Geologos 22, 1 (2016): 61–69
doi: 10.1515/logos-2016-0005

Peat decomposition – shaping factors, significance in environmental studies and methods of determination; a literature review

Danuta Drzymulska

Department of Botany, Institute of Biology, University in Białystok, K. Ciołkowskiego 1J, 15-245 Białystok, Poland.
e-mail: drzym@uwb.edu.pl

Abstract

A review of literature data on the degree of peat decomposition – an important parameter that yields data on environmental conditions during the peat-forming process, i.e., humidity of the mire surface, is presented. A decrease in the rate of peat decomposition indicates a rise of the ground water table. In the case of bogs, which receive exclusively atmospheric (meteoric) water, data on changes in the wetness of past mire surfaces could even be treated as data on past climates. Different factors shaping the process of peat decomposition are also discussed, such as humidity of the substratum and climatic conditions, as well as the chemical composition of peat-forming plants. Methods for the determination of the degree of peat decomposition are also outlined, maintaining the division into field and laboratory analyses. Among the latter are methods based on physical and chemical features of peat and microscopic methods. Comparisons of results obtained by different methods can occasionally be difficult, which may be ascribed to different experience of researchers or the chemically undefined nature of many analyses of humification.

Keywords: plant remains, humification, microscopic view of peat, humidity of mire surface, palaeoclimate

1. Introduction

The degree of peat decomposition reflects the quantitative ratio of dark amorphous matter, consisting of humic compounds and the other products of plant decomposition to the non-decomposed matter. This parameter shapes many physical and chemical properties of peat, such as water capacity, content of colloidal parts and contractility. Besides, the degree of decomposition yields data on the humidity of the past mire surface during the peat-forming process. A decrease in the degree of peat decomposition is treated as an indicator of a rise of the ground water table. It is generally recognised that peat decomposition is low during times of high water table levels or wet climatic conditions, but high during times of low water table levels or dry climatic conditions (Clymo, 1984). The degree of peat decomposition in historic sections reflects the hydrological conditions during the time of peat formation, or more exactly, at the time of peat burial in the catotelm.

For postglacial and interglacial peat, the degree of its decomposition is not correlated with the age of the deposit (Jasnowski, 1957). Slightly decomposed peat in the deep old layers of the deposit is common, whereas the roof layers are quite often highly decomposed.

The aim of the present review is threefold: (i) to present different aspects of the peat decomposition process, including the importance of this parameter from hydroecological and palaeoecological points of view, (ii) to review various methods for the determination of this parameter critically, (iii) to point out current possibilities of the comparison of results obtained by different methods.

2. Factors shaping peat decomposition

Plant tissues can be preserved in peat when special conditions of biological decomposition in the peat-forming layer are met (Oświt, 1977). This layer is formed in the living part of the deposit, at depths of 0.2-0.7 m (Botch & Masing, 1979). Plant decomposition is inhibited there, because of a lack of access to oxygen.

In acrotelm aerobes, Actinomycetales and fungi transform biomass into humus under periodical aerate conditions. Decomposition is generally fast there, and most of the initial plant mass is mineralised (Malmer & Wallén, 2004). The storage of sediments formed in the acrotelm takes place in the catotelm, i.e., the dead part of the mire. Among two closely connected types of transformations constituting the decomposition of peat – namely mineralisation and humification, the first process proceeds mainly in the acrotelm, whereas the second occurs exclusively in this zone (Grosse-Brauckmann, 1990). As a result of mineralisation organic matter is transformed into mineral compounds. Humification leads to the formation of humic acids containing UV- absorbing aromatic components (Blackford & Chambers, 1993; Klavins et al., 2008). Occasionally, the terms "decomposition" and "humification" are incorrectly used as synonyms.

Grosse-Brauckmann (1996) distinguished two kinds of decomposition processes. The first takes place in "living" mires and is connected with peat forming ("primary decomposition"), and the second can take place later, mainly after drainage ("secondary decomposition"). Secondary decomposition is the result of mire surface drainage, when the oxygenation of peat results in re-decomposition (Grosse-Brauckmann, 1996). Drained mires are devoid of acrotelm, and mineralisation becomes the main process. It must be stated that occasionally bogs are drained spontaneously by a lowering of their water level. These types of stagnation are known from the past. Grosse-Brauckmann (1990) presented the example of tree trunks found in peat. They turned out to be much younger than the peat mass they were recovered from. In one case this difference was about 1,000 years. This means that these trees actually grew on highly mineralised stagnant peat.

The main factors conditioning the decomposition of peat can be divided into biogenous (activity of soil micro-organisms – invertebrates, fungi, bacteria) and abiogenous (influences of wind, rain, snow, frost, physical crumbling of material, eluviation) (Botch, 1978). Obviously, the intensity of decomposition also depends of the kind of plant tissues, which in turn depends of their different chemical composition. This process is certainly too complex to be dependent of the change of a single factor only.

