Reconstructing Early Atlantic to Early Subatlantic peat-forming conditions of the ombrotrophic Misten Bog (eastern Belgium) on the basis of high-resolution analyses of pollen, testate amoebae and geochemistry

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ABSTRACT. A seven metres thick peat bog (Misten, Hautes-Fagnes, Belgium) has been studied at high resolution in order to reconstruct the conditions of peat formation and evolution on the basis of pollen, testate amoebae analysis, and geochemistry. The sampled section of the peat bog corresponds to the most part of the Atlantic period, all the Subboreal period and the earliest Subatlantic period, i.e. a time interval between 7300 cal BP and 2000 cal BP. The identification of tie-points in the pollen assemblages recognized in a previous work (Persch, 1950) performed in the periphery of the same peat-bog, allows accurate correlation of the two sites, 460 cm thickness of peat in the central part corresponding to 230 cm thickness of peat in the periphery. The well constrained dates of the tie-points in the present work provide a more precise chronology of the events identified in Persch's pollen diagram. A comparison of pollen data in both sites demonstrates that, as expected, the *Corylus* pollen rain is proportionally more important and the *Quercetum mixtum* pollen rain proportionally less important in the central area of the peat bog than in the periphery. The study of the testate amoebae in the central part of the peat bog is the major contribution of the present work. A stratigraphically constrained analysis resulted in the identification of five biozones, the zonation being mainly built on the fluctuations observed between *Archerella (Amphitrema) flavum* and *Difflugia pulex*. Three transfer functions have been applied and compared. Coupled with the humification values of each level, it allows a very accurate approach of the water-table level, and hence of local climatic conditions, at the time of the peat formation. Combination of pollen results and testate amoebae zonal subdivisions allows the definition, dating and interpretation of 18 rather short time intervals with an approximate duration of 200 to 300 years each. Our results validate and expand a previously published climate interpretation that combined geochemical data and a preliminary testate amoebae analysis.

KEYWORDS: Misten peat-bog, Hautes-Fagnes, Atlantic, Subboreal, Subatlantic, pollen analysis, testate amoebae, geochemistry.

RÉSUMÉ. Reconstruire les conditions de formation de la tourbe entre l'Atlantique ancien et le Subatlantique ancien dans la tourbière du Misten (Est de la Belgique) sur la base d'analyses à haute résolution du pollen, des thécamoebiens et de la géochimie. La tourbière du Misten (Hautes-Fagnes, Belgique), épaisse de 7 mètres, a été étudiée avec pour objectifs la reconstitution de l'évolution de la tourbière et des conditions de la formation de la tourbe, à partir de l'analyse des grains de pollen et spores, des thécamoebiens, ainsi que de la géochimie. La partie étudiée de la tourbière représente une grande partie de la période Atlantique, l'entièreté de la période Subboréal et le début de la période Subatlantique, soit environ l'intervalle de temps compris entre 7300 cal BP et 2000 cal BP. La reconnaissance d'assemblages polliniques repères définis par un travail plus ancien (Persch, 1950), réalisé dans la périphérie de la même tourbière, permet de corréler étroitement entre eux les deux sites étudiés, 460 cm d'épaisseur dans la partie centrale de la tourbière correspondant à 230 cm d'épaisseur dans la périphérie. La datation précise des repères polliniques dans la séquence qui fait l'objet de ce travail permet d'obtenir une chronologie plus precise des événements reconnus dans le diagramme pollinique de Persch en 1950. La comparaison des données polliniques indique que, comme attendu, la pluie pollinique de *Corylus* est proportionnellement plus importante et celle du *Quercetum mixtum*, moins importante dans la partie centrale de la tourbière qu'à la périphérie de celle-ci. L'analyse des thécamoebiens dans la partie centrale de la tourbière constitue l'apport majeur du présent travail. Cinq biozones ont été identifiées par une analyse contrainte stratigraphiquement. La zonation obtenue est essentiellement basée sur les fluctuations *d'Archerella (Amphitrema) flavum* et *Difflugia pulex*. Trois fonctions de transfert ont été appliquées et comparées. Couplée à la mesure du taux d'humification des niveaux concernés, elles permettent une analyse détaillée du taux d'humidité de la tourbe, et donc des conditions climatiques locales au moment de la formation de cette dernière. L'intégration des résultats polliniques dans la zonation basée sur les thécamoebiens permet de définir, de dater et d'interpréter 18 intervalles de temps relativement courts, de l'ordre de 200 à 300 ans chacun. Nos résultats valident et complètent une première interprétation climatique combinant analyse géochimique et données préliminaires acquises sur les thécamoebiens.

MOTS CLES: Tourbière du Misten, Hautes-Fagnes, Atlantique, Subboréal, Subatlantique, analyse pollinique, thécamoebiens, géochimie.

1. Introduction

Peatlands offer unique opportunities for high-resolution climate reconstruction. In the Hautes-Fagnes Plateau (Eastern Belgium), culminating at 694 m a.s.l., peatlands cover 3750 ha, including about 1000 ha of raised bogs protected since 1957 in a state nature reserve. The topographic conditions for areas where peat accumulates are given by Wastiaux et al. (2000). A general description of the Belgian peatland vegetation, in particular those of the Hautes-Fagnes, is provided by Frankard et al. (1998).

The Hautes-Fagnes are situated in a key position among European peat deposits, under both oceanic and continental influences (Streel, 1959). Previous studies of the Hautes-Fagnes peat archives using palynology have already demonstrated their potential for reconstructing regional vegetation changes (e.g. Persch, 1950; Dricot, 1960; Damblon, 1978, 1994).

The saddle-raised Misten Bog (50°33′50′′N, 06°09′50′′E, 620 m a.s.l.), located in the Hautes-Fagnes Plateau, contains some of the deepest peat deposits of this area, with more than 7 m of peat in its centre (Fig. 1). The bog has been cut along its outer rim, mainly in the north-eastern and south-eastern edges. Misten Bog sits on an isolated plateau that prevents the bog from receiving lateral mineral inputs, e.g. through small streams. The vegetation on the site is mainly composed of *Sphagnum ssp* and *Polytrichum strictum,* built up into low hummocks, structured by *Eriophorum vaginatum*. Rare hollows are dominated by
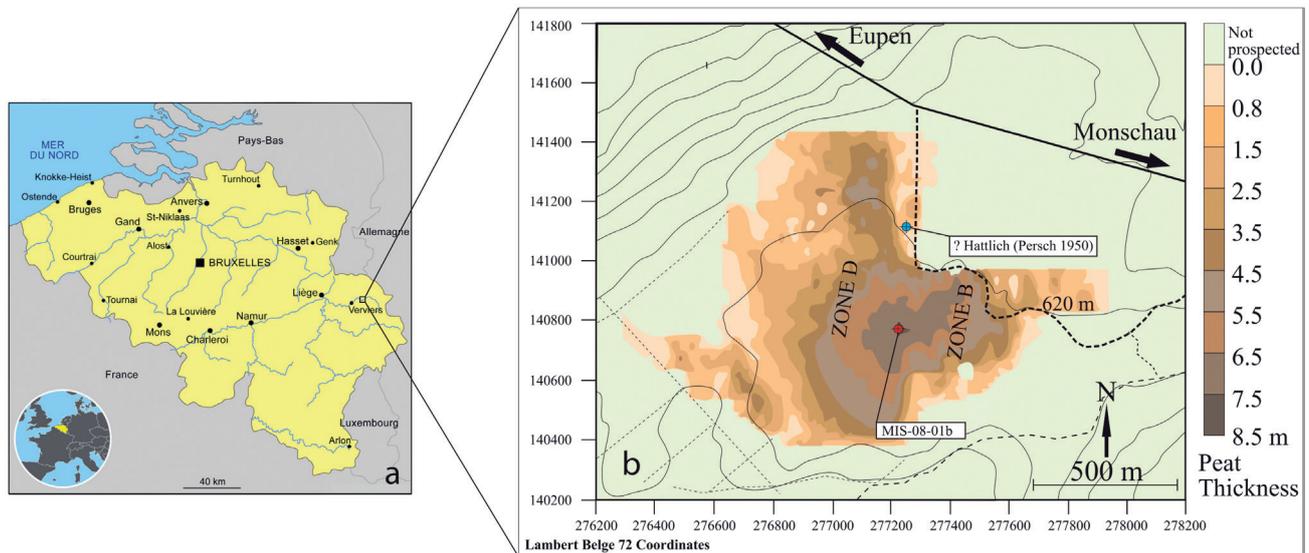
Figure 1. (a) Location of the Misten peat bog in eastern Belgium, and (b) map of the Misten peat bog, modified from Allan et al. (2013). The colourings indicate the peat thickness as deduced from surface radar prospection (Wastiaux, 2002). The red dot shows the location of the MIS-08-01b core (this study), and the blue dot the probable location of the Hattlich pollen diagram of Persch (1950).

Eriophorum angustifolium, Narthecium ossifragum and a few *Rhynchospora alba*. Hummocks are currently hidden by *Erica tetralix, Calluna vulgaris* and a few *Vaccinium spp.* shrubs, reflecting a recent drying trend (Streel et al., 2014). The site is also surrounded by *Molinia coerulea.*

Schwickerath (1937) and Persch (1950) carried out pollen analyses (at 12 cm and at 5 cm intervals respectively) from marginal sections of the Misten bog. Persch (1950) used Overbeck & Schneider's (1938) classification of Holocene vegetation landscapes to subdivide the pollen sequence (from their Boreal Subzone VII to Subatlantic Subzone XI). Additionally, he introduced a quantitative approach based on *Corylus* abundance (from their Boreal Subzone VII to Subboreal Subzone IX) defining 4 maxima CI, CII, CIII and CIV as well as on *Fagus* abundance (within their Subzone XI) defining 4 further maxima FI, FII, FIII and FIV. He suggested that these fluctuations in *Corylus* and *Fagus* abundance could be used to date and correlate between different regional pollen diagrams. This approach was subsequently used in the Hautes-Fagnes area by several authors (e.g. Dricot, 1960; Damblon, 1978; Streel et al., 2014).

2. Objectives of the study

The main objectives of the present work are:
(i) to provide a palynological study at high resolution of the deepest area of the Misten peat bog (Hautes-Fagnes, Belgium);
(ii) to compare our results with those obtained by Persch (1950) at the periphery of the Misten peat bog;

(iii) to analyse and characterize the testate amoebae assemblages of the Misten peat bog;
(iv) to test the application of three transfer functions, to interpret the variations of the testate amoebae in terms of wetness characteristics at the surface of the peat bog central area;
(v) to integrate results based on pollen and testate amoebae in order to propose a detailed biostratigraphy of the site.

3. Materials and methods

3.1. Sampling, radiocarbon dating and chronology

In February 2008, a peat core (MIS-08-01, 755 cm long) was collected from the central part of the Misten site (Fig. 1). The top 100 cm were sampled by using a titanium Wardenaar corer (Wardenaar, 1987) from the University of Heidelberg. Results on palynology and testate amoebae were published by Streel et al. (2014). The lower part (MIS-08-01b), sometimes named below the "long core", was cored with a Belorussian corer (Belokopytov & Veresnevich, 1955) and reached a depth of 7.5 m (Allan et al., 2013).

