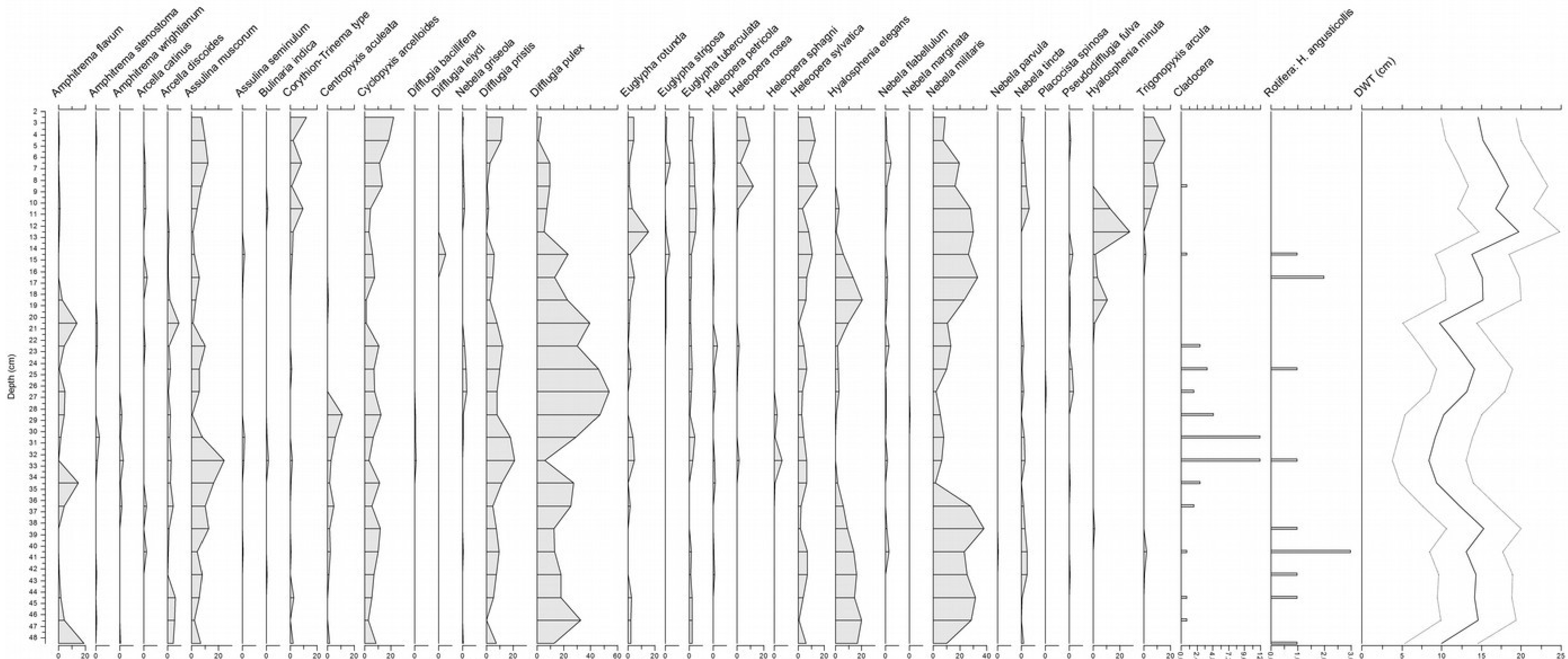

Figure 86: Percentage testate amoebae diagram from core B, Annaghbeg, Co. Galway. Reconstructed DWT values, calculated using the central Irish transfer function, are shown on the right (bold line), with bootstrapped errors shown in dotted lines.

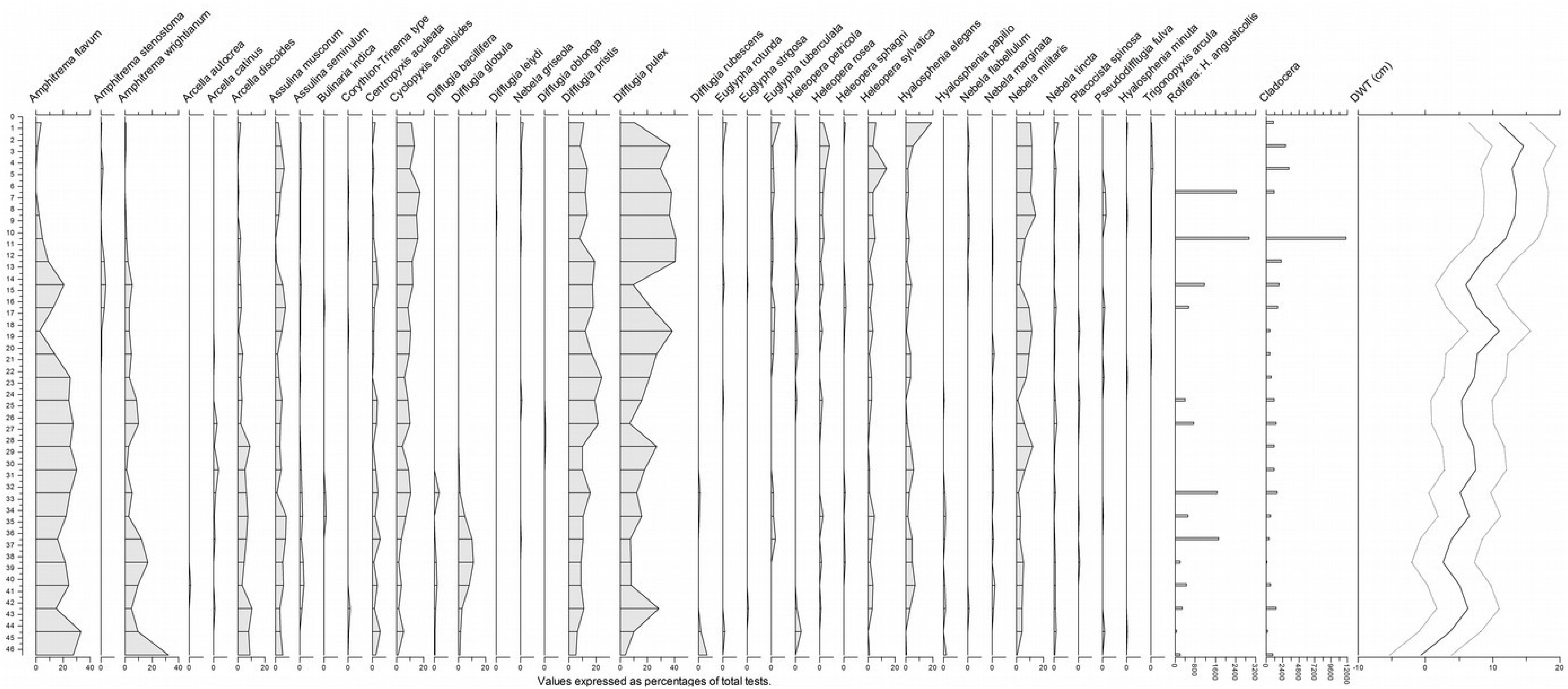

Figure 87: Percentage testate amoebae diagram from core C, Annaghbeg, Co. Galway. Reconstructed DWT values, calculated using the central Irish transfer function, are shown on the right (bold line), with bootstrapped errors shown in dotted lines.

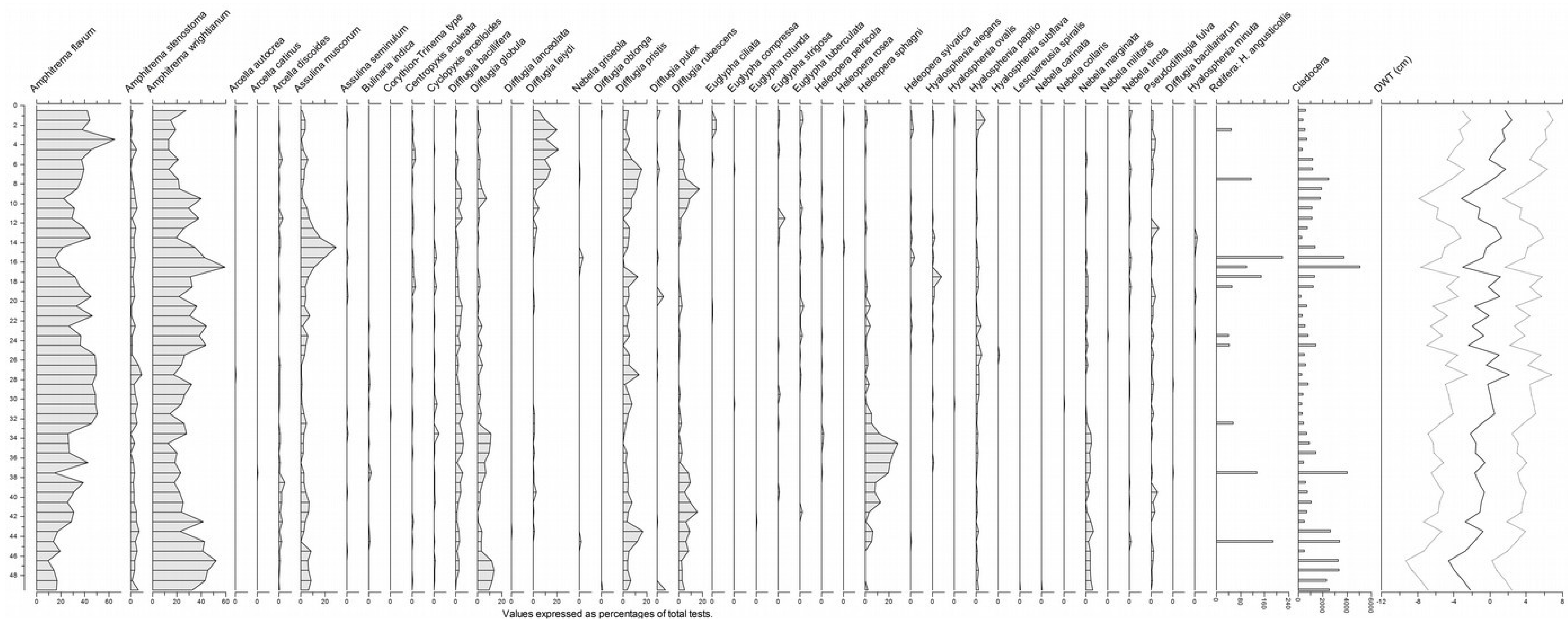

Figure 88: Percentage testate amoebae diagram from core D, Annaghbeg, Co. Galway. Reconstructed DWT values, calculated using the central Irish transfer function, are shown on the right (bold line), with bootstrapped errors shown in dotted lines.

8.3.4 Compilation of composite water table reconstruction

To facilitate comparisons with instrumental weather data, a composite water table record was produced from the three short cores (B, C, and D). This was desirable since, due to the sampling resolution (cores B and C were analysed at 2cm resolution, core D at 1cm resolution), and slower peat accumulation rates during the late 19th century, each core does not have a datapoint in every decade. In order to produce a composite record, the 'tuning and stacking' (Charman *et al* 2006) method was employed. This involves harmonising ('tuning') the original chronologies to a common chronology, and combining ('stacking') the proxy records. Although this approach has been criticised (Blaauw 2012; Swindles, Blaauw, *et al* 2012), so long as records show consistent features, and chronologies are not tuned beyond the confidence intervals of the original age vs depth models, this method may be considered robust and has been widely used (Charman *et al* 2006; Charman 2007; Swindles, Blundell, *et al* 2010).

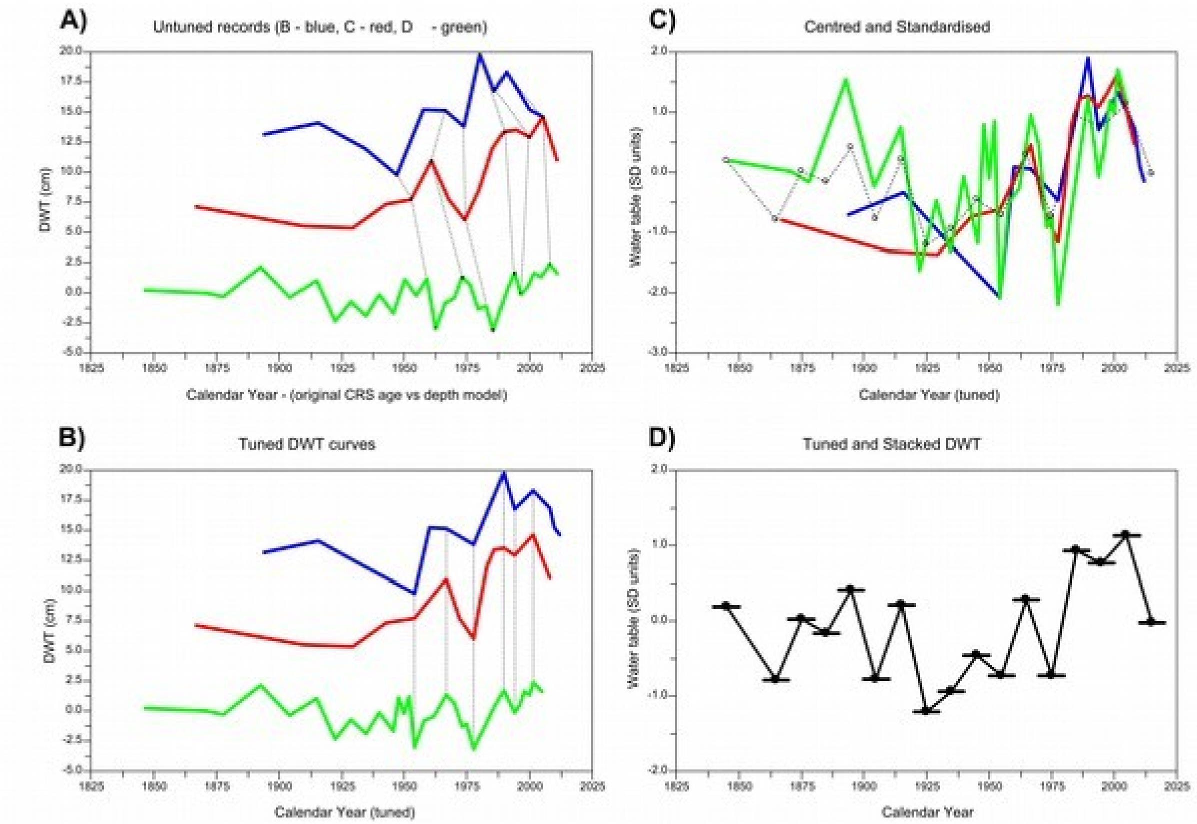

Figure 89: Compilation of composite DWT curve from Annaghbeg. 1) DWT curves (bootstrap errors omitted for clarity) plotted against original CRS chronology. Tiepoints used for tuning are shown by black dots connected by dashed lines. 2) DWT curves plotted against revised (tuned) chronology. 3) Tuned DWT curves converted to SD units. 4) Composite decadal mean water table curve.

Figure 89A shows the DWT curves from cores B, C, and D plotted against original chronologies. For clarity, bootstrapped errors are not shown. Black dots connected by dotted lines show six tie-points, or common features (selected on the basis of a visual examination of the data) of each DWT curve used for tuning. These tie-points were assigned new revised dates by taking the mean of the original calendar dates from the CRS age vs depth models. Linear interpolation was used to estimate ages of intervening levels. Figure 90 shows the revised age vs depth models for these cores (bold line), compared to the original CRS model (dotted line). In general, revised dates were within 10 years of the original dates. As a further check on the validity of these revised dates, ^{137}Cs curves are also plotted (red line). All three curves show two distinct peaks in ^{137}Cs values, these are expected to relate to atmospheric nuclear weapons tests (peaking in 1963) and the Chernobyl disaster in 1986 (Monna *et al* 2009). In general, the revised chronologies show slightly improved agreement with the dates of these events (Table 55). In spite of this, the revised chronologies are not necessarily any more accurate or 'correct' than original age estimates, but these do facilitate compilation of the proxy records of past hydrology. DWT curves plotted against revised chronologies are shown in Figure 89B.

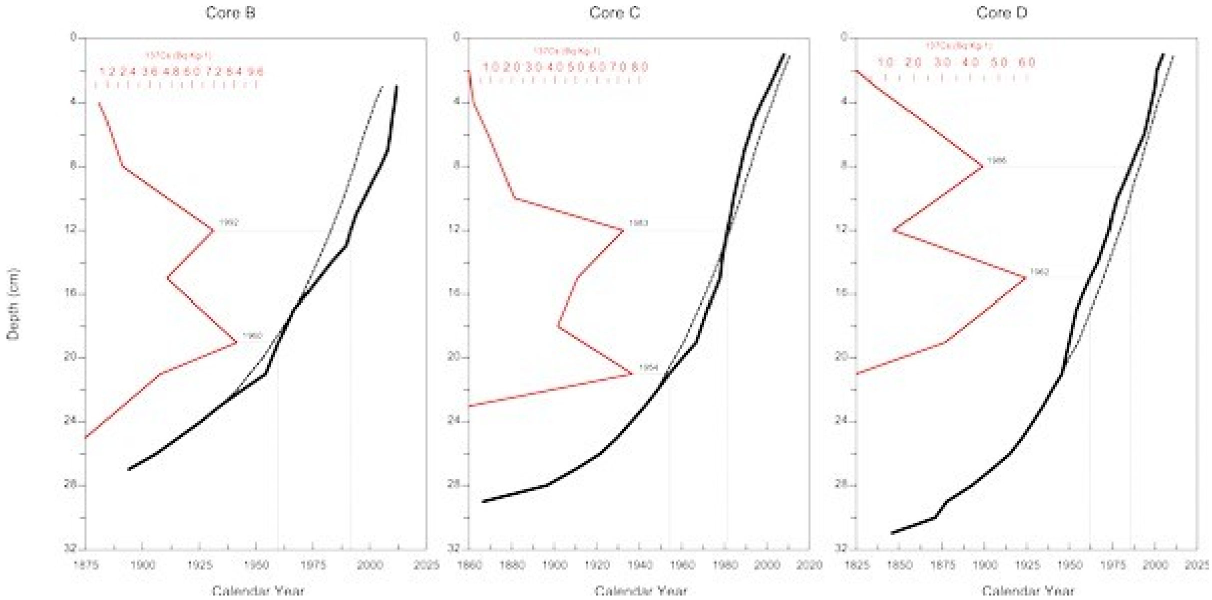

Figure 90: Revised (tuned) age vs depth models for cores B, C, and D, Annaghbeg. Revised age vs depth models are shown by bold black lines, original CRS models are shown by dotted lines. ^{137}Cs curves are shown in red, plotted against depth.

Table 55: Comparison of date estimates for peaks in ^{137}Cs for cores B, C, and D, Annaghbeg, from original and revised (tuned) chronologies.

Core	Lower Peak (*c. 1963*)		Upper peak (*c. 1986*)	
	Original date	Revised date	Original date	Revised date
B	1958	1960	1993	1992
C	1953	1954	1983	1983
D	1970	1962	1991	1986

Due to the apparently persistent nature of the different microforms sampled, the DWT values obtained from cores B, C and D vary in absolute terms. With tuned chronologies, decadal average DWT from cores B and C, and C and D are significantly correlated (both r = 0.79, p < 0.001, r^2 = 62%). However, cores B and D are not significantly correlated. This result may be intuitive since core C is from an intermediate microtopographic position between cores B (hummock top) and D (hollow). An implication of this is that, in spite of common features, not all hydrological changes are reflected in all three cores. A combined record would reflect an 'average' signal which may lack some finer detail. To combine these records, and compensate for the marked differences in absolute DWT values and magnitudes of change, DWT values were 'centred and standardised' and converted to SD units (standard deviations from the mean). The standardised water table curves are plotted together in Figure 89C. In spite of the differences discussed above, these show reasonable visual agreement, particularly in the latter part of the 20th century.

Given the sampling resolution of the three curves, and the chronological uncertainties associated with these records, it was impractical to produce an annually resolved record. Therefore, the approach of Charman *et al.* (2004) was employed and decadal means of each core were calculated; these were then averaged, resulting in the decadally-averaged tuned and stacked water table record shown in Figure 89D.

8.4 Instrumental weather data

The six instrumental weather datasets examined were selected to cover as wide a temporal range as possible and to be as representative as possible of weather conditions at Annaghbeg bog. Characteristics of these datasets are given in Table 56. All six datasets contain precipitation data, whilst four also have mean daily air temperature data (Armagh, Birr, Dublin, and Galway). The dataset covering the longest time span is from Armagh Observatory, with mean daily air temperature data from AD 1796 onwards. The shortest datasets are from two precipitation stations close to Annaghbeg bog, at Ahascragh, Co. Galway, and Taughmaconnell, Co. Roscommon. Of the three long records, which stretch into the 19th century, the nearest is from Galway, 51km west of Annaghbeg bog, this record is, however, rather discontinuous missing data for large parts of the late 19th and mid 20th centuries.

Table 56: Instrumental weather datasets near to Annaghbeg bog, Co. Galway.

Station	**Distance from Annaghbeg**	**Variable and Temporal range (cal yr AD)**	**Notes**
Armagh Observatory	152km to NE	Temperature: 1796 – 2002 Precipitation: 1838 – 2001	
Ahascragh	7km to W	Precipitation: 1941 – 1987	Missing some data 1977-1982.
Birr Castle	40km to SE	Temperature: 1954 – 2013 Precipitation: 1954 – 2013	
Phoenix Park, Dublin	130km to E	Temperature: 1881 – 2010 Precipitation: 1881 – 2006 Evapotranspiration: 1942-2010	
Galway	51km to W	Temperature: 1861 – 2002 Precipitation: 1861 – 2002	Missing data 1871 – 1883 and 1952 – 1981.
Taughmaconnell	6.5km to E	Precipitation: 1953 – 1985	Missing 1970 – 1981.

From these datasets, annual precipitation, summer (June, July, August) precipitation, annual mean temperature, and mean summer, and mean winter (December, January, February) temperature were calculated.

Annual and summer precipitation totals are significantly correlated in all six datasets. Similarly, annual, summer, and winter mean daily temperature are all significantly correlated. Correlations between annual and seasonal mean daily temperature are all stronger than correlations between summer and annual precipitation, suggesting overall greater coherence and 'smoothness' in the temperature data. In all datasets annual mean daily temperature and annual precipitation are not significantly correlated, however, summer mean daily temperature and summer precipitation are somewhat negatively correlated (Armagh r = -0.42, Birr r = -0.44, Dublin r = -0.36, Galway r = -0.36, all p <0.01). Winter temperatures are strongly correlated with winter North Atlantic Oscillation (NAO) index, and weakly correlated with annual mean daily temperature. Annual precipitation totals are not significantly correlated with winter NAO index, although ten-year running means of both variables are correlated (r = *c.*-0.3, p <0.01).

From 1942 onwards, additional data was available from Dublin, allowing evapotranspiration to be calculated using the Penman (1948) equation. Using these data, annual effective precipitation (precipitation minus evapotranspiration – P-E) and estimated growing season deficit were calculated. Estimated annual growing season deficit was calculated using the method described by Charman (2007, p.218): being the sum of all monthly deficits where evapotranspiration exceeded monthly precipitation. Larger and more frequent deficits were usually recorded between May and August, but deficits were occasionally recorded in each month of the year. This reflects the relatively low seasonality associated with Ireland's maritime climate. The mean growing season deficit recorded between 1942 and 2008 was 670mm. Wetter periods with below average deficits occur in the early 1960s and late 1970s, whilst notable periods of higher than average water deficit occur in 1975 and 1976, and between 1989 and 1991.

Figure 91 shows all annual temperature (upper panel) and all annual precipitation records, with bold coloured lines showing ten-year running means. Although these datasets are widely dispersed across Ireland (see Figure 81), correlations between these datasets are generally strong; temperature records show stronger cross-site correlations than precipitation. The gridded IPCC data for Annaghbeg (-8.25ºE 53.25ºN), shown by the magenta dots, appear to closely match the temperature data from the long continuous records from Armagh and Dublin, suggesting that these records are likely to approximate temperatures at Annaghbeg bog.

A clear longitudinal precipitation gradient (increasing precipitation westwards) is evident. The IPCC precipitation data closely match the higher annual precipitation totals from the more westerly weather stations (Galway, Ahascragh, and Taughmaconnell), rather than the lower precipitation recorded at sites east of the 8ºW meridian.

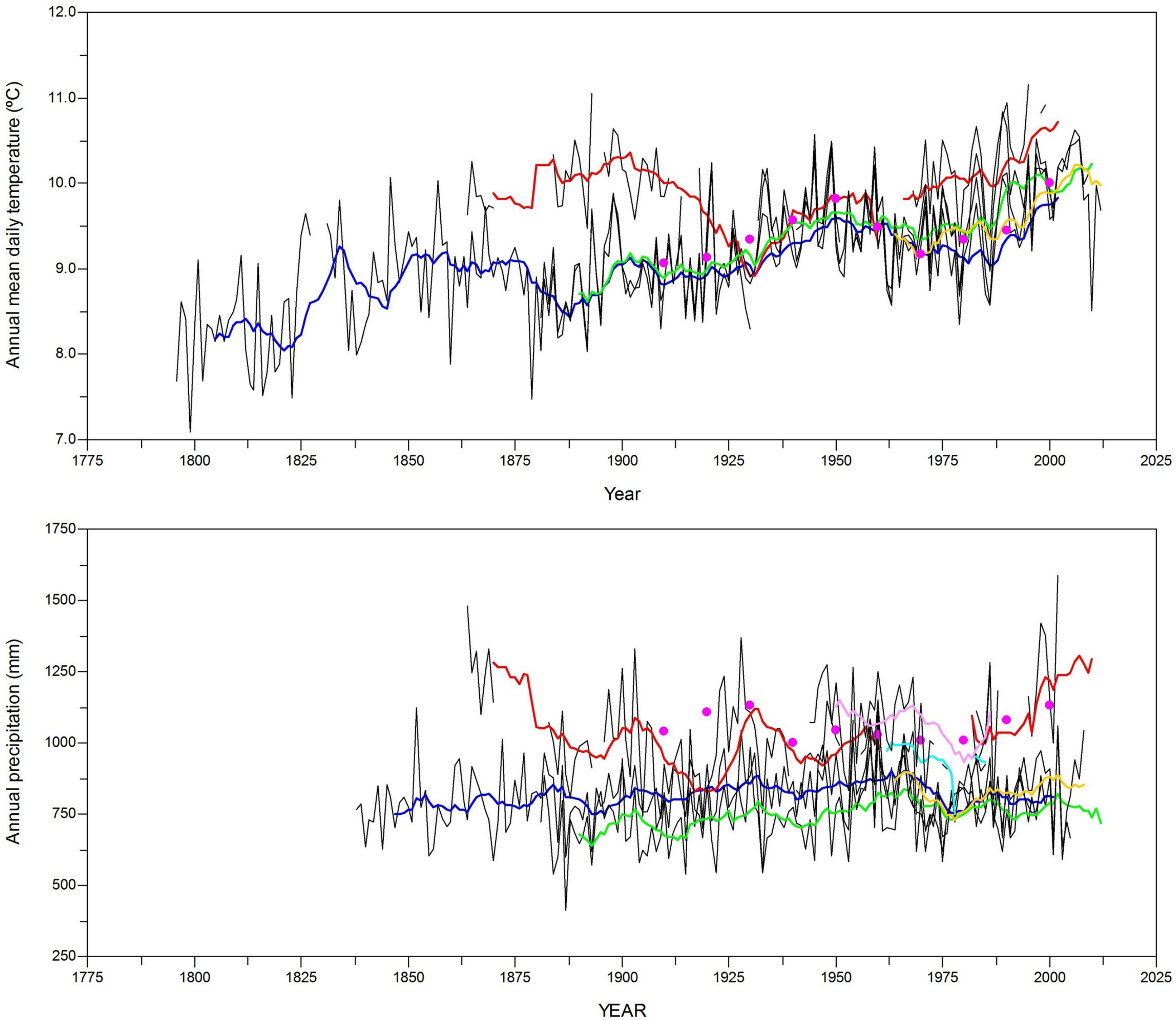

Figure 91: Instrumental weather data from Ireland. Upper panel: annual mean daily temperature. Lower: annual precipitation. Thin black lines indicate annual data from all datasets, bold coloured lines show ten-year running means, red – Galway, dark blue – Armagh, green – Dublin, amber – Birr, sky blue – Taughmaconnell, pink – Ahascragh. Magenta dots show IPCC gridded mean decadal values for the 0.5º grid square in which Annaghbeg is located.

The discontinuous nature of the Galway record (red line) may account for the occasional lack of agreement between this record and others, and this record is therefore of limited utility for this study, and has been excluded from further analysis below. Similarly, the precipitation records from Ahascragh and Taughmaconnell may be too short to allow detailed investigation of the links between BSW and instrumental weather data. The main feature of these precipitation records is the drought in the mid-1970s, which is also clearly recorded in the precipitation data from Armagh. Whilst the record from Armagh has the advantage of being long and continuous, the data from Galway do appear to suggest important differences in trend over the last *c.* 150 years. The precipitation data from Galway show a decrease in precipitation through the latter part of the 19th century and a notable increase in precipitation from the latter part of the 20th century. Data from Armagh and Dublin show a trend towards slightly increased precipitation throughout the 19th and earlier 20th century up to the mid-1970s drought. This is followed by a recovery in precipitation, but without the notable increase in rainfall shown in the Galway record in the late 1980s and 1990s.

8.5 Comparisons between reconstructed DWT and climate data

To assess the climatic drivers of the DWT record from Annaghbeg, these data were compared with the instrumental weather datasets described above. To facilitate comparisons with the decadally-resolved composite water table record, instrumental climate data were also converted to decadal averages. Following the approach of Charman *et al*. (2004), the effects of longer-term climatic forcing were also analysed by comparing climate data averaged over both the contemporary decade and the preceding decade (+ 10 years), and preceding two decades (+ 20 years). Correlation coefficients of these relationships are shown in Table 57.

*Table 57: Correlations between the composite water table curve from Annaghbeg and climate data averaged over the contemporary decade, and averaged over the contemporary decade plus the preceding ten, and twenty years. * p<0.05, **p<0.01*

	Contemporary decade	**+ 10 years**	**+ 20 years**
Annual Temperature			
Armagh *(1860s-2000s)*	0.38	0.31	0.37
Dublin *(1880s-2000s)*	0.45	0.47	***0.67**
Birr *(1950s-2010s)*	0.43	0.61	0.24
IPCC *(1900s-1990s)*	0.36	0.42	0.2
JJA Temperature			
Armagh	0.51	***0.52**	****0.65**
Dublin	0.36	0.44	0.6
Birr	0.42	***0.82**	0.46
IPCC	0.41	0.46	0.32
Annual Precipitation			
Armagh	-0.16	0.16	0.32
Dublin	0.26	0.18	0.46
Birr	0.45	0.27	0.2
Taughmaconnell *(1950s-1980s)*	****-0.95**	---	---
Ahascragh *(1940s-1980s)*	0.57	-0.28	0.39
IPCC	-0.04	-0.14	-0.41
JJA Precipitation			
Armagh	-0.25	0.02	0.14
Dublin	-0.21	-0.4	***-0.68**
Birr	0.36	0.35	0.14
Taughmaconnell	0.06	-0.43	-0.09
Ahascragh	-0.31	-0.54	-0.28
IPCC	-0.5	-0.64	****-0.84**
Precipitation – Evapotranspiration			
Dublin – Annual *(1940s-2000s)*	0.36	0.28	0.01
Dublin – growing season deficit	-0.29	***-0.78**	-0.53
NAO *(1860s-2010s)*			
Winter (DJF)	-0.05	---	---
Summer (JJA)	***-0.55**	---	---

The only variable that shows a statistically significant correlation with reconstructed water tables in contemporary decades is annual precipitation from the short record from Taughmaconnell – the nearest weather station to Annaghbeg bog. When climate variables are averaged over the contemporary and preceding decades, significant correlations are obtained with annual temperature (Dublin + 20 years), summer temperature (Armagh + 10 and +20 years, Birr + 10 years), summer precipitation (Dublin + 20 years, and IPCC + 20 years), and estimated growing season deficit (Dublin + 10 years).

Temperature variables generally show more consistent relationships with the reconstructed water tables than precipitation – this reflects the greater spatial heterogeneity of precipitation. This is illustrated by records from Birr: despite being only *c.* 40km away from Annaghbeg, precipitation variables from Birr do not show any significant correlations with reconstructed water tables, but temperature variables do.

Reconstructed water tables were not significantly correlated with the station-based winter NAO records, but a significant negative correlation with summer NAO index values from contemporary decades was found.

8.6 Climate forcing and microtopography

To assess intra-site variability in response of BSW to climate forcing, DWT records from the three individual cores (B, C and D) were separately compared with instrumental climate data.

It is important to stress that the chronologies of the original records were tuned to produce the composite water table curve; this was carried out to facilitate comparisons with instrumental climate data. Tuning chronologies of cores may lead to circular reasoning, which would thus invalidate any comparisons between individual records (Charman 2007, p.218; Blaauw 2012). Comparisons with instrumental weather data were therefore carried out using the independent un-tuned chronologies of each core.

Since climatic data from Dublin generally showed the strongest relationships with the composite water table curve from Annaghbeg (see Section 8.5, above), this dataset was compared with DWT data from individual cores. Due to the lower sampling resolution of cores B and C, these cores did not always have data for some decades up to the mid 20th century. Therefore the period 1950-2009 was used for comparisons between individual cores, as all three cores had data from each decade in this period.

Correlations with un-tuned water table chronologies are shown in Table 58, correlations with data based on tuned chronologies are shown in parentheses. For comparison with individual cores, correlations between the composite water table record and climate variables over the period 1950 to 2009 are shown in italics.

*Table 58: Correlations between individual un-tuned water table records from Annaghbeg and climate data from Dublin, 1950-2009. Climate data were averaged over the contemporary decade, and averaged over the contemporary decade plus the preceding ten, and twenty years. Correlations with water tables based on tuned chronologies are given in parentheses. Correlations between variables and the composite water table record for the same period are shown in italics. Only variables which showed significant relationships with the composite record (see Table 57) are shown. * p<0.05, **p<0.01*

Dublin (1950s-2000s)	**Contemporary decade**	**+ 10 years**	**+ 20 years**
Annual Temperature	*Composite: *__0.71__*	*Composite: 0.63*	*Composite: 0.61*
Core B	0.32 (-0.6)	0.17 (0.43)	-0.01 (0.38)
Core C	****0.91 (*0.75)**	****0.87 (*0.72)**	*0.82 (0.7)
Core D	0.5 (***0.71**)	0.63 (0.7)	0.68 (***0.75**)
JJA Temperature	*Composite: 0.51*	*Composite: 0.63*	*Composite: 0.37*
Core B	0.09 (0.46)	0.26 (-0.48)	0.14 (0.14)
Core C	***0.74** (0.47)	****0.87** (0.69)	0.67 (0.5)
Core D	0.61 (0.52)	0.56 (0.66)	0.52 (0.52)
JJA Precipitation	*Composite: -0.34*	*Composite: -0.36*	*Composite: *__-0.75__*
Core B	0.34 (-0.37)	0.05 (-0.52)	-0.53 (***-0.79**)
Core C	-0.17 (-0.15)	-0.37 (-0.1)	***-0.8** (-0.68)
Core D	-0.17 (-0.4)	-0.27 (0.28)	-0.11 (-0.6)
Growing season deficit	*Composite: -0.16*	*Composite: *__-0.78__*	*Composite: -0.53*
Core B	-0.27 (-0.3)	-0.53 (*-0.8)	-0.26 (-0.44)
Core C	-0.29 (-0.08)	****-0.86 (*-0.72)**	***-0.75** (-0.53)
Core D	-0.27 (0.0)	-0.17 (-0.65)	-0.67 (-0.46)

Correlations between individual un-tuned records and climate variables from Dublin are generally all similar in direction of relationship, and are comparable to those obtained with the tuned composite water table record. All cores generally show positive relationships with temperature variables, and negative relationships with summer precipitation and growing season water deficit.

