

Chemical characteristics of some peatlands in southern Poland

M. Malawska, A. Ekonomiuk and B. Wilkomirski

Department of Plant Systematics and Geography, Warsaw University,
Al. Ujazdowskie 4, 00-478 Warsaw, Poland

SUMMARY

The study described here investigated the differences in chemical characteristics between peat deposits with different geological origin, geomorphology, hydrology and botanical composition. The variation of chemical properties with depth was compared between fen, transition mire and raised bog peat deposits occurring in south and south-west Poland. Degree of decomposition, pH, Na⁺, K⁺, Mg²⁺, Ca²⁺, N, ash and humic substances content were determined, and cluster analysis was used to describe the chemical variation amongst peat samples and peatland sites. The peat deposits showed high chemical variability between mire types, and even within the same botanical peat type; and peat from geographically distant peatlands could be chemically more similar than peat from different locations within a single mire complex. Thus, purely botanical classifications appear to be of limited utility as indicators of the conditions under which peat formation occurred.

KEY WORDS: peat geochemistry, mire classification, peat species.

INTRODUCTION

Peatlands are difficult to classify because of their floristic diversity and their stratigraphic, hydrological and geomorphological variety. They have been classified on the basis of origin (Millar 1976), but the most widely used classifications are based either on vegetation or on water source.

Many classifications are based on vegetation because the majority of studies have focused on plant ecology and conservation, or on forest management. Dominant species and plant associations are used especially in local studies (Semeniuk 1987; Brinson 1993; Matuszkiewicz 2001). The current Finnish classification identifies a series of mire types on the basis of ecological gradients in attributes such as wetness, nutrient status and the distinction between the mire margin and the mire centre, e.g. forested types vs. treeless types (Heikurainen & Pakarinen 1982; Ruuhijärvi 1983). For Estonia, Masing (1975) distinguishes two types of mire vegetation, minerotrophic and oligotrophic, on the basis of nutrient status.

Three peatland types, namely raised bogs, transition mires and fens, are distinguished on the basis of the source of water (Weber 1911; Sjö, 1946; Stewart & Kantrud 1971). Raised bogs depend solely on precipitation (i.e. they are ombrogenous) and, like mountain mires with nutrient-poor water supplies, are classed as

oligotrophic peatlands. By contrast, fens develop as mesotrophic and eutrophic ecosystems because they are irrigated predominantly by groundwater and/or surface water which introduces mineral material derived from the surrounding areas. Transition mire is an intermediate type where neither precipitation nor surface/groundwater dominates the water balance. However, Damman (1995) suggests that water source is less important than mineral status for explaining vegetation patterns.

The mineral components of peat are derived from inorganic matter contained in sediments and by adsorption from groundwater (Steinmann & Shotyk 1997), so that the source of water significantly influences peat geochemistry (Malawska & Wilkomirski 2004). The involvement of surface water in the hydrological regime causes relatively high-amplitude temporal fluctuations in soil wetness, oxygen and nutrient levels, which enhance microbiological processes and so promote the humification and mineralization of dead plant material. Therefore, especially for fen peat, geochemistry is also strongly influenced by the hydrological regime (Dellwig *et al.* 2002). *Sphagnum* peat develops under ombrogenous conditions, but as the plant residues are buried, decomposed and compressed, ombrogenous peat may become minerogenous as a result of increasing groundwater influence. Steinmann & Shotyk (1997) suggest that peat with botanical components typical

of raised bogs can thus display chemical properties typical of minerogenous fens, and *vice versa*. Therefore, the use of solely botanical classifications of peat to infer the trophic status of peatlands might lead to false conclusions about their genesis.

Numerous publications describe the inorganic geochemistry of peat and mire formation, especially their adsorption and other physico-chemical properties and their capacity to accumulate organic matter; and consider peatlands as sites of biogenic accumulation (e.g. Dehmer 1995; Shotyky 1997; Twardowska *et al.* 1999; Lopez-Buendia *et al.* 1999; Duan & Ma 2001; Bechtel *et al.* 2001; Lehtonen *et al.* 2001; Dellwig *et al.* 2002; Ringqvist *et al.* 2002, Ringqvist & Öborn 2002). On the other hand, relatively few papers deal with the basic geochemical properties of peat that has similar botanical composition but was formed under different conditions (Twardowska *et al.* 1999, Steinmann & Shotyky 1997; Wassen *et al.* 1998).

The aim of the study reported here was to compare the chemical properties of peat formed in mires that differ in their geological origin, geomorphology, hydrology and botanical composition. Since there are few published descriptions of the peat deposits of Poland, this work also complements existing knowledge of the global variety of peatlands.

SITES AND METHODS

Peat samples were collected from four areas in southern and south-western Poland, namely the Sudeten Mountains (peatlands D1-D3), the Silesian Lowland (peatlands E1, E2), the Orawa Basin (peatlands F1, F2) and the Tatra Mountains (peatlands G1-G5). These areas are covered predominantly by forests and meadows. Table 1 gives details of the peatlands that were sampled, and their locations are shown in Figure 1. Most of them are designated as nature reserves and National Parks.

Raised bogs D1 and D2 are Strict Nature Reserves located on a watershed in mountains of gneiss and sandstone, and they are surrounded by forests. Fen D3 lies alongside a mountain stream with a stony bed, it is not surrounded by forests, and it is used as a meadow.

Fens E1 and E2 developed in a valley on fertile clay soils and Upper Miocene sandy soils, and have typical fen vegetation.

Peatlands F1 and F2 developed where a layer of impermeable loam overlies Quaternary gravel. Raised bog F1 has two domes, and is fed by precipitation and by surface water from the upper

river terrace. It has characteristic raised bog vegetation with dwarf mountain pine and *Sphagnum* moss, and was designated as a nature reserve in 1925. Transition bog F2 is a near-watershed fluvial-soligenous mire that is used as a pasture.

The Tatra Mountains peatlands are located in the Tatra National Park, where raised bogs developed on nutrient-poor substrates in closed fluvio-glacial and glacial basins. They are fed by precipitation and mineral-poor surface water draining from crystalline rock catchments. Their vegetation consists of spruce forest, dwarf mountain pine and *Sphagnum* moss (intermontane *Sphagnum* raised bogs). Bogs G2 and G4 were formed by the terrestrialization of small lakes, whilst fen G1 is a sedge-grass hay meadow overlying impermeable clay within the boundary of the town of Zakopane.

The study sites were visited between June and October 2001. The locations at which peat coring was carried out were selected on the basis of geological documentation. At each site, a peat sample was collected from each horizon of the stratigraphic profile using a Russian sampler with chamber length 0.5 m. The total number of samples was 45, and these were stored at -20°C.

