GEOLOGICA BELGICA (2014) 17/2: 148-160

Late Subatlantic history of the ombrotrophic Misten Bog (Eastern Belgium) based on high resolution pollen, testate amoebae and macrofossil analysis

Maurice STREEL[1] *, Jérémie BEGHIN[1], Philippe GERRIENNE[1], Marie-Noëlle HINDRYCKX[2], Cedric LUTHERS[3], Mona COURT-PICON[4], Philippe FRANKARD[5], Mohammed ALLAN[6] & Nathalie FAGEL[6]

1. PPP, Département de Géologie, Université de Liège, Allée du 6 Août, B18 Sart Tilman B4000-Liège, Belgium
2. Didactique des sciences biologiques, Département des sciences de la vie, Université de Liège, Allée de la chimie 3, B6 CIFEN Sart Tilman B4000-Liège, Belgium
3. Cellule « Qualité de l'air », ISSeP, rue du Chéra 200, B4000-Liège, Belgium
4. Earth and Life History Division, Archaeosciences Unit, IRSNB, Rue Vautier 29, B1000-Bruxelles, Belgium
5. Département de l'Etude du Milieu naturel et agricole, DGOARNE, Avenue Maréchal Juin 23, B-5030 Gembloux, Belgium
6. AGEs, Département de Géologie, Université de Liège, Allée du 6 Août, B18 Sart Tilman B4000-Liège, Belgium
** Corresponding author (Maurice.Streel@ulg.ac.be)*

ABSTRACT. Misten Bog has through time received homogeneous pollen rain dominated successively by *Fagus, Quercus* and *Picea*. Based on the limits separating six pollen zones across nine cores, we show that the areas of major peat production have moved with time from one side of the bog to the other. The reduction of thickness of peat was strongly dependant on the proximity of peat cutting area since the 12th Century. Before the cutting, an *Alnus* wood that encircled the bog regressed during the Vandal Minimum (500-800 AD) and never recovered. During this age interval, testate amoebae indicate a drier period on the peat bog. From the 12th to the 14th Centuries, there was a slight increase of non arboreal pollens linked to farming. From the 14th to the 16th Centuries testate amoebae indicate again a drier period on the peat bog but whether this is linked to climate change or human pressure is unclear. From the 16th Century onwards, *Sphagnum* sect. *Cuspidata* almost disappeared but *Sphagnum imbricatum* persisted until the 19th Century. Pollens linked to farming culminated again during the early part of the 19th Century. High concentration of Si, Ti and N are probably linked to the increasing farming in the neighborhood as well as to industrial mining processes in the region and might have influenced these changes on the peat bog. The theory of cyclical hollow/hummock succession versus rather stationary hummocks is discussed.

KEYWORDS: palaeoecology, Hautes-Fagnes, Vandal Minimum, Medieval Warm Period, Little Ice Age, *Sphagnum imbricatum*, cyclical hollow/hummock theory, stationary hummock theory

1.Introduction.

1.1. The Hautes-Fagnes plateau and the Misten bog

The Hautes-Fagnes plateau (Eastern Belgium), culminating at 694 m a.s.l., has a relatively cool and humid climate conducive to the development of peatlands. The Cambro-Ordovician bedrock (mainly quartzites and slates) gave rise to an alteration layer rich in clay. During glacial episodes, loess accumulated but remains only locally on the highest parts of the land. Peat soils 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 has accumulated 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). The average precipitation is *c.* 1440 mm/yr and the mean annual temperature over the Hautes-Fagnes averages 6.7 °C (Mormal & Tricot, 2004). 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, 1996). Data from this area are equally important to improve understanding of past climatic changes for this part of Europe.

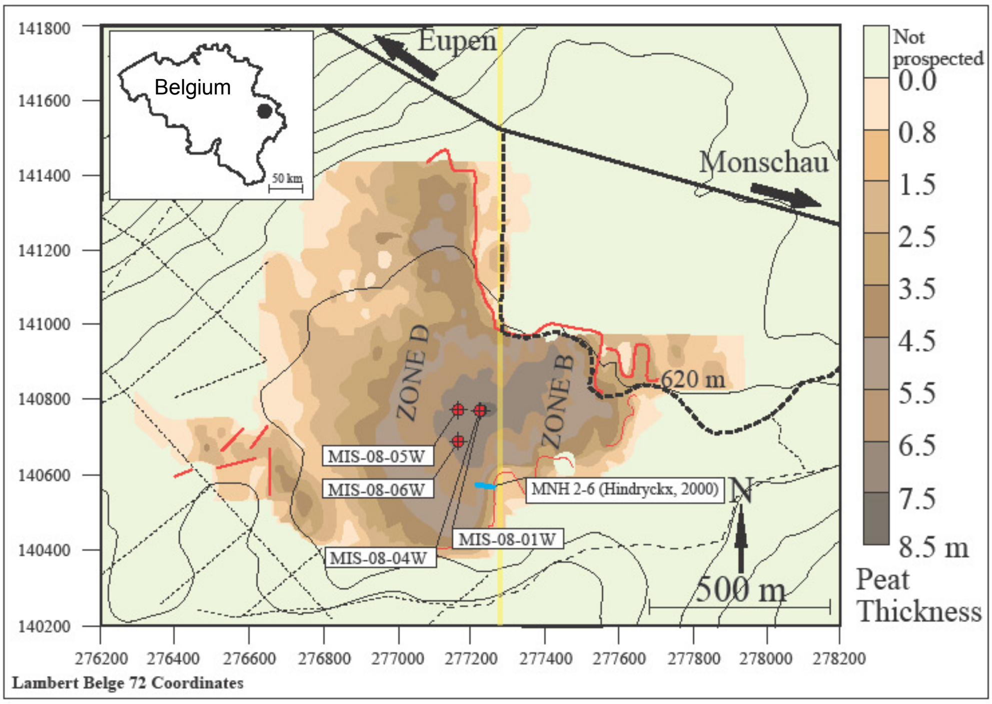


Figure 1. The Misten bog (Hautes-Fagnes, Eastern Belgium) and the location of the peat profiles. Peat thickness after Wastiaux (2002). Thick dotted lines are access pathways. Thin dotted lines are forested roads. Red lines are the cutting fronts (stopped after the 2nd world war). The vertical yellow stripe represents the main drain, dug in 1774 as a boundary limiting peat cutting activities (ZONE B) from the now preserved part (ZONE D). It was partially active until 1970.

The saddle-raised Misten Bog (50°33´50´´N, 06°09´50´´E, 620 m a.s.l.) is located in the Hautes-Fagnes Plateau and contains some of the deepest peat deposits of this area, with more than 7 m of peat in its centre (Fig. 1).

A central drain, dug in 1774 as a boundary limiting ancestral peat cutting activities from more preserved part (Nekrassoff, 2007), was partially active until 1970. The bog has also 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. Rare hollows are dominated by *Rhynchospora alba* or *Narthecium ossifragum*. Hummocks are currently hidden by abundant amounts of *Erica tetralix*, *Calluna vulgaris* and a few *Vaccinium* spp. shrubs, reflecting the recent drying of the bog which is also surrounded by *Molinia* grass.

1.2. Field work

Cores were collected (Fig. 1) in February 2008 from the deepest part of the peat bog using a Wardenaar corer (Wardenaar, 1986). Cores 01W, 04W were taken in and around one single hummock at a very short distance from each other. Core 05W was taken about 50 m to the west of core 01W and core 06W (De Vleeschouwer et al., 2012) 100 m to the south. Additionally, we will take into account 5 other cores, each of them made by alternation of two boxes of 30 cm long and 5 cm wide. They were studied by M.N. Hindryckx during her thesis in 2000 but are still unpublished. The 5 cores (MNH 2 to 6) were taken at the edge of the preserved part of the peat bog, 200 m south of cores 01W and 04W. MNH 2 is the core taken nearest the border rim of the peat bog at a short distance from an old peat-cutting vestige. The other MNH cores were taken in a westerly direction toward the peat bog centre, at 10 m for MNH 3, 20m for MNH 4, 30m for MNH 5 and 40m for MNH 6.

1.3. Previous pollen analysis in the Misten bog.

1.3.1 Schwickerath (1937) and Persch (1950) carried out pollen analyses (at 12 cm and at 5 cm interval respectively) from marginal sections of the 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 Subzone VII to 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 by different authors in the Hautes-Fagnes (e.g. Dricot, 1960; Mullenders & Knop, 1962; Deumer et al., 1964; Trullemans, 1971; Damblon, 1978).

However Persch (1950) did not have access to radiocarbon analysis at that time. He nevertheless proposed a rather detailed estimated age of the four *Fagus* maxima. For that purpose, he chose two well-dated biostratigraphic pinning points, separated by 120 cm in his sequence. The two dates are the base of the Subatlantic Period, known then at 600 BC, and the top of the section with the first rise of *Pinus* pollen known as being cultivated since AD 1800 in the region. Assuming constant peat accumulation rate of Misten Bog, he extrapolated the age of the four maxima of the abundance in *Fagus* pollen: *Fagus* maximum FI around AD 1, FII around AD 700, FIII around AD 1200, FIV around AD 1600. (Table 1)

When compared to a much more recent work on Misten Bog (see below.) the dates suggested by Persch (1950) are not confirmed (Streel, 2011). Only the *Fagus* maximum FI was rather well dated compared to 4 successive calibrated ^{14}C dates (AD 86-AD 258) refined by wiggle matching techniques (Streel et al., 2005; Renson et al*.*, 2008) in another locality of the Hautes-Fagnes, 10 km south of Misten Bog.

1.3.2. De Vleeschouwer et al. (2012) and Allan et al. (2013a) reproduced pollen diagrams respectively of the 1 m deep core 06W and of the 1 m deep core 01W (Fig. 1) from a former unpublished report (De Vleeschouwer et al*.*, 2010)

In these pollen diagrams, 9 zones (1 to 9) were recognized from the base to the top with a major limit occurring between Zone 2 and 3 where a sharp drop of *Fagus* pollen is recorded.

Pollen zones 1 and 2 were noted in the unpublished report as belonging to Zone IX and the next pollen zones to Zone X of Firbas (1949). (Table 1)

1.4. Aim of the paper.

We compare the data provided by the Misten cores 01W and 06W, dated with radiocarbon analyses, with 7 other cores taken in the same peat bog. The paper will explore well defined and well dated major quantitative features matched throughout the peat bog, assuming that pollen rain was equally distributed on its rather small surface. The aim of the paper is to demonstrate the potential of detailed sampling to establish a pollen zonation traceable across several cores in the same peat bog in order to establish chronological correlation between them. Furthermore, the paper will use these new techniques to estimate peat accumulation rates across that bog and the lateral variation of the constitutive vegetation through time.