The correlation coefficients between un-tuned data from core C and all variables are stronger compared to those with the tuned dataset. This might potentially indicate that the original chronology obtained for core C is the most accurate, but this is impossible to test without further independent chronological control. Conversely, correlation coefficients with untuned data from core B are weaker than with the tuned chronology. Variability in the relative strengths of these relationships may be partially attributed to chronological uncertainty, although this uncertainty may mask genuine differences between individual cores at sub-decadal timescales (see discussion below). Nevertheless, the record from core C does appear to genuinely show stronger correlations with instrumental climate data, showing the strongest correlations with almost all variables with both tuned and untuned chronologies.

8.7 Discussion

Comparisons between the composite decadal water table record from Annaghbeg and instrumental climate data supports the findings of previous studies (Charman *et al* 2004, 2009; Barber and Langdon 2007; Charman 2007) showing statistically significant correlations with both annual and summer temperatures, and annual and summer precipitation. In addition, confirming the findings of Charman (2007), statistically significant correlations were obtained with a record of estimated growing season water deficit. A significant correlation with summer NAO index values support the notion that changes in hydroclimate in Ireland are related to patterns of change in the relative strength of the westerlies. Comparisons between climate data average over preceding decades and water tables show that longer-term patterns in climate forcing have a significant effect on BSW.

A stated aim of this study was to investigate the intra-site consistency of the BSW record, in particular the effect of microtopography. To this end, three replicate cores were analysed: a core taken from the top of a *Calluna* topped *Sphagnum* sect. *Acutifolia* hummock (core B), a core from the edge of this hummock (core C), and a core from the adjacent *Sphagnum papillosum* hollow (core D). Although, as shown in section 8.3.4 above, the absolute values and overall magnitudes of change in DWT varied between cores, some general features of the DWT curve were consistent. Relationships between DWT records from individual cores and instrumental data were also explored.

Over decadal to multi-decadal timescales, both wetter and drier microforms respond in the same direction to climatic forcing as predicted by Barber (1981), and supporting the findings of Niinemets *et al.* (2011). However, correlations with instrumental weather data were strongest for core C lending support to the suggestion of Barber (1994) and Barber *et al* (1998) that the most sensitive coring location would be intermediate between hollows and hummocks. Testate amoebae assemblages from core C showed features common to both other cores, and reconstructed water tables showed the greatest range in absolute values (15.3 cm, compared with 11.3cm for core B, and 6.9cm for core D).

Better chronological control of these sequences allowing comparison between annually resolved water tables and climatic data may potentially reveal more clear differences in the response of different microforms at the sub-decadal scale. Holocene peatland palaeoenvironmental studies, such as those presented in this research, usually focus on centennial to millennial scale environmental change (e.g. Charman 2010; Langdon *et al* 2012; Swindles *et al* 2013); therefore sub-decadal inconsistency in the relative response of cores from different microforms may not necessarily have a dominant effect on the interpretation of palaeoenvironmental data. Given that the typical accumulation rate of Holocene ombrotrophic peats is often in excess of 10 years cm^{-1} (Clymo 1983, 1984; Belyea and Clymo 2001; van Bellen *et al* 2011), such fine chronological resolution requires analysis at very fine sampling resolution (mm scale) which is currently only experimental (Amesbury *et al* 2011). Indeed, it may be doubtful that microscopic proxies such as testate amoebae or pollen can be resolved at the sub-decadal scale except, perhaps, in uncompressed and rapidly accumulating surface peats (Moore 1989; Joosten and de Klerk 2007; Swindles and Plunkett 2011).

Nevertheless, differences in the relative sensitivity of different microforms should be borne in mind when interpreting records of past hydrological change. Hummock and hollow microforms are often persistent features, and are usually identifiable in the fossil record by examination of the peat stratigraphy and dominant testate amoebae communities. Conversion of quantitative DWT values to SD units (as carried out in the compilation of the composite record, section 8.3.4) goes some way towards compensating for differences in absolute DWT between microforms. However, sequences that are intermediate between drier and wetter microforms are likely to contain the most climatically sensitive record, and may be more sensitive than sequences from other microforms.

8.8 Conclusions

- Analysis of short cores from a variety of surface microforms from Annaghbeg, an intact raised bog in Co. Galway, show that these microforms have been persistent features, at least for the last ~150 years.

- Hummocks (drier microforms) and hollows (wetter) are inhabited by distinctive testate communities, with intermediate microforms having intermediate testate communities.
- DWT records from all three locations show common trends. DWT from a hummock (core B) and a hollow (core D) were both strongly correlated with DWT from an intermediate location (core C). However, DWT from cores B and D were not correlated.
- Reconstructed DWT from a composite record show statistically significant correlations with instrumental climate data when averaged over periods of 10 to 30 years. This shows that long-term weather patterns are reflected by the BSW record.
- Statistically significant relationships between DWT and both annual and summer temperature, annual and summer precipitation, growing season water deficit, and summer NAO index values were found.
- The record from core C, intermediate between a hummock and a hollow, show the greatest range in DWT values.
- When analysed separately, the DWT record from core C shows stronger correlations with instrumental climate data than the other two cores.
- This apparently confirms the suggestion of Barber *(1994)* that cores from intermediate microforms are likely to contain the most climatically sensitive record.

Chapter 9: Compilation of Holocene bog surface wetness records

This chapter presents evidence for Holocene climatic variability in the bog surface wetness (BSW) records from central Ireland presented in Chapter 7. To this end, two approaches were utilised: first composite water table curves were produced using the 'tuning and stacking' method (Charman *et al* 2006); second, the synchroneity of hydrological events observed across sites was assessed using the 'time window' approach (Blaauw, Christen, *et al* 2007). Using these methods, composite records were produced for the Derryfadda and Littleton bog chain sub-regions, as well as for the whole central Ireland study area, using data from all nine palaeohydrological sequences. In this way, variability at the sub-regional, as well as at the regional scale was examined.

9.1 Methods

9.1.1 Tuned and stacked records

The application, and criticisms, of the 'tuning and stacking' method are discussed in Chapter 2 (Section 2.1.9). The method was first applied to non-annually resolved testate amoebae-derived reconstructed water table records by Charman *et al*. (2006) using data from 10 ombrotrophic peat sequences in northern Britain. Methods closely followed those described by Charman *et al.*, and are summarised below:

1. Testate amoebae-derived depth to water table (DWT) data from each site were converted to time series utilising the Bayesian age vs depth models presented in Chapter 7.
2. Long-term autogenic trends were removed by applying a LOWESS filter (span = 0.5), and converting values to residual values from the LOWESS smooth line. Values were then centred and standardised (expressed as standard deviations from the mean).
3. Working on the assumption that there are no significant differences in climatic forcing between sites within each sub-regional cluster of sites (i.e. the Derryfadda bogs and the Littleton chain of bogs), chronologies of records within these sub-regions were 'tuned':
    i. Based on a visual inspection of the standardised and detrended time series

from each sub-region, a number of 'tie-points' were identified – i.e. common hydrological events that were apparently synchronous or near-synchronous.

ii. Dates of these tie-points were synchronised by calculating the mean date (based on the *maximum a posteriori* age estimate from the age vs depth model) of each event, and assigning the average date to each event.

iii. Revised age vs depth models were calculated using linear interpolation between tie-points.

iv. The resulting age vs depth models were checked to ensure that revised ages fall within the 95% confidence intervals of the original models.

4. The resulting revised time series were then 'stacked': 100 year running mean water tables (SD units) were calculated. No attempt was made to tune the chronologies of records between sub-regions.

9.1.2 The “time-window” approach

Blaauw *et al.* (2007) describe a method to quantitatively assess the potential synchroneity of events between proxy archives. This approach was applied to the DWT records from central Ireland, using the “Ages.Of.Events” command in the Bacon (Blaauw and Christen 2011) age vs depth modelling package.

In order to identify significant shifts to wetter conditions in each dataset, DWT data from each study site were detrended by converting values to residuals from a LOWESS smooth line (span = 0.5). Wet-shift events were inferred where water tables dropped by 1 SD unit or more. Bayesian age vs depth models, based on AMS ^{14}C dates were then re-run for each sequence, and the probabilities that a wet-shift event occurred within a given “time-window” was calculated. Probabilities were calculated for events in each sequence for a variety of time-window sizes: 50 years, 100 years, 200 years, 300 years, and 500 years, in each case with time-windows moving in steps of 10 years. The probability that wet shifts occurred across multiple sites was calculated by multiplying probabilities from corresponding time-windows across sites.

9.2 Tuned and stacked BSW records

9.2.1 Derryfadda bogs

Figure 92 shows the original DWT records (left) from Gowla (top), Killaderry (middle), and Castlegar (bottom), residual DWT values and tiepoints (centre), and the standardised water tables (SD units) plotted against the revised age models (right). Tuned and standardised water table data were then used to create a 100 year running mean (averaged over the preceding 100 years) stacked water table record shown in Figure 93. Datapoints for the period prior to *c.*3200 cal BP were sparse (i.e. frequently less than one datapoint per 100 years), therefore the stacked record is discontinuous prior to 3200 cal BP. For this reason,

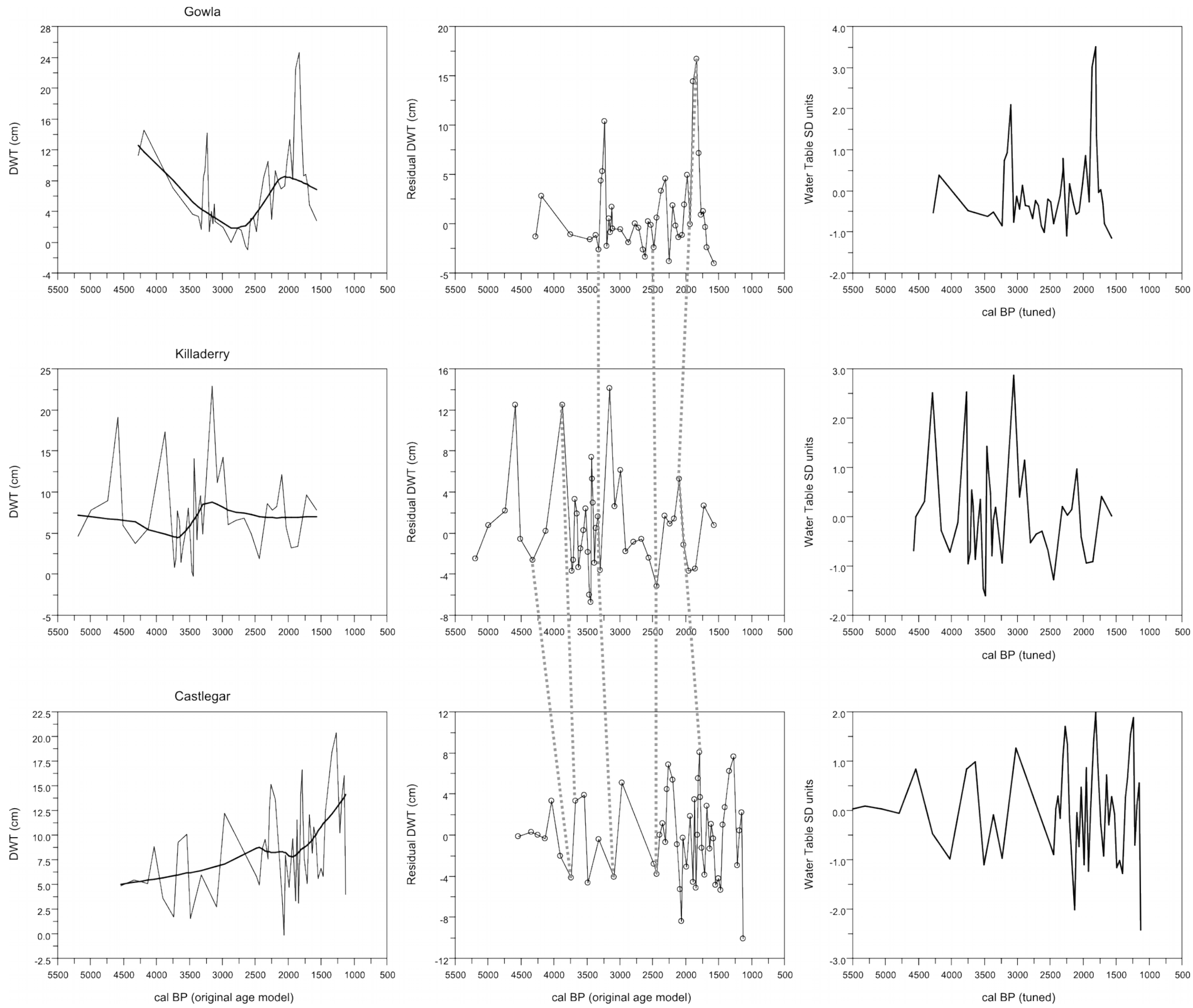

Figure 92: Tuning of DWT records from the Derryfadda bogs. Left: DWT plotted against original MAP age vs depth model (fine line) and LOWESS smooth line (bold). Centre: residual DWT values plotted against original age vs depth model with tiepoints indicated by dotted grey lines. Right: centred and standardised water tables plotted against revised age vs depth models.

only the period from 3500 cal BP to 1000 cal BP is shown in Figure 93.

As might be expected given the tuning process, individual records generally show good correspondence, however the record from Killaderry indicates drying *c.* 2100-2000 cal BP when the records from the other sites indicate wet conditions. The tuned and stacked record from the Derryfadda bogs shows considerable variability during the Late Holocene. Marked phases of wetter bog surface conditions occur between *c.* 2780 and 2380 cal BP, *c.* 2130 and 1860 cal BP, and *c.* 1550 and 1370 cal BP. Wetter phases are punctuated by periods of dry surface conditions at *c.* 3100 cal BP, *c.* 2300 cal BP, *c.* 1800 cal BP, and *c.* 1200 cal BP.

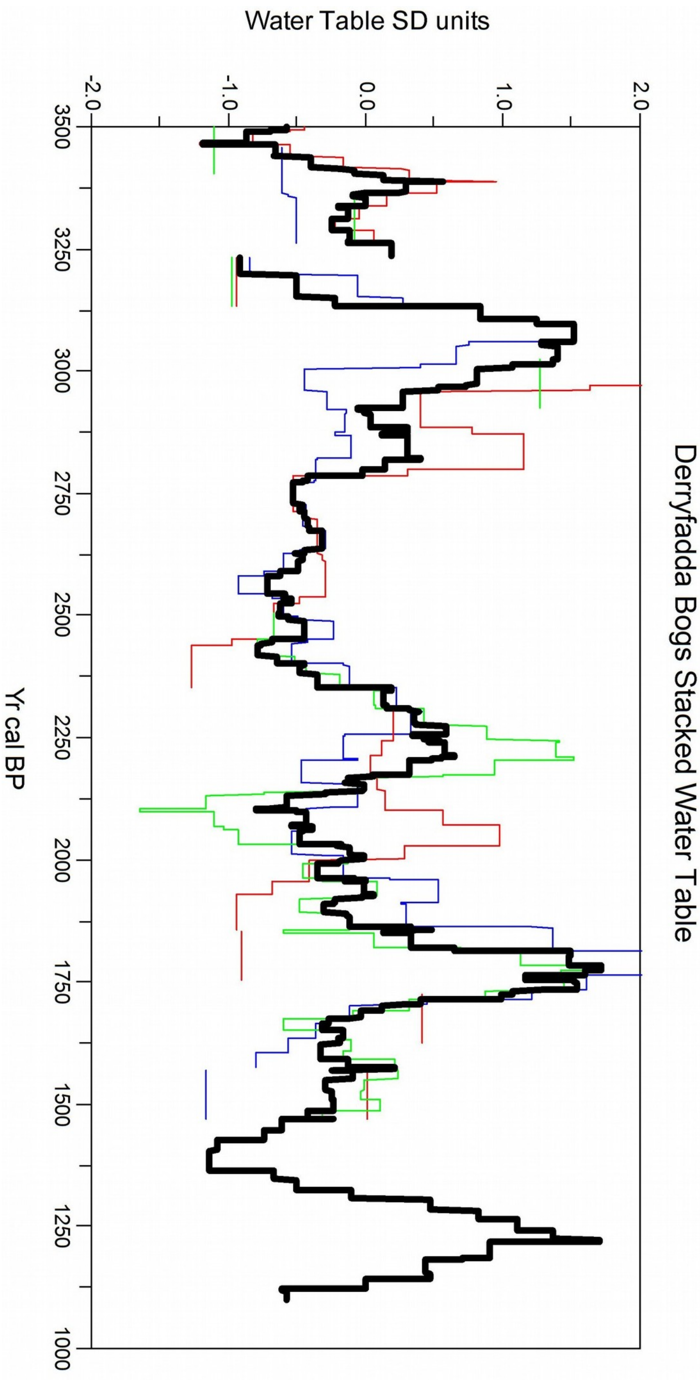

Figure 93: Tuned and stacked water table, Derryfadda bogs. 100 year running mean stacked water table shown by the bold black line. Fine coloured lines show 100 year running mean values for individual sites: blue – Gowla; red – Killaderry; green – Castlegar. Only the period from 3500 to 1000 cal BP is shown as data is discontinuous prior to 3500 cal BP. Note that negative values indicate wetter conditions.

9.2.2 Littleton chain

Figure 94 shows the original DWT records (left) from Inchirourke (top), Longfordpass (second from top), Littleton (second from bottom), and Killeen (bottom), residual DWT values and tiepoints (centre), and the standardised water tables (SD units) plotted against the

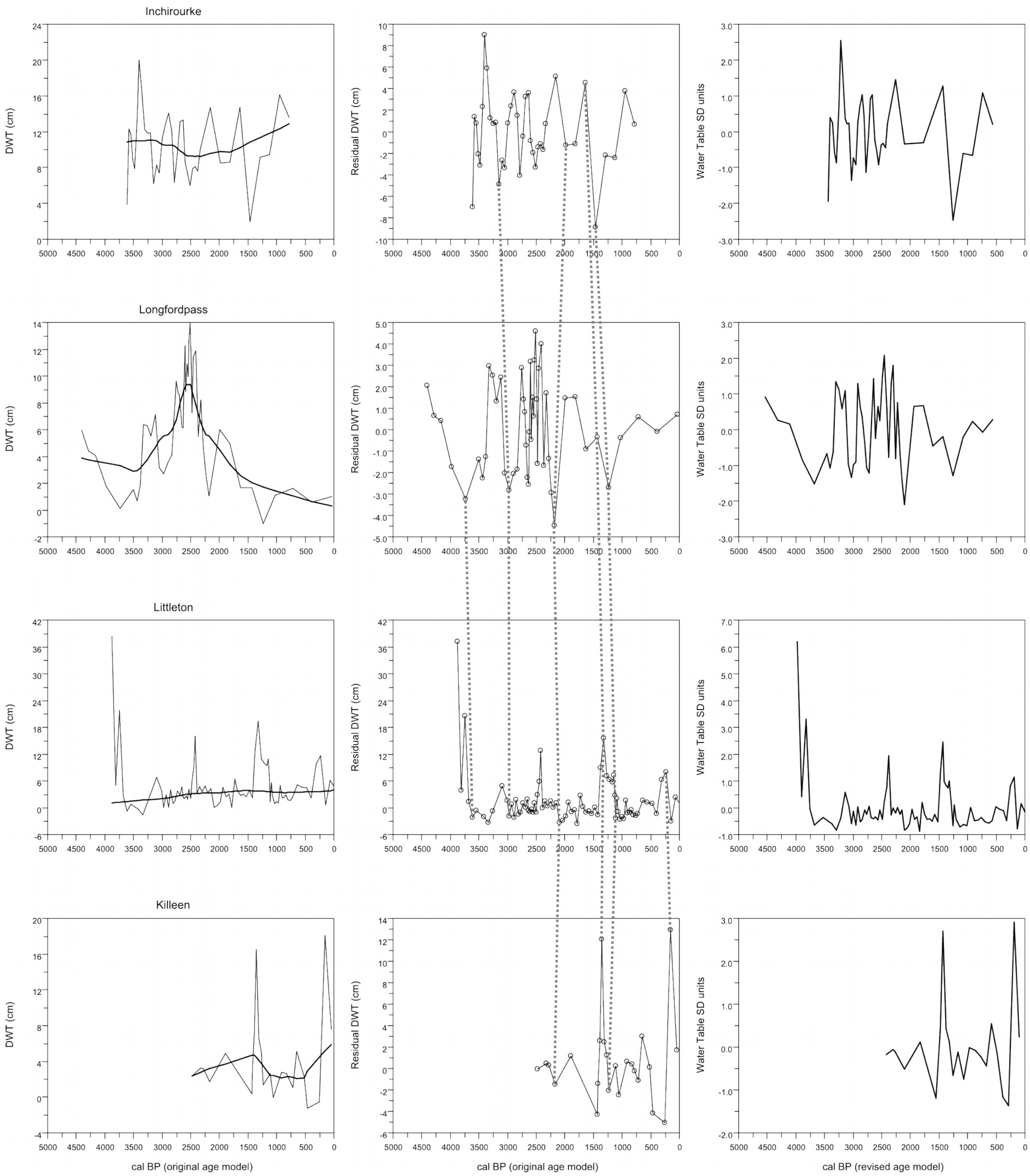

Figure 94: Tuning of DWT records from the Littleton chain of bogs. Left: DWT plotted against original MAP age vs depth model (fine line) and LOWESS smooth line (bold). Centre: residual DWT values plotted against original age vs depth model with tiepoints indicated by dotted grey lines. Right: centred and standardised water tables plotted against revised age vs depth models.

revised age models (right). Tuned and standardised water table data were then used to create a 100 year running mean (averaged over the preceding 100 years) stacked water table record shown in Figure 95. Datapoints for the period prior to *c.*3200 cal BP were sparse (i.e. frequently less than one datapoint per 100 years), therefore the stacked record is discontinuous prior to 3200 cal BP. For this reason, and to aid comparison with Figure 93, only the period from 3500 cal BP to 1000 cal BP is shown in Figure 95.

As in the record from the Derryfadda bogs, the tuned and stacked water table record from the Littleton chain of bogs shows considerable variability throughout the Late Holocene. Wet intervals are recorded at *c.* 3050-2950 cal BP, *c.* 2750-2650 cal BP, *c.* 2150-1950 cal BP, *c.* 1650-1500 cal BP, and at *c.* 1250-1160 cal BP. Dry phases are shown at *c.* 3150 cal BP and *c.* 1400 cal BP.

The correspondence between the stacked record from the Littleton bogs, and that from the Derryfadda bogs, summarised above, is especially good between *c.* 3100 and 1800 cal BP, with both records showing dry conditions at *c.* 3100 cal BP followed by wet phases shortly after *c.* 2800 cal BP and at *c.* 2150 cal BP. This may lend weight to the hypothesis that these records contain a regional palaeoclimate signal.

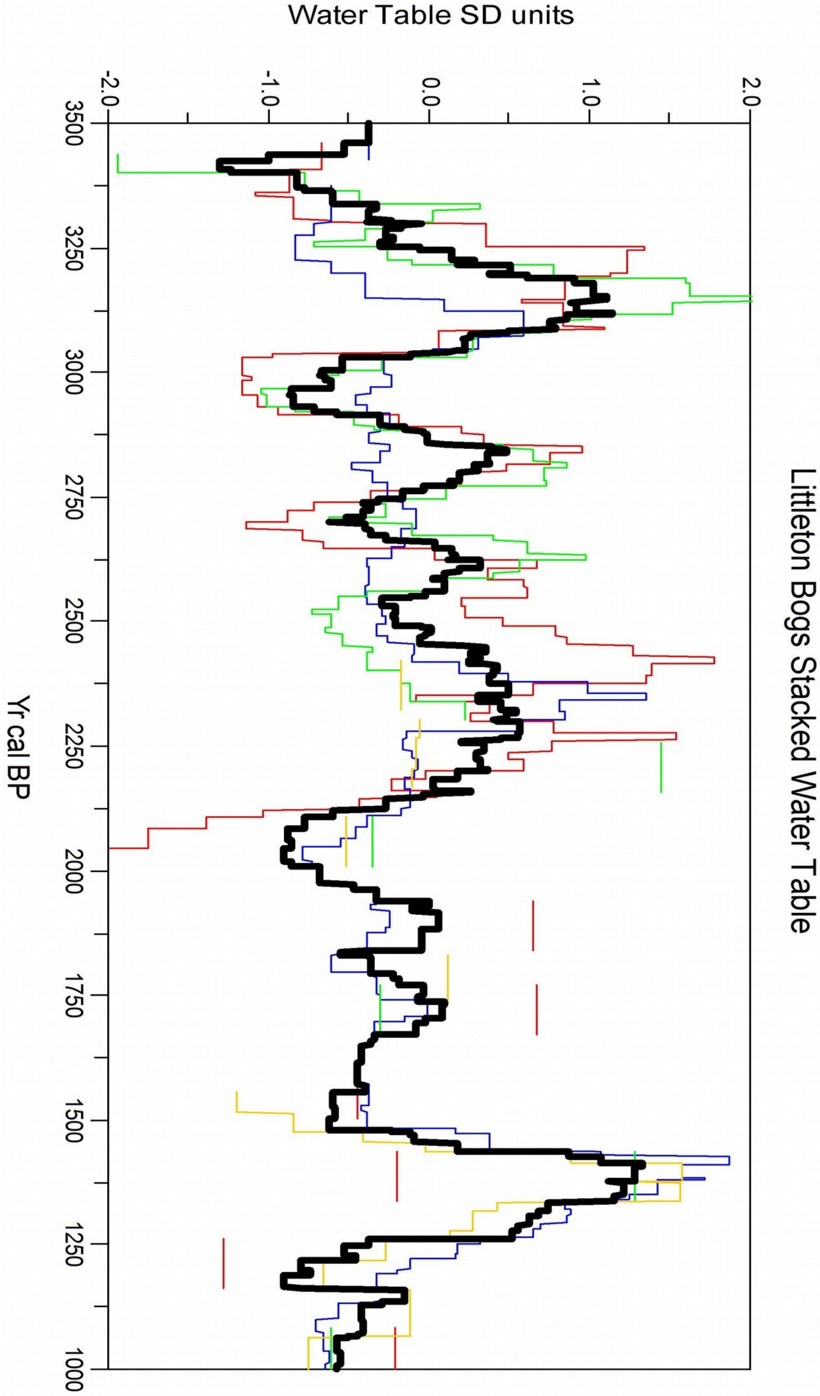

Figure 95: Tuned and stacked water table, Littleton bogs. 100 year running mean stacked water table shown by the bold black line. Fine coloured lines show 100 year running mean values for individual sites: blue – Littleton; red – Longford pass; green – Inchirourke; orange – Killeen. Only the period from 3500 to 1000 cal BP is shown as data is discontinuous prior to 3500 cal BP. Negative values indicate wetter conditions.

9.2.3 Central Ireland regional stacked record

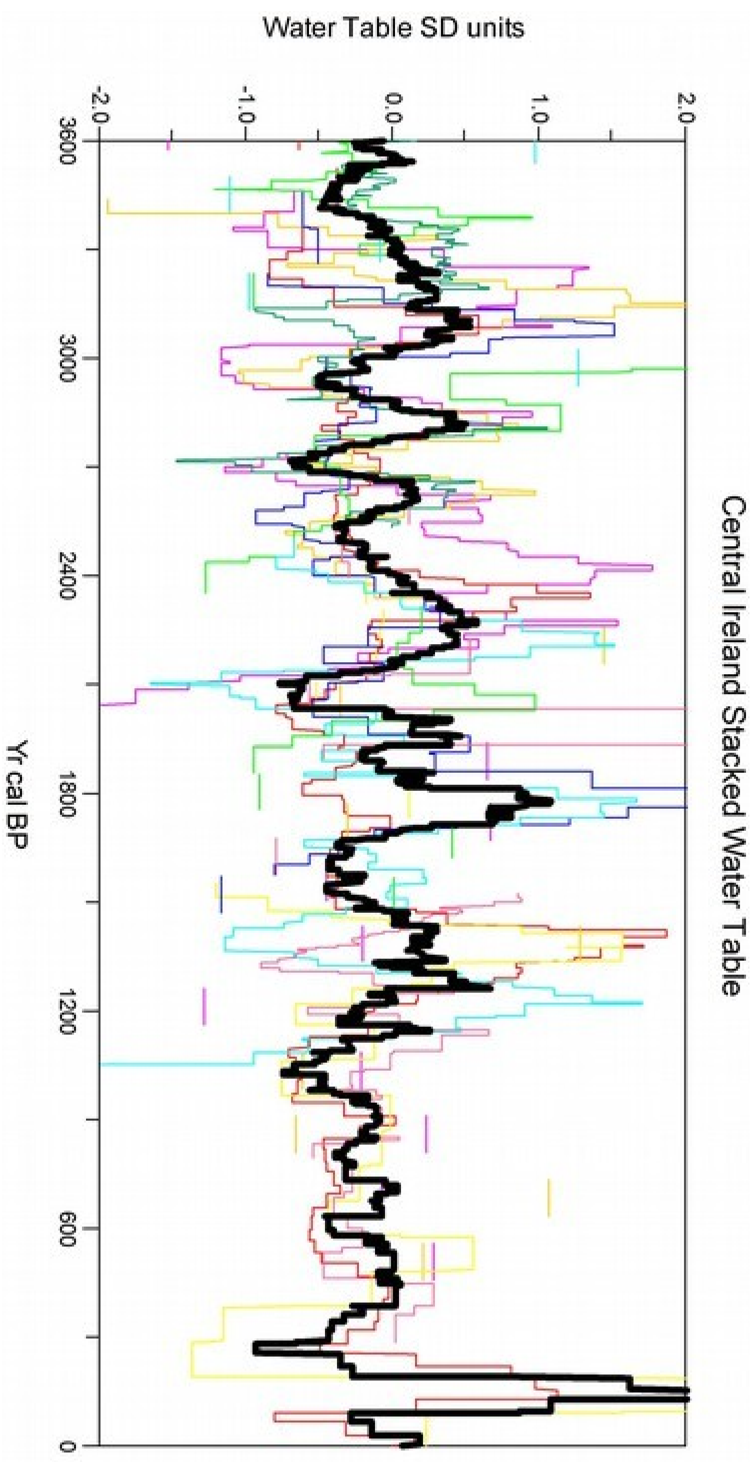

Figure 96: Central Ireland tuned and stacked peatland water table record. 100 year running mean stacked water table shown by the bold black line. Fine coloured lines show 100 year running mean values for individual sites. Only the period from 3600 to 1000 cal BP is shown as data is discontinuous prior to 3600 cal BP. Negative values indicate wetter conditions.

Figure 96 shows the tuned and stacked bog water table record from all nine study sites in central Ireland. This record was produced by stacking the tuned water table records from the Derryfadda and Littleton groups of bogs along with 100 year running means of the detrended and standardised water table records from the two remaining sites: Cloonshannagh and Kinnegad. No further tuning of chronologies was carried out.

Thin coloured lines in Figure 96 showing the 100 year moving average water table of each individual site shows a greater degree of heterogeneity than is observed in the records from the Derryfadda and Littleton sub-regions (shown in Figure 93 and Figure 95, respectively). Nevertheless the composite record, produced by averaging those from the individual sites, shows a distinct pattern of variability comparable both in magnitude and frequency to the stacked records from the two sub-regions.

Wet phases are recorded at *c.* 3530-3440 cal BP, *c.* 3000-2900 cal BP, *c.* 2750-2650 cal BP, *c.* 2550 cal BP, *c.* 2150-2050 cal BP, *c.* 1700-1500 cal BP, *c.* 1050 cal BP, and *c.* 300-250 cal BP. Drier intervals occur at *c.*3100 cal BP, *c.* 2850 cal BP, *c.* 2300-2200 cal BP, *c.* 1800 cal BP, and *c.* 200-100 cal BP.

9.2.4 Comparisons with other regional palaeoclimate records

Mayewski *et al.* (2004, p.245) identified several phases of rapid climate change (RCC) during the Late Holocene in the Northern Hemisphere based upon the synthesis of terrestrial, marine and ice core records: *c.* 4200-3800 cal BP, *c.*3200-2400 cal BP, *c.*1400-1000 cal BP, and *c.*600-0 cal BP. There is some degree of correspondence between RCC and phases of hydrological change observed in the central Ireland stacked water table record: the wet phases at *c.* 3000-2900 cal BP, *c.* 2750-2650 cal BP, and at *c.* 2550 cal BP coincide with RCC at *c.*3200-2400 cal BP; the wet phase at *c.* 1050 cal BP coincides with the *c.* 1400-100 cal BP RCC event; the wet phase at *c.* 300-250 cal BP occurs during the RCC from *c.* 600 cal BP onwards. However the frequency of hydrological change observed in the central Irish stacked record is too great to be explained by RCC events alone.

Given the geographic position of Ireland on the eastern fringe of the North Atlantic, and the importance of the influence of North Atlantic atmospheric circulation patterns on Ireland's weather (Davies *et al* 1997, pp.26–29), strong linkages might be expected between Irish palaeoclimate records and proxy records of changes in the North Atlantic circulation. Bond *et al.* (1997) identified a series of events during the Holocene defined by peaks in ice-rafted debris in cores from the North Atlantic ocean floor. Three such 'Bond events' were identified during the Late Holocene: at *c.* 4300 cal BP, *c.* 2800 cal BP, and at *c.* 1400 cal BP. Whilst the event at *c.* 2800 cal BP does appear to coincide with a prominent period of wet conditions visible in both sub-regional stacked records and in the central Irish stack, the correspondence between the Bond *et al.* record and the central Irish stacked water table record is poor since the latter exhibits much higher frequency variability.

