

Widespread drying of European peatlands in recent centuries

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110 **Keywords:** Wetlands; Climate change; Hydrology; Carbon; Europe

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116 An article for *Nature Geoscience* (revision 2)

117 **Climate warming and human impacts are thought to be causing peatlands to dry,**
118 **potentially converting them from sinks to sources of carbon. However, it is unclear**
119 **whether the hydrological status of peatlands has moved beyond their natural envelope.**
120 **Here we show that European peatlands have undergone substantial, widespread drying**
121 **during the last ~300 years. We analyse testate amoeba-derived hydrological**
122 **reconstructions from 31 peatlands across Britain, Ireland, Scandinavia and continental**
123 **Europe to examine changes in peatland surface wetness during the last 2000 years.**
124 **60% of our study sites were drier during the period CE 1800-2000 than they have been**
125 **for the last 600 years; 40% of sites were drier than they have been for 1000 years; and**
126 **24% of sites were drier than they have been for 2000 years. This marked recent**
127 **transition in the hydrology of European peatlands is concurrent with compound**
128 **pressures including climatic drying, warming and direct human impacts on peatlands,**
129 **although these factors vary between regions and individual sites. Our results suggest**
130 **that the wetness of many European peatlands may now be moving away from natural**
131 **baselines. Our findings highlight the need for effective management and restoration of**
132 **European peatlands.**

133

134 Peatlands have acted as globally-important carbon (C) sinks since the Last Glacial
135 Maximum^{1,2} and contain ~20% of the soil C pool, despite only covering ~3% of the global
136 landmass^{3,4}. Peatlands accumulate C when the production of plant litter exceeds losses from
137 microbial decomposition⁵. The maintenance of a shallow water table and near-saturated
138 surface conditions are important for inhibiting C losses from microbial respiration in peatlands⁶.
139 Several factors threaten the persistence of peatland ecosystem services: climate change, peat
140 extraction, drainage, burning and land-use modification⁷. Field manipulations⁸ and modelling
141 studies⁹ have indicated that the deepening of peatland water-tables leads to increasing peat
142 oxidation, in turn causing the peat C stock that has built up over millennia to be decomposed
143 and released to the atmosphere as carbon dioxide, with likely global-scale implications for
144 climate change^{8,10}. In Europe, peatlands store approximately five times more carbon than

145 forests¹¹ and about half of Europe's total soil organic C¹². These huge C stores deserve an
146 important place in Europe's climate mitigation measures and greenhouse gas emissions
147 policies.

148

149 The current stability of peatland ecosystem services is poorly understood. In particular, it is
150 unclear whether the current hydrological condition of peatlands has been substantially
151 influenced by recent climate change and human impacts. Peatland hydrological processes are
152 involved in multiple negative feedbacks at the site scale that may confer a degree of resistance
153 and resilience against climate-induced drying¹³. This is set against clear shifts in
154 palaeohydrological conditions in peat records, which are mostly interpreted as reflecting
155 periods of past climate change¹⁴. Although monitoring of peatland water tables is now
156 relatively commonplace, the longest instrumental records cover no more than a few decades,
157 and are thus unable to provide any long-term context for the role of climate and human impacts
158 in peatland drying. For example, one of the longest instrumental peatland water-table records
159 in the world is from Männikjärve bog in Estonia. However, this record only began in CE 1951
160 and is therefore still too short to show long-term changes ([Supplementary Section 1](#)).

161

162 **Hydrological change in European peatlands**

163 In the absence of long-term hydrological monitoring data, testate (or shell-forming) amoebae
164 can be used to reconstruct past water-table depths (WTDs) from peat profiles using statistical
165 transfer function models¹⁵. Several such studies in Europe have reported deepening water
166 tables in recent centuries^{14,16,17}. We carried out a preliminary meta-analysis of 84 published
167 testate-amoeba-based reconstructions ([Methods](#)) in order to assess general trends reported
168 in the literature. The meta-analysis shows that shifts to drier conditions in European peatlands
169 over the last 300 years have been reported in 69% of study sites; while shifts to wetter
170 conditions have been reported in just 7% of sites; the remaining 24% of the records have
171 either shown unclear trends or lack the chronological quality or sampling resolution needed to
172 determine any shift ([Supplementary Section 2](#)). The most commonly reported ages of dry

173 shifts in the last ~200 years are CE 1850 (8%), 1900 (13%) and 1950 (13%) ([Supplementary](#)
174 [Section 2](#)). However, these records are difficult to compare because of variations in
175 chronological precision, temporal resolutions, transfer functions, and age modelling
176 approaches. Here we present the first European-wide network of WTD reconstructions using
177 high-quality, high-resolution testate amoeba data ([Methods](#), [Supplementary Section 3 and 4](#)),
178 and develop accurate chronological models for each site using Bayesian methods
179 ([Supplementary Section 5](#)). We use the reconstructions to examine hydrological changes in
180 European peatlands over the last two millennia and to determine the state of peatland
181 hydrology in recent centuries in the context of longer-term baselines. Reconstructions from a
182 range of peatland types (raised bogs, blanket peatland, poor fens and permafrost plateaus)
183 were included in the analysis.

184

185 There is considerable variability in the water-table records between sites owing to regional
186 climatic variability, differences in site response and chronological uncertainties. 78% of sites
187 in Britain, Ireland, Scandinavia and the Baltics have undergone significant drying in the last
188 400 years (Fig. 1); while the other 22% of sites in these regions exhibited no significant
189 change. 46% of sites in continental Europe have undergone significant drying in the last 400
190 years, 31% exhibited no significant change, while the remaining 23% have become
191 significantly wetter – the only three sites in the entire dataset to do so. For each site we binned
192 the reconstructed WTDs into 200-year intervals and calculated the average WTD for each bin.
193 The use of 200-year bins strikes an appropriate balance between sufficient data points within
194 each bin to allow statistical confidence, and enough bins to allow the identification of temporal
195 trends. Considering all sites together, we found that 60% were drier in the period CE 1800-
196 2000 (200-year average bins) than they have been for the last 600 years (CE 1400-2000);
197 40% of sites were drier than they have been for 1000 years (CE 1000-2000); and 24% were
198 drier than they had been during the entire 2000-year record (since CE 1). We recognise that
199 some of the individual peatlands in our dataset have exhibited high-magnitude dry- (and

200 indeed wet-) shifts earlier in the record, but it is only during the last 300 years that a consistent
201 and coherent drying trend has emerged across multiple sites.

202

203 Local regression (loess) models highlight general trends in the compiled data (Fig. 2).
204 Compiled records from all three regions show shallow water tables during the Little Ice Age
205 (LIA) followed by rapid drying to present day. Deep water tables are evident during the
206 Medieval Warm Period (MWP) in Britain, Ireland and Scandinavia, although there is no clear
207 response to the MWP in Continental Europe. British and Irish sites show shallow water tables
208 towards the end of the Dark Age Cold Period (DACP), but this is not apparent in other regions.
209 In Scandinavia, this lack of signal may reflect low data density at this time and large
210 chronological errors. Change-point analysis identifies significant transitions to drier conditions
211 during the past 300 years in the compiled data: CE 1914 in Britain and Ireland; CE 1777 and
212 1990 in Scandinavia and the Baltics; and CE 1756 in Continental Europe. When all sites are
213 combined a change-point at CE 1751 is identified.

