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► To cite this version:

Mariusz Lamentowicz, Michal Slowiński, Katarzyna Marcisz, Malgorzata Zielińska, Karolina Kaliszan, et al.. Hydrological dynamics and fire history of the last 1300years in western Siberia reconstructed from a high-resolution, ombrotrophic peat archive. *Quaternary Research*, 2015, 84, pp.312-325. 10.1016/j.yqres.2015.09.002 . insu-01240109

HAL Id: insu-01240109

<https://insu.hal.science/insu-01240109v1>

Submitted on 8 Dec 2015

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Hydrological dynamics and fire history of the last 1300 years in western Siberia reconstructed from a high-resolution, ombrotrophic peat archive

Mariusz Lamentowicz^{a,b}, Michał Słowiński^{c,d}, Katarzyna Marcisz^{a,b}, Małgorzata Zielińska^{a,b}, Karolina Kaliszan^a, Elena Lapshina^e, Daniel Gilbert^f, Alexandre Buttler^{f,g,h}, Barbara Fiałkiewicz-Kozielec^b, Vincent E.J. Jasse^{g,h}, Fatima Laggoun-Defargeⁱ, Piotr Kołaczek^b

- ^a Laboratory of Wetland Ecology and Monitoring, Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Dziegielowa 27, PL–61 680 Poznań, Poland
- ^b Department of Biogeography and Paleoecology, Adam Mickiewicz University, Dziegielowa 27, 61-680 Poznań, Poland
- ^c Department of Environmental Resources and Geohazards, Institute of Geography and Spatial Organization, Polish Academy of Sciences, Kopernika 19, 87-100 Toruń, Poland
- ^d GFZ German Research Centre for Geosciences, Section 5.2–Climate Dynamics and Landscape Evolution, Telegrafenberg, D-14473 Potsdam, Germany
- ^e Yugra State University, Chekhova 16, 628012 Khanty-Mansiysk, Russia
- ^f Laboratoire de Chrono-environnement, UMR 6249 CNRS, Université de Franche-Comté, 16 Route de Gray, 25030 Besançon Cedex, France
- ^g Swiss Federal Research Institute-WSL, Community Ecology Research Unit, Station 2, CH-1015 Lausanne, Switzerland
- ^h École Polytechnique Fédérale de Lausanne (EPFL), School of Architecture, Civil and Environmental, Engineering (ENAC), Laboratory of Ecological Systems (ECOS), Station 2, CH-1015 Lausanne, Switzerland
- ⁱ Université d'Orléans, CNRS/INSU, BRGM, ISTO, UMR, 45071 Orléans, France

Abstract

Siberian peatlands provide records of past changes in the continental climate of Eurasia. We analyzed a core from Mukhrino mire in western Siberia to reconstruct environmental change in this region over the last 1300 years. The pollen analysis revealed little variation of local pine-birch forests. A testate amoebae transfer function was used to generate a quantitative water-table reconstruction; pollen, plant macrofossils, and charcoal were analyzed to reconstruct changes in vegetation and fire activity. The study revealed that Mukhrino mire was wet until the Little Ice Age (LIA), when drought was recorded. Dry conditions during the LIA are consistent with other studies from central and eastern Europe, and with the pattern of carbon accumulation across the Northern Hemisphere. A significant increase in fire activity between ca. AD 1975 and 1990 may be associated with the development of the nearby city of Khanty-Mansiysk, as well as with the prevailing positive Arctic Oscillation.

Keywords

- Testate amoebae; Pollen; Macrofossils; Transfer function; Peat; Siberia; Charcoal

43 **Introduction**

44 Northern hemisphere peatlands are important archives of past environmental
45 change and sinks of carbon (Charman, 2002; Loisel et al., 2014). However, climate
46 change and human impacts (e.g. wetland drainage and nutrient deposition) trigger
47 increased emission of this stored carbon into the atmosphere (Payne et al., 2013; Ward
48 et al., 2013). Given these ongoing stressors, there is an urgent need to better understand
49 the various processes involved in peatland dynamics (Dise, 2010; Loisel and Yu, 2013).
50 Paleoenvironmental approaches provide a useful perspective on the present state and
51 long-term history of peatlands (Seddon et al., 2014), and the application of coupled
52 biotic and abiotic proxies enables a detailed reconstruction of climate change, peatland
53 ecosystem development, and changes in the surrounding landscape (Gałka et al., 2013).

54 The last millennium is a critical period for paleoenvironmental study, as it
55 features both climatic variability, such as the Medieval Warm Period (MWP) and the
56 Little Ice Age (LIA), and increasing anthropogenic impacts, leading up to the dramatic
57 increases in pollution and global temperatures observed over the last 200 years (Jones
58 and Mann, 2004). Peatland ecosystems experience various types of anthropogenic and
59 natural disturbances, including wetland drainage, forest management, and fire (Dise,
60 2010). The response of peatlands to disturbance and climate change has been well
61 studied in Europe (Lamentowicz et al., 2008; Lamentowicz et al., 2011; van der Knaap et
62 al., 2011), but the paleoecology of Siberian bogs remains largely unexplored.

63 The hydrological dynamics of Siberian peatlands over the last millennium are of
64 particular interest, and testate amoebae, protists that are abundant in peatlands and
65 sensitive to hydrological conditions, can be used as a reliable proxy for the quantitative
66 reconstruction of past variability in water tables (Blundell et al., 2008; Booth et al.,
67 2008; Hendon and Charman, 2004; Turner et al., 2014). However, while some research
68 has explored the ecology and taxonomy of testate amoebae in Siberian bogs (Bobrov et
69 al., 2013; Kurina et al., 2010; Muller et al., 2009), modern calibration studies have not
70 been carried out in this region. Such calibration data sets for testate amoebae are
71 urgently needed so that this proxy can be utilized for the reconstruction of past
72 hydrological variations in western Siberia.

73

74 Several analyses of Siberian peatlands have focused on carbon accumulation
75 (Beilman et al., 2009; Borren et al., 2004; Lapshina and Plogova, 2011; Lapshina et al.,
76 2001; Turunen et al., 2001), but few peatland studies in this region have generated
77 paleoecological inferences (Bobrov et al., 2013; Kremenetski et al., 2003; Liss et al.,
78 2001; Peregon et al., 2007a; Peregon et al., 2007b; Pitkänen et al., 2002). This is in
79 contrast to work in Northwest Europe and North America, where a large number of
80 high-resolution, multi-proxy studies have been performed in peatlands (Blundell and
81 Barber, 2005; Booth et al., 2006; Kaislahti Tillman et al., 2010; Swindles et al., 2007;
82 Turner et al., 2014). The lack of such studies in Siberia is unfortunate, as Siberian
83 peatlands cover much larger areas than in other parts of Eurasia. Moreover,
84 paleoenvironmental records from Siberian peatlands have the potential to improve our
85 understanding of past changes in both the continental climate of Eurasia and pristine
86 vegetation that no longer exists in Europe (Solomeshch, 2005).

87 Charcoal records from peatlands have been used to reconstruct past fire activity
88 in Europe (Gałka et al., 2013; Sillasoo et al., 2011) and North America (Lavoie and
89 Pellerin, 2007), but only limited research of this type has been carried out in Siberia
90 (Turunen et al., 2001), despite the global importance of peatland fires (Turetsky et al.,
91 2015). It is believed that during the last decade burning has increased in Siberia due to
92 the prevailing positive Arctic Oscillation (Balzter et al., 2005). This relationship can only
93 be verified with a paleoecological approach, since mapped fire data and instrumental
94 weather data cover only short time scales. Over longer intervals, increased fire activity
95 may be related to the prolonged drought events that are recorded by hydrological
96 changes in peatlands. Charcoal data have not been regularly compared to quantitative
97 paleohydrological reconstructions (Tweiten et al., 2009). Nevertheless, the study by
98 Marcisz et al. (2015) showed that a coupled analysis of charcoal and testate amoebae
99 could improve our understanding of past droughts and heat waves overlong temporal
100 scales.

101 In this study we apply three methodological approaches that previously have not
102 been used together in Siberia: (i) a testate amoebae transfer function was used for a
103 quantitative water table reconstruction; (ii) pollen and plant macrofossils were used to
104 reconstruct vegetation history; and (iii) a charcoal record was used to infer past fire

105 activity. The integration of these proxies allows us to explore the response of boreal
106 peatlands, forest communities, and fire regimes to climate change. This research focus
107 aligns well with the PAGES—Asia2k research program (Ahmed et al., 2013). A modern
108 calibration study also improves our understanding of testate amoebae ecology in the
109 boreal region of Siberia.

110

111 **Study site**

112 The Mukhrino mire is located on the eastern bank of the Irtysh River, near the
113 confluence with the Ob River in the middle taiga area of western Siberia, about 20 km
114 from Khanty-Mansiysk (60°54' N, 68°42' E). This region is located in the Boreal climate
115 zone, which corresponds to the Sub-Arctic climate zone of western Europe (Fig. 1). The
116 mean annual temperature is -1.3°C , the coldest month being January, with a mean
117 temperature of -18.9°C ; the warmest month is July, with a mean temperature of 17.1°C .
118 The mean annual precipitation is 553 mm (Kremenetski et al., 2003). In 2009, the
119 Mukhrino Field Station was built at the margin of a giant mire complex. It is managed by
120 the UNESCO Chair of Environmental Dynamics and Climate Change at Yugra State
121 University, Khanty-Mansiysk, Russia (Elger et al., 2012). The Mukhrino mire complex is
122 typical for the West Siberian middle taiga. It is a complex of oligotrophic-raised bogs
123 (*Pinus sylvestris* and *P. sibirica*, *Eriophorum vaginatum*, *Ledum palustre*, *Chamaedaphne*
124 *calyculata*, *Betula nana*, and *Sphagnum fuscum*) patterned with ridge-hollows (*Carex*
125 *limosa*, *Scheuchzeria palustris*, *Sphagnum balticum*, *S. jensenii*, and *S. papillosum*) and
126 oligo-mesotrophic fens (*Carex rostrata*, *Menyanthes trifoliata*, *E. russeolum*, *S. fallax*, *S.*
127 *jensenii*, and *S. majus*) (Filippov and Lapshina, 2008). This area is characterized by the
128 absence of permafrost (Bleuten and Filippov, 2008). The Mukhrino peatland has a peat
129 thickness between 3 m and 4.5 m. Its hydrology is dependent on micro-topography and
130 changes seasonally. During the summer, groundwater in poor fens and hollows is
131 between 5 cm and 20 cm below the moss surface, while in raised bog areas with
132 *Sphagnum* hummocks the water table is 40 cm to 80 cm below the surface (Bleuten and
133 Filippov, 2008).