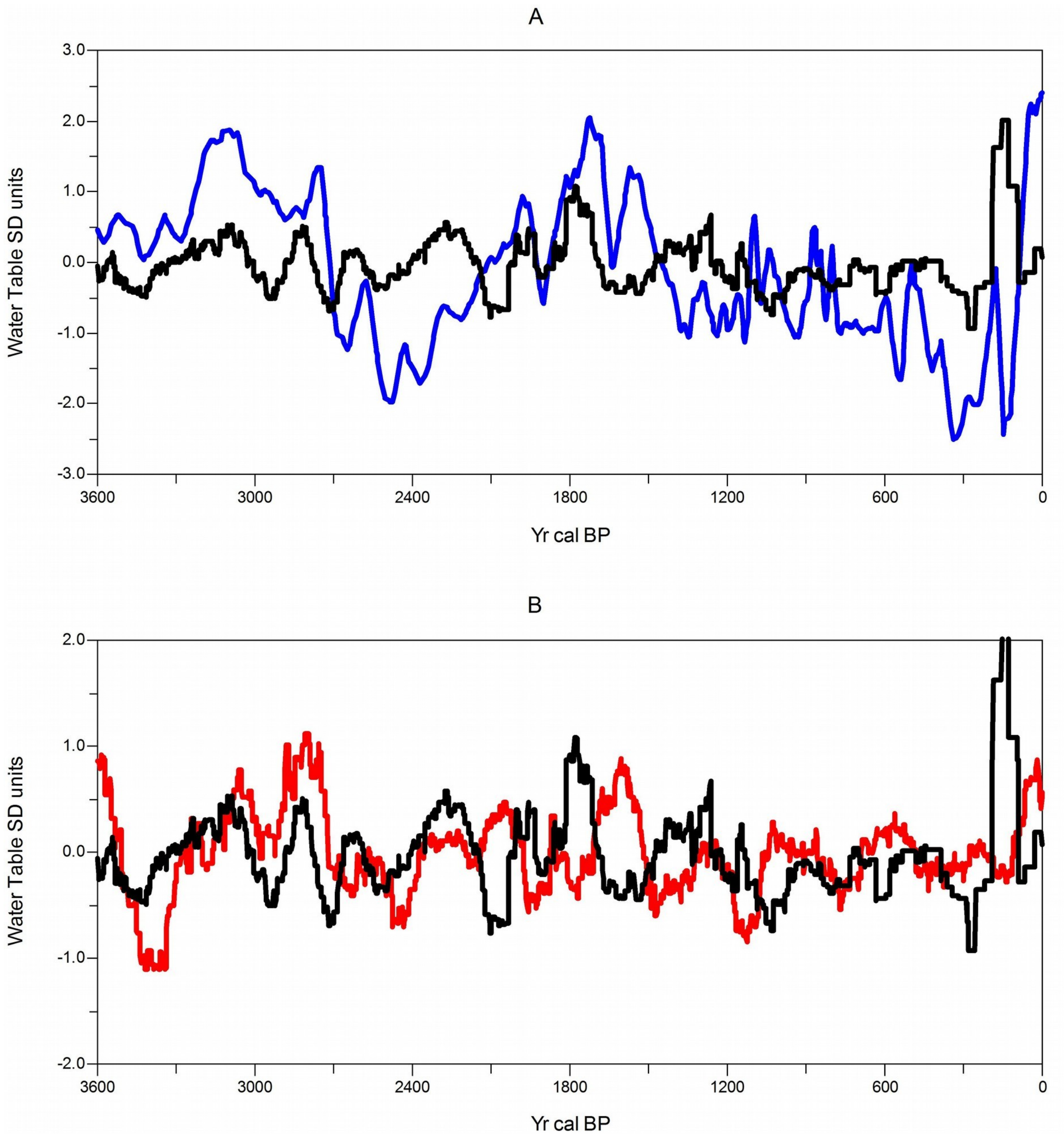

Figure 97: Comparison between the central Ireland stacked peatland water table record (bold black line in both panels) and A) – Swindles et al. (2013) Irish composite water table record (blue line – LOWESS smooth, centred and standardised); B) - Charman et al. (2006) stacked northern Britain water table (red line – 100 year running mean).

Charman (2010) reviewed evidence for Mid- to Late Holocene climate variability in the British Isles and identified patterns of variability of comparable frequency (i.e. centennial) to that observed in the central Irish stacked record. The composite peatland water table records of Charman *et al.* (2006) (northern Britain) and Swindles *et al*. (2013) provide direct comparators for the central Irish record. Figure 97 shows the central Irish stacked record plotted alongside the Irish composite record of Swindles *et al.* (A, blue line) and the Charman *et al.* northern Britain stacked record (B, red line). All three records show high-frequency centennial variability, although the Swindles *et al.* record exhibits a degree of low-frequency variability not evident in the central Irish or northern British record. Direct correspondence between records is, however, generally poor with the exception of some periods of apparent agreement (e.g. around 2000 cal BP with the Swindles *et al.* record, and around 3100 cal BP to 2600 cal BP with Charman *et al.*).

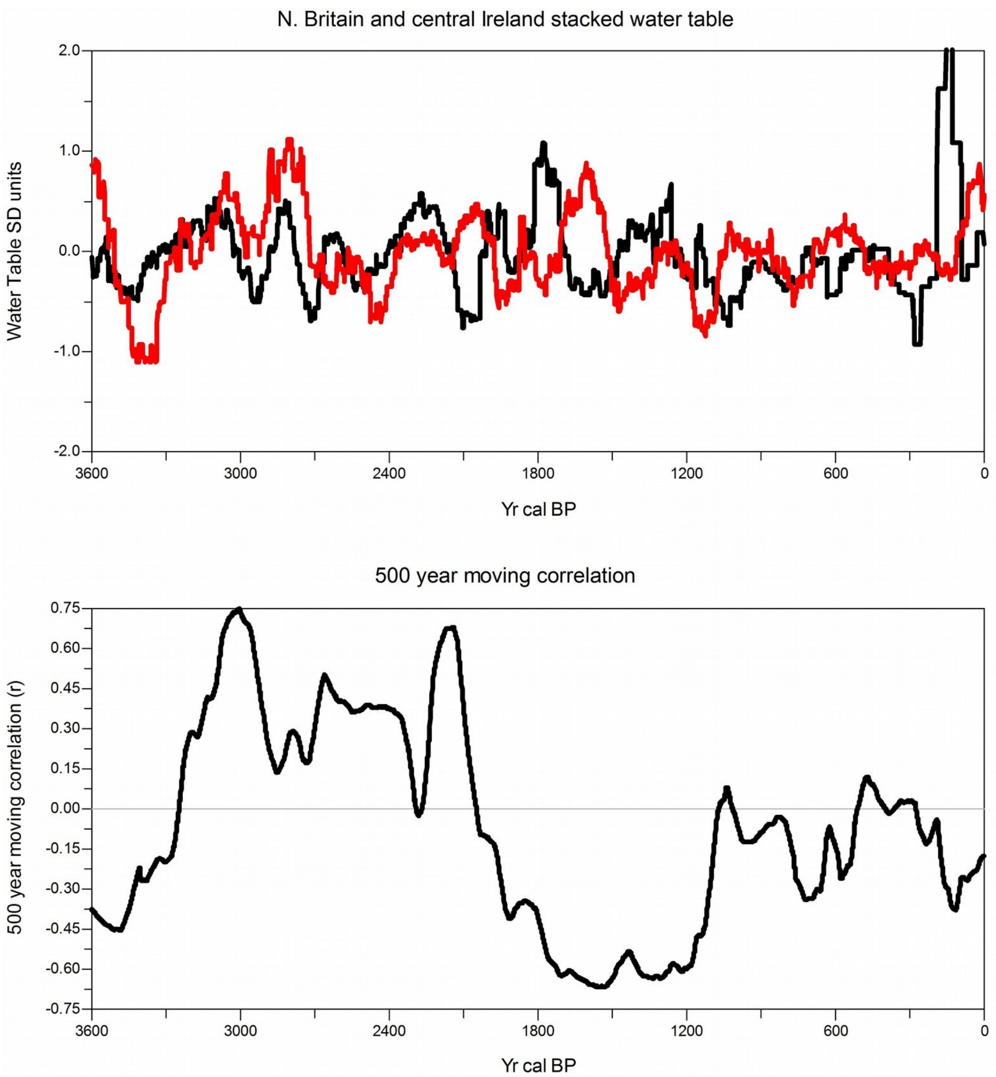

Figure 98: 500 year moving correlation coefficient between the central Ireland and Northern Britain stacked water table records (lower panel). Upper panel shows the two records for comparison.

Given that, unlike the Swindles *et al.* record, the central Irish and northern British stacked records are 100 year moving averages it is possible to obtain correlations between the records. Although the records over the full period 4535-0 cal BP are uncorrelated (r = -0.09, p<0.001), correlations between the records vary over time. Figure 98 shows the 500 year moving correlation coefficient between the two records; strong correlations (r=0.75) are apparent between the two records during the period *c.* 3200-2400 cal BP, but the records appear to be out of phase (negatively correlated) during *c.* 1800-1200 cal BP. Given the high frequency of variability in both records, the low or negative correlations may be a result of a number of factors: a) genuine leads and lags in climatic response in the two regions; b) local variability or climatic insensitivity of records during certain intervals; c) the considerable chronological uncertainties inherent in the data; or d) a combination of these factors. This finding supports the conclusion of Swindles *et al. (2013)* that coherence between water table records is highly variable except during intervals such as at *c.* 2700 cal BP (i.e. the Subboreal to Subatlantic transition) consistent with the RCC event at 3200-2400 cal BP defined by Mayewski *et al.* (2004).

9.3 Assessing the synchroneity of hydrological events

Identifying the effects of genuine local variability in climatic response of individual hydrological records is only possible if chronological uncertainties can be taken into account in compiling regional palaeoclimate records. Much criticism of the tuning and stacking method as focused on the issue of tackling chronological uncertainties in peatland records (Blaauw 2012; Swindles, Blaauw, *et al* 2012; Swindles *et al* 2013). The 'time-window' approach of Blaauw *et al. (2007)* provides an alternative method of comparing proxy records without compromising the independent chronologies of each record.

9.3.1 Cloonshannagh Bog

A total of 12 increases in BSW (drops in DWT values) were observed at Cloonshannagh. Utilising the 'time-window' approach, Figure 99 shows the probability that such an event occurs within a given time window. Probability peaks at *c.* 1450 cal BP, where there is >95% certainty that a wet shift occurs within a 100 year time-window around this date.

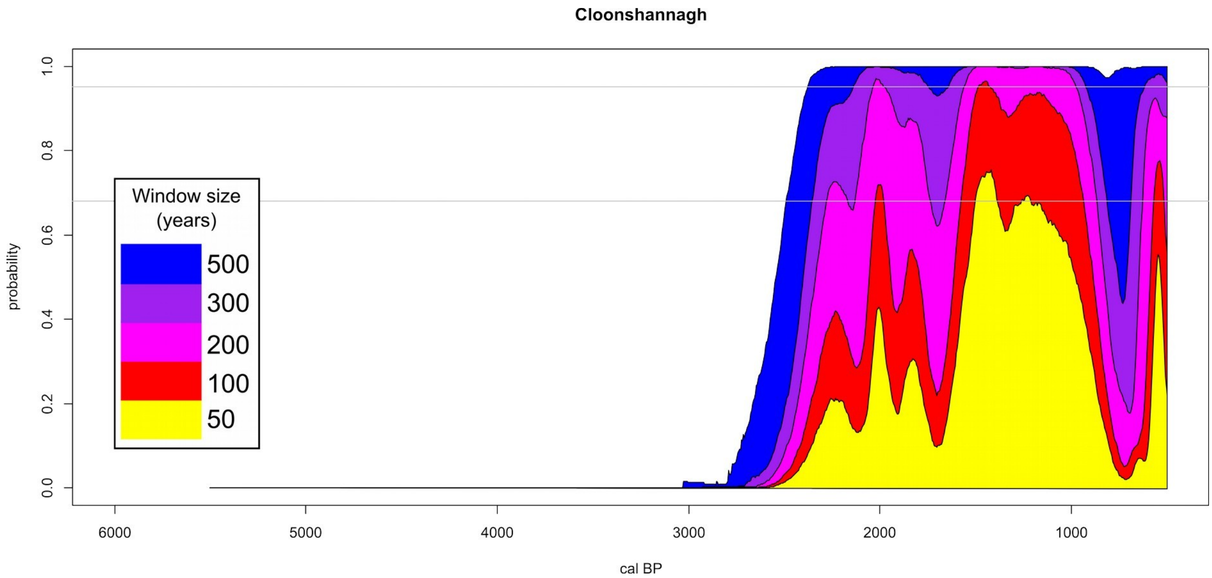

Figure 99: Probability that wet shifts occur within a given time-window, Cloonshannagh bog. Yellow: 50 year time window; Red: 100 years; Magenta: 200 years; Purple: 300 years; Blue: 500 years. Horizontal grey lines indicate 68% and 95% probability.

9.3.2 Kinnegad Bog

A number of small-magnitude wet shifts were recorded in the sequence at Kinnegad bog, therefore the probability plot shown in Figure 100 displays >68% probability of a wet shift occurring at least once per 100 years (i.e. within a 100 year time-window) throughout most of the period between *c.* 4000-2500 cal BP. Sharp peaks in probability occur at *c.* 2800 and *c.* 2600 cal BP indicating ~90% and ~80% likelihood, respectively, that wet-shifts occur

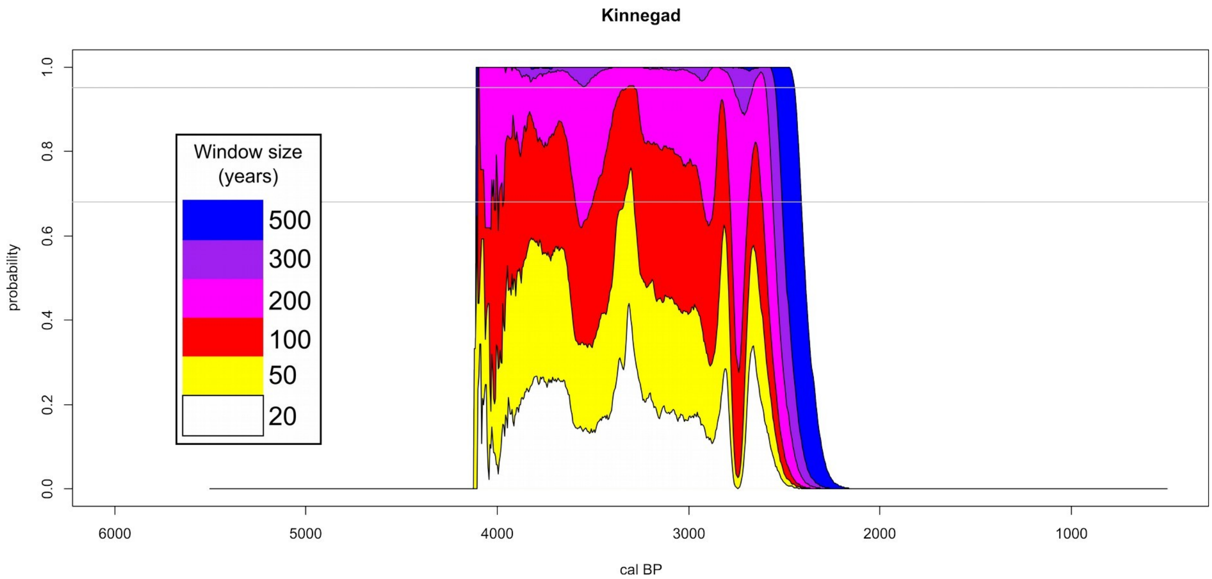

Figure 100: Probability that wet shifts occur within a given time-window, Kinnegad bog. Horizontal grey lines indicate 68% and 95% probability.

within 100 years of these dates. An earlier peak in probability (>95% within a 100 year time window) reflects a further well-dated wet shift at *c.* 3200 cal BP.

9.3.3 Derryfadda bogs

Figure 101 shows time-window probability plots for (from top) Gowla, Killaderry, and Castlegar bogs, and (bottom panel) the probability that wet shifts occur at all three sites within the same time-window. Based on the chronologies of these sequences, the confidence that synchronous events occur at all three sites (bottom panel) within time-windows of 50-200 years is low, there is high probability (>95%) that wet-shifts occur within 500 years at all sites between *c.* 3900-3100 cal BP, at around *c.* 2700 cal BP, and between *c.* 2200-1500 cal BP.

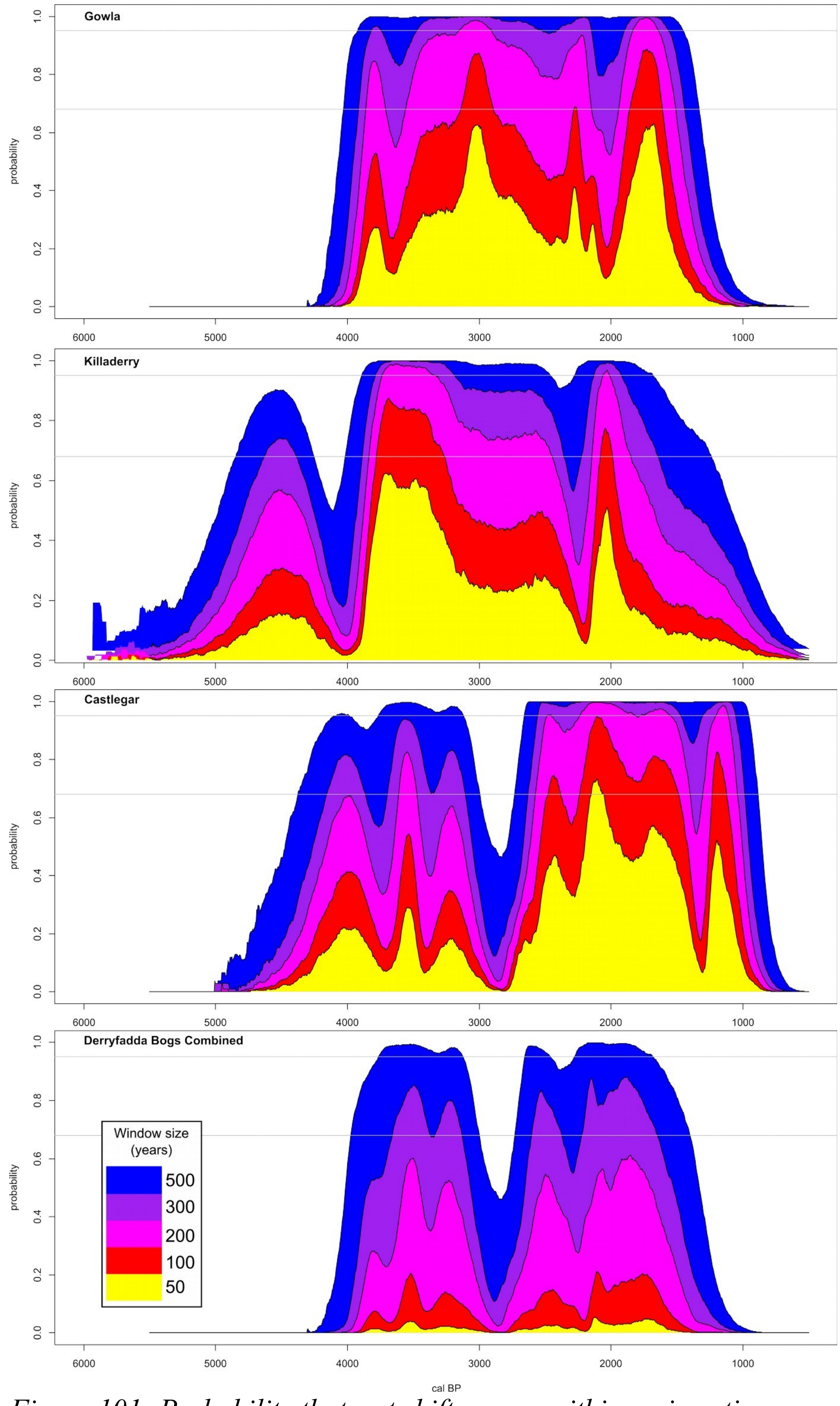

Figure 101: Probability that wet shifts occur within a given time-window, Derryfadda bogs. From top: Gowla bog; Killaderry bog; Castlegar bog; bottom: probability that a wet shift occurs in all three bogs within a given time-window.

9.3.4 Littleton bogs

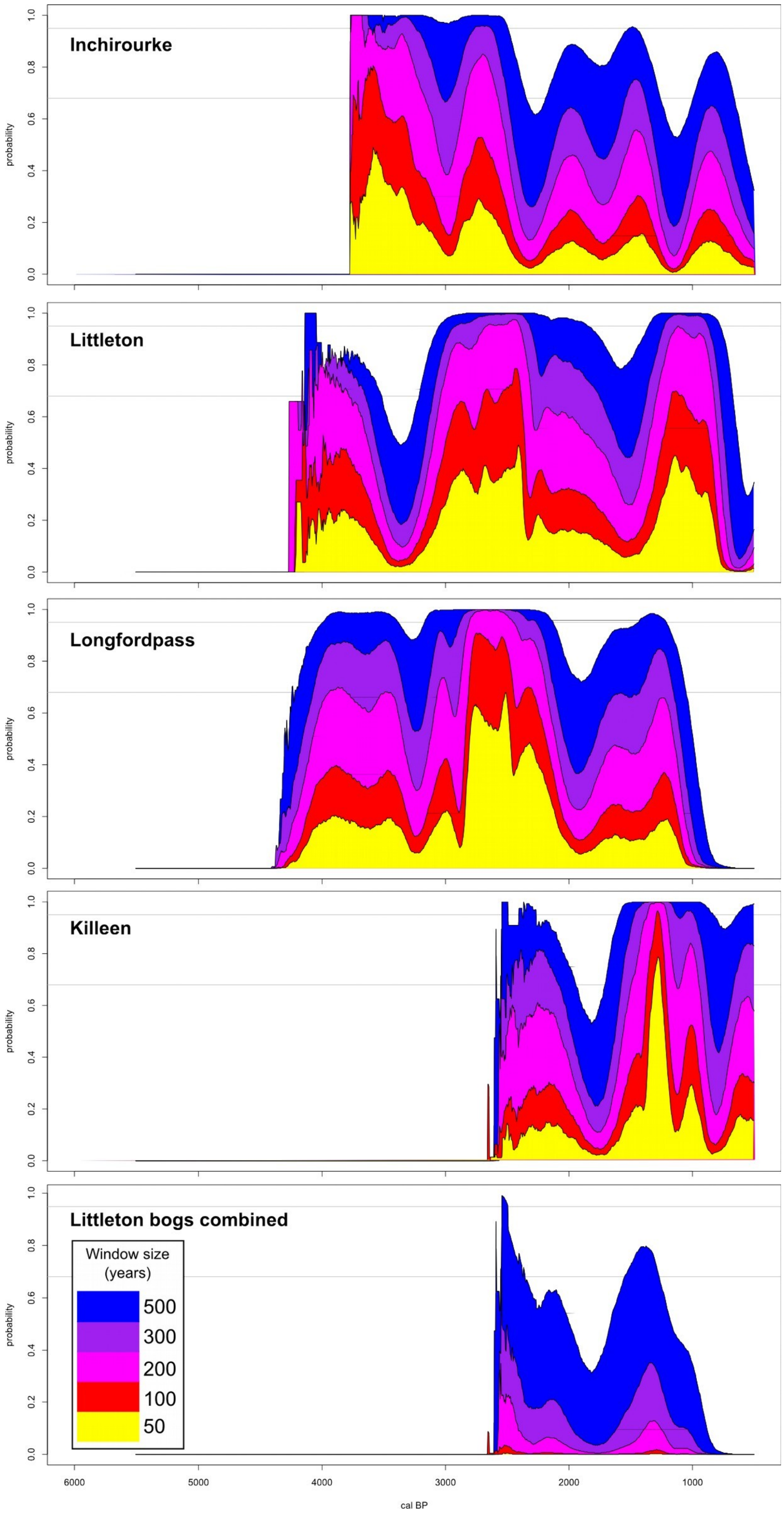

Figure 102: Probability that wet shifts occur within a given time-window, Littleton bogs. From top: Inchirourke; Littleton; Longfordpass; Killeen; bottom: probability that a wet shift occurs in all four bogs within a given time-window.

Figure 102 Shows the probabilities of wet shifts at (from top) Inchirourke, Littleton, Longfordpass and Killeen bogs, whilst the bottom panel shows the probability that a wet shift occurs at all of the sites in the Littleton chain of bogs within the same time-windows. All data from Killeen post-dates *c* 2800 cal BP, therefore the combined probability plot shows no probability of synchronous events before this date. Nevertheless, the probability plot from Killeen bog shows a distinct peak at *c.* 1400 cal BP (>95% probability within a 100 year time-window), with the other sites showing more modest peaks in probability at this time. As a result, the combined plot shows a modest peak in probability (>68%) of a synchronous wet shift at all sites in the sub-region within a 500 year time-window of *c.* 1400 cal BP. The probability plots of Littleton and Longfordpass bogs show a high degree of similarity, displaying three main peaks, the most prominent of which being centred on *c.* 2800 cal BP.

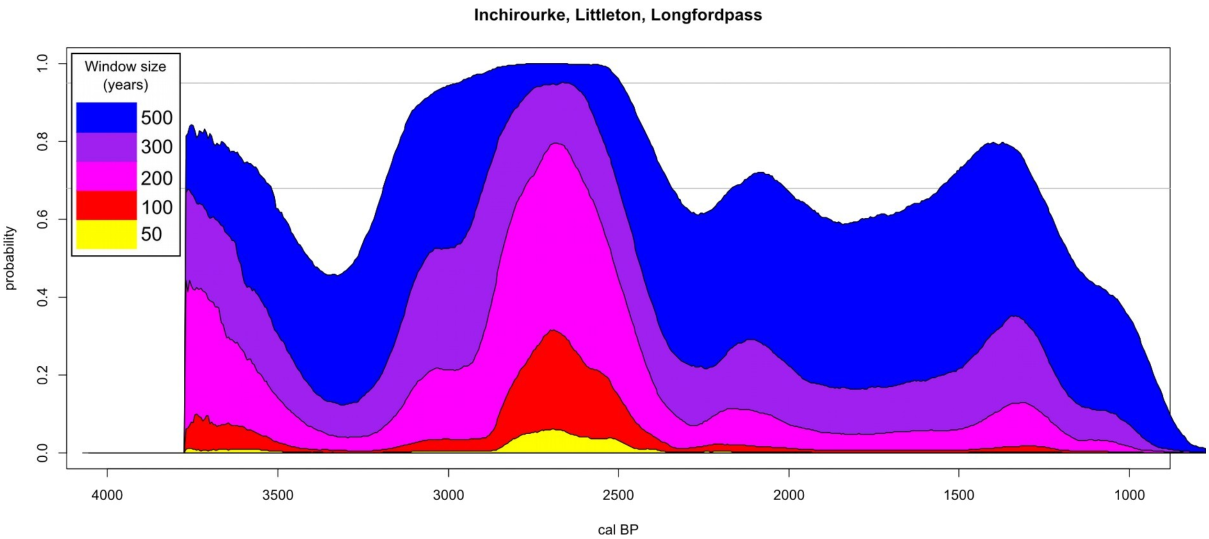

Figure 103: Probability that wet shifts occur at Inchirourke, Littleton and Longfordpass within the same time-window, 3700-500 cal BP.

Figure 103 shows a combined probability plot for Inchirourke, Littleton and Longfordpass bogs, for the period 3700-500 cal BP. This plot illustrates the peak in probability that a synchronous wet-shift occurs at these three sites at *c.*2700 cal BP (95% probability within a 300 year time window).

9.3.5 Assessing regional synchronicity

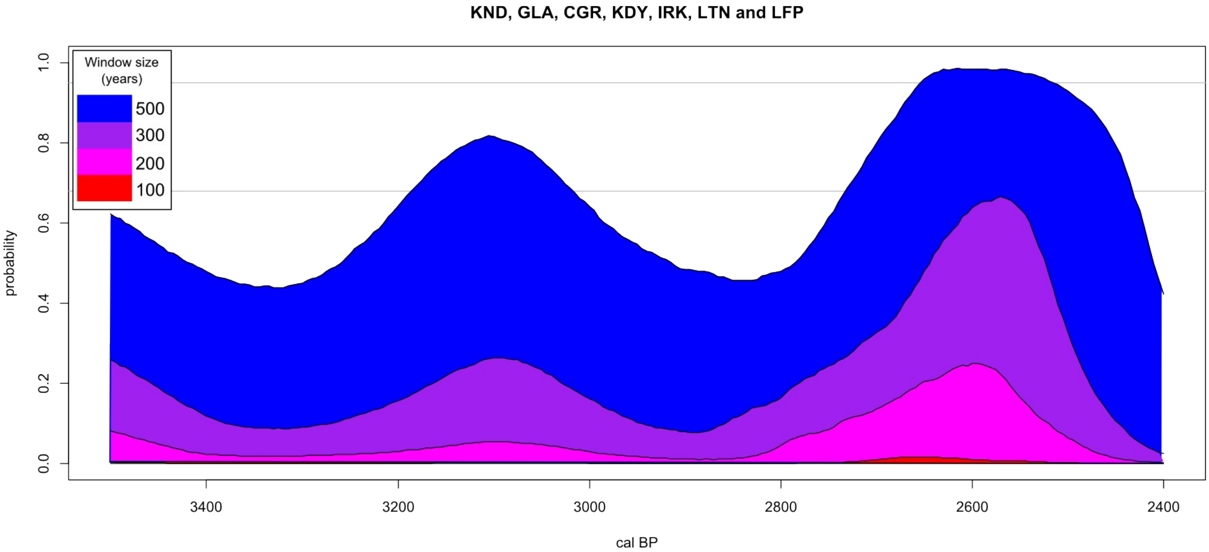

Figure 104: Probability that wet shifts occur in the same time window at Kinnegad, Gowla, Castlegar, Killaderry, Inchirourke, Littleton and Longfordpass bogs, 3500-2400 cal BP.

The probability that synchronous wet shifts occur between 3500 and 2400 cal BP in sites across the study region is shown in Figure 104, Cloonshannagh and Killeen bogs have not been included as the sequences from these sites do not span this time interval. The fact that time windows smaller than 300 years consistently have near-zero probability illustrates the degree of chronological uncertainty associated with most sequences. Nevertheless, peaks in probability at around 3100 cal BP and 2700-2600 cal BP indicate a strong likelihood (>68% and >95% probability respectively) that wet shifts occur within 500 years at all study sites at these times.

9.4 Discussion

Both 'tuning and stacking' and the 'time-window' methods provide complimentary approaches to the compilation of BSW records and investigating climatic forcing. Tuned and stacked records have the advantage of providing an easily interpretable single 'best estimate' of the regional BSW signal which may be readily compared with other palaeoclimate proxy data. Indeed, comparison with other similar datasets from nearby regions is perhaps one of the few means of objectively assessing the robustness of tuned and stacked records. Tuning and stacking relies, however, on the assumption that climatically driven hydrological change occurs synchronously across the study region. If this underlying assumption is false, then the tuned and stacked record will potentially suffer from the problem of 'sucking in' (sensu

Baillie 1991) multiple asynchronous hydrological events into a single region-wide, apparently climate-driven, event; furthermore any assessments of the robustness of a tuned and stacked record based on coherence (or the lack thereof) with other records from neighbouring regions will be spurious. The time-window approach therefore complements tuned and stacked records by allowing the (a)synchroneity of events to be objectively assessed on the basis of the un-tuned independent chronologies of each sequence (Blaauw, Christen, *et al* 2007).

The tuned and stacked BSW record from central Ireland displays a pattern of centennial-scale variability during the Late Holocene comparable to other similar proxy records from Northern Britain (Charman *et al* 2006) and from the whole of Ireland (Swindles *et al* 2013). Prominent features of this record include a series of wetter intervals at around 3500, 3000, 2700, 2100, 1600 and 1050 cal BP, which appear to correspond broadly to similar events shown in the records of both Charman *et al.* and of Swindles *et al.*

Direct correlation between the stacked records from central Ireland, and from Northern Britain (Charman *et al* 2006), are best during the period from around 3200-2400 cal BP, perhaps lending weight to the suggestion of Mayewski *et al*. (2004) that this is a period of hemisphere-wide rapid climatic variability. The time window approach clearly identifies the wet shift at *c.* 2700 cal BP as the most prominent and likely candidate for a synchronous climate-driven hydrological change across central Ireland. Correlations between the two stacked records are, however poor, even negative, during other time intervals. This lack of correlation may be attributed in part to the high degree of inter-site variability evident in the hydrological records from the nine individual study sites, reflected clearly in the very low likelihood of synchronous hydrological change within time windows of less than 500 years during most of the Late Holocene.

The time-window approach allows the identification of events which may merit further study and dating, and provide an objective means of formally testing the apparent synchroneity of events, such as at *c.* 2700 cal BP. Wiggle-matched 14C dating, further refining individual chronologies, may provide a means of further testing the synchronicity of the event at *c.* 2700 cal BP, and may allow investigation of the driving mechanisms of this event (Blaauw *et al* 2004; Mellström 2013).

It is apparent that BSW records from Ireland display both climate forcing and non-climatically driven variability and that the degree of coherence of the climate signal in these records varies through time, supporting a key conclusion of Swindles *et al.* (2013).

9.4.1 'Bog bursts'

As discussed in Chapter 7, the hydrological record from Littleton bog is characterised by a series of rapid shifts to very dry conditions, which given their similarity to similar events observed at the nearby Derryville bog (Caseldine and Gearey 2005), have been interpreted as possible bog bursts. Since these shifts towards dry conditions are the most prominent feature of the record from this site, the wet-shift events assessed using the time-window approach may be viewed alternatively as representing the point at which Littleton bog returns to wetter conditions (i.e. the *end* of bog burst events). Given that bog bursts are usually interpreted as events driven by internal bog processes, Swindles *et al.* (2013) explicitly excluded Derryville from their composite water table record as the presence of bog bursts were taken to indicate climatic insensitivity. The apparent chronological correspondence therefore between hydrological events at Littleton bog and other bogs in the Littleton group (which do not appear to show such events) may be regarded as surprising. This raises the possibility that bog bursts might potentially be climatically driven – i.e. that they occur as a response to increased moisture. This notion has some support in the literature (Warburton *et al* 2004). Following this tentative hypothesis, it may be possible that other sharp drops in water tables evident at other sites may also represent such non-linear climate response – sharp shifts to dry conditions are also noted at several sites (Gowla, Killaderry, Killeen and Cloonshannagh). The interpretation of the dry shifts as bog bursts at Derryville was supported by evidence from large scale intensive archaeological survey of the site; without similar supporting evidence the interpretation of sharp drops in DWT at other sites cannot be definitively confirmed. Nevertheless, given the high degree of inter-site variability observed in the hydrological records from sites both in central Ireland and in other regions, it appears that local and internal bog processes have a profound effect on raised bog hydrology. Internal bog processes and complex non-linear interactions between internal and external hydrological processes, such as bog bursts, must be considered when interpreting BSW data and comparing records between sites.

9.5 Conclusions

- Hydrological records from the nine study sites in central Ireland show significant centennial-scale variability throughout the Late Holocene.

- Considerable inter-site variability is evident in the hydrological records.
- Tuned and stacked records from sites in central Ireland show some common features with similar records produced for other regions of the British Isles, especially between *c.* 3200-2400 cal BP where at least one distinct shift to wetter conditions is apparent.
- Peatland BSW records appear to reflect a combination of both climatic forcing and local, potentially autogenic, variability. BSW records may respond more clearly to climate forcing during some time intervals than others. This may account for the apparent coherence in records between sites and regions during certain periods (e.g. 3200-2400 cal BP), but not in others.
- The process of tuning chronologies does not take into account the considerable chronological uncertainties inherent in peatland BSW records, therefore genuine leads and lags or sub-regional variability are impossible to assess.
- The 'time-window' approach provides an alternative method of comparing hydrological records between sites.
- Periods of enhanced probability of a synchronous wet shift occurring across sites in central Ireland were identified at around *c.* 3100 cal BP and *c.* 2700 cal BP.
- Analysis of hydrological records from the Littleton group of bogs in particular highlighted a peak in probability of a wet-shift at *c.* 2700 cal BP.
- Further refinement of ^{14}C chronologies, utilising 'wiggle-matching', may help to further test the synchronicity of the apparent climate event at *c.* 2700 cal BP.
- Bog bursts may occur in some sites as a response to climate forcing (e.g. potentially to increased wetness). If this hypothesis is correct, such non-linear responses to climate forcing may be more common than is currently recognised and must be taken into account when compiling composite bog surface wetness records.

Chapter 10: Human – Environment Interactions

This chapter will examine the evidence for human-environment interactions in former raised bogs in central Ireland. The palaeohydrological records presented in Chapter 7 will be compared with archaeological records (in Chapter 4) from the same sites. These comparisons, made in the light of the evidence for regional-scale Holocene climate variability (presented in Chapter 9), will assess the impacts of environmental change on the nature, intensity and duration of human activity in Irish raised bogs.

