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Spatial Variability in Podzolic Soils of Central and Northern Europe

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Preface

The results presented here represent a synthesis of the more than fifteen years of fieldwork that I have had the pleasure of carrying out in Finland, Estonia, Latvia, Lithuania, Belarus, Germany and Poland. It was done in the course of my participation in several research projects funded by the United States Environmental Protection Agency (EPA), as well as the Polish and Finnish Academies of Sciences, the University of Oulu, the USDA Forest Service and the Global Environment Facility (GEF).

At this point I would like to express my sincerest thanks to those who made my involvement in the above programmes a possibility, and most especially: Prof. Alicja Breymeyer (IGiPZ PAN), Dr Andrzej Bytnerowicz (USDA Forest Service, Riverside), Prof. Pavo Havasowi (University of Oulu), Docent Urho Mäkirincie (University of Oulu), Prof. Władysław Matuszkiewicz (IGiPZ PAN), Prof. Reginald Noble (Bowling Green State University, Bowling Green, Ohio), Prof. Rauni Ohtonen (University of Helsinki), Prof. David Reed and Prof. Glenn Mroz (Michigan Technological University in Houghton) and Dr Wethen Reed (US Department of Agriculture in Washington). I am also grateful to the authorities at the Universities in Helsinki, Turku and Oulu, as well as the heads of field stations of the Finnish Forest Research Institute (METLA), for making chemical laboratories available to me as I was engaging in fieldwork. I would also like to thank Roger Blair (US Environmental Protection Agency, retired) for assistance in editing the English version and publication in the United States.

The research described here is being continued with on Russian territory, within the framework of the European Commission's Sixth Framework Programme for Research and Technological Development – project e-LUP (*Simulating land-use processes – an interactive e-tool for SIA*), as well as through a project funded by the Polish Ministry of Education and Science – "Geographically conditioned trends and discontinuation of podzolic soil development – its genetic and ecological aspects".

The preliminary synthesis of the results described here was published in Polish (Degórski 2002). I hope that characteristic of podzolic soils presented in English will be very helpful for all, who are interested in this type of soil and its properties, as well as in soil geography. The original data are available at
http://www.igipz.pan.pl/geoekoklimat/degorski/home_pl.htm

Marek Degórski

1. Introduction

Podzolic soils were first distinguished as "podzols" in the second half of the 19th century by Russian soil scientists (after Glinka 1926 and Karpaczewski 1983), such that Sibirtsev introduced the type into the official classification of soils (Yaalon 1997). However, descriptions of podzolic soils may also in fact be found at the same time in the work of Scandinavian soil scientists (Barth 1856; Forchhammer 1857; Müller 1887). Subsequently, the term gained acceptance among – and was used by - soil scientists in many countries, irrespective of the classification actually in force (Muir 1961; Ponomariewa 1969; Petersen 1976; Mokma, Buurman 1982; Boul *et al.*, 1989), or else served in the devising of new regional names, such as *popiołoziem* in Poland (Chodzicki 1933).

To afford misunderstandings, the present study uses the diagnostic spodic horizon to be the criterion considered to distinguish podzolic soils. The definition of the spodic horizon was first set out in the American taxonomy of soils (Soil Survey Staff 1960, 1975), and then applied in FAO classifications (Dudal 1968, 1969), soil systematics (SGP 1989) and the World Reference Base for Soil Resources (1998). In fact, the Polish soil systematics consider the podzolic earths soils to encompass, not only the podzols (*Densic Podzols* according to the WRB Classification) and podzolic soils (Haplic podzols according to the WRB Classification) but also the rusty soils (*Distric Arenosols* according to the WRB Classification), with their diagnostic *sideric* horizon (Kowalkowski *et al*., 1981; Prusinkiewicz, Bednarek 1985; SGP 1989).

Podzolic soils are among the zonal soils in the boreal and sub-boreal climatic and vegetational belt. However, within the European regions of their zonal occurrence, their share in the overall soil cover is very variable. They represent about 39.7% of all soils on the Central Polish Lowlands (Prusinkiewicz, Bednarek and Pokojska 1980), and 67.7% on the Byelorussian Plain (Anoszko, 1978), as opposed to more than 75% of those in Finland (*Atlas of Finland* 1986). As azonal soils, they also occur in the Northern Hemisphere’s polar belt (Iceland and Spitsbergen), and in the Mediterranean region (FAO/UNESCO 1978; Certini *et al.*, 1998). Irrespective of geographical location, they are developed from sandy formations (Petaja-Ronkainen *et al.*, 1992; Sepponen 1985; Degórski 1998a; Lundström *et al.*, 2000a, b), and their occurrence links up with regions in which precipitation prevails over evapotranspiration (Głazowska 1981; Mokma, Buurman 1982; Bednarek, Prusinkiewicz 1997; Degórski 1997b; Lundström *et al.*, 2000a). They are also associated with ecosystems of acidophilous plant communities, most often coniferous forests[1] (Crocker 1952; Matuszkiewicz W. 1981; Ugolini *et al.*, 1981; Matuszkiewicz W., Matuszkiewicz A., Degórski 1994; Lundström *et al*., 2000a; Matuszkiewicz J. 2001).

World pedological literature, and especially that of Europe, devotes much space to podzolic soils, in relation to the understanding of mechanisms through which they arise (Lundblad 1934, 1936a, b; Rode 1937; Ponomariewa 1964, 1969; McKeague *et al*.. 1971; Sapek 1971; Prusinkiewicz 1972a, b; Kaniwec 1978; Pokojska 1979a, b, c; Mokma, Buurman 1982; Farmer, Fraser 1982; Mokma 1991; Raisanen 1996; Gustafsson *et al*., 1995, 1999, 2000; Lundström *et al*., 2000b; Melkerud *et al*., 2000; Olsson, Melkerud 2000), the influence of pedogenic processes on the vertical differentiation of soil properties (Duchaufour 1982; Birkeland 1984; Skłodowski *et al*., 988), and their characteristics in different parts of the Continent. The results of the research have been published, *inter alia*: for Northern Europe – Jauhiainen (1973), Hinneri (1974), Rajakorpi (1984), Koutaniemi *et al.*, (1988), Petaja-Ronkainen *et al*., (1992), Kahkonen (1996), Kowalkowski (1995, 1998), Lundström *et al*., . (2000 a, b), Melkerud *et al*., (2000), Olsson, Melkerud (2000), Western Europe – Mokma, Buurman (1982), Eastern Europe - Ponomariewa (1969), Głazowska (1981), Degórski (1995a, 1998b), Pietuchowa (1987), Khoroshev, Prozorov (2000) and the southern regions of the continent - Certini *et al.*, (1998).