Radiocarbon ages were obtained on macrofossil samples (stems, branches or leaves of plant material) extracted under a binocular microscope. Nine samples were prepared at the GADAM Centre (Silesian University of Technology, Gliwice, Poland) according to the protocol described by Piotrowska et al. (2011) and Piotrowska (2013). Radiocarbon dates (n = 15) obtained by acceleration mass spectrometry (AMS) were processed using the "Bacon" software (Blaauw & Christen,

Table 1. Results of 14C dating for the MIS-08-01b peat core. Independently calibrated age ranges were obtained with the OxCal4 program (Bronk Ramsey, 2009), and the modelled ages were obtained after "Bacon" calculations (Blaauw & Christen, 2011). In both cases, the IntCal09 calibration curve was used (Reimer et al., 2009). See Allan et al. (2013, table 2). We have included data from Reimer et al. (2013, IntCal13) for comparison purpose although all these data are practically similar.

Sample Name	Laboratory	Depth (cm)	Age 14C BP	Modelled age range calBP (Intcal09) (94.5% probability)	Modelled age range calBP (Intcal13) (94.5% probability)
MIS-01/245	GdA-2230	286.17	2980±25	3075–3255	3070–3226
MIS-01/282	GdA-2231	340.77	3470±20	3650–3830	3649–3829
MIS-01/334	GdA-2232	408.03	3770±30	4000–4240	4000–4239
MIS-01/381	GdA-2233	474.25	4300±30	4830–4960	4829–4960
MIS-01/450	GdA-2234	568.80	5050±20	5740–5895	5739–5894
MIS-01/476	GdA-2235	603.00	5210±30	5910–6095	5909–6095
MIS-01/517	GdA-2236	658.80	5680±20	6410–6495	6409–6495
MIS-01/541	GdA-2237	690.00	5940±20	6680–6840	6679–6843
MIS-01/589	GdA-2238	741.38	6235±20	7025–7250	7027–7250

2011) to establish an age–depth model as well as an age range for each slice of peat. The curve IntCal09 was used for calibration (Reimer et al., 2009; see also Reimer et al., 2013). The age–depth model was calculated for 600 cm of the studied peat core. The accumulation rate was set as a gamma distribution with a mean of 10 yr cm^{-1}. The accumulation variability was set with a beta distribution with strength of 4 and a mean of 0.7 (Allan et al., 2013).

The ranges of calibrated radiocarbon ages of dated peat layers involved in the present work (MIS-08-01b) are presented in Table 1. The age–depth model covering the period from ca. 7300 cal BP to 2000 cal BP was published by Allan et al. (2013). The age model reveals a relatively constant peat accumulation rate, with an average value of ca. 0.11 mm yr^{-1}. Consequently, the analysis of 1 cm thick sample represents ca. 9 years.

3.2. Pollen analysis

352 samples with known volume and weight were treated with HCl (10%) and submitted to KOH (10%). The residues were dissolved in 96% acetic acid and acetolysed (Faegri & Iversen, 1989). After centrifugation, the solutions were filtered through 200 μm and 12 μm mesh shieves. The isolated spores and pollen grains were then mounted in glycerin and counted up to a minimum of 300 (mean: 353) arboreal pollen grains excluding herbaceous pollen, bryophyte and fern spores. Pollen identification was aided by Moore et al. (1991), Reille (1992, 1995, 1998) and Beug (2004). Counting was performed for 352 samples at 1.5 centimetre intervals. TILIA and TILIA GRAPH were used for diagrams conception based on percentages (Grimm, 1990). A TILIA diagram and a stratigraphically constrained cluster analysis by incremental sum of squares method were generated (Grimm, 1987; CONISS in Fig. 2).

3.3. Testate amoebae analysis

3.3.1. Data treatment

352 samples for testate amoebae analysis were prepared following the recommendations of Booth et al. (2010). Testate amoebae were identified and quantified to the lowest possible taxonomic level according to the dichotomous key proposed by Charman et al. (2000). At least 100 individual tests were counted (Payne &

Mitchell, 2009), but this total was not reached for some samples. The relative frequency of each taxon was calculated and converted into a percentage of the total amount of the population. Samples with total count below the statistical threshold of 100 were not excluded from the dataset. Although this introduces statistical bias, it was chosen in order to avoid gaps in the diagrams

The diagram of the long core was drawn with the software Tilia (v.1.7.16, Copyright © 1991-2011 Eric C. Grimm). The taxa were clustered in three groups (1st = black, 2nd = medium grey and 3rd = light grey) based on their overall weight (%), calculated for all the profile, and also sorted, from the left to the right, by alphabetical order. A biozonation scheme was applied to the diagrams to facilitate the qualitative description and interpretation. Data were transferred in a spreadsheet with minimum value criteria of 7. Consequently, assemblage biozones were based on taxa that have the highest relative frequency. A stratigraphically constrained cluster analysis by the method of incremental sum of squares (CONISS, Grimm, 1987), (Tilia v1.7.16), with square-root transformation (Edwards & Cavalli-Sforza's chord distance) was applied.

#### 3.3.2. Calculation of the Shannon-Weaver Diversity index

The Shannon-Weaver Diversity index (Shannon & Weaver, 1963), was calculated for the long section and defined as (Beisel et al., 2003):

$$H' = -\sum_{i=1}^{S} \left(\frac{q_i}{Q}\right) \ln \left(\frac{q_i}{Q}\right)$$

where H' = code of the usual name (Shannon-Weaver Diversity index) in accordance with Smith & Wilson (1996), S = number of taxa in the community or species richness, and $\frac{q_i}{Q}$ = relative frequency of the ith taxon in the whole community, with Q = the total number of tests (all individuals for one level).

3.3.3. Transfer functions

Three transfer functions (Charman et al.; 2007 as described by Sillasoo et al., 2007; Lamentowicz et al., 2008; Amesbury et al., 2016) have been used to assign hydroclimatic conditions to the biozones identified with the CONISS analysis.
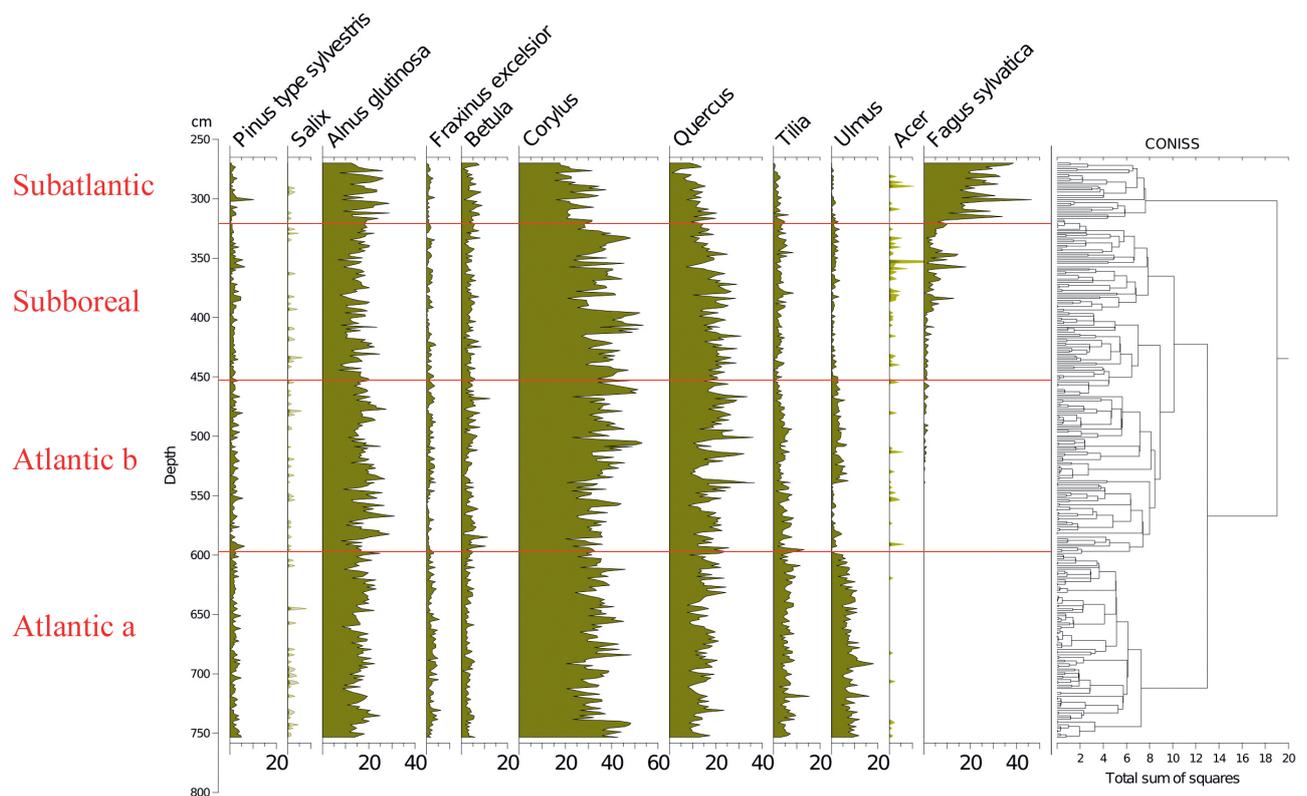
Figure 2. Evolution of the tree pollen rain on the Misten peat bog from the Atlantic up to the base of the Subatlantic. Silhouettes of *Acer* and *Salix* show 5x exaggeration of their percentage values.

4. Results and discussion

4.1. Pollen analyses

4.1.1. High resolution palynological analysis of the MIS-08-01b core

Figure 2 (Kamran et al., 2016) shows the evolution of the arboreal (or tree) pollen rain on the Misten peat bog between the Atlantic and the base of the Subatlantic. The studied section begins at the depth of 753.5 cm in the Atlantic period and continues to the depth of 270 cm in the early Subatlantic period. In this time span, the tree pollen percentages were high (94-100%), suggesting highly closed forest conditions in the surroundings, mainly consisting of trees such as *Alnus glutinosa, Corylus avellana, Quercus ssp.* and *Fagus sylvatica*. Four zones could be distinguished in the studied section including Atlantic a, Atlantic b, Subboreal and Subatlantic. In the Atlantic a/Atlantic b zone-boundary, located at the depth of 600 cm, the percentage of *Tilia* pollen exceeds that of *Ulmus*. The *Ulmus* decline in the Atlantic b/Subboreal boundary, at the depth of 450 cm, is possibly interpreted as resulting from human impact on the landscape (Troels-Smith, 1960; Turner, 1962; Iversen, 1973; Peglar, 1993; Peglar & Birks, 1993; Hannon et al., 2000). *Fagus sylvatica* appears in considerable proportion just from the beginning of the Subboreal and shows a sharp increase at the start of the Subatlantic period. Non arboreal pollen diagram (Fig. 3; Kamran et al., 2016) shows less than one percent of diverse taxa where one can notice the first occurrence of *Plantago lanceolata* type starting in the upper part of the Atlantic b period and the more accentuated presence (around one percent) of *Poaceae* in the upper part of the Subboreal period. These probable anthropogenic markers are present in low quantities. This is probably the result of long transport by the wind and does not presumably indicate any evidence of anthropic activity in the proximal surrounding of the peat bog.

