Peat humification and climate change:
a multi-site comparison from mires in south-east Alaska

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SUMMARY

Peatland records of Holocene palaeoclimate have been widely used in Europe. Their potential in western North America remains largely unexploited despite an abundance of candidate sites. Peat humification analysis is a widely used technique for palaeoclimatic inference from peatlands. This study attempts to demonstrate a climatic role in determining peat humification by comparing low-resolution peat humification records from five mires in south-east Alaska. Humification was determined by alkali extraction and colorimetry and records dated by radiocarbon and tephrochronology. Testate amoebae analysis was carried out across a major humification-inferred wet shift in three of the sites. The humification results show variability down the length of the cores but there is only limited agreement between records from different sites. Many general trends in the data appear to be out of phase and periods of proxy 'complacency' are shown. This study does not provide strong evidence for climatic forcing of humification in these sites. Methodological issues including possible problems with the age-depth models and the role of a peat-forming plant species signal in the humification data are discussed. The results support previous studies in suggesting the value of employing a multi-proxy, multi-site, and possibly multi-core approach in peat-based palaeoclimatology.

KEY WORDS: Holocene, palaeoclimate, palaeoecology, palaeohydrology, peatlands, testate amoebae.

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INTRODUCTION

Over recent decades, palaeoenvironmental records from peatlands have been used widely to reconstruct Holocene climate change. Analyses of preserved organic material are used to reconstruct changes in mire surface wetness, which in water-shedding, ombrotrophic mires are believed to be directly linked to climate (Barber 1981, Barber 1985). Numerous reconstructions of Holocene climate have been produced and results agree well with instrumental meteorological records and other proxy records of climate (Baker *et al.* 1999, Gunnarson *et al.* 2003, Charman *et al.* 2004, Schoning *et al.* 2005). Compared to other sources of past climate data, records from peatlands have the advantages of wide geographical range and potentially high resolution (Blackford 2000).

A number of proxies have been developed for use in peat-based palaeoclimate reconstruction, including analyses of plant macrofossils, testate amoebae, fossil lipids and isotopic ratios (Blackford 2000, Kuder & Kruge 1998, Ménot & Burns 2001). One of the most widely used techniques involves estimating degree of decomposition and is known as 'peat humification analysis'. In a drier climate it is assumed that water tables will be lower and it will

therefore take longer for plant material to reach the anoxic catotelm, resulting in greater decomposition. This principle is the basis of the 'stratigraphic' approach used in the earliest studies of climate from peat deposits (reviewed by Barber 1981); the humification technique allows the changes between and within stratigraphic units to be quantified. Degree of humification has commonly been determined in peat studies using an alkali extraction and colorimetry technique (e.g. Aaby & Tauber 1975, Aaby 1976, Blackford & Chambers 1991, 1995, Chambers & Blackford 2001, Roos-Barraclough *et al.* 2004, Borgmark 2005). This method attempts to extract humic acids which are produced in the decomposition process. It is assumed that more highly decomposed peat will produce a darker coloured alkali extract and therefore reduced light transmission (Blackford & Chambers 1993). Caseldine *et al.* (2000) showed that the organic acids extracted are primarily lower-weight fulvic acids, amino acids and polysaccharides rather than the humic acids previously assumed. A cause for concern is the extent to which these substances may be extracted from different plant species (Overbeck 1947). While a species signal is widely believed to have some effect on peat humification, the extent of the effect

is largely unknown. Blackford & Chambers (1993) suggested that the direction of change (i.e. wetter or drier) remained valid even across a species change appearing as a stratigraphic boundary, but Yeloff & Mauquoy (2006) showed otherwise, especially in the case of *Sphagnum cuspidatum*. Additional problems may be posed by the 'secondary decomposition' issue whereby the humification record may be affected by subsequent lowering of the water table (Tipping 1995, Borgmark & Schoning 2005). Despite these methodological issues, humification results from numerous studies show general agreement between sites and with other proxy records, suggesting that the technique is broadly reliable even though the underlying mechanisms remain unclear (Nilssen & Vorren 1991, Baker *et al.* 1999, Charman *et al.* 2001, Gunnarson *et al.* 2003, Hughes *et al.* 2006).

Establishing the relationship between climate and the peatland palaeoenvironmental record is crucial to the use of the methodology for climate reconstruction. One method of determining whether a climatic signal is preserved in peat deposits is to examine the palaeoecological records from multiple sites. If there is agreement in the pattern and timing of key inferred palaeohydrological changes in hydrologically separate peatlands, this provides compelling evidence for a common climatic forcing (Nilssen & Vorren 1991, Blackford 1993, Barber *et al.* 1998, Mauquoy *et al.* 2002, Charman *et al.* 2006).

The majority of palaeoclimate studies from peatlands have been carried out in Europe and particularly in the British Isles, the Netherlands and Fennoscandia. Peatland palaeoclimatology has been applied in fewer studies from North America (Warner & Charman 1994, Booth & Jackson 2003, Booth *et al.* 2004, Hughes *et al.* 2006) and has not been attempted in the Pacific Northwest, a region where ombrotrophic peatlands are particularly numerous and regional climate has shown considerable recent change.