Before analysis, the samples were thawed and air dried, and the fraction >2 mm was removed by dry sieving and discarded. The following properties were determined:

1. peat genus – the dominant peat-forming species, determined microscopically before drying and sieving;
2. ash content (ashing temperature 450°C);
3. soil reaction - pH(H₂O) and pH(KCl), determined potentiometrically using a pH meter;
4. content of extractable metal cations (Na⁺, K⁺, Mg²⁺, Ca²⁺), measured by atomic absorption spectrophotometry (AAS) on ammonium acetate (NH₄OAc) extracts;
5. percentage of soil organic carbon (C_{org}), humic acid organic carbon (C_{hum}) and fulvic acid organic carbon (C_f), determined by Tiurin's dichromate method (Kononowa 1968); and
6. percentage of total nitrogen (N), measured using a Kjeldahl automatic analyser.

RESULTS

The stratigraphy of the study mires is summarised in Table 2. The variation of geochemical properties with depth is shown in Table 3 for peatlands with only one or two stratigraphic horizons, and in Figures 2 and 3 for the remainder.

Of the five raised bogs sampled, Zieleniec (D1 and D2) and Bór na Czerwonym (F1) were the most

Table 1. Details of the study sites. For each site, the site code and site name are given, along with location (latitude and longitude), area, nutrient status, principal plant communities and a description of vegetation. Names of plant communities follow Matuszkiewicz (2001).

Study area	Site code	Site name	Area (ha)	Principal plant communities	Description of vegetation (<i>Flora Europaea</i> 1972)	Nutrient status	Location (latitude/ longitude)
Sudeten Mountains	D1	Zieleniec – Czarne Bagno	58	<u><i>Oxycocco Sphagnetea</i></u> Br.-Bl et. Tx 1943; <i>Sphagnion europeum</i>	Woodland with <i>Pinus montana</i> , <i>Pinus mughus</i> , <i>Pinus uliginosa</i> , <i>Eriophorum vaginatum</i> , <i>Calluna vulgaris</i> , <i>Andromeda polifolia</i> , <i>Vaccinium myrtillus</i> , <i>Vaccinium uliginosum</i> , <i>Oxycoccus quadripetalus</i> , <i>Drosera rotundifolia</i> , <i>Sphagnum magellanicum</i> , <i>Sphagnum acutifolium</i> .	oligotrophic	20° 20' N 16° 24' E
	D2	Zieleniec – Topielisko	64	<u><i>Oxycocco Sphagnetea</i></u> Br.-Bl et. Tx 1943; <i>Sphagnion europeum</i>	Woodland with <i>Pinus uliginosa</i> , <i>Pinus mughus</i> , <i>Betula nana</i> , <i>Betula verrucosa</i> , <i>Vaccinium myrtillus</i> , <i>Vaccinium vitis-idaea</i> , <i>Vaccinium uliginosum</i> , <i>Carex limosa</i> , <i>Drosera rotundifolia</i> , <i>Oxycoccus quadripetalus</i> , <i>Sphagnum acutifolium</i> , <i>Sphagnum magellanicum</i> , <i>Sphagnum cuspidatum</i> , <i>Polytrichum strictum</i> .	oligotrophic	20° 20' N 16° 24' E
	D3	Lasówka	7	<u><i>Carici-Drepanocladetea</i></u> Klass.nov.provis.; <i>Caricion canescenti-fuscae</i>	Wet meadow with <i>Carex fusca</i> , <i>Carex flava</i> , <i>Carex stellulata</i> , <i>Scirpus sylvaticus</i> , <i>Agrostis alba</i> , <i>Agrostis canina</i> , <i>Juncus effusus</i> , <i>Galium uliginosum</i> , <i>Sphagnum acutifolium</i> , <i>Alopecurus pratensis</i> , <i>Deschampsia cespitosa</i> , <i>Peucedanum palustre</i> , <i>Ranunculus repens</i> , <i>Ranunculus acris</i> , <i>Veronica chamaedrys</i> , <i>Lathyrus palustris</i> , <i>Poa pratensis</i> .	eutrophic	20° 35' N 16° 20' E
Silesian Lowland	E1	Chocianów I	297.4	<u><i>Vaccinio-Piceetea</i></u> Br.-Bl.1939; <i>Vaccinio uliginosi-Pinetum</i>	Woodland with <i>Pinus sylvestris</i> , <i>Betula verrucosa</i> , <i>Picea excelsa</i> , <i>Calluna vulgaris</i> , <i>Rhamnus frangula</i> , <i>Ledum palustre</i> , <i>Deschampsia flexuosa</i> , <i>Vaccinium myrtillus</i> , <i>Vaccinium vitis-idaea</i> , <i>Trientalis europea</i> , <i>Dryopteris thelypteris</i> , <i>Polytrichum strictum</i> , <i>Entodon schreberi</i> .	mesotrophic	51° 24' N 15° 60' E
	E2	Chocianów III	130	<u><i>Molinio-Arrhenatheretea</i></u> R.Tx.1937	Wet meadow (drained) with <i>Alopecurus pratensis</i> , <i>Festuca pratensis</i> , <i>Ranunculus repens</i> , <i>Festuca rubra</i> , <i>Poa pratensis</i> , <i>Galium palustre</i> , <i>Equisetum palustre</i> , <i>Potentilla anserine</i> , <i>Luzula campestris</i> , <i>Cirsium palustre</i> , <i>Carex panicea</i> , <i>Carex nigra</i> , <i>Lysimachia vulgaris</i> , <i>Ranunculus flammula</i> , <i>Caltha palustris</i> , <i>Lythrum salicaria</i> .	eutrophic	51° 24' N 15° 60' E

(continued)