10.1 Rationale

Previous studies examining the influence of environmental change on human activities and societies in Ireland were discussed in Chapter 2. The most recent such study, by Plunkett *et al (2013)*, set out to explicitly test environmentally deterministic hypotheses linking the construction of peatland trackways with records of past hydrological change in ombrotrophic bogs. The Plunkett *et al* study, perhaps ironically echoing the environmental determinism it set out to critique, adopted a 'top down' approach: comparing composite palaeoclimate records from across Ireland with an island-wide compilation of archaeological data. In contrast, this research adopts an approach more akin to studies such as Bermingham (2005) and Gowen *et al* (2005), in making direct comparisons between archaeological and environmental data from the same sites. There is evidence for considerable variability in the patterns of environmental change (see Chapter 9) obtained from sites across the study area of this research (defined in Chapter 3). Similarly, the archaeological record of Ireland varies at the regional scale (Cooney and Grogan 1994). For example, a clear regional pattern in the deposition of metalwork in wetlands is evident in North Munster, where swords occur in raised bog contexts far more frequently than elsewhere in Ireland (Grogan 1996, pp.36–38). This regional variability suggests, therefore, that analysis at the regional and site scales are appropriate. Indeed, this smaller scale of analysis may allow more nuanced contingent relationships to be identified (Head 2000). This may arguably be more informative for future archaeological research. Rather than identifying broad national patterns which do not vary through time, and which reduce interpretation of the evidence to broad generalisations, this research aims to identify human-environment relationships which may potentially vary regionally and chronologically.

10.2 Organisation, methods and approaches

The remainder of this chapter is organised on a site-by-site basis, with each study site and group of sites discussed in the same order as they were presented in Chapter 3, moving from north to south.

Two main approaches have been adopted to examine relationships between raised bog hydrology and the archaeological records:

(a) Reconstructed depth to water table (DWT) records were compared with summed probability density functions (PDF) of radiocarbon dated archaeology from each site. The use of the PDF of radiocarbon dates as a proxy for past human activity (Rick 1987; Aitchison *et al* 1991) is now widespread in archaeology and Quaternary science (Williams 2012). This method has been criticised on a number of grounds.

First, concern over the taphonomic bias in favour of the survival of younger sites (Surovell *et al* 2009), although the exact nature of this bias in the context of Irish peatland archaeological records is not clear. On one hand, the gradual denudation of the bog surface by milling would clearly suggest a bias towards younger features since these are nearer to the surface and more likely to be identified during survey. On the other hand, features very close to the surface are more likely to be damaged or destroyed by drainage and milling, and so more deeply buried and thus better preserved features may have been preferentially selected for dating (either consciously, or sub-consciously as they may seem more “impressive”).

Secondly, and perhaps of more significance for the present research, it has been noted that summing probability has the effect of accumulating the statistical scatter inherent in all radiocarbon dates, thus giving rise to the potentially misleading impression that phases of activity last longer and are more continuous than they really were (Bayliss *et al* 2007, pp.9–11). However, peatland archaeological sites such as trackways, although frequently clustered in particular areas, rarely have direct stratigraphic relationships with other sites, limiting the potential to use more precise Bayesian modelling techniques. For this reason, PDF were used by Plunkett *et al* (2013) to compare human activity in Irish bogs with palaeoclimate records. Recently it has been pointed out that PDF cannot be used to infer solar forcing of lake level changes in central Europe (Bleicher 2013). This is because the shape of probability density functions of radiocarbon dates are themselves profoundly affected by changes in solar activity. This same circularity of reasoning is also a pitfall when inferring the societal effects of climate events occurring chronologically close to (or as a result of) solar forcing, such as the '2.8 event' (Swindles *et al* 2007b). Nevertheless, for comparison with other studies PDF of archaeological features are compared with DWT curves from the same sites.

(b) Narrative descriptions of hydrological change and human activity are given, organised by archaeological period. These narratives include discussion not only of archaeological features on the raised bogs themselves, but also sites on the surrounding drylands. Although this approach is not quantitative, this does allow the identification of associations and trends at the local scale, which could feed in to more interpretive approaches. Although many traditional environmental and wetland archaeological studies have shied away from such interpretive approaches (Van de Noort and O'Sullivan 2007), and arguably from archaeological theory generally, there remains great potential for more nuanced understanding of the archaeological evidence when data from the physical environment is integrated (e.g. Head 2000). Recently, authors have been attempting to integrate 'scientific' empirical and more theoretical strands of research, resulting in a more pragmatic approach (e.g. Morris and Maltby 2010; Preucel and Mrozowski 2010; Boulden 2012). This may potentially inform more socially-engaged interpretations of the archaeological evidence, incorporating approaches such as, for example, phenomenology (Tilley 1994).

Whilst being on a milled production bog is undoubtedly an entirely different sensory experience to walking on a wooden trackway across a pristine raised bog, palaeoenvironmental studies (which reconstruct conditions with reference to modern analogues) have the potential to inform richer interpretations of sites. These data could be incorporated, for example, into a "'soft' phenomenological approach" (Chapman 2001, p.5), where basic phenomenological responses (sights, sounds) are combined with more "traditional archaeological data" (Hamilton *et al* 2006, p.33). These essential phenomenological responses, although rarely referred to as such, are very often implicit in interpretations of peatland palaeoenvironmental data: "dry", "hummocky", "wet","quaking", "unstable", all these terms describe aspects of the experience of the bog surface environment which can be inferred from data.

Another potentially useful concept in the interpretation of the peatland archaeo-environmental record is that of the 'taskscape' (Ingold 1993). Ingold conceives of the taskscape as the space of human activity, which creates, and is created by, 'dwelling' in the landscape. The temporality of the landscape is highlighted, as is the way in which features of the landscape, plants, animals, and humans, incorporate it into their activities, and in the process continually modify it (1993, p.170). The concept of the taskscape illustrates the inseparable nature of built structures and the natural environment, and of social and economic activity and natural processes.

Ingold's taskscape is illustrated using Breugel's 16th century painting *The Harvesters* as an example; there are numerous potential parallels to be found in the peatland archaeo-environmental record. Ingold highlights the way in which the landscape of hills and valleys depicted in the painting are the product of continual processes of change (albeit at a scale too slow to be perceived in a human lifetime). Raised bogs, being dynamic environments sensitive to climatic and seasonal change illustrate this temporality, potentially over much shorter time scales; like the tree in the painting, "its temporality is more consonant with human dwelling" (Ingold 1993, p.168). In the same way as the cut face of the cornfield in the painting "is an interface, whose outline is progressively transformed... a fine example of the way in which form emerges through movement" (Ingold 1993, p.168), so too does the act of construction of trackways transform the raised bog. Finally, since the church in the painting, in the same way as the other features of the landscape, is a result of the self-transforming nature of the world, it is subject to the same ongoing processes of dwelling and change; this is paralleled in the temporality of peatland archaeological structures, which require maintenance, and are all eventually engulfed by the raised bog.

Only through analysis of the archaeological record with palaeoenvironmental data from the same sites can such interpretations be considered, moving beyond simplistic positivist generalities.

10.3 Mountdillon Bogs: Cloonshannagh, Co. Roscommon

Figure 105 shows the PDF of 15 ^{14}C dated archaeological features (late Neolithic platform CLS-PF-32 is excluded as it is significantly earlier than the palaeohydrological record) on Cloonshannagh bog compared with reconstructed DWT (plotted against *maximum a posteriori* age estimate of the age vs depth model), and with the estimated probability of a wet-shift event (100 year time window). The PDF curve shows several phases of human activity, from the Late Bronze Age up to the Post-Medieval period. The PDF of dated archaeology was not significantly correlated with DWT from Cloonshannagh (r = 0.21, p = 0.18), but showed a significant negative correlation with the probability of wet shift (100 year time window) data (r = -0.74, p < 0.001).

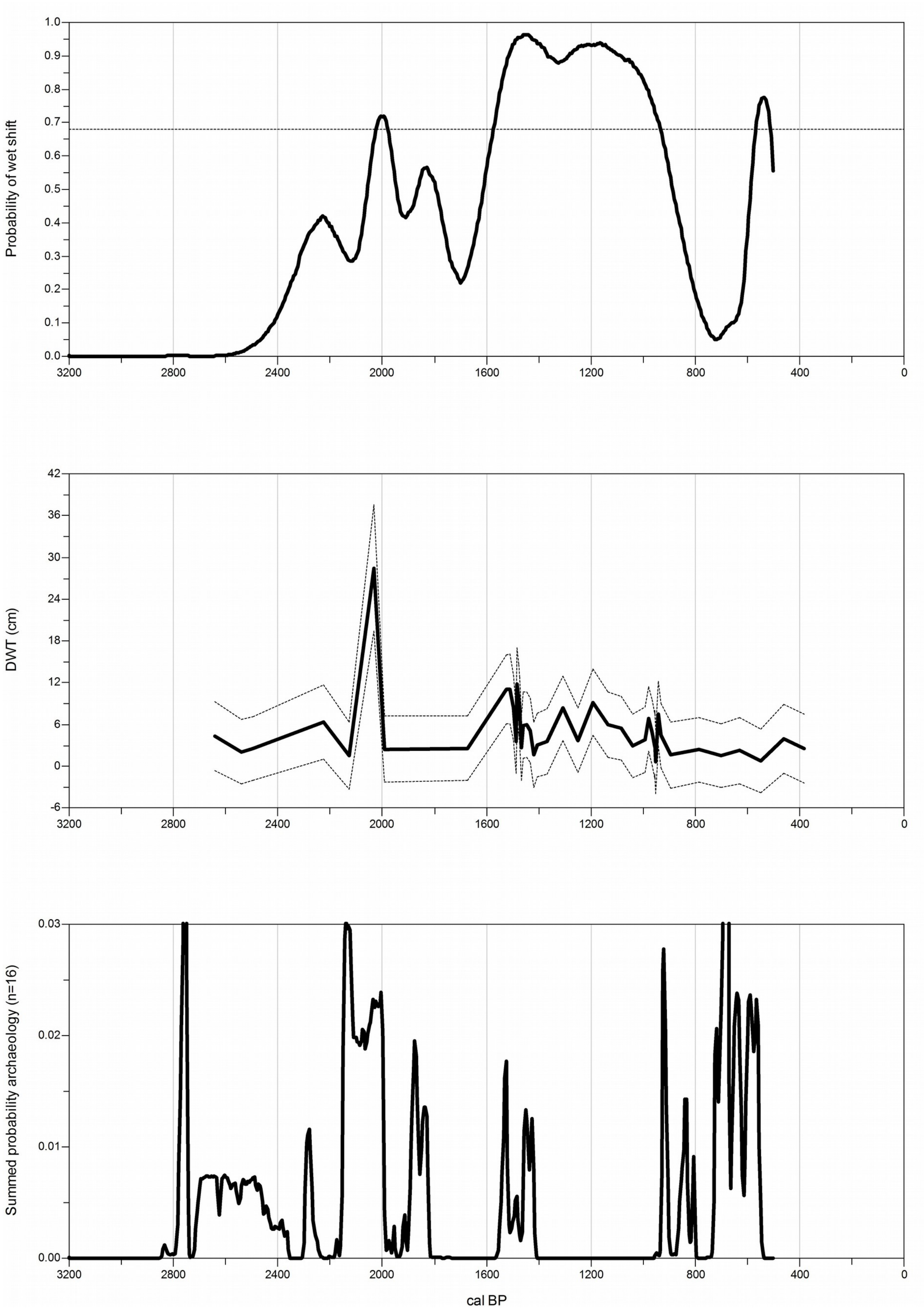

Figure 105: Comparison between PDF of archaeological sites (bottom), DWT (middle), and probability of a wet shift (100 yr time-window) (top), Cloonshannagh.

10.3.1.1 Late Bronze Age (*c.* 2950 – 2550 cal BP)

Platform CLS-PF-33 is the only feature definitely dated to the Late Bronze Age at Cloonshannagh; the date ranges corduroy trackway CLS-CT-5, and platform CLS-PF-34 span from the end of the Late Bronze Age to the Iron Age, potentially suggesting continuity into the Iron Age. The palaeohydrological record from Cloonshannagh begins during this period, indicating, at least at the coring location, that the onset of ombrotrophic conditions was around this time. The DWT curve indicates moderately wet conditions from *c.* 2650 cal BP onwards.

10.3.1.2 Iron Age (*c.* 2550 – 1550 cal BP)

Human activity on Cloonshannagh appears to peak during the Iron Age. This activity appears to occur in at least two main phases: CLS-CT-5 and CLS-PF-34 may both possibly date to the earliest part of the Iron Age, during a period of moderately wet conditions continuing from the Late Bronze Age. At *c.* 2200 cal BP a shift to wet conditions occurs, followed immediately by a sharp drop in water tables – possibly caused by a bog burst. The main phase of Iron Age activity on Cloonshannagh appears to coincide broadly with this sequence of rapid hydrological change, the exact chronological relationship is difficult to discern, although the large corduroy trackway CLS-CT-1 appears to have probably been constructed after the possible bog burst. Other features built at around this time include a hurdle trackway (CLS-HT-2), and at least two platforms (CLS-PF-23, and PF-40). It is possible that other undated structures also date to this period: artefacts associated with a further corduroy trackway CLS-CT-6, including two anthropomorphic figures, closely parallel CLS-CT-1, and Corlea 1 (Raftery 1996), both of which date to the middle part of the Iron Age, suggesting that this structure may also be of similar date. Three undated platform structures appeared to be associated with CLS-CT-6 (CLS-PF-13, PF-14, and PF-15). Furthermore, two other sections of hurdle trackway CLS-HT-3, HT-22, and HT-26, were also excavated, which may be of similar date to the Iron Age CLS-HT-2. If all of these structures do indeed date to the Iron Age, this would suggest a period of very intense activity on the site, perhaps with several phases of construction or repair: several platforms overlap each other, and there is definite evidence of at least two phases of construction on CLS-CT-1. In the context of the rapid hydrological change at Cloonshannagh during the Iron Age, possibly associated with a bog burst it would appear that the multitude of smaller features (platforms and short hurdle tracks) may have been localised responses to the unstable bog surface. The large corduroy trackways clearly involved considerable effort to construct, and warranted maintenance and repair in spite of, or perhaps because of, these unstable conditions. The presence of anthropomorphic figures on two of these large trackways is enigmatic, but may have related to some form of ritual significance, attached either to the trackways themselves, the environment, or both.

10.3.1.3 Early Christian (*c.* 1550 – 1150 cal BP)

Only one structure at Cloonshannagh was dated to the Early Christian period: platform CLS-PF-39. The DWT data show moderately dry conditions at the beginning of this period, followed by a sharp shift to very wet conditions at *c.* 1450 cal BP. It appears to be likely that CLS-PF-39 was constructed at around the same time as this wet shift, or during the subsequent period of wet, but variable, surface conditions. Following the wet shift, water tables fluctuated considerably throughout the remainder of the Early Christian period, showing a trend towards drier surface conditions up until *c.* 1200 cal BP. The area south of Cloonshannagh bog is traditionally associated with a monastery founded by the 6th century AD Saint Barry; it may be that CLS-PF-39 was constructed to facilitate travel across Cloonshannagh to this ecclesiastical site.

10.3.1.4 Medieval (*c.* 1150 – 500 cal BP)

Five features were dated to the Medieval period at Cloonshannagh: three deposits of archaeological wood (CLS-AW-19, AW-35, and AW-37), a platform structure (CLS-PF-27) and a corduroy trackway (CLS-CT-38) appear to indicate human activity on the site throughout the period. The DWT curve appears to show a gradual increase in surface wetness throughout the Medieval period, with the archaeological structures apparently being constructed during this wet period.

10.3.1.5 Post-Medieval (*c.* 500 cal BP onwards)

The latest dated structure at Cloonshannagh bog were the heavily-truncated remains of a corduroy trackway (CLS-CT-16), this structure may have dated either to the very end of the Medieval period, or shortly after. Reconstructed water tables show wet conditions persisting at this site during this time.

10.3.1.6 Summary

Dated archaeological structures at Cloonshannagh bog show a number of periods of activity on this site, most notably during the Iron Age, and again during the Medieval period. In both periods, this activity is part of a wider human landscape: activity during the Iron Age, in particular CLS-CT-1, appears to closely parallel activity at Corlea, 12km to the east across the river Shannon, during the same period; the features constructed during the Medieval period (and possibly during the Early Christian, and Post-Medieval periods) however, may relate to ecclesiastical activity taking place just to the south of the site. In both cases these phases occur during variable, but generally wet periods on the bog. In general there does not appear to be a clear correspondence between the occurrence of archaeological features and reconstructed water tables. The strong statistical correlation between the PDF of ^{14}C dated features and the probability of a wet shift occurring appears to largely be due to the sharp decline in the PDF at 2000 cal BP, at around the same time as a rise in water tables following the possible bog burst; this result should be regarded with caution due to the small sample size of ^{14}C dated structures, but may represent a genuine response to the drastic hydrological changes at Cloonshannagh, where the possible bog burst may have discouraged trackway construction (and may have affected existing structures) for a time. Indeed, the proliferation of features during the Iron Age, and the evidence for repeated repair and replacement of features may be interpreted as reflecting a practical response to the dynamic and changeable environment.

10.4 Bog of Allen: Kinnegad, Co. Meath

Figure 106 shows the PDF of 7 ^{14}C dated archaeological features (the latest feature, KND-AW-9, is not shown as this significantly post-dates the hydrological data) on Kinnegad bog compared with reconstructed DWT (plotted against *maximum a posteriori* age estimate of the age vs depth model), and with the estimated probability of a wet-shift event (100 year time window). The PDF curve appears to show a single main phase of activity at Kinnegad during the Early, Middle and Late Bronze Age, with peaks in probability at *c*. 3200 and *c.* 2900 cal BP. The PDF of dated archaeology was not significantly correlated with DWT from Kinnegad ($r = 0.04$), but showed a significant correlation with the probability of wet shift (100 year time window) data ($r = 0.4$, $p < 0.001$).

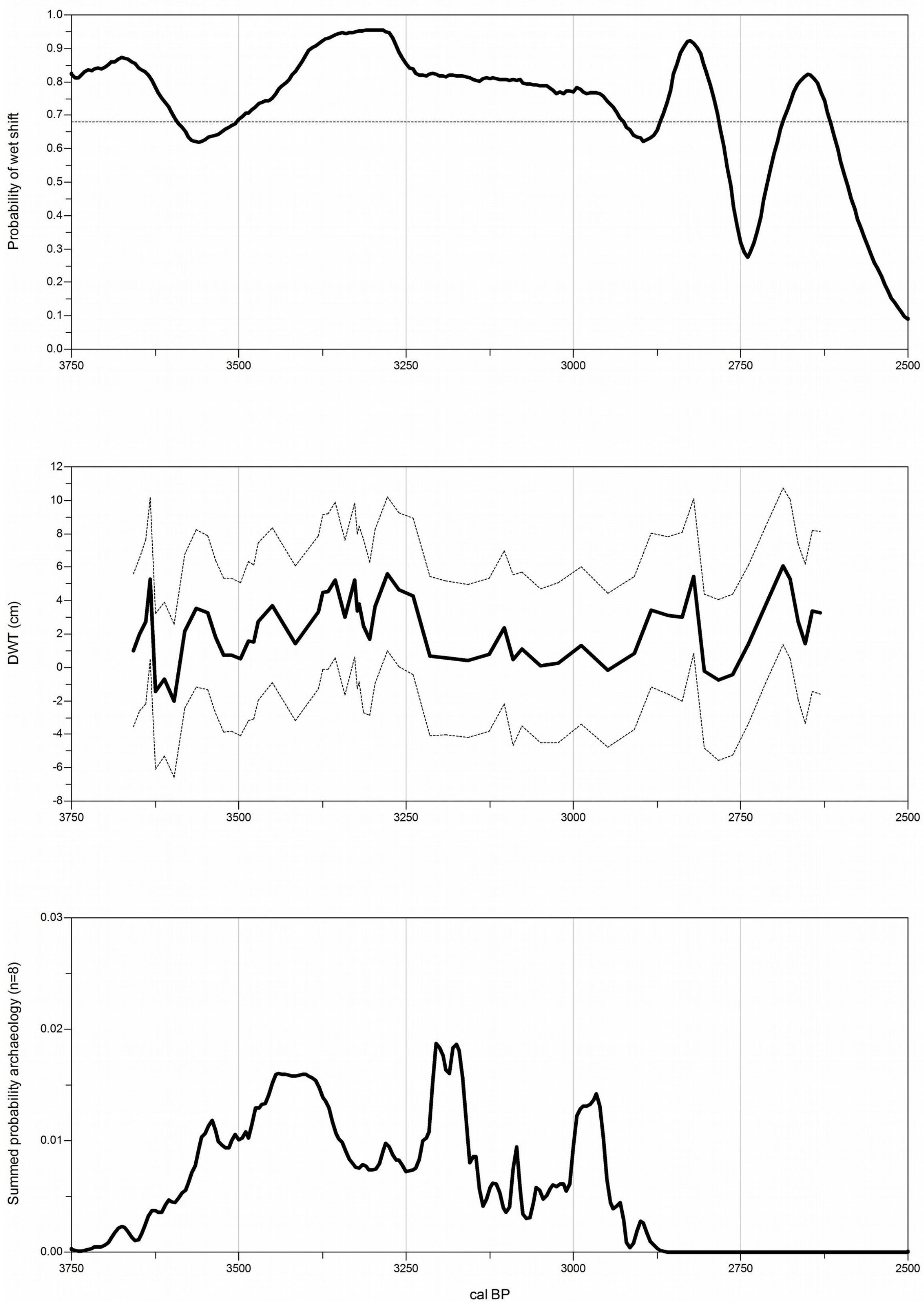

Figure 106: Comparison between PDF of archaeological sites (bottom), DWT (middle), and probability of a wet shift (100 yr time-window) (top), Kinnegad.

10.4.1.1 Early Bronze Age (*c.* 4150 – 3450 cal BP)

During the latter part of this period (from *c.* 3700 cal BP onwards), the DWT curve shows marked hydrological changes. A sharp shift to very wet conditions (water table above the bog surface) occurred at *c.* 3680 cal BP, this was followed by a lowering of water tables, and another less abrupt shift to wet conditions at *c.* 3550 to 3450 cal BP. Plank path KND-PP-3 was dendrochronologically dated to 3519±9 cal BP, and thus appears to have been constructed during this second period of wet conditions. Other features dated using radiocarbon may potentially date to the latter part of this period, or the earlier part of the Middle Bronze Age; these include another plank path (KND-PP-1), a brushwood trackway (KND-BT-8), and two platforms (KND-PF-10, and PF-11). In addition, an undated deposit of archaeological wood (KND-AW-2) was discovered underlying KND-PP-1; this feature was directly underlain by poorly-humified *Sphagnum – Menyanthes* peat, providing further direct evidence for human activity at Kinnegad during periods of wet conditions in the Early Bronze Age.

10.4.1.2 Middle Bronze Age (*c.* 3450 – 2950 cal BP)

Several features (KND-PP-1, KND-BT-8, KND-PF-10, and KND-PF-11) may date either to the earlier part of the Middle Bronze Age, or to the latter part of the preceding period. In addition to this, two potentially near-contemporary platforms (KND-PF-4 and PF-5) definitely date to this period. During the first half of the Middle Bronze Age (up to *c.* 3200 cal BP), reconstructed water tables appeared to fall, showing a trend towards moderate bog surface conditions, this was followed by a step-change back to wet conditions, with water tables at, or very near to, the bog surface. A further platform structure (KND-PF-7) may date either to the end of the Middle Bronze Age, or the beginning of the Late Bronze Age, indicating a degree of continuity of activity at Kinnegad throughout this period.

10.4.1.3 Late Bronze Age (*c.* 2950 – 2550 cal BP)

The only feature that may date to the earlier part of the Late Bronze Age at Kinnegad was a single platform structure (KND-PF-7). This platform structure directly overlies part of brushwood trackway KND-BT-8, which may be indicative of continuity of activity, possibly the repair or re-use of the earlier structure. The DWT curve indicates that water tables dropped during the early part of the Late Bronze Age, probably contemporary with the platform. This was followed by a sharp shift to very wet bog surface conditions at *c.* 2800 cal

BP, this coincides with the beginning of a long gap in the archaeological record at Kinnegad.

10.4.1.4 Early Christian (*c.* 1550 – 1150 cal BP)

No features at Kinnegad bog were dated from the earlier part of the Late Bronze Age until the Early Christian period. The latest dated feature was a deposit of archaeological wood (KND-AW-9), indicating some level of human activity at the site during this period. Due to truncation of the peat sequence, no hydrological data was available for this period.

10.4.1.5 Summary

The archaeological and palaeohydrological records from Kinnegad bog mostly relate to the Bronze Age period. The archaeological record shows evidence for a range of activity, including plank-built trackways, a brushwood trackway, and a number of platforms. Direct stratigraphic relationships between some of these structures are clear evidence for some degree of continuity in activity during the Bronze Age. Most structures were dated using radiocarbon, and these dates generally have large errors making more detailed discussion of the chronological relationships between these structures impossible. Nevertheless, the dendrochronological date from KND-PP-3 clearly shows activity during the Early Bronze Age, and platform KND-PF-7 clearly shows continuity of activity at least until the end of the Middle Bronze Age. Human activity during the Early Bronze Age (plank path KND-PP-3, and deposit KND-AW-2) clearly appears to have occurred during a period where bog surface conditions at Kinnegad were very wet, with water tables near to, or even above, the bog surface. By the beginning of the Late Bronze Age, water tables began to drop, but this was followed by a sharp shift to wet conditions, possibly driven by regional climate forcing (see Chapter 9). No archaeological features appear to be contemporary with this wet climate event, and no further dated features were recovered from Kinnegad until the Early Christian period. Whilst the lack of archaeological features in the latter part of the Late Bronze Age appears to be genuine, it is possible that evidence for Iron Age human activity may have been truncated by milling as the peat core from Kinnegad was missing peat from the Iron Age onwards.

10.5 Derryfadda Bogs, Co. Galway

10.5.1 Gowla bog

Figure 107 shows the PDF of all eight ^{14}C dated archaeological features on Gowla bog compared with reconstructed DWT (plotted against *maximum a posteriori* age estimate of the age vs depth model), and with the estimated probability of a wet-shift event (100 year time window). The PDF curve appears to suggest a single phase of activity during the Middle Bronze Age on Gowla bog, with a conspicuous peak at 3360 cal BP, this may be an artefact of the small overlap in calibrated 95% confidence intervals of GLA-BT-1, GLA-PF-2, and GLA-BT-3 (the dates of the latter two features have near-identical calibrated age ranges). There is then a large gap during the Late Bronze Age, where there are no dated features. Iron Age activity on Gowla bog appears (on the basis of the dated structures) to have been sporadic. No statistically significant correlations were found between the PDF and either DWT or the probability of wet shifts (r = 0.06 and -0.04, respectively). Despite the lack of correlation, the PDF curve highlights the lack of any dated archaeological sites on Gowla between at least *c.* 3200 and 2400 cal BP, during which time the DWT curve shows the wettest values.

10.5.1.1 Middle Bronze Age (*c.* 3450 – 2950 cal BP)

Evidence for human activity during the Early Bronze Age on Gowla bog was represented by three features. All three features appear to date to the earlier part of this period, before *c.* 3250 cal BP. Possibly the earliest was brushwood trackway GLA-BT-1, which may have been contemporary with, or replaced slightly later in the Middle Bronze Age by GLA-BT-3 and GLA-PF-2. During the earlier part of this period, probably contemporary with these archaeological features, DWT values indicate moderately wet conditions, having shown a long-term trend towards wetter conditions through the preceding Early Bronze Age. An abrupt shift to dry conditions, which appears to have post-dated the archaeology occurred at *c.* 3250 cal BP, this was followed by a shift to increasingly wet conditions.

10.5.1.2 Late Bronze Age (*c.* 2950 – 2550 cal BP)

No dated archaeological features were found on Gowla bog during this period. DWT values indicate very wet bog surface conditions throughout this period.

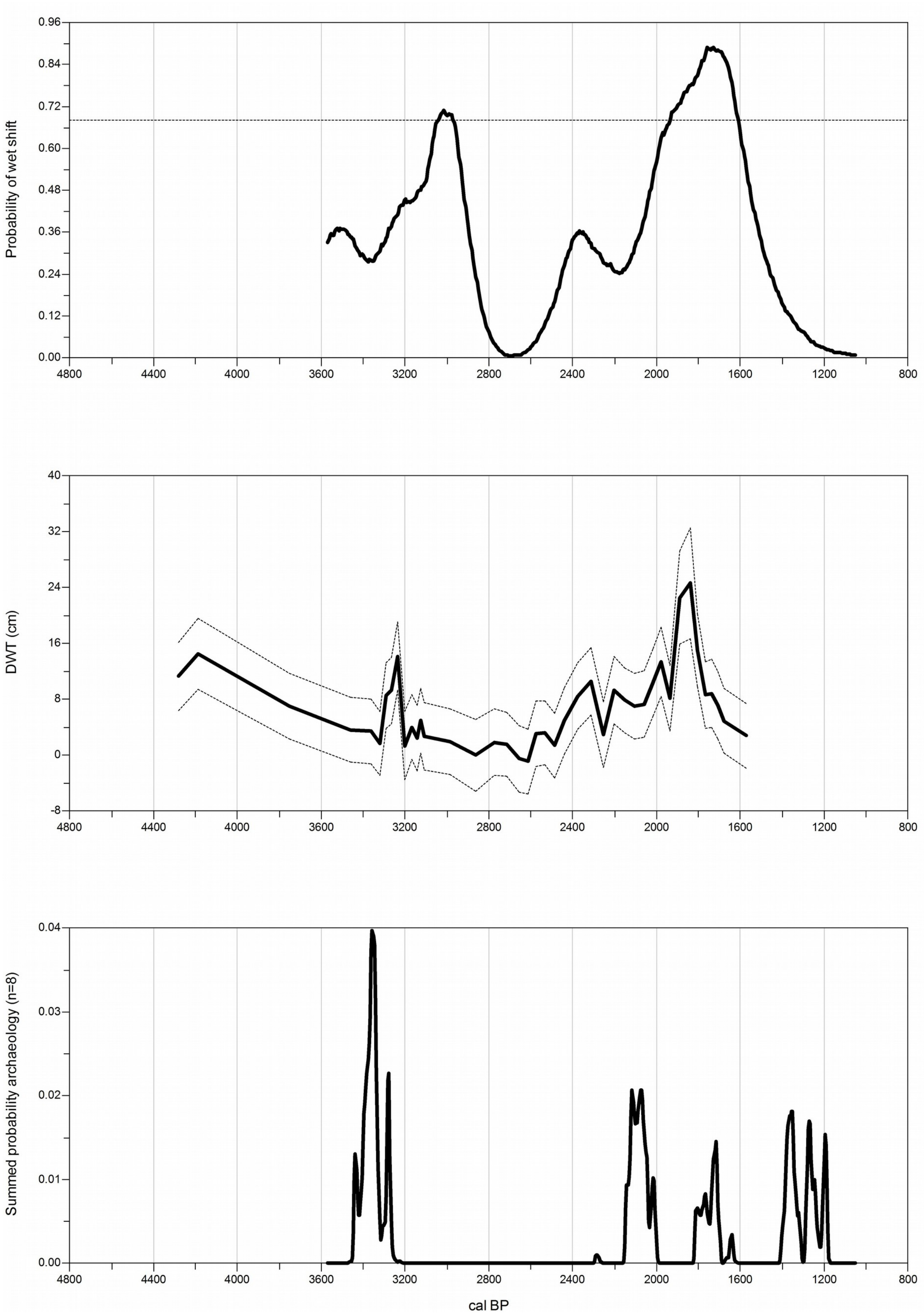

Figure 107: Comparison between PDF of archaeological sites (bottom), DWT (middle), and probability of a wet shift (100 yr time-window) (top), Gowla.

10.5.1.3 Iron Age (*c.* 2550 – 1550 cal BP)

In the earlier part of the Iron Age, DWT values generally increase, indicating drier conditions, these are punctuated by a brief wetter interval at *c.* 2250 cal BP, which appears to pre-date the Iron Age archaeology on Gowla. Three features were dated to the Iron Age: brushwood trackway GLA-BT-8 and platform GLA-PF-4 appear to be more or less contemporary, and were constructed during a period of dry bog surface conditions at Gowla. After this, DWT values show a sharp shift towards very dry bog conditions at *c.* 1900 cal BP, followed by a sharp drop in DWT indicating a return to wet conditions. The drastic nature of the shifts in water tables may possibly indicate a bog burst. A second Iron Age brushwood trackway, GLA-BT-7 was constructed during this period of wetter conditions. This trackway was constructed on a similar alignment to GLA-BT-8.

10.5.1.4 Early Christian (*c.* 1550 – 1150 cal BP)

Due to truncation, no palaeohydrological data were recovered for this period from Gowla bog, however a plank path GLA-PP-5 dating to this period was found. This is consistent with other substantial peatland structures on the other nearby bogs during the Early Christian and Medieval periods (see below).

10.5.1.5 Summary

The archaeological records from Gowla bog appear to indicate repeated episodic activity on this site. The Middle Bronze Age and Iron Age structures all appear to be similar in construction and all have similar alignments, suggesting that these structures may have performed similar functions or been connected to the same persistent foci of activity, perhaps related to the *fulachtaí fia* which are recorded on the SMR immediately west of the Derryfadda bogs. It should be noted that a further 11 similar features on similar alignments were noted during survey, but not dated. The palaeohydrological record from Gowla suggests a dynamic and changeable environment, with notable wet shifts, both following large fluctuations in DWT at *c.* 3250 and *c.* 1900 cal BP. These events, particularly the latter, may have been related to bog bursts, possibly driven by regional-scale shifts to a wetter climate (see Chapter 9). No dated features appear to date to the times of these events. It may be that the relatively simple construction of these sites (longitudinally-lain brushwood), and the possibly episodic timing of their construction is a practical response to this changeability, whilst maintaining broad continuity in activity in the area. Although trackways were constructed during both wet and dry periods, this would suggest awareness of the dynamic nature of this environment and an engagement with it.

10.5.2 Killaderry bog

Figure 108 shows the PDF of the 17 ^{14}C dated archaeological features on Killaderry bog compared with reconstructed DWT (plotted against *maximum a posteriori* age estimate of the age vs depth model), and with the estimated probability of a wet-shift event (100 year time window). The PDF curve shows several phases of activity at Killaderry, from the Neolithic up to the Medieval period. Early evidence of human activity was sporadic; and whilst dated evidence was more abundant from the Middle Bronze Age onwards, the PDF curve appears to show generally episodic construction of peatland features. The PDF curve shows distinct lulls between 2350 and 2050 cal BP and 1900 to 1400 cal BP. The PDF of dated archaeology was not significantly correlated with DWT from Killaderry (r = -0.07), but had a very weak negative correlation with the probability of wet shift (100 year time window) data (r = 0.09, p < 0.01). This is apparently due, at least in part, to the lull in the PDF of the archaeology between *c.* 3850 and 3350, during which period a clear wet shift occurred.

10.5.2.1 Neolithic (*c.* 5950 – 4350 cal BP)

Neolithic activity on Killaderry bog is evidenced by the construction of an unexcavated plank path (KDY-PP-31). No hydrological data are available from the period in which this plank path was constructed, since this appears to pre-date the shift to ombrotrophic conditions at the sampling location. This suggests that this feature was probably constructed in a fen-type environment. The peat stratigraphy from the fen peats from Killaderry indicate a wet environment dominated by herbaceous plants. During the latter part of the Neolithic, DWT data show a shift towards drier (possibly ombrotrophic) conditions. This is followed by a significant wet shift at the end of the Neolithic period, at some time around *c.* 4500 cal BP.