Owing to the significant differences in peatland morphology, vegetation and climate between this region and the well-studied sites in Europe, the dominant forcing of climate on the palaeoenvironmental record cannot be assumed *a priori*. In eastern North America, for example, a recent study suggested that climate was relatively unimportant to peatland development (Muller *et al.* 2003). At more coastal locations in Canada, Hughes *et al.* (2006) showed consistency between sites and between peat-bog data and other climate proxies for the North Atlantic region, suggesting that regional factors as well as site characteristics can affect climatic sensitivity. The study reported here uses a

multi-site approach to test the value of peat deposits in south-east Alaska as a proxy climate record. Multiple low-resolution records are produced to determine whether there is consistency in the long-term pattern of change and to provide preliminary regional palaeoclimate data.

METHODS

Peat samples were collected in June 2002 from five peatland sites in south-east Alaska, namely: Point Lena, Eaglecrest, Spaulding Meadows, Chilkoot Pond and Mount Riley (Figure 1). All are *Sphagnum*-dominated peatlands which receive little or no groundwater input (Dachnowski-Stokes 1941, Payne 2003, Payne & Blackford 2004). Cores were extracted from the deepest area of peat at each site using a Russian peat corer (chamber 500 mm long, 50 mm diameter) (Aaby & Digerfeldt 1986). Twin boreholes were used and the cores overlapped by 50 mm. Core stratigraphies were recorded in the field, and the dominant peat type noted (Figure 2). The upper portion of the primary core from Point Lena was damaged in transit, so analyses of the upper sediments were carried out on a second core extracted from 20 m away.

Contiguous samples (50 mm long, *ca*. 10 mm wide) were removed from the cores, oven dried and ground. In most cases a 0.1 g sub-sample was boiled in 9% NaOH for one hour, filtered through Whatman Qualitative 1 filter paper and diluted. For the Point Lena site, more available peat allowed the use of larger sub-samples of 0.2 g. Transmission at 540 nm was measured three times and the mean calculated. Readings were corrected for loss on ignition using the formula $H_c=H_r/(1/LOI)$ where H_c is the corrected humification value, H_r is the raw transmission value and LOI is loss on ignition expressed as a proportion (Blackford & Chambers 1993, formula incorrectly printed in that paper). As problems have been encountered with humification measurements in mineral-rich peats, probably due to very small mineral fragments passing through the filter paper (Payne & Blackford 2008), some samples with low LOI values (high mineral contents) at the bases of the cores were excluded.

Cores were dated using conventional and AMS radiocarbon dates as well as a micro-tephra layer present in all the sites and dated to *ca*. 300 cal. BP (Payne *et al*. 2008; Table 1). Conventional dates used bulk samples which, because of sample size requirements and the limited amount of material remaining after other analyses, often represented 10 cm or more of core length. Carefully selected and cleaned *Sphagnum* leaves and stems were used for
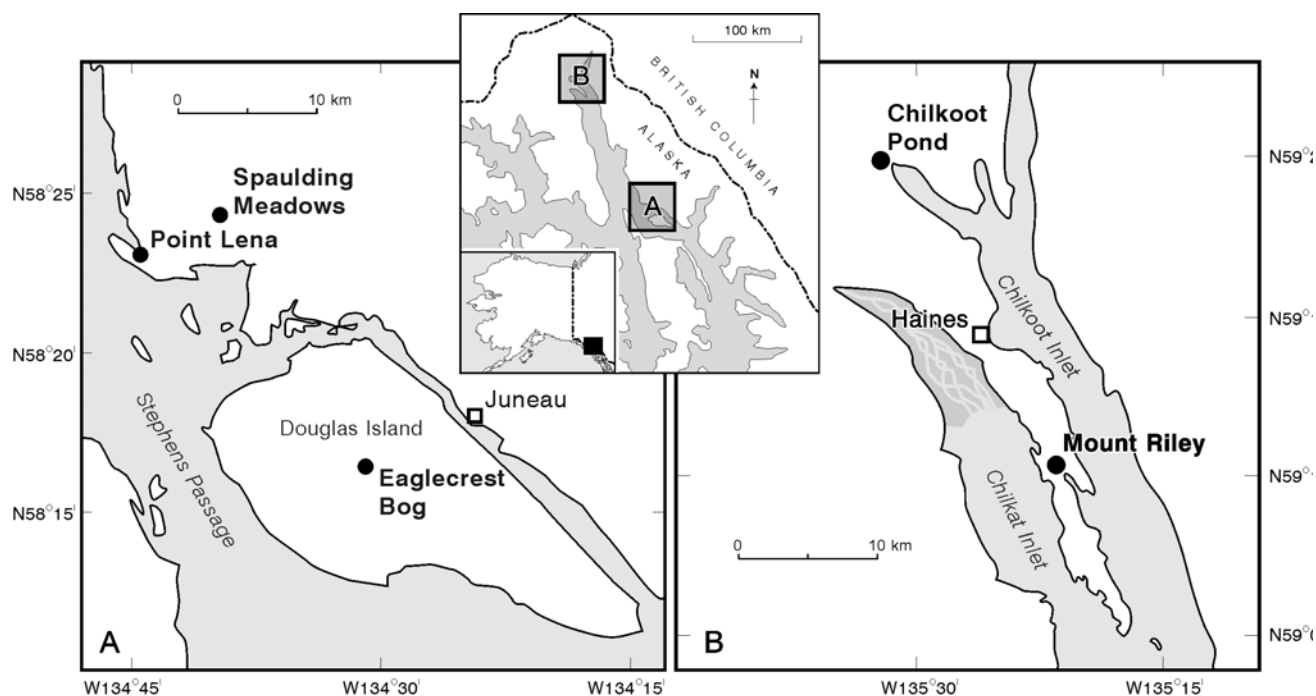
Figure 1. Location map showing the five peatland sites and the towns of Juneau and Haines.