214

215 **Potential climatic drivers**

216 The shifts are closely linked with recent climate change as evidenced through comparison with
217 reanalysis of instrumental climate data (Fig. 3; [Supplementary Section 6](#)). In Britain and
218 Ireland, increased dryness in peatlands corresponds with a major decrease in summer (June-
219 July-August: JJA) precipitation (up to 25 mm quarter⁻¹) and an overall increase in summer
220 temperature (up to 1°C), when we compare the second halves of the 19th and 20th centuries.
221 In Scandinavia and the Baltics, most peatlands that have undergone deepening water tables
222 over the same time period have also experienced a major increase in mean annual
223 temperature of up to 2.5°C (Fig. 3B; [Supplementary Section 6](#)). In Continental Europe, the
224 sites that have become drier are in areas that have warmed by up to 1°C (JJA). The five sites
225 in Continental Europe that have become wetter between the second halves of the 19th and
226 20th centuries are located in regions that have experienced an increase in rainfall over this
227 interval (Fig. 3A). Fig. 3C shows that most study sites have undergone significant drying from

228 the 17th to the 20th centuries, except three in continental Europe. Gridded climate proxy data
229 suggest that precipitation has decreased across Europe over the last ~400 years
230 (Supplementary Section 6), which is consistent with this trend. The variation in response of
231 our study sites to precipitation and temperature may reflect the finding that summer water
232 deficit is controlled by summer precipitation in mid-latitude oceanic peatlands whereas
233 summer temperature plays a greater role in higher latitude, continental settings¹⁸.

234

235 **Human impacts on peatland ecosystems**

236 We tested for other possible influences on peatland hydrology in addition to climate (Fig. 4).
237 We classify 42% of our sites as having been significantly damaged by human activities; 29%
238 have minor damage; and 29% are relatively undamaged. The human activities that have
239 contributed to site degradation include peat cutting, drainage, burning, grazing, afforestation
240 and scientific activities (e.g. installation of infrastructure and equipment). All these factors may
241 have contributed to site-scale drying in recent centuries. It is clear that our sites in Britain and
242 Ireland have seen more extensive degradation than elsewhere, particularly through cutting,
243 drainage, burning and grazing. Two sites in Scandinavia have suffered severe damage from
244 afforestation. Only two of our 31 sites (6%) have had no damage to the best of our knowledge
245 (Lappmyran, Sweden and Jelenia Wyspa, Poland).

246

247 All global land areas have experienced an increase in atmospheric N deposition over the
248 timeframe of our reconstructions²⁰. Atmospheric N deposition has been shown to cause shifts
249 in peatland plant communities, and increases in plant productivity through fertilisation²¹
250 (Berendse et al., 2001). Conversely, ecosystem respiration also increases with N deposition
251 through removal of nutritional constraints on microbial activity and the production of more labile
252 plant litter^{22,23}. However, we are aware of no field or modelling evidence for changes in
253 peatland WTD as a direct result of N deposition.

254

255 Climate-driven drying of European peatlands is likely to have been exacerbated by direct
256 human impacts during recent centuries. The hydrological shifts occurred at a time of rapidly
257 expanding human populations across Europe²⁴, expanding cropland, and increasing land-use
258 intensity²⁵. It is impossible to separate the effects of climate and direct human impacts in our
259 records, as they are superimposed upon one another. Global and regional climate model
260 projections for Europe generally agree on continued warming and reduced growing season
261 moisture availability into the 21st century²⁶. This may lead to continued water-table drawdown,
262 which has been linked to catastrophic loss of peat C stocks through enhanced aerobic
263 decomposition⁹. Our study sites include several of the least damaged peatlands in Europe;
264 however, it is clear that almost all peatlands in Europe have been affected by human activities
265 to some extent. The compound pressures of climate change and human impacts may push
266 European peatlands beyond their capacity for resistance by overriding negative feedbacks
267 amongst ecohydrological processes¹³. Furthermore, a hydrological tipping point may exist in
268 peatlands where irreversible changes in plant communities and a shift from C sink to source
269 is triggered in response to drying^{27,28}. Indeed, many European peatlands have already
270 undergone shifts in vegetation composition over the last 300 years, including changes in
271 *Sphagnum* communities²⁹, and increases in grass, sedge³⁰ and shrub (e.g. *Calluna vulgaris*)³¹
272 cover.

273

274 Projects are underway to restore peatlands across Europe, in order to maintain and enhance
275 their vital ecosystem services, primarily through damming or blocking of artificial drains and
276 gullies³². These actions may be vital in mitigating against soil C stock loss due to both
277 anthropogenic impacts and future climatic warming. Our data suggest that European
278 peatlands are in a state of transition, which may cause them to become drier than their natural
279 baselines. Management strategies and restoration efforts (e.g. drain blocking) need to take
280 these findings into account.

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283 **References**

- 284 1. Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W. & Hunt, S. J. Global peatland dynamics
285 since the Last Glacial Maximum. *Geophys. Res. Lett.* **37**, L13402 (2010).
- 286 2. Gallego-Sala, A. V. *et al.* Latitudinal limits to the predicted increase of the peatland carbon
287 sink with warming. *Nat. Clim. Chang.* **8**, 907–913 (2018).
- 288 3. Scharlemann, J. P. W., Tanner, E. V. J., Hiederer, R. & Kapos, V. Global soil carbon:
289 Understanding and managing the largest terrestrial carbon pool. *Carbon Manag.* **5**, 81–91
290 (2014).
- 291 4. Xu, J., Morris, P. J., Liu, J. & Holden, J. PEATMAP: Refining estimates of global peatland
292 distribution based on a meta-analysis. *Catena* **160**, 134–140 (2018).
- 293 5. Clymo, R. S., Turunen, J. & Tolonen, K. Carbon accumulation in peatland. *Oikos* **81**, 368
294 (1998).
- 295 6. Holden, J. Peatland hydrology and carbon release: Why small-scale process matters.
296 *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **363**, 28912913 (2005).
- 297 7. Page, S. E. & Baird, A. J. Peatlands and global change: response and resilience. *Annu.*
298 *Rev. Environ. Resour.* **41**, 35–57 (2016).
- 299 8. Dorrepaal, E. *et al.* Carbon respiration from subsurface peat accelerated by climate warming
300 in the subarctic. *Nature* **460**, 616–619 (2009).
- 301 9. Ise, T., Dunn, A. L., Wofsy, S. C. & Moorcroft, P. R. High sensitivity of peat decomposition
302 to climate change through water-table feedback. *Nat. Geosci.* **1**, 763–766 (2008).
- 303 10. Gill, A. L. *et al.* Deep peat warming increases surface methane and carbon dioxide
304 emissions in a black spruce-dominated ombrotrophic bog. *Global Change Biol.* **23**, 5398–
305 5411 (2017).
- 306 11. Limpens, J. *et al.* Peatlands and the carbon cycle: from local processes to global
307 implications – a synthesis. *Biogeosciences* **5**, 1475–1491 (2008).
- 308 12. Panagos, P., Hiederer, R., Van Liedekerke, M. & Bampa, F. Estimating soil organic carbon
309 in Europe based on data collected through an European network. *Ecol. Indic.* **24**, 439–450
310 (2013).

- 311 13. Waddington, J. M. *et al.* Hydrological feedbacks in northern peatlands. *Ecohydrology* **8**,
312 113–127 (2015).
- 313 14. Swindles, G. T. *et al.* Centennial-scale climate change in Ireland during the Holocene.
314 *Earth-Science Rev.* **126**, 300–320 (2013).
- 315 15. Amesbury, M. J. *et al.* Development of a new pan-European testate amoeba transfer
316 function for reconstructing peatland palaeohydrology. *Quat. Sci. Rev.* **152**, 132–151 (2016).
- 317 16. Charman, D. J., Blundell, A., Chiverrell, R. C., Hendon, D. & Langdon, P. G. Compilation
318 of non-annually resolved Holocene proxy climate records: stacked Holocene peatland
319 palaeo-water table reconstructions from northern Britain. *Quat. Sci. Rev.* **25**, 336–350
320 (2006).
- 321 17. Marcisz, K. *et al.* 2015. Long-term hydrological dynamics and fire history during the last
322 2000 years in CE Europe reconstructed from a high-resolution peat archive. *Quat. Sci. Rev.*
323 **112**, 138–152 (2015).
- 324 18. Charman, D. J. Summer water deficit variability controls on peatland water-table changes:
325 implications for Holocene palaeoclimate reconstructions. *Holocene* **17**, 217–227 (2007).
- 326 19. Compo, G. P. *et al.* The twentieth century reanalysis project. *Q. J. R. Meteorol. Soc.* **137**,
327 1–28 (2011).
- 328 20. Galloway, J. N. *et al.* Nitrogen cycles: past, present, and future. *Biogeochemistry* **70**, 153–
329 226 (2004).
- 330 21. Berendse, F. *et al.* Raised atmospheric CO₂ levels and increased N deposition cause shifts
331 in plant species composition and production in *Sphagnum* bogs. *Glob. Chang. Biol.* **7**, 591–
332 598 (2001).
- 333 22. Bragazza, L. *et al.* Atmospheric nitrogen deposition promotes carbon loss from peat bogs.
334 *Proc. Natl. Acad. Sci.* **103**, 19386–19389 (2006).
- 335 23. Juutinen, E. *et al.* Responses of vegetation and ecosystem CO₂ exchange to 9 years of
336 nutrient addition at Mer Bleue Bog. *Ecosystems* **13**, 874–887 (2010).
- 337 24. McEvedy, C. & Jones, R. *Atlas of World Population History*. (Penguin, 1978).