A	B	C	D	E
	Subatlantic phase			
	The conifer period			
	Xd2,Xd3,Xd4 (other *Picea* subzones)		(9/8/7)	
	Xd1 (1st *Picea* subzone)		6	6
	Xc (*Pinus* zone)	5	5	5
	The oak period			
	Xb (*Quercus* peak)	4	4	4
FIV	Xa	3	3	3
	The beech period			
FIII	IXe	2	2	2
FII	IXd	1	1	1
	IXc			
FI	IXb			
	IXa*			
	Subboreal phase			
	VIII**			

A: Persch 1950 after Streel 2011
B: De Vleeschouwer et al. 2010
C: De Vleeschouwer et al. 2012
D: Allan et al. 2013
E: Present paper
* From the beginning of Subatlantic phase (Firbas 1949)
** The Subboreal phase (Firbas 1949)

Table 1. Zonal correlation between previous pollen studies in the Misten.

2. Materials and methods

2.1. Pollen analysis

In total, 293 pollen samples (including MNH cores) were studied with a minimum of 300 pollen grains counted by sample. The core 01W has been entirely sampled and studied for pollen analysis at 1 cm interval (76 samples). The other cores (04W, 05W and 06W) present a lower resolution (32, 26, 45 samples analyzed respectively) at 3 or 4 cm interval. However the higher part of core 04W (from the top to 34.2 cm), of core 05W (from the top to 22.3 cm) and of core 06W (from the top to 20.2 cm) were studied for pollen analysis at 1 cm interval as well as the lower part of core 06W (from 82.6 cm to the base). The 5 MNH cores were sampled at 3 cm interval except the higher part which was studied at 1 cm interval (from the top to 8 cm in cores MNH4 and MNH6; from the top to 9 cm in cores MNH2 and MNH5; from the top to 10 cm in core MNH3).

For each sample, 2 g of fresh material was dissolved in 10% HCl. Humic acids were removed by hot (not boiling) 10% KOH. The residues were then dissolved in 96% acetic acid and treated by acetolysis (Faegri & Iversen, 1989). After centrifugation, the solutions were filtered through 200 µm and 12 µm mesh sieves. The residues on the 12 mµ sieve were washed in 96% alcohol and transferred in glycerin to be mounted on glass slides. Identification of pollen was aided by Moore et al. (1991), Reille (1992, 1995, 1998), Beug (2004) and a reference collection. Pollen percentages were calculated on an arboreal pollen sum (AP) in order to emphasize the main climatically induced changes in the regional surrounding forest.

2.2. Macrofossil analysis

Macrofossil analyses were carried out by D. Mauquoy (in unpublished report De Vleeschouwer et al*.,* 2010) on cores 01W (each 1 cm), 04W (each 4 cm), 05W (each 4 cm), 06W (each 1 cm). Samples were boiled with 5% KOH and sieved through a diameter 125µm mesh retaining the larger size fraction. Macrofossils were scanned using a stereomicroscope (×10–50), and identified using an extensive reference collection of type material (Mauquoy & van Geel, 2007). Volume percentages were estimated for all components with the exception of seeds, *Eriophorum vaginatum* spindles, *Sphagnum* spore capsules, and charcoal particles, which were counted and expressed as the number (n) present in each subsample.

2.3 Testate amoebae analysis

Testate amoebae analyses were carried out on core 01W (each 1 cm). They were prepared following the recommendations suggested by Booth et al. (2010). Only two taxa (*Amphitrema wrightianum* and *Difflugia pulex*) are considered in this paper. A more complete contribution is in preparation (Surface wetness reconstruction using testate amoebae analysis of the mid to late Holocene Misten peat bog, Hautes-Fagnes, eastern Belgium by Beghin Jérémie, Salpeteur Thomas, Charman Dan, Lamentowicz Mariusz, Gerrienne Philippe, Streel Maurice, Court-Picon Mona, Allan Mohammed, Fagel Nathalie and Javaux Emmanuelle.)

2.4. Chronology

Age/depth-models for cores 01W (Allan et al., 2013a) and 06W (De Vleeschouwer et al., 2012) were constructed using ^{14}C dates and CRS modeled ^{210}Pb ages. Radiocarbon dates were translated to calendar years using the IntCal09 calibration curve (Reimer et al*.,* 2009). Age depth-models were then drawn (using an autoregressive process with a degree of "memory", Blaauw & Christen, 2005, 2011) (Fig. 2). From these models, calendar age distributions were constructed for all depths. 22 dates were placed on core 06W, 5 dates on core 01W and basal dates on cores 04W and 05W. MNH cores were not dated.

3. Results and discussion

3.1. Definition and correlation of pollen zones and their application for evaluating peat accumulation rates and climatic versus human influences on Misten Bog

Based on experience gained from the previous works of Persch (1950), Dricot (1960) and Damblon (1978) we know that less abundant taxa like *Alnus, Betula, Carpinus* and *Corylus* were not so important in subdividing Subatlantic pollen diagrams in the Hautes-Fagnes area. *Carpinus*, however, is known to reach 10 % only during the late part of the Beech Period (Persch 1950) and, for that reason, is added to the list of arboreal taxa living outside the bog.

In contrast, *Corylus* abundance is not diagnostic during the late Subatlantic. Furthermore, its preference for marginal parts of forested soil (Damblon 1978) suggests some edaphic control on their local distribution. For these reasons *Corylus* is omitted from the zonation. The same is true for *Betula* whose abundance is difficult to interpret in term of possible natural wooding of the bog; pollen grains of *Betula pubescens* (possibly living on the bog) and *Betula pendula* (living mainly with *Quercus* around the bog) cannot be discriminated under a light microscope. *Alnus* was growing in the minerotrophic areas (the "laag") surrounding the ombrotrophic central part of the peat bog. The degree to which local pollen production can be used to interfere with more regional pollen rain is a matter that will be discussed below.

We have used stratigraphically constrained cluster analysis (CONISS Grimm, 1987), with data converted to proportions and square root transformation, on 5 taxa living outside the peat bog (*Fagus, Carpinus, Quercus, Picea and Pinus*) for all cores. To highlight the limits suggested in these cores by the CONISS analysis they have been emphasized using simplified arboreal pollen diagrams. Abundances of fewer than 5 % have been omitted for more clarity of these diagrams which incorporate also *Alnus* percentages (not in the CONISS analysis) for further discussion. TILIA graphs (Grimm, 1990) of cores 01W, 04W, 05W and 06W are given in addenda 1 to 4.

3.1.1. Definition of the zones in cores 01W and 06W. (Fig. 3)

Cluster analysis of core 01W delimites clearly three superzones (Beech, Oak and Conifer) and several zones, which correspond to the empirical subdivisions, from 1 to 6, formerly used in recent papers (Table 1). The most obvious zones, from the top to the base, are *Picea* zone 6, *Quercus* zone 4 and *Fagus* zones 1 and 2; all strongly dominated by their eponymous taxon, often two times more abundant than other taxa. We believe that these correspond to specific pollen rains, which remained constant most often during several hundred years.

The cluster analysis of core 06W matches all these subdivisions but does not delimitate the superzones highlighted in cluster analysis of core 01W. This is probably the result of the heterogeneity in the sampling density of both cores (1 cm resolution for both cores except from 22,9 cm to 79,7 cm on core 06W where sampling occurred every 3 cm).

Intermediate zone 5 is less easy to define with *Picea* being less abundant than *Pinus* if these pollens are present. Also, the cluster analysis of both cores proposes to subdivide zone 3 in subzones

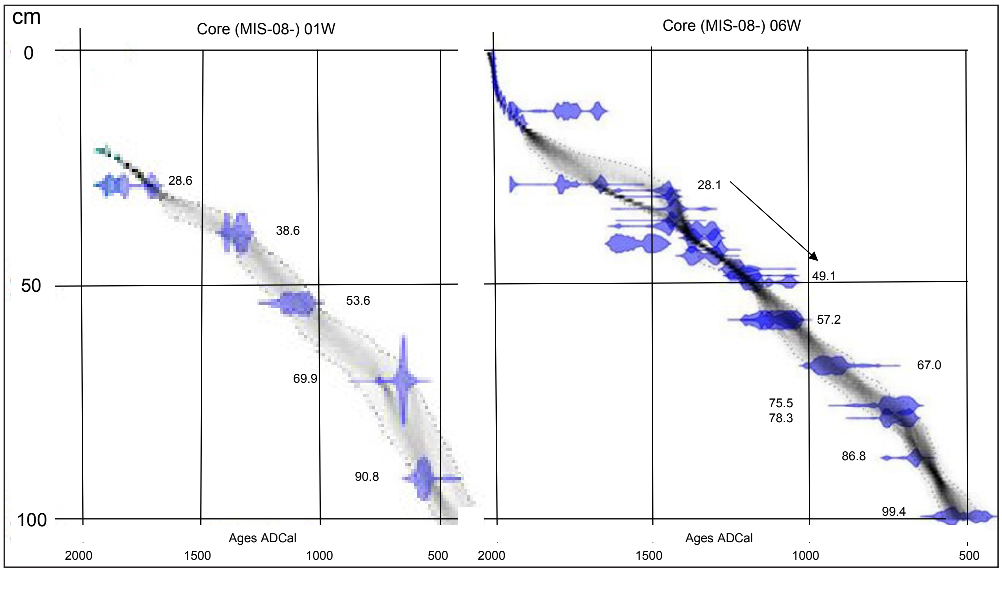


Figure 2. Age/depth models. Core (MIS-08-) 01W reproduced from Allan et al. (2013). Core (MIS-08-) 06W reproduced from De Vleeschouwer et al. (2012). Depth of ^{14}C data are noted within the figures. The grey range of the age/depth models illustrate the 95% confidence interval of the data.