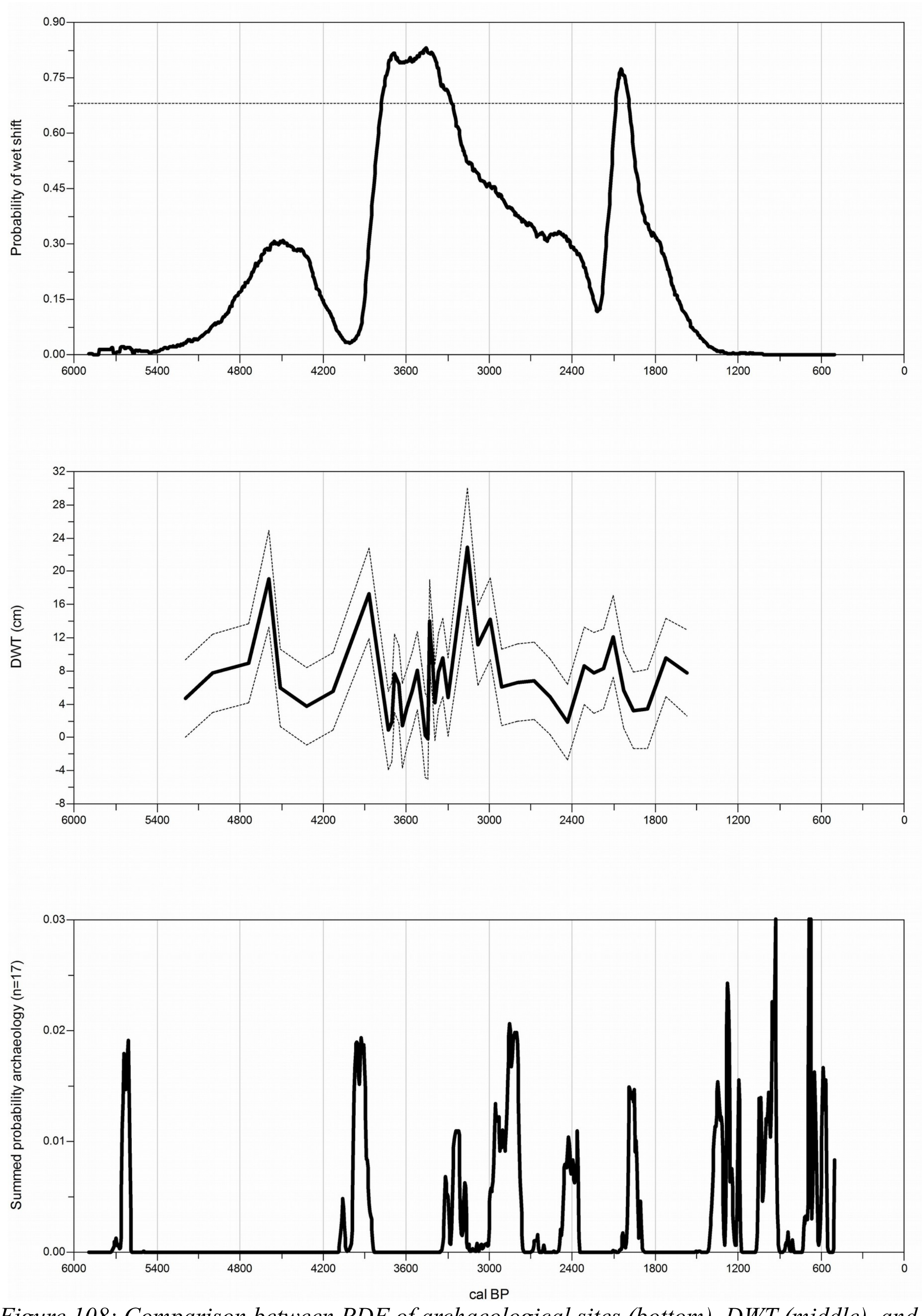

Figure 108: Comparison between PDF of archaeological sites (bottom), DWT (middle), and probability of a wet shift (100 yr time-window) (top), Killaderry.

10.5.2.2 Early Bronze Age (*c.* 4150 – 3450 cal BP)

Two trackways were dated to this period, both constructed from longitudinally-lain split timber planks. KDY-PP-32 and KDY-PP-33 have very similar 95% calibrated age ranges, indicating that these may have been broadly contemporary. Following the wet shift at the end of the Neolithic, DWT increases steadily up to 17cm, indicating dry bog surface conditions. The construction of the two Early Bronze Age structures apparently coincides with this period of drier conditions. A shift to wetter conditions almost certainly appears to post-date these structures. Based on the age vs depth model from Killaderry, this shift appears most likely to occur between *c.* 3800 and 3300 cal BP.

10.5.2.3 Middle Bronze Age (*c.* 3450 – 2950 cal BP)

One structure, brushwood trackway KDY-BT-2 was definitely dated to the Middle Bronze Age at Killaderry. Excavation of this structure also revealed at least four undated platform structures associated with this trackway (KDY-PF-13, 14, 15, and 16). One of these, KDY-PF-17 was directly beneath KDY-BT-2, whilst KDY-PF-14 was constructed directly on top of the trackway. This sequence of structures appears to indicate some degree of continuity of activity at Killaderry, although no peat had accumulated between these structures, without additional dates for these other structures the duration of this activity is impossible to quantify precisely. The hydrological record from Killaderry was variable in this period, with a trend towards drier conditions up to *c.* 3150 cal BP, followed by a shift to wet bog conditions. Based on the age vs depth model, the chronological relationship between this wet shift and KDY-BT-2 is unclear, and the two may be broadly contemporary. Nevertheless, water tables were variable throughout the Early Bronze Age at Killaderry, and the construction of the numerous platform structures under, around, and above KDY-BT-2 may be interpreted as a response to these dynamic conditions. For example, KDY-PF-14 may have been a partial repair or re-surfacing of KDY-BT-2. This pattern of replacement and repair may indicate that human activity was more continuous in this period than the PDF may appear to suggest. The overall impression of continuity of activity during this period at Killaderry is reinforced by the construction of KDY-BT-27, which was of similar construction and on a similar alignment to KDY-BT-2, and may date either to the end of the Middle Bronze Age or the earlier part of the Late Bronze Age, and was almost certainly constructed after the shift to increased BSW.

10.5.2.4 Late Bronze Age (*c.* 2950 – 2550 cal BP)

The broad pattern of trackway and platform construction appears to continue into the Late Bronze Age. Two structures were dated to this period: platform KDY-PF-25 and the substantial corduroy trackway KDY-CT-1. These structures have overlapping calibrated 95% confidence age ranges, and may be broadly contemporary. KDY-CT-1 was a substantial trackway constructed from transverse roundwood and split planks. This trackway was traced across the majority of Killaderry bog, and appeared to cross the whole bog. The alignment of KDY-CT-1 is very similar to the earlier KDY-BT-2, indeed the earlier brushwood trackway underlies the later structure in places. This again suggests some degree of continuity in the pattern of human activity into the first half of the Late Bronze Age. The DWT curve shows increasingly wet conditions throughout the whole of this period. The PDF highlights the lack of dated features between at least *c.* 2750 and 2500 cal BP, during which time the DWT curve indicates very wet conditions. A trackway, KDY-BT-26, which may date either to the end of the Late Bronze Age or the beginning of the Iron Age, was constructed following this lull, apparently during this period of wet conditions.

10.5.2.5 Iron Age (*c.* 2550 – 1550 cal BP)

Whilst KDY-BT-26 may date to the beginning of this period, there is a marked reduction in dated features during the Iron Age. The DWT curve indicates variable bog surface conditions: initially water tables drop, and moderately dry bog conditions are indicated, however a well dated abrupt shift to wet conditions occurs at *c.* 2050 cal BP. A deposit of archaeological wood, KDY-AW-28, post-dates this wet shift, and indicates some human activity during the subsequent period of wet conditions at Killaderry. The nature of this activity is unclear – this deposit of archaeological wood may represent the remains of a rather insubstantial structure or the heavily-truncated remains of a larger feature.

10.5.2.6 Early Christian – Medieval periods (*c.* 1550 – 500 cal BP)

No hydrological data was available from Killaderry due to truncation of the peat sequence. However, the north west to south east communication route continued to be important during the later periods: the Early Christian gravel trackway, KDY-GT-5, which followed the same route as the Late Bronze Age KDY-CT-1, and the Medieval trackway KDY-CT-18. These substantial trackways appear to be associated with ecclesiastical sites west of Killaderry.

10.5.2.7 Summary

The archaeological evidence from Killaderry is dominated by the continual importance of the communication route from north west to the south east. Examples of trackways traversing the bog date from the Neolithic to the Medieval periods. These trackways were constructed during both wetter and drier periods, and particularly during the Middle Bronze Age, there is evidence of replacement and repair, perhaps in response to changeable surface conditions. However, abrupt wet shifts at *c.* 3800 to 3300 cal BP and *c.* 2050 cal BP do appear to be associated with lulls in trackway construction.

10.5.3 Castlegar bog

Figure 109 shows the PDF of 12 ^{14}C dated archaeological features on Castlegar bog (the three latest features are not shown as these are much later than the latest hydrological data) compared with reconstructed DWT (plotted against *maximum a posteriori* age estimate of the age vs depth model), and with the estimated probability of a wet-shift event (100 year time window). The PDF curve shows a main phase of activity at Castlegar during the Late Bronze Age and Iron Age, with further peaks at the very end of the Iron Age and in the Early Christian period. The PDF curve shows several peaks between *c.* 2300 and 2800 cal BP; the calibrated date ranges of at least four features span this period. These peaks may partially be an artefact of the distinct plateau in the radiocarbon calibration curve (Reimer *et al* 2009) during this period, giving the impression that all these features may be contemporary, and that they may all be closely contemporary with features dated to just before and just after the 'hallstatt plateau' (Becker and Kromer 1993). The PDF of dated archaeology showed a weak negative correlation with DWT from Castlegar (r = -0.34, p < 0.05), but was not correlated with the probability of wet shift (100 year time window) data (r = 0.01).

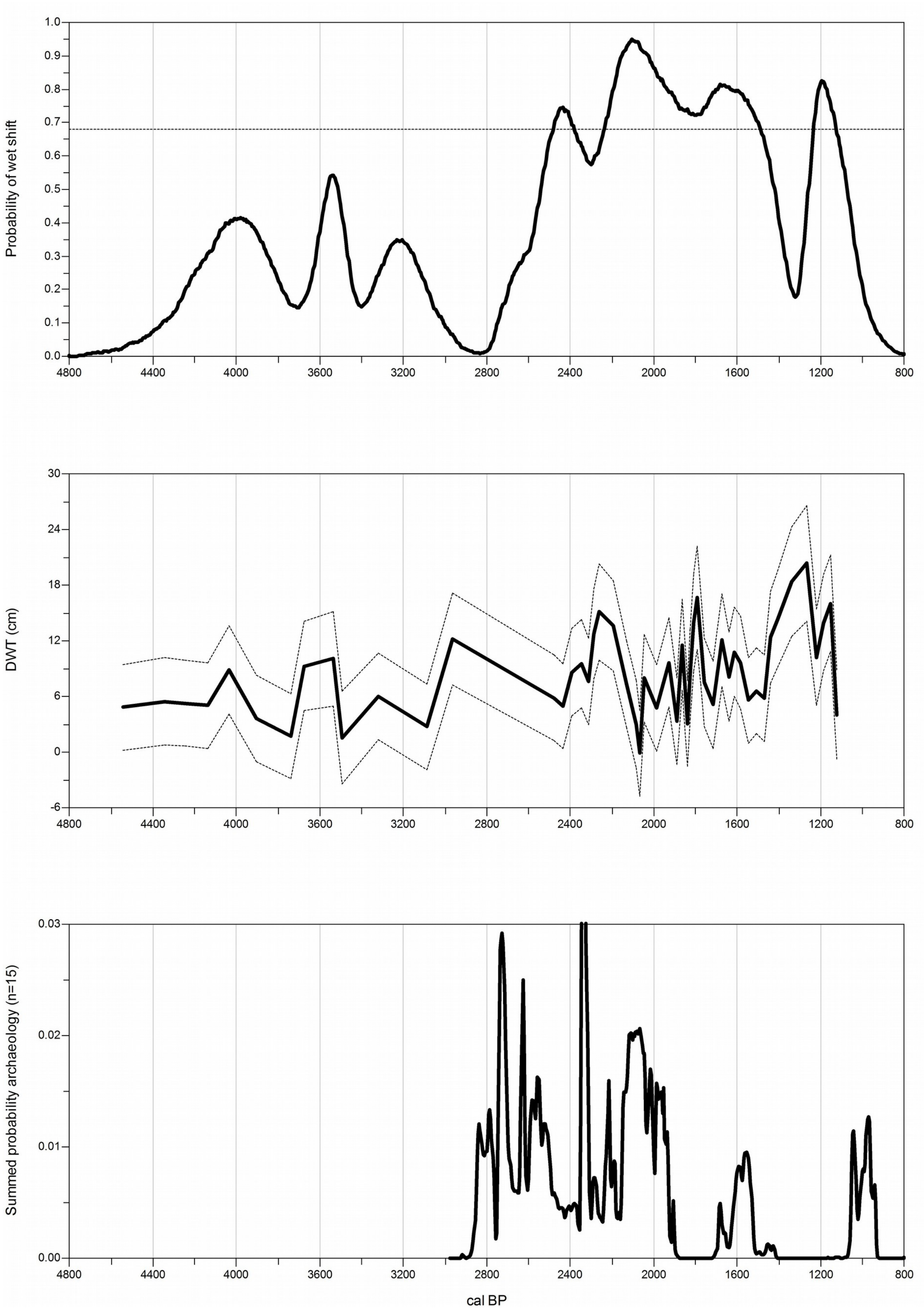

Figure 109: Comparison between PDF of archaeological sites (bottom), DWT (middle), and probability of a wet shift (100 yr time-window) (top), Castlegar.

10.5.3.1 **Late Bronze Age (*c.* 2950 – 2550 cal BP)**

The earliest dated features at Castlegar bog date to the Late Bronze Age. The earliest of these are roundwood paths CGR-RP-11 and CGR-RP-7, the latter possibly being a replacement for the former. Other features dating to the Late Bronze Age include a brushwood trackway (CGR-BT-5), another roundwood path (CGR-RP-17), and two platforms (CGR-PF-12, and CGR-PF-15); the calibrated ^{14}C age ranges of these features all span the plateau in the calibration curve between *c.* 2800 and 2400 cal BP. Although this plateau makes inferences about the relative chronology of these features, there appears to be reasonably good evidence for continuity of activity during this period: roundwood paths of similar construction appear to be replaced every century or so. The DWT curve during this period apparently shows moderately dry conditions at the beginning of this period, but wet conditions at the end. There is, however, a gap in testate amoebae data (due to poor preservation) during this period, therefore other hydrological changes from this period will not have been recorded.

10.5.3.2 **Iron Age (*c.* 2550 – 1550 cal BP)**

Four features were definitely dated to the Iron Age. Brushwood trackway CGR-BT-6, and the possibly near-contemporary platforms CGR-PF-8 and CGR-PF-16, suggest a similar pattern of activity seen in the Late Bronze Age. The construction of roundwood paths also apparently continued into the Iron Age at Castlegar: due to large chronological uncertainties (see above) CGR-RP-17 may date to the early part of this period, and is paralleled perhaps a few centuries later by the construction of CGR-RP-13. These features were all constructed during the first half of the Iron Age (before *c.* 1900 cal BP), and the considerable overlap in the calibrated age ranges of these structures was responsible for the peak in the PDF between *c.* 2150 and 1900 cal BP. This period of apparently intensive activity on Castlegar appears to correspond to a period of decreasing DWT, suggesting a shift from dry to wet conditions at *c.* 2190 cal BP. This was followed by a period of variable water tables during the later Iron Age, with a general trend towards moderately dry conditions. No features were dated to the period between at least *c.* 1900 and 1700 cal BP. This apparent lull in activity is interrupted by the construction of the large corduroy trackway CGR-CT-2 either at the end of the Iron Age, or the beginning of the Early Christian period.

10.5.3.3 Early Christian – Medieval periods (*c.* 1550 – 500 cal BP)

Later features at Castlegar bog appear to indicate a change in activity patterns, or at least a change in the methods of construction of trackways: using split timbers and planks to construct plank paths and corduroy trackways. The earliest such structure, CGR-CT-2 was constructed either at the very end of the Iron Age, or the beginning of the Early Christian period. The DWT curve shows a shift from moderate to moderately wet conditions at the beginning of the Early Christian period, CGR-CT-2 may have been contemporary with this shift to slightly wetter conditions. This wet shift is followed by a marked shift towards dry bog surface conditions, which persisted until another shift to wetter conditions at *c.* 1200 cal BP. Due to truncation of the peat sequence there are no hydrological data after *c.* 1100 cal BP. During the Medieval period plank path CGR-PP-14, and later, the large corduroy trackway CGR-CT-1 were also constructed on a similar alignment to CGR-CT-2. These structures appear to be aligned towards the ecclesiastical centre at Eglish Abbey. Indeed, CGR-CT-1 may have been constructed at around the same time as the foundation of the Abbey in AD 1436 (514 cal BP). This suggests that this route, and possibly the location of the Abbey itself, may have been an important focus of activity since the earliest part of the Early Christian period.

10.5.3.4 Summary

Human activity at Castlegar appears to have occurred during two broad phases. The first phase is characterised by construction of roundwood paths, brushwood trackways and platforms during the Late Bronze Age and the first half of the Iron Age. The second broad phase is characterised by the construction of more robust plank-built structures connecting the location of Eglish Abbey (built during the latter part of the Medieval) with the area of dry land at Dalysgrove. Comparisons between palaeohydrological data and the dates of features in the earlier, late prehistoric, phase are confounded by the possible effects of changes in solar activity on the radiocarbon calibration curve at *c.* 2800 cal BP. In other sites, this event is associated with a shift to wet conditions (see Chapter 9), but at Castlegar no data were available at this time. Nevertheless, it appears that the late prehistoric structures at Castlegar, mostly post-date 2800 cal BP may have been associated with moderately wet, but variable, bog surface conditions. During the later phase of activity, it appears that both CGR-CT-2, and the medieval plank path CGR-PP-14, were constructed *after* decreases in DWT (i.e. wet shifts). Conversely, during the dry interval between *c.* 1470 and 1200 cal BP, no dated features have been recovered. This may suggest that these trackways enabled the maintenance of this route (connected to the site of later Medieval ecclesiastical activity) during wetter phases at Castlegar.

10.6 Littleton Chain, Co. Tipperary

10.6.1 Inchirourke bog

A single plank was the only dated archaeological feature at Inchirourke bog. IRK-PP-1 was dendrochronologically dated to after 3557 cal BP (after 1607 BC) during the Early Bronze Age. This trackway appears to have been constructed very soon after transition from a fen-type environment to the onset of ombrotrophic conditions at Inchirourke bog, which occurred at *c.* 3600 cal BP. DWT values show a trend towards dry bog conditions from *c.* 3600 to 3400 cal BP during which time this plank path was constructed.

10.6.2 Longfordpass bog

Four of the five dated features on Longfordpass bog were dated using dendrochronology. Unlike other sites, where the majority of features were dated using AMS ^{14}C, these relatively precise dates, allow greater precision when comparing archaeological and palaeohydrological records; however, to provide a direct comparison with the other sites, a summed PDF was also produced for features from Longfordpass utilising the "Simulate" function of OxCal v4.2 (Bronk Ramsey 1995; Bronk Ramsey *et al* 2010). Three of the dendrochronological dates provide a *terminus post quem* date (e.g. "after 986 BC"), for these features radiocarbon dates are simulated for the calendar year ten years after this *terminus post quem*; all dates were simulated with an uncertainty of ±20 years. Figure 110 shows the PDF of dated archaeological features on Longfordpass bog (one ^{14}C dated feature, and four dendrochronologically-dated features) compared with reconstructed DWT (plotted against *maximum a posteriori* age estimate of the age vs depth model), and with the estimated probability of a wet-shift event (100 year time window).

The simulated PDF was not significantly correlated with reconstructed DWT values ($r = -0.27$, $p = 0.13$), although a significant negative correlation was obtained with the probability of a wet shift ($r = -0.17$, $p = 0.002$). This appears to be mainly due to the sharp drop in the PDF and the sharp rise in wet shift probability at *c.* 2800 cal BP.

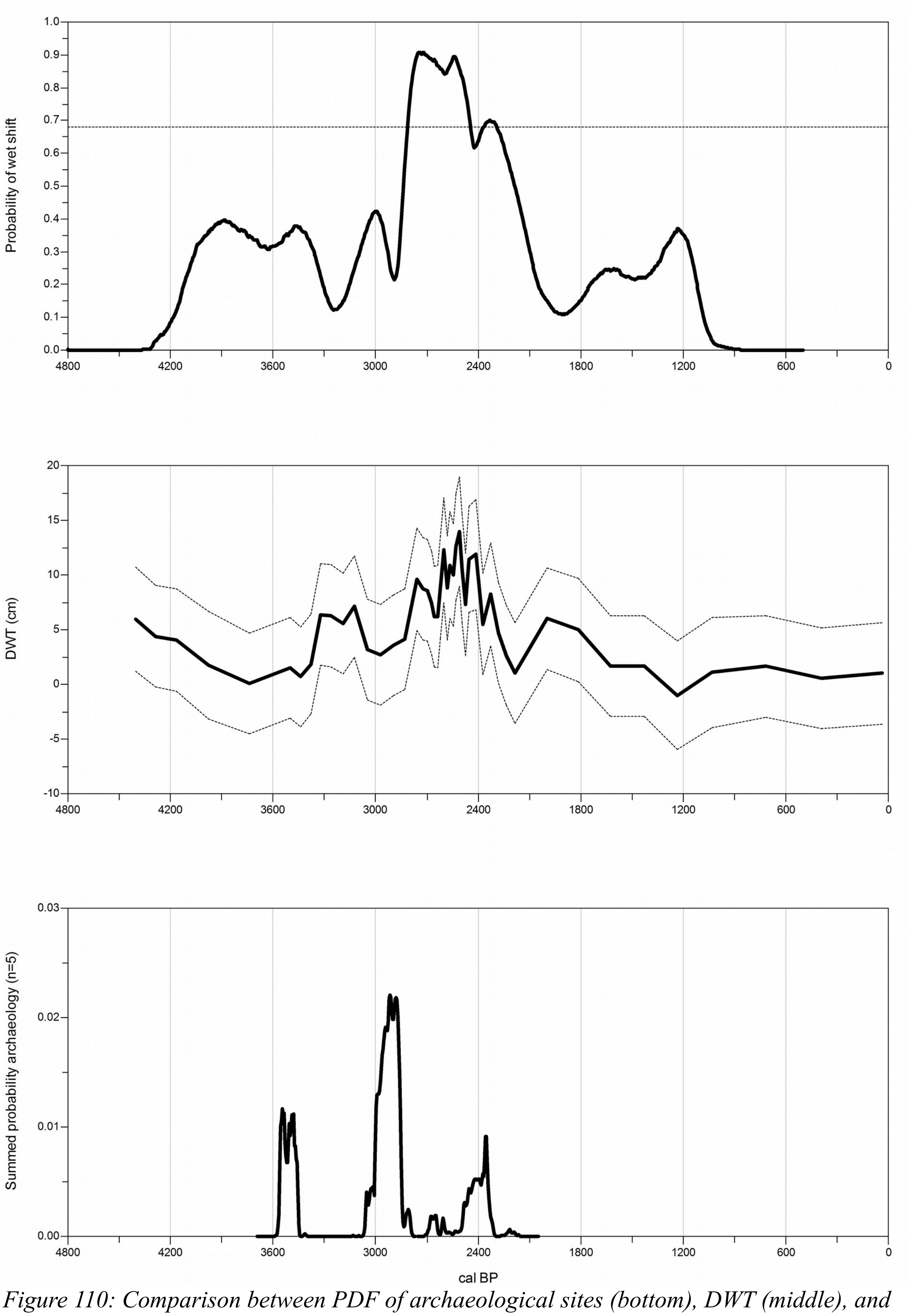

Figure 110: Comparison between PDF of archaeological sites (bottom), DWT (middle), and probability of a wet shift (100 yr time-window) (top), Longfordpass.

10.6.2.1 Early Bronze Age (*c.* 4150 – 3450 cal BP)

Plank path LFP-PP-5 was constructed at *c.* 3510 cal BP. This trackway appears to have been part of a wider regional system of communication, with contemporary, or near-contemporary, trackways of very similar construction having been found in other bogs in the Littleton chain (Derryville, Inchirourke, and Littleton). This structure was constructed during a period of wet bog surface conditions, with very high water tables, no more than at most *c.* 4cm below the surface. These conditions prevailed throughout the Early Bronze Age, and it is during this time that the onset of ombrotrophic conditions occurred at the sampling location.

10.6.2.2 Middle and Late Bronze Age (*c.* 3450 – 2550 cal BP)

Further trackways were constructed at Longfordpass at around the time of the transition from the Middle – Late Bronze Age. The earliest of these was constructed from longitudinal roundwoods (LFP-RP-3, after 2985 cal BP), followed by another plank path (LFP-PP-2, after 2954 cal BP), and finally a corduroy trackway (LFP-CT-1, after 2936 cal BP). These trackways may all be near-contemporary, or alternatively they may represent successive replacement of trackways crossing Longfordpass east to west. The latest trackway (LFP-CT-1) in particular, may again be a part of a wider regional communication system, with similar trackways built at around the same time at Littleton and Derryville. Reconstructed water tables from Longfordpass show that water tables were generally lower during the Middle Bronze Age than they had been during the Early Bronze Age (*c.* 6-7cm below surface), but this was interrupted by another wet shift, at around *c.* 3000 cal BP. The end of the Middle and beginning of the Late Bronze Age, when these three trackways were constructed was characterised by wet surface conditions. This was followed by a period of falling water tables, possibly caused by an increase in peat accumulation accompanying a shift towards *Sphagnum*-dominated floristic communities. The trend towards lower water tables was punctuated by a sharp wet shift at *c.* 2800 cal BP, almost certainly post-dating the construction of trackways at Longfordpass.

10.6.2.3 Iron Age (*c.* 2550 – 1550 cal BP)

The latest dated feature at Longfordpass is a deposit of archaeological wood (LFP-AW-4), which was interpreted as a possible animal trap. In spite of the lack of trackways such as those constructed during the Bronze Age, this feature indicates the continued presence of people around Longfordpass bog during the Iron Age. During this period, reconstructed water tables show a large degree of variability overlain over a general trend to lower water tables as the rapid build up of *Sphagnum* peat continued.

10.6.2.4 Summary

The Bronze Age at Longfordpass appears to be characterised by the construction of large trackways traversing the bog from east to west. These trackways, both during the Early Bronze Age, and the Middle/Late Bronze Age, have parallels with other similar trackways in other nearby bogs in the Littleton Bog system. In additions, most of these trackways were constructed from large split timbers and planks. Both of these factors may suggest a degree of organisation of labour at the local scale. At Longfordpass, it appears that these structures were built during periods of wetter surface conditions. After the last dated trackway was constructed, a further wet shift at *c.* 2800 cal BP (apparently driven by regional climate change, see Chapter 9), appears to have driven marked changes in the bog system, including hydrological changes, and accompanied by changes in accumulation rate and the floristic communities present on the bog. Although no trackways were constructed on Longfordpass during the Iron Age, the continued use of this bog by people is demonstrated by the construction of a possible animal trap.

10.6.3 Littleton bog

Figure 111 shows the PDF of the 6 ^{14}C dated archaeological features and a simulated radiocarbon date for the single dendrochronologically-dated feature at Littleton bog compared with reconstructed DWT (plotted against *maximum a posteriori* age estimate of the age vs depth model), and the estimated probability of a wet-shift event occurring within a 100 year time-window. The PDF curve appears to indicate three principle phases of human activity at Littleton: around *c.* 3500 cal BP, *c.* 3000 cal BP, and between *c.* 2400-1700 cal BP. The PDF of dated archaeology was not significantly correlated with DWT from Littleton (r=-0.19), but was significantly but weakly negatively correlated with the probability of a wet shift (100 year time window) (r=-0.27, p<0.0001). The latter is apparently due to absence of dated archaeological features during periods where DWT values rise sharply and subsequently fall sharply - interpreted as possible bog bursts (Casparie 2001; Van Geel *et al* 2014).

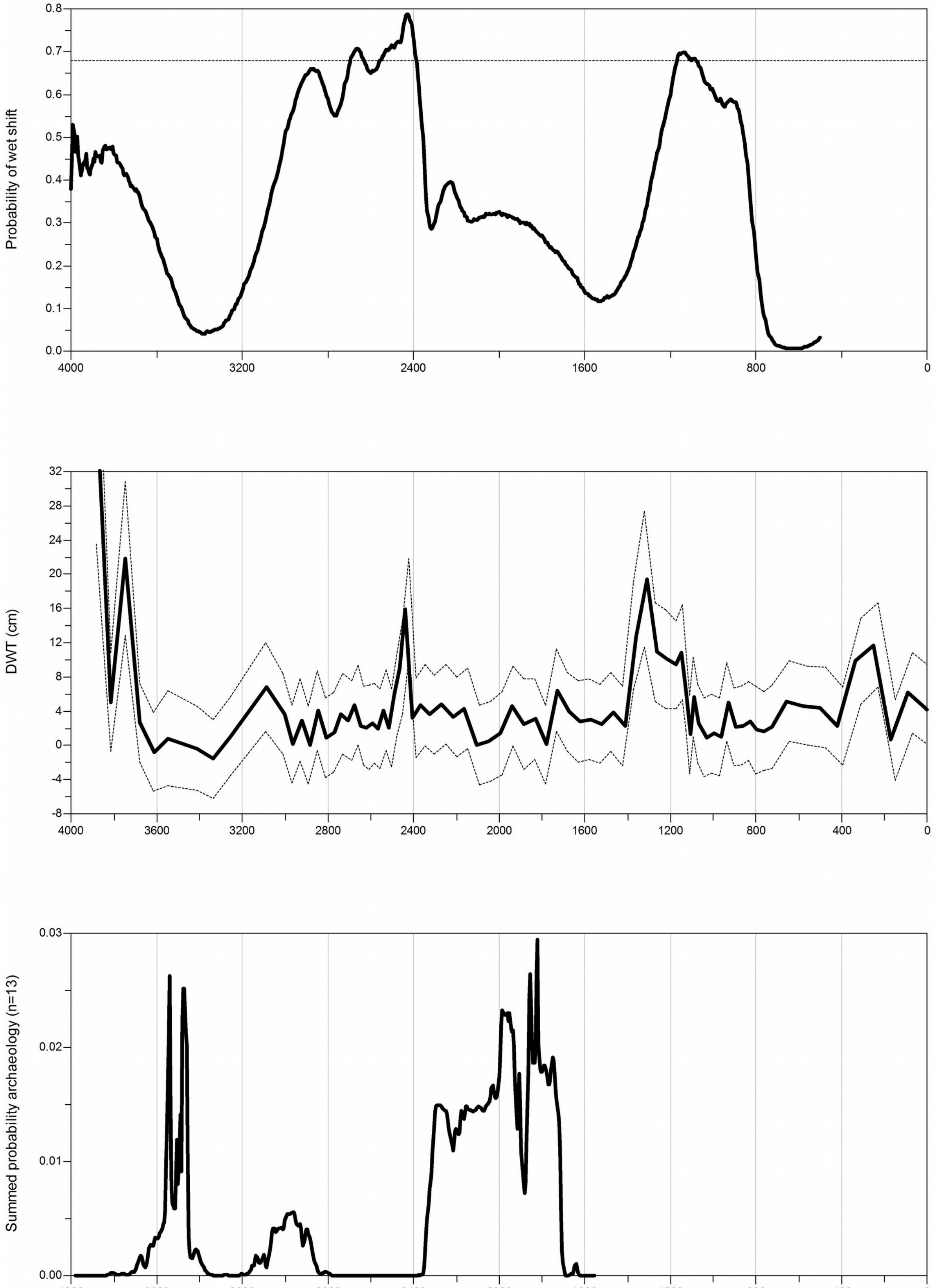

Figure 111: Comparison between PDF of archaeological sites (bottom), DWT (middle), and probability of a wet shift (100 yr time-window) (top), Littleton.

10.6.3.1 Bronze Age (*c.* 4150 – 2550 cal BP)

Three archaeological features at Littleton bog date to the Bronze Age: two plank paths LTN-PP-2, and LTN-PP-13) and a large corduroy trackway (LTN-CT-1). At the beginning of the Bronze Age, the DWT curve indicates dry BSW conditions at Littleton, this is followed by a sharp shift towards wetter conditions at *c.* 3800 cal BP after which DWT values indicate persistently wet to moderate conditions throughout the rest of the Bronze Age during which time the three large plank-built trackways were constructed. Perhaps the most notable feature of the BSW records from Littleton is a series of sharp shifts towards dry conditions, followed by a rapid return to wet conditions. These have been interpreted as possible bog-burst events: such an event appears to occur at around the Bronze Age to Iron Age transition.

10.6.3.2 Iron Age (*c.* 2550 – 1550 cal BP)

11 dated features (all brushwood trackways and platforms) at Littleton date to the Iron Age. The DWT curve shows two possible bog-burst events during the Iron Age, one at around the Bronze Age to Iron Age transition, and a second at the end of the Iron Age at *c.* 1350 cal BP, between these events, DWT values indicate persistently moderate to wet conditions (DWT ranging between 6cm and 0cm). All the Iron Age structures at Littleton appear to have been constructed during this wetter interval, and dated archaeological features are absent during the time of the possible bog burst events.

10.6.3.3 Summary

Two distinct phases are evident in the archaeological record at Littleton bog: on the one hand, during the Bronze Age, trackways are constructed from large split timbers, whilst during the Iron Age structures were constructed almost exclusively from brushwood. This change may be related to a number of culturally-dependant social, economic or technological factors. The most striking feature of the BSW record from Littleton is the occurrence of a series of potential bog-burst events. The significant negative correlation between the PDF of dated archaeological structures and probability of a hydrological event at Littleton appears to be due to the coincidence between lulls in the archaeological records and the rapid hydrological changes associated with the possible bog burst events. Such events may have caused considerable short-term disruption in the immediate vicinity of the site, and as such, the absence of archaeological features on the bog in the immediate aftermath of these events appears to be intuitive.

Whether the bog burst event at the Bronze Age-Iron Age transition was a causative factor in the change in building materials used in the trackways remains a matter of conjecture. LTN-PF-8 and LTN-PF-12, both dating to the Iron Age, display evidence of more than once phase of construction/use; brushwood technology may hypothetically have allowed structures on the occasionally unstable surface of Littleton bog to have been more easily maintained and repaired.

10.6.4 Killeen bog

Figure 112 shows the PDF of the 3 ^{14}C dated archaeological features on Killeen bog compared with reconstructed DWT (plotted against *maximum a posteriori* age estimate of the age vs depth model), and with the estimated probability of a wet-shift event (100 year time window). The PDF curve shows three phases of activity at Killeen: during the Late Bronze Age, the Iron Age, and in the Early Christian-Medieval period. The PDF of dated archaeology was not significantly correlated with DWT from Killeen (r = -0.13), but had a very weak positive correlation with the probability of wet shift (100 year time window) data (r = 0.14, p < 0.01).

