

Can pollution bias peatland paleoclimate reconstruction?

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A B S T R A C T

Peatland testate amoebae are widely used to reconstruct paleohydrological/climatic changes, but many species are also known to respond to pollutants. Peatlands around the world have been exposed to anthropogenic and intermittent natural pollution through the late Holocene. This raises the question: can pollution lead to changes in the testate amoeba paleoecological record that could be erroneously interpreted as a climatic change? To address this issue we applied testate amoeba transfer functions to the results of experiments adding pollutants (N, P, S, Pb, O₃) to peatlands and similar ecosystems. We found a significant effect in only one case, an experiment in which N and P were added, suggesting that pollution-induced biases are limited. However, we caution researchers to be aware of this possibility when interpreting paleoecological records. Studies characterising the paleoecological response to pollution allow pollution impacts to be tracked and distinguished from climate change.

Keywords: Climate
Holocene
Testate amoebae
Nitrogen
Phosphorus
Ozone
Sulphur
Lead
Transfer function
Biological proxy

Introduction

Peatlands are an increasingly utilized source of data on Holocene paleoclimate (Blackford, 2000; Chambers and Charman, 2004). Ombrotrophic peatlands receive all their moisture from the atmosphere so changes in their surface wetness largely reflect the balance between precipitation and evapotranspiration. Many proxies have been developed to reconstruct surface wetness variability from peats (Chambers et al., 2012), including the widely used analysis of testate amoebae (Mitchell et al., 2008). Several transfer functions have been established to enable quantitative reconstruction of water table depths from amoeba assemblages (Mitchell et al., 1999; Payne et al., 2006; Charman et al., 2007), the results of which are increasingly important to our understanding of Holocene climate change (Charman, 2001).

The direct link between the peat surface and the atmosphere makes ombrotrophic peatlands sensitive to climate but also makes them extremely sensitive to atmospheric pollution. In many industrialised regions of the world there are few, if any, peatlands unaffected by anthropogenic

pollution. For instance, output from the European Monitoring and Evaluation Programme deposition model (Jonson et al., 1998) shows that almost all of Europe (99.6%) receives nitrogen (N) deposition above the natural background (~0.5 kg N ha⁻¹ yr⁻¹; Dentener et al., 2006) and a majority (68.6%) receives sufficient for impacts on peatland plants to occur (>5 kg N ha⁻¹ yr⁻¹ critical load lower limit: UNECE, 2010). Some paleoecologically well-studied peatlands receive considerable pollution; for instance, N deposition at Walton Moss in northern England (Barber and Langdon, 2007) is around 18 kg N ha⁻¹ yr⁻¹, almost four times the lower limit of the critical load. Pollution has been widespread over the last 150 yr and has had major impacts on some peatlands. Large areas of blanket bog in the southern Pennines of northern England have been extensively degraded by sulphur (S) and metal pollution since the mid-19th century (Lee, 1998). Impacts may also extend deeper in time. Geochemical records show anthropogenic input of heavy metals to peatlands spanning several thousand years (e.g., Shotyk et al., 1998; Martínez-Cortizas et al., 1999) and eutrophication by anthropogenic dust has been proposed as a mechanism for the late-Holocene decline of *Sphagnum austini* in many European peatlands (Hughes et al., 2007). Throughout the Holocene peatlands have been exposed to intermittent, but potentially significant, natural pollution by volcanogenic sulphur and animal urine, faeces and cadavers (Augustine and Frank, 2001; Carter et al., 2007). Most paleoecologically

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studied peatlands will have been exposed to pollutants for at least some of their history.