AMS dating, giving considerably greater precision. Age-depth models were constructed by linear interpolation between the mid-points of the calibrated age ranges. Linear interpolation is a simplistic approach but is generally considered the most appropriate strategy when dating evidence is limited. For the Lena Point site it was assumed that accumulation rate was equivalent between the two cores and a combined age-depth model was applied. Dates are referred to as calibrated ^{14}C years BP ('cal. BP') based upon these age-depth models.

Humification results were linearly detrended and are presented as residuals on an inferred-age axis. The humification results for several of the cores showed a major increase in transmission values at around 100 cm depth. In an attempt to validate this change, testate amoebae analysis was applied to short sequences across the relevant core segments. Samples of 10 mm thickness were extracted every 20 mm from the relevant regions of the Eaglecrest, Spaulding Meadows and Mount Riley cores. Samples were prepared following Hendon & Charman (1997) by boiling, sieving at 15 and 300 μm and mounting in glycerol. Amoebae were counted and identified using the taxonomic scheme described by Payne *et al.* (2006). A count of 150 tests was aimed for but concentrations were found to be very low, particularly at the bases of the sequences. Due to these problems, counts were limited to six 20 x 20 mm coverslips. A transfer function derived from similar mires in south-central Alaska (Payne *et al.* 2006) was used to provide

quantitative estimates of depth to water table, referred to here as TI-DWT (testate amoebae inferred depth to water table). Boot-strapping (1000 cycles) was used to provide estimates of model-specific standard error.

RESULTS

The surficial peat deposits of all five sites are dominated by *Sphagnum*, but below this the constituents of the peat vary. Only at Point Lena is *Sphagnum* the most abundant peat component throughout the length of the core. At Eaglecrest, most of the core is dominated by monocotyledons, while at Spaulding Meadows, Mount Riley and Chilkoot Pond there is shifting dominance between *Sphagnum*, monocotyledons and occasionally Ericaceae (Figure 2). The humification results show variability down the length of the cores with some indication of damping with depth (Figure 2, Figure 3). Dating evidence from Mount Riley, Spaulding Meadows, Point Lena and Eaglecrest indicate that the sequences span the majority of the Holocene (Table 1, Figure 2). Age-depth models suggest that accumulation rates vary between about 10 and 50 years cm^{-1}. Two dates for the base of the Chilkoot Pond core give ages of 300–500 cal. BP. These dates contrast with the radiocarbon date from 33 cm depth, suggesting an improbably high accumulation rate. In addition, a tephra at the base of the core shows a high degree of similarity to that

Table 1. Dating evidence for the five peatland sites. Radiocarbon dates calibrated using OxCal v.3.10 (Ramsey 2005) based on the IntCal04 dataset showing 2σ age range. The tephra layer is discussed in more detail by Payne *et al.* (2008).

Site	Depth (cm)	Evidence	Age range (cal. years BP)
Chilkoot Pond	33–34	AMS radiocarbon date SUERC-5914, tephra layer (257 +/- 22 BP)	280–320
	140–152	Conventional radiocarbon date Gd-15809 (470 +/- 80 BP)	310–570
	175–176	AMS radiocarbon date SUERC-565 (468 +/- 55 BP)	410–570
Mount Riley	32–33	Tephra layer	*ca*. 300
	100–112	Conventional radiocarbon date Gd-19055 (5390 +/- 100 BP)	5938–6324
	210–211	AMS radiocarbon date SUERC-564 (8688 +/- 65 BP)	9530–9890
Spaulding Meadows	26–27	Tephra layer	*ca*. 300
	95–105	Conventional radiocarbon date Gd-19058 (1780 +/- 80 BP)	1547–1860
	196–197	AMS radiocarbon date SUERC-566 (7207 +/- 53 BP)	7940–8170
Eaglecrest	32–33	Tephra layer	*ca*. 300
	100–112	Conventional radiocarbon date Gd-19056 (2310 +/- 95 BP)	2116–2621
	162–163	AMS radiocarbon date SUERC-5917 (4485 +/- 30 BP)	5030–5300
	195–196	AMS radiocarbon date SUERC-567 (6183 +/- 56 BP)	6940–7250
	365–366	AMS radiocarbon date SUERC-568 (9244 +/- 49 BP)	10260–10560
Point Lena	39–40	Tephra layer*	*ca*. 300
	100–101	AMS radiocarbon date SUERC-5913 (1428 +/- 28 BP)	1290–1375
	275–276	AMS radiocarbon date SUERC-569 (2423 +/- 51 BP)	2340–2620
	520–521	AMS radiocarbon date SUERC-570 (7919 +/- 83 BP)	8580–9010

* For Point Lena, the tephra layer was in the secondary core B; the radiocarbon dates are from core A.

at 33 cm (Payne *et al.* 2008). These findings suggest that peatland development has followed an unusual pattern at this site. A possible explanation is that the peatland developed as a floating mire (schwingmoor) on the adjacent pond, with peat accumulating both from the base of the water body and as a floating mat above. Due to these chronological uncertainties, results from this site are not considered further.