134

135

136

137 **Materials and methods**

138 *Field sampling*

139 In summer 2012, a 1m peat core was sampled with a long serrated knife and
140 sliced in the field into 1cm samples. Each slice was divided into four subsamples to be
141 used in the four analyses. These peat samples were then packed into plastic bags and
142 transported to the laboratory. They were kept refrigerated until processing.

143 In addition, 65 moss samples and 5 liverworts were collected in the summers of
144 2012 and 2013 in the mire around Mukhrino station for the construction of a calibration
145 data set to be used in the testate amoebae transfer function. Surface samples were taken
146 along a wet-dry gradient from pools to the tops of hummocks. Water table depth was
147 measured once during the sampling campaign, together with pH and conductivity.

148

149 *Chronology and peat accumulation rate*

150 Eleven AMS (Accelerator Mass Spectroscopy) ^{14}C dates were obtained in the
151 Poznań Radiocarbon Laboratory (Poland) in 2013. The samples subjected to dating
152 contained *Sphagnum* stems and leaves and these were carefully cleaned from rootlets to
153 avoid contamination by younger carbon (Table 1). The basis for the chronology of the
154 Mukhrino peat profile is a Bayesian age-depth model constructed using the OxCal v. 4.2
155 program (Bronk Ramsey, 2008), with the application of the IntCal13 (Reimer et al.,
156 2013) and NH1 post-bomb (Hua et al., 2013) atmospheric curves. For the calculation of
157 the model with a 0.5cm resolution, the *P_Sequence* function with parameters $k_0=1$ and
158 $\log_{10}(k/k_0)=0.3$ was applied. The most distinct changes in the peat structural
159 composition and pollen concentration of the profile were introduced using the *Boundary*
160 command. The first boundaries were established at depths of 100 cm and 0 cm (the
161 bottom and top of the model, respectively), followed by 86.5 cm and 50.5 cm (both
162 reflecting rapid changes in pollen concentration and bulk density (cf. Fiałkiewicz-Kozieł
163 et al., 2015)). The age of the top of profile (0 cm) was set as AD 2012.7 (the August
164 2012—the date of the core retrieval). Hereafter, ages are presented as median (μ) values
165 of the modeled ages, and expressed as AD years. The peat accumulation rate (P),

166 expressed as cm/yr, was calculated according to the formula: $P_{\text{depth}} = 1\text{cm} / (\mu_{\text{depth}-0.5\text{cm}} -$
167 $\mu_{\text{depth}+0.5\text{cm}})$.

168

169 ***Pollen and charcoal***

170 Twenty-four samples (1 cm thick, each 2 cm³ in volume) were prepared with a
171 standard preparation procedure with the application of hydrofluoric acid to remove
172 silica, followed by acetolysis (Berglund and Ralska-Jasiewiczowa, 1986). A *Lycopodium*
173 tablet (20,848 spores, produced by the University of Lund) was added to each sample to
174 enable the calculation of pollen concentrations (Stockmarr, 1971). Pollen slides
175 mounted with glycerin were analyzed using a light microscope at 400× and 1000×
176 magnification and counted to a sum of arboreal pollen (AP) >500 grains. Two samples
177 with pollen concentrations <10,000 grains/cm³ were counted to <500 AP grains. Then,
178 on the same slides, microscopic charcoal particles (10-100 μm in length) were counted
179 at 200× magnification, alongwith *Lycopodium* spores, until a sum of 200 was reached
180 (Finsinger and Tinner, 2005; Tinner and Hu, 2003). Pollen grains were identified with
181 the assistance of the modern pollen slide collection of the Institute of Geocology and
182 Geoinformation of Adam Mickiewicz University in Poznań (Poland), as well as available
183 keys and atlases (e.g. Beug, 2004; Moore et al., 1991). Percentages of pollen and spores
184 were calculated relative to the sum of trees, shrubs, and herbs, excluding the pollen of
185 wetland plants and dwarf shrubs. Charcoal accumulation rates (CHAR), expressed as
186 charcoal pieces/cm²/yr, were calculated by multiplying charcoal concentrations (CHAC,
187 pieces/cm³) by the sediment accumulation rate for each analyzed level (Davis and
188 Deevey, 1964).

189

190 ***Testate amoebae***

191 Fossil testate amoebae were analyzed in subsamples taken at 1cm intervals,
192 whereas modern testate amoebae assemblages used to create the new transfer function
193 were examined from surface moss samples. All of these samples were prepared by
194 sieving and back-sieving (Booth et al., 2010). The testate amoebae were analyzed at
195 200–400× magnification, and a minimum of 150 tests per sample were performed
196 whenever possible (Payne and Mitchell, 2008). The identification was performed at the

197 highest possible taxonomical resolution based on the available literature (e.g.
198 Grospietsch, 1958; Mazei and Tsyganov, 2006; Ogden and Hedley, 1980).

199

200 ***Macrofossils***

201 For the analyses of plant macrofossils, contiguous samples of 3 cm³ (96 core
202 samples) were analyzed at varying resolutions (2-cm resolution between 0 cm and 10
203 cm depth; 1-cm resolution below 10 cm depth). Each sample was wet sieved through a
204 0.2 mm mesh and macrofossils were identified under a binocular microscope using
205 several keys (Birks, 2007; Grosse-Brauckmann, 1974, 1992; Laine et al., 2011; Tobolski,
206 2000) and reference specimens collected in Siberia. Additionally, macroscopic charcoal
207 particles were counted wherever present.

208

209 ***Bulk density and ash content***

210 Bulk density (BD; g cm⁻³) and ash content (AC; %) were measured to characterize
211 the physical properties of the peat. BD was determined on the basis of 5-cm³
212 subsamples, which were dried at 105°C for 24 h and then weighed. The dry weight (g)
213 was divided by the fresh sample volume (cm³) (Chambers et al., 2011). AC for 94
214 duplicates was obtained by measuring the LOI₅₅₀, where LOI₅₅₀ is the loss on ignition at
215 550°C as defined by Heiri et al. (2001), and calculating using the equation $AC = 100\% -$
216 LOI_{550} .

217

218 ***Numerical analyses***

219 A Hellinger-transformed testate amoebae community matrix was used as a
220 response matrix (Legendre and Gallagher, 2001). Redundancy analyses (RDA) were
221 employed to relate abiotic variables (water table, pH and conductivity) to biotic
222 communities. The significance of the model, axes, and variables was tested using a
223 Monte Carlo test with 999 permutations. Computations were performed in R 3.0.1
224 (Team, 2013), using the *vegan* package (Oksanen et al., 2011).

225 A quantitative water table reconstruction was developed using the local testate
226 amoebae calibration data set from 68 moss samples collected in the Mukhrino peatland

227 in 2012 and 2013. The training set was based on the relative abundance (percentage of
228 entire community in a sample) and tested using common models in paleoecology, such
229 as partial least squares (PLS), weighted averaging (WA), and weighted averaging partial
230 least squares (WA-PLS) (Juggins and Birks, 2012). Prior to analysis, species present in
231 less than three samples were removed. The best performing model was assessed using
232 RMSEP, R^2 , and maximum bias criteria. Then, the model was used for the quantitative
233 inference of the water table. Sample specific errors of the reconstruction were calculated
234 using bootstrapping (Birks, 1995). Calculations were performed using C2 software
235 (Juggins, 2003).

236

237 **Results and Interpretation**

238 ***Ecology of testate amoebae***

239 A total of 64 testate amoebae taxa species and subspecies from 23 genera were
240 identified at the Mukhrino mire. The most abundant taxa were *Archerella flavum* (20%),
241 *Hyalosphenia papilio* (15%), *Assulina muscorum* (8%), and *Phryganella acropodia* (7%).
242 The Shannon-Weiner diversity index ranged between 1.37-2.59. RDA revealed three
243 clusters of species (Fig. 3A). Species composition shows that *Assulina muscorum*, *A.*
244 *seminulum*, *Trigonopyxis arcula*, *Trinema lineare*, and *Arcella catinus* are correlated with
245 low depth to water table (DWT), whereas *Nebela carinata* is an indicator of wet
246 conditions. *Hyalosphenia papilio* occurs in plots with higher pH and conductivity (EC),
247 and a moderately wet environment. *Cyclopyxis arcelloides*, *Diffflugia bacillifera*, *D.*
248 *bacilliarum*, *D. globulosa*, and *Amphitrema wrightianum* are related to lower pH and
249 conductivity. Other species are located in the middle of the hydrological gradient. The
250 full model explains 19.2% of the variation. DWT is strongly negatively correlated with
251 axis 1 (13.1% variation explained), whereas pH and conductivity are negatively
252 correlated with axis 2 (4.9% variation explained). The overall permutation test (999
253 random permutations) showed that RDA was significant and axes 1 and 2 were highly
254 significant (axis 1— $p < 0.001$, axis 2— $p < 0.002$). DWT was the most significant variable
255 ($p < 0.001$), followed by pH ($p < 0.005$) and conductivity ($p < 0.021$).