Podzolic soils have likewise been studied in many physico-geographical mesoregions of Poland (Musierowicz 1954; Marcinek 1960; Borowiec 1961; Pondel 1961, 1963; Prusinkiewicz 1961b, 1965, 1969, 1972b; Siuta 1961; Dzięciołowski 1963, 1974; Prusinkiewicz, Noryśkiewicz 1966; Uggla 1968; Kowalkowski, Nowak 1968a, b; Jauhiainen 1969; Plichta 1970; Dzięciołowski, Kociałkowski, 1973; Uggla, Roszko 1974; Skiba 1977; Kuźnicki *et al*. 1978a,b; Białousz 1978; Konecka-Betley 1983; Czępińska-Kamińska 1986; Degórski 1990; Konecka-Betley et al.,1994; Chodorowski 1995; Bednarek 1991; Komornicki, Skiba 1996; Tobolski *et al*., 1997; Świercz 1997; Prusinkiewicz, Michalczuk 1998; Janowska 2001), though only more rarely has work been done over larger parts of the country (Miklaszewski 1912; Czerwiński 1965; Degórski, 2002).

Notwithstanding this extensive bibliography, the literature lacks work describing the spatial differentiation of the properties of podzolic soils on the supra-regional scale. and relating this to geographical variability of the factors conditioning the process of pedogenesis. This paper is an in-depth conceptualisation of these issues through an analysis of many soil

[1] in the zonal range of occurrence of podzolic

properties defined in material collected by a single author employing the same laboratory methods. The absence of such a study was one motivation behind the work presented here. The research carried out hitherto had mostly concentrated on a single geographical region, while studies of large spatial extent mostly confined themselves to narrowly-selected soil properties (Skłodowski 1974).

Other types of soil have been subject to much fuller characterisations of the dependent relationships between selected pedogenic factors and the variability of geographical zones, or altitudinal zones in the mountains and their influence on the development of the properties of the given soil cover (Skiba 1985; Melke 1997). This is the first such study for podzols for the region described above.

In approaching the studies described here, I assumed that, if a defined soil type arises across a quite broad spatial spectrum – i.e. with the influence of geographically-varied pedogenic factors, then this must to some degree influence the geographical variability in soil properties (Fig.1). The hypothesis advanced thus relates to interdependence between basic pedogenic factors and the development of soil cover and its properties (Dokuczajew 1948-1949). Geographical influences include the type of weathering process, and in particular the breakdown of silicates and aluminosilicates (Duchaufour 1982; Catt 1988; Bednarek, Prusinkiewicz 1997), the quantity and quality of organic matter (Jenny 1941; Crocker 1952; Prusinkiewicz 1961a; Sapek 1971; Liski 1995; Lisk *et al.*, 1997; Degórski 2001c), the profile-related scope of impact of pedogenic processes (Yaalon 1975;

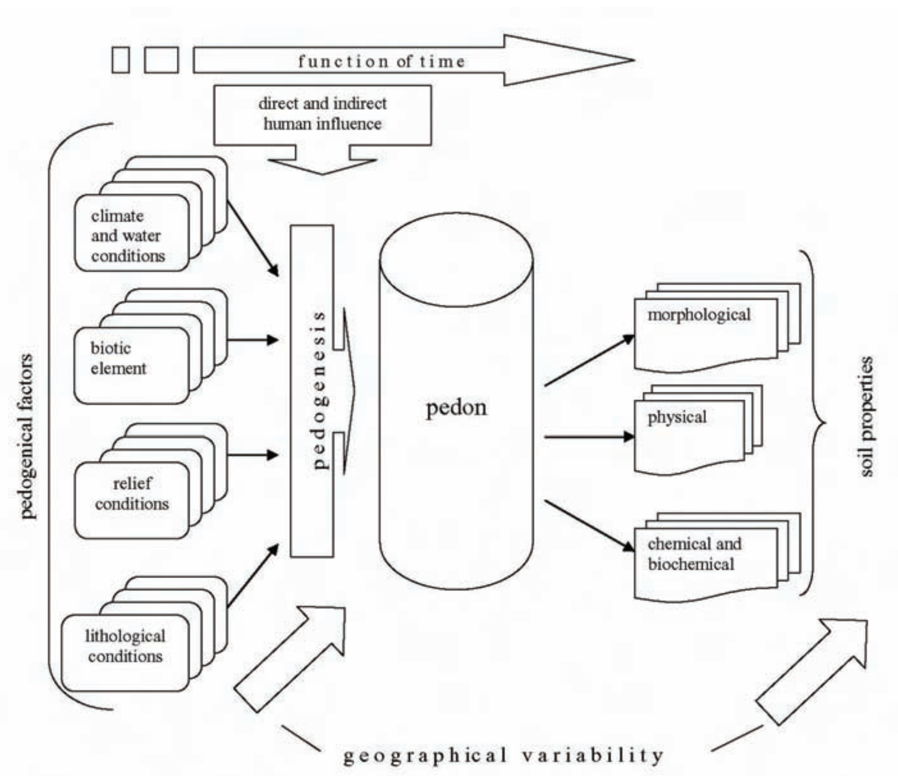

Figure 1. Relationship between geographical variability of pedogenic factors and soil properties.

Birkeland 1984; Kowalkowski *et al.*, 1994) and the course of elemental pedological processes (Jenny 1941; Catt 1988; Degórski 2000). Each process by which a soil develops comprises a specific complex of pedogenic microprocesses appropriate to it; these operating within single-phase or multi-phase cycles in the soil environment (Catt 1987; Kowalkowski *et al.*, 1994) that are mainly determined by biotic and climatic factors (Jenny 1941; Crocker 1952; Ugolini *et al* 1981; Degórski 2001b). The processes in question shape primary features and morphology of contemporary soil cover, while the development of the profile may continue over a period of several hundred thousand years (Catt 1988; Boul *et al.*,1989). Time is thus an important element in pedogenesis determining the degree of soil development.

According to M. Głazowska (1981),"permanent" properties of the pedosphere are of cardinal importance in studies of the geographical differentiation of contemporary soil covers. Included among these are: the sequence of genetic horizons, mineral composition, and transformations of organic matter, as well as those physico-chemical properties that allow the development of pedogenic processes to be better understood. In this regard, the dynamics of many processes ongoing in soils contemporarily (e.g. changes in soil moisture, reaction and the activity of soil solutions) are seen as characterizing nothing more than their state at the given moment. Furthermore, the considerable spatial variability in the properties of soils developing through the above processes at the microhabitat level ensures that the latter may represent a very important augmentation of the information on how a given pedon or polypedon functions (Degórski 1995c, 1998c, 2000, 2001b).