Testate amoebae analysis was complicated by low test concentrations. Despite an intensive sampling effort, counts were as low as 7 for some samples from the bases of the sequences, with many samples having totals under 50 (Figure 4). These low concentrations may be due to low amoebae abundance in the peat on deposition, loss of tests through decomposition (Payne 2007, Swindles & Roe 2007) or dilution by fine degraded organic material. At the base of all three testate amoebae profiles, the most abundant taxa are *Phryganella acropodia* type and *Assulina muscorum*. The Alaskan transfer function and previous studies from around the world indicate that *A. muscorum* is

typical of moderately dry conditions (Payne *et al.* 2006). The hydrological preferences of *P. acropodia* type are less well known with optima values varying from moderately wet (Bobrov *et al.* 1999) to very dry (Mitchell *et al.* 1999), most probably because the group includes several species which may have different optima. In the Alaskan study the taxon is typical of moderately dry conditions; this is perhaps the most frequent finding from previous research. Through the profiles there are increases in *Archerella flavum* at Mount Riley, *Archerella flavum, Arcella arenaria* type and *Hyalosphenia papilio* at Spaulding Meadows, and *Archerella flavum, Amphritrema stenostoma* and *Amphritrema wrightianum* at Eaglecrest. With the exception of *Arcella arenaria* type these taxa are mostly considered to be typical of wetter conditions. TI-DWT results are discussed site by site along with the humification data. These results may well be compromised by the low counts although Payne & Mitchell (submitted) suggest that a 'true' palaeoenvironmental signal may be apparent even with very low counts. If the low test concentrations
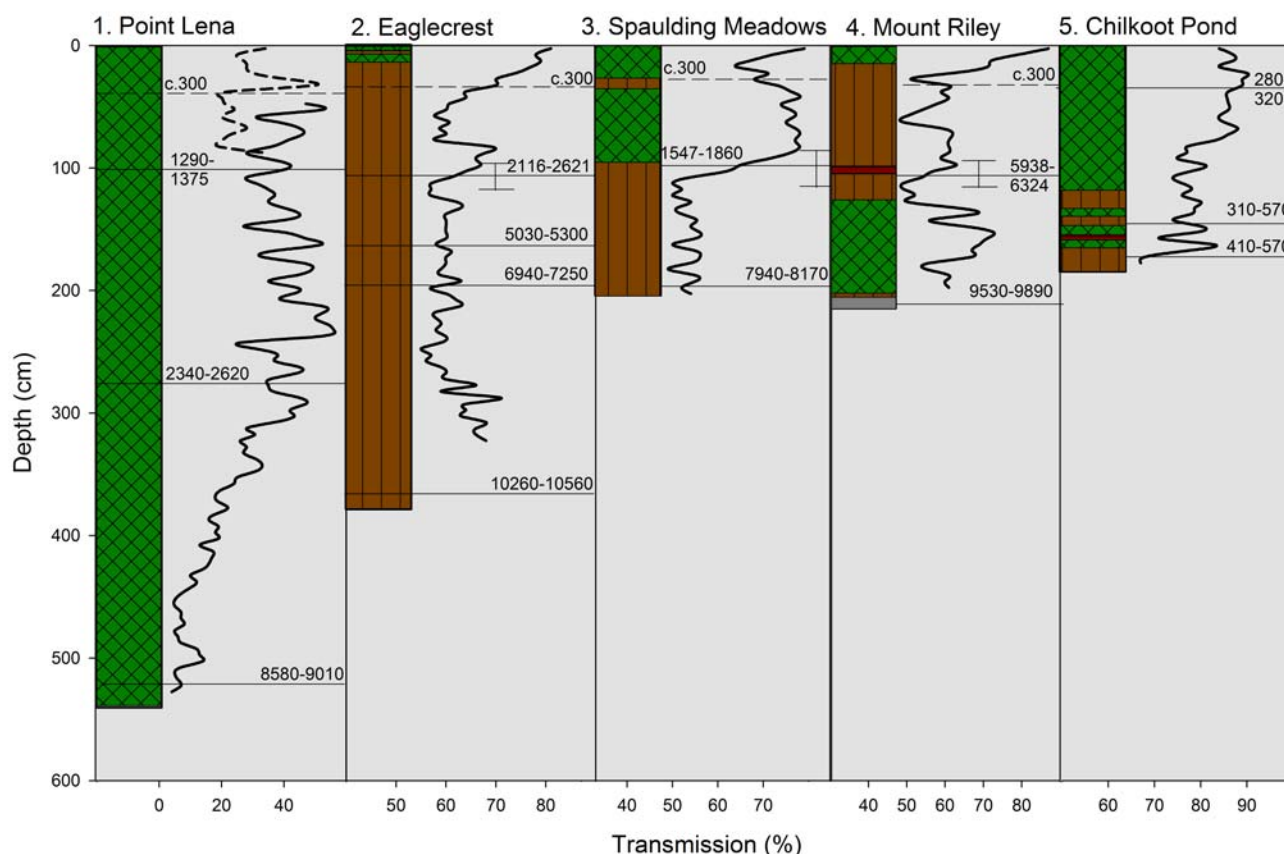
Figure 2. Stratigraphy, raw humification results and dating evidence for the five peatland sites. Stratigraphy of the peat cores is shown as peat macrofossil composition: *Sphagnum* (green), Monocotyledons (brown), Ericaceous material (red) and amorphous peat with no recognisable macrofossils (grey). Only the most abundant macrofossil component is shown. Humification results as raw % transmission at 540 nm, data points connected by spline curves. Note that methodology for the Point Lena site was slightly different from that used for the other sites; the broken curve indicates data from the second core (see Methods). Higher transmission values are taken to represent less decomposed peat and wetter conditions. Dating evidence: radiocarbon dates (solid horizontal lines) with their calibrated age ranges (Table 1) and cryptotephra layers (dashed horizontal lines) as described by Payne *et al.* (2008). The regions subjected to testate amoebae analysis are shown by the 'H' shaped bars.