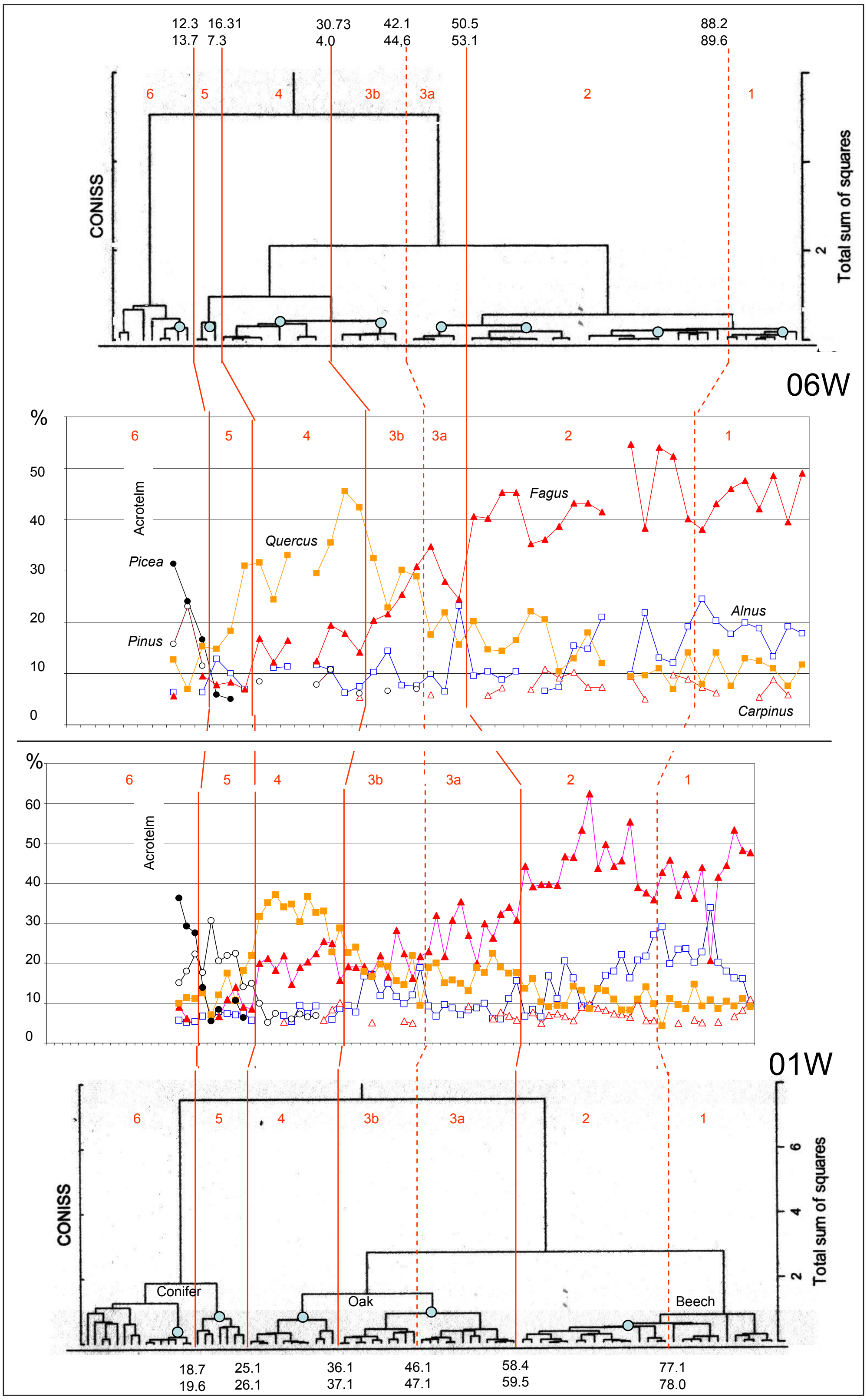


Figure 3. Comparison pollen diagrams linking CONISS analyses of 01W and 06W, the two cores with age/depth-model. The percentages (higher than 5%) of *Fagus, Carpinus, Quercus, Picea* and *Pinus* i.e. the main arboreal taxa living outside the peat bog + *Alnus* are represented. Three superzones (Beech, Oak and Conifer) are identified. Zones 1 to 6, including subzones 3a and 3b limits are in red, their exact position in both cores being indicated

3a and 3b, since *Quercus* is still dominated by *Fagus* in subzone 3a, but alternates its relative abundance with the other arboreal taxa in subzone 3b. Zone 2 (*Fagus* reaching 40% or more) can be differentiated from Zone 1 by several higher maxima of *Fagus* (FIII of Persch 1950) and an almost continuous presence of *Carpinus* (5 to 10%). Zone 1 can also be characterized by *Alnus* abundance which, although rather variable, declines from zone 1 to 2.

The transitional period (Zone 3) from *Fagus* dominance to *Quercus* dominance may be explained by human activity. *Quercus* acorns were used as cattle fodder, whereas its wood was also intensively used for any building. *Quercus* forests were therefore favored. *Fagus* is not only unable to survive wood fires, but was also regularly coppiced for charcoal production, dating back to the 16th century in the Rurbusch forest, a few km south of the Misten (Liégeois-Lemaitre, 1957).

The rise of *Pinus sylvestris* in the upper half of Zone 4 may correspond to the first culture of this species in the neighboring Hertogenwald in 1750 (Pahaut & Oldenhoven de Guertechin, 1962). However, *Pinus* pollen grains are light and transport long distances, which is not the case of heavier *Picea* pollen. Strictly local production of *Pinus* pollen grains is therefore uncertain.

The ^{210}Pb and ^{14}C dates available for cores 01W and 06W have been used to check the age of the zonal limits (Table 2, Fig. 4). Keeping the correlations within their respective 95% confidence interval, both age/depth-models are compatible with the notable

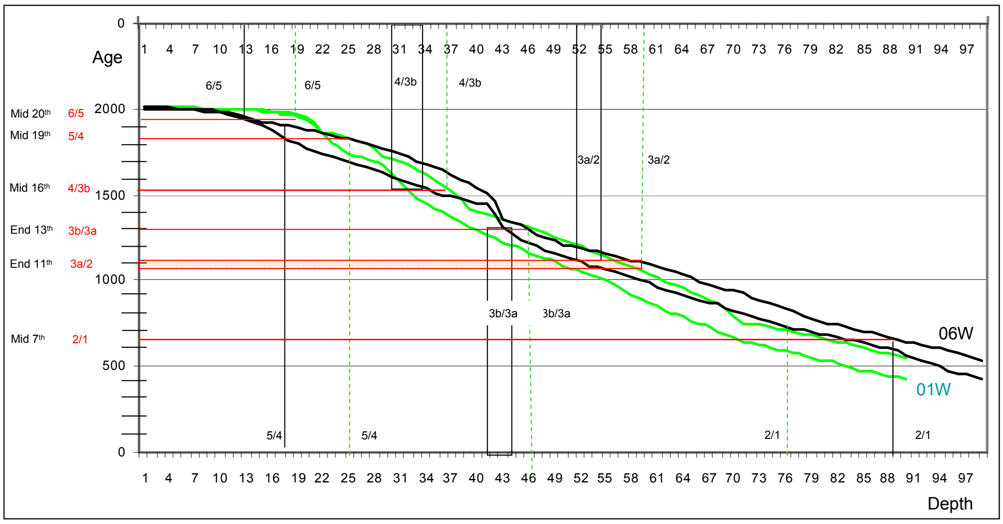


Figure 4. Overlapping of both age/depth models and estimated age of the pollen zone limits.
Green thick line and vertical dashed lines refer to core 01W. Black thick line and vertical lines refer to core 06W. Red horizontal lines connect compatible ages of the pollen zone limits (See also Table 2). Limits 3a/2 are not compatible and should better read as Middle 12th Century (See text).

exception of the limit 3a/2. With this limit being based on a very distinctive pollen signal (a sharp drop in abundance of *Fagus*), we suggest that the poorly supported 01W age/depth-model is largely responsible of the more than one century difference in age and that the mean date of end 11th Century applied on Table 2 and Fig. 4 should better read as middle 12th Century.

3.1.2. Application of the zonal scheme to the other cores

CONISS analysis of core 05W (Fig. 5) is very similar to the proposed subdivisions for core 01W (Fig. 3). This is less evident for the CONISS analysis of core 04W, although the comparison of cores 05W and 04W is easy from their comparison through the simplified arboreal pollen diagrams.

The correlation (Fig. 6) between all 5 simplified arboreal pollen diagrams of MNH cores is a good opportunity to test the pollen zonation and demonstrate that the thickness of peat accumulated during zone 4 to 6 is progressively reduced from MNH6 to MNH2 on the rather short distance of 40 m (See 3.1.4.). Note that the sample 31 in Zone 4 of core MNH 6 is considered a probable field contamination by *Picea* pollen during sampling and is therefore excluded from the interpretation. The subdivision of zone 3 in two subzones is not that easy to recognize in these cores and is therefore omitted.

3.1.3. Validity of the zonal scheme as time-lines

We have been able to recognize the zonal scheme at different distances between the core locations: 100m (01W, 05W, 06W and MNH2 cores), 10m (All MNH cores), 1m (Cores 01W and 04W). According to the age/depth-models, the duration of each zone varies from 500 years (Zone 2) to 100 years (Zone 5), i.e. at a centennial scale. We know no similar published study made at comparable scales in a similar forest environment. Hughes et al (2000) used pollen correlation in northern England between two ombrotrophic lowland peat bogs situated on similar geology, with

A	B	C	D	E	D	E	C	B	A	F
	01W		Blaauw	01W	Blaauw	06W		06W		
6//5	18.7	19	1958	1964-1954	1940	1949-1930	13	12.3	**6//5**	Middle 20th
	19.6	20	1946	1952-1941	1928	1935-1921	14			
					1915	1926-1905	15	13.7		
5//4	25.1	26	1770	1818-1723	1881	1909-1842	17	16.3		
	26.1	27	1747	1795-1705	1863	1900-1816	18	17.3	**5//4**	Middle 19th
					1623	1719-1564	32	30.7		
4//3b	36.1	37	1445	1520-1367	1607	1698-1549	33			
	37.1	38	1412	1481-1344	1589	1675-1533	34			
					1573	1659-1516	35	34.0	**4//3b**	Middle 16th
					1336	1361-1312	43	42.1		
3b//3a	46.1	47	1220	1293-1142	1306	1347-1276	44			
	47.1	48	1200	1275-1123	1281	1329-1240	45			
					1256	1297-1218	46	44.6	**3b//3a**	End 13th
					1149	1188-1106	52	50.5		
3a//2	58.4	59	978	1060-897	1135	1179-1089	53			
	59.5	60	958	1041-875	1121	1168-1075	54			/Middle 12th
					1106	1156-1062	55	53.1	**3a//2b**	End 11th/
2//1	77.1	78	633	690-564	612	646-569	90	88.2	**2a//1b**	Middle 7th
	78.1	79	619	679-552	596	635-549	91	89.6		