Experimental studies have shown changes in abundance and community composition of peatland testate amoebae in response to a wide range of pollutants. The mechanisms behind these changes are poorly understood but may include direct toxic effects through absorption or ingestion of pollutants, indirect effects through interactions with predators, prey, symbionts and parasites and indirect effects through changes to the amoeba's physical and chemical environment. Species with relative abundance changes demonstrated in response to pollution in peatland experiments include many that are also considered good indicators of hydrological conditions such as *Nebela carinata* and *Heleopera sphagni* (wet indicators negatively affected by lead (Pb): Nguyen-Viet et al., 2008), *Assulina muscorum* (a dry indicator negatively affected by N and P: Mitchell, 2004) and *Bullinularia indica* (a dry indicator positively affected by N: Mitchell and Gilbert, 2004). These findings raise an important possibility: that pollution could force changes in the paleoecological record that could be mis-interpreted as a climatic change. Pollution impacts are most likely in the last 150 yr but cannot be excluded through most of the Holocene.

Methods

Here we address this issue by applying testate amoeba transfer functions to the results of several pollution experiments to see whether pollution is capable of leading to changes in the peatland paleoclimate record independent of real climatic change. Such changes may be due to either a real pollution-induced change in local wetness (for instance through impacts on vegetation) or other direct or indirect impacts of pollution on testate amoebae.

We consider all experiments that address the impact of anthropogenic pollutants on peatland testate amoebae. These experiments include most of the major pollutants that are known to drive ecological change in peatlands, including sulphur (Payne, 2010; Payne et al., 2010), ozone, lead (Nguyen-Viet et al., 2008) and nitrogen alone (Gilbert et al., 1998; Mitchell and Gilbert, 2004; Payne et al., 2012), and in combination with other macronutrients (Mitchell, 2004). All experiments have suggested some evidence for impacts on testate amoebae, although the scale of these impacts and the approach to data analysis varied among the studies. We paired the experiments with testate amoeba transfer functions from the same region or the closest available region (Table 1) with taxonomic harmonisation carried out as required (full details are given in Supplementary Table 1: note particularly the broad groupings required for the experiment of Gilbert et al., 1998). The published transfer functions were applied with bootstrap error estimation (1000 cycles: Line et al., 1994) using C^2 (Juggins, 2003). Both the inferred water table depths and their associated errors were analysed to identify any significant differences between treated and control samples. Analyses used t-tests for the simplest experimental designs, one-way analysis of variance (ANOVA) where there were multiple treatment levels, nested-ANOVA where there was pseudo-replication, repeated measures ANOVA (RM-ANOVA) for experiments over multiple time-periods or depths, and Pearson's r for a gradient experiment. Appropriate tests for normality, sphericity and heteroscedasticity were applied and some data were $\ln(x + 1)$ transformed.

Results

For most experiments we found no statistically significant difference in inferred water-table depth or boot-strapped errors (Table 1). The sole exception was the experiment of Mitchell (2004) in which N and P were applied to an Arctic Alaskan fen (Boelmann et al., 2003). This dataset is relatively small (7 samples), but the effect of treatment is large, with a mean difference in inferred water-table depth of 18 cm

Table 1 Key features of experimental studies and results of data analyses showing test used and results where significant (ns = non-significant). Separate tests were conducted for inferred water table (TI-DWTT) and boot-strapped errors (eSEP; 1000 cycles). Applied rates include only experimental additions and not ambient atmospheric inputs.