4.1.2. Comparison between MIS-08-01b and Hattlich diagrams

a) General considerations
We do not know exactly where Persch (1950) collected his samples, but he writes they come from about 500 m south of the Eupen-Monschau road, at 620 m a.s.l., which means more or less at the intersection of the track giving access to the Misten, the old trace of the cutting front and the related level curve (Fig. 1). We think that the Hattlich material came probably from a cutting trench and not from a core. Indeed, Persch's (1950) diagram stops more or less at 1800 AD suggesting, by comparison with the Misten area (Streel et al., 2014), that about 20 cm of superficial peat was inappropriate for pollen analysis, as often noted at the top of peat cutting. Moreover, Hattlich is 4 m deep, which corresponds to the depth of the peat bog at its periphery (see Fig. 1). Peat where MIS-08-01b was taken is more than 7 m thick, although covering a smaller time span as will be demonstrated later. That gives us a chance to compare peat growth under slightly different ecological conditions, the two studied areas being separated by a few hundred metres.

Percentages of taxa in the Hattlich diagram were calculated, as was often done during the last century, on the sum of Arboreal Pollen (AP) without *Corylus*. This last taxon can therefore reach very high percentages as shown in the Boreal period (VII) (a maximum of 287%, Fig. 4). To compare MIS-08-01b with the published Hattlich diagram, the sum of AP without *Corylus* was recalculated. The taxa taken into consideration by Persch (1950) for correlation purpose are those used in the Overbeck & Schneider's (1938) zonation (Table 2), i.e. *Betula, Corylus, Fagus*, the *Quercetum mixtum* (sum of *Quercus, Fraxinus, Tilia* and *Ulmus*) and *Pinus*. Persch obviously added *Alnus* to emphasize the start of the "*Betula* peat" (his "Birkenbruchtorf"; Fig. 4) in a rather wet environment of the Boreal *Corylus/Ulmus* forest. The base of the MIS-08-01b profile did not reach such environment, perhaps because the drilling system could not penetrate the woody (?) substrate. The base of the profile reached the minerotrophic part of the peat bog (Salpeteur, 2011). Pollen rain of *Alnus, Betula* and *Pinus* was not used for correlation in the present paper. On Figure 4c, Pinus, always less than 5%, is even omitted. We emphasize the ratio *Tilia* versus *Ulmus* (Fig. 4a), a useful character in the lower half of both diagrams, and the percentages of *Corylus* (Fig. 4b), more useful in the upper half. The *Fagus/Quercetum mixtum* (= QM) competition (Fig. 4c) is essential to show the change of the climate near the top of the diagrams.

b) Comparison of available ages of selected tie-points in four localities
We selected nine tie-points recognizable in both diagrams (Table 3). They are retained from the Persch's Hattlich diagram
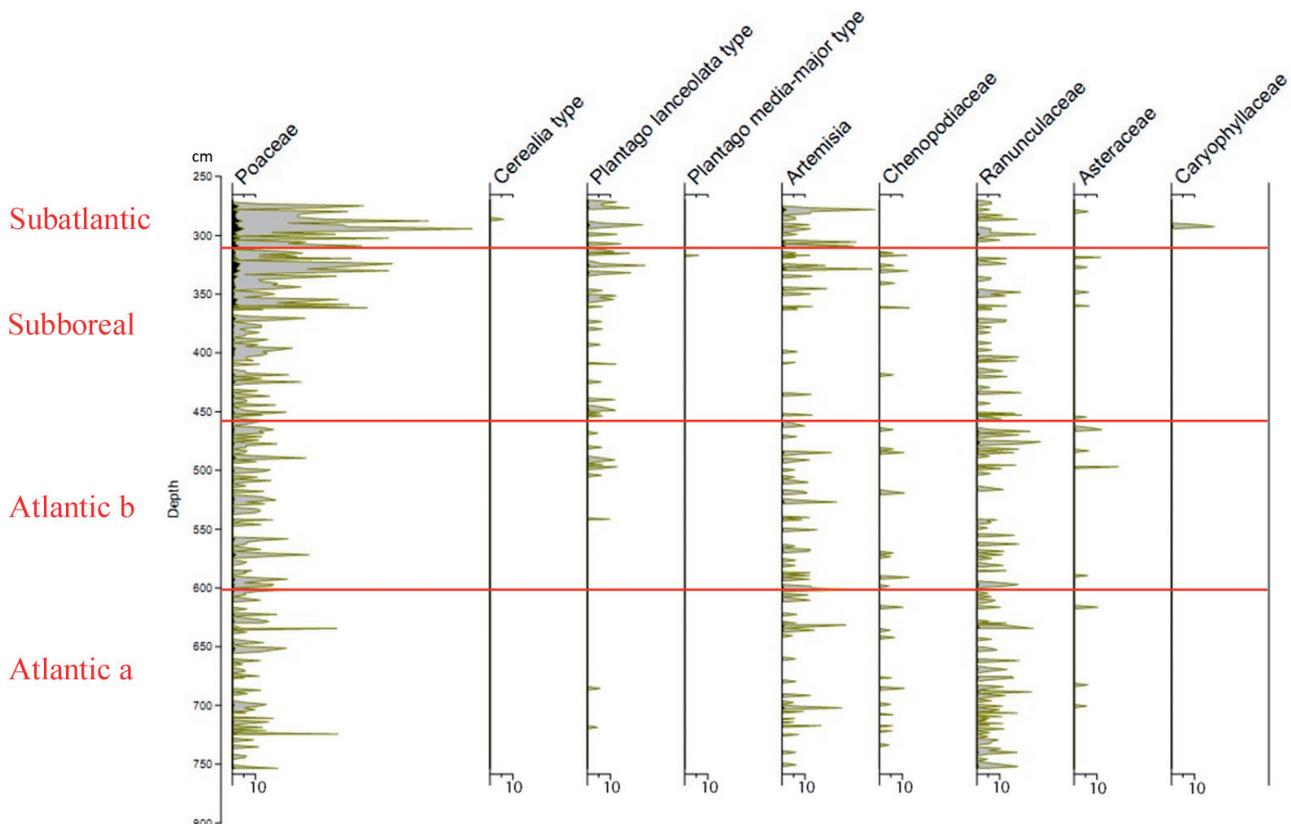
Figure 3. Non arboreal pollen diagram showing the taxa represented by less than one percent (from Kamran et al., 2016). Silhouettes show 20x exaggeration of their percentage values.
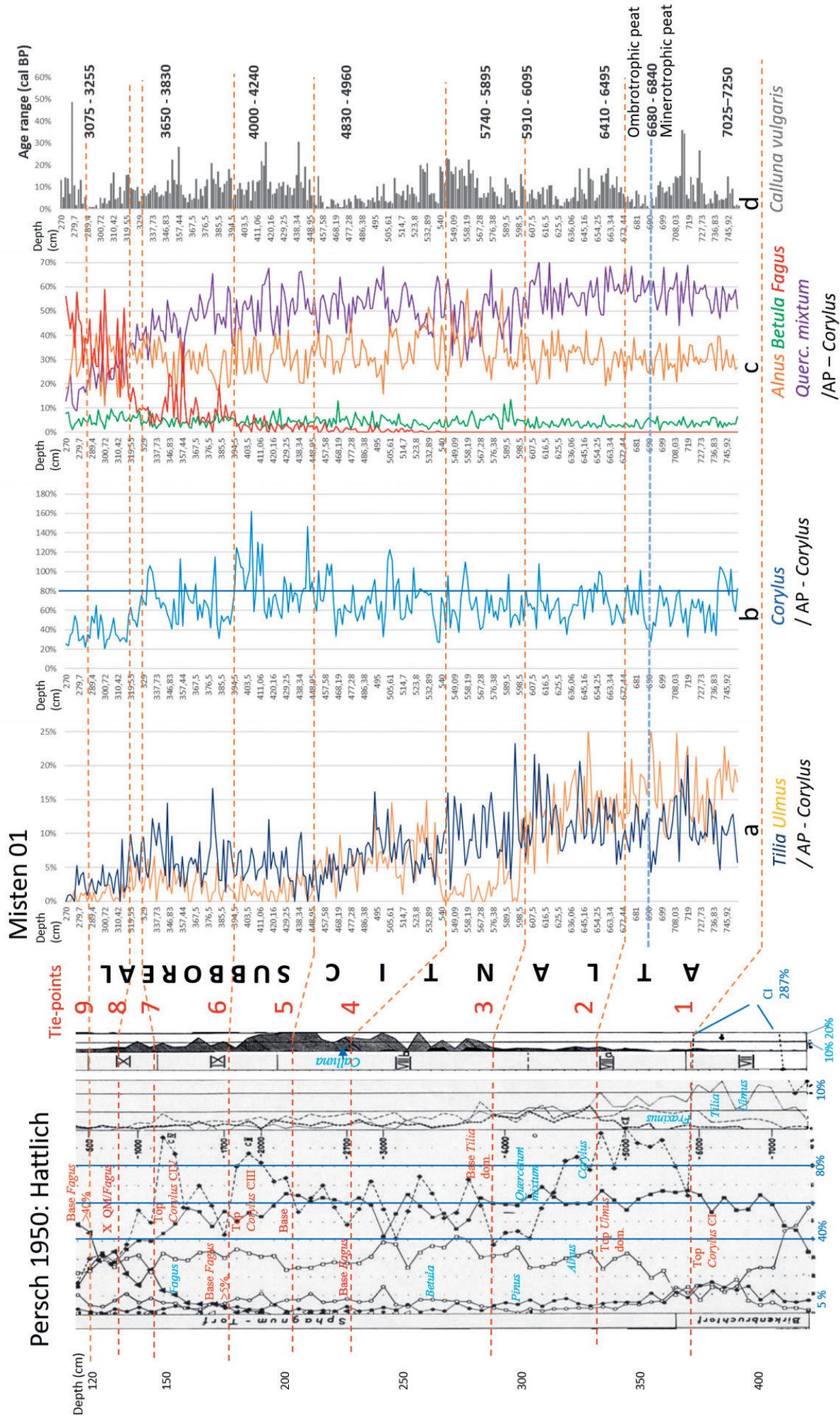
Figure 4. Comparison of Hattlich (Persch, 1950) and MIS-08-01b (this study) pollen data.
All data based on AP without *Corylus*. Position of the 9 tie-points is recognized in both diagrams. Ages are given in calBP (see Table 1) with modelled age range (94.5% probability). Atlantic/Subboreal limit suggested at tie-point 5.
The Misten diagram obviously does not reach the Boreal/Atlantic limit observed in the Hattlich diagram.

Table 2. Floristic and climatic characteristics in the Hautes-Fagnes deduced by Persch (1950) from Overbeck & Schneider's (1938) zonation.