Pedogenic processes are also influenced by destructive human activity that disturbs their natural course within the cycle of soil development, as well as their internal structure (Degórski 1995d; Manikowska 1999). This can be true of direct use or indirect influences through the transfer of pollution (Degórski 1995d). The communities of pine forest associated with podzolic soils are also characterised by the greatest spatial continuity of forest utilisation in Poland (Degórska 1996) and in northern Europe (Jauhiainen 1973).

A primary aim of the work described here is to determine the influence of geographically-diversified pedogenic factors on the spatial variation to selected morphological, physical, chemical and biochemical properties of the podzolic soils of the Eastern and Northern European soil regions (as understood by Głazowska 1981), and then to point out the regional differences thereof, and the diagnostic significance these may have in studies of the spatial variability of soil cover. I attempt to assess the influence of two groups of pedogenic factors – the biotic/climatic and the morpholithological – on the contemporary geographical differentiation of properties of podzolic soils. The results obtained for spatial variability in podzolic soils as regards defined properties have then been set against the geographical divisions of the pedosphere that are already in existence (Volobujev 1973; Głazowska 1981; Boul et al., 1989; Bednarek, Prusinkiewicz 1997).

The focus of the work presented here is on two taxonomic units within the order of podzolic earths, i.e. the podzolic soils (*Haplic Podzols*) and the rusty-podzolic soils[2] (*Distric Arenosols*, or *Hiperdistric Arenosols*), the nomenclature of which is in line with official Polish soil systematics (SGP 1989).

2. Research assumptions

The fact that many endogenous and exogenous factors of the geographical environment have an influence on the spatial variability of soil properties is sufficient to necessitate a strict definition of both assumptions and procedures as pedological work is carried out on the geographical scale so that comparisons between different soil profiles can be made. These activities should seek to obtain a set of elements (soils), shaped in similar natural conditions, by the same habitat factors, and hence differentiated only in temporal and spatial terms. Also of importance in assessing the courses of pedogenic processes is such a selection of research sites as will guarantee the least possible prior modification of the soils for analysis by human activity (Mukherjee 1994; Degórski 1997a; Gworek, Degórski 1997). The choice of research sites was guided by the following criteria:

- autogenic soil with an endo-percolative type of water regime,
- located at an altitude of less than 300 m a.s.l.,
- flat surface with an slope of less than 2^o,
- permeable rocky material beneath,
- glaciofluvial sediments,
- supported a forest ecosystem with a prevalence of Scots pine in the tree stand,
- minimum tree-stand ages of 80 years,
- not characterised by the direct impact of humankind on the ecosystem.

As research sites were denoted, every effort was also made to ensure their representativeness of the given geographical region in respect of its geoecological conditioning (Degórski 1997b). From among the 418 pits dug in podzolic or rusty-podzolic soils within the study area, the 39 selected for detailed analysis were those with habitat characteristics most typical

[2] in line with the definition in the *Systematyka Gleb Polski* (SGP 1989), the rusty-podzolic soils are a sub-type of the rusty soil type, while podzolic soils have been identified as a type rank.

for the given geographical unit (Table 1). The remainder served in the verification of the many variables linked with profile morphology, as well as the differentiation of certain soil properties (Degórski 1994a, 2001a).

Table 1. Geographical locations of research plots.

Profile	Location of research plots				
	Plot/country	sub-province	macroregion	latitude N	longitude E
1	Kevo / Finland	Lapland	Northern Lapland	69°44’46,48”	27°01’20,78”
2	Kessi / Finland	Lapland	Northern Lapland	69°01’23,21”	28°30’21,56”
3	Oulanka / Finland	Lapland	Southern Lapland	66°21’33,45”	29°21’34,12”
4	Tennila / Finland	Lapland	Southern Lapland	66°56’23,45”	25°56’21,34”
5	Muhos / Finland	Ostrobothnia	Western Ostrobothnia	64°43’25,45”	26°01’48,40”
6	Luopioinen / Finland	Finnish Lakelands	Hamme	61°32’34,28”	24°48’35,44”
7	Lammi / Finland	Finnish Lakelands	Hamme	61°09’34,21”	25°00’12,08”
8	Hattula / Finland	Finnish Lakelands	Hamme	61°11’45,38”	24°50’12,34”
9	Vitsiola / Finland	Finnish Lakelands	Hamme	61°05’23,78”	24°55’57,32”
10	Punkaharju / Finland	Finnish Lakelands	Karelian Lakeland	61°39’41,64”	29°16’54,88”
11	Tipu / Estonia	Eastern Baltic Costland	Estonian Lowland	58°18’59,84”	24°59’37,82”
12	Jaunjelgava / Latvia	Eastern Baltic Lakeland	Courland Lakeland	56°37’22,24”	24°53’16,61”
13	Mincia / Lithuania	Eastern Baltic Lakeland	Lithuanian Lakeland	55°25’50,32”	26°01’05,70”
14	Strazdai / Lithuania	Eastern Baltic Lakeland	Lithuanian Lakeland	55°08’31,45”	26°09’46,12”
15	Płaska / Poland	Eastern Baltic Lakeland	Lithuanian Lakeland	53°52’27,92”	23°18,30,14”
16	Browsk / Poland	Podlasie-Byelorussian Plateaus	North Podlasie Plain	52°53’19,32”	23°37’10,05”
17	Józefów / Poland	Północne Podkarpacie	Sandomierz Basin	50°28’38,42”	22°59’29,06”
18	Baranowicze / Belarus	Podlasie-Byelorussian Plateaus	Western Pre-Polesie	52°56’47,68”	25°53’04,32”
19	Krasna Swoboda / Belarus	Podlasie-Byelorussian Plateaus	Western Pre-Polesie	52°48’14,76”	27°08’51,96”
20	Soligors / Belarus	Berezina-Desna Lowland	Eastern Pre-Polesie	52°52’24,54”	28°25’49,66”
21	Bychow / Belarus	Berezina-Desna Lowland	Eastern Pre-Polesie	53°14’22,35”	30°12’44,27”
22	Słowgorod / Belarus	Berezina-Desna Lowland	Eastern Pre-Polesie	53°25’28,43”	31°06’47,80”
23	Chotimsk / Belarus	Berezina-Desna Lowland	Central Sub-Dnieper	53°20’57,29”	32°37’38,00”
24	Uzłogi / Belarus	Berezina-Desna Lowland	Central Sub-Dnieper	53°20’53,58”	32°35’54,04”
25	Chrisdorf / Germany	Western Baltic Lakelands	North Mecklenburg Lakeland	53°06’08,50”	12°25’47,91”
26	Namyślin / Poland	Southern Baltic Lakelands	Toruń-Eberswald Proglacial Channel	52°39’41,36”	14°32’11,47”
27	Gościm / Poland	Southern Baltic Lakelands	Toruń-Eberswald Proglacial Channel	52°44’22,33”	15°42’21,82”
28	Krucz / Poland	Southern Baltic Lakelands	Toruń-Eberswald Proglacial Channel	52°47’17,81”	16°26’13,96”
29	Bobrowniki / Poland	Southern Baltic Lakelands	Toruń-Eberswald Proglacial Channel	52°48’50,93”	19°00’44,18”
30	Skrwilno / Poland	Southern Baltic Lakelands	Chełmno-Dobrzyń Lakeland	52°48’10,81”	19°19’49,27”
31	Glinojeck / Poland	Central Polish Lowlands	North Mazovian Lowland	52°49’36,93”	20°19’28,70”
32	Ceranów / Poland	Central Polish Lowlands	South Podlasie Lowland	52°38’08,32”	22°16’57,40”
33	Brok / Poland	Central Polish Lowlands	Central Mazovian Lowland	52°40’36,50”	21°42’37,45”
34	Nowe Miasto / Poland	Central Polish Lowlands	South Mazovian Elevation	51°35’02,64”	20°37’05,36”
35	Miedzierza / Poland	Central Małopolska Uplands	Przedborze Upland	51°06’28,38”	20°25’06,86”
36	Złoty Potok / Poland	Silesian-Cracovian Uplands	Kraków-Częstochowa Upland	50°43’16,10”	19°32’17,15”
37	Klucze / Poland	Silesian-Cracovian Uplands	Kraków-Częstochowa Upland	50°20’59,05”	19°39’12,63”
38	Tworóg / Poland	Central Polish Lowlands	Silesian Lowland	50°34’56,20”	18°44’21,35”
39	Kuźnia Raciborska / Poland	Central Polish Lowlands	Silesian Lowland	50°10’58,78”	18°20’35,18”