Table 1 continued

Study area	Site code	Site name	Area (ha)	Principal plant communities	Ecosystems	Nutrient status	Location (latitude/longitude)
Orawa Basin	F1	Bór nad Czerwonym	86.8	<u>Vaccinio-Piceetea</u> Br.-Bl.1939; <u>Vaccinio-Mugetum</u> /Oxycoccetosum	Wooded type with <i>Pinus uliginosa</i> , <i>Betula verrucosa</i> , <i>Pinus mughus</i> , <i>Eriophorum vaginatum</i> , <i>Vaccinium uliginosum</i> , <i>Andromeda polifolia</i> , <i>Oxycoccus quadripetalus</i> , <i>Calluna vulgaris</i> , <i>Drosera rotundifolia</i> , <i>Drosera anglica</i> , <i>Carex limosa</i> , <i>Polytrichum strictum</i> .	oligotrophic	49° 27' N 20° 02' E
	F2	Puścizna Rękowiańska	187.	<u>Molinio-Arrhenatheretea</u> R.Tx.1937; <u>Molinietum coeruleae</u>	Wet meadow with <i>Festuca rubra</i> , <i>Alopecurus pratensis</i> , <i>Ranunculus acer</i> , <i>Anthoxanthum odoratum</i> , <i>Trifolium pratense</i> , <i>Melampyrum pratense</i> , <i>Rumex acetosa</i> , <i>Holcus lanatus</i> , <i>Orchis</i> sp., <i>Viola tricolor</i> , <i>Luzula campestris</i> , <i>Carex nigra</i> , <i>Myosotis palustris</i> , <i>Festuca pratensis</i> , <i>Dactylis glomerata</i> , <i>Daucus carota</i> .	eutrophic	49° 28' N 19° 50' E
Tatra Mountains	G1	Pardałówka	9	<u>Carici-Drepanocladetea</u> Klass.nov.provis.; <u>Caricetum caespitosa</u>	Wet meadow with <i>Deschampsia caespitosa</i> , <i>Briza media</i> , <i>Phleum pratense</i> , <i>Anthoxanthum odoratum</i> , <i>Cynosurus cristatus</i> , <i>Festuca pratensis</i> , <i>Carex panicea</i> , <i>Carex fusca</i> , <i>Equisetum arvense</i> , <i>Rhinanthus angustifolius</i> , <i>Trifolium hybridum</i> , <i>Trifolium repens</i> , <i>Cirsium plaustre</i> , <i>Galium uliginosum</i> , <i>Ranunculus acer</i> , <i>Sphagnum recurvum</i> , <i>Drosera rotundifolia</i> .	mesotrophic	49° 0.8' N 19° 45' E
	G2	Smreczyński Staw	0.8	<u>Oxycocco Sphagnetee</u> Br.-Bl et. Tx 1943; <u>Sphagnetalia magellanic</u>	Treeless type with <i>Eriophorum vaginatum</i> , <i>Vaccinium myrtillus</i> , <i>Vaccinium vitis-idaea</i> , <i>Carex limosa</i> , <i>Carex nigra</i> , <i>Caltha palustris</i> , <i>Lycopodium annotinum</i> , <i>Aulacomnium palustre</i> , <i>Polytrichum strictum</i> , <i>Sphagnum</i> sp.	oligotrophic	49° 12' N 19° 51' E
	G3	Ornak	0.6	<u>Oxycocco Sphagnetee</u> Br.-Bl et. Tx 1943; <u>Sphagnetalia magellanic</u>	Treeless type with <i>Vaccinium myrtillus</i> , <i>Vaccinium vitis-idaea</i> , <i>Eriophorum vaginatum</i> , <i>Polytrichum strictum</i> , <i>Oxycoccus quadripetalus</i> , <i>Oxycoccus microcarpum</i> , <i>Calluna vulgaris</i> , <i>Sphagnum</i> sp.	oligotrophic	49° 12' N 19° 51' E
	G4	Toporowe Stawy	1.8	<u>Oxycocco Sphagnetee</u> Br.-Bl et. Tx 1943; Pino mugo-Sphagnetum	Treeless type with <i>Pinus mughus</i> , <i>Scheuchzeria palustris</i> , <i>Carex limosa</i> , <i>Sparganium affine</i> , <i>Oxycoccus quadripetalus</i> , <i>Vaccinium uliginosum</i> , <i>Erica tetralix</i> , <i>Ledum palustre</i> , <i>Melamyrum silvaticum</i> , <i>Carex fusca</i> , <i>Carex stellulata</i> , <i>Drosera rotundifolia</i> .	oligotrophic	49° 17' N 20° 1.5' E
	G5	Pańszczycza Wielka	7.4	<u>Oxycocco Sphagnetee</u> Br.-Bl et. Tx 1943; Pino mugo-Sphagnetum	Treeless type with <i>Pinus mughus</i> , <i>Eriophorum vaginatum</i> , <i>Andromeda polifolia</i> , <i>Oxycoccus quadripetalus</i> , <i>Vaccinium uliginosum</i> , <i>Vaccinium myrtillus</i> , <i>Drosera rotundifolia</i> , <i>Sphagnum rubellum</i> , <i>Sphagnum magellanicum</i> , <i>Sphagnum fuscum</i> , <i>Polytrichum strictum</i> , <i>Polytrichum commune</i> .	oligotrophic	49° 16' N 20° 02' E

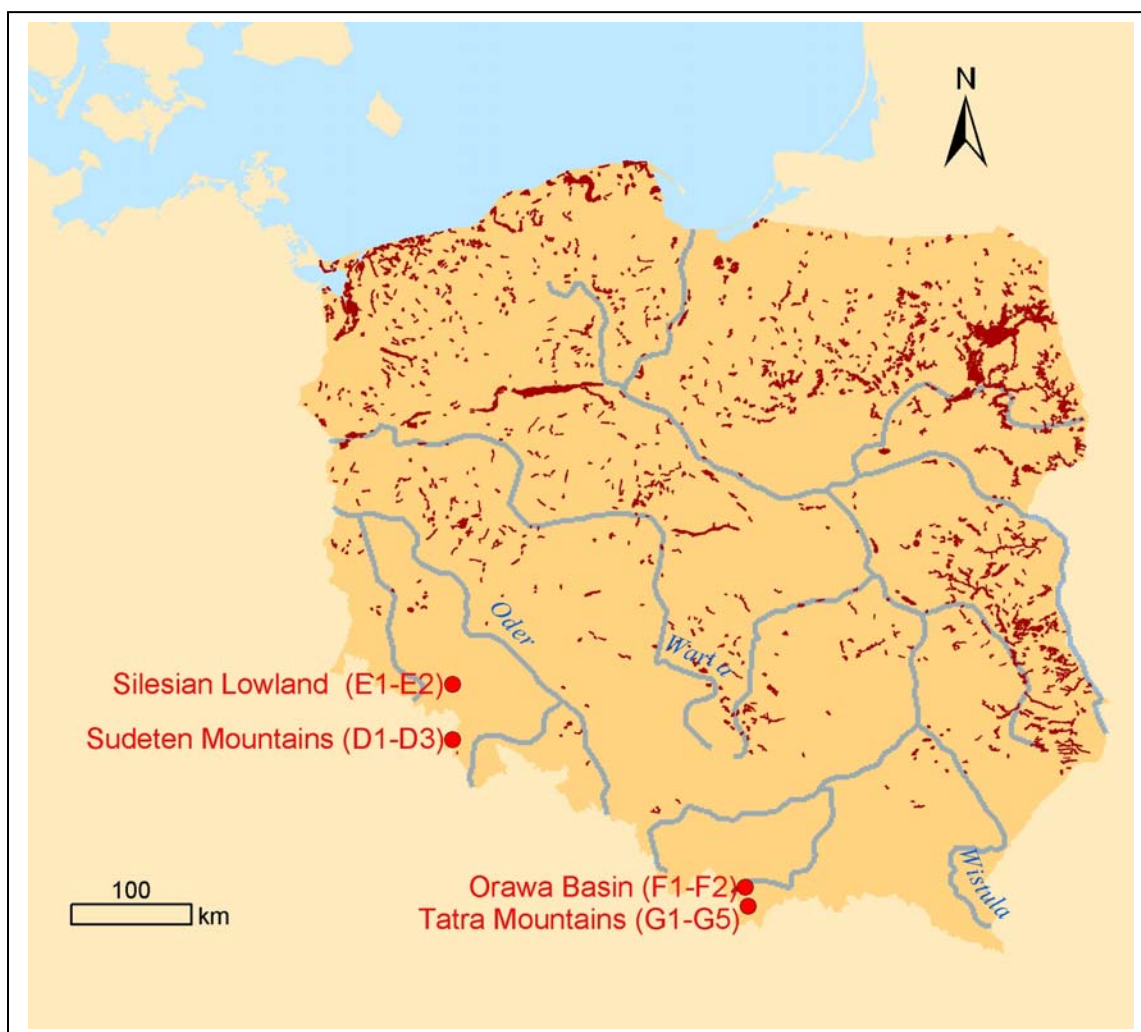


Figure 1. Map of Poland showing the locations of the four study areas in relation to principal rivers (blue) and mires (dark red).

diverse and had the thickest peat deposits. The peat deposits in the fens were relatively shallow with low stratigraphic diversity. The Chocianów fens (E1 and E2) had sedge peat, and the transition mire F2 and the fen G1 had birch and alder wood peat.