256

257 ***Testate amoeba calibration data set***

258 RDA revealed DWT as the most important variable for testate amoeba
259 communities. Consequently, we used this variable for building the transfer function. The
260 calibration tests show that the model performed well and generated acceptable levels of
261 significance (Table 2). For the reconstruction, WA-PLS component 2 was selected, as it
262 had the lowest RMSEP (7.7 cm) and highest R^2 (0.74) (Fig. 3B,C, Table 2). Subsequently,
263 WA-PLS was applied for the quantitative estimation of the past water table dynamics.

264

265 ***Chronology, sediment accumulation rate, bulk density and ash content***

266 Tenout of eleven¹⁴C dates provide a reliable age-depth model spanning the past
267 1300 ± 30 years, with an agreement index (A_{model}) of 82% ($A_{\text{model}}=60\%$ is the lowest
268 critical value; Bronk Ramsey, 2008)(Fig. 2). Date Poz-59502 was excluded; its individual
269 agreement of 0% decreased the A_{model} below the critical value. The peat accumulation
270 rates featured a close correspondence with peat properties. Those peat sections
271 characterized by lower BD and AC have higher accumulation rates compared to sections
272 with higher values for these physical parameters (Fig.2). Significant changes in bulk
273 density were followed by changes in plant composition, as revealed by the macrofossil
274 analysis (Fig. 4). The highest peat accumulation rate values occurred at ca. AD 1997–
275 2012 (1.18–1.41 cm/yr) and ca. AD 1970–1980(0.89–0.9 cm/yr). Slightly lower
276 accumulation occurred at ca. AD 1948–1970 (0.74–0.76 cm/yr) and ca. AD 1980–1997
277 (0.64–0.65 cm/yr). The period between ca. AD 1948 and 2012 featured the lowest BD
278 and AC (0.05–0.09 g/cm³ and 1.3–2.6%, respectively). During the oldest period (ca. AD
279 712–780), peat accumulated at the rate of 0.18–0.23 cm/yr. During that interval, BD was
280 high and fluctuated between 0.09– 0.11 g/cm³, with the exception of a distinct increase
281 to 0.15 g/cm³. AC ranged from 2.3 to 3.9%, with one distinct peak of 4.8% at ca. AD
282 737. The lowest rates of peat accumulation occurred between ca. AD 780 and
283 AD 1948(0.02–0.03 cm/yr). This interval is characterized by the highest values of BD
284 (0.09–0.19 g/cm³) and AC (2.7–6.9%, peaking at ca. AD 1425). These high BD values
285 were strongly related to the presence of *E. vaginatum* tissues and unidentified organic
286 matter (Figs. 2 and 4). Very low rates of peat accumulation may also suggest some
287 discontinuities during that period, and this prompts a very careful interpretation of
288 charcoal accumulation rates (CHAR) for this section.

289

290 **Peatland and forest development**

291 Four proxies, including plant macrofossils (Fig. 4), pollen (Fig.5), testate amoebae
292 (Fig. 6), and charcoal (Fig. 7), were used to reconstruct the main developmental stages of
293 the Mukhrino bog, fire history, and changes in the composition of the surrounding
294 vegetation. These stages were delimited visually to five zones (MU1-5).

295

296 **MU1 (100-86 cm, ca. AD 712-780)**

297 At the beginning of the record, testate amoebae indicate a high water table.
298 *Archerella flavum* dominates, accompanied by *Hyalosphenia papilio*, *Heleopera sphagni*,
299 and *Amphitrema wrightianum*. This assemblage suggests pool *Sphagnum* communities.
300 DWT oscillates around 12 cm (Fig. 6).

301 Macrofossils also indicate a relatively high groundwater table, as *Sphagnum* cf.
302 *balticum* remains from sec. Cuspidata (Fig. 4) are typical for wet parts of the mire (e.g.,
303 carpets and lawns). *Eriophorum vaginatum* also suggests moist conditions (Hölzer,
304 2010).

305 The pollen spectra (*Pinus sylvestris* type, *Pinus sibirica* type, and *Betula*) reflect
306 the presence of pine-birch forests, not only in this zone but in the entire profile,
307 suggesting that vegetation composition varied little over the last 1300 years. Additional
308 arboreal components of the forest include *Populus*, *Salix*, and *Alnus* in moist habitats, as
309 well as “dark coniferous” forest, including *Picea* sect. *Eupicea* and *Abies*. In this zone, the
310 pollen of *Picea* sect. *Eupicea* (probably *P. abies* ssp. *obovata*) reaches its maximum values
311 (2.5–4.5%). However, at the end of this zone (ca. AD 750) declining *Picea* percentages
312 suggest a slight retreat of spruce.

313 CHAR reached 1935 pieces/cm²/yr at ca. AD 730, then decreased. CHAC
314 oscillated between 1945 and 8690 pieces/cm³.

315

316 **MU2 (86-58 cm, ca. AD 780-1882)**

317 In Zone MU2, the testate amoebae record features the disappearance of
318 *Archerella flavum* and *Sphagnum balticum*. Concurrently, percentages of dry indicators,
319 such as *Arcella catinus*, *Trigonopyxis arcula*, and *Phryganella acropodia*, increase. DWT
320 increases gradually from approximately 13 to over 40 cm.

321 Toward the top of this zone, *Sphagnum magellanicum* and *Eriophorum vaginatum*
322 macrofossils indicate gradually decreasing bog surface wetness, and at the same time
323 *Sphagnum cf. balticum* disappears abruptly *Sphagnum magellanicum* has a broad niche,
324 but generally occurs at a water table depth of ca. 24 cm (Hölzer, 2010). Wood and
325 Ericaceae remains appear in this zone, suggesting a lower water table and the
326 development of local shrub communities (Fig. 4).

327 The pollen assemblages in Zone MU2 are similar to those of the previous zone. A
328 minor peak in *Abies* pollen percentages (2.5%) occurs in the older part of MU2, whereas
329 in the younger part of the zone there is a peak in *Corylus* (1.8%; probably *C. avellana*).
330 Such low *Corylus* pollen percentages indicate long-distance transport (cf. Tallantire,
331 2002).

332 This zone is characterized by high CHAR values (56–737 pieces/cm²/yr) and a
333 maximum of CHAC at ca. AD 1505(29,800 pieces/cm³).

334

335 **MU3 (58–40 cm, ca. AD 1882–1970)**

336 *Arcella catinus* percentages decline considerably in Zone MU3, whereas other dry
337 indicators, such as *Trigonopyxis arcula* and *Phyganella acropodia*, remain relative
338 abundant. *Nebela militaris* first becomes abundant in this zone. This species usually
339 indicates a higher water table than *T. arcula* or *P. acropodia*, but the habitat was still
340 quite dry, as indicated by the abundance of *Sphagnum fuscum*. DWT indicates a gradually
341 increasing water table.

342 An abrupt transition between *Sphagnum magellanicum* and *S. fuscum* took
343 place ca. AD 1900; this shift was accompanied by an increase in the percentages of
344 Ericaceae, as well as higher wood remains.

345 In MU3, *Artemisia* reaches its highest percentages in the profile (ca. AD 1882–
346 1966; 3.5–5.5%), possibly reflecting higher landscape openness. Spheroidal

347 carboniferous particles (SCP) appear in this zone, suggesting coal burning in the
348 surrounding area or distant transport from industrialized areas (Swindles et al., 2015).

349 CHAC decreased from 7716 to 616 pieces/cm³, while CHAR ranged between 264
350 and 637 pieces/cm²/year. Macroscopic charcoal (particles >200 µm) at the depth
351 corresponding to ca. AD 1900 indicate local fires (Fig. 4).

352

353 **MU4 (40-22.5 cm, ca. AD 1970-1994)**

354 In Zone MU4 testate amoebae assemblages, *Nebela militaris* continues to indicate
355 a low water table, but the reconstructed water depth shows a gradual increase, reaching
356 a value of approximately 9 cm.

357 At this time the bog was dominated by *Sphagnum fuscum* (as high as 90%).
358 *Polytrichum* first occurs in MU4, suggesting a low water table and hummock
359 development. *Pinus* bark suggests the presence of pines in the hummocky dwarf shrub-
360 *Sphagnum* communities. Ericaceae and wood remains decreased gradually, perhaps
361 reflecting a higher water table.

362 Pollen data in MU4 feature the highest value of *Rubus chamaemorus* (max. 2%);
363 its presence suggests the development of a hummock. SCP values increase after ca. AD
364 1985, likely signaling the increasing industrialization in the region (Swindles et al.,
365 2015). CHAR increased abruptly to 6899 pieces/cm²/yr in ca. AD 1975. At the same time,
366 CHAC was 7726 pieces/cm³.

367

368 **MU5 (22.5-0 cm, ca. AD 1994-2012)**

369 The microfossil record in Zone MU5 suggests a low water table, as indicated by
370 the stable values for *Sphagnum fuscum* and *Polytrichum* remains, although *Hyalosphenia*
371 *elegans*, *H. papilio*, and *Archerella flavum* point to higher habitat wetness. Other species,
372 such as *Nebela militaris*, *Phryganella acropodia*, and *Trigonopyxis arcuata*, decreased in
373 this period.

374 A decrease in the *Rubus chamaemorus* pollen percentages suggests the retreat of
375 hummock habitats from the coring location.