A = limits of zones; B = recalculated depth; C = sample number; D = wmean AD
E = 95% confidence interval; F = Approximate age

Table 2. Calendar age distribution reconstructed by Blaauw (See Blaauw & Christen, 2011) for all depths of pollen zone limits in 01W and 06W. Grey confidence intervals 95% are compatible (except 3a/2 See text)

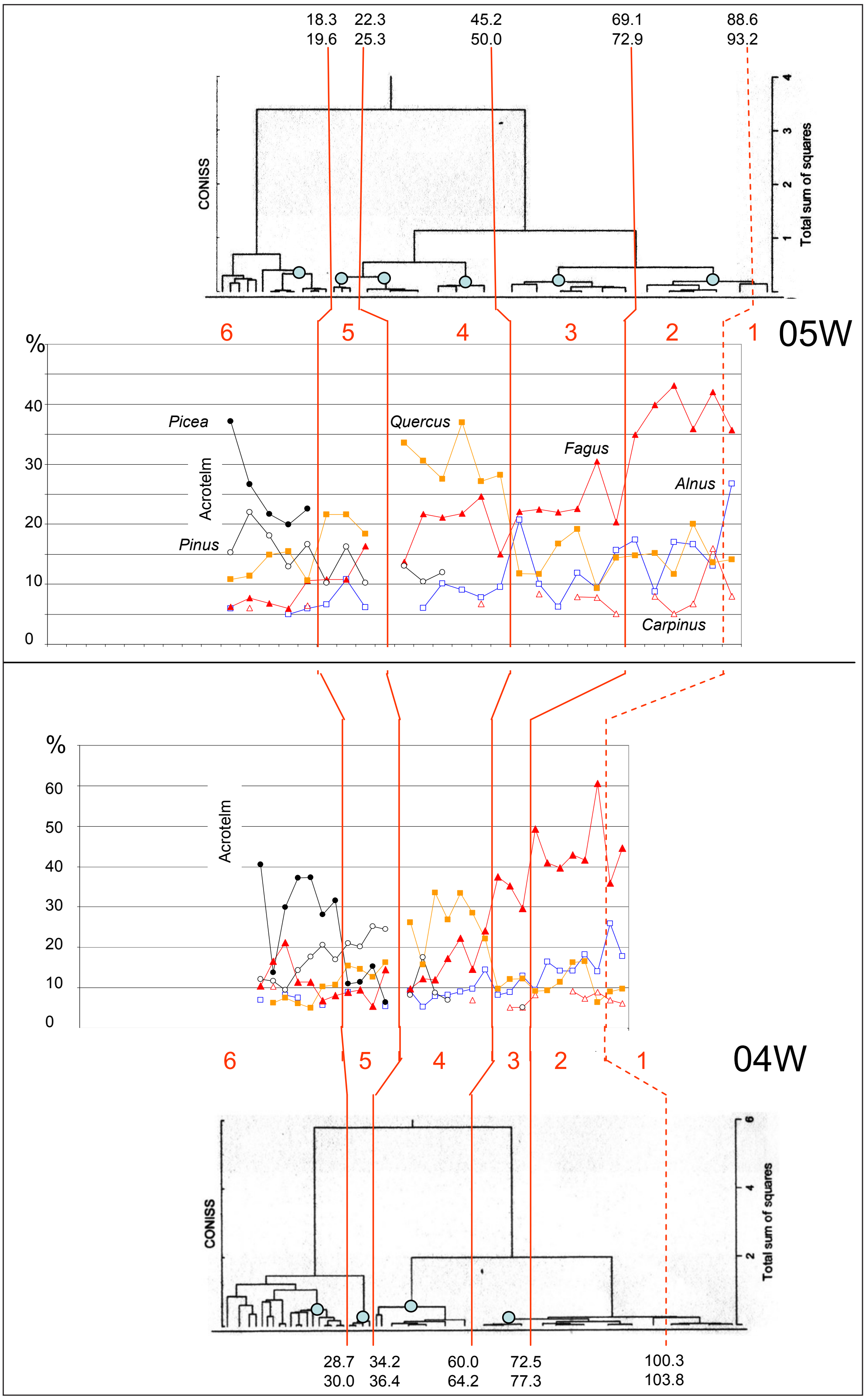


Figure 5. Comparison pollen diagrams linking CONISS analyses of 04W and 05W. The percentages (higher than 5%) of *Fagus, Carpinus, Quercus, Picea* and *Pinus* i.e. the main arboreal taxa living outside the peat bog + *Alnus* are represented. Zones 1 to 6 limits are in red, their exact position in both cores being indicated.

similar basin size and local climate but distant of 3 kilometers. They identified 7 regional pollen zones based on main species of arboreal pollen in the lower Holocene. The recent contribution on the Engbertsdijksveen (eastern Netherlands) casting uncertainty of pollen proxy for correlation (Blaauw & Mauquoy, 2012) is not that convincing. The nearest hills of up to 50-70 m height above sea level that could have produced acceptable regional pollen were kilometers in distance. Consequently, during the Subatlantic period, these authors selected regional pollen *Fagus* and *Corylus* never reached more than 10 to 20 %, i.e. rather low percentages to help correlation, compared with the high percentages used in our zonal scheme. Only their third and last choice of regional pollen, *Alnus,* was regularly reaching between 40 and 60 % but they correspond to the vegetation cover of the whole region, for instance floodplain, being probably depending on the local water level fluctuations to a greater extent, if not on regime change of the small river 8 km away. Brown (1988) has made valuable comments on the importance of interactions between geomorphology and *Alnus* dynamic in similar environment.

Accepting that the age/depth-models of 01W and 06W, within their respective 95% confidence interval, are almost compatible (See 3.1.1.) and taking into account the dense forested environment producing in abundance the succession of the selected key pollen markers, we shall consider the limits between our zones as the best time-lines available.

3.1.4. Variation of peat thickness in each zone

Fig. 7 demonstrates that the thickness of each zone in the nine

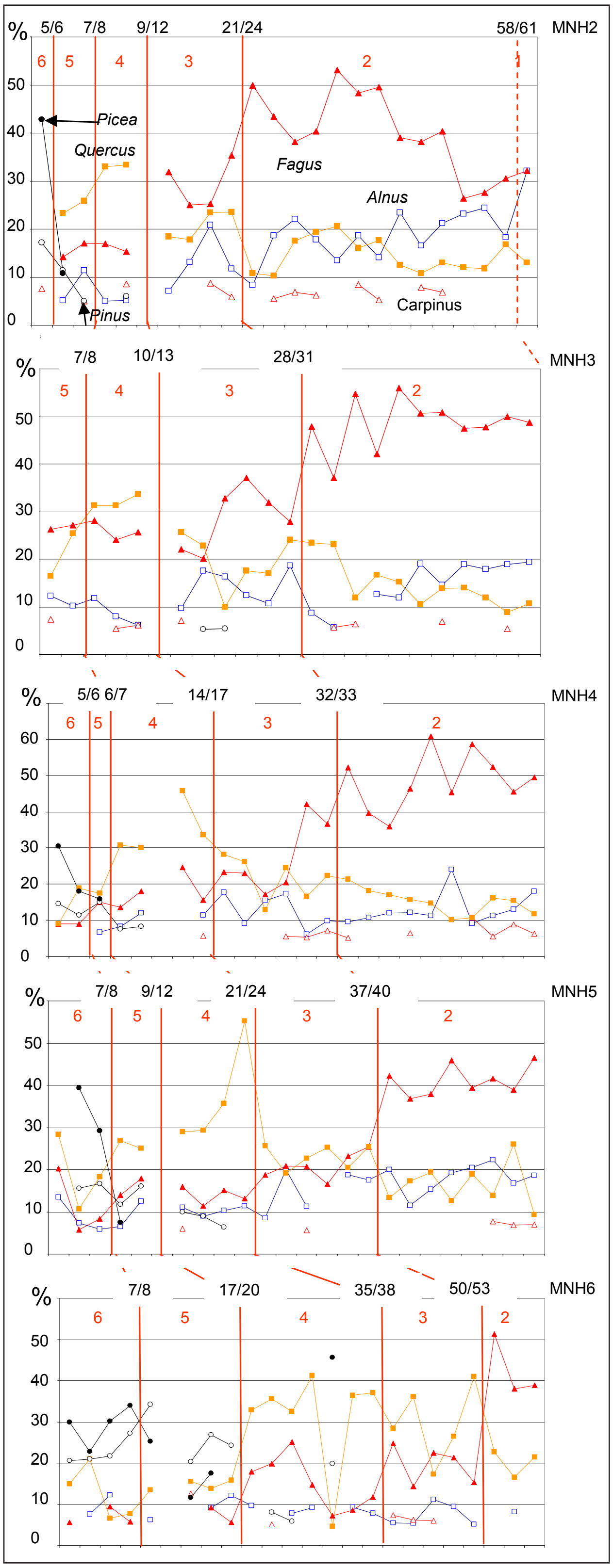


Figure 6. Comparison pollen diagrams of the 5 cores MNH. The percentages (higher than 5%) of *Fagus, Carpinus, Quercus, Picea* and *Pinus* i.e. the main arboreal taxa living outside the peat bog + *Alnus* are represented. Zones 1 to 6 limits are in red, their exact position in both cores being indicated. MNH 2 is the core taken nearest the border rim of the peat-bog at a short distance from an old peat cutting vestige. The other MNH cores were respectively taken in the west direction, i.e. toward the peat bog centre, at 10 m for MNH 3, 20m for MNH 4, 30m for MNH 5 and 40m for MNH 6.