For most of the peatlands studied, the degree of decomposition was lowest in the surface layers, and highest in deep and intermediate layers (Figure 2a). The marked increase in peat decomposition in the bottom layers of fen E1 and raised bogs F1 and G4 is interesting. The lowermost deposits at E1 and G4 consisted of gyttja and hence had a high degree of decomposition (100%). In the surface layers of the raised bogs, the degree of decomposition was low, typically not exceeding 20%, whereas it reached almost 50% at the surface of fen E1. In the deeper layers of the raised bogs, peat decomposition could exceed 50%. The raised bog G5 was exceptional in that the degree of decomposition was low, reaching

a maximum of <50% at a depth of about 2 m, and decreasing to half this value at *ca.* 3.6 m depth. Table 3 shows that the surface layers of all the shallow mires were more decomposed than their deeper layers. The peat of fen D3 was characterised by a low degree of decomposition.

Ash content increased with depth at most sites. The exceptions were raised bogs D1, D2 and G5 and the shallow, low-diversity fens where it decreased slightly (Figure 2b).

Figure 2c shows profiles of total nitrogen content. The peat from the two Silesian Lowland fens (E1, E2) were richest in total nitrogen. For most of the profiles, the lowest nitrogen contents were measured in the surface layers. They increased slightly with depth, but at most sites did not exceed 2%. Fen E1 and raised bog G5 were exceptions. At fen E1, nitrogen content increased with depth from the surface, reached a maximum (above 2%) in the

Table 2. Stratigraphic profiles of the study mires. Peat species are indicated as follows: *alb*: *Alno-Betuleti* peat; *aln*: *Alneti* peat; *bet*: *Betuleti* peat; *cab*: *Carici-Bryaleti* peat; *cap*: *Carici-Phragmiteti* peat; *car*: *Cariceti* peat; *cus*: *Cuspidato-Sphagneti* peat; *ers*: *Eriophoro-Sphagneti* peat; *eus*: *Eusphagneti* peat; *pin*: *Pineti* peat; *pis*: *Pino-Sphagneti* peat; *spc*: *Sphagno-Cariceti* peat (Peat Genetic division of raw material according to Polish Standard PN-85/G-02500; Polish Committee for Standardization classification of peat according to its botanical composition, 1985).

STUDY AREA	SITE CODE	PEAT DEPTH (CM)	PEAT SPECIES
SUDETEN MOUNTAINS	D1	60-225	<i>ers</i>
		225-450	<i>eus</i>
		450-575	<i>ers</i>
		575-725	<i>ers</i>
		725-810	<i>cus</i>
	D2	100-175	<i>ers</i>
		175-325	<i>ers</i>
		325-400	<i>eus</i>
		400-455	<i>spc</i>
		455-530	<i>car</i>
		530-600	<i>ers</i>
	D3	15-40	<i>car</i>
SILESIA LOWLAND	E1	60-70	<i>cab</i>
		70-115	<i>car</i>
		115-200	<i>cap</i>
		200-310	<i>cab</i>
		310-365	<i>gyttja with organic remains</i>
		365-420	<i>algal gyttja</i>
	E2	30-73	<i>alb</i>
		73-130	<i>cap</i>
ORAWA BASIN	F1	50-160	<i>cus</i>
		160-240	<i>ers</i>
		240-295	<i>spc</i>
		295-350	<i>pis</i>
		350-395	<i>pis</i>
		395-430	<i>pin</i>
	F2	20-50	<i>bet</i>
		50-80	<i>aln</i>
TATRA MOUNTAINS	G1	20-55	<i>aln</i>
		55-110	<i>aln</i>
	G2	15-35	<i>pin</i>
		35-80	<i>ers</i>
	G3	60-125	<i>eus</i>
		125-180	<i>ers</i>
		180-210	<i>ers</i>
		243-280	<i>pis</i>
	G4	125-200	<i>ers</i>
		200-270	<i>eus</i>
		270-325	<i>spc</i>
		325-390	<i>gyttja with wood</i>
	G5	20-110	<i>eus</i>
		110-205	<i>ers</i>
		205-355	<i>bry</i>
		355-420	<i>bry</i>

sedge peat, and then decreased in the basal gyttja layers. In raised bog G5, total nitrogen content declined significantly with depth below 1 m, and its value in the basal layer of moss peat was similar to that in the surface layer.

Figure 2d shows profiles of peat acidity (pH in water and KCl). In most layers of the peat deposits, the pH(H₂O) was weakly acid (< 6), and it was most commonly ca. 4. The largest variation in pH was recorded in fen E1, where pH increased with depth until it was almost neutral, but the deeper layers were weakly acidic.

High contents of humic substances (humic and fulvic acids; Figure 3 and Table 3) occurred in all the peat types. For raised bogs, the highest contents were found in the *Pineti* and *Pino-Sphagneti* peats; for fens, in *Alneti* and *Alno-Betuleti*; and for transition bogs, in *Sphagno-Cariceti*. In general, the raised bogs of the Tatra Mountains had the lowest contents of humic substances. Fulvic acids are more highly oxidised than, and may indeed be

degradation products of, humic acids. For most of the peat deposits, the content of humic acids was 1.5-2 times that of fulvic acids, indicating a high degree of humification. The content of humic substances increased with depth in raised bogs D1, D2, F1 and G3; and an opposite trend was apparent in fen E1 and raised bog G5.

Figures 3(c, d) and Table 3 show profiles of the content of the exchangeable cations Na⁺, K⁺, Mg²⁺ and Ca²⁺ in the peat deposits. Bivalent cations were dominant, and Ca²⁺ was the most abundant ionic species. The peat from the Sudeten Mountains raised bogs (D1, D2) was poorest in cations. Peat from fen F1 and the Tatra raised bogs (G3, G4) had relatively high cation contents; and raised bog G5, which developed from a moss fen, was richest in cations. Na⁺ predominated over K⁺ in most of the sites but in raised bog D1, K⁺ was more abundant than Na⁺. Site D3 was the only shallow peatland where K⁺ ions were more abundant than Na⁺ ions, and K⁺ concentrations were very low in all of the

Table 3. Chemical properties of peat horizons at sites D3 (Sudeten Mountains), E2 (Silesian Lowland), F2 (Orawa Basin) and G1-2 (Tatra Mountains). See legend to Table 2 for key to peat species.