376 SCP records reveal increased coal burning between AD1994 and AD 2000 (max.
377 267 particles/cm²/yr). CHAR and CHAC reached maximum values of 914 pieces/cm²/yr
378 and CHAC of 759 pieces/cm³, respectively, with a decreasing trend toward the top of the
379 zone.

380

381 **Discussion**

382 ***Calibration data set and ecology of testate amoebae***

383 Numerous studies have analyzed testate amoebae ecology in various
384 biogeographical settings in Russia (Bobrov et al., 1999; Bobrov et al., 2002; Bobrov et al.,
385 2003; Bobrov et al., 2013; Mazei and Embulaeva, 2009; Mazei et al., 2009; Mazei et al.,
386 2007; Payne et al., 2012; Tsyganov et al., 2015), but there have been few such studies in
387 Siberian peatlands (Bobrov et al., 2002; Kurina et al., 2010; Mazei and Kabanov, 2008).
388 Our calibration study at Mukhrino mire illustrates the relationship between testate
389 amoebae community composition and several environmental parameters. The
390 redundancy analysis demonstrated the importance of water table depth, which is
391 consistent with findings from other regions (Lamentowicz and Mitchell, 2005; Qin et al.,
392 2013; Tolonen et al., 1994; Van Bellen et al., 2014). Acidity was a less important
393 parameter, perhaps due to the limited range of the sampled habitats. The overall species
394 composition of testate amoebae at Mukhrino mire was not different from those
395 described in Europe or North America (Booth, 2007; Charman et al., 2007). The most
396 abundant species in wet parts of the gradient are the mixotrophic species *Hyalosphenia*
397 *papilio* and *Archerella flavum*, as well as *Nebela carinata*. In *Sphagnum fuscum*
398 hummocks, which were the driest part of the gradient, *Assulina muscorum*, *Trigonopyxis*
399 *arcula*, and *Arcella catinus* dominated.

400 A characteristic feature of this Siberian peatland is that minerotrophic species are
401 absent, as the habitat is purely organic and very acidic. An advantage of our study is that
402 the training set was taken from a pristine bog, large enough to exclude any bordering
403 effect, and then applied to a core also representing pristine conditions. In Europe, in
404 contrast, testate amoebae training sets are often collected from raised bogs that have
405 experienced disturbance, possibly biasing reconstructions derived from them. We think
406 that the new calibration data set from Siberia is important for its inferences concerning

407 paleohydrological dynamics in order to better assess the processes that drive carbon
408 accumulation. In our application of the testate amoebae transfer function to the 1300-
409 year-long core from Mukhrino mire, the composition of the modern communities was
410 similar to that of the fossil assemblages, and thus the transfer function could be used to
411 reconstruct past hydrological conditions with confidence (Juggins and Birks, 2012).

412 *Hydrology, fires, and forests in western Siberia*

413 As the Mukhrino mire record is the first from Siberia in which the paleohydrology
414 of the last millennium has been quantitatively reconstructed based on a modern-
415 calibration training set, we can only relate our findings to other records from other parts
416 of Eurasia. The dry stage at AD 780–1882 in the Mukhrino profile is similar to dry
417 intervals described in other studies from central and eastern Europe (Gałka et al., 2014;
418 Lamentowicz et al., 2009). In the case of Polish sites, however, unstable hydrological
419 conditions rather than permanent drought prevailed (Marcisz et al., 2015). This may
420 suggest that the drought increased in intensity from west to east, being most severe in
421 continental areas like western Siberia. The recent study of Feurdean et al. (2015)
422 provides a regional summary of paleohydrological change in bogs of central and eastern
423 Europe and supports the interpretation of the LIA as dry in eastern sites and
424 contrastingly wet in western sites.

425 Under the continental conditions of western Siberia, the influence of climate on
426 peatlands during the LIA may have been different than was the case in oceanic western
427 Europe. In western Europe, wet conditions may have arisen due to increased summer
428 precipitation and a change in air circulation patterns (Magny et al., 2010; Magny et al.,
429 2008). The growth of alpine glaciers during the LIA is consistent with higher
430 moisture (Holzhauser et al., 2005), and the only existing high-resolution bog record from
431 the eastern Swiss Alps revealed a wet trend during the LIA (van der Knaap et al.,
432 2011). Similarly, the peatlands of the British Isles indicate moist conditions during the
433 LIA (Charman et al., 2006). Changes in temperature may also be involved in the shifts
434 observed in the Mukhrino mire record. Cool temperatures could have limited peat
435 accumulation, generating changes in our proxies that are suggestive of a dry phase. The
436 extensive carbon accumulation database from northern latitudes reveals such a trend
437 during the LIA, with carbon sequestration rate declining during the transition from the
438 MWP to the LIA. This was probably because the LIA featured the combination of lower

439 temperatures and increased cloudiness, suppressing net primary productivity (Charman
440 et al., 2013). However, given the distance between western Europe and Siberia, it may
441 be the case that the climatic causes of dry conditions during the LIA at eastern sites were
442 different from those operating further to the west.

443 Because our study is based on a single core, alternative explanations for the
444 peatland development and peat accumulation changes should be taken into account. The
445 patterns that we have observed could also be related to autogenic development of the
446 peatland itself. Peat vegetation forms various distinct microhabitats in the Mukhrino
447 mire, including very wet pools with open water, flarks overgrown by pines (so-called
448 *ryam* forest, which is typical for raised bogs in western Siberia), and *Sphagnum* lawns.
449 Changes in the water table may have been caused by migration (or alternative
450 development) of those microhabitats on the peatland surface. Moreover, because the
451 core was sampled on the margin of the flark, it is plausible that what we have
452 interpreted as low water table conditions is instead related to the change of surface
453 microhabitats from a pool to the flark (Zobel, 1988). It may be the case that the observed
454 hydrological shifts are related to both internal feedbacks (Swindles et al., 2012) and
455 allogenic forcing (Barber, 1981); additional work at Mukhrino is needed to determine
456 the relative importance of these factors.

457 Fire is a key process that influences the physical and biological structure of boreal
458 forests (Stocks et al., 2001). Wildfires affect all characteristics of the ecosystem,
459 including species composition and diversity, biogeochemical cycles and energy flows,
460 and carbon cycling (van Bellen et al., 2012). Wildfires in boreal ecosystems are highly
461 dependent not only on climatic conditions (such as heat waves or hydrological stress),
462 but also on forest management and the accumulation of woody debris (Gennaretti et al.
463 (2013). Our study revealed a lack of dramatic shifts in vegetation in the Mukhrino area
464 over the last 1300 years. *Pinus sylvestris*, *P. sibirica*, and *Betula* were the dominant taxa,
465 with *Alnus*, *Picea*, *Populus* and *Abies* as additional components (Fig. 5). However, one
466 intriguing change is the decline of *Picea* (probably *Picea abies* ssp. *obovata*) at AD 750, a
467 time of stable hydrological conditions and decreasing fire activity. *Picea abies* is thought
468 to be poorly adapted to fire and drought due to its relatively thin bark and shallow root
469 system (Niklasson et al., 2002; Zackrisson, 1977). Thus, the parallel declines in *Picea* and
470 CHAR in the Mukhrino record are somewhat unexpected, although paleoecological

471 studies from Fennoscandia, where this phenomenon has been widely investigated, also
472 feature unclear findings (Bradshaw et al., 2010). Several studies reported the expansion
473 of *P. abies* during times of increased fire activity (Barnekow et al., 2008; Brown and
474 Giesecke, 2014; Carcaillet et al., 2007; Rosén and Hammarlund, 2007), but others found
475 that fire decreased prior to *P. abies* expansion (Tryterud, 2003; Ohlson et al., 2011).
476 Additional studies spanning longer time scales are needed to better understand the
477 relationship between *P. abies* and fire in Siberia and other boreal regions.

478 The charcoal record from Mukhrino mire is of particular relevance given the
479 significant amount of carbon emitted by burning peatlands (French et al., 2004;
480 Kasischke et al., 2005; Turetsky et al., 2015). The Mukhrino profile featured maximum
481 CHAR values at ca. AD 1975 and two smaller peaks (at ca. AD 1984 and AD 2000),
482 indicating higher fire activity during the last 60 years than at any point in the last
483 millennium (Fig. 7). This shift may be linked with the fast development of the nearby
484 city of Khanty-Mansiysk, which saw fast population growth starting in the 1950s. The
485 finding of oil and gas in the region had a major impact on the development of local
486 industry and caused a rapid influx of population from 18,000 in 1956 to 1,478,000 in
487 2006 (official data from the Khanty-Mansi Autonomous Okrug). This substantial
488 increase in population not only had an impact on the development of the city itself, but
489 also contributed to the pressure on the environment in the region. Human penetration
490 into forests increased, contributing to higher fire activity during recent decades. A key
491 change was the completion of a bridge across the Irtysh River in around 2005, as only a
492 few hunters visited the Mukhrino area prior to this improved access. Moreover, the
493 nearest oil fields, located 100-200 km away, started to develop on the left bank of the
494 Irtysh River only 5-7 years ago. Thus it appears that fires in the Mukhrino area have
495 experienced little human influence during most of the last 1300 years. A similar increase
496 in fire activity over the past 60 years is noticeable in boreal forests of Canada (Stocks et
497 al., 2002).

498 An alternative explanation for the observed increase in fire is that changes in
499 climate may have caused increased burning and extended fire seasons during the last
500 half of the twentieth century in Canada and Siberia (Dale et al., 2001; Kirilenko and
501 Sedjo, 2007; Wotton and Flannigan, 1993). Barichivich et al. (2014) showed that rapid
502 summer warming since the 1980s is a significant driver of increased evapotranspiration,

503 which affects summer drought severity in the northern latitudes. In turn, drier
504 conditions may lead to higher intensity of fires and longer growing seasons in Siberia
505 and other boreal regions (Flannigan et al. (2013).The Arctic Oscillation (AO) also
506 appears to influence the inter-annual variability of fire in Siberia, with higher fire
507 activity during the positive phase of the AO (Balzter et al., 2005, 2007; Sukhinin et al.,
508 2004). Our record provides data that can be related to AO as well as to human activity,
509 however, we need more peat profiles from W Siberia to be sure that this is climatic
510 forcing.