With regard to plant roots and rhizomes, Grosse-Brauckmann (1986) listed two features that decide about their transformation into recognisable plant macrofossils. The first one is "specific decomposition resistance", which is the result of specific histological and chemical properties (e.g., pine wood, *Eriophorum vaginatum* sheaths disintegrate slowly). The second feature is deep ground penetration, which enables anaerobic conditions to be attained (long rhizomes of *Phragmites australis* and *Equisetum fluviatile* and roots of *Eriophorum* sp. are particularly extreme examples). If there is a large age discrepancy between the peat matrix and the plant organs which are found there, a mixed composition of macrofossils appears. Such peat was named "displacement peat" (Weber, 1930; according to Grosse-Brauckmann, 1986).

However, in general, vegetative plant organs, especially leaves and stems, decompose rapidly, forming an amorphous peat mass. Therefore, there is virtually no possibility to find them in peat in a recognisable form, i.e. with a remaining cellular structure.

Botch & Masing (1979) grouped plants according to their disintegration degree. Plants rich in nitrogen, calcium and carbohydrates belong to the first group. Bacteria and soil invertebrates attack them quickly and intensively, so within 2–3 years they mineralise almost entirely. Many brown and peat mosses, twigs of dwarf shrubs and roots of some plants belong to the other group. These plants are the most resistant to decomposition. Such resistance of peat mosses could be linked to the presence of sphagnol in their tissues (Obidowicz, 1975; Rydin & Jeglum, 2008). Coulson & Butterfield (1978) presented data on the loss of mass during the first year of tissue decomposition. For *Sphagnum recurvum* this was 16.2%, and for *Calluna vulgaris* 25.6%. However, according to Van der Linden & Van Geel (2006), the decomposition rate between *Sphagnum* species also varies. Very "wet-growing" species such as *Sphagnum cuspidatum* tend to decompose faster when exposed to air than relatively dry growing species such as *Sphagnum rubellum*.

Peat decomposition is also shaped by the pH of the substratum: the higher the pH, the greater the intensity of decomposition (Grosse-Brauckmann, 1990). Therefore, plants of raised bogs, where pH is low, decompose less than fen plants. The chemical composition of bog peat is also less profitable for microbes, and these organisms are not abundant in deposits of acidic peat (Botch & Masing, 1979).

3. Peat decomposition as a source of data on environment

The proportion of non-decomposed remains to humus in peat depends of local hydrological conditions. A high state of decomposition points to a relatively dry mire surface, while a low state indicates more humidity during peat deposition (Van der Linden & Van Geel, 2006). However, it has to be noted that repeated dryfalling and re-wetting cycles might also affect deeper and older peat layers, and modify and superimpose the record of peat decomposition. Therefore, secondary decomposition may disturb the hydrological interpretation when only decomposition proxies are used (Biester et al., 2014).

A specific situation regarding peat decomposition was observed in river valleys. In wide valleys flooded by stagnating water for a long time, medium and highly decomposed, plastic, often silt-covered, reed fen peat was deposited. In contrast, under conditions of short-time flooding and constant inflow of ground water, medium-decomposed, rather fibrous tall sedge peat accumulated. Regular and constant groundwater inflow and absence of flooding lead to the accumulation of slightly decomposed sedge-moss peat with a fibrous-spongy structure. The whole year's superiority of rainfall over evaporation, and the presence of ground water in the surface level of mires leads to the sedimentation of slightly decomposed *Sphagnum* peat (Fig. 1), whereas its subsidence results in the accumulation of medium and highly decomposed cotton-grass peat material (Oświt, 1977; Oświt & Żurek, 1981; Żurek et al., 2002).

Bog peat is very often slightly decomposed (10–25%), while decomposition of fen peat, in most cases, reaches 20–70%. Analyses made by myself for 100 random selected samples of bog peat showed the following results: 67% of samples – peat slightly decomposed, 21% – medium decomposed, 9% – highly decomposed and 2% – humopeat. Analogously, for fen peat these values were 25%, 23%, 33% and 19%, respectively. Obviously, the proportions would be different if only S*phagnum* peat or alder peat were analysed. The former usually is slightly decomposed; the latter highly so.

There is a relationship between the degree of peat decomposition and the ash content in sediment. More decomposed peat contains more mineral matter, which is connected with mineralisation as part of the decomposition process. It is especially clearly visible in bog peat. Mineralisation of fen peat is more difficult to observe due to the content of mineral particles carried by water (Maksimow, 1965). On the other hand, Broder et al. (2012) stated, in ombrotrophic bogs of southern Patagonia (Argentina), that decomposition of peat was advanced near ash layers, suggesting the stimulation of decomposition by ash deposition.