site code	D3	E2		F2		G1		G2	
peat species	<i>car</i>	<i>alb</i>	<i>cap</i>	<i>bet</i>	<i>aln</i>	<i>aln</i>	<i>aln</i>	<i>pin</i>	<i>ers</i>
depth (cm)	15-40	30-73	73-130	20-50	50-80	20-55	55-110	15-35	35-80
degree of decomposition (%)	20	65	55	65	50	50	45	45	25
ash content (%)	69.3	15.38	8.54	6.21	25.65	6.44	24.33	5.92	1.31
N (%)	0.67	2.27	2.11	1.73	1.48	2.2	1.57	1.44	1.04
pH H ₂ O	4.56	5.73	5.68	5.75	5.43	5.05	4.3	4.48	4.57
pH KCl	4.28	5.42	5.25	5.15	5.02	4.66	4.12	3.28	3.19
total carbon (%)	4.9	17.09	9.84	9.71	9.89	9.43	7.72	6.26	5.04
humic acids (%)	1.53	13.28	9.19	6.6	7.71	8.13	3.66	5.25	3.31
fulvic acids (%)	3.37	3.81	0.65	3.11	2.18	1.3	4.06	1.01	1.73
Na ⁺ (mmol kg ⁻¹)	1.3	3.9	4.3	6.1	4.8	5.6	6.1	6.1	5.7
K ⁺ (mmol kg ⁻¹)	4.1	0.78	0.51	2.3	1.8	1.0	1.3	1.0	1.3
Mg ²⁺ (mmol kg ⁻¹)	3.8	19.2	23.8	392	378	49	371	81.3	118
Ca ²⁺ (mmol kg ⁻¹)	22.8	518.0	423.0	512.0	323.0	384.0	263.0	45.6	36.0

fens except for transition bog F2. In most cases, K⁺ concentrations were higher near the surface than in the deeper layers of the profiles.

Table 4 shows the mean, standard deviation and range of chemical measurements obtained for peat of each different botanical origin (peat species). These data indicate that chemical attributes varied widely even between peat samples belonging to the same botanical peat type (syntaxon). Fens were richest in nitrogen, carbon, and macro-elements. The most fertile fen peats were alder peats (*Alnioni*), which had the highest contents of exchangeable cations, organic carbon, nitrogen and ash. Sedge fen (*Magnocaricioni*) peat, like raised bog peat, was poor in exchangeable cations. The least fertile fens were moss fens (*Bryalo-Parvocaricioni*). Transition bog (*Minero-Sphagnioni*) peat contained less Na⁺ and K⁺ ions, humic substances and ash than raised bog peat. Peat from *Sphagnum* raised bogs (*Ombro-Sphagnioni*) and swamps (*Ledo-Pinioni*) had the lowest Ca²⁺, Mg²⁺ and total nitrogen content of all, but the highest K⁺ content. *Sphagnum* raised bogs were very similar to moss fens in terms of their total nitrogen and humic substances contents, possibly because similar plants (mosses) were present in both of these peat types.

Correlation coefficients were calculated to identify significant similarities and differences between the peat samples. Degree of decomposition was related to pH ($r^2 = 0.62$), ash content ($r^2 = 0.57$)

and total nitrogen content ($r^2 = 0.66$). Correlations were also found between Na⁺ and Mg²⁺ ($r^2 = 0.85$) and Na⁺ and K⁺ ($r^2 = 0.5$). No other significant correlations between chemical properties were found, but ash content was highly correlated with pH ($r^2 = 0.8$) and nitrogen content ($r^2 = 0.7$).

The chemical properties of the peat samples were also compared using cluster analysis (Figure 4). The cluster analysis distinguished two groups of similarity amongst the investigated peat types, namely (1) *Alnioni* and *Magnocaricioni* and (2) *Minero-Sphagnioni*, *Bryalo-Parvocaricioni* and *Ombro-Sphagnioni*. The most similar peat types were *Minero-Sphagnioni* and *Ombro-Sphagnioni* (Figure 4a). In terms of ash content, the most similar peat types were again *Minero-Sphagnioni* and *Ombro-Sphagnioni*, whilst the type that was most distinct from the others was *Alnioni* peat.

A second cluster analysis explored the similarity of peatlands in terms of their peat chemistry (Figure 4b). This analysis revealed the closest similarities between two pairs of raised bogs, namely D1 and G3, and F1 and G2. G4 and G5 were least similar to the other raised bogs and the fen E1 was least similar to all the other peatlands. Thus the chemical characteristics of peat from geographically distant mires were more similar than those of peat from different locations within a single mire complex. This may be due to local differences in conditions for peat formation arising from the small-scale diversity and mosaic character of peatland surfaces.