- 338 25. Ramankutty, N. & Foley, J. A. Estimating historical changes in global land cover:
339 Croplands from 1700 to 1992. *Global Biogeochem. Cycles* **13**, 997–1027 (1999).
- 340 26. Jacob, D. *et al.* Climate impacts in Europe under +1.5°C global warming. *Earth's Futur.* **6**,
341 264–285 (2018).
- 342 27. Jassey, V. E. J. *et al.* Tipping point in plant–fungal interactions under severe drought
343 causes abrupt rise in peatland ecosystem respiration. *Global Change Biol.* **24**, 972–986
344 (2018).
- 345 28. Lamentowicz, M. *et al.* Unveiling tipping points in long-term ecological records from
346 *Sphagnum*-dominated peatlands. *Biol. Lett.* **15**, 20190043 (2019).
- 347 29. Gałka, M. *et al.* Palaeoenvironmental changes in Central Europe (NE Poland) during the
348 last 6200 years reconstructed from a high resolution multi-proxy peat archive. *Holocene*
349 **25**, 421–434 (2015).
- 350 30. Gogo, S. *et al.* Invasion of a *Sphagnum*-peatland by *Betula* spp and *Molinia caerulea*
351 impacts organic matter biochemistry. Implications for carbon and nutrient cycling.
352 *Biogeochemistry* **106**, 53–69 (2011).
- 353 31. Turner, T. E. *et al.* Late Holocene ecohydrological and carbon dynamics of a UK raised
354 bog: impact of human activity and climate change. *Quat. Sci. Rev.* **84**, 65–85 (2014).
- 355 32. Parry, L. E., Holden, J. & Chapman, P. J. Restoration of blanket peatlands. *J. Environ.*
356 *Manage.* **133**, 193–205 (2014).

357

358 **Acknowledgements**

359 We thank all the organisations that have funded the data used in this analysis: Academy of
360 Finland (296423); Department for Employment and Learning (N. Ireland); European
361 Commission (Fifth Framework); INTERACT (European Community's Seventh Framework
362 Programme); Irish Discovery Programme; Leverhulme Trust; National Science Centre
363 (Poland); Natural Environment Research Council (UK); Natural Sciences and Engineering
364 Research Council of Canada; Netherlands Organisation for Scientific Research; Polish

365 National Science Centre (NCN - 2015/17/B/ST10/01656); Quaternary Research Association;
366 Russian Science Foundation (19-14-00102); Swiss Contribution to the enlarged European
367 Union; Swiss Federal Office for Education and Science; Swiss National Science Foundation;
368 World University Network; Wüthrich Fund (University of Neuchâtel); Yorkshire Water. TGS is
369 funded by the Leeds-York Natural Environment Research Council (NERC) Doctoral Training
370 Partnership (NE/L002574/1). TET acknowledges NERC Doctoral Training Grant
371 NE/G52398X/1. JMG – this paper represents a contribution from Natural Resources Canada
372 (NRCan contribution number / Numéro de contribution de RNCAN: 20190079). GTS
373 acknowledges financial support from the Dutch Foundation for the Conservation of Irish Bogs.
374 We thank Lee Brown and Andy Baird (University of Leeds) for constructive comments on the
375 manuscript. This is a contribution to the PAGES C-PEAT group. PAGES is supported by the
376 US National Science Foundation and the Swiss Academy of Sciences. We dedicate this work
377 to co-author Richard J. Payne who was tragically killed while climbing Nanda Devi in the
378 Garhwal Himalayas whilst the manuscript was in review.

379

380 **Author contributions**

381 G.T.S. designed the study. G.T.S., P.J.M., D.J.M., R.J.P., T.P.R., M.J.A., M.L., T.E.T., A.G.S.
382 and T.S. compiled site-based data and performed analyses. All other others provided data
383 or carried out a minor component of data compilation or analysis. G.T.S., P.J.M. and D.J.M.
384 carried out the composite data analysis and wrote the manuscript, with input from all
385 authors.

386

387 **Competing interests**

388 The authors declare no competing interests.

389

390 **Additional information**

391 **Supplementary information** is available for this paper at XX.

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395 **Publisher's note:** Springer Nature remains neutral with regard to jurisdictional claims in
396 published maps and institutional affiliations.

397

398 **Figure Captions**

399 Fig. 1. Standardised water-table depth data from each site classified into three broad
400 geographic regions (Britain and Ireland; Scandinavia and Baltics; Continental Europe). Data
401 from the last 2ka and CE 1600-present day are shown. Linear regression trend lines for the
402 period CE 1600 to present day are illustrated: solid trend lines indicate statistically-significant
403 models ($p < 0.05$); dashed trend lines indicate non-significant models. The percentage of sites
404 which have become significantly drier or wetter, and the percentage of those with non-
405 significant linear models, are shown. Please see **Methods** for references to previously
406 published data.

407

408 Fig. 2. Compiled standardised water-table data from all sites and the three broad geographic
409 regions (Britain and Ireland; Scandinavia and Baltics; Continental Europe). Greyscale
410 indicates the chronological precision of each data point (determined through Bayesian age
411 modelling). A locally-estimated scatterplot smoothing (loess) model is shown as a yellow line.
412 The red shading indicates 95% confidence limits on the loess function. The timings of the Dark
413 Ages Cold Period (DACP), Medieval Warm Period (MWP) and Little Ice Age (LIA) are
414 illustrated. Significant change point years are illustrated. Please see **Methods** for references
415 to previously published data.

416

417 Fig. 3. Comparison of peatland and climatic datasets. Changes in summer (June-July-August)
418 precipitation totals (A) and temperatures (B) interpolated from 2° latitude x 2° longitude grids
419 across Europe between the second half of the 19th and 20th centuries: (CE 1950-1999

420 average) minus (CE 1850-1899 average). Data taken from NOAA-CIRES Twentieth Century
421 Reanalysis (V2c)¹⁹. The points in (A) and (B) represent (CE 1950-1999 average) minus (CE
422 1850-1899 average) standardised water-table depths. Panel C shows (CE 1950-1999
423 average) minus (CE 1600-1699 average) standardised water-table depths. Literature-based
424 sites reporting a drying or wetting trend in the last ~200 years are also shown ([Supplementary](#)
425 [Section 2](#)). Please see [Methods](#) for references to previously published data.

426

427 Fig. 4. Matrix indicating the type and level (major, moderate, minor, none known) of human
428 impacts on each study site. A damage index was calculated as the total sum of all impacts.
429 The type of peatland is indicated in superscript font. Please see [Methods](#) for references to
430 previously published data.