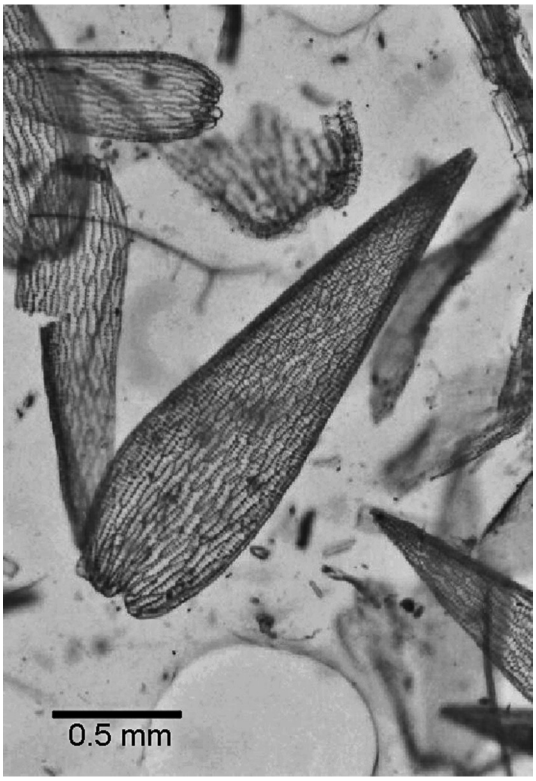

Fig. 1. Slightly decomposed *Sphagnum* peat (Kładkowe Bagno raised bog, northeast Poland) – microscopic view, ×74 (photo by D. Drzymulska).

Peat decomposition could be used as a source of data on past climate. In the case of the raised bog, this parameter is treated in fact as past climate-dependent. As this kind of peatland receives water merely as rainfall (and snowfall), i.e. solely from the atmosphere, a moisture signal (humidity of the mire surface) seems to be just climate-driven. Especially, peat decomposition data provide an indication of shifts to climatic wetness, because bog surface wetness is believed to be driven just primarily by precipitation reinforced by temperature (Charman et al., 2009). The possibility of such conclusions refers to lowland raised bogs and blanket mires. Lowland raised bogs occur in central and southern taiga and the cool, humid zone of mixed forests. Large complexes of them most often occupy spacious seaside valleys of the last glaciations in the region of the North Sea and the Baltic, not exceeding 100–200 m a.s.l. (Great Britain, Ireland, northern Germany, southern Scandinavia, Lithuania, Latvia and Estonia). Blanket bogs are a specific kind of raised bog that occur in the upland, submontane (200–500 m a.s.l.) and littoral zone of Ireland, Wales, northern England, Scotland and Norway.

The most comprehensive palaeoclimatic research based on the degree of peat decomposition was conducted in the British Isles and in Norway (Barber, 1981; Blackford & Chambers, 1991; Nilssen & Vorren, 1991; Blackford & Chambers, 1993; Barber et al., 1998; Blackford, 1998; Ellis & Tallis, 2000; Chiverrell, 2001; Mauquoy & Barber, 2002). The British most often used the method of chemical extraction of humic acids in NaOH, and then measured the light absorbance of the solution using a colorimeter filter, wavelength 540 nm. Changes to a higher percentage transmission are interpreted as changes to wetter surface conditions, thus resulting in lower rates of decomposition. Colorimetric analyses have been shown to be replicable, be applicable to all peat types and to show more variability than seen in the visible stratigraphic record, although problems remain regarding the effect of species change or rate of decomposition, and on the optical density of the humic extract (Blackford & Chambers, 1993). In theory, humification data indicate changes in the time elapsed between the death of the plant matter and the moment when its remains reach the anaerobic catotelm. Thus, these data represent a proxy for the position of the water table at the time of deposition – although this relationship remains unquantified (Blackford, 2000). Another limitation is the process of humic acid production which is not fully understood (Caseldine et al., 2000).

4. Methods of determination of peat decomposition

4.1. Field methods

Organoleptic features of peat are basic to estimates of its degree of decomposition. The main considered factors are the quantity and colour of squeezed-out water, as well as the consistence and structure of tissues remaining in the palm after squeezing.

Lubliner-Mianowska (1951) described the method that was worked out by Wallgren in 1915. The determination of peat decomposition came after the squeezing of a peat lump. The scale consisted of five degrees of peat decomposition: A – highly decomposed peat, AB – well-decomposed, B – slightly decomposed, BC – very slightly decomposed peat, C – non-decomposed peat.