10.6.4.1 Late Bronze Age (*c.* 2950 – 2550 cal BP)

Platform KLN-PF-2, a substantial structure constructed from roundwoods and split timbers was constructed on Killeen during either the late Bronze Age or the earliest part of the Iron Age. The hydrological record from Killeen begins in this period, suggesting that this structure was constructed at around the same period as the onset of ombrotrophic conditions at the sampling location. The DWT curve indicates wet to moderately wet bog surface conditions.

10.6.4.2 Iron Age (*c.* 2550 – 1550 cal BP)

Whilst KLN-PF-2 may have been possibly been constructed at the very beginning of this period, unambiguous evidence for Iron Age activity at Killeen is restricted to the construction of a narrow corduroy trackway (KLN-CT-1) during the latter part of the Iron Age. This trackway linked the dryland island of Derrynaflan to the surrounding drylands. The DWT curve indicates persistently wet-moderately wet conditions throughout the Iron Age, although preservation of testate amoebae is poor during this period, and there are few datapoints.

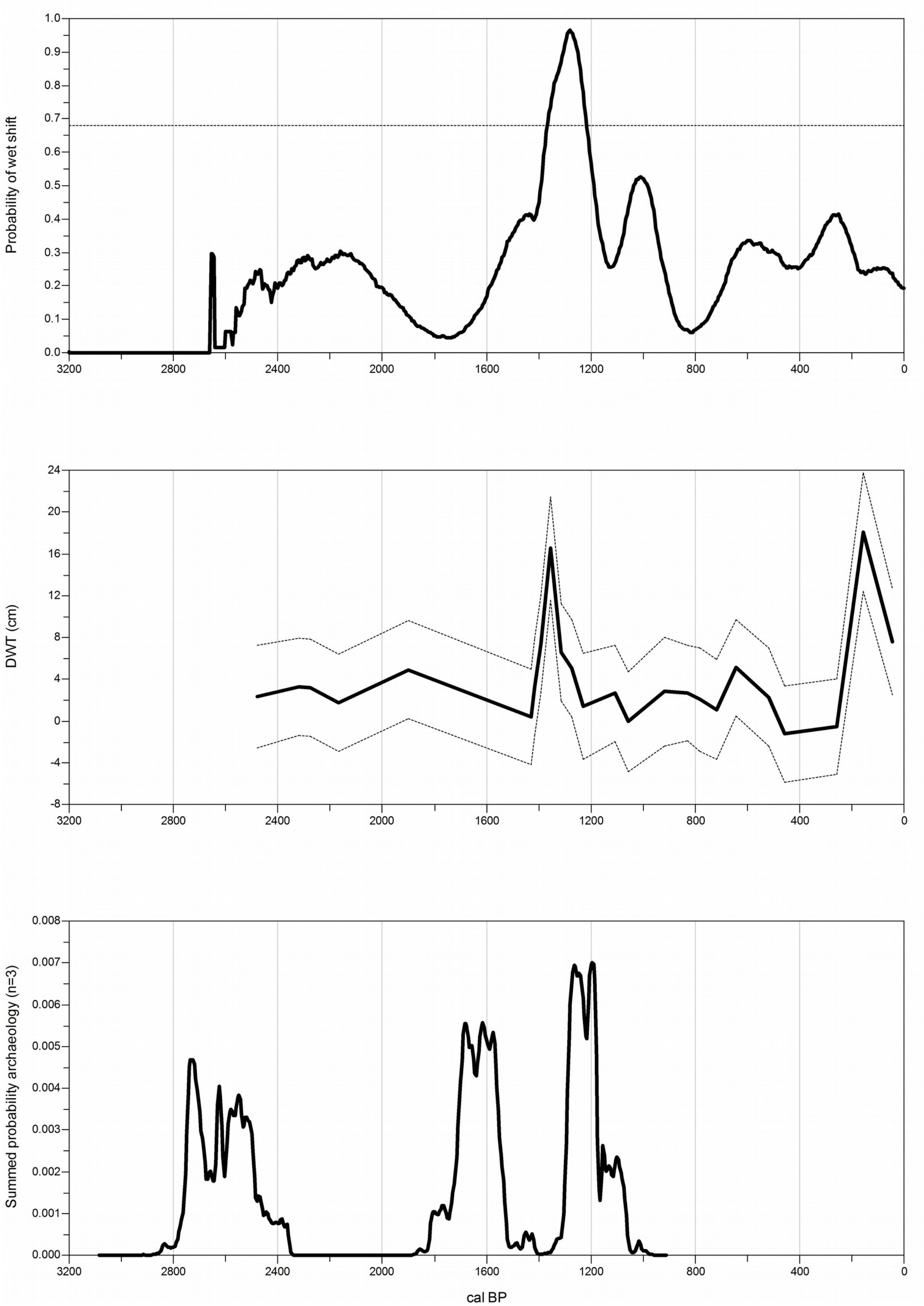

Figure 112: Comparison between PDF of archaeological sites (bottom), DWT (middle), and probability of a wet shift (100 yr time-window) (top), Killeen.

10.6.4.3 Early Christian-Medieval (*c.* 1550 – 500 cal BP)

During the Early Christian or Medieval period a roundwood path, KLN-RP-3, was constructed on Killeen bog, again linking Derrynaflan to the surrounding drylands. Excavation revealed at least two phases of construction of this trackway, possibly interrupted by a short hiatus (shallow peat deposits separate phases of construction in places. During the 8th and 9th centuries AD, possibly contemporary with this trackway, a monastery was founded on Derrynaflan. In addition a hoard of early Medieval metalwork was recovered from Derrynaflan in the 1980s. The DWT curve from Killeen indicates wet bog surface conditions punctuated by a drastic fall in water tables at *c.* 1350 cal BP, followed by a rapid return to wet conditions, this event may be possible evidence for a bog burst at Killeen. It appears likely that KLN-RP-3 was constructed soon after this event, which if caused by a bog burst may have caused considerable disruption to communication routes across the bog.

10.6.4.4 Summary

Although generally sporadic, the richest evidence for human activity on and around Killeen bog dates to the later Iron Age and Early Christian-Medieval periods. Both the late Iron Age corduroy trackway and the Early Christian roundwood path cross Killeen bog to link Derrynaflan to the drylands to the north east. As such, these structures appear to suggest continuity of this routeway from the Iron Age into later periods. The construction of these trackways is apparently punctuated by a possible bog burst, which may have interrupted this route of communication for a time. Nevertheless, hydrological records from Killeen indicate persistently wet bog surface conditions associated with all dated archaeological structures on the wetlands. These persistently wet conditions on the wetlands may conceivably have provided a marked contrast with Derrynaflan dryland island, highlighting the obvious importance of this place. If, as has been suggested (Ryan 1997, pp.999–1000), the Derrynaflan hoard was deposited during the period of extensive Viking raids during the 10th century AD, the wetness of the surrounding bog, may arguably have enhanced the perception of Derrynaflan as a suitably remote location.

10.7 Discussion

Figure 113 shows the central Irish tuned and stacked water table presented in Chapter 9 (top) alongside a PDF of all dated archaeological features from the nine study sites (lower panel). Both records show considerable variability during the Late Holocene, however, the two records are uncorrelated (*r*=-0.08). This lack of correlation reflects on the one hand the degree of inter-site variability in BSW records discussed in Chapter 9, and on the other hand the degree of inter-site variability in the history of human activity on each site illustrated above. This finding echoes a similar finding by Plunkett *et al. (2013)*.

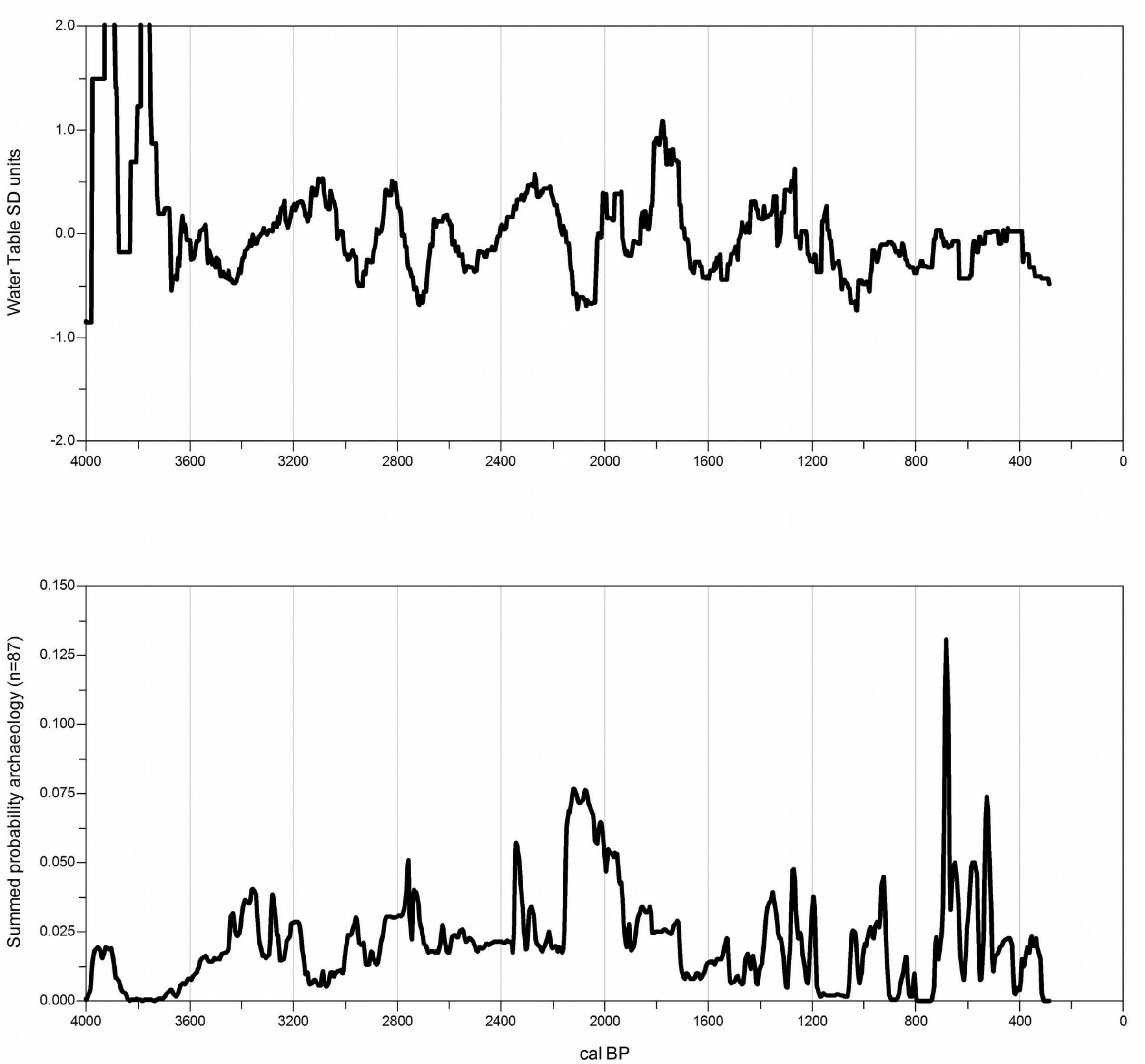

Figure 113: Comparison between the central Irish tuned and stacked water table record (top) and PDF of dated archaeological structures from all nine central Irish study sites (bottom). r=-0.08.

Whilst local variability is clearly apparent both in archaeological (discussed in this chapter) and palaeohydrological records (discussed in Chapters 7 and 9) from central Ireland, it does not follow that this lack of coherence at the regional scale precludes the identification of the agency of the environment in the archaeological record at the local scale. Variability in both BSW and archaeological records examined on a site-by-site basis exhibit "temporality...

consonant with human dwelling" (Ingold 1993, p.168). In other words, hydrological change at each study site appears at times to occur over timescales that are likely to have been perceived within the span of a single human life span, or at least a few generations. In some cases, for example at Littleton, where a series of rapid shifts to dry conditions may have occurred as a result of bog bursts, such events may have occurred over much shorter timescales (e.g. a single year or less). Although no consistent linear relationship is evident between BSW and the construction of archaeological sites, patterns of environmental and archaeological change show a variety of complex and contingent relationships reflecting both the "temporality of the landscape" (sensu Ingold 1993) and the phenomenological experience (sensu Tilley 1994) of living in and around these wetland environments.

Trackways are clearly constructed by individuals and groups as a response to specific local conditions – i.e. a need or desire for one reason or another to gain access into or across a raised bog. As such the interpretation of these archaeological features cannot be understood in isolation from their local environment. Comparisons of archaeological and palaeoenvironmental data on a site-by-site basis reflect a series of contingent human-environment relationships which are interpretively important to understanding human activity in and around raised bogs. The construction and replacement, or *lack* of replacement, of trackways at many sites reflects the temporality and the continual process of change visible at some sites: at Longfordpass a system of trackways possibly representing organised communication routes was maintained through the Middle and Late Bronze Age during a period of wet conditions at the site, but following changes in the local environment, in this case a shift towards more rapid accumulation of *Sphagnum* peat, perhaps driven by the potentially climate-driven shift to wetter conditions at *c.* 2700 cal BP, this system of trackways ceased to be maintained although the presence of a possible animal trap clearly indicates continuity of human activity in some form in the area. At Littleton too, continuity of human activity is also evident throughout the Bronze and Iron Ages, however gaps in the archaeological record coincide with a series of bog bursts. Further potential bog-burst events at Cloonshannagh, Gowla and Killeen also coincide with gaps in the construction of trackways.

At many sites, *continuity* of the importance of particular routeways across the landscape is a prominent feature: at Killaderry the routeway from north west to the south east was marked by a series of trackways from the Neolithic until the Medieval period. At Castlegar, trackways were constructed between the Late Iron Age/Early Christian and the

Medieval periods along the routeway from west to east towards the Dalysgrove dryland island. At Castlegar, later trackways built along this route appear to have been constructed following increases in surface wetness – whilst the continuing importance of this route in spite of changing environmental conditions might be taken to indicate "indifference" (c.f. Plunkett *et al* 2013), the coincidence of phases of changing hydrology and trackway construction at this site instead appear to indicate an engagement and reaction to the processes of natural environmental change.

At the regional scale, comparisons between archaeological and palaeoenvironmental records (e.g. Plunkett *et al* 2013) are confounded not only by the scale of chronological uncertainties but also by the degree of *local* variability of both records. It is clear, however, that there is no simple, predictable, relationship between human activity and environmental conditions in raised bogs in central Ireland. Correlation between the two records is arguably inappropriate since correlation only measures *linear* relationships for which there is no logical theoretical basis: there is no logical reason why people should need or desire to construct more trackways when bogs are dry or vice-versa. Instead, trackways are constructed as a result of the complex interaction between social and/or economic imperatives (the maintenance of routes of trade or communication, the religious or ritual significance of dryland 'islands', or the importance of activities, ritual or otherwise, on the bogs themselves) and a response to the specific environmental characteristics of the bogs (wet, soft, marshy ground, uneven surface, pools, hummocks etc.). As such trackways cannot be understood without considering their specific environmental context. Indeed, many 'socio-economic' and 'environmental' factors may be inextricably linked: for example, were dryland islands appropriate locations for ecclesiastical sites (thus necessitating the construction of communication routes to them) precisely because they were surrounded by wetlands? Although the relationships may not be linear or predictable, understanding the environmental context of individual peatland archaeological sites is interpretively important. Such relationships are contingent and variable, and therefore are best explored on a site-by-site basis.

Chapter 11: Conclusion

The concluding chapter of this thesis aims to draw together the lines of evidence presented in the preceding chapters and to test the hypotheses defined in Chapter 1 against that evidence. In the first section of this chapter, each hypothesis is addressed in turn. In the second part, a brief synthesis is presented alongside a series of concluding remarks. Finally, suggestions for future research on past human-environment interactions in Irish raised bogs are offered.

11.1 Hypotheses

The hypotheses outlined in Section 1.4 are tested against the evidence presented in this thesis. In each case, the default position (i.e. the "null hypothesis" - H_0) is stated and either retained or rejected.

11.1.1 Hypothesis I

H_0 – Bog surface wetness (BSW) records from raised bogs in central Ireland do not preserve a record of Holocene climatic variability.

In Section 2.1.5, the literature concerning debates around the climatic sensitivity of raised bogs was reviewed. The work of Barber (1981) successfully falsified cyclical models of raised bog development (Osvald 1923). Barber's conclusions were supported by the findings of Chapter 8, where hummock and hollow microforms were found to be persistent features. Furthermore, data presented in Chapter 8 supported findings in other studies (Barber and Langdon 2007; Charman *et al* 2009) suggesting statistically significant linkages between BSW records and instrumental weather data (precipitation and temperature). In Chapter 9, composite BSW records from central Ireland were found to show common features with other composite palaeoclimate records (Charman *et al* 2006; Swindles *et al* 2013), albeit with major periods of poor correspondence. Although chronological uncertainties were high, the probability of synchronous hydrological change within the study region showed peaks during some periods (e.g. 3200-2400 cal BP) when other studies appear to show evidence for rapid climate change (Mayewski *et al* 2004).

<u>The null hypothesis is therefore rejected</u>, and the following alternate hypothesis is

therefore proposed:

H_1 – BSW records from raised bogs in central Ireland are sensitive to Holocene climatic variability, and preserve a record of past changes.

11.1.2 Hypothesis II

H_0 – Subfossil testate amoebae recovered from peat cores from the study sites do not allow accurate and precise reconstruction of past BSW.

In Chapter 6 the relationship between testate amoebae and hydrological conditions was modelled, and a new central Ireland (CI) transfer function was developed. The new CI transfer function was found to perform similarly to other published testate amoebae transfer functions (Charman *et al* 2007; Swindles *et al* 2009; Turner *et al* 2013), although spatially independent cross validation suggested that performance statistics may have been somewhat overly-optimistic. The correspondence between DWT reconstructions based on the CI transfer function and instrumental weather data, presented in Chapter 8, further support the notion that such reconstructions reflect genuine patterns of environmental change.

<u>The null hypothesis is therefore rejected</u>, and the following alternate hypothesis is therefore proposed:

H_1 – Subfossil testate amoebae recovered from peat cores from the study sites do allow accurate and precise reconstruction of past BSW.

11.1.3 Hypothesis III

H_0 – Past human activity (as reflected in the construction of trackways) in raised bogs within the study area was unaffected by environmental conditions at those sites.

In Section 2.2.5 the literature on the interpretation of peatland archaeology in Ireland was discussed. Although there is no clear consensus on the exact role of the environment in shaping patterns of past human activity in raised bogs, the special nature of the wetland archaeological record is widely-recognised (Coles and Coles 1989). The variety in form of peatland archaeological structures uncovered within the study region, discussed in Chapter 4, hint at an active engagement with the specific environmental characteristics of raised bogs, with several sites showing evidence of repair or variation in the mode of construction in response to the immediate conditions on the bog surface (e.g. short trackways or platforms crossing areas of pool peat). Expanding on this, in Chapter 10 it was argued that peatland structures cannot be understood in isolation from their environment; in other words, a trackway is, by definition, built in response to the boggy character of the immediate environment.

For these reasons, the null hypothesis is rejected, and the alternate hypothesis is proposed:

H_1 – Past human activity in raised bogs within the study area was affected by environmental conditions at those sites.

11.1.4 Hypothesis IV

H_0 – Records of past BSW and records of past human activity (i.e. the archaeological record) cannot be usefully compared.

Chapter 10 explored ways in which archaeological records can be compared with BSW records from the same sites, presented in Chapter 7. Whilst chronological uncertainties inherent in both records generally prevented direct correlation between individual archaeological features and palaeoenvironmental data, broad relationships could be discerned. Where features were precisely dated using dendrochronology more secure inferences about contemporary environmental conditions could be made. Chapter 7 demonstrates that usable palaeohydrological records can be obtained from milled raised bogs with known archaeological records. Explicit consideration of the chronological uncertainties of both records was shown to allow site-specific contingent relationships to be explored, and since human activity on raised bogs is inherently related to local environmental conditions (see Hypothesis III) such relationships must be considered to be interpretatively important.

The null hypothesis is therefore rejected, and the following alternate hypothesis is proposed:

H_1 – Records of past BSW and records of past human activity can be compared in an interpretatively important way.

11.1.5 Hypothesis V

H_0 – There is no predictable or consistent relationship between trackway construction and environmental conditions across the study area.

As well as considering relationships between archaeological and BSW records on a site-by-site basis, in Section 10.7 the combined peatland archaeological record of the nine milled study sites was compared with the central Ireland stacked DWT curve presented in Chapter 9. The two records were found to be uncorrelated. This lack of a consistent linear relationship echoes the findings of Plunkett *et al. (2013)*. The apparent lack of a linear relationship between regional BSW and archaeological records is unsurprising given the considerable inter-site variability observed in both datasets. Whilst BSW records from central Ireland do appear to contain a significant palaeoclimate signal, major periods of poor correspondence were also identified in Chapter 9. BSW records were found to contain elements both of region-wide climate-driven change and local variability. When this is considered alongside the local variability evident in the archaeological record even within the relatively restricted study area explored in this thesis (see Chapter 4), it is apparent that there is no logical basis on which to expect a consistent, predictable, relationship between human activity and prevailing regional climatic conditions. That is not to say that human activity and local environmental conditions are unrelated (see Hypothesis IV), only that such relationships are localised, variable, contingent on specific localised conditions, and change through time.

The null hypothesis is therefore retained.

11.2 Conclusions

In the preceding chapters, both palaeoenvironmental and archaeological evidence has been presented in order to examine a specific set of human-environment interactions, namely the interactions between people and lowland raised bogs in central Ireland. The threads of evidence examined are, by necessity, limited to particular types of archaeological sites (mainly trackways, platforms and other, mostly wooden, peatland structures), and specific proxies of bog surface wetness (principally testate amoebae analysis).

The archaeological evidence is restricted by what is 'archaeologically visible', and thus is conditioned by the kinds of activities which leave physical traces in these specific peatland contexts. The choice of palaeoenvironmental proxies are similarly conditioned by the kinds of evidence which survive in these contexts (taphonomy) and by conscious choice, based on the type of signal which is thought to be of most interest – in this case water balance in ombrotrophic bogs. The methodological considerations, and attendant limitations, associated with these threads of evidence have been discussed at length throughout this thesis. As such, this thesis is firmly situated in the traditions of Quaternary palaeoecology, and environmental archaeology (with its strong traditional links to processualism).

These considerations in turn condition the specific research questions and hypotheses tested in this thesis, particularly that there is a consistent relationship between peatland structure construction and bog surface wetness. Previous studies (Bermingham 2005; Gearey and Caseldine 2006; Plunkett *et al* 2013) have also tested these same hypotheses, but these have usually focused explicitly on testing deterministic models of human-environment interaction, often explicitly linked to climate change. Whilst some patterns appear to be visible on individual sites (Bermingham 2005; Gearey and Caseldine 2006), broader patterns are inconclusive, concluding that the null hypothesis – that there is no clear or direct link between climate change and the archaeological record – must be retained (Plunkett *et al* 2013). Such conclusions tend to be reached on one hand due to the methodological issues inherent in these studies – in particular chronological correlation between the archaeological and palaeoenvironmental record, but also, arguably, because of the conceptual framework in which these studies are situated.

Previous studies have implied a clear and unproblematic separation between 'natural' environments, landscapes, and processes, and 'human' factors – societies, sites and artefacts, cultural landscapes, and cultural processes (drawing on Sauer 1925). In the context of these studies, this duality is expressed as 'natural' climate change, and processes of bog development on the one hand, and on the other hand the 'human' act of constructing trackways, and the cultural choices, and the technological and economic imperatives, that this entails. In this line of reasoning, it follows, then, that since the 'natural' and the 'human' factors are independent variables, the lack of a clear correlation between the two lines of evidence imply that natural processes do not play an important in role in cultural processes. There is little or no room for contingency in these relationships.

It is argued here that the absence of contingency in these theoretical models severely restricts their usefulness. If the 'natural' and the 'human' are so easily separable and environmentally deterministic models of human activity so obviously fail to account for the evidence at hand, what is the point of studying human-environment interactions at all? Contingency provides a far more useful model. This model is based on the belief that human and natural influences are mutually constituted and thus inseparable, that the boundaries between the human and the natural are in fact socially constructed (Head 2000, pp.7–8). Contingency "highlights the historical and local specificity that has to be accounted for in complete understanding and effective manipulation of ecological systems" (Parker and

Pickett 1997, p.18; in Head 2000, p.8).

There is abundant evidence for these kinds of contingent relationships in Irish prehistory: the ritual importance of wet places in the prehistory of Ireland (echoed across many parts of Europe) as evidenced by the votive deposition of metalwork in bogs, lakes and streams, mainly during the Bronze Age (Bradley 1998); the situation of the numerous *fulacht fiadh* beside streams and the edges of bogs in the Bronze Age (Waddell 1998b, p.174; O'Sullivan 2007a, p.162); bog bodies, deposited mostly during the Iron Age (Brindley and Lanting 1995); the location of monastic and other ecclesiastical foundations from the Early Christian period (Bitel 1990); and the construction, use, and changing meanings of *crannógs* up into the Early Medieval period (Frendengren 2002). All of these examples are very clearly rooted in what might be thought of as exclusively 'cultural' processes reflecting economic practices, religious beliefs and social mores, but at the same time no satisfactory interpretation of any of these can separate them from their situation within the 'natural' environment. There is clearly a dialectical relationship between changing environments, changing perceptions and connotations of these environments, and social change. Understanding these historically contingent dialectical relationships is a central part of understanding and interpreting past human activities and should be a focus for future research. It is from this perspective that the following conclusions are drawn.

- Testate amoebae provide a robust means of obtaining quantitative reconstructions of BSW from milled former raised bogs in central Ireland.
- Mid-Late Holocene BSW records from the study sites in central Ireland do appear to contain an important climate-driven signal during specific periods of apparent climate change (e.g. 3200-2400 cal BP) although considerable inter-site variability is also evident.
- Explicit examination of the chronological uncertainties inherent in peatland palaeoenvironmental records are needed in order to interpret and understand the driving mechanisms of such records.
- BSW records from milled raised bogs in central Ireland can be usefully compared with the archaeological records of the same sites in order to enhance archaeological interpretations of specific sites and features.
- There is no consistent, linear, or predictable relationship between trackway construction and BSW at the regional scale. Human-environment relationships are

best explored on a site-by-site basis.

- Environmentally-deterministic theories of human-environment interactions in raised bogs in central Ireland should be abandoned in favour of approaches focusing on localised, contingent relationships, drawing on wider developments in archaeological theory.

11.3 Further work

As discussed in Chapter 2, both palaeoenvironmental and archaeological investigations in raised bogs in central Ireland have a long history. The special value of the palaeoenvironmental and archaeological resources contained within central Irish raised bogs is widely-recognised; these resources are under threat: from peat extraction, development, and potentially, from future climate change. In response to these threats, formal programmes of palaeoenvironmental and archaeological research have been initiated (National Monuments Service 2013). Such programmes of work present the opportunity to obtain more data, from more sites than ever before. This in turn presents the opportunity not only to create regional composite records of Holocene environmental change and of numbers and the chronological clustering of the archaeological record, but crucially, to also examine local variability. As has been demonstrated in this thesis, local variability is a major feature of both the palaeoenvironmental and the archaeological records of Irish raised bogs. The aim of future work should not be to eliminate or mask such local variability, but should instead focus upon it.

This thesis has demonstrated the feasibility, and potential value, of examining human-environment relationships on a site-by-site basis. The primary constraint on such an approach is the inherent chronological uncertainty of both records. Improved chronologies utilising wiggle-matched AMS ^{14}C dating and Bayesian modelling have the potential to provide ever more detailed records of local and regional environmental change. More detailed exploration of the driving mechanisms of the BSW record, including modelling and comparisons with instrumental weather data, have the potential to improve understanding of the complex relationships between local environmental conditions and regional climate change. Finally, the utilisation of interpretative frameworks drawn from archaeological theorists, and from the humanities generally, have the potential, when combined with sensitive localised environmental reconstructions, to provide more detailed and nuanced understanding of the archaeological record. The local variability inherent in both palaeoenvironmental and archaeological records should not be seen as an obstacle to be overcome, but should instead be recognised as an opportunity to gain deeper, more nuanced, understanding of the way that people in the past experienced their environments.

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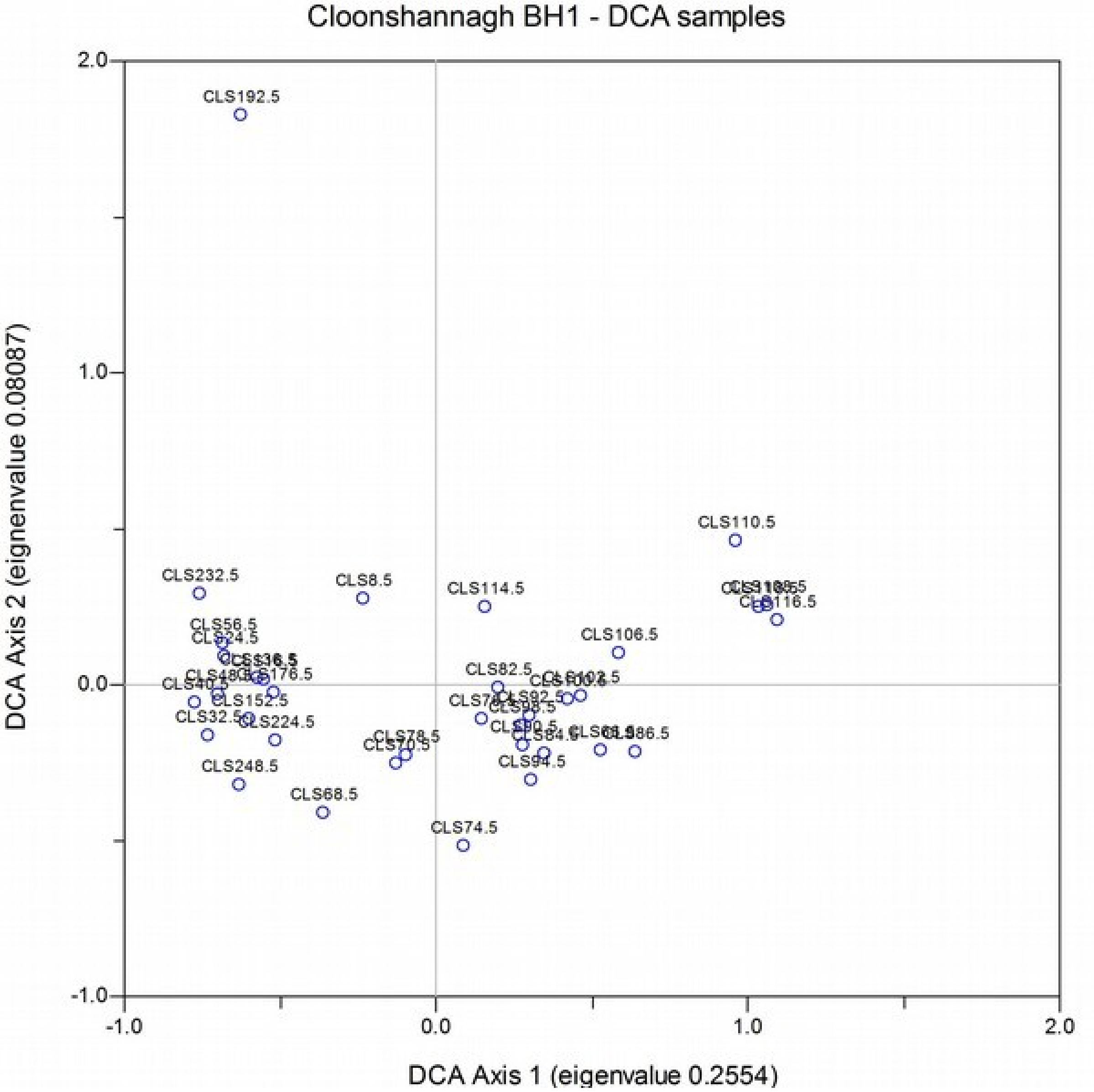
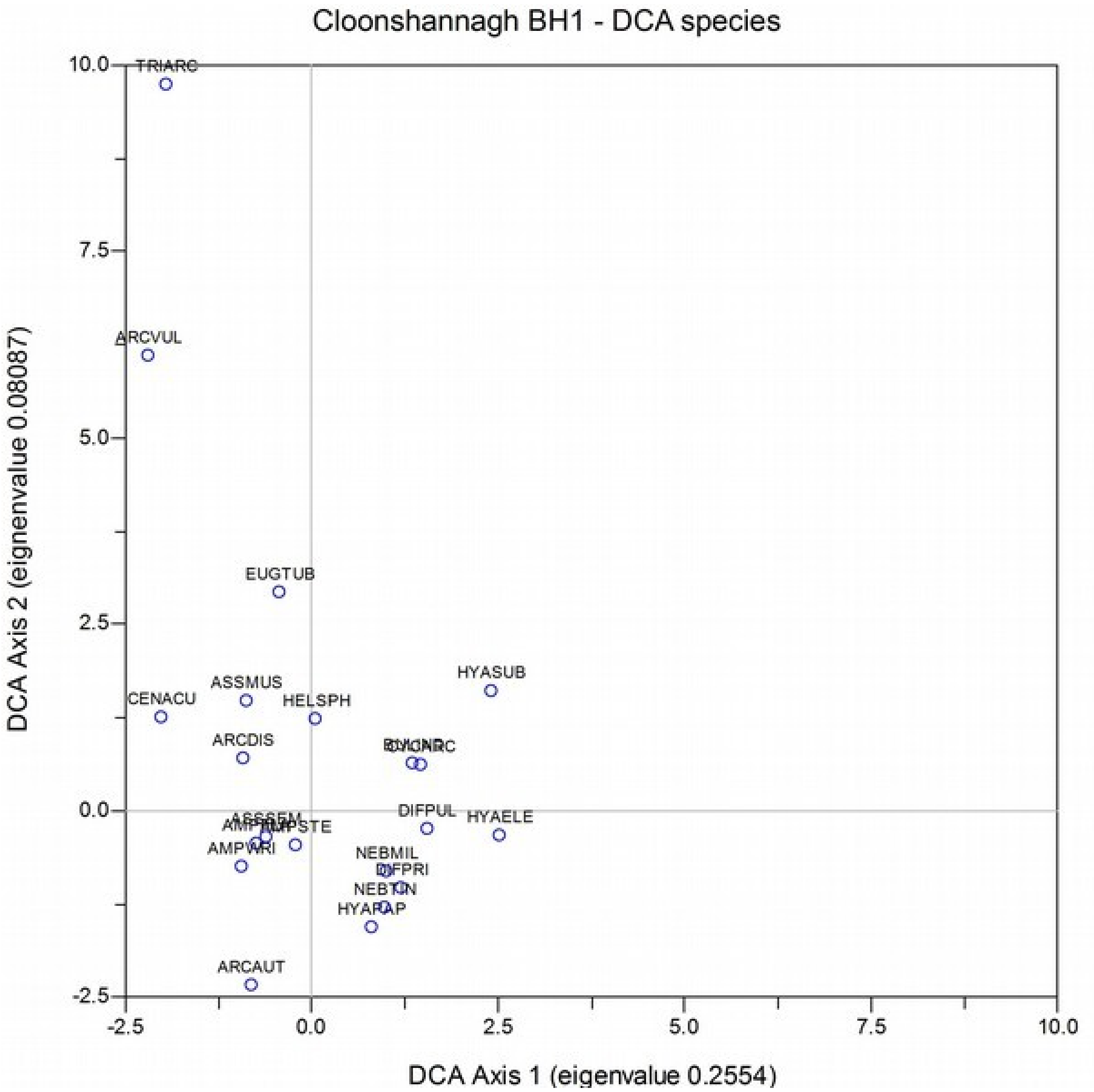
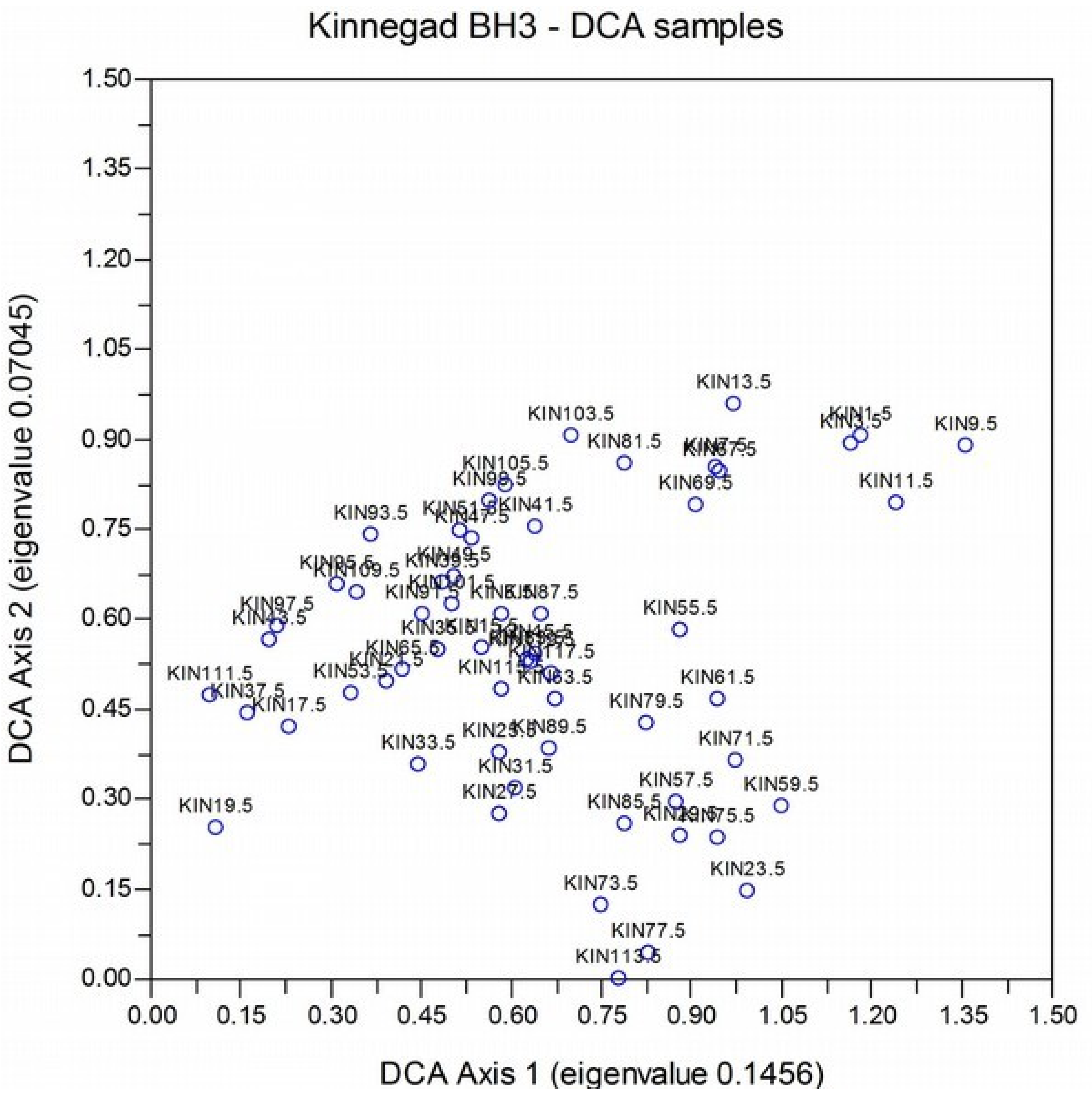
Appendix 1 – DCA biplots