431

432 **Methods**

433 **1. Justification of approach**

434 Peat profiles that span the most recent centuries are commonly within the aerobic zone
435 (previously referred to as the “acrotelm” in the diplotelmic peat model); therefore, semi-
436 quantitative reconstructions based on the degree of peat humification were excluded from the
437 meta-analysis as peat within the aerobic zone is subject to further decomposition.
438 Reconstructions using plant macrofossil approaches were also discounted as no European
439 transfer function currently exists for peatland plants. Therefore, only testate amoeba data are
440 considered here as 1) hydrology has consistently been shown to be the primary environmental
441 control of community composition over other factors in ombrotrophic peatlands^{33, 34}; 2) levels
442 of pollution associated with atmospheric deposition do not bias reconstructions³⁵; and 3) direct
443 comparison of records is possible between transfer-function based water table
444 reconstructions.

445

446 **2. Literature-based analysis**

447 To support our primary analysis of high-quality data we conducted a comprehensive literature-
448 based review of peat-based palaeohydrological reconstructions covering the last 300 years
449 from northwest Europe ([Supplementary Section 2](#)).

450

451 *2.1 Chronological quality*

452 Records were rated on chronological certainty and proxy resolution. Radiocarbon age-depth
453 models substantiated with known age stratigraphic markers (Hekla 1947 tephra, bomb-pulse),
454 or inferred age stratigraphic markers (Spheroidal Carbonaceous Particles (SCPs), *Pinus* rise)
455 bolstered with further radiometric dating (^{210}Pb , ^{241}Am), were rated the most chronologically
456 secure (rating = 1); records with radiocarbon-based age-depth models with a single inferred
457 age marker (SCPs or *Pinus* rise), or short records (200 years or less) with SCP-based
458 chronology were rated as chronologically good (rating = 2); those based on linear
459 interpolation of radiocarbon dates were assigned low chronological confidence (rating = 3).

460

461 *2.2 Human impacts*

462 The main human impacts recorded in the literature for each site (e.g. peat cutting, drainage,
463 burning, afforestation) were noted.

464

465 *2.3 Analysis*

466 The timing of any reported change to drier or wetter conditions in the last 300 years from each
467 paper was reported.

468

469 3. Quantitative analysis

470 3.1 Water-table reconstruction

471 Testate amoeba data from European peatlands were compiled and quality checked before
472 having their taxonomies harmonised to the taxonomic system of Amesbury et al. (2016)³⁶ for
473 transfer function application. Only datasets with high quality absolute chronologies for the last
474 ~200 years were selected for further analysis. Water-table reconstructions were carried out
475 using the pan-European transfer function of Amesbury et al. (2016)³⁶ with a weighted
476 averaging tolerance-downweighted model with inverse deshrinking. Water-table depth
477 reconstructions were converted to standard units (z-scores) following Swindles et al. (2015)³⁷.
478 Reconstructions were carried out on the full dataset and also a dataset after the weak silicic
479 idiosomic tests (*Corythion-Trinema* type, *Euglypha ciliata* type and *Euglypha rotunda* type³⁸)
480 were removed. In reality, there is virtually no difference between the two reconstructions
481 showing that the features observed in the uppermost peat profiles are not related to poor
482 preservation of weak siliceous tests (Supplementary Section 3 and 4). The reconstructions
483 ran on the data without the weak silicic idiosomic tests were used for subsequent analysis.

484

485 3.2 Age modelling

486 Age models were constructed for each site using chronological data including ¹⁴C, ²¹⁰Pb, and
487 other age-equivalent stratigraphic markers such as SCPs. Bayesian age models were
488 generated for each site to achieve good accuracy and quantification of age errors
489 (Supplementary Section 5) using R version 3.4.1³⁹, and the rbacon package (version 2.3.4)⁴⁰.
490 Bacon uses *a priori* information of peat accumulation rate, over multiple short sections of the
491 core to produce flexible, robust chronologies. We modelled all cores to determine the age
492 probability for each depth. Hereafter, all references to ages or years refer to the maximum
493 probability age at a given depth, as determined from the age model, unless otherwise
494 specified. We also used the age models to generate age error ranges for each depth.

495 *3.3 Trend lines*

496 A linear least-squares regression was carried out for each record for the period CE 1600-
497 present to determine whether there was a drying or wetting trend over this timeframe. An F-
498 test was used to determine whether each model provided a better fit to the data than a model
499 containing no independent variables. A standard t-test was used to evaluate the slope and
500 intercept coefficients. The analysis was completed using R version 3.4.1³⁹.

501

502 *3.4 Data compilation analysis*

503 All data were compiled within 4 groups: All sites; Britain and Ireland; Scandinavia and Baltics;
504 and Continental Europe. A LOESS smoothing function⁴¹ with an f-value (degree of smoothing)
505 setting of 0.02 was calculated for the compiled regional datasets. Changepoint analysis⁴² was
506 performed on the compiled data to identify major changes in mean and variance over time
507 (function `cpt.meanvar`) in the datasets using the package ‘Package ‘changepoint’⁴² in R
508 version 3.4.1³⁹. The temporal span used in this analysis was 1000 cal. CE to present. The
509 singular most likely changepoint in mean and variance was then identified using an “At Most
510 One Change” (AMOC) method under default settings. In addition, multiple changepoints in
511 mean and variance of the time series were then identified using “Pruned Exact Linear Time”
512 (PELT)⁴³ method under default settings, with the number of changepoints limited to a
513 maximum of 4.

514

515 *3.5 Climate analysis*

516 Temperature and precipitation data representing the period 1851-2010 were downloaded from
517 KNMI Climate Explorer (<https://climexp.knmi.nl/>). We used the NOAA-CIRES Twentieth
518 Century Reanalysis (V2c) dataset¹⁹ – a comprehensive global atmospheric circulation dataset
519 based on the assimilation of four-dimensional weather maps and their uncertainty from the

520 mid-19th century to the 21st century. Data were downloaded at a monthly temporal resolution
521 and at a spatial resolution of 2° latitude x 2° longitude for the spatial domain 40-70°N and
522 10°W-30°E. Maps showing change in summer temperature and precipitation across Europe
523 were produced by first splitting data into two 50-year time periods from 1850-1899 and 1950-
524 1999 respectively for the summer months of June, July and August. The difference between
525 these periods was then calculated and kriging was used within ArcMap to interpolate between
526 grid points to produce surface temperature and precipitation maps for Europe that represent
527 the change in summer temperature and precipitation between the second half of the 19th and
528 20th centuries. Graphs showing temporal changes in temperature and precipitation across
529 Europe were produced by first splitting data into four different spatial domains encompassing
530 (1) Britain and Ireland, (2) Scandinavia, (3) Continental Europe, and (4) the three regions
531 combined.

532

533 Changes for these four domains were then plotted as time series along with a smoothed line
534 based on loess smoothing. Linear trends were calculated using linear regression. Using the
535 years of the time series as the known x values and the climate data as the known y values, a
536 linear regression equation was constructed and then used to predict y values (i.e.
537 temperatures or precipitation) for the start and end years of the time series. The difference
538 between the values for these years was then computed and expressed as a percentage of the
539 temperature/precipitation value for the starting year.

540

541 Another set of time series for the same four regions was produced for the longer period of
542 1500-2000 based on temperature and precipitation reconstructions downloaded from KNMI
543 Climate Explorer based on datasets from Luterbacher et al. (2004)⁴⁴ and Pauling et al. (2006)⁴⁵
544 respectively. Please also see [Supplementary Section 6](#).

545

546 *3.6 Human impacts*

547 It is widely acknowledged that the majority of peatlands across Europe have been affected by
 548 human activity to at least some degree. Evidence of human activity for each site was recorded
 549 in several categories: cutting, drainage, burning, grazing, afforestation, and scientific activity
 550 (e.g. installation of scientific and monitoring equipment) within a matrix. The damage level for
 551 each individual category was noted as major (score 3), moderate (score 2), minor (score 1)
 552 and none known (score 0). A damage index for each site was calculated by summing the
 553 scores for each category (>4 = damaged site; 3-4 = minor damage; 0-2 = relatively
 554 undamaged).