511

512 **Acknowledgments**

513 We acknowledge the support of the International Network for Terrestrial Research and
514 Monitoring in the Arctic INTERACT that funded the project: “Functioning of Siberian
515 mire ecosystems and their response to climate changes” Project acronym: CliMireSiber
516 (PI: Fatima Laggoun-Defarge). We were also supported by RE-FIRE SCIEX project 12.286
517 and grant PSPB-013/2010 from Switzerland through the Swiss Contribution to the
518 enlarged European Union, as well as by grant 2011/01/D/ST10/02579 from the National
519 Centre of Science (NCN).This study is a contribution to the Virtual Institute of Integrated
520 Climate and Landscape Evolution (ICLEA) of the Helmholtz Association. We are grateful
521 to Christopher Bronk Ramsey for giving us important suggestions considering age-depth
522 modeling and to Monika Kołaczek for her useful remarks. Two anonymous reviewers
523 and associate editor Wyatt Osvald are thanked for important comments that helped to
524 improve the manuscript.

525

526 **Captions to figures**

527 Figure 1. Map of Eurasia showing the location of Mukhrino mire and indicating the range
528 of boreal forests.

529 Figure 2. Age-depth model for the Mukhrino mire core with bulk density and ash
530 content. Dates are listed on the left, along the depth scale (see Table 1), each of these are
531 presented with individual agreement of modeled and calibrated date, which is placed in

532 square brackets (for details see Bronk Ramsey (2008)). Abbreviations: Poz – laboratory
533 code of Poznań Radiocarbon Laboratory, TPS – total pollen sum.

534 Figure 3. Result of the redundancy analysis (RDA) of testate amoeba communities (A)
535 and measured environmental variables (pH and depth to the water table – DWT) from
536 modern surface samples collected from Mukhrino mire, (B) observed vs. predicted
537 model, and (C) residuals of the weighted averaging partial least squares model with
538 bootstrap cross validation (WA-PLSboot).

539 Species abbreviations: AMP WRI – *Amphitrema wrightianum*, ARC ARE – *Arcella*
540 *arenaria*, ARC ART – *Arcella artocrea*, ARC BAT – *Arcella bathystoma*, ARC CAT – *Arcella*
541 *catinus*, ARC DIS – *Arcella discoides*, ARC SP – *Arcella* sp., ARCH FLA – *Archerella flavum*,
542 ARC HEM – *Arcella hemisphaerica*, ARGSP – *Argygnia* sp., ASS MUS – *Assulina muscorum*,
543 ASS SCA – *Assulina scandinavica*, ASS SEM – *Assulina seminulum*, BULIND – *Bullinularia*
544 *indica*, CEN AER – *Centropyxis aerophila*, CEN ACU – *Centropyxis aculeata*, CEN ORB –
545 *Centropyxis orbicularis*, CEN CAS – *Centropyxis cassis*, CEN PLA – *Centropyxis platystoma*,
546 CEN SP – *Centropyxis* sp., COR DUB – *Corythion dubium*, CRY OVI – *Cryptodiffugia*
547 *oviformis*, CYC ARC – *Cyclopyxis arcelloides*, CYCKAH – *Cyclopyxis kahli*, CYPSP –
548 *Cyphoderia* sp., CYP AMP – *Cyphoderia ampulla*, DIFBACC – *Diffflugia baccilliarum*,
549 DIFBACI – *Diffflugia bacilifera*, DIFBRE – *Diffflugia brevicola*, DIFGLO – *Diffflugia globulosa*,
550 DIF LAN – *Diffflugia langeniformis*, DIF LEI – *Diffflugia leidyi*, DIF LIM – *Diffflugia limnetica*,
551 DIFOBL – *Diffflugia oblonga*, DIFURC – *Diffflugia urceolata*, DIFSP – *Diffflugia* sp., EUGCIL –
552 *Euglypha ciliata*, EUG COM – *Euglypha compressa*, EUGCOMGLA – *Euglypha compressa*
553 *glabra*, EUG CRI – *Euglypha cristata*, EUG ROT – *Euglypha rotunda*, EUGSTR – *Euglypha*
554 *strigosa*, EUG TUB – *Euglypha tuberculata*, EUGSP – *Euglypha* species, HEL PET –
555 *Heleopera petricola*, HEL SPH – *Heleopera sphagni*, HEL ROS – *Heleopera rosea*, HYAELE –
556 *Hyalosphenia elegans*, HYA PAP – *Hyalosphenia papilio*, NEB CAR – *Nebela carinata*, NEB
557 MIL – *Nebela militaris*, NEB TIN – *Nebela tinctoria*, PHRACR – *Phryganella acropodia*, PHR
558 PAR – *Phryganella paradoxa*, PHYGRI – *Physochila griseola*, PLA SPI – *Placocista spinosa*,
559 PSE GRA – *Pseudodiffflugia gracilis*, SPH LEN – *Sphenoderia lenta*, TRI ARC – *Trigonopyxis*
560 *arcula*, TRI SP – *Trigonopyxis* sp., TRINENC – *Trinema enchelis*, TRIN LIN – *Trinema*
561 *lineare*.

562 Figure 4. Plant macrofossil diagram for Mukhrino mire. Abbreviations: UOM –
563 unidentified organic matter. Non-% variables are provided as absolute values; , 5 times
564 exaggeration is presented as white silhouette.

565 Figure 5. Pollen percentage diagram for Mukhrino mire, 5 times exaggeration is
566 presented as white silhouette. SCP AR - spheroidal carbonaceous particles (SCPs)
567 accumulation rate.

568 Figure 6. Testate amoebae percentage diagram for Mukhrino mire, 5 times exaggeration
569 is presented as white silhouette. WA PLS Comp 2 (weighted averaging partial least
570 squares component 2) – model used for the DWT (depth to the water table) quantitative
571 reconstruction.

572 Figure 7. Summary diagram for Mukhrino mire with comparison of testate amoebae–
573 based water table reconstruction (DWT), charcoal influx (CHAR), and charcoal
574 concentration (CHAC). WA PLS Comp 2 (weighted averaging partial least squares
575 component 2) – model used for the DWT (depth to the water table) quantitative
576 reconstruction.

577

578 **Tables**

579 Table 1. Results of radiocarbon dating from the Mukhrino profile. Abbreviations: Poz –
580 laboratory code of the Poznań Radiocarbon Laboratory (Poland).

581 Table 2. Transfer function performance statistics. The best model is WAPLS Component
582 2.

583

584

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Fig. 1.

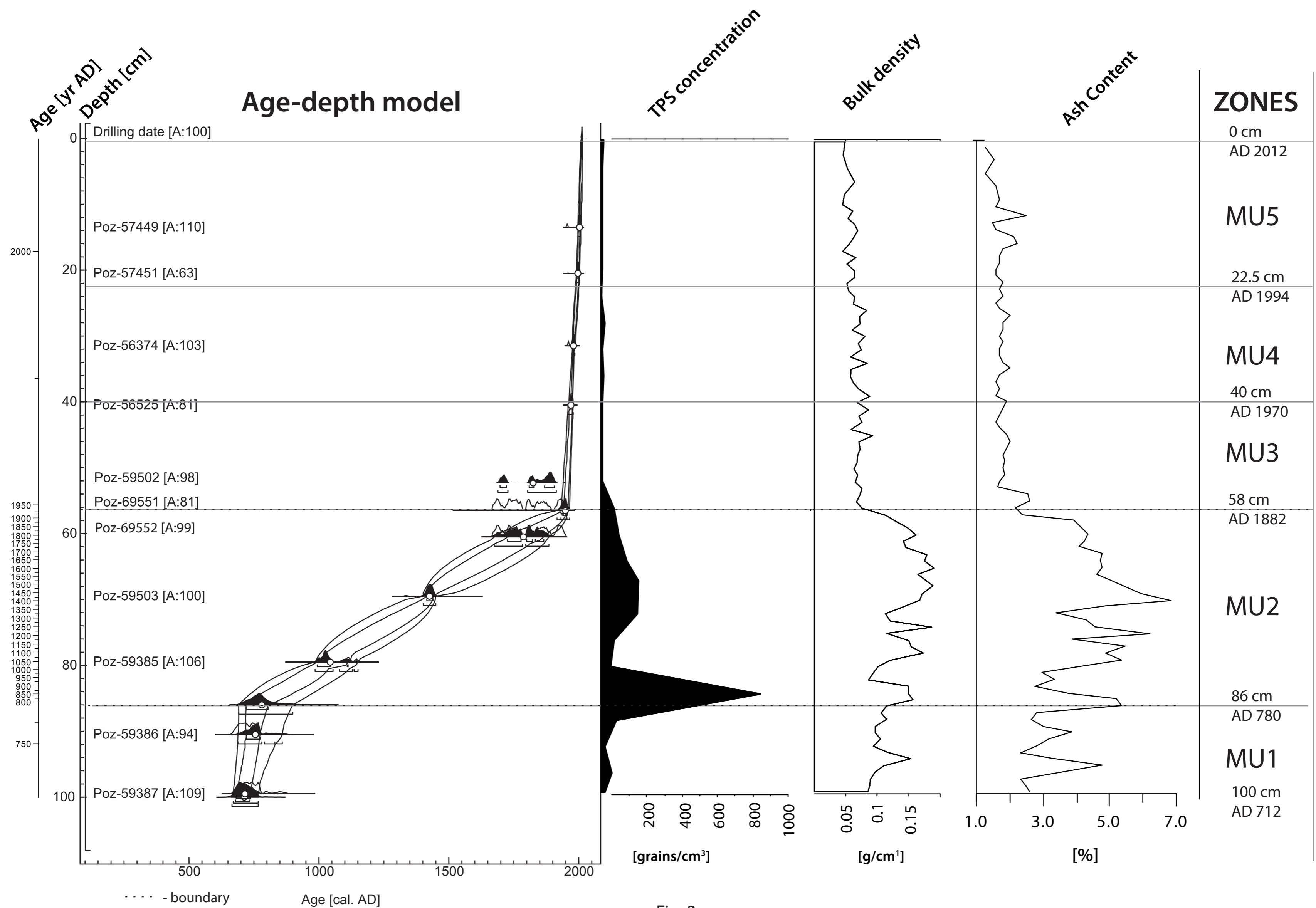


Fig. 2.