Cloonshannagh BH1 - DCA species
DCA Axis 2 (eigenvalue 0.08087)
DCA Axis 1 (eigenvalue 0.2554)
TRIARC
ARCVUL
EUGTUB
HYASUB
ASSMUS
CENACU
HELSPH
ARCDIS
DIFPUL
HYAELE
AMPWRI
NEBMIL
HYAPAP
ARCAUT
10.0
7.5
5.0
2.5
0.0
-2.5
-2.5
0.0
2.5
5.0
7.5
10.0



Kinnegad BH3 - DCA samples
DCA Axis 2 (eigenvalue 0.07045)
DCA Axis 1 (eigenvalue 0.1456)
1.50
1.35
1.20
1.05
0.90
0.75
0.60
0.45
0.30
0.15
0.00
0.00
0.15
0.30
0.45
0.60
0.75
0.90
1.05
1.20
1.35
1.50
KIN13.5
KIN103.5
KIN1.5
KIN3.5
KIN9.5
KIN81.5
KIN105.5
KIN99.5
KIN69.5
KIN11.5
KIN93.5
KIN47.5
KIN41.5
KIN49.5
KIN109.5
KIN91.5
KIN87.5
KIN97.5
KIN55.5
KIN65.5
KIN117.5
KIN111.5
KIN53.5
KIN63.5
KIN61.5
KIN37.5
KIN17.5
KIN79.5
KIN33.5
KIN89.5
KIN71.5
KIN31.5
KIN57.5
KIN59.5
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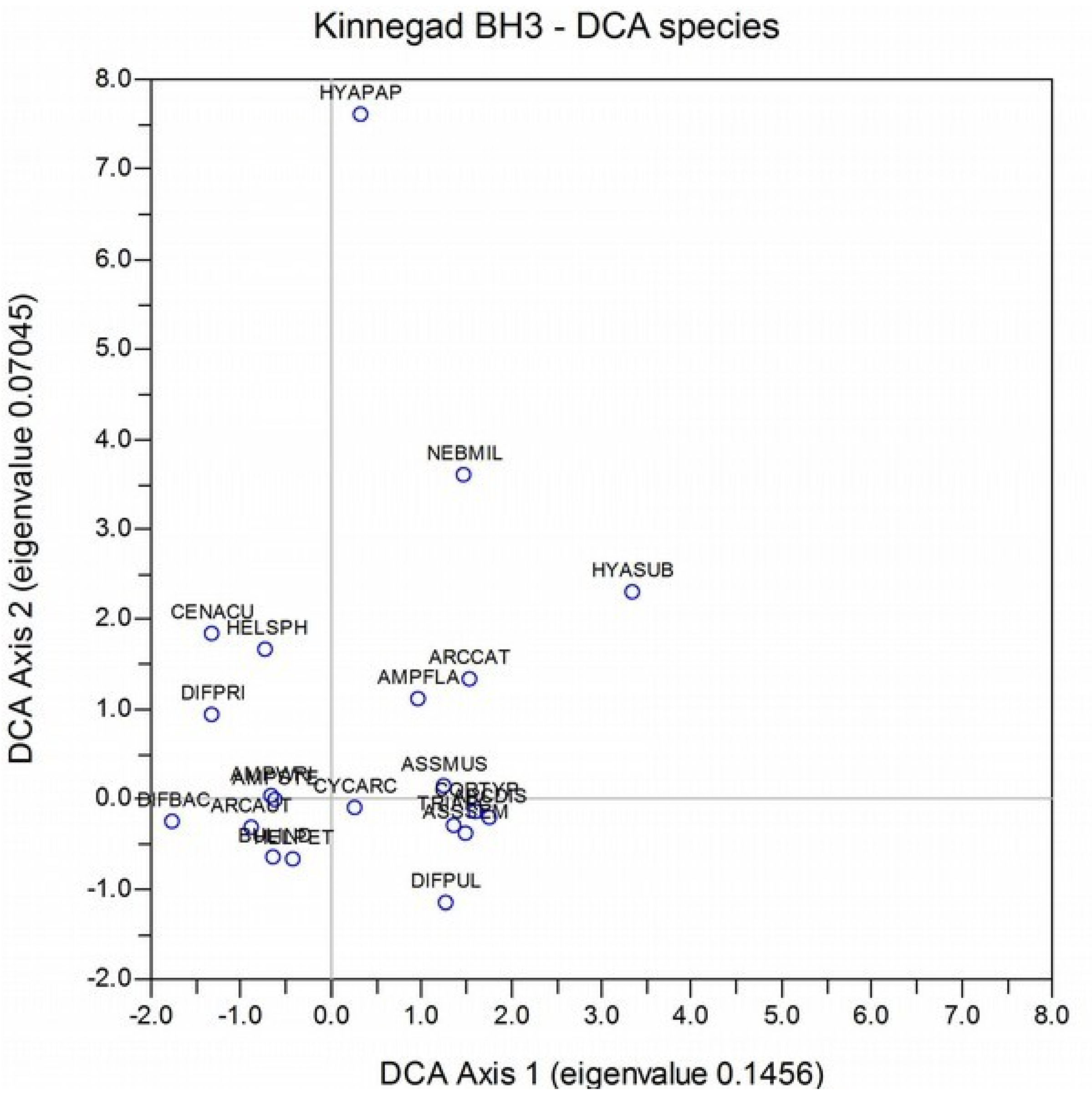
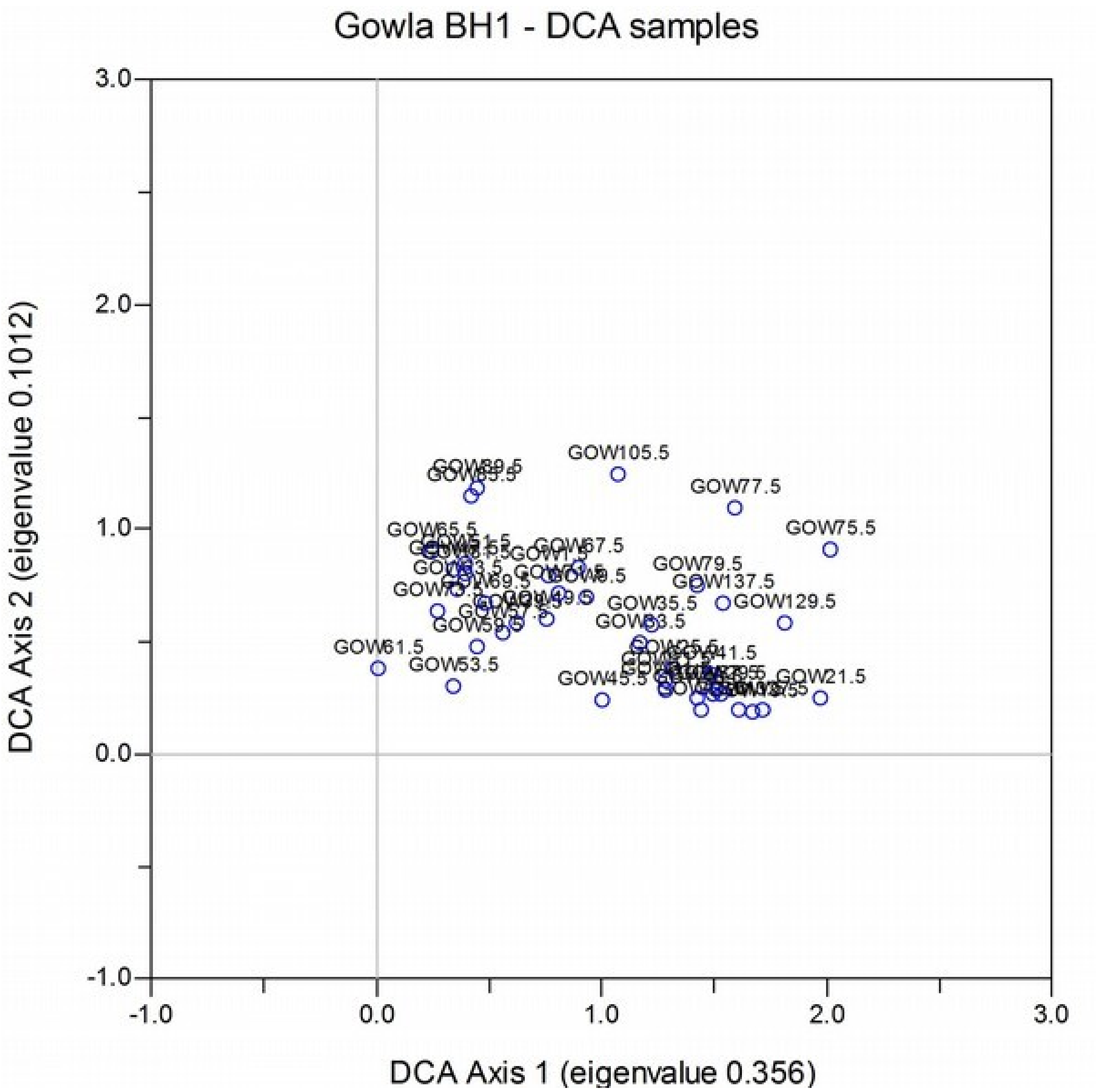
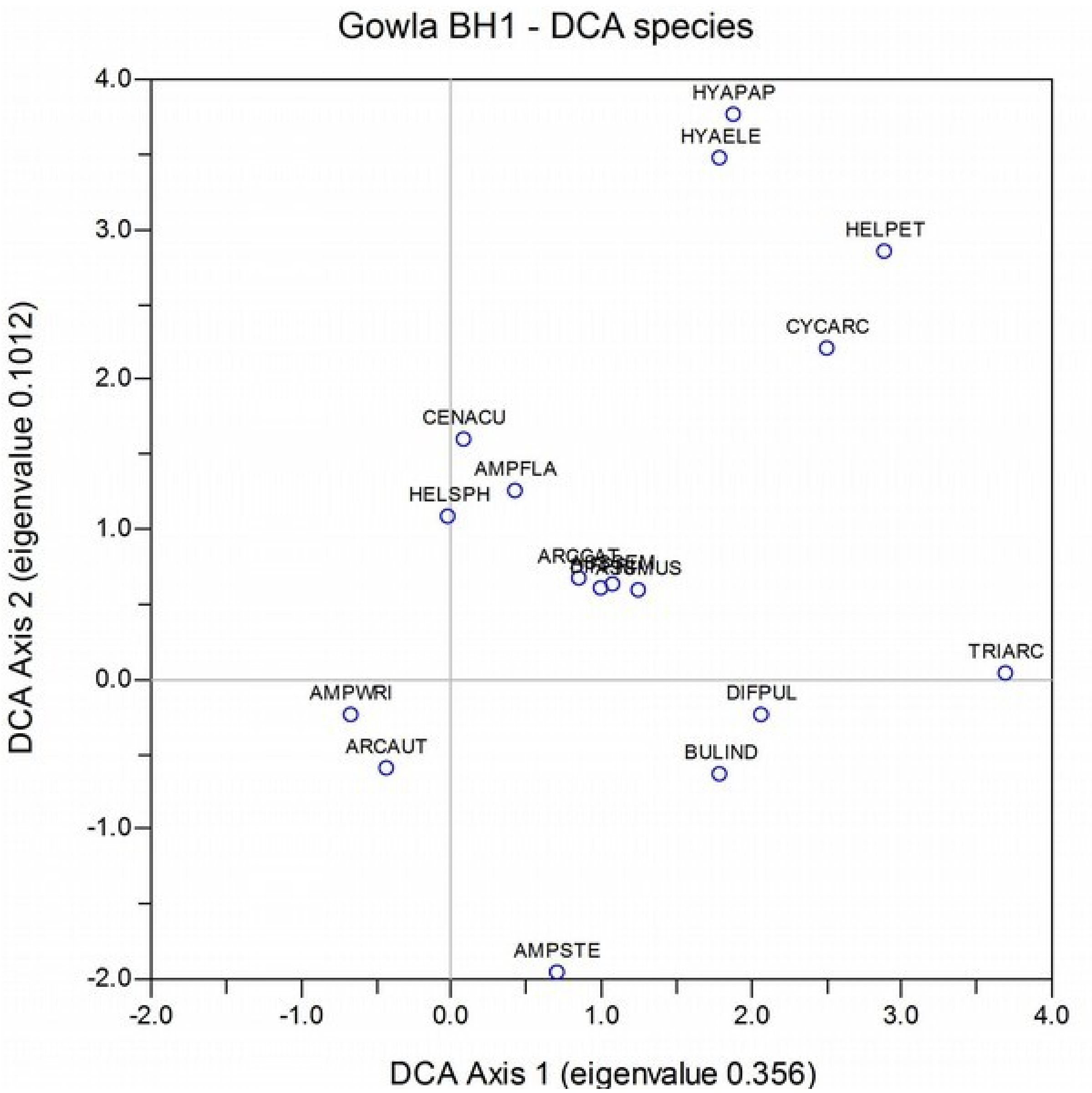
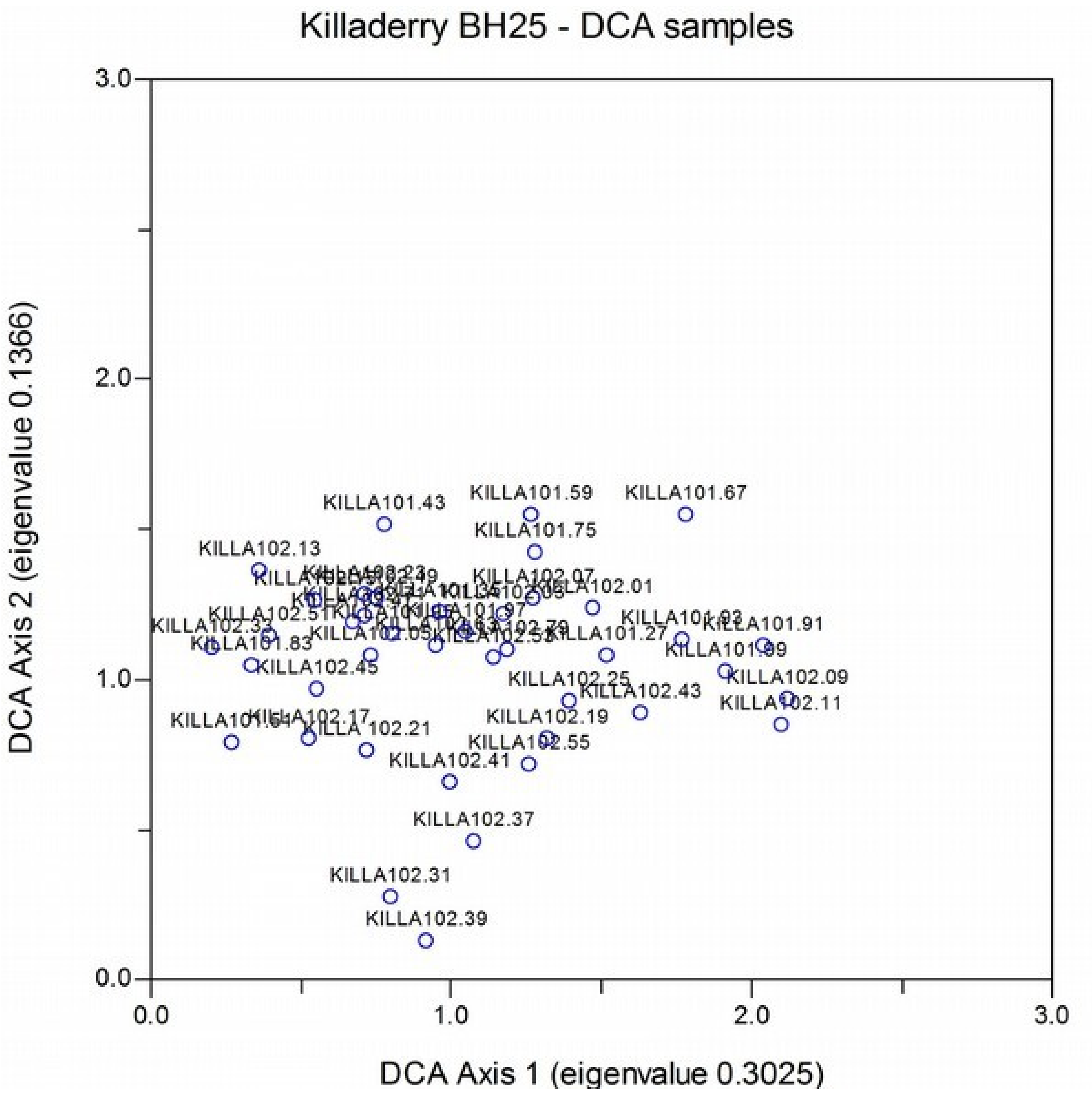
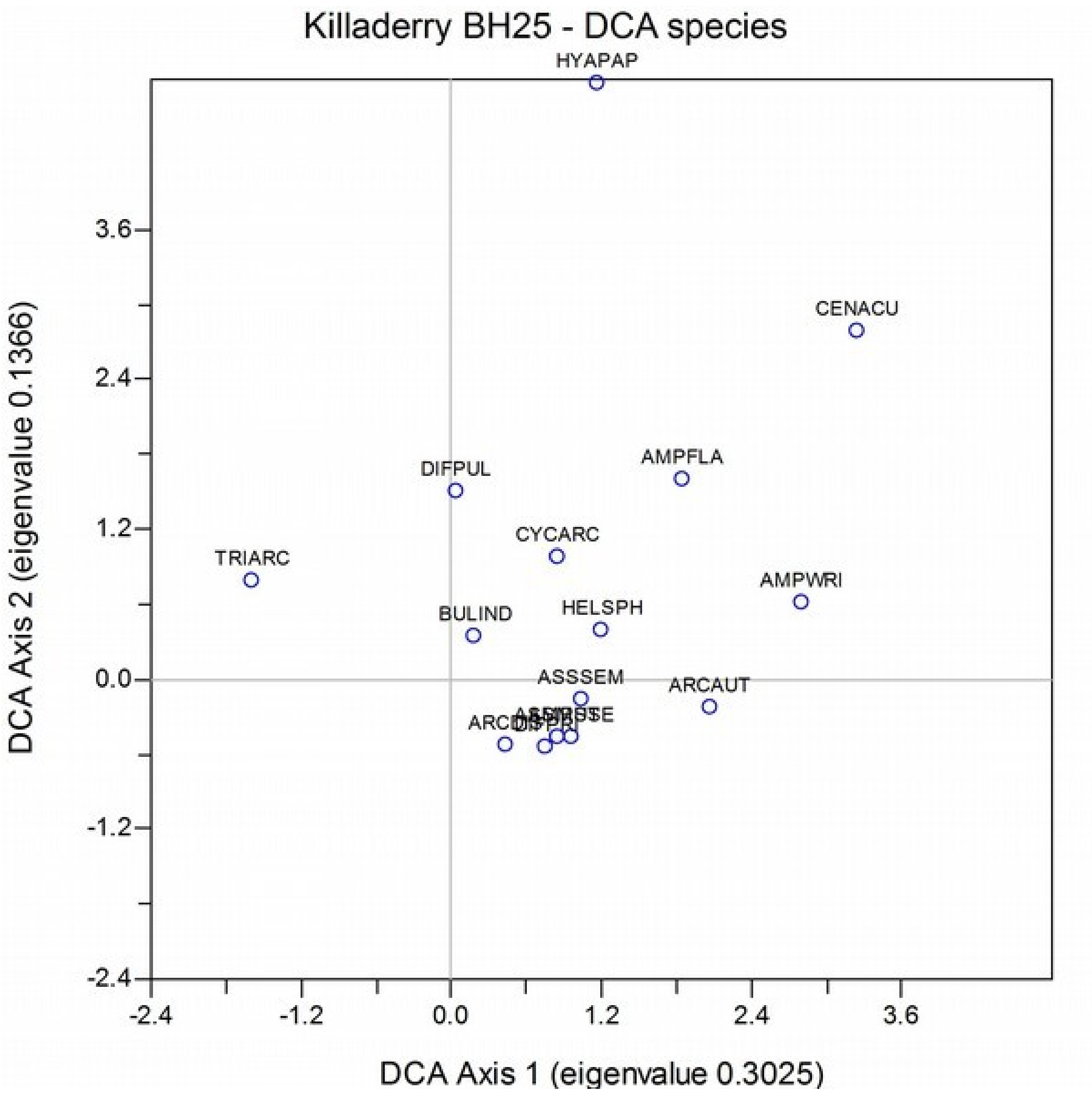
KIN27.5
KIN85.5
KIN75.5
KIN23.5
KIN73.5
KIN77.5
KIN113.5

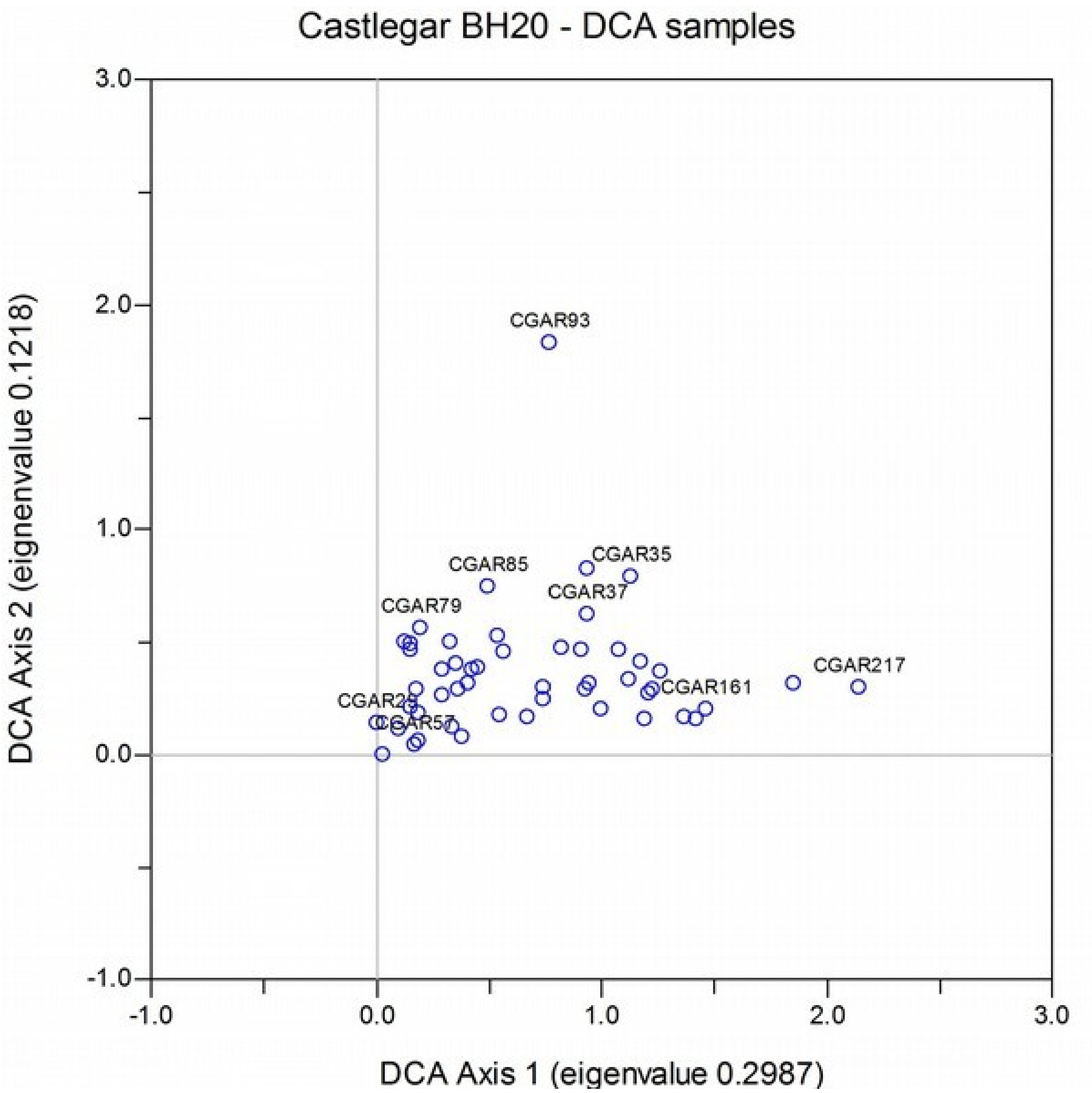

Kinnegad BH3 - DCA species
DCA Axis 2 (eigenvalue 0.07045)
DCA Axis 1 (eigenvalue 0.1456)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
HYAPAP
NEBMIL
HYASUB
CENACU
HELSPH
ARCCAT
AMPFLA
DIFPRI
ASSMUS
CYCARC
DIFBAC
ARCAUT
DIFPUL


Gowla BH1 - DCA samples
DCA Axis 2 (eigenvalue 0.1012)
DCA Axis 1 (eigenvalue 0.356)
3.0
2.0
1.0
0.0
-1.0
-1.0
0.0
1.0
2.0
3.0
GOW105.5
GOW77.5
GOW75.5
GOW65.5
GOW67.5
GOW79.5
GOW137.5
GOW129.5
GOW35.5
GOW61.5
GOW53.5
GOW45.5
GOW21.5

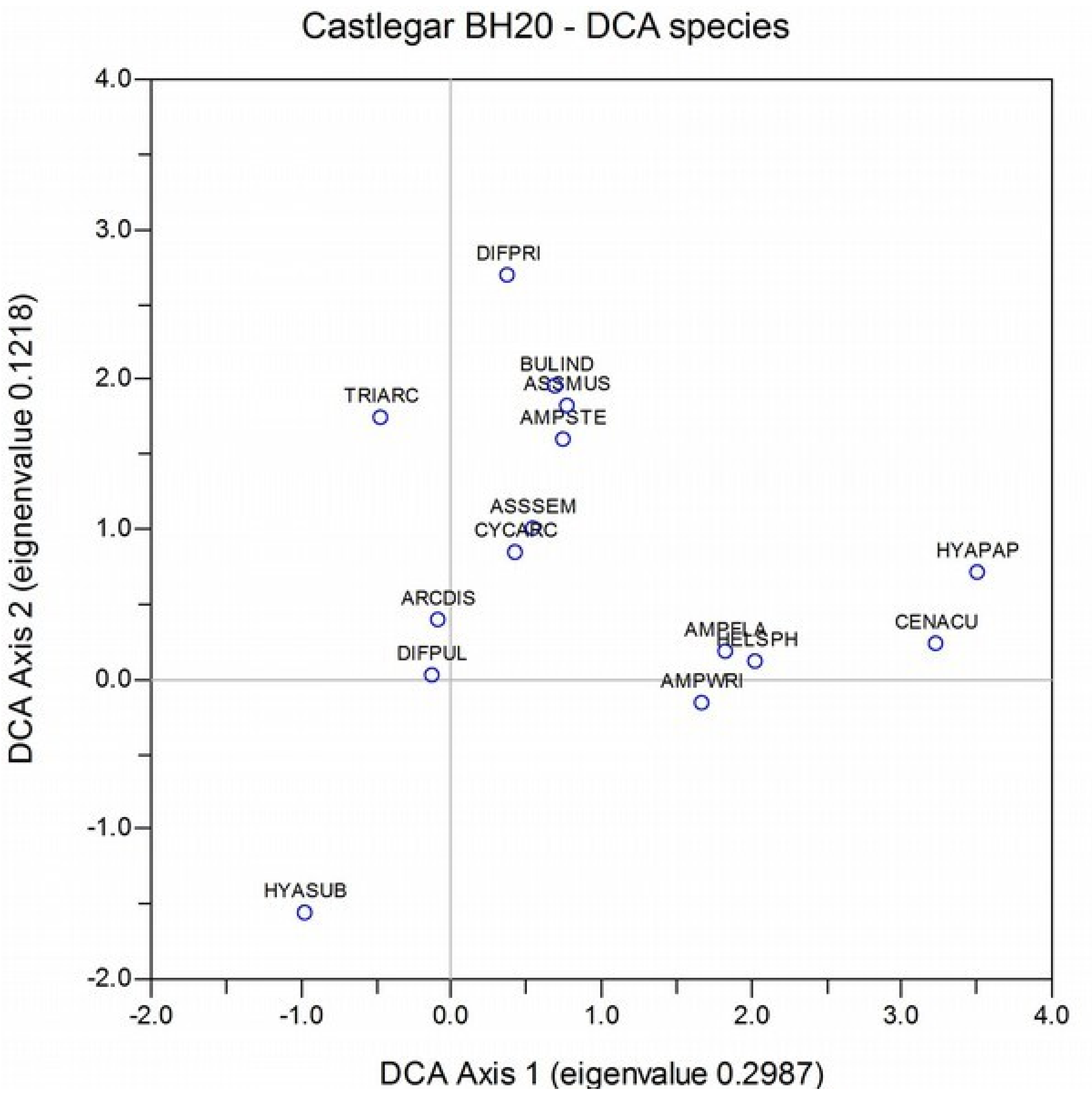

Gowla BH1 - DCA species
DCA Axis 2 (eigenvalue 0.1012)
DCA Axis 1 (eigenvalue 0.356)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
HYAPAP
HYAELE
HELPET
CYCARC
CENACU
AMPFLA
HELSPH
TRIARC
AMPWRI
DIFPUL
ARCAUT
BULIND
AMPSTE


Killaderry BH25 - DCA samples
DCA Axis 2 (eigenvalue 0.1366)
DCA Axis 1 (eigenvalue 0.3025)
0.0
1.0
2.0
3.0
KILLA101.43
KILLA101.59
KILLA101.67
KILLA101.75
KILLA102.13
KILLA102.07
KILLA101.97
KILLA101.27
KILLA101.99
KILLA102.45
KILLA102.09
KILLA102.25
KILLA102.43
KILLA102.19
KILLA102.17
KILLA 102.21
KILLA102.41
KILLA102.37
KILLA102.31
KILLA102.39