The von Post method, published in 1924, is more precise. It is described widely in the literature (Lubliner-Mianowska, 1951; Aaby, 1986; Grosse-Brauckmann, 1990; Gawlik, 1992; Tobolski, 2000). This method is called the "fist-method" (German "Faustmethode") or "squeezing" (German "Quetschmethode"). Every degree of decomposition is described with the letter H (in Latin *humositas*) and a number from 1 to 10. The lowest degree has the symbol H_0; the highest – H_{10}. The colour of water, its transparency, content of squeezed matter and its remains in the palm should be observed during the squeezing of the peat lump. In Poland a scale based on this method was developed in which every degree of peat humification has its proportional value. This method is still applied, especially in northern European countries. Maciak & Liwski (1979) presented a modified version of the von Post method, separately for fen and bog peat.

Numerous field methods were developed in the former Soviet Union (Maciak & Liwski, 1979). In 1924 Varlygin published a table, taking into account the proportional ranges of peat decomposition – 5 for fen peat and 4 for bog peat. This work was based on direct observations of peat after drilling. In the 1940s, Tjuremnov developed a method that included observations of colour, structure and content of characteristic plant remains. This method enables the determination of decomposition with a measurement accuracy of up to 10% for raised bog peat and 15–20% for fen peat. Varlygin & Minkina (1949) developed an original macroscopic method, the so-called smear method. Smears of peat are compared for intensity and colour with smears of standard scale. This determination of peat decomposition has been discredited now. The passive observation of peat is certainly inadequate, and can even be misleading.

Finally, the Troels-Smith (1955) method will be briefly presented. This is a five-degree scale (numbers from 0 to 4) concerning *turfa* peat components (macroscopic parts of mosses Tb, herbaceous plants Th and plants lignified Tl) and one limnic form of organic matter – *limus detrituosus* Ld. The degree of decomposition is described as the so-called decomposition index. For example, Tb^0 means *humositas* 0 for *turfa bryophytica*, Ld^3 – the third degree of decomposition for *limus detrituosus*. Every degree of this scale has its equivalent in the von Post scale. The T-S system, also describing sediment components and their physical proprieties, is still useful, especially in geological studies of the Quaternary, and in geography and archaeology (Birks & Birks, 1980; Aaby & Berglund, 1986).

The advantage of field methods for the determination of peat decomposition is undoubtedly their ability to assess this parameter quickly, directly in the field, during the collection of sediment. They require no instrumentation, are less time-consuming, and cheap. On the other hand, and particularly in the case of too little practice, they may result in erroneous conclusions. Therefore, in my opinion, they should be applied only in general assessments.

4.2. Laboratory methods

These types of methods can be divided into three groups: 1. Methods based on the physical features of peat; 2. Methods based on its chemical features; 3. The microscopic method.

4.2.1. Methods based on physical features of peat

Grouped here are the sieve (mechanical) (Maciak & Liwski, 1979; Gawlik, 1992) and volumetric-gravimetric method. In the sieve method, the degree of decomposition is estimated on the basis of fibre or humus content in the peat sample. This can be determined after the mechanical separation of humus and non-decomposed tissues. Kudryashov was a pioneer of the sieve method. Frazier & Lee (1971) used the sieve method for the chemical-thermal treatment of peat (boiling of material in HCl solution). Gravimetrically determined fibrous parts were then the basis of distinguishing three forms of peat decomposition: *fibric* – plant remains slightly decomposed, *hemic* – medium/highly decomposed and *sapric* – very highly decomposed. Grosse-Brauckmann (1990) also presented data on these forms.

The volumetric-gravimetric method is based on changes in peat density during the process of decomposition. Gawlik (1992) presented a review of the different kinds of this method. They seem to be similar to near soil-science investigations. Estimating the content of fibres could also be a good auxiliary method for palaeobotanical research.

4.2.2. Methods based on chemical features of peat

This group of methods is based on the determination of substances whose content changes in peat during its decomposition. Davydik (1987) applied the following rule: the higher the degree of peat decomposition, the higher the content of carbon in peat, and the lower oxygen content. Keppeler (1920; according to Gawlik, 1992) used the lowered carbohydrate content in plant material during the humification process (degradation of hemicellulose and cellulose). On the other hand, there are other polysaccharides which can be products of decomposition, so their concentration will increase in peat mass (Blackford & Chambers, 1993). Some methods are based on the amount of humic acids in peat. As peat decomposes, their proportion increases. However, changes in vegetation controlled by hydrology, i.e., shifts in vascular plant species (containing lignin) in peat which is dominated by *Sphagnum* (not containing lignin) during drier periods, may also lead to changes in the abundance of humic acids (Yeloff & Mauquoy, 2006; Chambers et al., 1997). Changes in humic acids may thus reflect a signal of vegetation changes more so than changes in humification or decomposition alone. Mathur & Farnham (1985) also paid attention to the significant role of the botanical composition of peat.