Periods	Vegetation characteristics
XI - Subatlantic Less warm than periods VII to X	*Fagus* prevailing on *Corylus* and on the *Quercetum mixtum*
X - Subboreal Late warm period	*Quercus* and *Fagus* phase of the mixed *Quercus-Corylus* forest
	Starting pejorative change of the climate
	Regression of *Corylus, Ulmus* and *Tilia*
	Fagus reaching *Quercetum mixtum* values
IX - Subboreal Late warm period	*Quercus* phase of the mixed *Quercus-Corylus* forest
	Start of the continuous presence of *Fagus*
	Fagus becoming more abundant in the upper part (>5%)
	Corylus more abundant than below (=CIII) (CIV)
VIII - Atlantic Middle warm period	*Ulmus* and *Tilia* phase of the mixed *Quercus -Corylus* forest
	First occurrence of *Fagus*
	Tilia prevailing on *Ulmus* (VIIIb)
	Ulmus and *Tilia* phase of the mixed *Quercus -Corylus* forest
	Corylus reaching 100% (=CII)
	Ulmus prevailing on *Tilia* (VIIIa)
VII - Boreal Early warm period	*Corylus* >> 100% (CI)
	Betula, Pinus abundant but decreasing
	Quercetum mixtum more and more abundant
	Ulmus reaching a maximum of 26%

and from the characteristics used by Overbeck & Schneider's (1938) zonation.

Table 3. Tie-points retained from the Persch's (1950) Hattlich diagram and from the characteristics deduced from Overbeck & Schneider's (1938) zonation.

Tie-points	Characteristics
TP 9	Top: *Fagus/Quercetum mixtum* co-dominant
	Base: *Fagus* >40% (=about base: XI)
TP 8	Base: *Fagus /Quercetum mixtum* co-dominant
TP 7	Top: *Corylus* CIV (=about base X)
TP 6	Top: *Corylus* CIII - Base: Fagus >5%
TP 5	Base: *Corylus* CIII (=about base IX)
TP 4	Base: *Fagus*
TP 3	Base: *Tilia* dominance (=about base VIIIb)
TP 2	Top: *Ulmus* dominance
TP 1	Top: *Corylus* CI (=base VIIIa)

Age data given by Persch (1950) on the Hattlich diagram (Fig. 4) result from extrapolation (about 50 cm of peat/1000 years or about 1 cm/20 years) below the then accepted age of 600 BC for the base of the Subatlantic. These data are here transformed (Table 4) in BP ages (by arbitrarily adding 1950 years) to facilitate the comparison with the Misten 01 data where we use 14C modelled age ranges with 94.5% probability and where the analysis of 1 cm thick sample represents ca. 9 years.

Tie-points were also used to correlate the Hattlich diagram with a diagram made in the Rurhof peat bog, about 10 km south (Paillet, 2016). Consequently, tie-points 6 and 8 were dated thanks

to Paillet's (2016) work (Table 4), corresponding respectively to the top *Corylus* CIII and to the intersection between QM and *Fagus* curves.

Tie-points (TP) were also used by Litt et al. (2009) in the Westeifel Volcanic Field (50 km south-east of the Hautes-Fagnes plateau), to correlate between Holz Maar and Meerfelder Maar varved sequences. We identified there three tie-points corresponding respectively to tie-points 2 (TP6 or after *Ulmus* decline), 4 (TP7 or base of Fagus continuous curve), and 7 (TP8 or last *Corylus* peak before increase of *Fagus*). Tie-point 4 (base of *Fagus* curve) shows the larger difference of age between Hautes-Fagnes Plateau and Westeifel. The base of *Fagus* continuous curve is indeed very difficult to identify as shown in the MIS-08-01b diagram (Fig. 4), but one must also take into consideration the possible difference of migration speed of the taxon across Middle Europe during the Atlantic period (Schmidt, 1995; Giesecke et al., 2007). Tie-points 2 (top of Ulmus dominance) and 7 (top of *Corylus* peak) seem to be more reliable than tie-point 4.

c) Analysis of intervals between tie-points in MIS-08-01b and Hattlich diagrams
Between tie-points 1 and 3, the most abundant group of taxa (the *Quercetum mixtum*) fluctuates around 60%, *Alnus* around 30%, *Betula* around 5% (Fig. 4). The *Quercetum mixtum* is however not homogeneous: *Ulmus* prevalence on Tilia is less and less obvious from 1 to 3. *Corylus* fluctuates between 60% and 80%, except near the base of the MIS-08-01b where it may reach 100% (maybe representing the CII of Persch, 1950) and in the upper part of interval 2-3 in the Hattlich diagram where that taxon fluctuates between 40% and 60%. The interval between tie-points 1 and 3 corresponds to the lower part (VIIIa) of the Atlantic period.

Between tie-points 3 and 4, the *Quercetum mixtum* fluctuates between 40% and 60% in the MIS-08-01b diagram, this probably

Table 4. Comparison of tie-point ages. BP ages for Hattlich or Westeifel are BC ages + 1950 yr.

Climatic zones	Tie-points		Hattlich BC	Hattlich BP	Misten calBP	Rurhhof calBP	Westeifel calBP
About base XI	Top *Fagus* /QM co-dom., base *Fagus* >40%	9	About 650	About 2600	3075-3255		About 2700
X	base *Fagus* /QM co-dom.	8	About 850	About 2800	3275	2994-3166	?
About base X	Top *Corylus* CIV	7	About 1150	About 3100	About 3650-3830		About 3840-3820
IX	Top *Corylus* CIII, base *Fagus* >5%	6	About 1700	About 3650	About 4000-4240	4080-4235	?
About base IX	Base *Corylus* CIII	5	About 2200	About 4150			About 5600
VIIIb	Base *Fagus*	4	Subabout 2700	About 4650	5478		?
About base VIIIb	Base *Tilia* dominance	3	About 4000	About 5950	5910-6095		?
VIIIa	Top *Ulmus* dominance	2	About 4800	About 6750	6410-6495		About 6250-6170
Base VIIIa	Top *Corylus* CI	1	About 6000	About 7950			About 8550

being the result of a marked regression of Ulmus. The slight increase of *Betula* and *Alnus* is only the counterpart of the decreasing value of the *Quercetum mixtum*. Nothing comparable is observed in the Hattlich diagram.

Between tie-points 4 and 5, the *Quercetum mixtum* fluctuates around 50% in the MIS-08-01b diagram, around 60% in the Hattlich diagram. *Tilia* and *Ulmus* values decrease from 4 to 5 (from less than 10% to less than 5%) in the MIS-08-01b diagram, but again nothing comparable is observed in the Hattlich diagram.

A continuous curve of *Fagus* is situated in the mid-Atlantic VIIIb in the MIS-08-01b and begins to be clearly visible around 540 cm, corresponding to tie-point 4. The interval between tie-points 3 and 5 corresponds to the upper part (VIIIb) of the Atlantic period.

Between tie-points 5 and 6, the *Quercetum mixtum* fluctuates around 50% in both diagrams. *Corylus* values reach more than 80% in the Hattlich diagram, from 100% to 160% in the MIS-08-01b diagram (the CIII of Persch, 1950).

Between tie-points 6 and 7, the characteristics are more or less similar to interval 5 and 6, including a possible CIV (Persch, 1950), except a major feature arising at tie-point 6 with the increasing, but irregular, development of *Fagus* (between 5% and 30% in the MIS-08-01b diagram) starting the competition with the *Quercetum mixtum*.

The interval between tie-points 5 and 7 corresponds to the lower part (IX) of the Subboreal period.

Between tie-points 7 and 8, *Fagus* fluctuates between 10% and 20% in both diagrams.

Between tie-points 8 and 9, the competition between *Fagus* and the *Quercetum mixtum* reach a maximum, both oscillating between 20% and 40%. *Corylus* decreases below 60% (between 40% and 60% in the MIS-08-01b diagram, between 30% and 40% in the Hattlich diagram).

The interval between tie-points 7 and 9 corresponds to the upper part (X) of the Subboreal period.

Tie-point 9 indicates the base of fluctuations of *Fagus* between 30% and 60% and a strong decrease of the *Quercetum mixtum* below 20%. It corresponds to the base of the (XI) Subatlantic period.

d) Major discrepancies between Hattlich and Misten diagrams
Based on the comparison of Hattlich and Misten sites (Table 5), we conclude that the central part of the peat bog (Misten site) received more *Corylus* pollen grains and less QM pollen grains than the periphery (Hattlich site). Such observation may reflect a more open vegetation (heath) in the centre allowing to "capture" there more pollen grains transported by wind than the presumably more forested periphery where local pollen rain was dominant. The distribution of *Calluna vulgaris* (Fig. 4) offers some possibility to evaluate the density of the shrub cover in the centre of the peat bog and on its periphery. Between tie-points 1 and 3 (VIIIa Atlantic period), *Calluna* never reaches 10% in the periphery but often more than 10%, reaching sometimes almost 20%, in the centre of the peat bog. Between tie-points 3 and 4 (VIIIb Atlantic period, during the strong reduction of *Ulmus*), *Calluna* density is almost similar in both environments. However, between tie-points 4 and 5, a strong reduction (5-10%) of *Calluna* occurs only in the centre of the peat bog. From tie-points 5 to 9 (Subboreal period) abundance of *Calluna* is again very similar in both environments, being more and more reduced from tie-points 6 to 9. These data probably reflect local changes in the centre of the peat bog.

4.2. Testate amoebae analyses

4.2.1. Testate amoebae zonation and Shannon-Weaver Diversity Index

The stratigraphically constrained cluster analysis resulted in the identification of five biozones (biozones A to E). The Shannon-Weaver Diversity Index was calculated for all samples. The variation of the Shannon-Weaver Diversity Index along the core is presented at Figure 5.

Biozone A (753.5 cm = 5300 BC/7250 BP to 662.58 cm = 4576 BC/6526 BP) displays high-amplitude fluctuations that seem to be alternating for both *Archerella (Amphitrema) flavum* and *Difflugia pulex* (Fig. 6). High value of the Shannon-Weaver's Diversity index occurs at the top of the biozone A.

Biozone B (662.58 cm = 4576 BC/6526 BP to 535.68 cm = 3528 BC/5478 BP) is dominated by *Difflugia pulex*; *Archerella (Amphitrema) flavum* however displays a high relative frequency (47%) at approximately the middle part. Within this biozone, testate amoebae reach a first taxonomic plateau of the Shannon-Weaver Diversity index.

Biozone C (535.68 cm = 3528 BC/5478 BP to 415.609 cm = 2263 BC/4213 BP) is dominated by *Archerella (Amphitrema) flavum*; *Difflugia pulex* however displays also a high relative frequency (50%) at approximately the middle part and three others at the upper part. Within this biozone, a second taxonomic plateau of the Shannon-Weaver Diversity index starts to be reached. According to Allan et al. (2013), a very high humification rate (= 78%) occurs at approximately 3000 BC/ 4950 BP.