3. Geographical locations of study areas

The work took in the area of zonal occurrence of podzolic soils, whose western and southern limits are constituted by the natural ranges of fresh Scots pine forest of the *Dicrano-Pinion* alliance, while the northern one relates to the distribution of the *Phyllodoco-Vaccinion* alliance (Bohn *at al*., 1996). The eastern limit was the political boundary (border) with the Russian Federation. The work was thus carried out in Germany, Poland, Belarus, Lithuania, Latvia, Estonia and Finland, between longitudes 12°25' and 32°37' E and latitudes 50°10' and 69°44' N (Fig. 2). The analysed profiles were within 13 sub-provinces encompassing 23 physico-geographical macroregions (Table 1), as adopted in line with division of Europe into physico-geographical regions by Kondracki (1997), and the nomenclature following Richter (1968), Aartolahti (1977), Demietjew, Romanowski (1977) and Kondracki (1992, 1994, 1995).

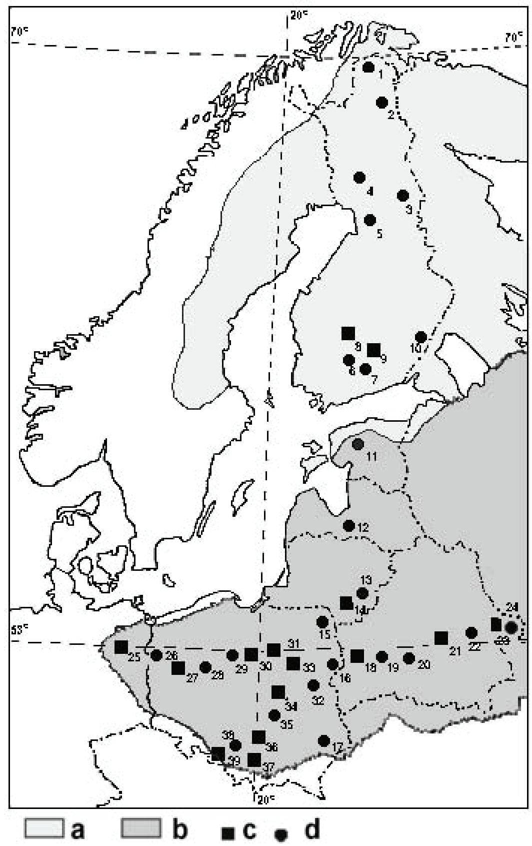

Fig. 2. Distribution of studied podzolic and podzolic-rusty soils in the northern and eastern European Soil Regions (according to the division by Głazowska 1981).
a – Northern European Region, b – Eastern European Region, c – podzolic-rusty soils, d - podzolic soils, 1-39 – numbers of soil profiles

Lapland

Northern Lapland

Profile 1 – *Kevo* (Finland); podzolic soil.

A pit was dug beyond the zone of longlasting permafrost, c. 200 m south of Lake Kevojarvi (Hinneri 1974, 1975), on a plain formed from glaciofluvial material markedly transformed periglacially and accumulating in the Holocene's Atlantic Period (c. 6000 years BP), with Scots pine occurring naturally (Kallio 1969, 1986; Tobolski 1975). From the syntaxonomic point of view, the plant community was classified as *Cladonio-Pinetum boreale betuletum tortuosae* (Roo-Zielińska, Solon 1997), an association extending over more than ten square kilometers in the Kevo area (Heikkinen *et al.*, 1998).

Profile 2 – *Kessi* (Finland); podzolic soil.

The pit was located in a flat part of a denuded esker, c. 1 km east of Lake Kessijarvi, on the Inari Plain formed from glaciofluvial material (Johansson 1988; Derone 1993; Johansson, Kujansuu 1995) that accumulated at the time of the deglaciation some 7200 years BP (Sepponen 1985). The vegetation here is of *Cladonio-Pinetum boreale* dry coniferous forest, wherein 96% of the trees in the stand are Scots pines (Sepponen 1985).

Southern Lapland

Profile 3 – *Oulanka* (Finland); podzolic soil.

A pit was dug in sandy cover on scoured ground moraine showing clear traces of aeolic processes (Koutaniemi 1979, 1981, 1984, 1987; Winkelmolen, Koutaniemi 1986). Deglaciation proceeded here from the Pre-boreal period 9300-9500 years BP, through to the Atlantic Period 7800 years BP (Koutaniemi *et al.*, 1988). The area is overgrown by fresh pine forest that Euroli *et al.* (1991) have assigned to the *Calamagrostio lapponicae-Pinetum* association, cf. the *Empetro-Pinetum fenoscandicum* as recognised by Matuszkiewicz *et al.* (1994b), but showing considerable analogies with the community of fresh pine forest of the *Geranium-Myrtillus* type when it comes to the Finnish classification (Soyrinki *et al.*, 1977).

Profile 4 – *Tennila* (Finland)*;* podzolic soil.