555

556 *3.7 Data sources*

557 All published data sources are provided below:

Site	Region	Country	Latitude	Longitude	Reference
Ardkill	Britain and Ireland	Ireland	53.3653	-6.9532	46
Ballyduff	Britain and Ireland	Ireland	53.0807	-7.9925	47
Butterburn	Britain and Ireland	England	55.0875	-2.5036	48
Cloonoolish	Britain and Ireland	Ireland	53.1865	-8.2569	46
Dead Island	Britain and Ireland	Ireland	54.8862	-6.5487	49
Derragh	Britain and Ireland	Ireland	53.7667	-7.4083	50
Keighley	Britain and Ireland	England	54.4253	-2.0369	51
Malham	Britain and Ireland	England	54.0964	-2.1750	52
Slieveanorra	Britain and Ireland	Ireland	55.0848	-6.1921	49
Bagno Kusowo	Continental Europe	Poland	53.8078	16.5872	53
Barschpfuhl	Continental Europe	Germany	53.0558	13.8494	54
Combe des Amburnex	Continental Europe	Switzerland	46.5397	6.2317	55
Gązwa	Continental Europe	Poland	53.8726	21.2201	56
Izery	Continental Europe	Poland	50.8519	15.3602	57
Jelenia Wyspa	Continental Europe	Poland	53.5918	17.9821	58
Linje	Continental Europe	Poland	53.1880	18.3098	59
Mauntschas	Continental Europe	Switzerland	46.4900	9.8544	60
Mechacz	Continental Europe	Poland	54.3314	22.4419	61
Praz-Rodet	Continental Europe	Switzerland	46.5667	6.1736	62
Słowińskie	Continental Europe	Poland	54.3619	16.4785	63
Stążki	Continental Europe	Poland	54.4244	18.0833	64
Tăul Muced	Continental Europe	Romania	47.5739	24.5450	65
Akerlänna Römösse	Scandinavia and Baltic	Sweden	60.0167	17.3667	66
Ältbergsmossen	Scandinavia and Baltic	Sweden	59.9667	18.6833	67

Gullbergbymossen	Scandinavia and Baltic	Sweden	59.6333	18.4333	67
Kontolanrahka	Scandinavia and Baltic	Finland	60.4783	22.4783	68
Lappmyran	Scandinavia and Baltic	Sweden	64.1647	19.5828	69
Lille Vildmose	Scandinavia and Baltic	Denmark	56.8391	10.1896	70
Männikjärve	Scandinavia and Baltic	Estonia	58.8667	26.2500	71
Stordalen 1	Scandinavia and Baltic	Sweden	68.3568	19.0484	72
Stordalen 2	Scandinavia and Baltic	Sweden	68.3564	19.0441	73

558

559 Water-table reconstruction data are provided in [Supplementary Section 7](#).

560

561 **Data availability statement**

562 The data that support the findings of this study are provided in [Supplementary Section 7](#).

563

564 **References**

565 33. Woodland, W. A., Charman, D. J. & Sims, P. C. Quantitative estimates of water tables and
566 soil moisture in Holocene peatlands from testate amoebae. *Holocene* **8**, 261–273
567 (1998).

568 34. Booth, R. K. Testate amoebae as proxies for mean annual water-table depth in *Sphagnum*-
569 dominated peatlands of North America. *J. Quat. Sci.* **23**, 43–57 (2008).

570 35. Payne, R. J., Mitchell, E. A. D., Nguyen-Viet, H. & Gilbert, D. Can pollution bias peatland
571 paleoclimate reconstruction? *Quat. Res.* **78**, 170–173 (2012).

572 36. Amesbury, M. J. *et al.* Development of a new pan-European testate amoeba transfer
573 function for reconstructing peatland palaeohydrology. *Quat. Sci. Rev.* **152**, 132–151
574 (2016).

575 37. Swindles, G. T. *et al.* Testing peatland water-table depth transfer functions using high-
576 resolution hydrological monitoring data. *Quat. Sci. Rev.* **120**, 107–117 (2015).

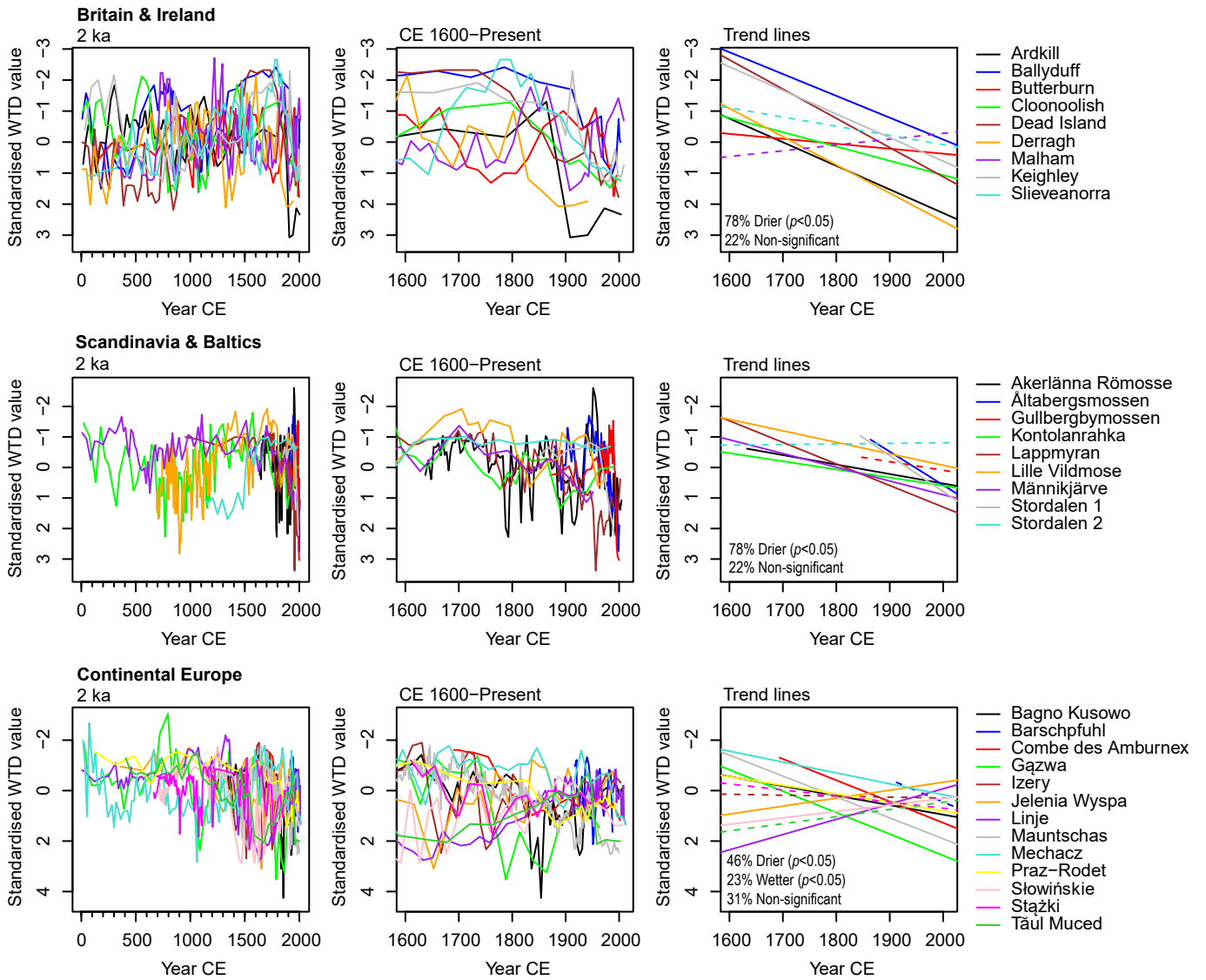
- 577 38. Swindles, G. T., Charman, D. J., Roe, H. M. & Sansum, P. A. Environmental controls on
578 peatland testate amoebae (Protozoa: Rhizopoda) in the North of Ireland: Implications
579 for Holocene palaeoclimate studies. *J. Paleolimnol.* **42**, 123–140 (2009).
- 580 39. R Core Team. *R: A language and environment for statistical computing*. R Foundation for
581 Statistical Computing, Vienna, Austria. <http://www.R-project.org/> (2017).
- 582 40. Blaauw, M. & Christen, J. A. Flexible paleoclimate age-depth models using an
583 autoregressive gamma process. *Bayesian Anal.* **6**, 457–474 (2011).
- 584 41. Cleveland, W. S. Robust locally weighted regression and smoothing scatterplots. *J. Am.*
585 *Stat. Assoc.* **74**, 829–836 (1979).
- 586 42. Killick, R. & Eckley, I. A. changepoint: An R package for changepoint analysis. *J. Stat.*
587 *Softw.* **58**, 1–19 (2015).
- 588 43. Killick, R., Fearnhead, P. & Eckley, I. A. Optimal detection of changepoints with a linear
589 computational cost. *J. Am. Stat. Assoc.* **107**, 1590–1598 (2012).
- 590 44. Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M. & Wanner, H. European seasonal
591 and annual temperature variability, trends, and extremes since 1500. *Science* **303**,
592 1499–1503 (2004).
- 593 45. Pauling, A., Luterbacher, J., Casty, C. & Wanner, H. Five hundred years of gridded high-
594 resolution precipitation reconstructions over Europe and the connection to large-scale
595 circulation. *Clim. Dyn.* **26**, 387–405 (2006).
- 596 46. Blundell, A., Charman, D. J. & Barber, K. Multiproxy late Holocene peat records from
597 Ireland: Towards a regional palaeoclimate curve. *J. Quat. Sci.* **23**, 59–71 (2008).
- 598 47. Swindles, G. T. *et al.* Centennial-scale climate change in Ireland during the Holocene.
599 *Earth-Science Rev.* **126**, 300–320 (2013).