Table 5. Comparison of pollen diagrams discrepancies between Hattlich (Persch, 1950) and Misten (this study).

| Tie-points intervals	Hattlich	Misten
Interval 8-9	*Corylus* 30-40%	*Corylus* 40-60%
Interval 5-6	*Corylus* >80%	*Corylus* >100 to 160%
Interval 4-5	QM 60% *Tilia -Ulmus* stable	QM 50%, fall of *Tilia-Ulmus* <10% to <5%
Interval 3-4	QM 50-60%	Fall of QM (40-60%) and *Ulmus*
High interval 2-3	*Corylus* 40-60%	*Corylus* 60-80%
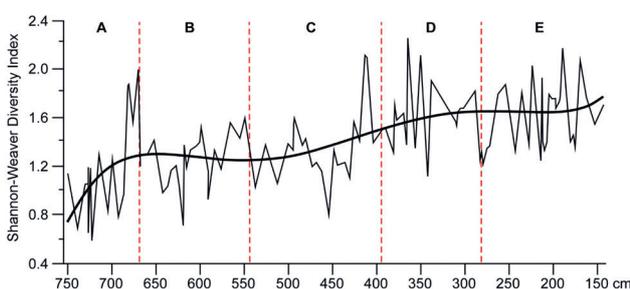
Figure 5. Shannon-Weaver Diversity index (based on testate amoebae). The Shannon-Weaver Diversity index is smoothed by a fifth-degree polynomial curve. Header shows biozones (A to E) defined by using CONISS (Grimm, 1987) in Fig. 6.

Figure 6. Distribution of selected testate amoebae in MIS-08-01b.
Grey dots indicate the samples that have not reached the statistical threshold of 100 counted tests. Instead of *Amphitrema flavum* read *Archerella (Amphitrema) flavum*. Pollen tie-points 1 to 9 are added for comparison purpose with Fig. 4.

Biozone D (415.61 cm = 2263 BC/4213 BP to 305.56 cm = 1326 BC/3276 BP) is not clearly dominated by *Archerella (Amphitrema) flavum* or *Difflugia pulex*. *Difflugia pulex* tends to decrease throughout the biozone. Two peaks of *Amphitrema wrightianum* are obvious at the top. *Cyclopyxis arcelloides* type fluctuates but never exceeds more than 15%. *Difflugia pristis* has a lower relative frequency than in lower zones. *Hyalosphenia subflava* presents a little but obvious positive shift. Relatively larger positive shifts are also displayed by *Bullinularia indica*, *Nebela militaris*, *Trigonopyxis arcula sensu lato*, *Hyalosphenia papilio* and *Trigonopyxis arcula minor* at approximately the middle part of

this biozone. *Arcella discoides* type is missing in biozone D except at the top. At the upper part of this biozone the second taxonomic plateau of the Shannon-Weaver Diversity index is reached.

Biozone E (305.56 cm = 1326 BC/3276 BP to 141.1 cm = 155 BC/2105 BP) is characterized by (i) a new composition of the testate amoebae assemblage with a high overall value of the Shannon-Weaver Diversity Index, (ii) the lower relative frequency (%) displayed by *Difflugia pulex* compared with the underlying biozones, (iii) the presence, with higher relative frequency, of alternating *Hyalosphenia subflava* and *Amphitrema wrightianum* and (iv) the obvious positive shifts of *Arcella*
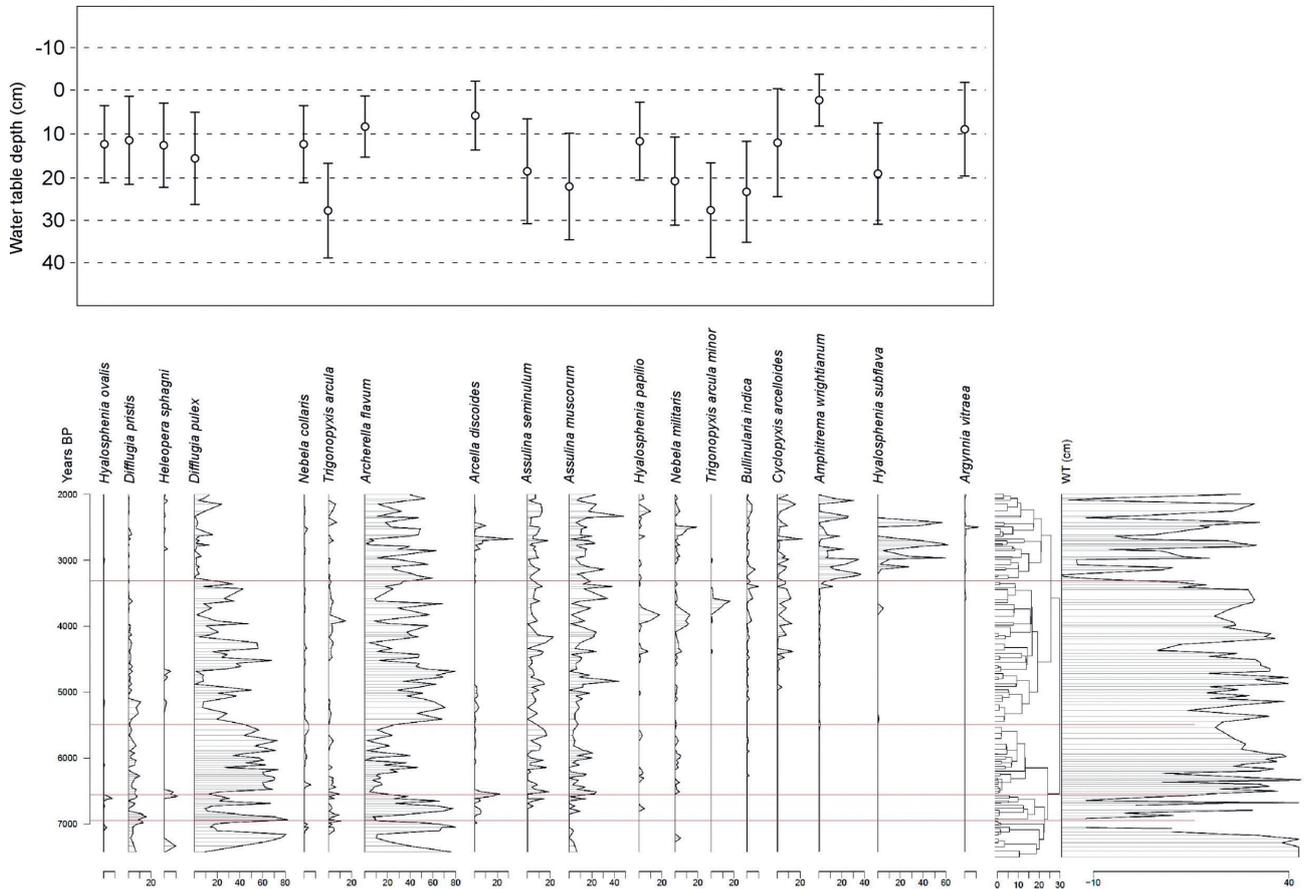
Figure 7. Distribution of selected testate amoebae in according to the data issued from the transfer function of Amesbury et al. (2016). Range and optimal distance of these taxa above the water-table (WT). Red lines position, deduced from CONISS analysis, is almost identical to subdivisions A to E in Fig. 6 except for the C/D limit.
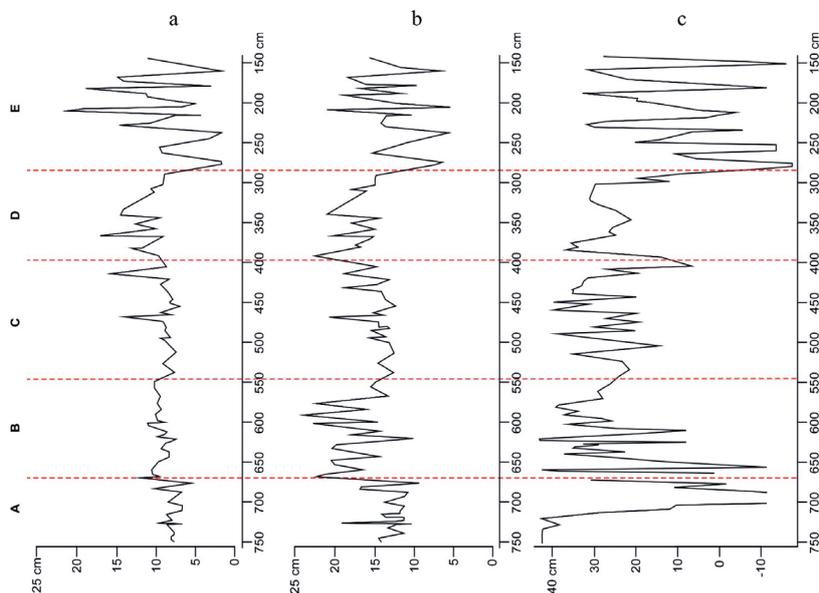
Figure 8. Distance of testate amoebae to water-table for the MIS-08-01b.

The curves of the depth to water-table (in cm) were inferred by using three testate amoebae transfer functions: **a,** from Charman et al. (2007); **b,** from Lamentowicz et al. (2008); **c,** from Amesbury et al. (2016) in Fig. 7. Header shows biozones (A to E) defined by using CONISS (Grimm, 1987) in Fig. 6.

discoides type, *Cyclopyxis arcelloides* type and *Nebela militaris* at approximately the middle part; *Trigonopyxis arcula sensu lato* is also present.

From the base to the top of the entire long core, the relative frequency of *Assulina muscorum* globally increases with major peaks of high relative frequency (> 40 %) in the biozones C, D (two at the bottom) and E.

4.2.2. Palaeo-hydroclimatic conditions of testate amoebae biozones

a) General considerations

The water-table depth optima and tolerances for the taxa used are presented at Figure 7, on the basis of the data of figure 5 of Amesbury et al. (2016). This diagram emphasizes the rather dry character of the Atlantic VIIIb and Subboreal IX and X, the majority of taxa selected being in the optima ranges living 10 to 20 cm above the WTD, reaching sometimes 20 to 30 cm above the WTD (Fig. 7). The wet character of the Subatlantic XI is emphasized by taxa like *Amphitrema wrightianum* type living 0-5 cm above the WTD or *Arcella discoides* and *Argynnia vitraea* living 5-10 cm above the WTD. Additionally, *Amphitrema wrightianum* is noted by Amesbury et al. (2016) as "skewed" to the Atlantic region, when most of the other taxa are "skewed" to the Continental region. Its high abundance at the base of the Subatlantic XI might be considered the result of a significant general change in the local climate of the Hautes-Fagnes Plateau.

In order to assign climatic characteristics to the five above-defined biozones, three transfer functions (Charman et al., 2007 as described by Sillasoo et al., 2007; Lamentowicz et al., 2008; Amesbury et al., 2016) have been applied. The results of the three transfer functions are broadly comparable (Fig. 8).

b) Detailed description of the palaeo-hydroclimatic conditions of the five biozones

Biozone A

A preliminary geochemical study (Salpeteur, 2011) showed that the fen-bog transition (FBT) started at 687 cm depth (mode ≈ 4773.5 BC/ 6723.5 BP) to finish at 663 cm (mode ≈ 4575.9 BC/6525.9 BP), which is the top of the biozone A (Fig. 6). Because ombrotrophic mires receive water mainly from atmospheric precipitation, the depth to water-table is linked to hydroclimatic conditions; on the other side, minerotrophic mires have significant input of water from surface runoff and groundwater (Charman, 1997). Because biozone A includes the minerotrophic part of the extant peat bog, palaeo-hydroclimatic conditions could with less certainty be assigned to this biozone as can be done for the stratigraphically upper ombrotrophic part. At the upper part of the biozone A, testate amoebae reach a first plateau of taxonomic diversity with a very high index of the Shannon-Weaver Diversity followed by an important dropdown (Fig. 5).This high amplitude difference could be due to the transition from minerotrophic to ombrotrophic conditions. Wetter surface conditions are proposed for the biozone A by using the three testate amoebae transfer functions. According to Allan et al. (2013), the time interval [5300-4700 BC/7250 BP-6650 BP] is characterized by wet climatic conditions (but see remarks above about the palaeo-hydroclimatic conditions in minerotrophic mires).