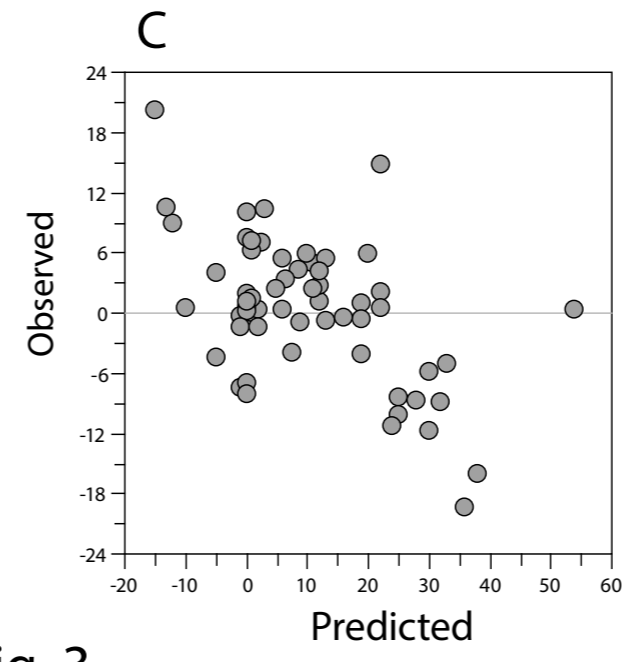
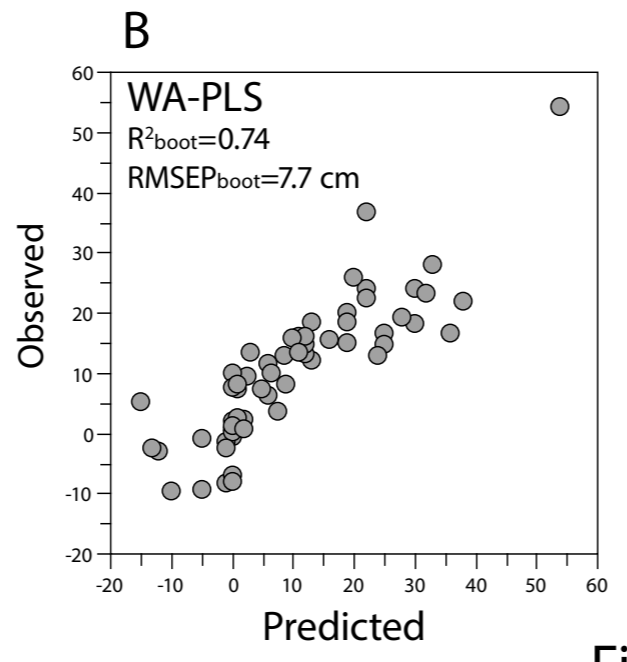
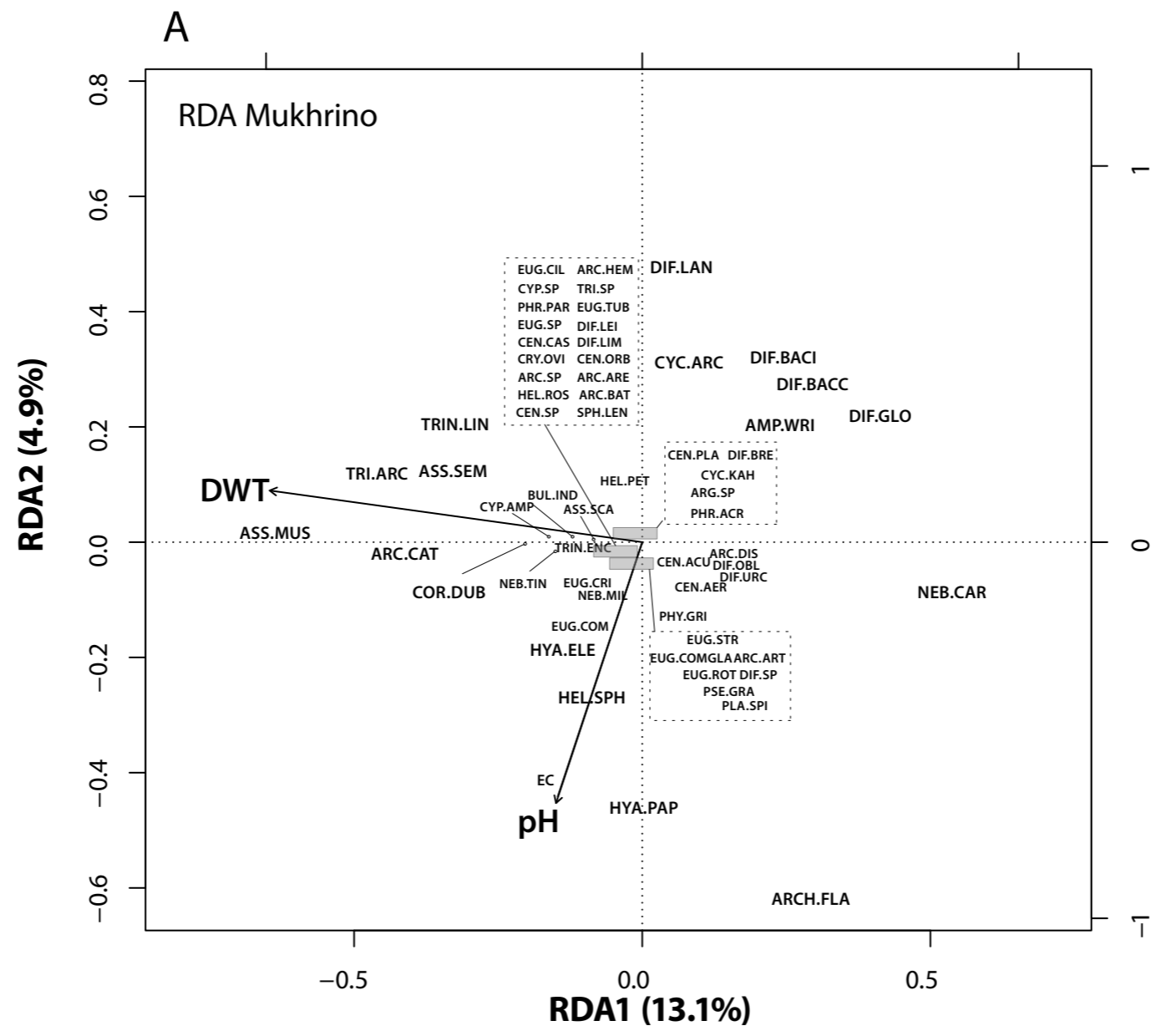


Fig. 3.