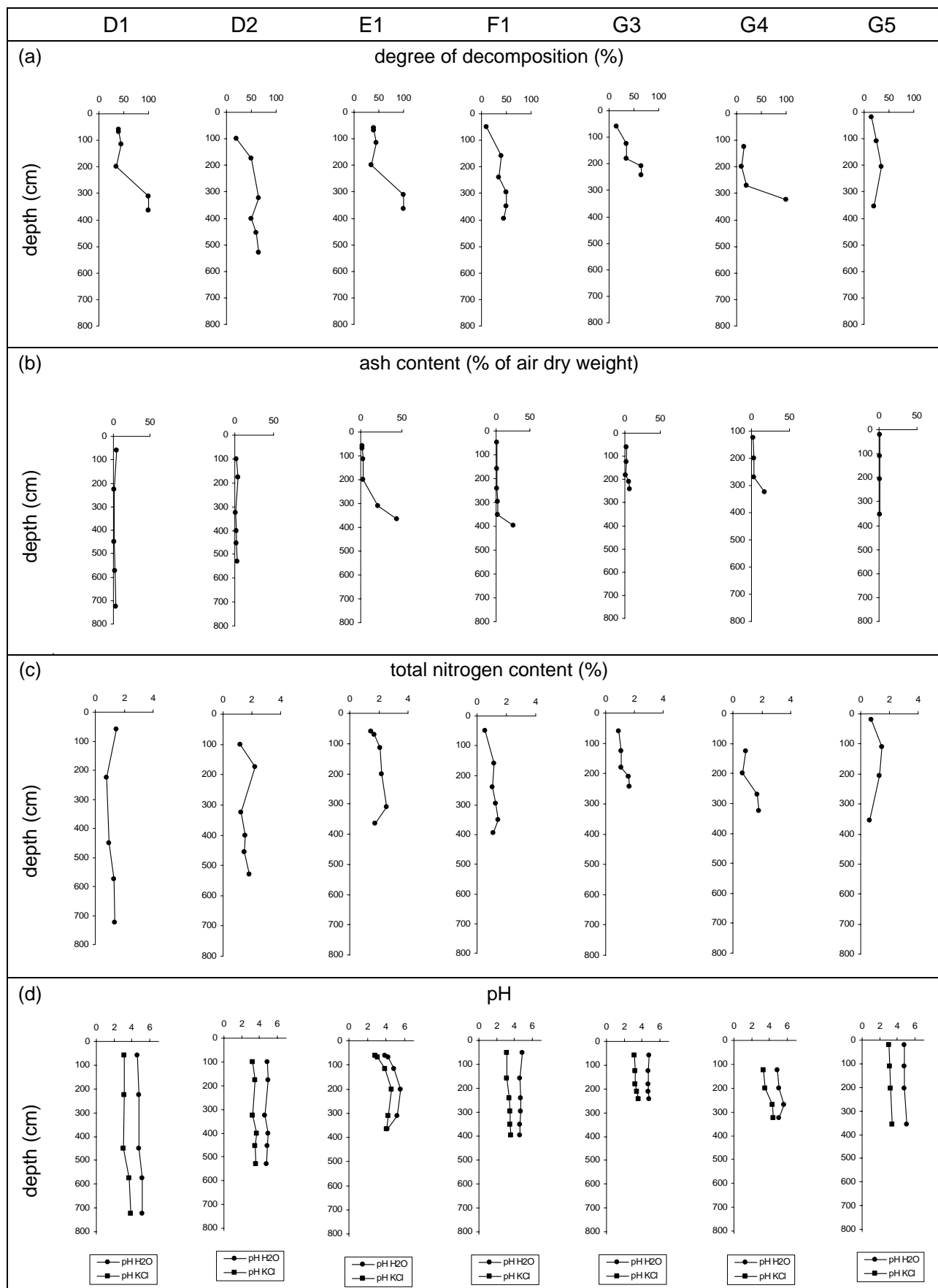


Figure 2. Profiles of (a) degree of decomposition, (b) ash content, (c) total nitrogen content and (d) pH for peatlands D1-2 (Sudeten Mountains), E1 (Silesian Lowland), F1 (Orawa Basin) and G3-5 (Tatra Mountains).

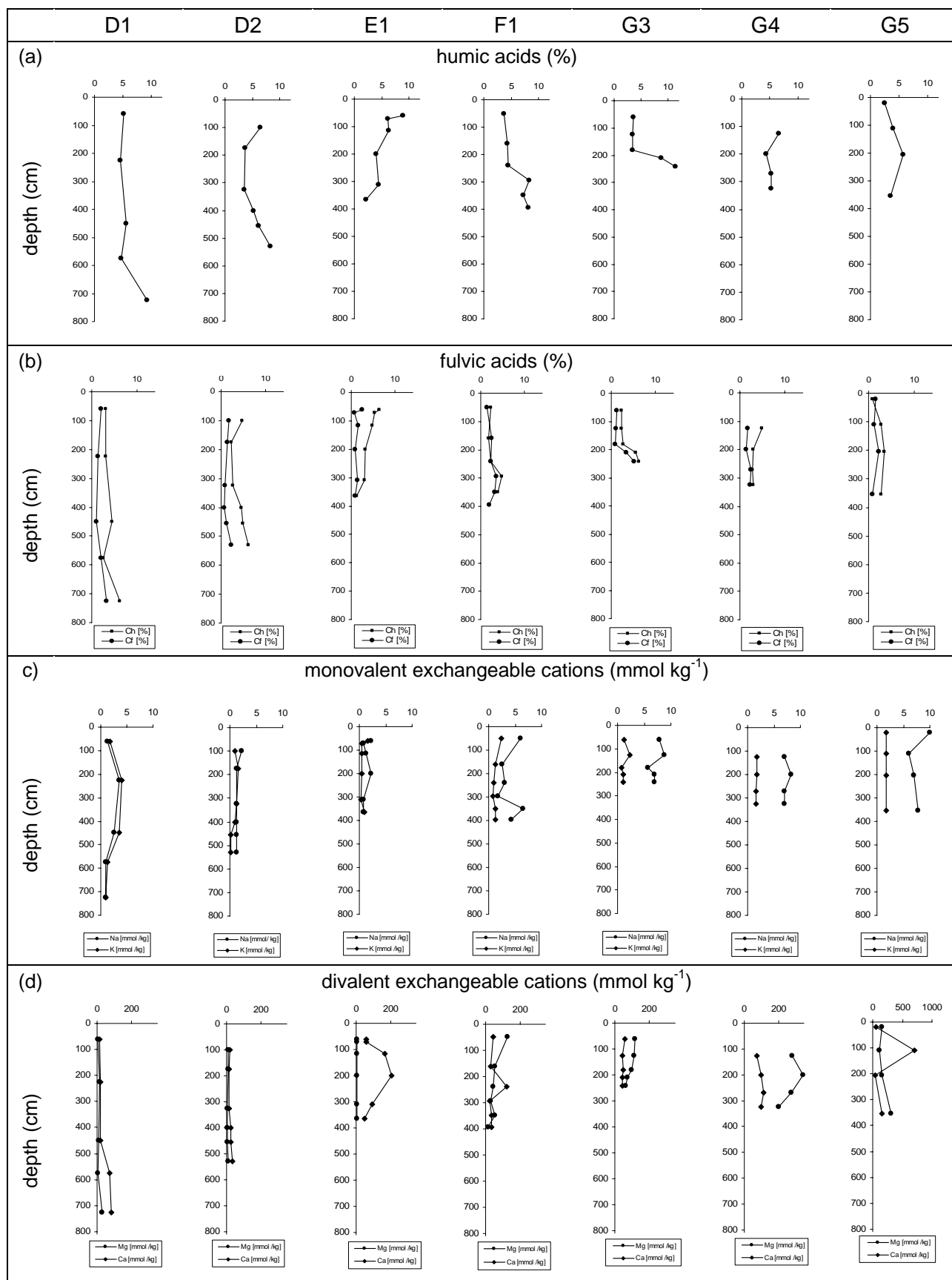


Figure 3. Profiles of (a) humic acids, (b) fulvic acids, (c) Na⁺ and K⁺, and (d) Mg²⁺ and Ca²⁺ for peatlands D1-2 (Sudeten Mountains), E1 (Silesian Lowland), F1 (Orawa Basin) and G3-5 (Tatra Mountains).

Table 4. The variation of peat chemical properties according to peat species (see legend to Table 2 for key). Mean, range and standard deviation (SD) are shown for each chemical property.