Biozone B

Drier climatic conditions can globally be assigned to biozone B. However, at least, one short wetter event with a relatively high amplitude (mode ≈ 4142.9 BC/6092.9 BP) occurs at the middle part of the biozone B, as shown by *Archerella (Amphitrema) flavum* (Fig. 6). According to Allan et al. (2013) the time interval [4700-4000 BC/6650 BP-5950 BP] is characterized by dry climatic conditions.

Biozone C

Wetter climatic conditions can globally be assigned to biozone C with, at least, a short drier event with a relative high amplitude (≈ 2880.8 BC/4830.8 BP) at the middle part, as shown by *Assulina muscorum*, and drier conditions at the upper part with, at most, two short drier event with a relative high amplitude (≈ 2571.2 and 2423.9 BC/4521.2 and 4373.9 BP), as shown by *Difflugia pulex* (Fig. 6). Nonetheless, it has to be noted that, within this biozone, there is the start of a climatic transition as shown by the first occurrences of *Cyclopyxis arcelloides* type and the start of the progressive decreasing of *Difflugia pristis* (Fig. 6). However, the percentages of *Difflugia pristis* in the upper part could be underestimated because this species is sometimes difficult to identify amongst organic debris. According to Allan et al. (2013) and Wanner et al. (2011), the time intervals between 3200 and 2500 BC (or 5150 and 4450 BP) are characterized by wet climatic conditions.

Biozone D

Biozone D is interpreted as a climatic transition interval (with high taxonomic diversity) as shown by the decrease of *Difflugia pulex* and *Difflugia pristis* but also with the increase of *Amphitrema wrightianum*, *Hyalosphenia subflava*, *Nebela militaris*, *Trigonopyxis arcula sensu lato*, *Hyalosphenia papilio* and *Trigonopyxis arcula minor*. The end of this climatic transition is obvious at the top of this biozone (at the transition from biozone D to biozone E) where *Difflugia pulex* reaches very low percentage of relative frequency (Fig. 6). During this period of time the population of *Archerella (Amphitrema) flavum* and *Difflugia pulex* alternate rapidly, with low differences between them; it is consequently difficult to safely qualitatively infer the bog surface wetness. Thanks to the three transfer functions, drier climatic conditions could be assigned to this biozone. At least three short events of driest conditions, with relative high amplitude, occurred at approximately 2238.3 BC/4188.3 BP, 2018.5 BC/3968.5 BP and 1798.8 BC/3748.8 BP, as shown by *Difflugia pulex* (Fig. 6). According to Allan et al. (2013) the time intervals [2500-2000 BC/4450-3950 BP (transition between biozone C to biozone D) and 2200-1800 BC/4150-3750 BP] are characterized by dry climatic conditions.

Biozone E

Biozone E is characterized by the end of a climatic transition displayed by testate amoebae assemblage (mainly by *Difflugia pulex, Amphitrema wrightianum* and *Hyalosphenia subflava*) with an overall high Shannon-Weaver Diversity index (Figs 5 and 6). Thanks to the three transfer functions, wetter climatic conditions could be assigned to the lower part of this biozone and drier climatic conditions could be assigned to the upper part of this biozone. Very high amplitude of water-table fluctuations occurred over this period of time (Figs 7 and 8). Two wet shifts are obvious at the lower part of this biozone at ≈ 1243 BC/3193 BP and 932 BC/2882 BP, as shown by *Archerella (Amphitrema) flavum*. At least, one short event of driest climatic conditions occurs at around 700 BC/2650 BP, as shown by *Hyalosphenia subflava* (Fig. 6). According to Allan et al. (2013), the time interval [1200-600 BC/3150-2550 BP] is characterized by dry climatic conditions.

4.2.3. Testate amoebae zonation based on dominant species and related humidity on the peat bog surface

The species with the highest overall relative weight (%) along the entire profile are *Archerella (Amphitrema) flavum (*suggesting wet conditions) and *Difflugia pulex (*suggesting drier conditions). The numbers of representatives of the two species seem to vary synchronously but in an opposite way, even though these species have non-significant negative linear correlation (r = -0.4). Accordingly, we tentatively use their respective abundance as indicative of wet (dominance of *Archerella (Amphitrema) flavum*) or dry (dominance of *Difflugia pulex*) conditions. *Assulina muscorum* has also high overall relative weight, but lower than that of the species above mentioned.

4.2.4. Integration of testate amoebae and pollen zonations

Integration of the two zonations permits the subdivision of the ombrotrophic part of the studied section into 18 smaller time intervals (Table 6; Fig. 9) with various pollen features corresponding to detailed humidity condition "registered" by the testate amoebae on the peat bog surface at each of the studied time intervals. As no significant anthropic actions could be demonstrated on and around that peat bog during that time span, it is assumed here that variations of humidity at the surface of the peat bog reflect also indirectly variation in general climatic conditions on the surrounding area.
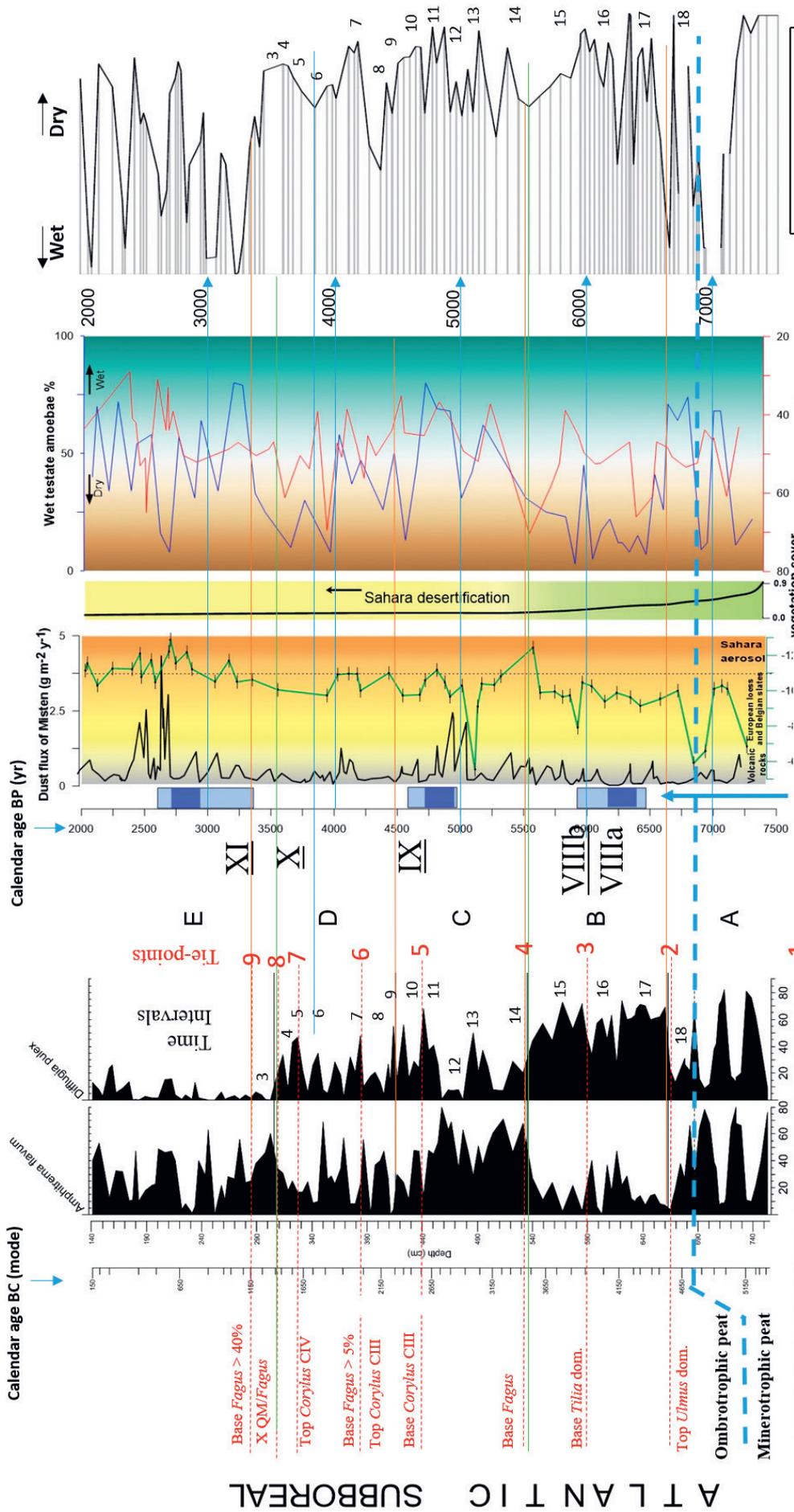
Figure 9. Comparison of the Misten proxies (pollen, dust flux, εNd, humification, and testate amoebae).

Pollen characteristics of tie-points from Fig. 4. Two main testate amoebae in Atlantic–Subboreal periods in the Hautes-Fagnes area, from Fig. 6 (instead of *Amphitrema flavum* read *Archerella (Amphitrema) flavum*). Time intervals as deduced from Table 6. Dust flux, εNd, humification, and testate amoebae from Allan et al. (2013). The testate amoebae were classified according to their affinity with wet conditions. The three vertical dark blue bars show the cold events according to Wanner et al. (2011) and the three light blue bars show the uncertainty in the length of cold events. The Saharan desertification model is from Claussen et al. (1999). Water-table (WT) (cm) are reproduced from Fig. 7.

Table 6. Testate amoebae, pollen zones, time-intervals, dates comparisons. Ages cal BP from Table 1, and Figs 4 and 6.