A pit was dug on a denuded esker showing signs of cryoturbation and deflation (Van Vliet-Lamoe *et al.* 1993). The landform in question arose in the Eoholocene, while aeolic processes developed in the Mesoholocene (Seppala 1995). Vegetation is of the *Geranium-Myrtillus* type of fresh pine forest community (Sepponen *et al.*, 1982).

Ostrobothnia

Western Ostrobothnia

Profile 5 **–** *Muhos* (Finland); podzolic soil.

This extensive coastal plain (around 25 km from the Gulf of Bothnia shoreline) comprises a series of coastal terraces elevated by isostatic processes (Jauhiainen 1973). The area including the soil pit was raised around 5800–6000 years BP (Pietilainen 1999), the pit itself being dug into glaciofluvial material accumulated during the Atlantic Period, and subsequently subject to aeolic processes (Aartolahti 1973, Gibbard 1973). The plant community is dry *Cladonio-Pinetum boreale*[3] pine forest.

Finnish Lakelands

Hamme

Profile 6 – *Luopioinen* (Finland); podzolic soil.

The pit was dug in glaciofluvial material on an esker (Wiśniewski 1973). The landform in question arose at the time of the Eoholocene deglaciation and was overlain upon earlier accumulation forms of bottom moraine and drumlins (Gluckert 1973; Rajakorpi 1984). The profile was obtained around 4 km south of Luopioinen. The local plant community is of the *Empetro-Pinetum fenoscandicum* association (Matuszkiewicz *et al.*, 1994a), corresponding in the Finnish classification with the *Calluna* form of the fresh pine forest habitat type (Heikkinen 1991).

Profile 7 – *Lammi* (Finland); podzolic soil.

The pit was dug in the glaciofluvial material forming one of the Eoholocene eskers in the Hamme region (Wiśniewski 1973), ca. 2 km south-west of Tuulos (Degórski 1994a). Vegetation here is of the *Empetro-Pinetum fenoscandicum* association (Matuszkiewicz *et al.*, 1994a), as corresponding with the *Calluna* form of the Finnish classification's fresh pine forest habitat (Heikkinen 1991).

Profile 8 – *Hattula* (Finland); rusty-podzolic soil.

The pit was dug in glaciofluvial material of the Hattula esker, located ca. 5 km east of the locality of the same name, this having arisen in the marginal zone of the Hameenkangas ice lobe, during the Eoholocene (Rajakorpi 1984). The vegetation comprises a Scots pine forest of the mixed/coniferous forest association *Serratulo-Pinetum* (Matuszkiewicz *et al.*, 1994a). Under the Finnish classification this is the *Vaccinium* form of the fresh pine forest habitat, albeit with a considerable participation of *Calamagrostis arundinacea* and *Galium boreale* in the herb-layer vegetation (Hekkinen 1991).

[3] Phytosociological diagnosis of research sites made after Roo-Zielińska and Solon (1997, 1998).

Profile 9 – *Vitsiola* (Finland); rusty-podzolic soil

The pit was dug in glaciofluvial material associated genetically with the accumulation of sediment as the Hameenkangas lobe retreated in Eoholocene times (Rajakorpi 1984). This is ca. 10 km east of Hameenlinn, and supports a pine forest within the *Serratulo-Pinetum* kind of mixed/coniferous forest vegetation (Matuszkiewicz *et al.*, 1994a). In Finnish terms it represents the *Vaccinium* form of the fresh pine forest habitat, again with considerable participation of *Calamagrostis arundinacea* and *Galium boreale* in the herb layer (Heikkinen 1991).

Karelian Lakeland

Profile 10 – *Punkaharju* (Finland); podzolic soil.

The pit was dug in glaciofluvial material, associated in terms of its sedimentation with the deglaciation processes ongoing in the marginal zone of the ice-sheet lobe from the last phase of the Vistulian Glaciation, ca. 10,600 years BP (Kontturi 1984). The vegetation is of dry *Cladonio-Pinetum boreale* pine forest (Roo-Zielińska, Solon 1997), classified in Finnish terms as the *Myrtillus* form of pine forest (Tonteri et al., 1990).

Eastern Baltic Coastland

Estonian Lowland

Profile 11 – *Tipu* (Estonia); podzolic soil.

The pit was dug in superficially-windblown glaciofluvial material of the Parnava pro-glacial channel, ca. 15 km east of Tipu village. The sediments in question link up with the accumulation taking place in the Late Pleistocene ca. 12,500 years BP (Liivrand 1984). The vegetation comprises the typical form of the fresh pine forest *Vaccinio-Pinetum boreale*.

Eastern Baltic Lakelands

Kurzema (Courland) Lakeland

Profile 12 – *Jaunjelgava* (Latvia); podzolic soil.

The pit was dug in glaciofluvial material of the Daugava proglacial channel, some 4 km south of today's river channel. These sediments are associated with the accumulation that took place here in the period of Late Vistulian deglaciation (Velichko *et al.*, 1984). The vegetation is of the sub-boreal variant to the typical form of *Peucedano-Pinetum* fresh pine forest.

Lithuanian Lakeland

Profile 13 – *Mincia* (Lithuania); podzolic soil.

The pit was dug on an outwash plain north of Lake Utenas, where the sedimentation of glaciofluvial material ceased around 14,000 years BP (Ceponiene, Sablevicius 1997). The area is now overgrown with the sub-boreal variant of *Peucedano-Pinetum* fresh pine forest.

Profile 14 – *Strazdai* (Lithuania); rusty-podzolic soil.

The pit was dug in glaciofluvial material close to a patch of ablation moraine, in the proximal part of the outwash plain and in a deluvial area (Bauziene 1999). The processes of accumulation of the sandy cover ceased around 14,000 years BP (Ceponiene, Sablevicius 1997). The vegetation is of the typical form of *Querco roboris-Pinetum* mixed/coniferous forest.

Profile 15 – *Płaska* (Poland); podzolic soil.

The pit was dug to the east of Lake Płaska, in the glaciofluvial material of an outwash plain that arose in the Poznań phase of the Vistulian Glaciation (Żurek 1991; Banaszuk 2001), i.e. some 17,000-17,700 years BP (Kozarski 1995). The vegetation is of the sub-boreal variant of *Peucedano-Pinetum* fresh pine forest in its typical form.

The Podlasie-Byelorussian Plateaus

North Podlasie Plain

Profile 16 – *Browsk* (Poland); podzolic soil.

The pit was dug on an accumulation plain formed from glaciofluvial material located on the Bielska Plateau, albeit at the zone of contact between it and the valley of the Upper Narew. This was part of the system of meltwater discharge during the period of ice-sheet deglaciation of the Wkra phase to the Warta stadial of the Odra Glaciation (Mojski 1973; Banaszuk 1996), the main phase of accumulation of material taking place around 140,000 years BP (Banaszuk 1996). The area now supports the sub-boreal variant of the typical form of *Peucedano-Pinetum* fresh pine forest.