CHEMICAL PROPERTY		PEAT SPECIES				
		<i>aln, alb</i>	<i>car, cap</i>	<i>cab, bry</i>	<i>spc</i>	<i>cus,, eus, pis, pin, ers</i>
degree of decomposition (%)	mean	52.5	44	32.5	35	38.6
	min - max	45 - 65	20 - 60	20 - 40	20 - 50	10 - 65
	SD	8.7	15.6	8.7	15	19.5
pH (KCl)	mean	5.125	4.84	4.85	5.1	4.784
	min - max	4.3 - 5.7	4.2 - 5.7	3.9 - 5.6	4.7 - 5.6	4.5 - 5.2
	SD	0.60	0.55	0.71	0.46	0.17
pH (water)	mean	4.8	4.02	3.4	3.8	3.344
	min - max	4.1 - 5.4	3.1 - 5.3	2.8 - 4.6	3.4 - 4.3	3.1 - 3.9
	SD	0.55	0.84	0.82	0.46	0.23
ash content (%)	mean	17.95	16.95	1.88	2.22	3.5174
	min - max	6.4 - 25.7	1.7 - 69.3	0.9 - 3.5	1.2 - 3.5	0.8 - 25.5
	SD	8.93	29.40	1.15	1.12	4.89
nitrogen content (%)	mean	1.88	1.61	1.4	1.43	1.22
	min - max	1.5 - 2.3	0.7 - 2.1	0.6 - 2.2	1 - 1.7	0.5 - 2.2
	SD	0.41	0.59	0.64	0.35	0.38
total organic carbon content (C org) (%)	mean	11.03	6.65	5.56	5	5.69
	min - max	7.7 - 17.1	4.9 - 9.8	3.6 - 8.9	4.5 - 5.3	2.5
	SD	4.14	1.87	2.42	0.42	2.30
humic acid content (%)	mean	8.2	5.15	3.93	3.27	3.72
	min - max	3.7 - 13.3	1.5 - 9.2	2.7 - 6.4	2.3 - 4.6	0.9 - 6.2
	SD	3.94	2.72	1.70	1.21	1.57
fulvic acid content (%)	mean	2.84	1.5	1.62	1.76	1.9692
	min - max	1.3 - 4.1	0.7 - 3.4	0.9 - 2.5	0.7 - 2.4	0.8 - 5.2
	SD	1.32	1.11	0.88	0.96	1.04
sodium content (mmol kg ⁻¹)	mean	5.2	1.7	4.8	3.9	4.6
	min - max	3.9 - 6.1	0.9 - 4.3	2.2 - 7.8	1.3 - 7.0	0.9 - 10.0
	SD	0.86	1.3	3.0	3.0	3.0
potassium content (mmol kg ⁻¹)	mean	1.3	1.3	1.4	1.3	1.5
	min - max	0.8 - 1.8	0.5 - 4.1	0.5 - 1.8	1.0 - 1.5	0.8 - 4.0
	SD	0.43	1.6	0.6	0.3	0.8
magnesium content (mmol kg ⁻¹)	mean	205.0	7.9	117.5	107.5	75.0
	min - max	19.0 - 378.0	3.3 - 23.8	3.3 - 305.0	5.0 - 274.0	2.9 - 347.5
	SD	197.0	8.8	144.0	145.5	85.54
calcium content (mmol kg ⁻¹)	mean	372.3	139.5	115.8	86.8	69.0
	min - max	263.0 - 518.0	22.8 - 422.5	43.5 - 207.8	22.5 - 123.8	14.5 - 708.0
	SD	109.1	169.0	78.9	55.8	134.9

DISCUSSION

The considerable increase in ash content of the lowermost layers of mires E1, F1, and G4 reflects the deposition by groundwater of a mineral fraction within the organic peat mass. Steinmann & Shotyk (1997) also observed that the ash content of peat increased steadily with depth, from values characteristic of ombrogenous *Sphagnum* peats

(>3%) in the surface layers to those typical of minerogenous peats (>5%) in the deeper layers (Naucke 1990). Much of the inorganic fraction of ombrogenous peat is derived from the weathering of crustal materials. In most of the samples taken from a raised bog in Switzerland, ash content was in the range 1-2.5% (Steinmann & Shotyk 1997). The ash generally originates from atmospheric inputs of pedogenic dust, so that ash concentration can

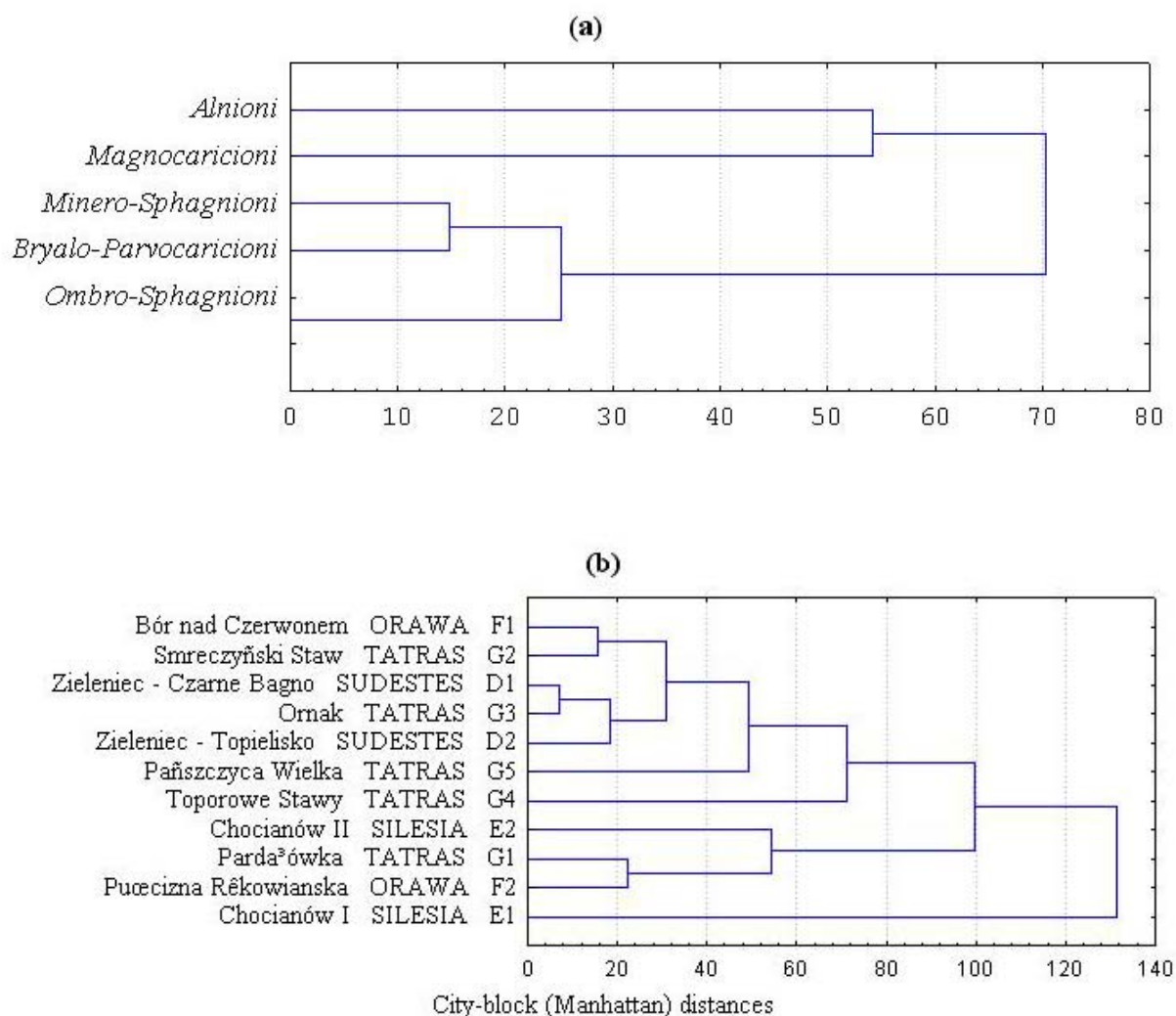


Figure 4. The results of cluster analyses showing (a) similarity between botanical peat types in terms of their degree of decomposition and (b) similarity between mire sites in terms of their peat chemistry. Peat from Site D3 was omitted from the analysis because it had a much higher mineral content than all other samples.

increase as a result of the decomposition of organic matter or by precipitation of new diagenetic solid phases. Thus the ash content of peat at the time of formation is a function of both the peat accumulation rate and the dust input rate. Peaks in ash content appear to be associated primarily with discrete periods of reduced peat accumulation and possibly higher rates of dust input. Ash content may also be enhanced by mineral dissolution (Steinmann & Shotyk 1997) and by forest and peatland fires (Dugmore *et al.* 1992, Blackford *et al.* 1992). A study conducted in central Europe indicated that ash content can also increase with increasing pine and spruce cover as afforestation progresses (Menke 1987; Hölzer & Hölzer 1987; Görres & Bludau 1992).