are due to test decay it is also possible that the reconstructions may be skewed by differential preservation (Mitchell *et al.* 2008).

At Point Lena, a highly variable humification curve shows frequent fluctuations, reflecting darker and lighter stratigraphic banding noted in the field. These fluctuations are more marked in the upper part of the profile (where resolution is highest). Marked increases in % transmission (inferred wet shifts) have been identified at several points, the most marked of which occurred at *ca.* 3600 and 2250 cal. BP (Figure 3). In the lower part of the diagram there is a long interval between dating points and relatively low resolution, but an inferred wet shift is apparent at *ca.* 8400 cal. BP.

At Eaglecrest the record is 10,000 years long, but

includes only a small number of distinct increases in % transmission. Between the onset of peat growth and 8100 cal. BP the direction is towards higher values (a drier peat surface), switching at around 8100 cal. BP, with minor peaks at 7900, 7400 and 6650 cal. BP. A long period of broad stability only changes at around 2350 cal. BP, with a final change to higher values at around 950 cal. BP. The analysis of testate amoebae through a short section of the Eaglecrest profile at the time of the inferred wet shift at *ca.* 2350 cal. BP shows an overall decrease in TI-DWT from 52 cm to 23 cm. This confirms the humification record as recording a wet shift, and adds a level of detail in that the overall trend is not constantly towards a wetter surface. This higher resolution study suggests that during the later part of
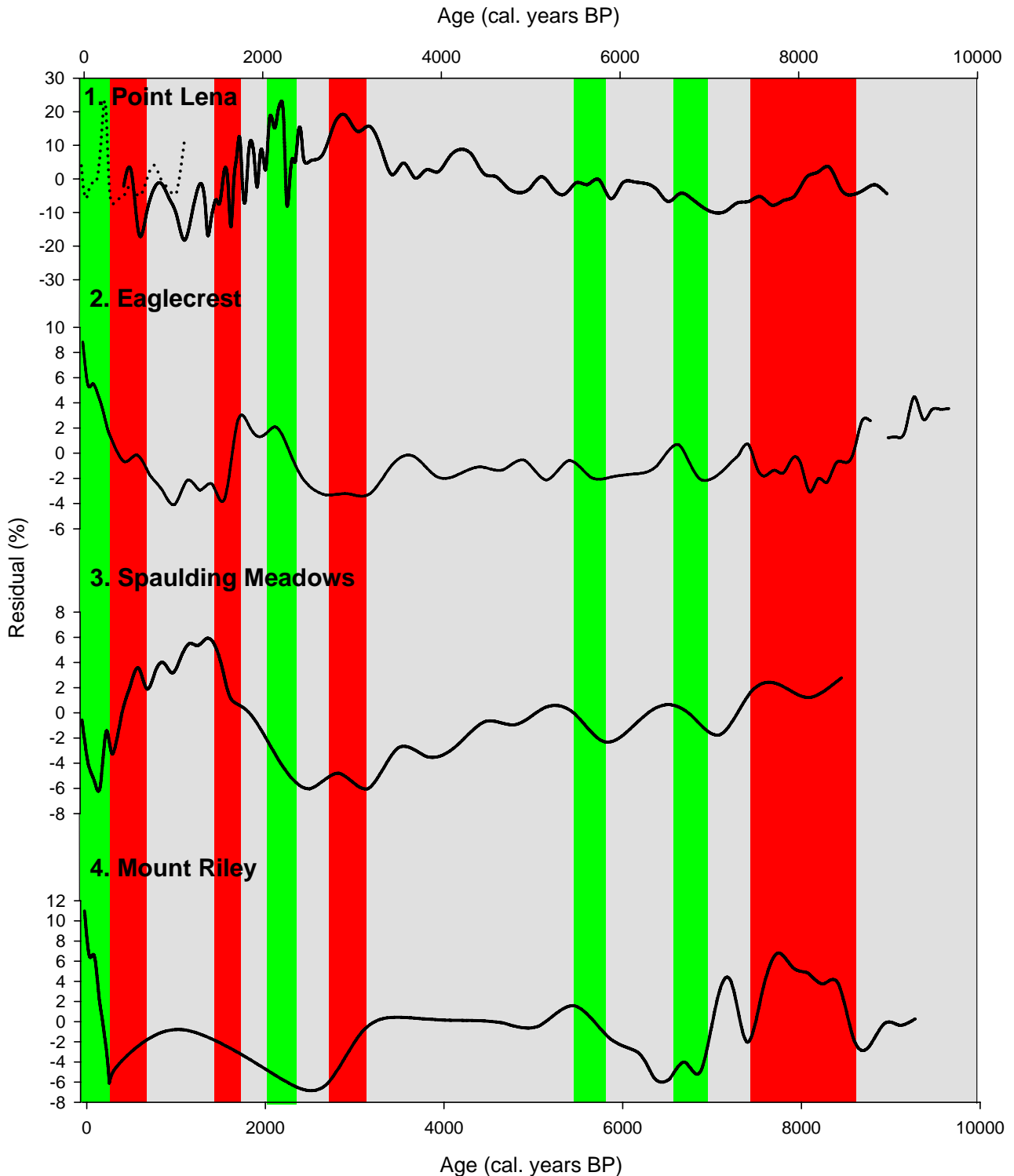
Figure 3. Detrended humification results displayed as residuals from a linear regression on an inferred age scale based on the humification data in Figure 2 and the dating evidence in Table 1. The dotted curve for Point Lena indicates data from the second core (see Methods). Green bars show periods where there is consistent directional change between at least three of the four records, and red bars show notable periods of difference between the records.
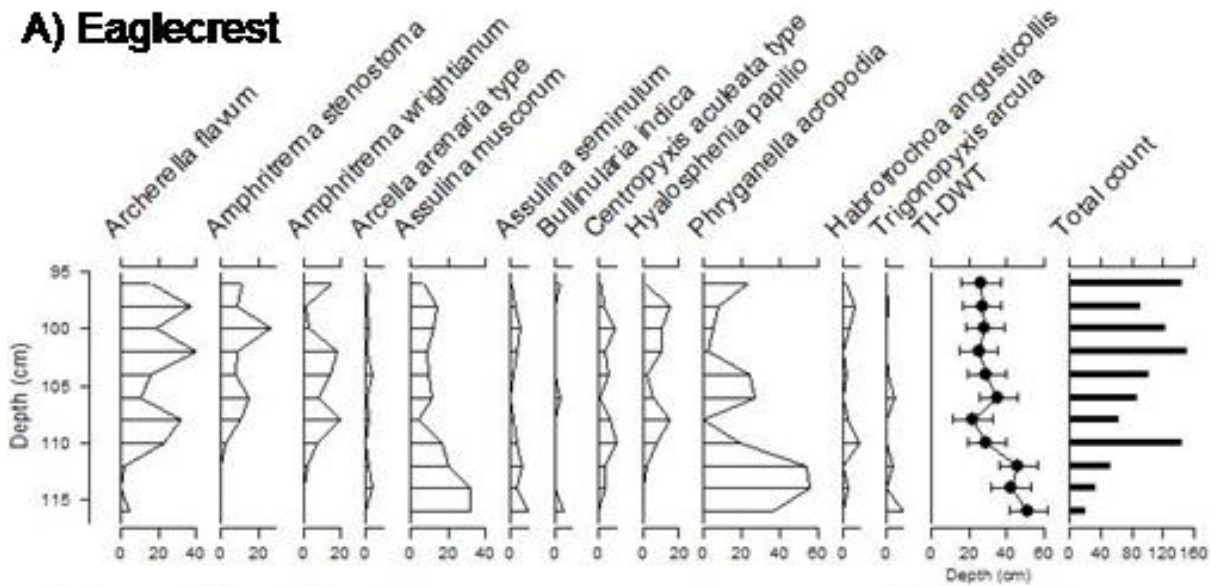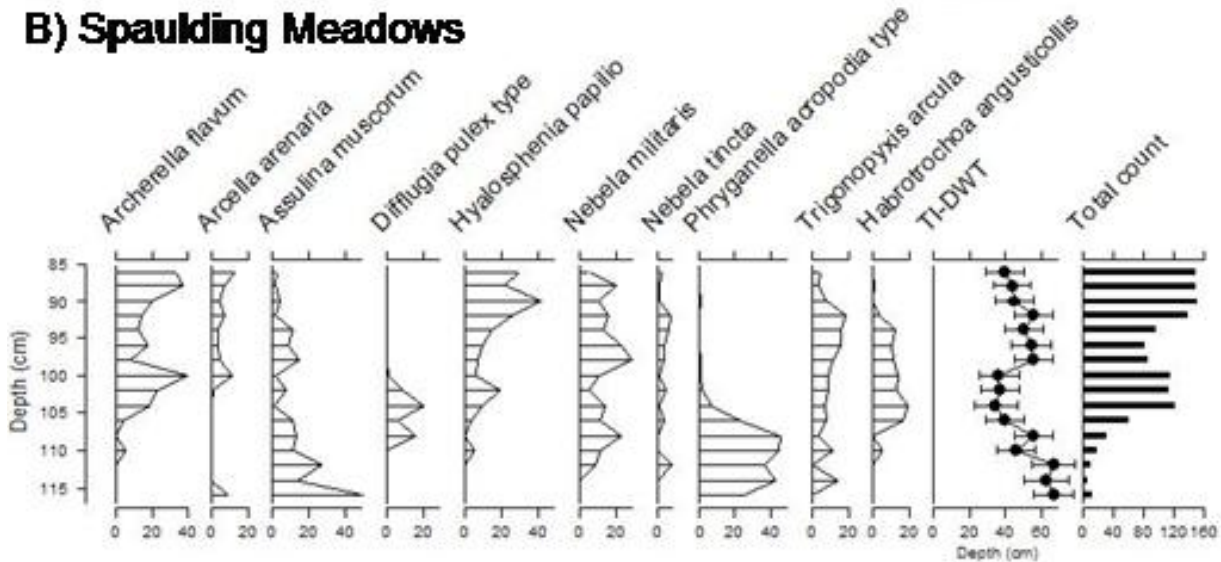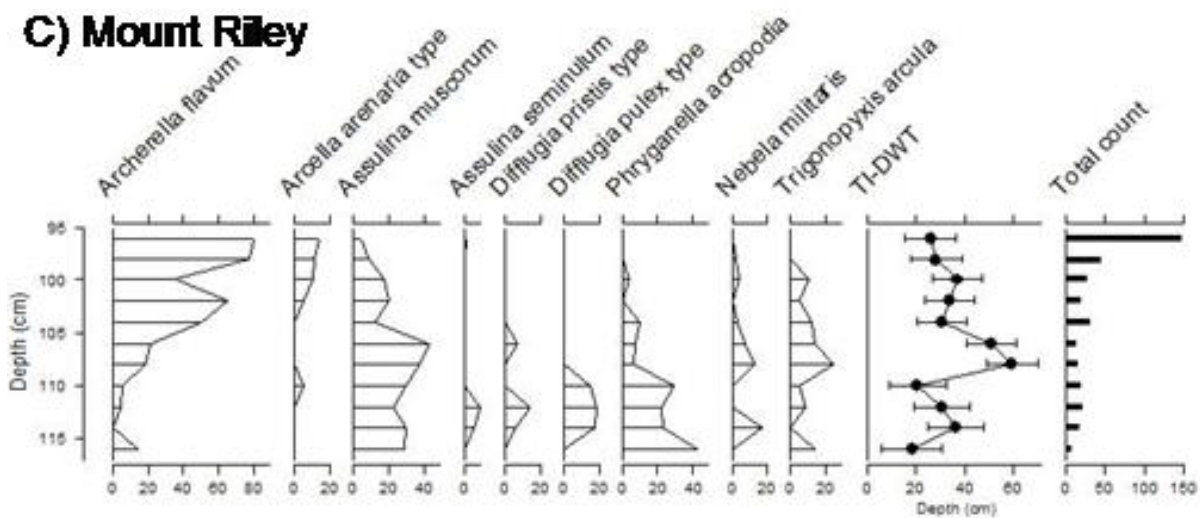
Figure 4. Testate amoebae results across three major humification changes showing major taxa, inferred water table depth (TI-DWT) and total numbers of amoebae counted. The TI-DWT results should be treated with caution due to the low counts.