Northern Podkarpacie

Sandomierz Basin

Profile 17 – *Józefów* (Poland); podzolic soil.

The pit is located on the Biłgoraj Plain, south-west of Józefów, in the immediate vicinity of the edge zone of the Roztocze Upland. The sandy plain on which the research was carried out arose through the impact of slope processes taking place during the Vistulian. The sands cover older sediments from the times of the San II Glaciation (Maruszczak, Wilgat 1956; Buraczyński 1993; Maruszczak 2001). The vegetation present is *Leucobryo-Pinetum* fresh pine forest in its typical form.

Podlasie-Byelorussian Plateaus

Western Pre-Polesie

Profile 18 – *Baranavičy* (Belarus); rusty-podzolic soil.

The pit was dug into glaciofluvial material on the Baranavičy Plain some 3 km east of the Ščara Valley and around 16 km south of Baranavičy. The accumulation of material took place here during the deglaciation of the Sož ice sheet (Pietuchowa 1987), which corresponds with the Warta stadial of the Odra Glaciation. The vegetation here is of mixed/pine forest *Querco roboris-Pinetum* in its typical form.

Profile 19 - *Krasna Slabada* (Belarus); podzolic soil.

The pit was dug in glaciofluvial material on the Sluč Plain, ca. 10 km west of the Sluč Valley and around 5 km south of the locality of Krasna Slabada. Material accumulated here during the deglaciation of the Sož ice sheet (Pietuchowa 1987), which corresponds with the Warta stadial of the Odra Glaciation. The vegetation present here is the sub-boreal variant of *Peucedano-Pinetum* sub-continental fresh pine forest.

Berezina-Desna Lowland

Eastern Pre-Polesie

Profile 20 – *Salihorsk* (Belarus); podzolic soil.

The pit was dug in glaciofluvial material on the Central Berezina Plain, ca. 20 km south of Staryja Darohi. Material accumulated here during the deglaciation of the Sož ice sheet (Pietuchowa 1987), which corresponds with the Warta stadial of the Odra Glaciation. The vegetation present is the sub-boreal variant of *Peucedano-Pinetum* sub-continental fresh pine forest.

Profile 21 – *Bychau* (Belarus); rusty-podzolic soil.

The pit was dug in glaciofluvial material within the Middle Dniepr (Dnjapro) Valley, around 2 km west of the river channel and 20 km south of Bychau. Material accumulated here during the deglaciation of the Sož ice sheet (Pietuchowa 1987), which corresponds with the Warta stadial of the Odra Glaciation. The vegetation present is the typical form of *Querco roboris-Pinetum* mixed/pine forest.

Profil 22 – *Slawharad* (Belarus); podzolic soil

The pit was dug in glaciofluvial material on the Čačersk Plain, around 3 km south of the Sož Valley and 4 km east of the locality of Slawharad (Slovgorod). The material in question accumulated here in the course of the deglaciation of the Sož ice sheet (Pietuchowa 1987), corresponding with the Warta Stadial of the Odra Glaciation. The vegetation present is the sub-boreal variant of *Peucedano-Pinetum* sub-continental fresh pine forest.

Central Sub-Dnieper

Profil 23 – *Chotimsk* (Belarus); rusty-podzolic soil.

The pit was dug in glaciofluvial material on the Orsa-Mahileu Plain, around 10 km south of Chotimsk (Chocimsk). The main accumulation of geological material here took place in the course of deglaciation of the Dniepr ice sheet (Pietuchowa 1987), corresponding in the Polish classification to the pre-maximal and maximal stadials of the Odra Glaciation. The vegetation here is of mixed/coniferous *Querco roboris-Pinetum* forest, in its typical form.

Profil 24 - *Uzlogi* (Belarus), podzolic soil.

The pit was dug in superficially-windblown glaciofluvial material accumulated in the course of deglaciation of the Dniepr ice sheet (Pietuchowa 1987), corresponding in the Polish classification to the pre-maximal and maximal stadials of the Odra Glaciation. The location is some 2 km east of Uzlogi and 5 km south of the Besedz' Valley. The area supports a wetter form of *Peucedano-Pinetum* fresh pine forest with *Molinia caerulea*.

Western Baltic Lakelands

North Mecklenburg Lakeland

Profile 25 – *Chrisdorf* (Germany); rusty-podzolic soil.

The pit was dug in the glaciofluvial material of an outwash plain in the Kyritz-Ruppiner Heide area, this arising in association with the Gardno Phase to the Vistulian Glaciation, located ca. 4 km west of Chrisdorf village. The vegetation is of *Leucobryo-Pinetum* fresh pine forest in the typical form.

Southern Baltic Lakelands

Toruń-Eberswald Proglacial Channel

Profile 26 –*Namyślin* (Poland)**;** podzolic soil.

The pit was dug north of Namyślin on the higher, right-bank terrace of the Odra Valley ca. 4 km from its actual channel (in the Frelenwald Basin). The terrace mainly comprises windblown glaciofluvial sands whose accumulation is associated with deglaciation of an ice sheet lobe of the Chojna sub-phase to the Gardno Phase of the Vistulian Glaciation (Kozarski 1995). The area has the typical form of fresh *Leucobryo-Pinetum* pine forest.

Profile 27 – *Gościm*; rusty-podzolic soil.

The pit was dug on a sandy glaciofluvial terrace extending within the lower Noteć Valley and representing part of the Toruń-Eberswald Proglacial Channel, whose genesis was itself linked with the Krajno-Wąbrzeźno sub-phase of the Vistulian Glaciation, at the time of outflow of meltwaters to the west (Sylwestrzak 1978; Kozarski 1995), i.e. ca. 16,800–17,000 years BP (Kozarski 1995). The site is ca. 7 km west of the village of Gościm, the vegetation being the typical form of *Leucobryo-Pinetum* fresh pine forest.

Profile 28 – *Krucz* (Poland); podzolic soil.

The pit was dug on a terrace built of glaciofluvial material, with clear traces of aeolian processes, in the Warta's Oborniki Valley ca. 14 km north of Wronki. The sands in this area accumulated as ice of the Chodzież sub-phase melted, ca. 17,700 years BP. The vegetation here is fresh pine forest of the *Leucobryo-Pinetum* association in its wetter form with *Molinia caerulea*.

Profile 29 – *Bobrowniki* (Poland); podzolic soil.

The pit was located on the Bobrowniki Plain, itself part of the Toruń Basin, on a terrace formed from deglaciated glaciofluvial material from the full Vistulian (Wiśniewski 1976) that has been windblown superficially since that time. The vegetation is of *Leucobryo-Pinetum* fresh pine forest in the typical form.