The degree of decomposition reflects the age and wetness of the mire at the time when the peat was

formed. Periods of drought can be attributed to climate change or to local effects such as peat drainage. Intensive forest clearance can also be accompanied by temporary drying of the mire surface. When the peatland is relatively dry, oxidation (decomposition) increases so that the rate of peat accumulation is slow, and more highly decomposed layers are formed (Ikonen 1993). An increase in dust deposition may also occur during dry periods. On the other hand, an increase in mire wetness often leads to the formation of less decomposed peat with a lower ash content; although a highly decomposed peat layer may develop under the influence of laterally penetrating water (Steinmann & Shotyk 1997).

No clear relationship between botanical peat type and ash content or degree of decomposition has been identified for the fens and bogs of southern

Poland. In general, however, the peat types found here can be placed in the same order of decreasing ash content and degree of decomposition (*gyttja* > *Alnioni* > *Magnocaricioni* > *Bryalo-Parvocaricion* > *Ombro-Sphagnioni*) as was reported by Twardowska *et al.* (1999) for peat deposits in north-eastern Poland.

The acidity of peat arises from a combination of natural factors, such as the absence of alkaline components from the organic parent material and the prevalence of precipitation over evaporation (which gives rise to high acidity in raised bogs), together with anthropogenic factors such as the deposition of acidic pollutants from the atmosphere. pH was similar in all of the peatlands in southern Poland that were investigated, pH(H₂O) ranging from 4.22 to 5.04 for the raised bogs, and from 4.30 to 5.68 for the fens. Thus the fens are weakly acidic, and the raised bogs are slightly more acidic than the fens. These ranges show greater overlap than those reported by Bohlin *et al.* (1989), who quotes pH values of 4.04–6 for *Sphagnum* raised bog and 4.9–6.0 for sedge fen.

The nitrogen contents observed in the mires of south-western Poland are not similar to those found by Ringqvist and Öborn (2002) in *Sphagnum* peat (0.7%) and sedge peat (3.2%). These authors reported that the main chemical differences between poorly humified *Sphagnum* (raised bog) and *Carex* (fen) peat were related to differences in site conditions during peat formation, which in turn reflected the requirements of the vegetation. *Carex* peats were formed exclusively in fens and most often in nutrient-rich mires with high pH and high microbial activity. Therefore sedge peat contained more nutrients and had higher pH, ash content and total nitrogen than *Sphagnum* peat.

Fen peat contains more carbon and nitrogen than raised bog peat. An increase in the rate of decomposition raises the total carbon content, which is used to indicate the age of peat. The concentration of humic acids also increases with the age, depth and decomposition rate of the peat (Duan & Ma 2001). Humic substances are ubiquitous organic constituents of a wide range of soils, peats, sediments and aquatic ecosystems. They are formed *in situ* during the chemical, physical and microbial degradation of biogenic compounds (Lehtonen *et al.* 2001). Dehmer (1995) found large amounts of humic and fulvic acids in a highly decomposed peat that had formed in an oxygen-rich environment. This may suggest that the rate of decomposition is related to wetness and organic acid content through geochemical processes that operate during temporary drying. The decomposition of organic matter also releases large quantities of inorganic

nitrogen, and this can account for high nitrogen levels in drained fens. Such a change in the soil processes that determine trophic conditions can influence, in turn, the development of soil micro-organisms. Thus, the drainage of a peatland raises the nitrogen content as well as the ash content and the decomposition rate (Okruszko 1991).

The relationships between decomposition rate, ash content, pH and total nitrogen that have been observed in south Polish peat are thus attributed to temporary drying of the mires accompanied by an increase in the rate of decomposition, a reduction of peat growth with unchanged mineral inputs and consequent increase in ash concentration, and the release of large amounts of mineral nitrogen with effects on trophic status and microbial processes. Temporary drying could also have a bearing on the low potassium concentrations that were observed (Okruszko 1991).

Mg²⁺ and Na⁺ may be derived from various sources, and the adsorption capacity of peat for these two ion species may differ. However, the K⁺ and Na⁺ profiles observed in southern Poland are very similar to those of raised bogs in Switzerland. At one Swiss site, the Ca²⁺ content of the surface layers was about 22.5 mmol kg⁻¹, rising to 150 mmol kg⁻¹ at the interface between ombrogenic and minerogenic peat (Steinmann & Shotyk 1997). Shotyk (1997) estimated that only 4.6% of Ca²⁺, 7.8% of Mg²⁺ and 11.6% of K⁺ supplied to a bog by rainwater was retained in the long term, whilst almost all of the Na⁺ was lost rapidly in lateral seepage through the poorly decomposed surface layer (acrotelm). Where the Ca:Mg ratio increases with depth, the Ca²⁺ supplied by rainwater must be augmented through the action of acidic pore water on minerals in the ash fraction (Steinmann & Shotyk 1997). Exchangeable cations should be more abundant in fens than in raised bogs due to their different water sources. The low K⁺ concentrations observed in south Polish fens can be associated with the high demand of the rich and diverse vegetation for this nutrient. K⁺ is less frequently limiting for the poorer vegetation of raised bogs, whose upper peat layers consequently have higher K⁺ concentrations than those of fens.

CONCLUSIONS

1. There are large differences in chemical characteristics between the peat deposits of fens, transition bogs and raised bogs in southern Poland.
2. Peat from geographically separate peatlands can be chemically more similar than peat from

different locations within a single mire complex, and this is probably attributable to the small-scale heterogeneity of mire surfaces.

3. The botanical peat types whose chemical properties are most similar are *Minero-Sphagnioni* and *Ombro-Sphagnioni*, and these belong to the same similarity group as *Magnocaricioni* and *Alnioni* peat.
4. Chemical attributes can vary widely between different peat deposits with the same botanical origin.
5. Thus, purely botanical classifications are of limited utility as indicators of the conditions under which peat formation occurred.

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Author for correspondence: Professor Bogusław Wilkomirski, Department of Plant Systematics and Geography, Warsaw University, Al. Ujazdowskie 4, 00-478 Warszawa, Poland.
 Fax: +48-22 55-30-500; E-mail: bowi@biol.uw.edu.pl or malma@biol.uw.edu.pl