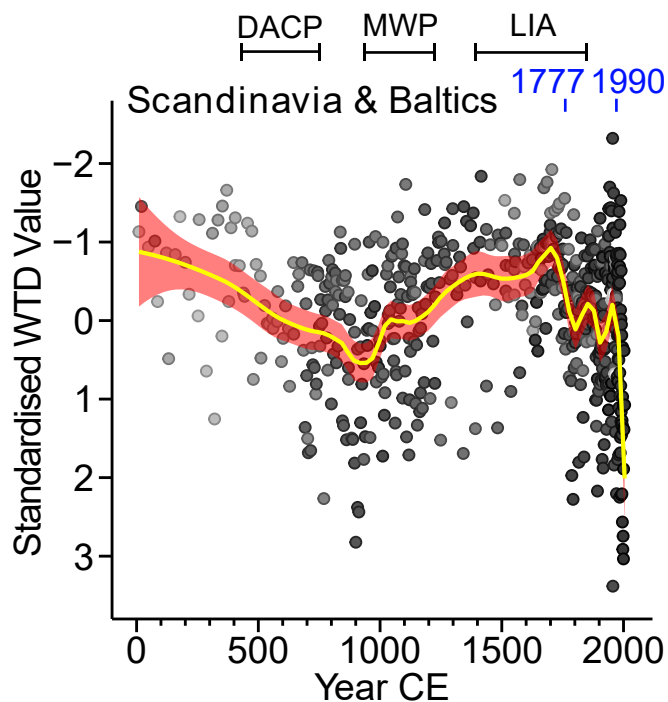
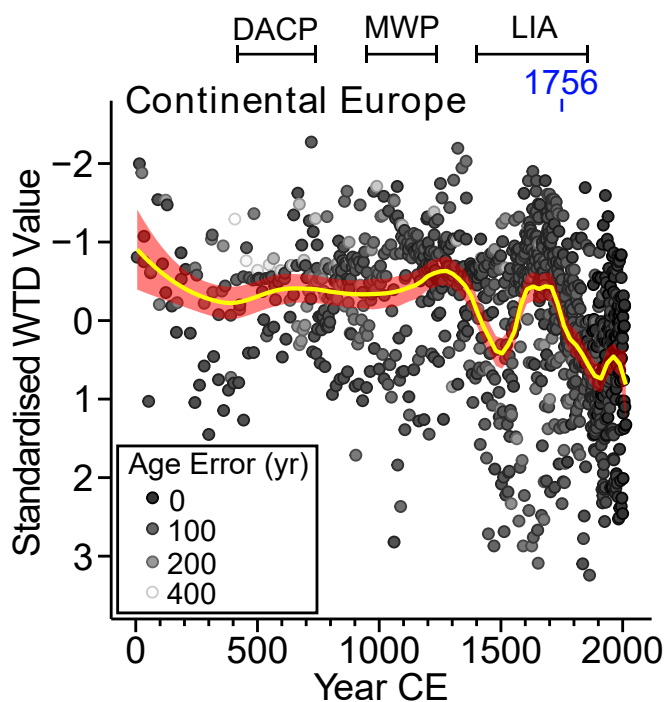
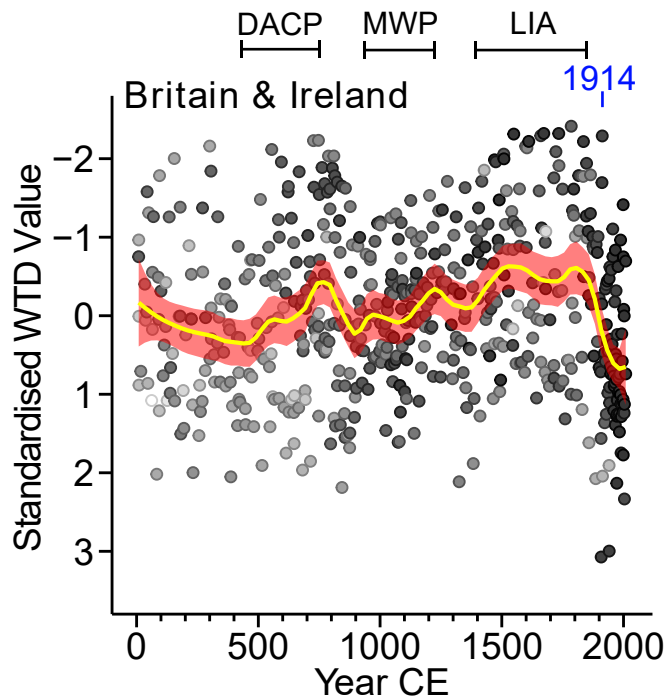
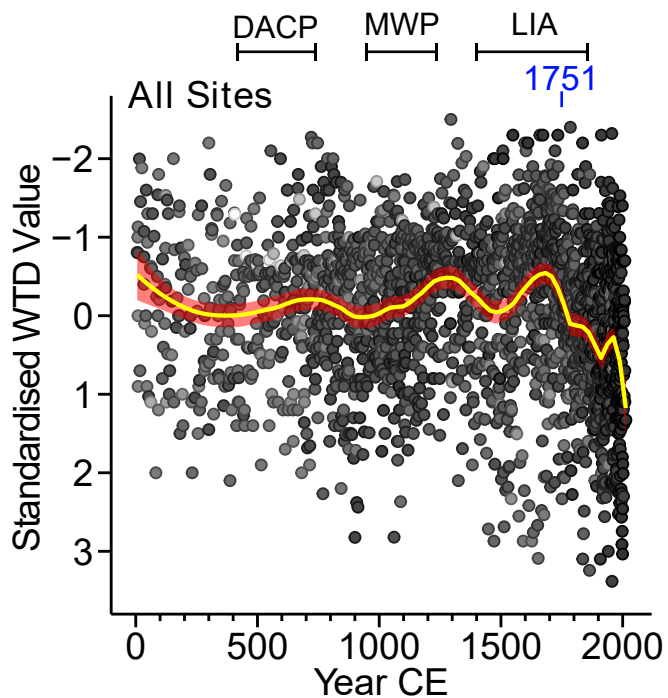
- 600 48. Mauquoy, D., Yeloff, D., Van Geel, B., Charman, D. J. & Blundell, A. Two decadal
601 resolved records from north-west European peat bogs show rapid climate changes
602 associated with solar variability during the mid-late Holocene. *J. Quat. Sci.* **23**, 745–763
603 (2008).
- 604 49. Swindles, G. T., Blundell, A., Roe, H. M. & Hall, V. A. A 4500-year proxy climate record
605 from peatlands in the North of Ireland: the identification of widespread summer ‘drought
606 phases’? *Quat. Sci. Rev.* **29**, 1577–1589 (2010).
- 607 50. Langdon, P.G., Brown, A.G., Caseldine, C.J., Blockley, S.P. and Stuijts, I. Regional climate
608 change from peat stratigraphy for the mid- to late Holocene in Central Ireland. *Quat. Int.*
609 **268**, 145–155 (2012).
- 610 51. Blundell, A., Holden, J. & Edward Turner, T. Generating multi-proxy Holocene
611 palaeoenvironmental records from blanket peatlands. *Palaeogeogr. Palaeoclimatol.*
612 *Palaeoecol.* **443**, 216–229 (2016).
- 613 52. Turner, T. E., Swindles, G. T. & Roucoux, K. H. Late Holocene ecohydrological and carbon
614 dynamics of a UK raised bog: Impact of human activity and climate change. *Quat. Sci.*
615 *Rev.* **84**, 65–85 (2014).
- 616 53. Lamentowicz, M. *et al.* Reconstructing climate change and ombrotrophic bog development
617 during the last 4000 years in northern Poland using biotic proxies, stable isotopes and
618 trait-based approach. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **418**, 261–277 (2015).
- 619 54. van der Linden, M., Broekens, P., Vickery, E., Charman, D., van Geel, B. Vegetation
620 history and human impact during the last 300 years recorded in a German peat deposit.
621 *Rev. Palaeobot. Palynol.* **152**, 158–175 (2008).
- 622 55. Sjögren, P. & Lamentowicz, M. Human and climatic impact on mires: A case study of les
623 Amburnex mire, Swiss Jura Mountains. *Veg. Hist. Archaeobot.* **17**, 185–197 (2008).