Chełmno-Dobrzyń Lakeland

Profile 30 – *Skrwilno* (Poland); rusty-podzolic soil.

The pit was established some 12 km east of Lipno on an outwash plain which arose in the course of ice-sheet stagnation at the line of the moraine in the Dobrzyń area, during the Poznań phase of the Vistulian (Dylikowa 1982), some 18,000–19,000 years BP (Kozarski 1995). The vegetation is of *Querco roboris-Pinetum* mixed/coniferous forest in its typical form.

Central Polish Lowlands

North Mazovian Lowland

Profile 31 – *Glinojeck* (Poland); rusty-podzolic soil.

The pit was dug on the Raciąż Plain, which was mainly shaped when meltwaters flowed off in the course of the Full Vistulian, as the ice sheet experienced stagnation on the Urszulewo Plain, ca. 4 km east of today's village of Glinojeck. The vegetation here is typical of the *Querco roboris-Pinetum* mixed/coniferous forest.

South Podlasie Lowland

Profile 32 – *Ceranów* (Poland); podzolic soil

The pit was dug on a plain terrace in the Bug Valley (specifically the Podlasie Gap), ca. 1 km south of the river channel, in glaciofluvial material. In the period of deglaciation, which took place here in the Eemian Interglacial, this was the track followed by meltwaters. The vegetation today is a wetter form of *Peucedano-Pinetum* fresh pine forest with *Molinia caerulea*.

Central Mazovian Lowland

Profile 33 – *Brok* (Poland); rusty-podzolic soil.

The pit was fug on a sandy terrace in the Lower Bug Valley around 10 km west of Brok, in superficial windblown glaciofluvial material. The vegetation there is the typical form of *Querco roboris-Pinetum* mixed/pine forest.

South Mazovian Elevation

Profile 34 **-** *Nowe Miasto* (Poland)*;* rusty-podzolic soil.

The pit was dug on the flood terrace of the Pilica (Białobrzeska) Valley. At the time of the maximum extent of the Odra Glaciation’s Warta Stadial, this served as a marginal valley discharging meltwaters. The terrace is formed from wind-eroded glaciofluvial sands and supports a vegetation of *Leucobryo-Pinetum* fresh pine forest.

Central Małopolska Upland

Przedborż Upland

Profile 35 – *Miedzierza*; podzolic soil.

The pit was dug to south of the Czarna Konecka Valley, on a sandy plain and in glaciofluvial material accumulated at the time of the stadial of the Odra Glaciation maximum (Klimek 1966). The vegetation here is the typical form of *Leucobryo-Pinetum* fresh pine forest.

Silesian-Cracovian Upland

Kraków-Częstochowa Upland

Profile 36 **-** *Złoty Potok* (Poland); rusty-podzolic soil.

The pit was dug on a sandy plain built of glaciofluvial sediments that accumulated during the stadial of the maximum Odra Glaciation (Klimek 1966). It is on the boundary between the Janów Plain and Lelów Threshold. The vegetation here is the typical form of mixed/coniferous forest of the association *Querco roboris-Pinetum*s.

Profil 37 – *Klucze* (Poland); rusty-podzolic soil.

The pit was dug in the Biała Przemsza Valley NE of Klucze, on a terrace of glaciofluvial material accumulated during the stadial of the Odra Glaciation’s maximum (Gilewska 1973). *Leucobryo-Pinetum* fresh coniferous forest in the typical form is present here.

Central Polish Lowlands

Silesian Lowland

Profile 38 – *Tworóg* (Poland); podzolic soil.

The pit was dug ca. 4 km south of Mała Panwa (on the Opole Plain), in glaciofluvial material accumulated during the stadial of the Odra Glaciation maximum (Klimek 1966). The sediments are characterised by the presence of wind erosion at the surface, as well as by the occurrence of various aeolian forms that Pernarowski (1968) is convinced originated in the Vistulian during the Pomeranian Stadial. The typical form of *Leucobryo-Pinetum* fresh coniferous forest grows here.

Profile 39 – *Kuźnia Raciborska* (Poland); rusty-podzolic soil.

The pit was dug within the Racibórz Basin (around 6 km north of the village of Nedza), on the fourth Odra accumulation terrace characterized by major aeolic transformation of glaciofluvial material (Pernarowski 1968; Waga 1994). The vegetation here represents the wetter form of *Querco roboris-Pinetum molinietosum* mixed/coniferous forest.

4. Methods

4.1. Methods of analysing pedogenic factors

The spatial differentiation between the study sites relative to pedogenic factors was analysed with regard to climatic, hydrological and morpholithological conditions, as well as plant cover. The analysis of contemporary climatic factors influencing the development of soil cover first took into account the elements responsible for the shaping hygrothermal relationships in the study areas. The type of weathering of lithological material, and indeed the functioning of whole ecosystems, depends upon these relationships. The main characteristics of the climate were characterised using information contained in relevant syntheses (Seppala 1976; Chomicz 1977; Pakonen, Laine 1984; Gidrometeocentr 1987; Wyszkowski 1987; Solantie 1990; Heino 1994), as well as the source data of the meteorological services in Finland (years 1961-1999), Estonia (1945-1999), Latvia (1945-1998), Lithuania (1925-1997), Belarus (1945-1997) and Poland (1951-1999)[4]. For the purposes of creating an orthogonal set, data for the years 1950-1997 were used to provide the basis for the adoption and application of procedures after Vogel-Daniels (1968) and Molga (1980), as well as Puchalski and Prusinkiewicz (1990). The indices calculated were:

[4] Data calculated on the basis of Monthly Agrometeorological Reviews (1951-1999), Institute for Meteorology and Water Management, Warsaw (Instytut Meteorologii i Gospodarki Wodneji, Podle_na 61.01673 Warszawa)

- annual amplitude of temperature (Ar), the difference between the greatest and lowest monthly mean air temperatures,
- the de Martone index of climatic dryness (A): $A = P / (t + 10)$, (where P is total annual precipitation in mm and t the mean annual air temperature),
- Sielaninov's hygrothermal index (H): $H = (P \times 10) / \sum t$, (where P is as above and $\sum t$ – the annual total for mean daily temperatures) (in Puchalski, *et.al.*, 1990),
- the Conrad-Pollak index (K), assessing the degree of oceanicity or continentality of climate: $K = \{[1.7 \times Ar / \sin(\varphi + 10)] - 14\}$, (where Ar is annual amplitude in temperature and φ the latitude).