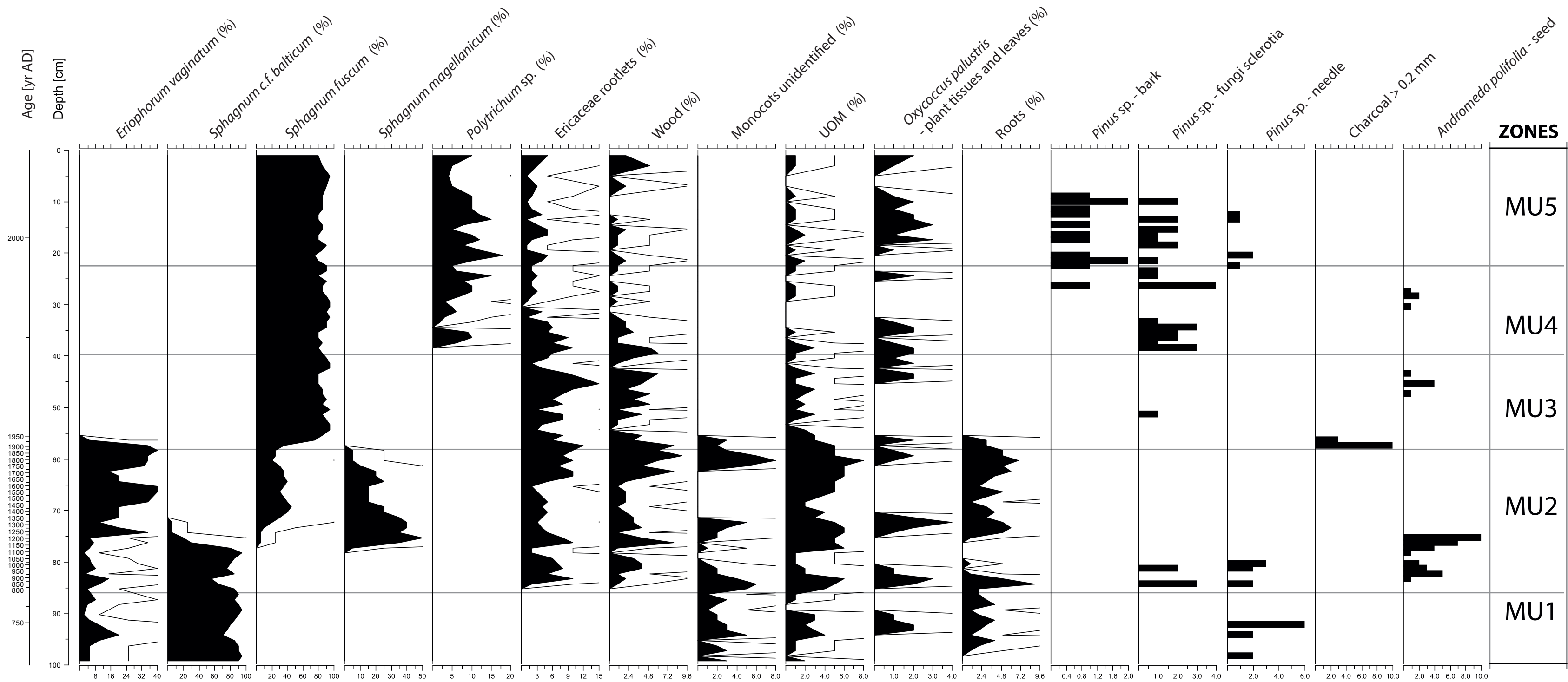


Fig. 4.

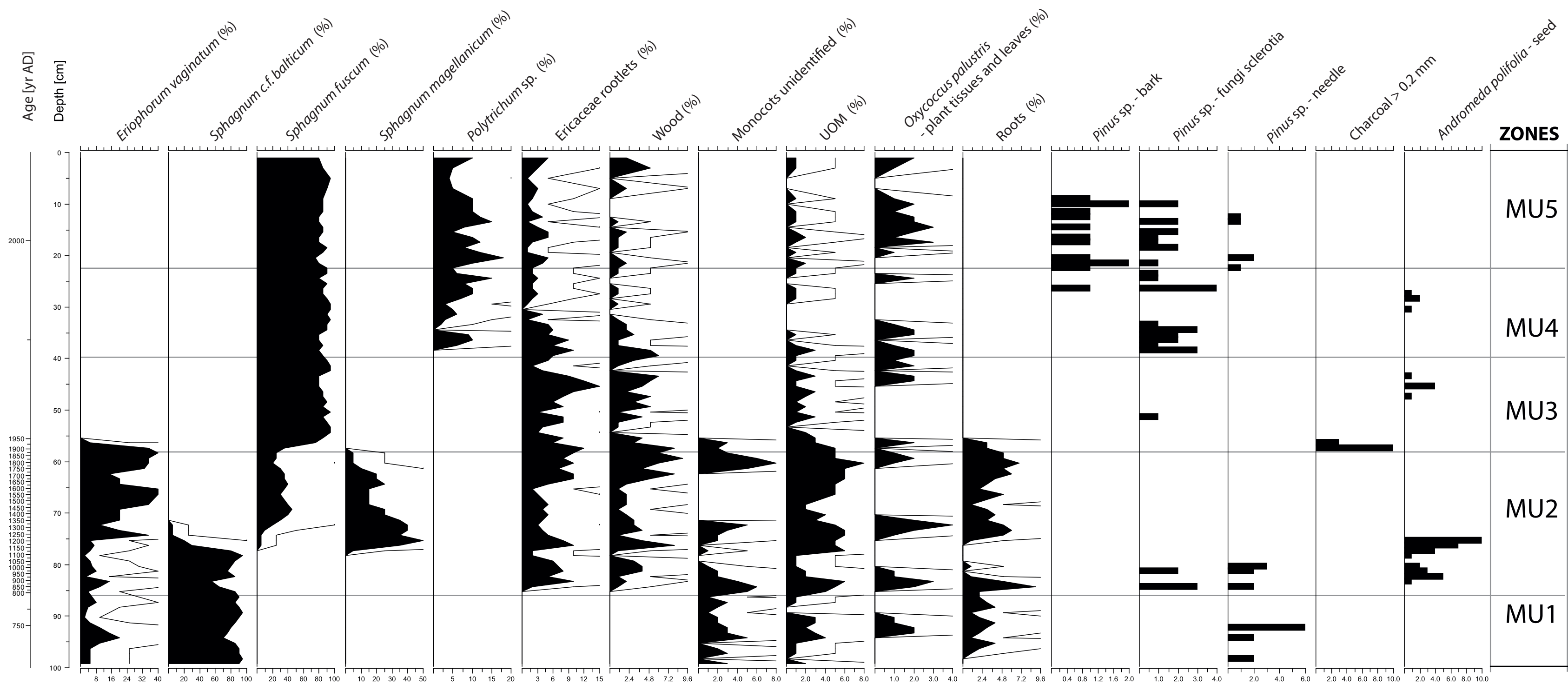


Fig. 4.

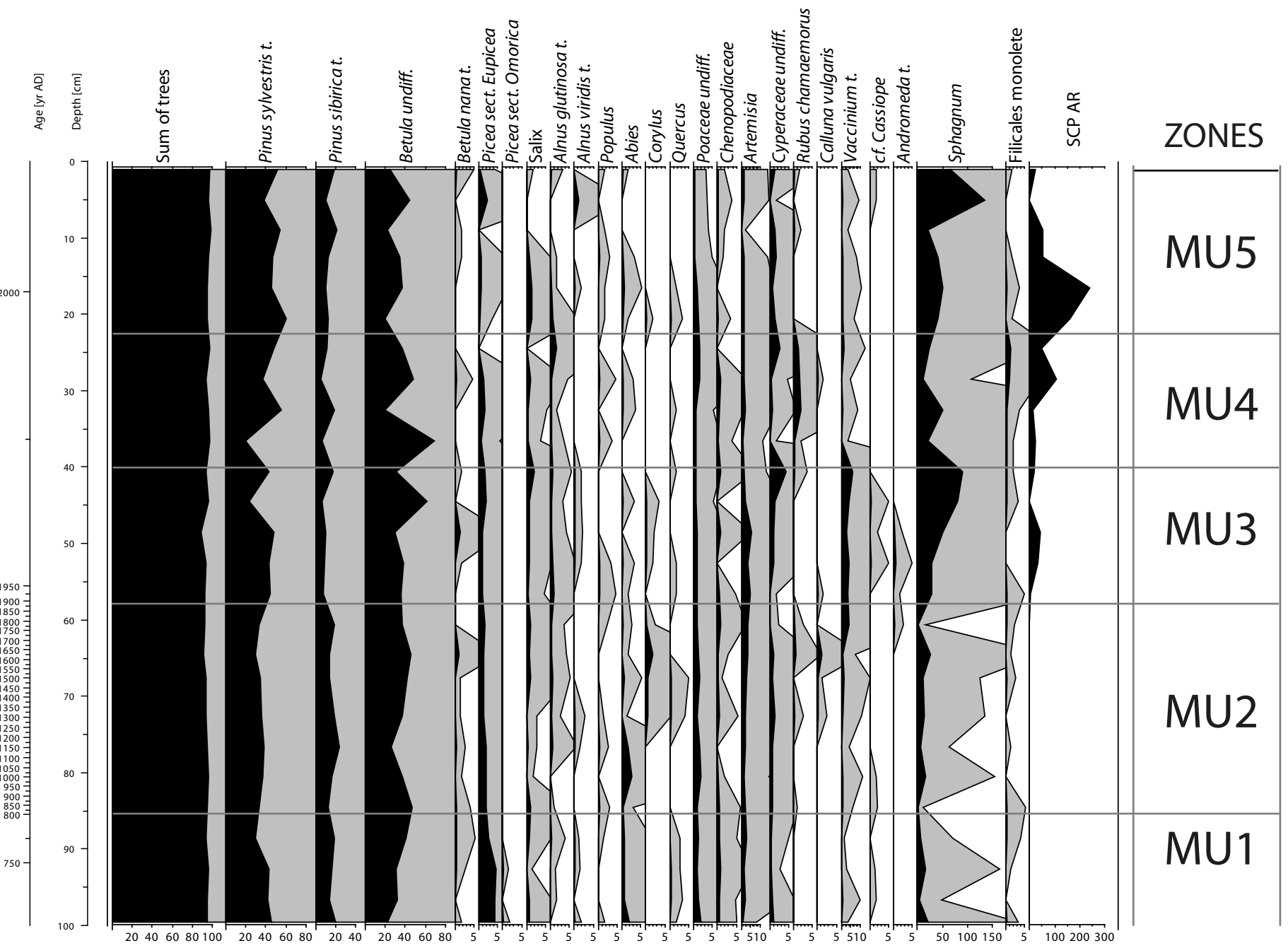


Fig. 5.