Study	Site	Transfer function	Pollutant(s)	Applied rate(s)	Application	Sampling occasions	Replicates	Pseudoreplicates	TI-DWTT test and results	eSEP test and results
Gilbert et al. (1998)	Pradeaux peatland (poor fen)	Lamentowicz et al. (2010)	N	1 g N m ⁻² yr ⁻¹ (as NH ₄ NO ₃) 3 g N m ⁻² yr ⁻¹ (as NH ₄ NO ₃)	Fortnightly for <30 weeks.	4	3	-	RM-ANOVA: ns	RM-ANOVA: ns
Mitchell (2004)	Tootik Lake (sedge tundra)	Payne et al. (2006)	N,P	10 g N m ⁻² yr ⁻¹ (as NH ₄ NO ₃) 5-10 g P m ⁻² yr ⁻¹ (reduced to lower level after first year)	Annual for 11 yr.	1	3	-	t-test: t ₅ = 4.1, p < 0.01	t-test: ns
Mitchell and Gilbert (2004)	Le Cachot (cut-over bog)	Mitchell et al. (1999)	N	1 g N m ⁻² yr ⁻¹ (as NH ₄ NO ₃) 3 g N m ⁻² yr ⁻¹ (as NH ₄ NO ₃)	Fortnightly for 2.5 yr.	1	4	-	RM-ANOVA: ns ^b	RM-ANOVA: ns
Nguyen-Viet et al. (2008)	<i>Sphagnum fallax</i> microcosms	Mitchell et al. (1999)	Pb	10 g N m ⁻² yr ⁻¹ (as NH ₄ NO ₃) 625 µg Pb L ⁻¹ (as PbSO ₄)	Continuously for <20 weeks.	3	3	-	RM-ANOVA: ns	RM-ANOVA: ns
Payne et al. (2010)	Moidach More (raised bog)	Charman et al. (2007)	S	2500 µg Pb L ⁻¹ (as PbSO ₄) 95 kg SO ₂ ha ⁻¹ yr ⁻¹ (as NaSO ₄)	Weekly/monthly for 18 months, samples 10 yr later.	1	3	25	Nested-ANOVA: ns	Nested-ANOVA: ns
Payne et al. (2012)	Ruabon (heather moorland) ^a	Charman et al. (2007)	N	120 kg N ha ⁻¹ yr ⁻¹ (as NH ₄ NO ₃)	Monthly for 20 yr.	1	4	5	Nested-ANOVA: ns	Nested-ANOVA: ns
Payne (2010)	Moss of Achnacree (raised bog)	Charman et al. (2007)	S	0.7 mol m ⁻² H ₂ SO ₄	Single application, samples after 7 yr.	1	1	10 or 20	Nested-ANOVA: ns	Nested-ANOVA: ns
Payne et al. (unpublished)	Whim Moss (blanket bog)	Charman et al. (2007)	N	NH ₃ fumigation gradient: 0.3-37 µg m ⁻³	Continuously (weather-dependent) for 9 yr.	1	-	-	Pearson's r: ns	Pearson's r: ns
Payne and Toet (unpublished)	Peatland mesocosms	Charman et al. (2007)	O ₃	Ambient + 10 ppb Ambient + 25 ppb Ambient + 35 ppb (10 in summer)	Continuously for 4 yr.	1	7/9	-	ANOVA: ns	ANOVA: ns

^a This site is not a peatland but is included here as floristically similar to UK peatlands with organic surficial soil and a similar testate amoeba community.

^b As data were not available for every quadrat for every sampling depth, separate ANOVAs were also conducted for each sampling occasion; all showed non-significant results.

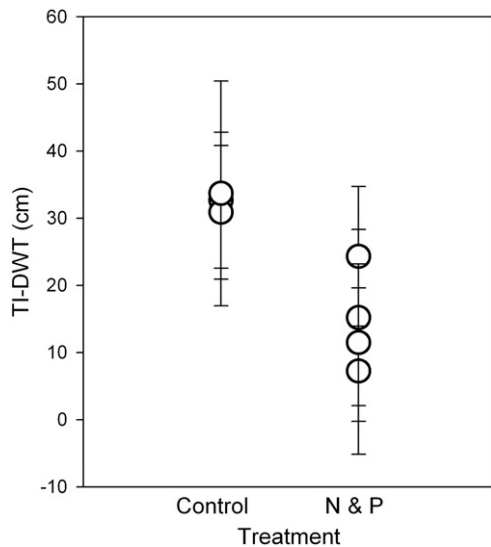


Figure 1. Testate amoeba-inferred water table (TI-DWT) for testate amoeba samples from the Toolik Lake N and P addition experiment (Mitchell, 2004) showing prediction and boot-strapped error for treated and control plots.