Blackford & Chambers (1993) distinguished a separate method – based on the chemical extraction of soluble material, with sodium hydroxide as the extractant. Studies by Aaby (1976) and Blackford & Chambers (1991) assumed that the colour of NaOH extracts was indicative of the degree of humification, i.e., the extent of decomposition. The results are expressed as percentage light transmission through an alkali extract of humic acid measured on an ultraviolet/visual spectrophotometer. However, the use of NaOH extracts as humic acid indicators has not been universally accepted. One of the reasons is the appearance of by-products during the extraction procedure.

C/N ratios are another common proxy of peat decomposition (Kuhry & Vitt, 1996). This approach is based on the observed residual enrichment of N relative to C during the mineralisation of organic matter, i.e., lower C/N ratios for more decomposed peat material. Thus, changes in C /N ratios are postulated to indicate mainly changes in bog surface wetness and concomitant changes in peat decomposition. However, C/N ratios differ widely between peatland plants (Hornibrook et al., 2000), and thus shifts in vegetation upon changes in surface wetness affect C/N ratios in peat, and may obscure the decomposition signal.

Owing to the turnover of organic matter and associated C losses in mires, a relationship between peat decomposition and stable isotope inventories of H, C, N, S and O could also be expected. However, the fate of these stable isotopes during peat decomposition, and their use as indicators are controversial. In fact, some studies have shown that the isotopic signature of peat was not affected by decomposition, but by specific parts of the plants investigated (Skrzypek et al., 2007); a rapid decrease in $\delta^{13}C$ in the upper peat layers is caused by the preferential decay of cellulose over lignins, the latter being isotopically lighter (Benner et al., 1987). Methane formation causes a strong increase in $\delta^{13}C$ content of residual peat (Charman et al., 1999; Jones et al., 2010). Therefore, to date the use of stable isotopes to elucidate decomposition processes is not fully confirmed.

4.2.3. Microscopic method

This method includes observations of water suspension of peat under a light microscope. On this basis the ratio of completely humified peat mass to whole peat mass in microscopic fields of vision is fixed for every peat sample. There are various modifications of this method, referring, e.g., to sample preparation (Maciak & Liwski, 1979). The microscopic method allows to qualify the degree of peat decomposition relatively precisely. Grosse-Brauckmann (1996) stressed its one great advantage: the peat component, which appears to be amorphous macroscopically, is often recognised as plant tissue with a cellular structure during microscopic study.

According to Obidowicz (1990), peat may be divided into:

1. Slightly decomposed (to 25%) – cellular structure of plant tissues well preserved.
2. Medium decomposed (30–40%) – visible changes in the structure of tissues, fairly large quantity of humus.
3. Highly decomposed (45–60%) – considerable changes in the structure of tissues, very large quantity of humus.
4. Humopeat (65% and more) – tissues changed so much that their identification is practically impossible.

This classification is used in palaeoecological studies, which are based on the microscopic analysis of vegetative plant remains (e.g. Drzymulska & Zieliński, 2013; Drzymulska et al., 2013).

According to Tobolski (2000), humopeat is not uniform, and can be classified as: fen humopeat (with spores of fern and plenty of Cyperaceae pollen), transitional-high humopeat (with peat moss spores and Ericaceae pollen), and undefined humopeat (without recognisable palynomorphs).

The microscopic method seems to be the most reliable of the laboratory methods. Its advantage is undoubtedly its ability to directly "access" the peat sample and to see plant tissues and humus, which allows the unambiguous separation of these two components of peat, and avoids confusing them. Two other laboratory methods are more indirect, and also require laboratory procedures and devices. For the microscopic method only an optical microscope is needed. However, it does require a certain amount of experience and is quite labour intensive. In my opinion, however, this is the best way for the determination of the degree of peat decomposition.

5. Different methods, yet comparable results?

A comparison of the various methods for determining the degree of peat decomposition is not the main goal of numerous papers. This is just one of the studied parameters, and its values are determined by only one preferred method. It would be interesting to check whether the results obtained by different methods are comparable or not. On the other hand, owing to the chemically undefined nature of many humification analyses, the comparison of results obtained by different methods can be difficult (Biester et al., 2014). Another factor involved might be different experiences of researchers, especially with regard to field methods.

However, Stanek & Silc (1977) did undertake such a comparative study and determined the degree of decomposition of peat by the following methods: von Post's method, using 10 classes of humification, pyrophosphate-soluble organic matter determination using an index derived from Munsell colour charts, unrubbed fibre content in the percentage of total, and rubbed fibre content in the total percentage of total. Amongst other things, the authors found that, in part, the pyrophosphate-solubility indices could be compared with the von Post degrees of decomposition. However, in the range of humified peats the method tends to lump peat types between which von Post's method would distinguish. In turn, the order of unrubbed fibre contents proved to be similar to those obtained in terms of the rubbed fiber content. Therefore, one of these methods would probably suffice for peatland surveys. The order of their values is also comparable to those obtained by the pyrophosphate-solubility index. Similarly, in the range of slightly decomposed peats, the rubbed fibre content method mirrors the order of degrees of decomposition obtained by the von Post method. However, in the range of humic peats the rubbed fibre contents method allows fewer types to be distinguished than with the von Post method.