the sub-section (106–96 cm depth) the water table rose less (from 35 to 23 cm) despite a steep humification curve.

At Spaulding Meadows the profile shows a slight declining trend through the period 7800–2500 cal. BP, which ends with a marked increase in transmission values accompanied by a stratigraphic change at *ca*. 2500 cal. BP. Within the period 1800–400 cal. BP, century-scale variability is recorded, similar in frequency to that at Point Lena. There is a final inferred wet shift in the upper horizons after the *ca*. 300 cal. BP tephra, at approximately 200 cal. BP. Testate amoebae across the section from 116–86 cm bracket the main wet shift in the profile. Overall, TI-DWT confirms a change to wetter conditions (62 cm to 40cm TI-DWT) but a marked reversal in this trend is shown at 100 cm, around 1700 cal. BP.

The Mount Riley profile shows five distinct humification changes which can be interpreted as wet shifts, firstly at *ca*. 8500 cal. BP, then at 7400 cal. BP and at 6450 cal. BP. Between 6000 and 3000 cal. BP the humification curve is stable, and the change to higher transmission values at around 2300 cal. BP is a gradual increase rather than an abrupt response. The final inferred wet shift is at *ca*. 250 cal. BP. The testate amoebae results show a significant peak in TI-DWT values (representing a dry mire surface) at 108 cm, but the results can be given little weight because very few tests were found in these samples.