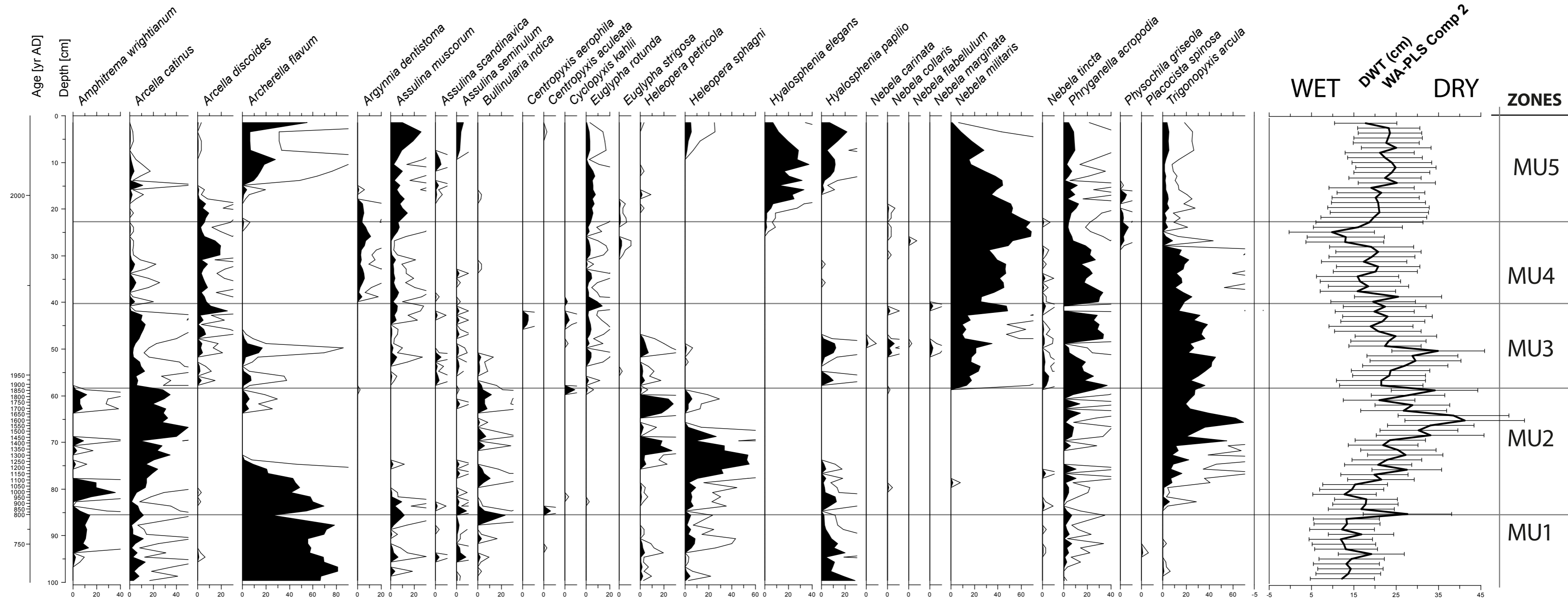


Fig.6.

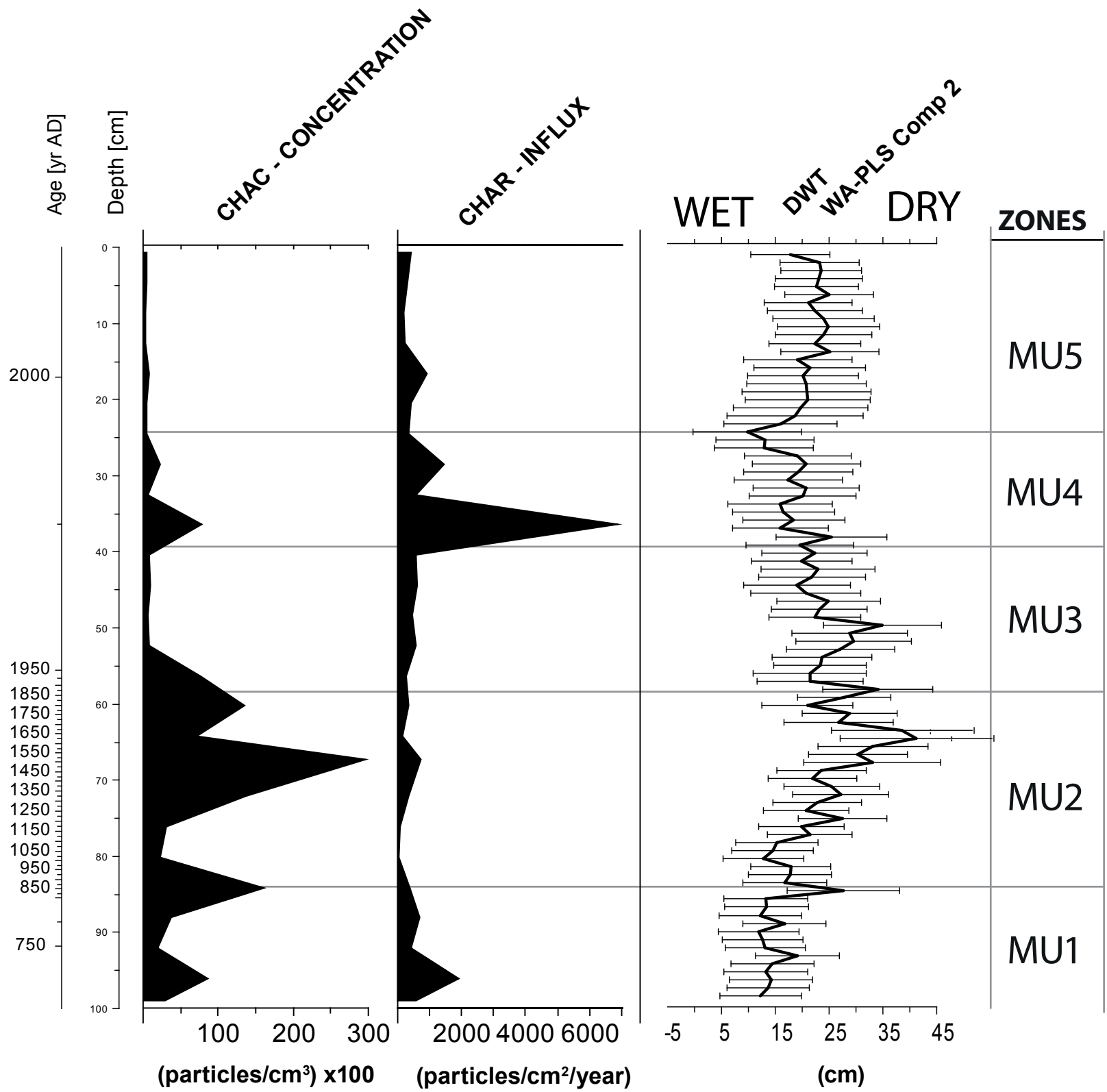


Fig. 7.

Table 1. Results of radiocarbon dating from the Mukhrino profile. Abbreviations: Poz – laboratory code of the Poznań Radiocarbon Laboratory (Poland)

Depth [cm]	Laboratory code	Age [¹⁴ C yr BP] pMC	Calibrated age, 2σ range [AD]; in brackets probability of the range of age	Material selected to date; remarks
13–14	Poz-57449	107.81 ± 0.34 pMC	1956–1957 (3.7%) 2001–2005 (91.7%)	<i>Sphagnum</i> stems
20–21	Poz-57451	110.13 ± 0.33 pMC	1957 (1.3%) 1996–2000 (94.1%)	<i>Sphagnum</i> stems
31–32	Poz-56374	130.35 ± 0.45 pMC	1961–1962 (4.9%) 1978–1980 (90.5%)	<i>Sphagnum</i> stems
40–41	Poz-56525	145.69 ± 0.4 pMC	1962–1963 (7.9%) 1972–1974 (87.5%)	<i>Sphagnum</i> stems
51–52	Poz-59502	70 ± 30	1691–1730 (24.3%) 1810–1924 (71.1%)	<i>Sphagnum</i> stems; excluded from age-depth modelling
56–57	Poz-69551	145 ± 30	1668–1710 (16.3%) 1717–1782 (29.2%) 1797–1891 (33.5%) 1909–1948 (16.4%)	<i>Sphagnum</i> stems
60–61	Poz-69552	140 ± 30	1669–1780 (43.1%) 1798–1891 (36.8%) 1909–1945 (15.5%)	<i>Sphagnum</i> stems
69–70	Poz-59503	495 ± 30	1400–1450	<i>Sphagnum</i> stems
79–80	Poz-59385	995 ± 30	986–1052 (63.8%) 1081–1158 (31.6%)	<i>Sphagnum</i> stems
90–91	Poz-59386	1270 ± 30	663–778 (92.3%) 792–804 (1.3%) 819–821 (0.2%) 842–859 (1.6%)	<i>Sphagnum</i> stems
99–100	Poz-59387	1260 ± 30	669–779 (85.3%) 791–829 (5.9%) 838–865 (4.2%)	<i>Sphagnum</i> stems

Table 2. Transfer function performance statistics. The best model is Weighted Averaging Partial Least Squares Component 2

Model	R2	Ave_Bias	Max_Bias	RMSEP
PLS				
PLS Component 1 for WT	0,51	0,33	40,51	10,34
PLS Component 2 for WT	0,64	0,23	28,31	8,90
PLS Component 3 for WT	0,68	0,07	23,67	8,49
PLS Component 4 for WT	0,67	-0,09	19,52	8,73
PLS Component 5 for WT	0,65	-0,26	16,03	9,47
WAPLS				
WAPLS Component 1 for WT	0,63	0,34	23,21	8,60
WAPLS Component 2 for WT	0,74	-0,28	17,74	7,70
WAPLS Component 3 for WT	0,73	-0,91	15,56	8,43
WAPLS Component 4 for WT	0,72	-1,08	17,39	9,06
WAPLS Component 5 for WT	0,71	-1,15	16,61	9,59
WA				
Weighted averaging model (inverse deshrinking) for WT	0,64	0,28	22,12	8,54
Weighted averaging model (classical deshrinking) for WT	0,65	0,36	16,79	9,18
Weighted averaging model (tolerance downweighted, inverse deshrinking) for WT	0,75	0,62	18,12	7,88
Weighted averaging model (tolerance downweighted, classical deshrinking) for WT	0,75	0,77	16,35	8,11