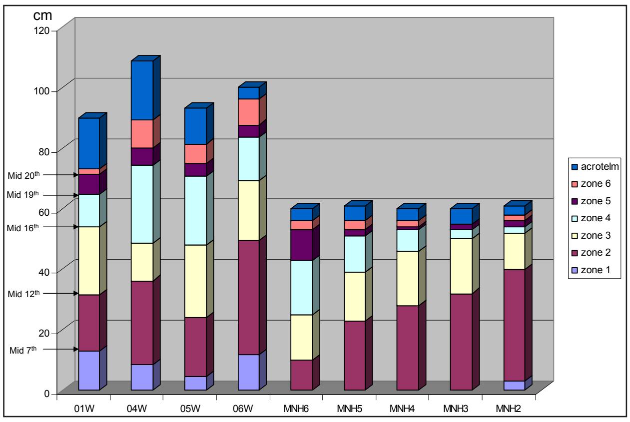


Figure 7. Peat thickness corresponding to each zone in the 9 investigated cores.

cores is variable. Cores MNH6 to MNH3 were not deep enough to reach the limit 1/2 but cores MNH2 and 06W show that the peat accumulation rate during Zone 2 was distinctly higher in the south-eastern part of the bog than in the central part between the mid-7th and mid-12th centuries (see also Fig 4). During zone 3 (between the mid-12th and mid-16th centuries) the cores present a more equal peat accumulation rate than during zone 2, but is however often more important in the central part of the bog than in the south-eastern part. In core MNH2, the rate is distinctly the lowest. That reduction of peat thickness in core MNH2 is interpreted as a result of the proximity of an area of peat cutting during the 14th Century (Hindryckx & Streel, 2000). The disturbed area is still visible today and would have lowered the local water table and consequently decreased peat accumulation. Lowering of the water table reached core MNH4, 20 m further west inside the bog, during Zone 4 (between the mid-16th and mid-19th centuries) and core MNH5, 10 m further west, during Zone 5 (between the mid-19th and mid-20th centuries.

Cores 01W and 04W, taken at the same hummock, present conspicuous peat thickness difference in zones 2 to 4. This is probably due to the longer persistence of *Sphagnum imbricatum* and *S. papillosum* in core 04W than in core 01W as these species build more peat than the other species of *Sphagnum* (See 3.2.).

3.1.5. Climatic versus human influence on the Misten peat bog

Mainly based on the distribution of the hydrophilous testate amoebae *Amphitrema wrightianum,* Beghin et al. (2011) recognize a severe drop at the limit between zones 1 and 2 in the core 01W suggesting that a dry period started during the 7th Century (the Vandal Minimum). This dry period had probably a severe effect on the *Alnus (A. glutinosa)* community surrounding the ombrotrophic bog with its pollen percentage dropping from 25 % to 15 % in most cores, around the limit 1/2.

However, although a new abundance of the same testate amoebae indicates a more humid climate in the second half of Zone 2 (Beghin et al., 2011), during the Medieval Warm Period, *Alnus* pollen percentages continue to decrease and maintain around 10 % from the limit 2/3 i.e. the mid-12th Century to the limit 4/5 in the mid-19th Century. *Alnus* was used as green manure by foresters and was also collected for easy burning. Its decreasing pollen percentages may have been controlled by human activity, like opening cultivated clearing in the forest.

Pollen percentages of *Cerealia*-type *and Plantago* (especially *P. lanceolata* which is a common weed of cultivated land in Ardenne region) can help to solve the question.

In Fig. 8, the zones 1 to 6 are projected, with their AP based limits, on the diagrams of these two NAP pollens in cores 01W, 04W, 05W and 06 W. In zones 1 and 2, *Cerealia*-type percentages stay always below 2%, but reach 3% and even 4% immediately after the 2/3 zonal limit, i.e. in the mid-12th Century, which corresponds to the sharp decline of the *Fagus* forest. They show a first maximum to 6% in Zone 3 before decreasing near the end of that zone in early 16th Century, i.e. at the start of one of the major solar phase (the Spörer phase after Reimer et al., 2009) of the Little Ice Age.

A second maximum of *Cerealia-type* and a significant increase of *Plantago* is reached in the second half of Zone 4 and during Zone 5, i.e. near the end of the Little Ice Age, decreasing in the later zone, during the 19th Century. The recent regression of the cultivated area is probably linked to the *Picea* plantations.

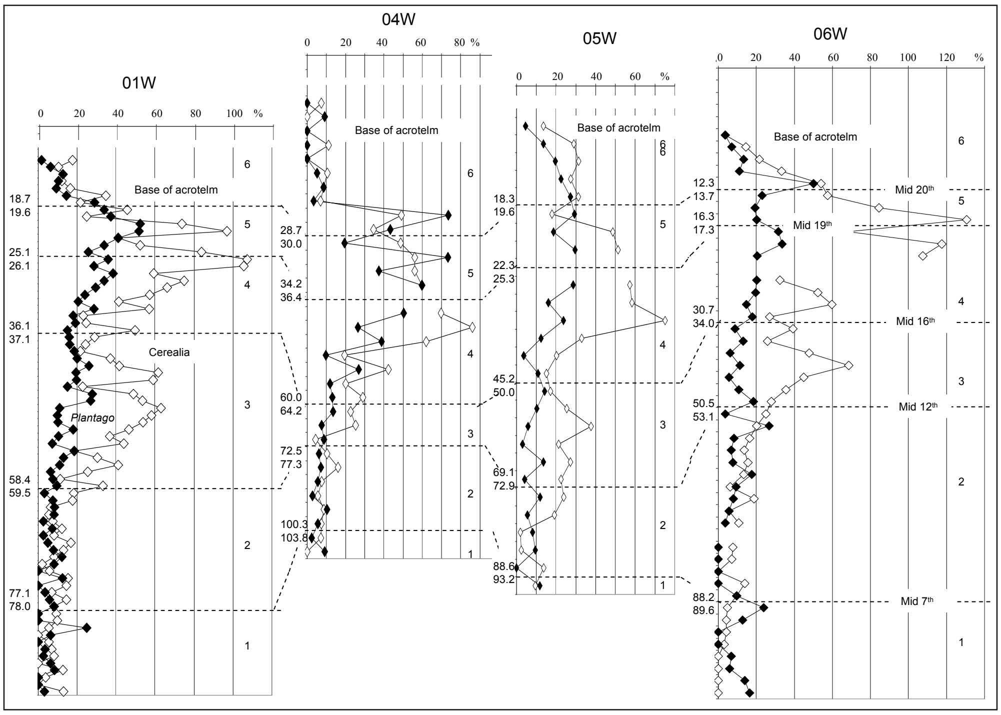


Figure 8. Comparison of percentages of selected anthropogenic indicators (*Cerealia* type, *Plantago)* in cores 01W, 04W, 05W and 06W. Limits between zones from Figs.3 and 5.

We therefore suggest a major climatic event to be responsible of the *Alnus* regression before the mid-12th .Then the human impact on these local woods starts with the Medieval Climatic Maximum but was slightly reduced during the major phases of the Little Ice Age.

In Fig. 9, we have opposed two species of testate amoebae, the hydrophilous *Amphitrema wrightianum* and the hygrophilous *Difflugia pulex*. *D. pulex* is abundant during the dry Vandal Minimum when *A. wrightianum* is almost absent. The latter recovers during the Medieval Warm Period but is replaced again by *D. pulex* from the end of the 12th to the mid-16th centuries, i.e. about the same period of the Little Ice Age when non arboreal pollens linked to farming are decreasing. *A. wrightianum* dominates again during the early part of the 19th Century when non arboreal pollens linked to farming are increasing again, and then disappears from the record at mid-19th Century.

3.2. Application of the pollen zones to demonstrate and date the lateral variation of the Misten bog vegetation in the past.

During the last Century, a controversy raised about how the bog vegetation was building the peat. We refer to Barber (1981) for a deep discussion of the involved opposite theories: the regeneration complex theory and the stationary hummocks theory (Fig. 10). We have here the opportunity to compare an independent plant macrofossils analysis within each pollen zones to demonstrate the lateral variation of the constitutive vegetation in the past and discuss these theories.

3.2.1 Comparison of macrofossil (mainly Sphagnum*) data in each zone (Fig. 11).*

Fifty years ago, the Hautes-Fagnes peat bogs vegetation cover was described (Streel, 1959) as showing three major steps of evolution: (i) *Sphagnum* sect*. Cuspidata* characteristic of

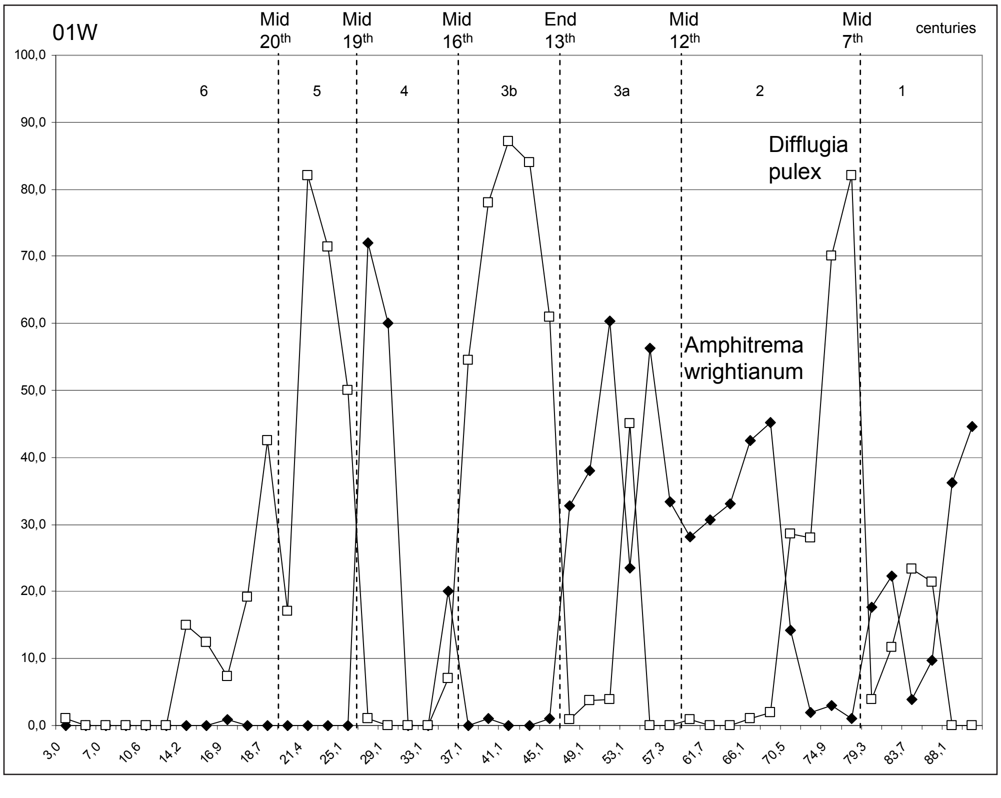


Figure 9. Proportion of two testate amoebae in core 01W. Limits between zones from Figs.3.