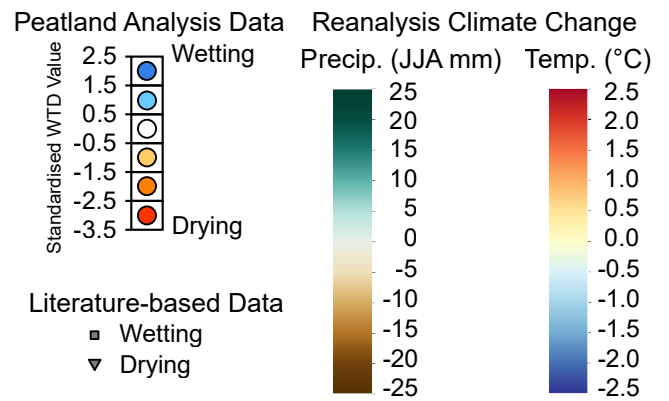
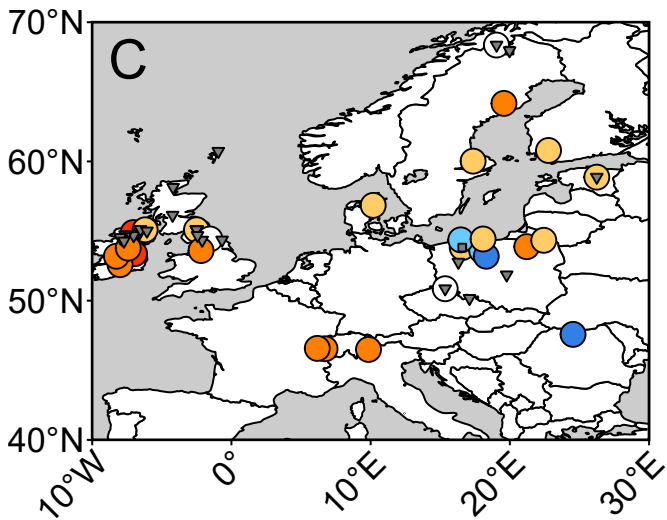
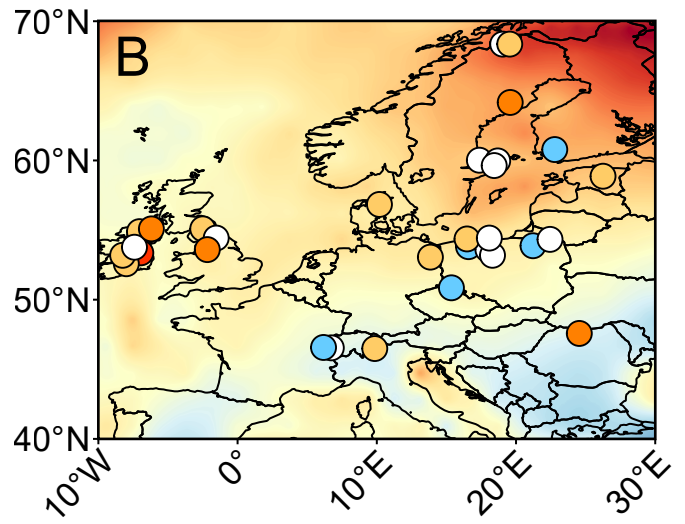
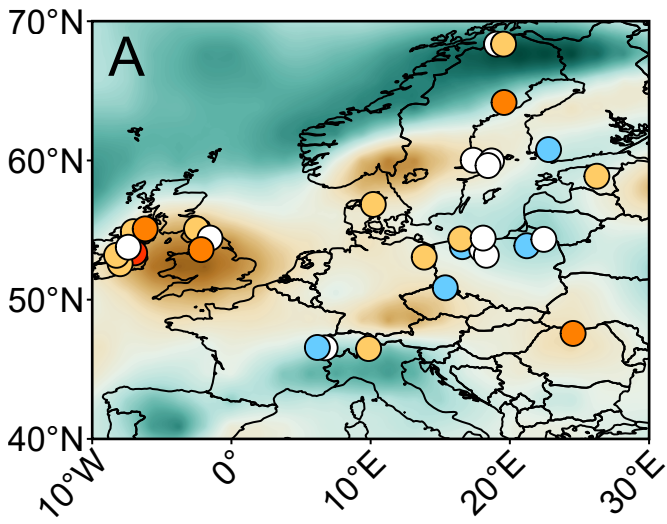
- 624 56. Gałka, M. *et al.* Palaeoenvironmental changes in Central Europe (NE Poland) during the
625 last 6200 years reconstructed from a high-resolution multi-proxy peat archive. *Holocene*
626 **25**, 421–434 (2015).
- 627 57. Kajukalo, K., Fiałkiewicz-Kozieł, B., Gałka, M., Kołaczek, P. & Lamentowicz, M. Abrupt
628 ecological changes in the last 800 years inferred from a mountainous bog using testate
629 amoebae traits and multi-proxy data. *Eur. J. Protistol.* **55**, 165–180 (2016).
- 630 58. Lamentowicz, M., Tobolski, K. & Mitchell, E. A. D. Palaeoecological evidence for
631 anthropogenic acidification of a kettle-hole peatland in northern Poland. *Holocene* **17**,
632 1185–1196 (2007).
- 633 59. Marcisz, K. *et al.* Long-term hydrological dynamics and fire history over the last 2000 years
634 in CE Europe reconstructed from a high-resolution peat archive. *Quat. Sci. Rev.* **112**,
635 138–152 (2015).
- 636 60. van der Knaap, W. O. *et al.* A multi-proxy, high-resolution record of peatland development
637 and its drivers during the last millennium from the subalpine Swiss Alps. *Quat. Sci. Rev.*
638 **30**, 3467–3480 (2011).
- 639 61. Gałka, M. *et al.* Unveiling exceptional Baltic bog ecohydrology, autogenic succession and
640 climate change during the last 2000 years in CE Europe using replicate cores, multi-
641 proxy data and functional traits of testate amoebae. *Quat. Sci. Rev.* **156**, 90–106
642 (2017).
- 643 62. Mitchell, E. A. D. *et al.* The palaeoecological history of the Praz-Rodet bog (Swiss Jura)
644 based on pollen, plant macrofossils and testate amoebae (Protozoa). *Holocene* **11**, 65–
645 80 (2001).