Changes in peat decomposition proxies in the cores of two peat bogs using C/N ratios, Fourier transform infrared spectra absorption (FTIR) intensities, Rock Eval® oxygen and hydrogen indices, ^{13}C and ^{15}N isotopic signatures, and UV-absorption

(UV-ABS) of NaOH peat extracts were compared in detail by Biester et al. (2014). As they determined all decomposition proxies, except for UV-ABS and ^{15}N, isotopes show similar patterns in their records and reflect the different extents of signals of decomposition. Future studies need to show to what extent these results can be generalised for other sites, and how decomposition proxies compare at sites with different botanical, hydrological or climatic backgrounds.

6. Conclusions

Von Post defined peat decomposition (or more precisely, the humification process) as "the degree of disintegration of the organic substances, regardless of the way this disintegration has taken place, and of what substances resulted from it" (Aaby & Berglund, 1986, p. 233). There are various aspects of the peat decomposition process. It can be examined from the point of view of the susceptibility of plant tissues to decomposition, as well as in relation to climatic and habitat conditions.

Hydrologic and climatic conditions, as well as the pH of the substratum, influence the rate of plant decomposition. It should be noted that changes in the degree of peat decomposition could be used to determine hydrologic changes in the past. Decrease of decomposition means an improvement of mire watering. Knowledge about the decomposition of ombrogenous peat is vital in palaeoclimatic research. Changes in decomposition, i.e. changes in hydrologic conditions, are interpreted as information about past climate because of the fact that precipitation is the only source of water in ombrogenous mires.

References

Aaby, B., 1976. Cyclic climatic variations in climate over the last 5500 years reflected in raised bogs. *Nature* 263, 281–284.

Aaby, B., 1986. Palaeoecological studies of mires. [In:] B.E. Berglund (Ed.): *Handbook of Holocene Palaeoecology and Palaeohydrology*. John Wiley & Sons, Chichester, 145–165.

Aaby, B. & Berglund B.E., 1986. Characterization of peat and lake deposits. [In:] B.E. Berglund (Ed.): *Handbook of Holocene Palaeoecology and Palaeohydrology*. John Wiley & Sons, Chichester, 231–246.

Barber, K.E., 1981. *Peat stratigraphy and climatic change*. Balkema, Rotterdam, 219 pp.

Barber, K., Dumayne-Peaty, L., Hughes, P., Mauquoy, D. & Scaife, R., 1998. Replicability and variability of the recent macrofossil and proxy-climate record from raised bogs: field stratigraphy and macrofossil data from Bolton Fell Moss and Walton Moss, Cumbria, England. *Journal of Quaternary Science* 13, 518–528.

Benner, R., Fogel, M. L., Sprague, E. K. & Hodson, R. E., 1987. Depletion of c in lignin and its implications for stable carbon isotope studies. *Nature* 329, 708–710.

Biester, H., Knorr, K.-H., Schellekens, J., Basler, A. & Y.-M. Hermanns, Y.-M., 2014. Comparison of different methods to determine the degree of peat decomposition in peat bogs. *Biogeosciences* 11, 2691–2707.

Birks, H.J.B. & Birks, H.H., 1980. *Quaternary Palaeoecology*. Edward Arnold, London, 289 pp.

Blackford, J.J., 1998. Holocene climatic variability in the North Atlantic region as shown by peat bog records. *Fróδskaparrit* 46, 155–162.

Blackford, J.J., 2000. Palaeoclimatic records from peat bogs. *Trends in Ecology & Evolution* 15, 193–198.

Blackford, J.J. & Chambers, F.M., 1991. Proxy records of climate from blanket mires: evidence for a Dark Age (1400 BP) climatic deterioration in the British Isles. *The Holocene* 1, 63–67.

Blackford, J.J. & Chambers, F.M., 1993. Determining the degree of peat decomposition in peat-based palaeoclimatic studies. *International Peat Journal* 5, 7–24.

Botch, M.S., 1978. Niekotoryje zakonomiernosti razlozjenija rastienij na bolotach kak osnova dinamiki bolot [Some regularities of plant decomposition in mires as a base for mire dynamics]. [In:] O.L. Liss (Ed.): *Gienjezis i dinamika bolot* [*Origin and dynamics of mires*]. Izdatielstwo Moskovskowo Uniwiersitjeta, Moskva, 18–24.