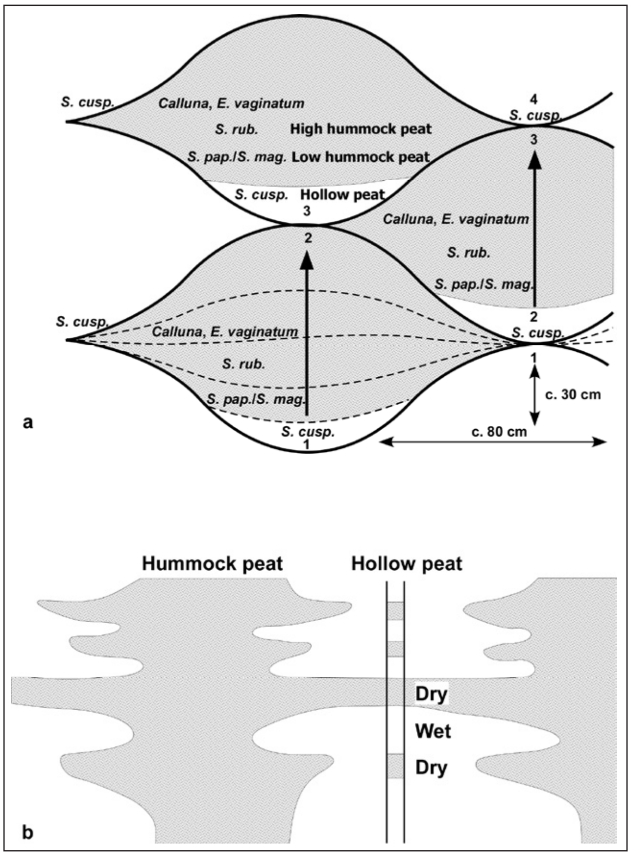


Figure 10. a. Idealized cycles of the Regeneration complex theory of Von Post & Sernander 1910, after Barber 1981, modified. b. Stationary hummocks theory of Aaby 1976, modified.

hollows evolving (ii) in low hummock with *S. papillosum, S. magellanicum* and sometimes *S. imbricatum* and (iii) higher hummock with *S. rubellum* and other *S.* sect. *Acutifolia*, covered by *Calluna vulgaris*, lichens and liverworts. Extension of the latter at the expense of *Sphagnum* was believed to prepare the first step toward a new hollow place between surrounded hummocks continuing to grow, as an application of the regeneration complex theory (Sernander, 1909, Von Post & Sernander, 1910).

In the past, from the mid-7th to the mid-16th Century, during zones 1 to 3, the vegetation in cores 01W, 05W and 06W was rather homogenous with a group of *Sphagnum* sect. *Cuspidata,* characteristic of "hollow places", alternating in most cores with low hummock of *S. imbricatum*. In core 01W, Zone 3, the succession of *Sphagnum* sect. *Cuspidata,* characteristic of hollows and the low hummock of *S. imbricatum* coincides with the change from the hydrophilous *Amphitrema wrightianum* to the hygrophilous *Difflugia pulex*. After G. Mallon, Sheffield (personal communication, December 2013) *D. pulex* has an optimum at around 10-15 cm from the water table.

The step hollows seems to follow or be linked with the development of *Eriophorum vaginatum* peat. During the transition from 3 to 4, the decline of *S. imbricatum* started, replaced by *S. papillosum* and the "hollow" step with *S.* sect. *Cuspidata* seems to have disappeared except in Core 05W.

The wide occurrence of *E. vaginatum* peat immediately below the surface (zone 6 in core 06W) is probably linked to running fires on the peat bog. Often today when *Sphagnum* is allowed to reinstall, *S. fallax* is observed, as it is on the top of core 05W.

The *Sphagnum* content is also totally different during the conifer period in core 01W compared with 05W and 06W, distant of 50 m and 100 m, with respectively an acrotelm (zones 7-8-9) of *S. magellanicum,* versus *S. papillosum* versus *S. fallax* above a homogeneous layer (zone 6) of *E. vaginatum.*

A large number of charcoal particles indicate that the most recent trace of important running fires on the peat bog is in zone 6 of core 06W followed immediately by an *E. vaginatum* development and subsequently by the reinstallation of *S. papillosum*.

Traces of fire on the peat bog also occur in almost all cores from late Zone 3 to zones 4 and 5, i.e. from the early 16th Century to the mid-20th Century, sometimes linked to *E. vaginatum* extension. Fires occurred more sporadically in Zones 1 and 2 i.e. before the 12th Century.

Aaby (1976), reproduced by De Vleeschouwer et al. (2011), considers that the locations of individual hummocks and hollows change little through time and that their interfaces do vary, becoming wetter and drier in response to fluctuations in climatic conditions i.e. synchronously as clearly suggested by their scheme.

We do not have enough sections to validate or falsify this theory for the Misten area but zones 1 to 3 of core 04W illustrate

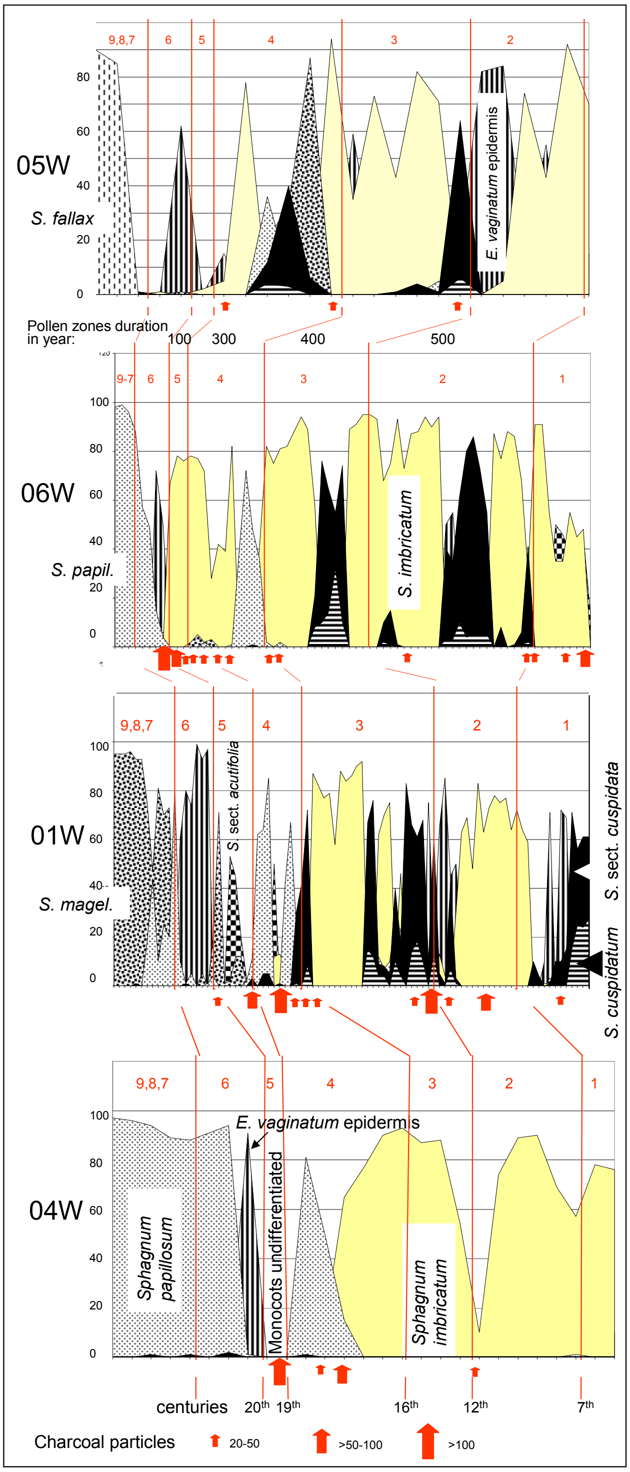


Figure 11. Simplified macrofossil diagrams (%) of cores 01W, 04W, 05W and 06W

Limits between zones from Figs. 3 and 5. Red arrows are charcoal occurrences.

Cores 01W and 04W were taken at a short distance in a same hummock.

such a situation with a hummock of *S. imbricatum* persistent during at least 1000 years. Aside, in Core 01W (1 m distant), there is an alternation of hollows with *S.* sect. *cuspidata* and hummocks of *S. imbricatum*. However, comparisons of cores 05W and 06W with core 01W demonstrate that although hollows with *S.* sect. *Cuspidata* in Zone 3 seems to be more or less synchronous, they are not in Zone 2. Aaby (1976) scheme is therefore too much simplified.

On another hand, hollow versus hummock cycles are clearly seen in core 05W from zones 3 and 4 and also in core 01W from the top of zones 3 to 5, i.e. during 300 to 400 y.

We, therefore, suggest that both theories are not mutually exclusive and perhaps that the development of one or the other mode of building peat bogs is rather dependent on the initial morphology of the bog. For instance raised saddle moors like the Misten should perhaps not be assimilated to the almost coastal flat raised moors known from many northwestern European countries.

3.2.2. The decline of S. imbricatum*, a climatic change or a human perturbation?*

In Misten Bog, during the transition from zones 3 to 4 (near the Mid-16th Century), the decline of *S. imbricatum* started, replaced by *S. papillosum*. *S. imbricatum* is still present in zone 5 in cores 06W, between the end of the 18th Century and the mid-20th Century.

According to Mauquoy & Barber (1999), the decline of *S. imbricatum* in Great Britain is noted in the 15th Century but its regression is noted as early as the 6th century (Charman 1990). However Barber (1981) found *S. imbricatum* to exist on highest hummocks up to 1800 AD in the British Isles. Goode (1970) also found that, if *S. imbricatum* declined in the wet lawn environments in the past, it is still found today on top of hummocks. Consequently, when applying the Dupont (1986) indexes to plant macrofossils to have a quantitative appreciation of water level changes, *S. imbricatum* is normally given (Mauquoy in De Vleeschouwer et al., 2010, p.39, Daley & Barber, 2012) a value of 5, placing it fairly in the middle of the hydrological gradient higher than the value given to most of other *Sphagnum* species, which implies a rather dry environment.

However, if *S. imbricatum* is no longer producing thick peat layer, it still occurs today in the Hautes-Fagnes where it may constitute part of the lower hummocks, between 0 to 25 cm above the water table, and is present in 34 % of the phytosociological survey of another raised saddle moor of the Hautes-Fagnes (Streel, 1959). Schwickerath (1944) noted in the same area the presence of communities he named *Sphagnetum imbricati* completely dominated by the eponym species and also linked to low hummocks. It happens therefore that *S. imbricatum* ecological needs are not yet well understood, being different for instance in the Hautes-Fagnes compared to the British Isles (See also Green 1968).