Depth (cm)	Age calBP	Thec./pol.Zones	Pollen features	This paper	Time intervals
				SubAtl. short driest	1
			Fagus >>, QM <<	Subb.-SubAtl.wet	2
286	3075-3255	**Base TP9**	(base *Fagus* >40%		About base XI
		E between TP8-9	*Fagus* >>, QM <<	Subb. wet	3
	3275	**Base E= base TP8**	(base QM/*Fagus*)		
		D between TP7-8	*Corylus* <, *Fagus* >	Subb. dry	4
		D lowermost TP7-8	*Corylus* <<	Subb. driest	5
		D base TP7	(top *Corylus* IV)		About base X
341	3650-3830	D between TP6-7	*Corylus* >, *Fagus* >	Subb. dry	6
		D lowermost TP6-7	*Tilia* - *Corylus* >>	Subb. driest	7
		D base TP6	(base *Fagus* >5%)		
408	4000-4240	D upper TP5-6	*Corylus* >>	Subb. dry	8
		D middle TP5-6	*Tilia* >>	Subb. driest	9
	4213	**Base D**			
		C lowerTP5-6	*Ulmus* <<, *Calluna* >>	Subb. drier	10
		C base TP5	(base *Corylus* III)		About base IX
		C upper TP4-5	*Ulmus* >, *Calluna* >>	Atl. drier	11
474	4830-4960	C middle TP4-5	*Ulmus* <	Atl. wet	12
		C lower TP4-5	*Tilia* - *Ulmus* >	Atl. drier	13
		C lowermost TP4-5	*Ulmus* >>	Atl. wet	14
	5478	**Base C=base TP4**	(base *Fagus*)		
569	5740-5895	B TP3-4 lower	*Ulmus* <<, *Calluna* >	Atl. dry	15
603	5910-6095	**B base TP3**	(Base *Tilia* dom.)		About base VIIIb
		B TP2-3 upper	*Ulmus* <	Atl. short wet	16
		B TP2-3 lower	*Tilia* >	Atl. dry	17
659	6410-6495	**B base TP2**	(Top Ulmus dom.)		
	6551	**Base B**			
		A TP1-2 ombrotr.	*Quercus* - *Corylus* >	Atl. wet	18
690	6680-6840	Fen-bog transition			
741	7025-7250	A TP1-2 minerotr.			
	7424	**Base A**			

The analysis of these 18 time intervals gives interesting information on the behaviour of some taxa in response to climatic fluctuations. Increasing values of *Tilia* are noted in dry to driest conditions from the Atlantic (VIIIa and VIIIb) to the Subboreal IX, a situation met with *Calluna* on the peat bog in Atlantic VIIIb and Subboreal IX (Fig. 4). *Corylus* values increase with dry/driest conditions in Subboreal IX, but decrease with the same conditions in Subboreal X. *Fagus* increases in dry conditions of Subboreal IX and X but also in wet conditions of Subboreal X and Subatlantic XI. *Ulmus* increases and decreases indifferently in dry and wet conditions during the Atlantic (mainly VIIIb), giving some support to the existence of an anthropic effect on the distribution of this taxon (See 4.1.1).

4.3. Mineral dust analysis

Based on dust flux data from Allan et al. (2013), the climate imprint in the Misten record during Mid- and Late Holocene and especially for two dust enriched intervals (5150 to 4750 cal BP and from 2750 to 2550 cal BP) is evaluated (Fig. 9).

(i) Peat growth at the Misten site starts at ~7300 cal BP, and becomes ombrotrophic from 6700 cal BP. Damblon (1994) pointed to the wet and warm climate of the Atlantic VIIIa period (6500 cal BP- 6000 cal BP; partially met by time-intervals 18 and 16), which is consistent with the warmest period of the Holocene described in Greenland by Johnsen et al. (2001) (see also Davis et al. (2003)).

(ii) From 6700 to 5500 cal BP, the dust flux and humification remain relatively constant. The decrease in percentages of wet testate amoebae and the better representation of heathlands in pollen diagrams from the area (Damblon, 1994), show slightly drier local environments met by time-intervals 17 and 15, suggesting a rather dry climate with an increase of *Tilia* proportion in the local QM Atlantic vegetation. The definitive dominance of *Tilia* on *Ulmus* (near 6000 cal BP) separates the Atlantic VIIIa and the Atlantic VIIIb periods. These dry conditions might reflect the cooling event noted in Wanner et al. (2011) from 6500 to 5900 cal BP. A brief episode of wetter conditions (time-interval 16) has little impact on this QM drier Atlantic vegetation. During this interval, there is no significant change in the dust flux intensity but the relatively dry conditions promote the erosion of local soils. Between 8000 and 5500 cal BP, the Sahara aridification increases and the Saharan vegetation cover decreases. Then the available terrigenous material increases (Claussen et al., 1999; de Menocal et al., 2000; Bout-Roumazeilles et al., 2013).

(iii) During the period from 5500 to 2550 cal BP, the Misten dust flux increases compared to the mean value in the previous intervals. At 4700 cal BP, time-intervals 12 (and 13?) suggest a rather wet climate with adequate local QM Atlantic vegetation, corresponding with a positive humidity anomaly at the scale of the northern hemisphere between 4800 and 4600 cal BP as described in Wanner et al. (2011). These time-intervals are characterized by wet local conditions underlined by the high wet testate amoebae content and the low humification degree. The humid conditions are in agreement with the plant cover changes of the Hautes-Fagnes Plateau deduced from palynology (Damblon 1994) (i.e. local increase in hygrophilous and aquatic pollen taxa). Between 4500

and 4000 cal BP, the general decrease of wet testate amoebae and the increase of the humification degree both indicate a drier local environment, starting with time-interval 11. The observed increase in dust flux may relate to important local erosion. The glaciers retreat in Europe from 4200-3800 cal BP (Mayewski et al., 2004) and the lake level minima (Magny, 2004) confirm a dry interval which is correlated with the first Subboreal (IX) period characterized by *Corylus* developments (time-intervals 8 and 6), and the last *Tilia* increase (time-intervals 9 and 7). Between 3700 and 3200 cal BP, the second Subboreal (X) period shows a progressive change from dry (time-intervals 5 and 4) to wet conditions (time-interval 3, with *Fagus* starting dominance in the QM forest). Between 3200 and 2550 cal BP, the dust flux increases and reaches its maximum value in the core. The humification degree decreases and wet testate amoebae strongly increase. The regional pollen data indicates a strong expansion of beech forests at the expense of the mixed oak woodlands, whereas alders and birches developed again near and on wetlands. These changes point to a climatic deterioration with alternating wet and dry conditions, but also to soil degradation (Damblon, 1994). They coincide with a cold event identified by Wanner et al. (2011) between 3300 and 2500 cal BP. Time-interval 2 where *Fagus* pollen grains reach more than 40% of the Arborean Pollen (AP) assemblage can be roughly identified to the beginning of the Subatlantic period (XI).

According to the pollen analysis, anthropic activities appeared in the Hautes-Fagnes Plateau around 3500 BP, but they remained low and did not seem to have affected local ecological evolution before 2550 BP (dates from Damblon, 1994).

(iv) Between 2550-2000 cal BP, the dust flux displays high values (averages of 0.6 g m^{-2} yr^{-1}). At the same time, a low humification degree (35%) is consistent with cold and dry conditions and an intensification of the human impact is recorded in the pollen diagrams of the Hautes-Fagnes area (Damblon, 1994). This period is therefore most probably characterized by the influence of human activities related to land use change (regional erosion due to forest clearing and soil cultivation activities).

5. Conclusion

The present work is dedicated to the study at high resolution of the central area of Misten peat bog (Hautes-Fagnes, Belgium) in order to reconstruct the conditions of peat formation and evolution on the basis of pollen and testate amoebae analysis. The Subboreal and Atlantic pollen diagram of this study has been compared and correlated with the diagram obtained from the periphery of the Misten peat bog (Persch, 1950). Nine tie-points have been selected and characterized, some of them being well dated by radiocarbon ages. Two of those tie-points are recognized, at about the same age, in the Westeifel region at 50 km from the study area.

As expected, the central part of the Misten peat bog is shown to have received more *Corylus* pollen grains and less QM pollen grains than the periphery located at a few hundred metres. It presumably reflects a more open vegetation with adequate peat-forming vegetation in the centre, allowing the "capture", there, of more pollen grains transported by wind than in the periphery where the local pollen rain of the *Quercetum mixtum* might be more important. The distinction between the central part of the peat bog and its periphery is also reflected in the distribution of the heavier pollen tetrads of *Calluna* which decrease significantly more on the central peat bog than at the periphery during the youngest part of the Atlantic VIIIb (around 4600-4800 cal BP), characterized by wet conditions and high water-table level. That period of time corresponds to a positive humidity anomaly at the scale of northern hemisphere.

The testate amoebae analysis allows the assignment of globally drier climatic conditions to the transition (6410-6495 to around 5478 cal BP) from Atlantic VIIIa to Atlantic VIIIb. Wetter climatic conditions may globally be assigned to most of the higher part (5478 to around 4521 cal BP) of Atlantic VIIIb. The Subboreal period IX (around 4374 to 3650-3830 cal BP) is interpreted as a climatic transition interval (with high taxonomic diversity), the Subboreal period X (3650-3830 to 3075-3255 cal BP), marking a clear trend to the wetter climate of the Subatlantic (XI) period.

The integration of the detailed testate amoebae data within the pollen zones allows the subdivision of the ombrotrophic part of the Misten section in 18 smaller time intervals. Increasing

values of *Tilia* are noted in dry to driest conditions from the Atlantic (VIIIa and VIIIb) to the Subboreal IX. *Ulmus* increases and decreases indifferently in dry and wet conditions during the Atlantic (mainly VIIIb) giving some support to the existence of an anthropic effect on the distribution of this taxon. The definitive dominance of *Tilia* on *Ulmus* (near 6000 cal BP) separates the Atlantic VIIIa and the Atlantic VIIIb periods. These dry conditions might reflect the cooling event noted in North America (Residual Laurentide Ice Sheet) from 6500 to 5900 cal BP.

7. References

Allan, M., Le Roux, G., Piotrowska, N., Beghin, J., Javaux, E., Court-Picon, M., Mattielli, N., Verheyden, S. & Fagel, N., 2013. Mid- and late Holocene dust deposition in Western Europe: the Misten peat bog (Hautes Fagnes – Belgium). Climate of the Past, 9, 2285–2298. https://doi.org/10.5194/cp-9-2285-2013

Amesbury, M.J., Swindles, G.Y., Bobrov, A., Charman, J., Holden, J., Lamentowicz, M., Mallon, G., Mazei, Y., Mitchell, E.A.D., Payne, R.J., Roland, T.P., Turner, T.E. & Warner, B.G., 2016. Development of a new pan-European testate amoeba transfer function for reconstructing peatland palaeohydrology. Quaternary Science Reviews, 152, 132-151. https://doi.org/10.1016/j.quascirev.2016.09.024

Beisel, J-N., Usseglio-Polatera, P., Bachmann, V. & Moreteau, J.C., 2003. A comparative analysis of evenness index sensitivity. Hydrobiology, 88, 1, 3–15. https://doi.org/10.1002/iroh.200390004

Belokopytov, I. E. & Veresnevich, V. V., 1955. Giktorf's peat borers, Torfânaâ promyslennost', 8, 9–10.

Beug, H.-J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiet. Friedrich Pfeil, München, 452 p.

Blaauw, M. & Christen, J. A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis, 6, 457–474. https://doi.org/10.1214/11-BA618

Booth, R.K., Lamentowicz, M. & Charman, D.J., 2010. Preparation and analysis of testate amoebae in peatland palaeoenvironmental studies. Mires and Peat, 7, 1–7.

Bout-Roumazeilles, V., Combourieu-Nebout, N., Desprat, S., Siani, G., Turon, J.-L. & Essallami, L., 2013. Tracking atmospheric and riverine terrigenous supplies variability during the last glacial and the Holocene in central Mediterranean, Climate of the Past, 9, 1065–1087. https://doi.org/10.5194/cp-9-1065-2013

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon, 51, 337–360. https://doi.org/10.1017/S0033822200033865

Charman, D.J., 1997. Modelling hydrological relationships of testate amoebae (Protozoa: Rhizopoda) of New Zealand peatlands. Journal of the Royal Society of New Zealand, 27, 465–483. https://doi.org/10.1080/03014223.1997.9517549

Charman, D.J., Hendon, D. & Woodland, W.A., 2000. The identification of testate amoebae (Protozoa: Rhizopoda) in peats. Quaternary Research Association, London, Technical Guide no. 9, 147 p.