Botch, M.S. & Masing, V.V., 1979. *Ekosistemy bolot SSSR* [*Mire ecosystems of the USSR*]. Nauka, Leningrad, 187 pp.

Broder, T., Blodau, C., Biester, H. & Knorr, K.H., 2012. Peat decomposition records in three pristine ombrotrophic bogs in southern Patagonia. *Biogeosciences* 9, 1479–1491.

Caseldine, C.J., Baker, A., Charman, D.J. & Hendon, D., 2000. A comparative study of optical properties of NaOH peat extracts: implications for humification studies. *The Holocene* 10, 649–658.

Chambers, F.M., Barber, K.E., Maddy, D. & Brew, J., 1997. A 5500-year proxy-climate and vegetation record from blanket mire at talla moss, borders, Scotland. *The Holocene* 7, 391–399.

Charman, D. J., Hendon, D. & Packman, S., 1999. Multiproxy surface wetness records from replicate cores on an ombrotrophic mire: Implications for Holocene palaeoclimate records. *Journal of Quaternary Science* 14, 451–463.

Charman, D.J., Barber, K.E., Blaauw, M., Langdon, P.G., Mauquoy, D., Daley, T.J., Hughes, P.D.M. & Karofeld, E., 2009. Climate drivers for peatland palaeoclimate records. *Quaternary Science Reviews* 28, 1811–1818.

Chiverrell, R.C., 2001. A proxy record of late Holocene climate change from May Moss, northeast England. *Journal of Quaternary Science* 16, 9–29.

Clymo, R.S., 1984. The limits to peat bog growth. *Philosophical Transactions of the Royal Society B* 303, 605–654.

Coulson, J.C. & Butterfield, J., 1978. An investigation of biotoc factors determining the rates of plant decomposition on blanket bog. *Journal of Ecology* 66, 631–650.

Davydik, I.I., 1987. An approach to the determination of the state of decomposition pf peat and other organic substances. *International Peat Journal* 2, 19–27.

Drzymulska D. & Zieliński, P., 2013. Developmental changes in the historical and present-day trophic status of brown water lakes. Are humic water bodies a uniform aquatic ecosystem? *Wetlands* 33, 909–919.

Drzymulska D., Kłosowski, S., Pawlikowski, P. & Zieliński, P. & Jabłońska, E. 2013. The historical development of vegetation of foreshore mires beside humic lakes; different successional pathways under various environmental conditions. *Hydrobiologia* 703, 15–31.

Ellis, C.J. & Tallis, J., 2000. Climatic control of blanket mire development at Kentra Moss, north-west Scotland. *Journal of Ecology* 88, 869–889.

Frazier, B.E. & Lee, G.B. 1971. Characteristics and classification of three Wisconsin histosols. *Soil Science Society of America Proceedings* 35, 776–780.

Gawlik, J., 1992. *Wpływ stopnia rozkładu torfu i stanu jego zagęszczenia na właściwości wodno-retencyjne utworów torfowych* [*Effect of plant decomposition degree and its density on water-retention features of peat sediments*]. Wydawnictwo IMUZ, Lublin – Falenty, 86 pp.

Grosse-Brauckmann, G., 1986. Analysis of vegetative plant macrofossils. [In:] B.E. Berglund (Ed.): *Handbook of Holocene Palaeoecology and Palaeohydrology*. John Wiley & Sons, Chichester, 591–618.

Grosse-Brauckmann, G., 1990. Ablagerungen der Moore. [In:] K. Göttlich (Ed.): *Moor- und Torfkunde*. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 145–165.

Grosse-Brauckmann, G., 1996. Classification of peat and peatbogs in Germany and its botanical, ecological and pedological foundations. [In:] G.W. Lüttig (Ed.): *Peatlands Use – Present, Past and Future*. Proceedings of the 10th International Peat Congress, Bremen, Vol. 2. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 21–38.

Hornibrook, E.R.C., Longstaffe, F.J., Fyfe, W.S. & Bloom, Y., 2000. Carbon-isotope ratios and carbon, nitrogen and sulfur abundances in flora and soil organic matter from a temperate-zone bog and marsh. *Geochemical Journal* 34, 237–245.

Jasnowski, M., 1957. *Calliergon trifarium* Kindb. w układzie stratygraficznym i florze torfowisk holoceńskich Polski [*Calliergon trifarium* Kindb. in startygraphy and flora of the Holocene mires of Poland]. *Acta Societatis Botanicorum Poloniae* 26, 701–718.

Jones, M.C., Peteet, D.M. & Sambrotto, R., 2010. Late-Glacial and Holocene δ15n and δ13c variation from a Kenai Peninsula, Alaska peatland. *Palaeogeography Palaeoclimatology Palaeoecology* 293, 132–143.