A recent survey in the Hautes-Fagnes area (A. Vandenpoorten, Liège, personal communication November 2013) however suggests that only the subspecies *"affine"* of *S. imbricatum* is present today. As significant portions of the *S. imbricatum* peat in the Misten obviously belong to another subspecies i.e. *S. imbricatum* ssp. *austinii* (G. Mallon, Sheffield, personal communication) one can assume that the two subspecies might have different ecological needs as already suggested in Norway by Flatberg (1986).

Numerous explanations (Hughes et al., 2007) have been proposed to explain the decline of *S. imbricatum*, including (1) a climate "wet-shift"; (2) interspecific competition between *Sphagnum* species: (3) deposition of eroded soils/dust; (4) drainage/peat cutting, grazing and burning.

(1) A climate "wet-shift" on top of the last *S. imbricatum* peat is only noticeable in core 01W at the limit 3/4 (mid-16th century), not in the other cores.

(2) In all cores, the last *S. imbricatum* peat is surmounted by *E. vaginatum* or *S. papillosum* peat, not by *S. magellanicum* as often shown in the British Isles (Stoneman et al. 1993; Hughes et al., 2008), excepted in core 05W/ Zone 4. The competition between *S. imbricatum* and *S. magellanicum* is not confirmed in the Misten bog.

(3) High concentration in Si and Ti in the Misten (Allan and Fagel *in* De Vleeschouwer et al. 2010, fig. 39; Allen et al. 2013b) is obvious in the second half of Zone 4 and during Zone 5, i.e. near the end of the Little Ice Age. It corresponds to the second maximum of *Cerealia*-type and the significant increase of *Plantago*. There is also higher concentration of N in the same time range (Leclercq *in* De Vleeschouwer et al. 2010, fig. 58). Atmospheric deposits might have played a role in the final disappearance of *S. imbricatum* peat as suggested by Van Geel & Middledorp (1988),

(4) but it corresponds also to a period of maximum of peat cutting and grazing i.e. a period of increasing desiccation of the peat bog.

4. Conclusion

Enclosed permanently in woods, the Misten ombrotrophic bog has received homogeneous pollen rain through time, dominated successively by *Fagus, Quercus* and *Picea*. These arboreal pollen assemblages allow recognition of 6 pollen zones. After checking the compatibility of ages of their mutual limits with two age/depth models, these limits are used as time-lines. Based of these time-lines separating pollen zones across 9 cores we show that the areas of major peat production were moving with time from one side of the peat bog to another. The reduction of thickness of peat was strongly dependant on the proximity to areas of peat cutting since the 12th Century. The progressive drying of the surface of Misten Bog through time in the edge of the preserved part of the peat bog is demonstrated.

A major extension of the *Alnus* wood around the bog corresponded to a rather climatic humid period before the 7th Century. On the contrary the decreasing abundance of *Alnus* pollens during the 7th Century might correspond to the dryer climate of the Vandal Minimum. This is corroborated by a change of dominance of hydrophilous to hygrophilous testate amoebae. Later on, as a consequence of increasing human pressure, *Alnus* wood did not recover, although a more suitable climate was present during the Medieval Warm Period.

Wood cutting of *Fagus* is obvious since the mid-12th Century. Its decreasing influence on the pollen rain is explained by its poor capacity to compete with *Quercus* favored by human activities.

From the mid-12th to mid-16th centuries, there is a slight increase of *Cerealia*-type and *Plantago* pollens which indicates the progress of farming processes in the region but the major extension of farming is noted by a higher abundance of *Cerealia*-type pollens during the early part of the 19th Century, a period of last occurrence of abundant hydrophilous testate amoebae. Farming was probably reduced during the major phases of the Little Ice Age.

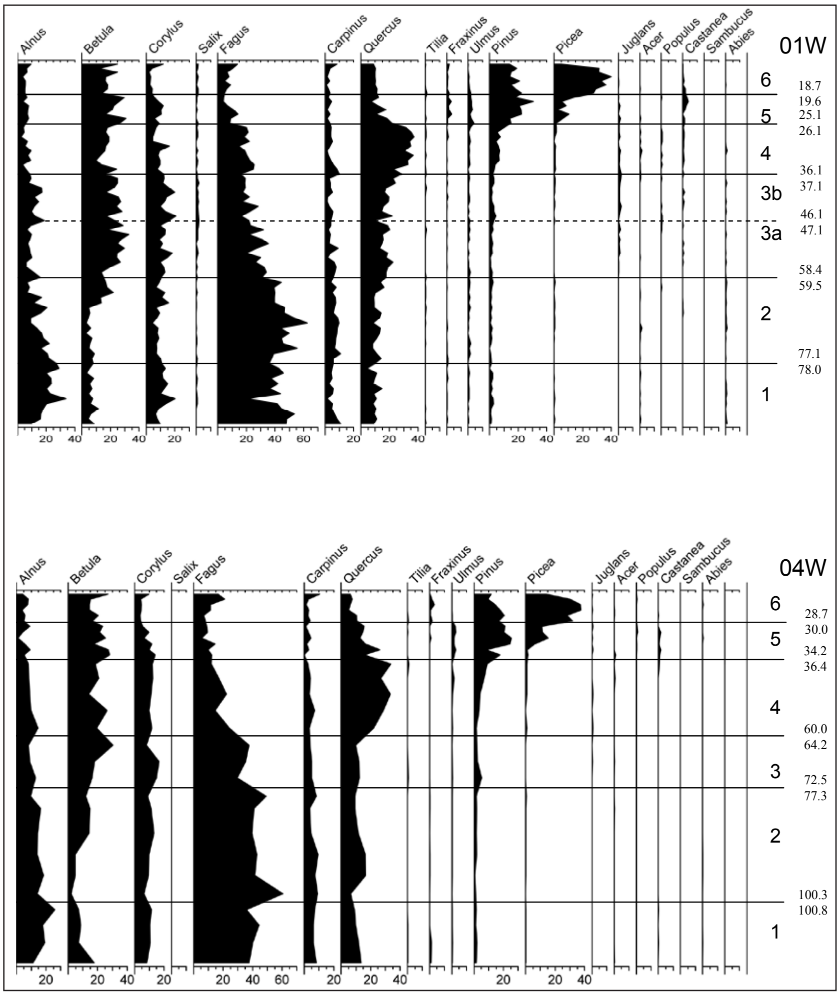
From the mid-16th Century, *S.* sect. *Cuspidata* peat almost disappeared, reflecting a lowering of the water level due probably to major peat cuttings at the outer rim of the Misten bog, mainly in the North-Eastern and South-Eastern edges.

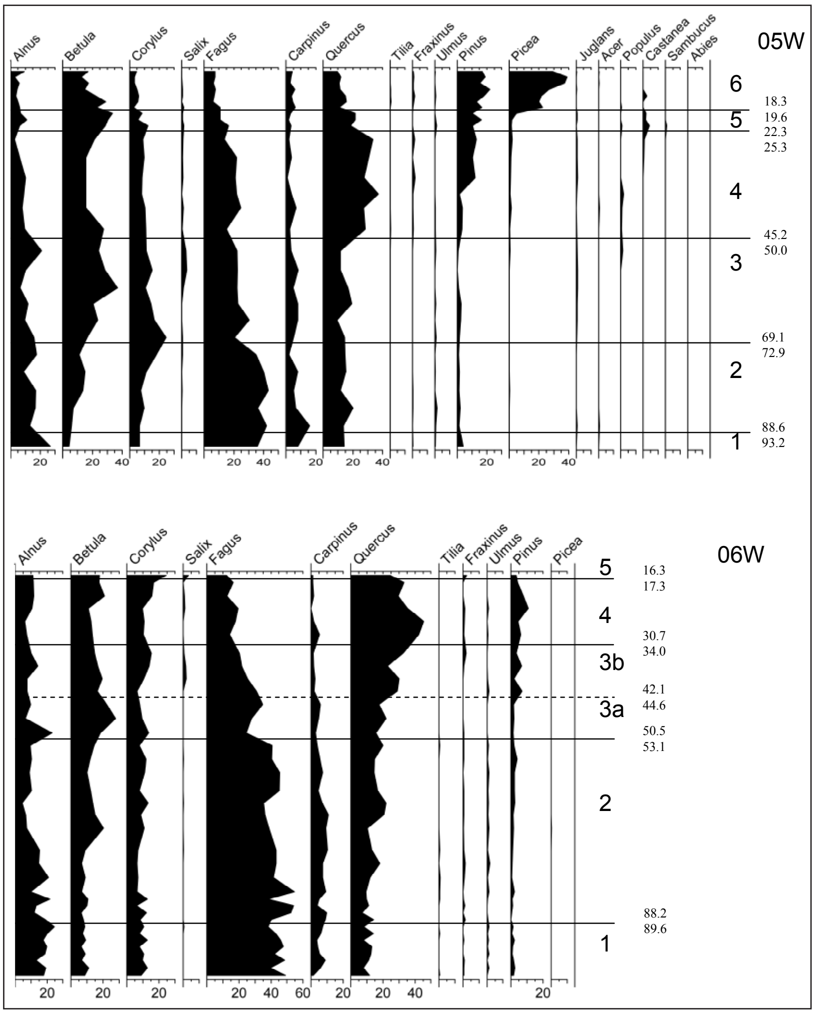
High concentration of Si, Ti, and N is obvious also in the second half of that period and also between the mid-19th and mid-20th centuries, a probable consequence of the increasing farming activity and of the industrial revolution. They might also have played a role on the final disappearance of *Sphagnum imbricatum* peat during the 19th Century.

On another hand, we have suggested that the apparently opposite theories for building peat, the regeneration complex theory and the stationary hummocks theory, are not mutually exclusive and that the development of one or the other mode was perhaps rather dependent on the geomorphology of the bog.

5. Acknowledgements

We are very grateful to Gunnar Mallon (University of Sheffield) who improved substantially the spelling of our manuscript and for his constructive remarks. We thank the referees, Freddy Damblon (Brussels) and Elodie Faure (Toulouse) for their comments on an earlier version of the manuscript. We also thank Maarten Blaauw (Belfast) for providing calendar age distribution in cores 01W and 06W. We are grateful also to Marcela Mezzatesta –Giraldo for her technical assistance.