Charman, D.J., Blundell, A. & ACCROTELM members, 2007. A new European testate amoebae transfer function for palaeohydrological reconstruction on ombrotrophic peatlands. Journal of Quaternary Science, 22, 209–221. https://doi.org/10.1002/jqs.1026

Claussen, M., Kubatzki, C., Brovkin, V., Ganopolski, A., Hoelzmann, P. & Pachur, H. J., 1999. Simulation of an abrupt change in Saharan vegetation in the mid-Holocene. Geophysical Research Letters, 26, 2037–2040. https://doi.org/10.1029/1999GL900494

Damblon, F., 1978. Etudes paléo-écologiques des tourbières en Haute Ardenne. Ministère de l'Agriculture, Administration des Eaux et Forêts, Service de la Conservation de la Nature, 10, 126 p.

Damblon, F., 1994. Les dépôts tourbeux et l'histoire de la végétation sur le plateau des Hautes-Fagnes (Belgique), Annales de la Société géologique de Belgique, 117, 259–276.

Davis, B.A.S., Brewer, S., Stevenson, A.C., Guit, J. and Data Contributors, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews, 22, 1701–1716. https://doi.org/10.1016/S0277-3791(03)00173-2

De Menocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L. & Yarusinsky, M., 2000. Abrupt onset and termination of the African Humid Period: Rapid climate responses to gradual insolation forcing. Quaternary Science Reviews, 19, 347–361. https://doi.org/10.1016/S0277-3791(99)00081-5

Dricot, E.-M., 1960. Recherches palynologiques sur le plateau des Hautes- Fagnes. Bulletin de la Société Royale de Botanique de Belgique, 92, 157–196.

Faegri, K. & Iversen, J., 1989. Textbook of pollen analysis. Wiley, Chichester, 328 p.

Frankard, P., Ghiette, P., Hindryckx, M-N., Schumacker, R. & Wastiaux, C., 1998. Peatlands of Wallony (S-Belgium). Suoseura, 49, 33–47.

Giesecke, T., Hickler, T., Kunkel, T., Sykes, M.T. & Bradshaw, R.H.W., 2007. Towards an understanding of the Holocene distribution of Fagus sylvatica L. Journal of Biogeography, 34, 1, 118–131. https://doi.org/10.1111/j.1365-2699.2006.01580.x

Grimm, E.C., 1987. CONISS: A fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers & Geosciences, 13, 13–35. https://doi.org/10.1016/0098-3004(87)90022-7

Grimm, E.C., 1990. TILIA and TILIA GRAPH PC spreadsheet and graphics software for pollen data. INQUA commission for study of the Holocene. Sub-commission on data-handling methods. Newsletter, 4, 5–7.

Hannon, G.E., Bradshaw, R. & Emborg, J., 2000. 6000 years of forest dynamics in Suserup Skov, a seminatural Danish woodland. Global Ecology and Biogeography, 9, 101–114. https://doi.org/10.1046/j.1365-2699.2000.00145.x

Iversen, J., 1973. The development of Denmark's nature since the last glacial. Danmarks geologiske Undersoegelse, Raekke V, 7-C, 1–126.

Johnsen, S.J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P.,Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjörnsdottir, A.E. & White, J., 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRI. Journal of Quaternary Science, 16, 299–307. https://doi.org/10.1002/jqs.622

Kamran, K, Court-Picon, M., Gerrienne, P. & Streel, M., 2016. Misten peat Bog: High resolution palynological record (Poster). MVP-PPMB meeting-Liège, December 21, 2016. Miscellanea palaeontologica 2016, Program and Abstract, p. 11, 12.

Lamentowicz, M., Obremska, M. & Mitchell, E.A.D., 2008. Autogenic succession, land-use change, and climatic influences on the Holocene development of a kettle hole mire in Northern Poland. Review of Palaeobotany and Palynoloy, 151, 21–40. https://doi.org/10.1016/j.revpalbo.2008.01.009

Litt, T., Schölzel, C., Kühl, N. & Brauer, A., 2009. Vegetation and climate history in the Westeifel Volcanic Field (Germany) during the past 11 000 years based on annually laminated lacustrine maar sediments. Boreas, 38, 679–690. https://doi.org/10.1111/j.1502-3885.2009.00096.x

Magny, M., 2004. Holocene climatic variability as reflected by mid-European lake-level fluctuations, and its probable impact on prehistoric human settlements. Quaternary International, 113, 65–79. https://doi.org/10.1016/S1040-6182(03)00080-6

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G. Rack, F., Staubwasser, M., Schneider, R.R. & Steig, E.J., 2004. Holocene climate variability. Quaternary Research, 62, 243–255. https://doi.org/10.1016/j.yqres.2004.07.001

Moore, P.D., Webb, J.A. & Collinson, M.E., 1991. Pollen Analysis. Blackwell Scientific Publications, Oxford, 216 p.

Overbeck, F. & Schneider, S., 1938. Mooruntersuchungen bei Lüneburg und bei Bremen und die Reliktnatur von Betula nana in Nordwestdeutschland. Zeitschrift für Botanik, 33, 1–54.

Paillet, M., 2016. Etude paléopalynologique de la tourbière haute active du Rurhof (Hautes-Fagnes, Belgique). Unpublished Bachelor thesis. Haute école de la province de Liège, La Reid, Belgium, 90 p.

Payne, R.J. & Mitchell, E.A.D. 2009. How many is enough? Determining optimal count totals for ecological and palaeoecological studies of testate amoebae, Journal of Paleolimnology, 42, 483–495. https://doi.org/10.1007/s10933-008-9299-y

Peglar, S.M., 1993. The mid-Holocene Ulmus decline at Diss Mere, Norkfolk, UK: a year-by-year pollen stratigraphy from annual laminations. Holocene, 3, 1–13. https://doi.org/10.1177/095968369300300101

Peglar, S.M. & Birks H.J.B., 1993. The mid-Holocene Ulmus fall at Diss Mere, south-east England disease and human impact? Vegetation History and Archaeobotany, 2, 61–68. https://doi.org/10.1007/BF00202183

Persch, F., 1950. Zur postglazialen Wald-und Moorentwicklung im Hohen Venn. Decheniana, 104, 81–93.

Piotrowska, N., 2013. Status report of AMS sample preparation laboratory at GADAM Centre, Gliwice, Poland. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 294, 176–181. https://doi.org/10.1016/j.nimb.2012.05.017

Piotrowska, N., Blaauw, M., Mauquoy, D. & Chambers, F.M., 2011. Constructing deposition chronologies for peat deposits using radiocarbon dating. Mires and Peat, 7/10, 1-14.

Reille, M., 1992. Pollen et Spores d'Europe et d'Afrique du Nord. Laboratoire de botanique historique et de palynologie, Marseille, 520 p.

Reille, M., 1995. Pollen et Spores d'Europe et d'Afrique du Nord. Supplément 1. Laboratoire de botanique historique et palynologie, Marseille, 327 p.

Reille, M., 1998. Pollen et Spores d'Europe et d'Afrique du Nord. Supplément 2. Laboratoire de botanique historique et de palynologie, Marseille, 521 p.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J. & Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50000 years cal BP. Radiocarbon, 51/4, 1111–1150. https://doi.org/10.1017/S0033822200034202

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J, 2013. IntCal13 and Marine13 radiocarbon age calibration curves, 0-50.000 years cal BP. Radiocarbon, 55/4, 1869–1887. https://doi.org/10.2458/azu_js_rc.55.16947

Salpeteur, T., 2011. Reconstitution de la transition minérotrophie-ombrotrophie de la tourbière du Misten (Hautes-Fagnes belges): approche géochimique et biologique. Unpublished Master thesis. University of Liège, Belgium, 90 p.

Schmidt, P.A., 1995. Übersicht der natürlichen Waldgesellschaften Deutschlands. Schriftenreihe der Sächsischen Landesanstalt für Forsten, 4/95, 95 p.

Schwickerath, M., 1937. Die nacheiszeitliche Waldgeschichte des Hohen Venns und ihre Beziehung zur heutigen Vennvegetation. Abhandlungen der Preussischen Geologischen Landesanstalt, Neue Folge, 184, 7–31.

Shannon, C.E. & Weaver, W., 1963. The Mathematical Theory of Communication. University of Illinois Press, Urbana, 125 p.

Sillasoo, U., Mauquoy, D., Blundell, A., Charman, D., Blaauw, M., Daniell, J.R.G., Toms, P., Newberry, J., Chambers, F.M. & Karofeld, E., 2007. Peat multi-proxy data from Männikjärve bog as indicators of Late Holocene climate changes in Estonia. Boreas, 36, 20–37. https://doi.org/10.1111/j.1502-3885.2007.tb01177.x

Smith, B. & Wilson, J.B., 1996. A consumer's guide to evenness indices. Oikos, 76, 1, 70–82.

Streel, M., 1959. Etude phytosociologique de la fagne Wallonne et de la fagne de Cléfay (structure et évolution des associations végétales à sphaignes dans les Hautes-Fagnes de Belgique). Académie Royale de Belgique, Classe des Sciences, Mémoires in 8°, 31/1, 108 p.

Streel, M., Beghin, J., Gerrienne, P., Hindrickx, M-N., Luthers, C., Court-Picon, M., Frankard, P., Allan, M. & Fagel, N., 2014. Late Subatlantic history of the ombrotrophic Misten Bog (Eastern Belgium) based on high resolution pollen, testate amoebae and macrofossil analysis. Geologica Belgica, 17/2, 148–160.

Troels-Smith J., 1960. Ivy, mistletoe and elm: climatic indicators- fodder plants. Danmarks geologiske Undersoegelse, Raekke IV, 4, 1–32.

Turner, J., 1962. The Tilia decline: an anthropogenic interpretation. New Phytologist, 61, 328–341. https://doi.org/10.1111/j.1469-8137.1962.tb06304.x

Wanner, H., Solomina, O., Grosjean, M., Ritz, S.P. & Jetel, M., 2011. Structure and origin of Holocene cold events. Quaternary Science Reviews, 30, 3109–3123. https://doi.org/10.1016/j.quascirev.2011.07.010

Wardenaar, E., 1987. A new hand tool for cutting peat profiles. Revue canadienne de botanique, 65, 1772–1773. https://doi.org/10.1139/b87-243

Wastiaux, C., 2002. Topographie de surface et de sub-surface des zones tourbeuses des réserves naturelles domaniales des Hautes-Fagnes : Rapport de synthèse, Convention C60 entre le Ministère de la Région Wallonne, Direction générale des Ressources naturelles et de l'Environnement, et l'Université de Liège. Unpublished report. Ministère de la Région Wallonne, Namur, 52 p.

Wastiaux, C., Halleux, L., Schumacker, R., Streel, M. & Jacqmotte, J-M., 2000. Development of the Hautes-Fagnes peat bogs (Belgium): new perspectives using ground-penetrating radar. Suoseura, 51, 115–120.