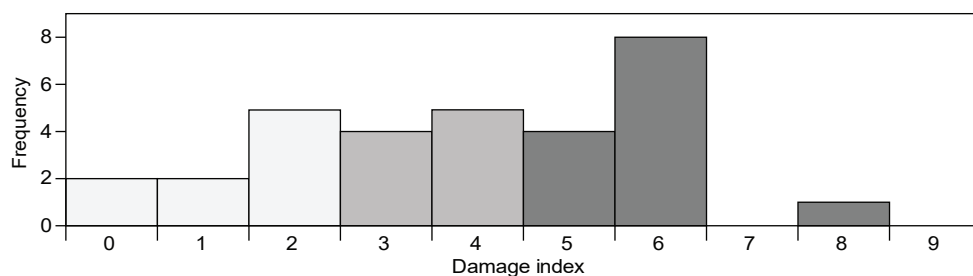
- 646 63. Lamentowicz, M. *et al.* Climate and human induced hydrological change since AD 800 in
647 an ombrotrophic mire in Pomerania (N Poland) tracked by testate amoebae, macro-
648 fossils, pollen and tree rings of pine. *Boreas* **38**, 214–229 (2009).
- 649 64. Lamentowicz, M. *et al.* Climate change and human impact in the southern Baltic during
650 the last millennium reconstructed from an ombrotrophic bog archive. *Studia Quaternaria*
651 **28**, 3–16 (2011).
- 652 65. Feurdean, A. *et al.* Last Millennium hydro-climate variability in Central–Eastern Europe
653 (Northern Carpathians, Romania). *Holocene* **25**, 1179–1192 (2015).
- 654 66. van der Linden, M., Vickery, E., Charman, D., van Geel, B. Effects of human impact and
655 climate change during the last 350 years recorded in a Swedish raised bog deposit.
656 *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **262**, 1–31 (2008).
- 657 67. Schoning, K., Charman, D. J. & Wastegård, S. Reconstructed water tables from two
658 ombrotrophic mires in eastern Sweden compared with instrumental meteorological
659 data. *The Holocene* **15**, 111–118 (2005).
- 660 68. Väliranta, M. *et al.* High-resolution reconstruction of wetness dynamics in a southern
661 boreal raised bog, Finland, during the late Holocene: A quantitative approach. *Holocene*
662 **17**, 1093–1107 (2007).
- 663 69. van der Linden, M., Barke, J., Vickery, E., Charman, D., van Geel, B. Late Holocene human
664 impact and climate change recorded in a north Swedish peat deposit. *Palaeogeogr.*
665 *Palaeoclimatol. Palaeoecol.* **258**, 1–27 (2008).
- 666 70. Mauquoy, D., Yeloff, D., van Geel, B., Charman, D. & Blundell, A. Two decadal resolved
667 records from north-west European peat bogs show rapid climate changes associated
668 with solar variability during the mid-late Holocene. *J. Quat. Sci.* **23**, 745–763 (2008).

- 669 71. Väiliranta, M. *et al.* Reconstructing peatland water tables using transfer functions for plant
670 macrofossils and testate amoebae: A methodological comparison. *Quat. Int.* **268**, 34–
671 43 (2012).
- 672 72. Swindles, G. T. *et al.* The long-term fate of permafrost peatlands under rapid climate
673 warming. *Sci. Rep.* **5**, 17951 (2015).
- 674 73. Gałka, M. *et al.* Vegetation succession, carbon accumulation and hydrological change in
675 subarctic peatlands, Abisko, Northern Sweden. *Permafr. Periglac. Process.* **28**, 589–
676 604 (2017).
- 677

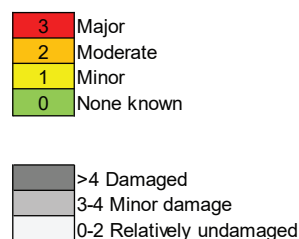








	Cutting	Drainage	Burning	Grazing	Afforestation	Scientific activity	Damage index	Country	Latitude	Longitude
Britain & Ireland										
Ardkilly ^{RB}	2	1	2	1	0	0	6	Ireland	53.3653	-6.9532
Ballyduff ^{RB}	2	2	1	1	0	0	6	Ireland	53.0807	-7.9925
Butterburn ^{RB}	1	1	1	1	2	0	6	England	55.0875	-2.5036
Cloonoolish ^{RB}	2	1	2	1	0	0	6	Ireland	53.1865	-8.2569
Dead Island ^{RB}	1	1	1	1	0	0	4	Ireland	54.8862	-6.5487
Derragh ^{RB}	2	1	1	1	0	0	5	Ireland	53.7667	-7.4083
Keighley ^{BP}	1	1	2	1	0	0	5	England	54.4253	-2.0369
Malham ^{RB}	1	1	1	1	0	0	4	England	54.0964	-2.1750
Slieveanorra ^{RB}	1	1	1	1	2	0	6	Ireland	55.0848	-6.1921
Continental Europe										
Bagno Kusowo ^{RB}	2	2	1	1	2	0	8	Poland	53.8078	16.5872
Barschpfuh ^{RB}	0	0	0	1	2	0	3	Germany	53.0558	13.8494
Combe des Amburnex ^{PF}	1	1	1	2	1	0	6	Switzerland	46.5397	6.2317
Gazwa ^{RB}	1	2	1	1	1	0	6	Poland	53.8726	21.2201
Izery ^{RB}	0	1	1	1	0	0	3	Poland	50.8519	15.3602
Jelenia Wyspa ^{PF}	0	0	0	0	0	0	0	Poland	53.5918	17.9821
Linje ^{PF}	1	2	0	0	0	2	5	Poland	53.1880	18.3098
Mauntschas ^{PF}	0	0	0	1	0	0	1	Switzerland	46.4900	9.8544
Mechacz ^{RB}	0	1	0	0	1	0	2	Poland	54.3314	22.4419
Praz-Rodet ^{RB}	0	0	0	1	0	0	1	Switzerland	46.5667	6.1736
Słowińskie ^{RB}	1	2	0	1	0	0	4	Poland	54.3619	16.4785
Stażki ^{RB}	1	2	0	1	0	0	4	Poland	54.4244	18.0833
Tăul Muced ^{RB}	0	0	0	1	2	0	3	Romania	47.5739	24.5450
Scandinavia & Baltics										
Akerlännä Römossa ^{RB}	1	1	0	0	0	0	2	Sweden	60.0167	17.3667
Åltabergsmossen ^{PF}	0	1	0	1	3	0	5	Sweden	59.9667	18.6833
Gullbergbymossen ^{RB}	1	1	0	1	3	0	6	Sweden	59.6333	18.4333
Kontolanrahka ^{RB}	0	1	0	0	1	0	2	Finland	60.4783	22.4783
Lappmyran ^{PF}	0	0	0	0	0	0	0	Sweden	64.1647	19.5828
Lille Vildmose ^{RB}	1	1	1	1	0	0	4	Denmark	56.8391	10.1896
Männikjärve ^{RB}	0	1	1	0	0	1	3	Estonia	58.8667	26.2500
Stordalen 1 ^{PP}	0	0	0	0	0	2	2	Sweden	68.3568	19.0484
Stordalen 2 ^{PP}	0	0	0	0	0	2	2	Sweden	68.3564	19.0441



RB = Raised bog (ombrotrophic)
 BP = Blanket peatland (ombrotrophic)
 PP = Permafrost plateau (ombrotrophic)
 PF = Poor fen