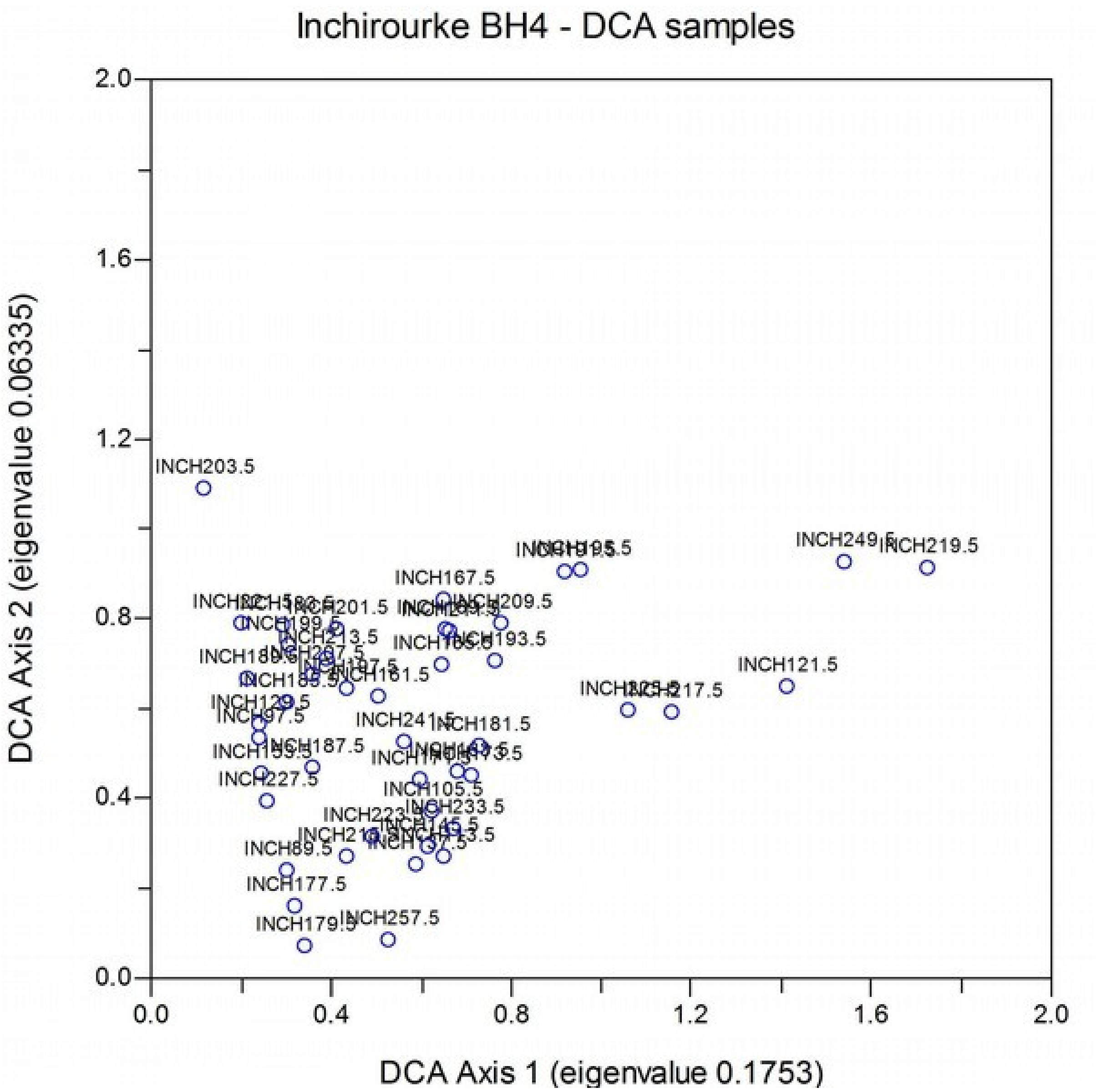

Killaderry BH25 - DCA species
HYAPAP
CENACU
AMPFLA
DIFPUL
CYCARC
TRIARC
AMPWRI
BULIND
HELSPH
ASSSEM
ARCAUT
3.6
2.4
1.2
0.0
-1.2
-2.4
-2.4
-1.2
0.0
1.2
2.4
3.6
DCA Axis 2 (eigenvalue 0.1366)
DCA Axis 1 (eigenvalue 0.3025)



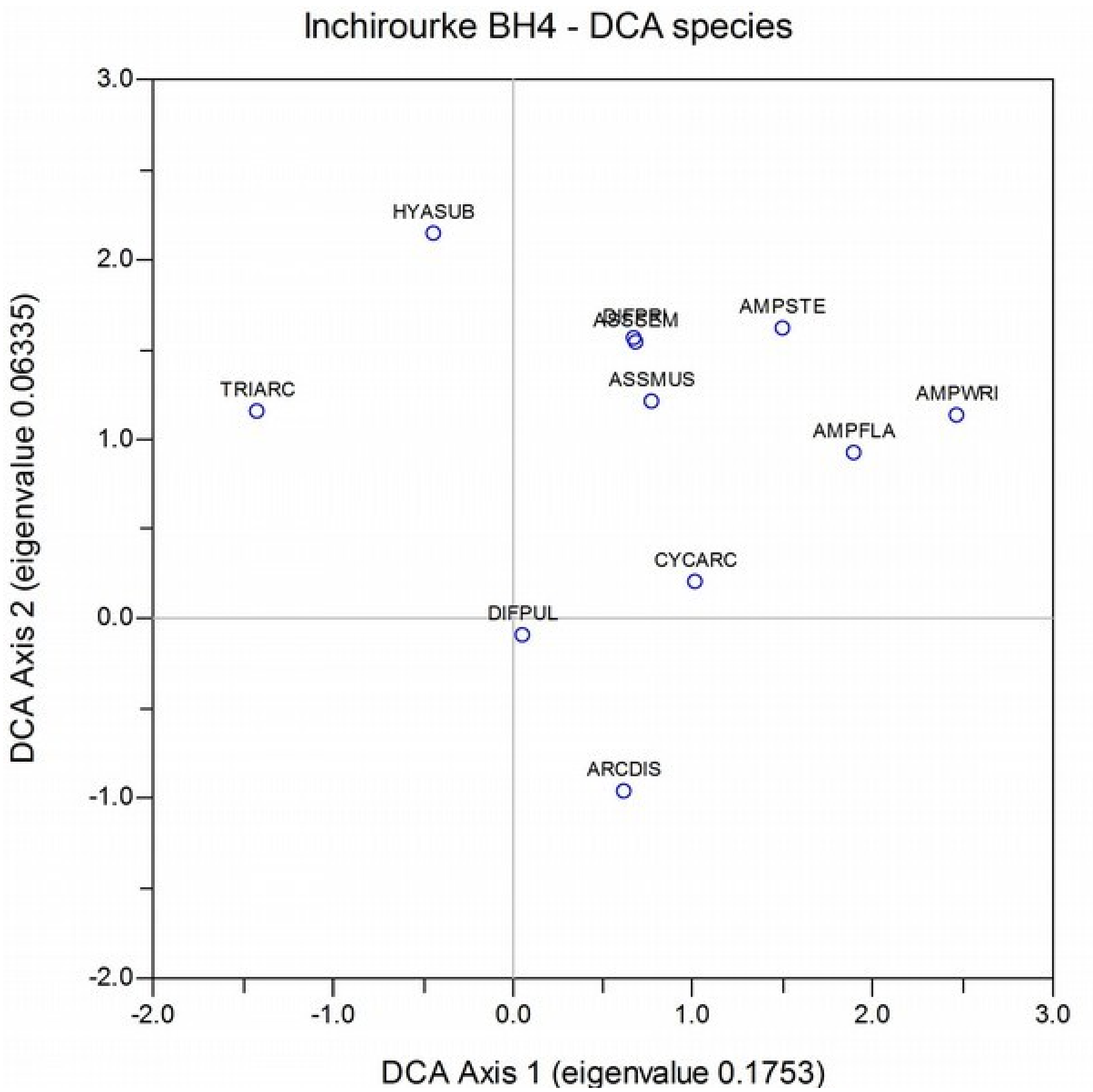
Castlegar BH20 - DCA samples
DCA Axis 2 (eignenvalue 0.1218)
DCA Axis 1 (eigenvalue 0.2987)
3.0
2.0
1.0
0.0
-1.0
-1.0
0.0
1.0
2.0
3.0
CGAR93
CGAR85
CGAR35
CGAR37
CGAR79
CGAR217
CGAR161
CGAR57



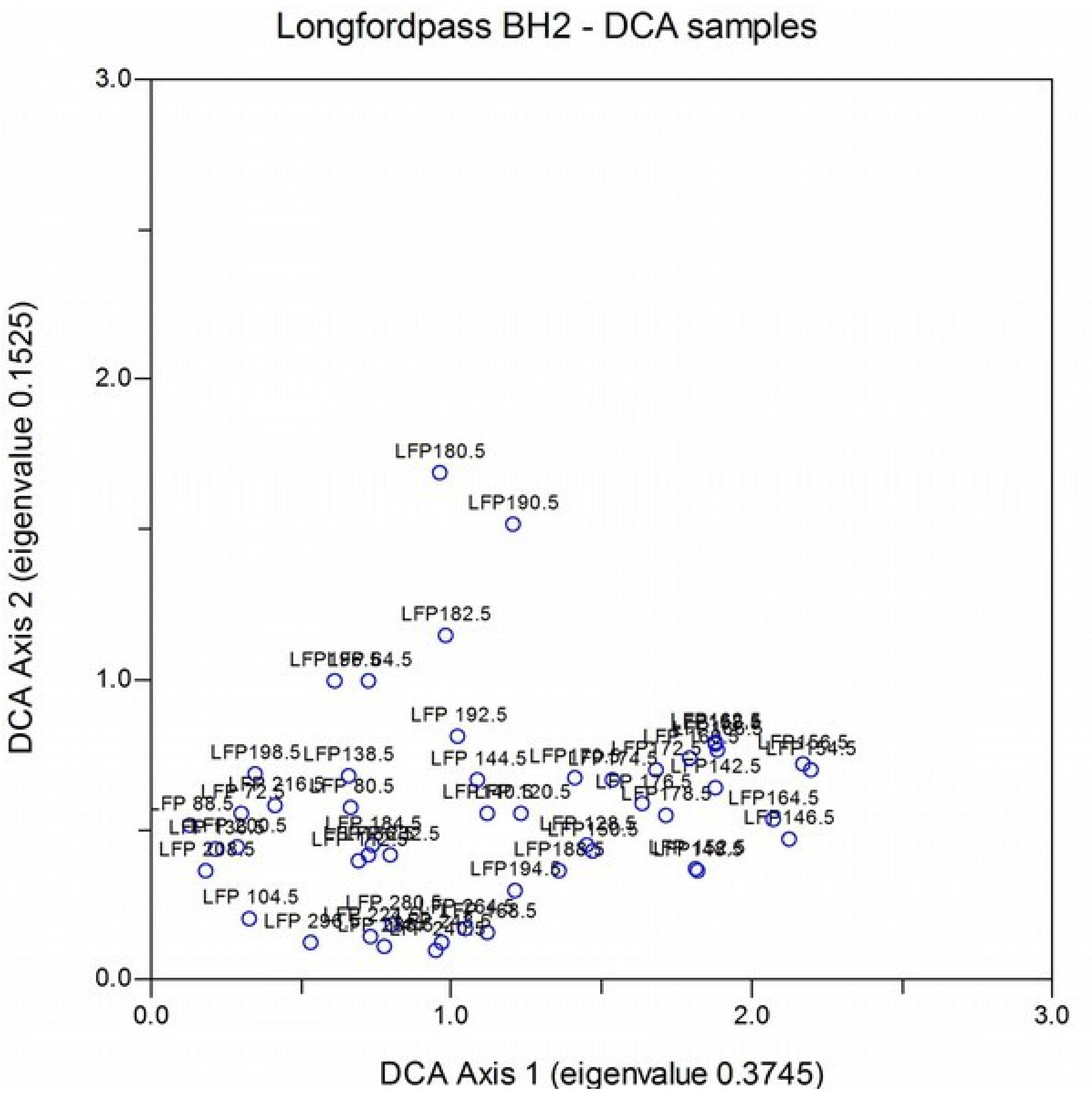
Castlegar BH20 - DCA species
DCA Axis 2 (eignenvalue 0.1218)
DCA Axis 1 (eigenvalue 0.2987)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
DIFPRI
BULIND
ASSMUS
TRIARC
AMPSTE
ASSSEM
CYCARC
HYAPAP
ARCDIS
CENACU
AMPELA
HELSPH
DIFPUL
AMPWRI
HYASUB

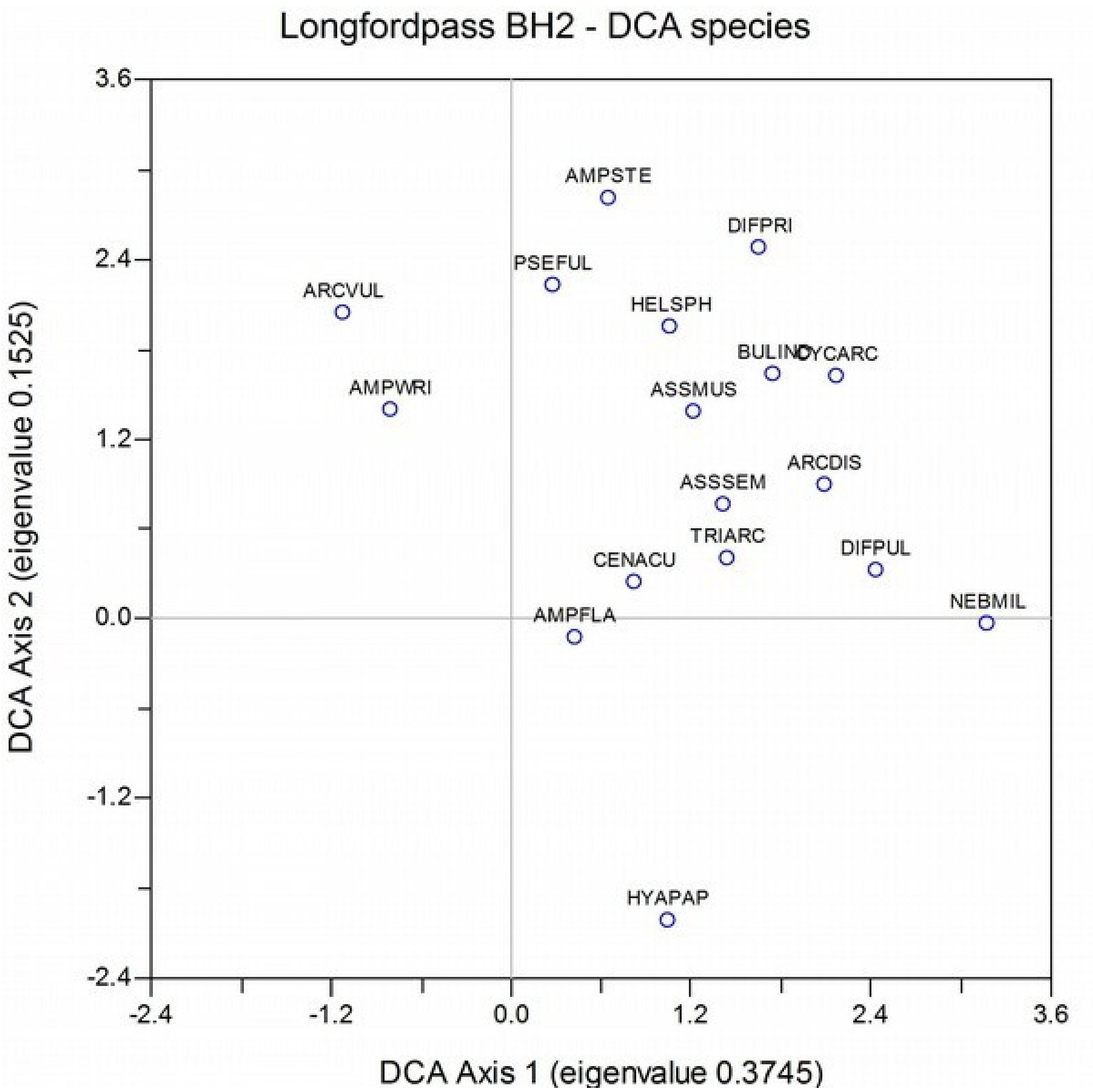


Inchirourke BH4 - DCA samples
DCA Axis 2 (eigenvalue 0.06335)
DCA Axis 1 (eigenvalue 0.1753)
0.0
0.4
0.8
1.2
1.6
2.0
INCH203.5
INCH167.5
INCH209.5
INCH201.5
INCH199.5
INCH213.5
INCH193.5
INCH249.5
INCH219.5
INCH121.5
INCH217.5
INCH185.5
INCH161.5
INCH129.5
INCH97.5
INCH241.5
INCH181.5
INCH187.5
INCH227.5
INCH105.5
INCH233.5
INCH89.5
INCH177.5
INCH179.5
INCH257.5



Inchirourke BH4 - DCA species
DCA Axis 2 (eigenvalue 0.06335)
DCA Axis 1 (eigenvalue 0.1753)
3.0
2.0
1.0
0.0
-1.0
-2.0
-2.0
-1.0
0.0
1.0
2.0
3.0
HYASUB
AMPSTE
TRIARC
ASSMUS
AMPWRI
AMPFLA
CYCARC
DIFPUL
ARCDIS


Longfordpass BH2 - DCA samples
DCA Axis 2 (eigenvalue 0.1525)
DCA Axis 1 (eigenvalue 0.3745)
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
LFP180.5
LFP190.5
LFP182.5
LFP 192.5
LFP198.5
LFP138.5
LFP 144.5
LFP 80.5
LFP 72.5
LFP 104.5
LFP142.5
LFP164.5
LFP146.5
LFP178.5
LFP194.5



Longfordpass BH2 - DCA species
DCA Axis 2 (eigenvalue 0.1525)
DCA Axis 1 (eigenvalue 0.3745)
3.6
2.4
1.2
0.0
-1.2
-2.4
-2.4
-1.2
0.0
1.2
2.4
3.6
AMPSTE
DIFPRI
PSEFUL
ARCVUL
HELSPH
BULIND
CYCARC
AMPWRI
ASSMUS
ARCDIS
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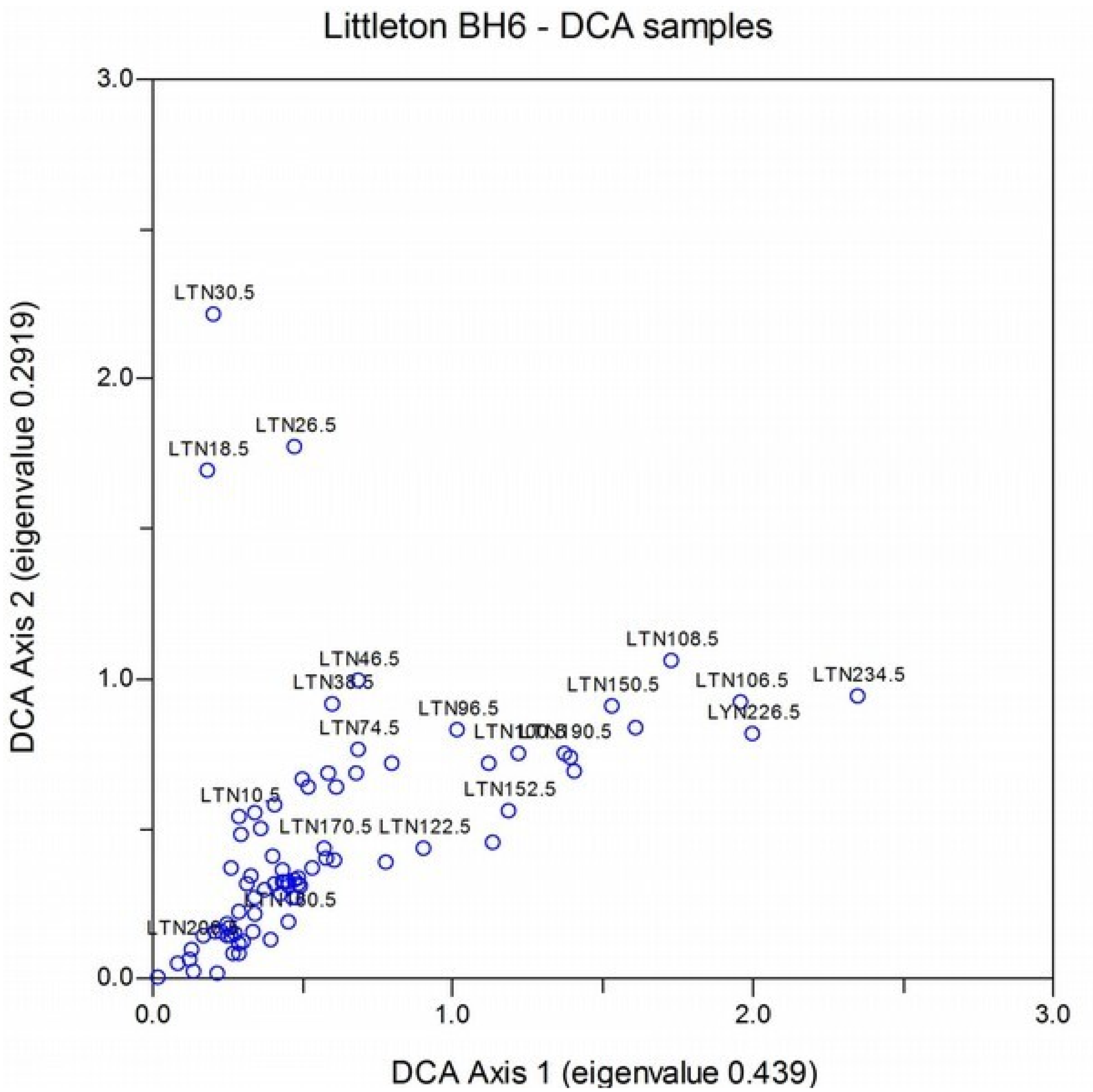
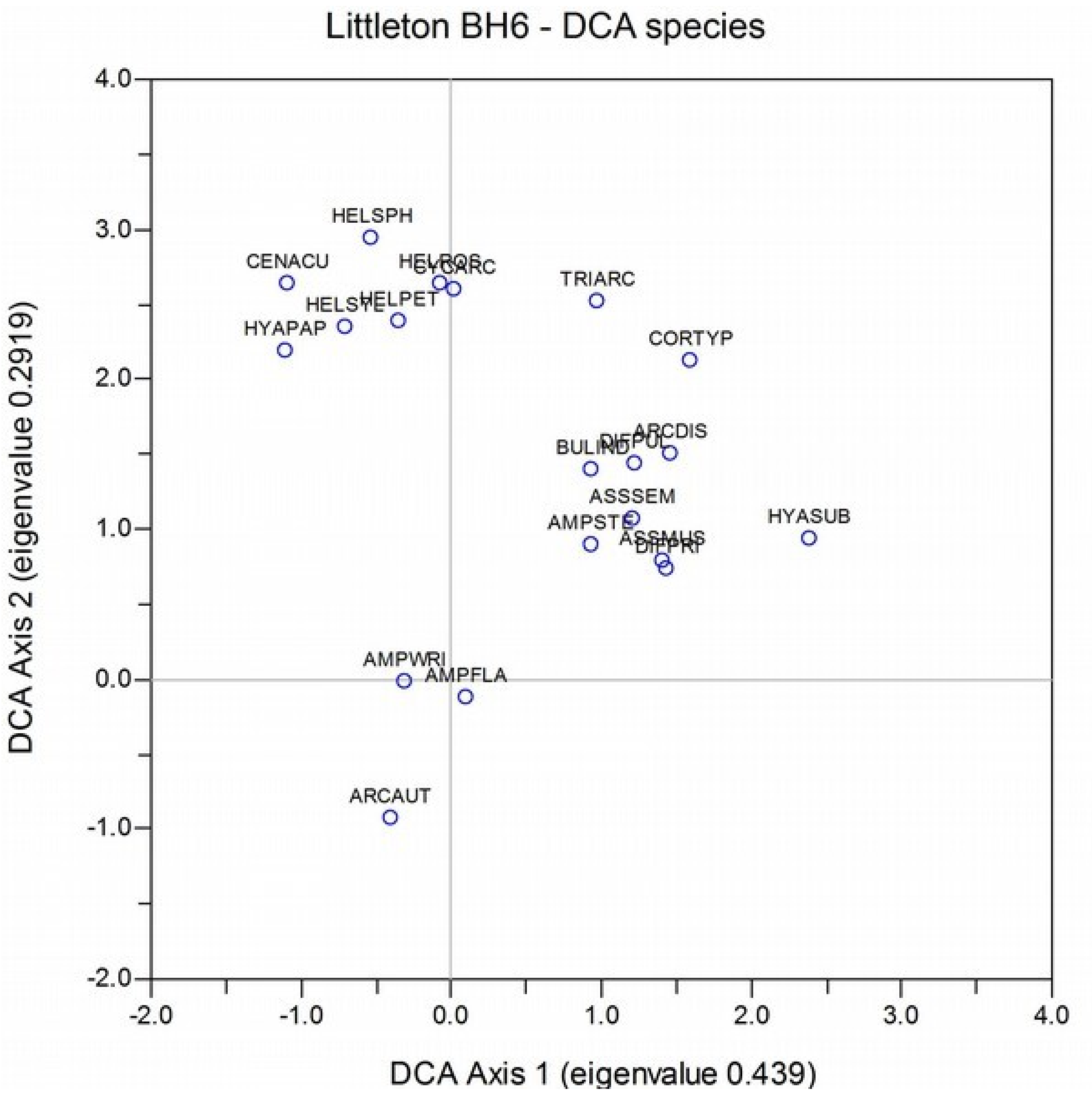
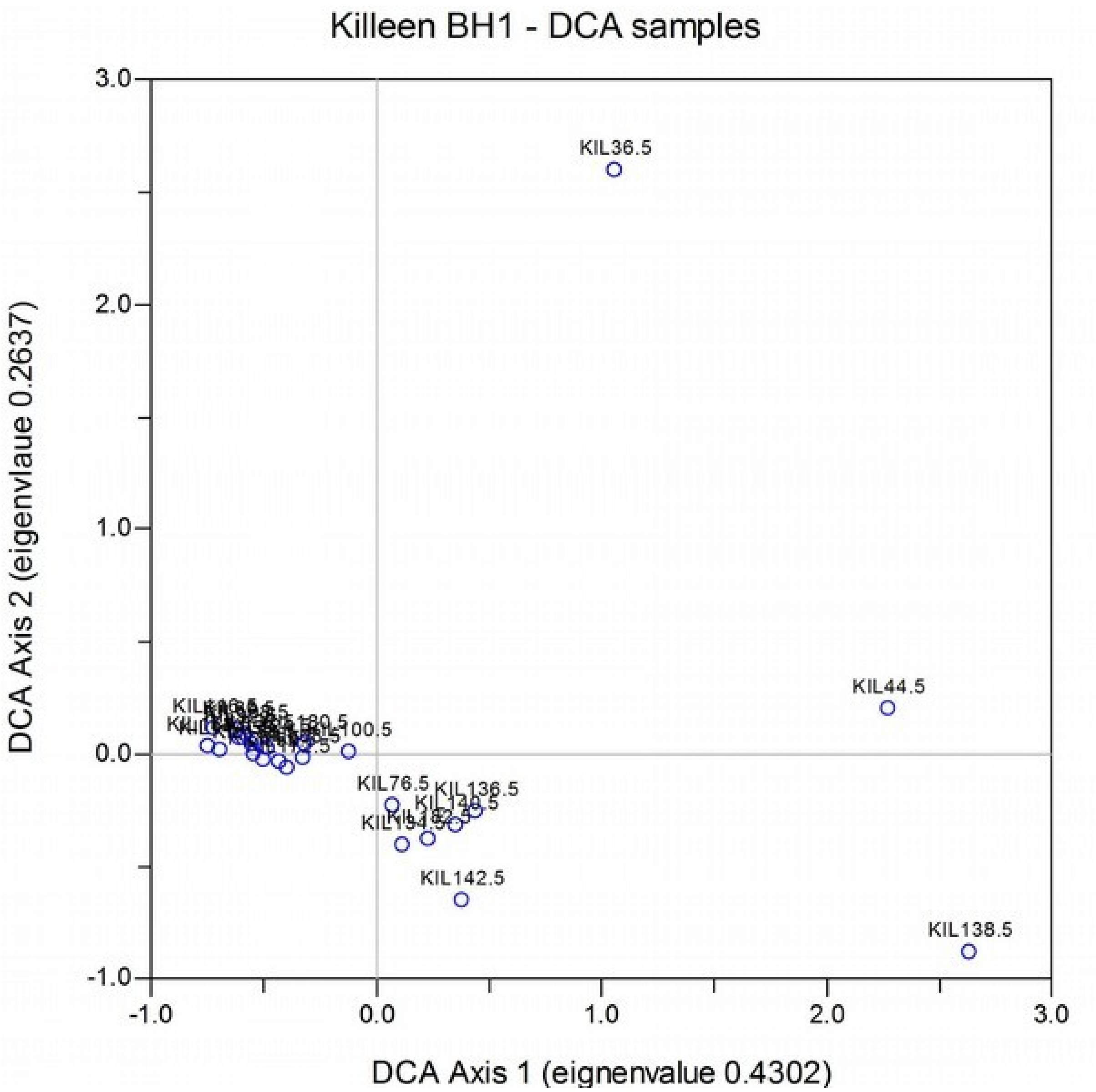
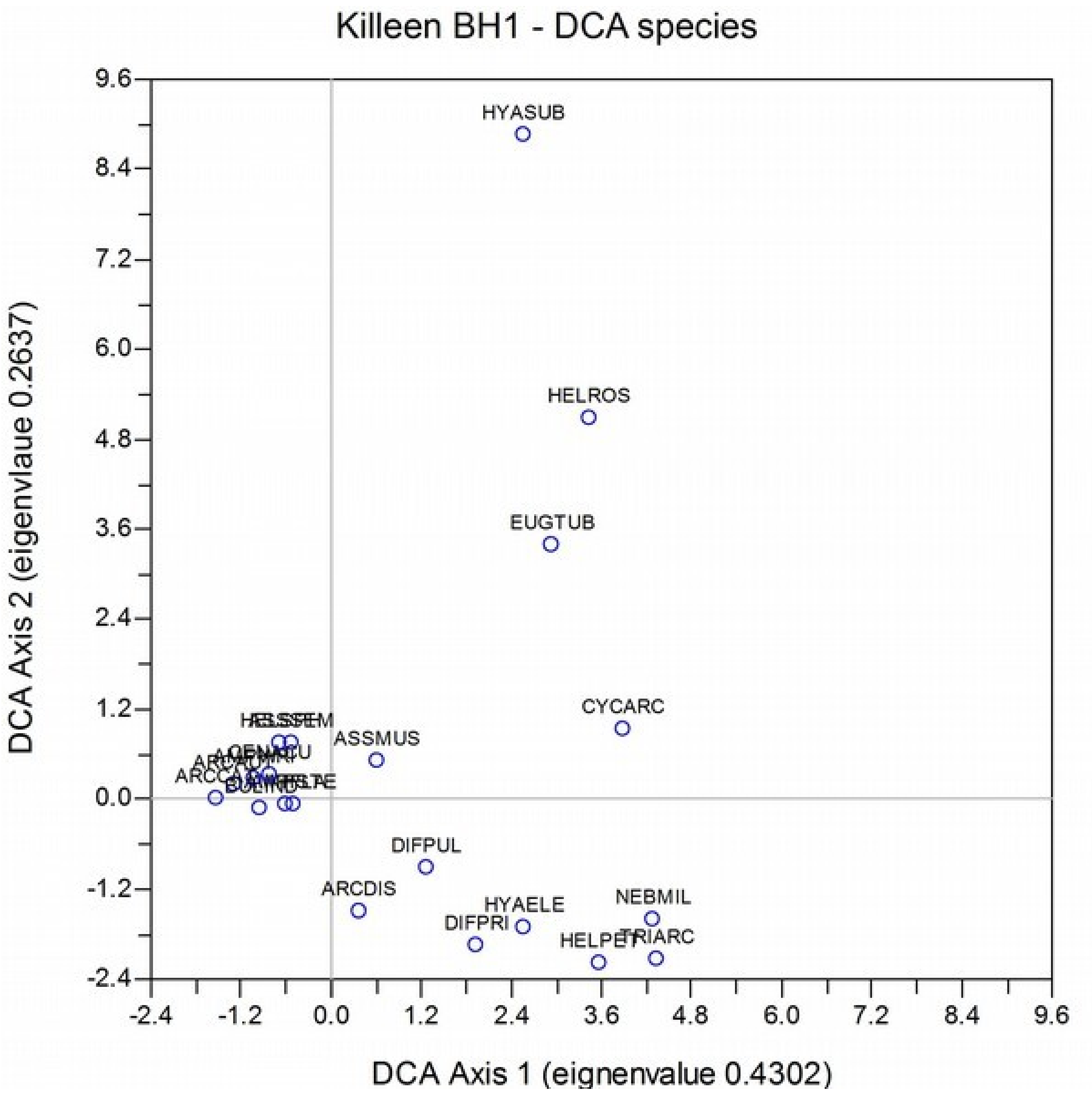
NEBMIL
AMPFLA
HYAPAP



Littleton BH6 - DCA samples
DCA Axis 2 (eigenvalue 0.2919)
DCA Axis 1 (eigenvalue 0.439)
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
LTN30.5
LTN26.5
LTN18.5
LTN108.5
LTN46.5
LTN38.5
LTN150.5
LTN106.5
LTN234.5
LTN96.5
LYN226.5
LTN74.5
LTN152.5
LTN10.5
LTN170.5
LTN122.5


Littleton BH6 - DCA species
HELSPH
CENACU
TRIARC
HELSYL
HELPET
HYAPAP
CORTYP
ARCDIS
BULIND
ASSSEM
HYASUB
AMPSTE
AMPWRI
AMPFLA
ARCAUT
DCA Axis 2 (eigenvalue 0.2919)
DCA Axis 1 (eigenvalue 0.439)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0


Killeen BH1 - DCA samples
KIL36.5
KIL44.5
KIL100.5
KIL76.5
KIL136.5
KIL142.5
KIL138.5
DCA Axis 2 (eigenvlaue 0.2637)
DCA Axis 1 (eignenvalue 0.4302)
3.0
2.0
1.0
0.0
-1.0


Killeen BH1 - DCA species
HYASUB
HELROS
EUGTUB
CYCARC
ASSMUS
DIFPUL
ARCDIS
HYAELE
NEBMIL
DIFPRI
HELPET
TRIARC
DCA Axis 2 (eigenvlaue 0.2637)
DCA Axis 1 (eignenvalue 0.4302)

Appendix 2 – Abbreviations used in the text
ADS – Archaeological Development Services (Ireland) Ltd
AMS – Accelerator Mass Spectrometry
AW – Archaeological Wood
BH - Borehole
BnM – Bord na Móna PLC
BP – uncalibrated radiocarbon years Before Present
BSW – Bog Surface Wetness
BT – Brushwood Trackway
CA – Correspondence Analysis
cal BP – calendar years Before Present (AD 1950)
CCA – Canonical Correspondence Analysis
CGR – Castlegar bog

CI – Central Ireland

CLS – Cloonshannagh bog

Co. - County (e.g. Co. Galway = County Galway)

CT – Corduroy Trackway

D – Simpson's diversity index

DCA – Detrended Correspondence Analysis

dGPS – differential Global Positioning System

DWT – Depth to Water Table

FBT – Fen-Bog Transition

GA – County Galway

GLA – Gowla bog

GT – Gravel Trackway

H' – Shannon diversity index

HT – Hurdle Trackway

Humo - Humification

IRK – Inchirourke bog

KDY – Killaderry bog

KLN – Killeen bog

KND – Kinnegad bog

LFP – Longfordpass bog

LTN – Littleton bog

ME – County Meath

m O.D. - metres above Ordnance Datum

NAO – North Atlantic Oscillation

NaOH – Sodium hydroxide

NHA – Natural Heritage Area

PDF – Probability Density Function

P-E – Precipitation minus Evapotranspiration

PF - Platform

PP – Plank Path

R – species richness

RCC – Rapid Climate Change (*sensu* Mayewski *et al.* 2004)

RMSEP – Root Mean Square Error of Prediction

RO – County Roscommon

RP – Roundwood Path

SAC – Special Area of Conservation

SMR – Sites and Monuments Register

TN – County Tipperary North

Appendix 3 – Common names of plant taxa

Alnus – alder

Andromeda polifolia – bog rosemary

Betula – birch

Calluna vulgaris – heather

Carex panicea – carnation sedge

Cladonia rangifera – reindeer lichen

Cyperaceae – sedge family

Drosera – sundew

Ericaceae – heather family

Erica tetralix – cross-leaved heath

Eriophorum vaginatum – hare's tail cotton grass

Menyanthes trifoliata – bogbean

Molinia caerulea – purple moorgrass

Myrica gale – bog myrtle

Narthesium ossifragum – bog asphodel

Phragmites australis – common reed

Pinus - pine

Rynchospora alba – white-beaked sedge

Scirpus cespitosus - deergrass

Sphagnum – bog moss

Sphagnum cuspidatum – feathery bog moss

Vaccinium oxycoccos – bog cranberry