(Fig. 1), and the result is highly significant ($p < 0.01$). This reflects widespread changes in the ecosystem noted in this experiment, including large increases in above-ground plant biomass. The difference in inferred water-table depth may be related to a reduction in *Sphagnum* cover and collapse of low hummocks caused by a shift to more minerotrophic conditions, and therefore reflects real differences in wetness. The treatment level in this experiment is high and few peatlands will be exposed to this level of anthropogenic N and P pollution. However, urine, faeces and cadavers might produce temporally and spatially localized impacts of a similar scale.

Discussion

Our overall results are positive for testate amoeba-based paleoclimate reconstruction and provide little evidence for a confounding influence of pollution, even at experimental dosages that are unrealistically high. It may be that impacts would appear in some experiments with longer treatments, although non-significant results are found in some studies with treatment periods up to 20 yr. A possibility not directly addressed by our study is that pollution may degrade the quality of the paleoecological record, for instance by promoting decomposition, making analysis more difficult without changing results.

There are several possible factors that may contribute to the non-significant results of most of our analyses: i) the relative abundance changes of taxa may be too small to affect TI-DWT, ii) the taxa responding may be too rare to affect TI-DWT, iii) taxa may have water-table optima towards the centre of the gradient exerting less influence on TI-DWT results, iv) taxa responding positively and negatively may have similar optima, or v) taxa responding may have different optima that counteract each other (e.g., decline in wet indicators but also decline in dry indicators). The optima of sensitive species provide support for all of possibilities iii–v in different datasets (Supplementary Table 2). It is possible that changes of similar magnitude could produce a significant difference in inferred water table if the initial community were different. For instance, if we apply the final mean difference in taxon relative abundance in the Pb addition experiment of Nguyen-Viet et al. (2008) to a dataset from Alaskan peatlands (Payne et al., 2006), there is a significant difference in inferred water table (paired t -test: $t_{90} = -11.4$, $p < 0.001$). This is an unsophisticated test but makes the point that our negative results do not entirely rule out the possibility of pollution leading to inferred wetness changes.

The possible confounding influence of pollution has been addressed in other areas of paleoecology (Holtgrieve et al., 2011) but has received little consideration in the peatland archive despite the large quantity of modern ecological research addressing pollution impacts in peatlands. For instance, in dendroclimatic research it is known that pollution can cause changes in ring width independent of climate, which can compromise climate calibration and reconstruction for the recent past (e.g., Thompson, 1981; Wilson and Elling, 2004). Crutzen (2002) has coined the term *Anthropocene* to encapsulate the idea that different forcings may operate in the recent era in which human activity has been a dominant driver of environmental change compared to the more distant past. Our results provide little evidence that pollution compromises climate reconstruction, but it would be unwise to ignore pollution as a possible agent of paleoecological change in the peatland record. Further experimental studies characterising the paleoecological response to pollution would be helpful to allow pollution and climate impacts to be differentiated.

Acknowledgments

RJP was supported by the UK Natural Environment Research Council through the BiodiverERsA project PEATBOG and by a fellowship from the Conseil Régional de Franche-Comté. HNV is partially supported by the Swiss National Centre of Competence in Research (NCCR) North-South: Research Partnerships for Mitigating Syndromes of Global Change and Financial support for the Alaska study came from the Swiss National Science Foundation (Postdoctoral Fellowship #81NE-62574 to EADM). Thanks to Mariusz Lamentowicz and Dan Charman for the use of their transfer functions. Thanks to all our collaborators on the component studies, particularly those who set-up and monitored the experiments including: Lucy Sheppard, Ian Leith, Vince Gauci, Sylvia Toet, Chris Field, Simon Caporn, and Martin Sommerkorn. Two anonymous reviewers and editor Wyatt Oswald provided helpful comments on a previous version of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.yqres.2012.05.004>.

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