DISCUSSION

Recent studies have highlighted the complexity of the relationship between peat humification, peatland hydrology and climate (Caseldine *et al*. 2000, Yeloff & Mauquoy 2006). While there is undoubtedly a link between climate and peat humification, this relationship now appears to be more complex than was assumed in early studies. The data reported here illustrate some of the problems.

The humification records show variability down the length of the cores but correlation between sites is not clear (Figure 3). There are some periods when several of the sites show consistent changes. Perhaps most convincing is a major increase in transmission values in all sites around 2400–2100 cal. BP. There is no indication of major climatic change during this period from other regional palaeoclimate records, although such data are sparse. Other coincident inferred wet-shifts are seen in at least three sites around 7000–6700 cal. BP,

5800–5500 cal. BP and at the very top of the sequence. The change at the top of the sequence probably represents the transition to little-decomposed acrotelm peat. The changes at 7000–6700 cal. BP and 5800–5500 cal. BP are comparatively small and these older periods have greater dating uncertainties; however, these dates are broadly synchronous with wet periods inferred from peatlands in western Canada at around 6900 and 5500 cal. BP (Yu *et al*. 2003).

Despite the replication of some wet shifts between sites there are also very considerable differences between the profiles. Several major changes are either not shown in all sites or are considerably out of phase. For instance from 2800 to 3200 cal. BP the Point Lena data show a phase of high transmission values, while the Eaglecrest and Spaulding Meadows records show a phase of low transmission values, and at Mount Riley a declining trend of transmission values is shown. From 1500 to 1700 cal. BP the Mount Riley record shows a gradually increasing trend, the Spaulding Meadows site shows a rapidly increasing trend, the Eaglecrest site shows a rapidly declining trend and the Point Lena site shows fluctuating values with an overall decline in transmission. The testate amoebae results lend only limited corroboration to the humification data. Where the humification results show major wet shifts in all sites the testate amoebae results show a limited shift to wetter conditions at Eaglecrest, a slight shift to wetter conditions at Spaulding Meadows and a distinct dry peak at Mount Riley. However, the testate amoebae results are based on very low counts and transfer function results must be treated with caution, particularly for Mount Riley.

Overall, the data suggest more dissimilarity than similarity between site records and do not allow us to demonstrate a clear link between peat humification and climate change. Thus they provide only limited evidence for climatic forcing of peat humification in south-east Alaska. Reasons for this may include both limitations of the methods used in this study and real problems with applying these techniques in the study region.

A major consideration may be the limitations of the dating framework. Comparatively few dates were available and the age-depth models are based on linear interpolation with the consequent assumptions of linear accumulation and accumulation rate changes centred on the dating points - assumptions which may well be misplaced. Limitations of dating may lead to changes being out of phase between sites but not to the apparent differences in the patterns of change. Another

important factor is the coarse resolution of the humification records. Samples for humification analysis represented 50 mm vertical thickness of peat. Although the samples are contiguous, this sampling resolution will have caused minor changes to be smoothed out. This cannot explain why some long-term trends apparently do not match between cores, however. A further possibility for the different long-term trends is climatic differences between the sites. This could conceivably explain differences between the northern (Chilkoot Pond and Mount Riley) and southern (Point Lena, Eaglecrest, Spaulding Meadows) sites, but the results show that there is at least as much difference within these two groups as between them, making such an explanation unlikely.

Although the problems may lie with the methodologies of this study, it is also possible that peat humification in south-east Alaska may be only indirectly related to climate change. There are several factors which may contribute to this. The most likely is a plant species signal. It has long been known that colorimetric humification analysis may be affected by plant species changes independent of real hydrological change (Overbeck 1947). In some situations the species signal may predominate over the hydrological signal leading to inaccurate palaeoclimatic inferences (Yeloff & Mauquoy 2006). Several major humification changes do coincide with stratigraphic changes, for instance the major transmission increases in the Spaulding Meadows and Mount Riley sites at around 100 cm. However, there are also major humification changes which do not coincide with major stratigraphic change, for example at 100 cm in the Eaglecrest site. Where there does appear to be broad synchronicity between humification and stratigraphic change the humification change is not always exactly coincident with the stratigraphic change. This is perhaps unsurprising as the stratigraphic change shows the point where the dominant macrofossil component shifts, not the onset of the palaeohydrological change which may be earlier. While it is possible that testate amoebae are also sensitive to vegetation change (*cf.* Payne & Mitchell 2007) it is not clear that any relationship would lead to a TI-DWT change. A plant species signal may well explain some of the variability in the humification data, but is unlikely to be the sole driver. It is also possible that other factors such as fires, bog bursts and the influence of animals influence the ecology and stratigraphy of these sites in such a way that the climatic signal is masked except at times of particularly marked change.

Thus it appears that there may be particular difficulties attached to use of the humification technique to reveal information about palaeoclimate in south-east Alaska. Our study has illustrated the desirability of studying multiple proxies and sites, and ideally well-dated replicate cores from the same site, to gain a fuller understanding of the relationship between peat stratigraphy and climate change.

ACKNOWLEDGEMENTS

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