TILIA graphs (Grimm, 1990) of cores 01W (addendum 1), 04W (addendum 2), 05W (addendum 3) and 06W (addendum 4), reproduced from De Vleeschouwer et al. 2010. All relative values are on arboreal pollen sum (AP). All value below 10% are also exaggerated 4 x.

6. References

Aaby, B., 1976. Cyclic climatic variations in climate over the past 5500 yr reflected in raised bogs. Nature 263, 281-284.

Allan, M., Le Roux, G., Sonke, J.E., Piotrowska, N., Streel, M. & Fagel, N., 2013a. Reconstructing historical atmospheric mercury deposition in Western Europe using Misten peat bog cores, Belgium. Science of the Total Environment 442, 290-301.

Allan, M., et al., 2013b. High-resolution reconstruction of atmospheric deposition of trace metals and metalloids since AD 1400 recorded by ombrotrophic peat cores in Hautes-Fagnes, Belgium. Environmental Pollution 1, 1-14.

Barber, K.E., 1981. Peat stratigraphy and climatic change. A palaeoecological test of the theory of cyclic peat bog regeneration. A.A. Balkema, Rotterdam 219p.

Beghin, J., Demoulin, A., Javaux, E., Gerrienne, P. & Streel, M., 2011. Modèle climatique des Hautes-Fagnes belges (pollens, thécamoebiens et humification) de 80 AD à 1350 AD, Application de ce modèle à la problématique des glissements de terrain subatlantiques du Pays de Herve. In Gerrienne P, & Steemans, P., Miscellanea palaeontologica 2011, program and abstracts, MVP-PPMB meeting, Liège Nov. 30, 2011, 3-5.

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

Blaauw, M. & Christen, J.A., 2005. Radiocarbon peat chronologies and environmental change. Applied Statistics 54, 805-816.

Blaauw, M. & Christen, J.A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis 6, 457-474.

Blaauw, M. & Mauquoy, D., 2012. Signal and variability within a Holocene peat bog – Chronological uncertainties of pollen, macrofossil and fungal proxies. Review of Palaeobotany and Palynology 186, 5-15.

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.

Brown, A.G. 1988. The palaeoecology of *Alnus* (alder) and the Postglacial history of floodplain vegetation. Pollen percentage and influx data from the West Midlands, United Kingdom. The New Phytologist 110, 425-436.

Charman, D.J., 1990. Origins and development of the Flow Country blanket mire, northern Scotland, with particular reference to patterned fens. Unpublished PhD thesis, University of Southampton.

Daley, T.J. & Barber, K.E., 2012. Multi-proxy Holocene palaeoclimate records from Walton Moss, northern England and Dosenmoor, northern Germany, assessed using three statistical approaches. Quaternary International 268, 111-127.

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 pp.

Damblon, F., 1996. Les dépôts tourbeux et l'histoire de la végétation sur le plateau des Hautes-Fagnes (Belgique). Annales de la Société géologique de Belgique 117 (2), 259-276.

Deumer, J.M., Gilot, E. & Carpon, P.C., 1964. Louvain Natural Radiocarbon measurements II. Radiocarbon 6, 160-166.

De Vleeschouwer, F., Luthers, C., & Streel, M., 2010. Recherche d'intérêt général et pluridisciplinaire relative aux modalités de l'accumulation récente de la tourbe dans la tourbière ombrogène du Misten (Hautes-Fagnes) en relation avec les changements climatiques et les effets des activités humaines. Convention entre le Ministère de la Région Wallonne (DGRNE) et l'Université de Liège, Visa 08/13701. 99 pp. http:etat.environnement.wallonie.be/index.php ? page=etudes detaillées

De Vleeschouwer, F., Chambers, F.M. & Swindles, G.T., 2011. Coring and Sub-sampling of peatlands for palaeoenvironmental research. Mires and peat 7, 1-10.

De Vleeschouwer, F., et al., 2012. A millennial record of environment change in peat deposits from the Misten (East Belgium). Quaternary International 268, 44-57.

Dricot, E.-M., 1960. Recherches palynologiques sur le plateau des Hautes-Fagnes. Bulletin de la Société Royale de Botanique de Belgique 92 (1,2), 157-196.

Dupont, L.M., 1986. Temperature and rainfall variation in the Holocene based on comparative palaeoecology and isotope geology of a hummock and a hollow (Bourtangerveen, The Netherlands). Review of Palaeobotany and Palynology 48, 71-159.

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

Firbas, F., 1949. Spät- und Nacheiszeitliche Waldgeschichte Mitteleuropas nördlich der Alpen. Bd 1: Algemeinde Waldgeschichte. 480 pp.

Flatberg, K.I., 1986. Taxonomy, morphovariation, distribution and ecology of the *Sphagnum imbricatum* complex with main reference to Norway. Gunneria 54, 1-118.

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

Geel, B. van & Middledorp, A.A., 1988. Vegetational history of Carberry Bog (Co. Kildare, Ireland) during the last 850 years and a test of the temperature indicator value of ^{2}H/^{1}H measurements of peat samples in relation to historical sources and meteorological data. New Phytologist 109, 377-392.

Green, B.H., 1968. Factors influencing the Spatial and Temporal Distribution of *Sphagnum imbricatum* Hornsch. Ex Russ. in the British Isles. Journal of Ecology, 56, 1, 47-58.

Goode, D.A., 1970. Ecological studies on the Silver Flow National Nature Reserve. Unpublished PhD thesis, University of Hull.

Grimm, E,C., 1987. CONISS : a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers and Geosciences 13 (1), 13-35.

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.

Hindryckx, M.-N., 2000. Evolution régressive de la végétation des tourbières à sphaignes enhaute Ardenne. Thèse de doctorat, Université de Liège. 269 pp + annexes.

Hindryckx, M.-N. & Streel, M., 2000. L'altération des bords de la tourbière active du Misten par l'exploitation de la tourbe pourrait dater du début du 14^e siècle. Hautes Fagnes 4, 95-101.

Hughes, P.D.M., Mauquoy, D., Barber, K.E. & Langdon, P.G., 2000. Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England. The Holocene 10 (4) 465-479.

Hughes, P.D.M., Lomas-Clarke, S.H., Schulz, J. & Jones, P., 2007. The declining quality of Late Holocene ombrotrophic communities and the lost of *Sphagnum austinii* (Sull. ex Aust.) on raised bogs in Wales. The Holocene 17, 613-625.

Hughes, P.D.M., Lomas-Clarke, S.H., Schulz, J. & Barber, K.E., 2008. Decline and localized extinction of a major raised bog species across the British Isles: evidence for associated land-use intensification. The Holocene 18, 1033-1043.

Liégeois-Lemaitre, T., 1957. Histoire d'une forêt du Haut Plateau Ardennais en vue d'une étude phytogéographique. Bulletin de la Société Royale des Sciences-Liège 26 (6), 354-368.

Mauquoy, D. & Barber, K.E., 1999, Evidence for climatic deteriorations associated with the decline of *Sphagnum imbricatum* Hornsch, ex Russ, in six ombrotrophic mires from northern England and the Scottish Borders. The Holocene 9 (4), 423-437.

Mauquoy, D. & van Geel, B., 2007. Mire and peat macros. In: Elias, S.A. (Ed.), Encyclopedia of Quaternary science, volume 3. Elsevier, Philadelphia, 2315–36.

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

Mormal, P. & Tricot, C., 2004. Aperçu climatique des Hautes-Fagnes. Institut Royal météorologique de Belgique, Publication scientifique et technique 36. 27 pp,

Mullenders, W. & Knop, C., 1962. Recherches palynologiques dans les Ardennes belges, I. La tourbière du Grand Passage. Bulletin de la Société Royale de Botanique de Belgique 94 (1), 163-175.

Nekrassoff, S., 2007. Images et visages des Hautes-Fagnes. Evolution d'un paysage et de sa perception. Liège, 120 pp.

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.

Pahaut, P. & Oldenhove de Guertechin, X, 1962. Texte explicatif de la planchette d'Eupen 136^E. Carte des sols de la Belgique. 139 pp,

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

Post, L. von & Sernander, R., 1910. Pflanzen-physiognomische Studien auf Torfmooren in Närke. XI international geological Congress: Excursion Guide No. 14 (A7) Stockholm. 48 p.

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

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

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

Reimer, P.J., et al., 2009, IntCal09 and Marine09 Radiocarbon Age Calibration Curves, 0-50,000 Years cal BP. Radiocarbon 51, 1111-1150.

Renson, V., Fagel, N., Mattielli, N., Nekrassoff, S., Streel, M. & De Vleeschouwer, F., 2008. Roman road pollution assessed by elemental and lead isotope geochemistry in East Belgium. Applied Geochemistry 23, 3253-3266

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.

Schwickerath, M., 1944. Das Hohe Venn und seine Randgebiete. Vegetation, Boden und Landschaft. Pflanzensoziologie 6, Jena, 1-278.

Sernander, R., 1909. De scanodaniska torfmossarnas stratigrafi. Geologiska Föreningens i Stockholm Förhandlingar 31, 423-448.

Stoneman, R., Barber, K. & Maddy, D., 1993. Present and past ecology of *Sphagnum imbricatum* and its significance in raised peat-climate modelling. Quaternary Newsletter 70, 14-22.

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 XXXI (1), 104 pp.

Streel, M., 2011, Nouvelles données modifiant l'ancien schéma chrono-stratigraphique du « Subatlantique » (Persch 1950) dans les Hautes-Fagnes. In Gerrienne P, & Steemans, P., Miscellanea Palaeontologica, program and abstracts, MVP-PPMB meeting, Liège Nov, 30, 2011, 18-19.

Streel, M., Renson, V., Fagel, N., Nekrassoff , S. & De Vleeschouwer, F., 2005. La route pavée au travers des tourbières de la fagne des Wez (Via Mansuerisca ?) est-elle romaine ou mérovingienne ? La vérité est-elle … à mi-chemin ? Hautes Fagnes 259 (3), 20-25.

Trullemans, D., 1971. Etude palynologique de la tourbière de Ste Gertrude en Ardenne belge. Mémoire du Laboratoire de Palynologie et Phytosociologie, Université de Louvain. 90 pp.

Wardenaar, E.P.C., 1986. A new hand tool for cutting peat profiles. Canadian Journal of Botany 65, 1772-1773.

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. Rapport inédit. 52 pp + annexes.

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 (3), 115-120. Helsinki.

Manuscript received 21.08.2013, accepted in revised form 20.01.2014, available on line 15.02.2014