Klavins, M., Sire, J., Purmalis, O. & Melecis, V., 2008. Approaches to estimating humification indicators for peat. *Mires and Peat* 3, 1–15.

Kuhry, P. & Vitt, D.H., 1996. Fossil carbon/nitrogen ratios as a measure of peat decomposition. *Ecology* 77, 271–275.

Lubliner-Mianowska, K., 1951. *Wskazówki do badań torfu. Metody geobotaniczne, polowe i laboratoryjne* [*Guideline for peat studies. Geobotanical, field and laboratory methods*] . Państwowe Wydawnictwo Techniczne, Katowice, 88 pp.

Maciak, F. & Liwski, S., 1979. *Ćwiczenia z torfoznawstwa* [*Peat-science practice*]. Skrypty SGGW, Akademii Rolniczej w Warszawie, Warszawa, 159 pp.

Maksimow, A., 1965. *Torf i jego użytkowanie w rolnictwie* [*Peat and its agricultural use*]. PWRiL, Warszawa, 395 pp.

Malmer, N. & Wallén, B., 2004. Input rates, decay losses and accumulation rates of carbon in bogs during the last millennium: Internal processes and environmental changes. *The Holocene* 14, 111–117.

Mathur, S.P. & Farnham, R.S., 1985. Geochemistry of humic substances in natural and cultivated peatlands. [In:] G.R. Aiken, D.M. McKnight, R.L. Wershaw & P. MacCarthy (Eds): *Humic substances in soil, sediments and water*. John Wiley & Sons, New York, 53–86.

Mauquoy, D. & Barber, K., 2002. Testing the sensitivity of the palaeoclimatic signal from ombrotrophic peat bogs in northern England and the Scottish Borders. *Review of Palaeobotany and Palynology* 119, 219–240.

Nilssen, E. & Vorren, K.D., 1991. Peat humification and climate history. *Norsk Geologisk Tiddskrift* 71, 215–217.

Obidowicz, A., 1975. Entstehung und Alter einiger Moore im nördlichen Teil der Hohen Tatra. *Fragmenta Floristica et Geobotanica* 21, 3, 289–466.

Obidowicz, A., 1990. Eine Pollenanalytische und Moorkundliche Studie zur Vegetationsgeschichte des Podhale-Gebietes (West-Karpaten). *Acta Palaeobotanica* 30, 147–219.

Oświt, J., 1977. Naturalne siedliska torfotwórcze jako podstawa wyróżniania jednostek przyrodniczych [Natural peat-forming habitats]. *Roczniki Nauk Rolniczych Seria F* 79, 29–50.

Oświt, J. & Żurek, S., 1981. Rekonstrukcja rozwoju zabagnień w pradolinie Biebrzy. *Zeszyty Naukowe Akademii Rolniczej we Wrocławiu* 134, 59–70.

Rydin, H. & Jeglum, J., 2008. *The Biology of Peatlands*. Oxford University Press, Oxford, 343 pp.

Skrzypek, G., Kałużny, A., Wojtuń, B. & Jędrysek, M.-O., 2007. The carbon stable isotopic composition of mosses: A record of temperature variation. *Organic Geochemistry* 38, 1770–1781.

Stanek, W. & Silc, T., 1977. Comparisons of four methods for determination of degree of peat humification (decomposition) with emphasis on the von Post method. *Canadian Journal of Soil Sciences* 57, 109–117.

Tobolski, K., 2000. *Vademecum Geobotanicum. Przewodnik do oznaczania torfów i osadów jeziornych* [*Vademecum Geobotanicum. Manual for peat and lacustrine sediment recognising*]. Wydawnictwo Naukowe PWN, Warszawa, 508 pp.

Troels-Smith, J., 1955. Karakterisering af løse jordarter [Characterization of loose soils]. *Danmarks Geologiske Undersogelse* IV, Reakke 3,10, 1–73.

Yeloff, D. & Mauquoy, D., 2006. The influence of vegetation composition on peat humification: Implications for palaeoclimatic studies. *Boreas* 35, 662–673.

van der Linden, M. & van Geel, B., 2006. Late Holocene climate change and human impact recorded in a south Swedish ombrotrophic peat bog. *Palaeogeography, Palaeoclimatology, Palaeoecology* 240, 649–667.

Varlygin, P. D. & Minkina, C.I., 1949. Polevoj sposób opredelenija stepeni razlozienija torfa – syrca posredstvom mazkov [Field method of determination of peat decomposition degree by smears]. *Torfjanaja Promyslennost* 3, 21–23.

Żurek, S., Michczyńska, D.J. & Pazdur, A., 2002. Time record of palaeohydrologic changes in the development of mires during the Late Glacial and Holocene, North Podlasie Lowland and Holy Cross Mts. *Geochronometria* 21, 109–118.

Manuscript received 6 March 2015
Revision accepted 1 February 2016