The degree of development of the analysed soils was assessed using morphological indices, account being taken of the sequences and thicknesses of genetic horizons, as well as their coloration (Schaetzl, Mokma 1988; Barett, Schaetzl 1992; Bain *et al.*, 1993), and their chronosequences (Prusinkiewicz and Noryśkiewicz 1966; Jauhiainen 1973; Vreeken 1975; Kowalkowski 1988; Bain *et al.* 1993). Later stages of the work make these subject to verification using the results of chemical analyses of the degree of weathering of rocks (Bednarek, Pokojska 1996; Lundström *et al.*, 2000a).

The morpholithological conditions at the study sites were determined through research by the author, in the course of multiple field trips made in the years 1989-2000.The structure to the vegetation of forest sites in the research area as a whole was evaluated using phytosociological releves produced directly in the study areas - Matuszkiewicz *et al.*, (1994a and b); Roo-Zielińska and Solon (1997, 1998).

4.2. Research methods in soil science

Soil material was taken in samples mixed for each genetic horizon of the soils from 10 points at each of the 39 study sites identified for detailed analysis. The proposed solutions to the theoretical problems set by the present study required determinations of a series of soil characteristics and properties. The following features and properties were in fact determined on the basis of the procedures described.

Morphological features

- thickness of soil horizons, the arithmetic mean of 50 measurements, with classification of pedons following the system of soil systematics in force and applied in Poland (SGP 1989);
- coloration of soils from Munsell (1971).

The soil substratum

- mineral composition for four fractions corresponding with grain sizes in the ranges 0.5-0.8 mm, 0.3-0.5 mm, 0.2-0.3 mm and 0.06-02 mm. The light fraction was studied under a binocular microscope. In the light of the difficulties with the"dry" defractionation of some coalesced soil samples, powdered preparations were also studied in immersion under a polarized-light microscope. Heavy minerals were distinguished in bromoform in the 0.06-0.2 mm fraction. The totals for resistant, moderately resistant and non-resistant minerals were calculated from profiles 1, 3, 7, 11, 15, 16, 20, 24, 26, 29, 31, 35 and 39;
- the abrasion of prepared quartz grains of diameter 0.5-1 mm using the mechanical graniformometric method of Krygowski (1964), the results serving in the calculation of selected further indices, i.e. the grain abrasion index (Wo) and index of non-homogeneity (Nm);
- soil grain-size distribution, by sieving as well as on the basis of the aerometric method from Bouyoucos, as modified by Casagrande and Prószyński (in Dobrzaski and Uziak, 1972). Material was assigned to granulometric groups and fractions in line with determinations from the Polish Soil Science Society, the results serving in the calculation of selected further granulometric indices, i.e. mean grain diameter (GSS), standard deviation (GSO), the co-factor of asymmetry, i.e. skewness (GSK) and graphic curtosis (GSP), after Folk and Ward (1957). The calculations were carried out using version 2.0 of the *Analiza uziarnienia* ("Grain Analysis") computer program (Prusinkiewicz 1993).

Physical properties of soils

- bulk density (BD) in samples of undisturbed structure collected into 100 cm^3 steel rings in the case of the mineral horizons and 10 cm^3 in the case of the organic horizons;
- real specific gravity (RSG) determined picnometrically;
- moisture (W) determined using the drying and weighing method[5];
- field capacity (PPW) by the method from Kaczyński as modified by Królowa;
- maximal capillary capacity (KPW max) by the method from Kaczyński as modified by Królowa;
- maximal hygroscopicity (MH) by Nikolaev's method.

Soil organic matter

- fractional composition of the humus in the organic and humus horizons by extraction and fractionation of humic compounds after Duchaufour and Jacquin (1966); with a division

[5] Soil moisture was determined on the basis of 10 measurements made in months within the warm (April–September) half of years 1995-1998.

into the light (free) fraction and heavy (bound) fraction via decanting with a solution of sodium pyrophosphate – using the method of Monnier and Ture (1962);

- lactic dehydrogenase activity in organic and humus horizons after the model from Casidy *et al.*, (1964);
- content of organic carbon (C_{to}) with Alten's Method in the organic horizon and with a modified version of Tiurin's (1965) Method in the mineral horizons;
- organic carbon following sodium pyrophosphate extraction (C_p) using a SHIMADZU automatic carbon analyser;
- bulk density of organic carbon (D_C) and carbon reserve (M_C), using the methodology from Liska and Westman (1995), where $D_C = C_{org}$ x BD corrected for the content of the skeletal fraction (>1mm)[6], while $M_C = 1m^2 \sum D_C$ for each genetic horizon.

Chemical properties of soil

- reaction (pH_{H2O} and pH_{KCl}), determined potentiometrically;
- total nitrogen (N), by a modified Kjeldahl method;
- nitrate nitrogen ($N\text{-}NO_3^-$) in 0.03 M acetic acid extract, using the distillation method in a Bremner apparatus reducing nitrates using Devarda's alloy;
- ammonium-nitrogen ($N\text{-}NH_4^+$), extracted in 0.03 M ethanoic acid by the method of MgO distillation in a Bremner apparatus;
- total phosphorus (P_o), following extraction in 20 % HCl by the calorimetric method using ammonium molybdenate and applying tin (II) chloride as a reducing agent;
- plant-available phosphorus (P_a), following extraction in NH_4Cl and using a colorimetric method;
- exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), following extraction of samples in 1 M ammonium ethanoate at pH 6.8, and the ASA method;
- hydrolytic acidity (H_h) – by the Kappen method;
- exchangeable aluminium (Al^{3+}) by the Sololov method;
- exchangeable acidity (H_w) by the Sokolov method;
- iron (Fe_p), aluminium (Al_p) and carbon (C_p) associated in humus complexes with sesquioxides, in a 0.1M extract of sodium pyrophosphate using the method from McKeague (1981);
- content of iron (Fe_z) extracted with 20 HCl using the method of Pejwe and Rinkis, after prior combustion of organic matter in a muffler furnace at 450°C (Rinkis 1963);

[6] correction calculated on the basis of a series of measurements defining the mean content of the skeletal fraction.

- amorphous iron (Fe_o) and aluminium (Al_o), in an extract of Tamm's (oxalate) reagent (Van Reeuwijk 1995);
- free iron (Fe_d) from a citrate-dithionite extraction following the method of Mehr and Jackson (1960);

The results obtained were also used in the calculation of:

- total porosity (PT) – as (RSG – BD)/RSG;
- air capacity (ACA) – as PT - PPW;
- total exchangeable base cations (S) – i.e. the sum of Ca^{++}, Mg^{++}, K^+ and Na^+;
- capacity of the sorption complex (T) as H_h + S;
- degree of saturation of soils with base cations (V) as S/T x 100%;
- index of soil elasticity (Ui), as $\sum Ca^{2+}Mg^{2+}\cdot T^{-1}$ (Ulrich *et al.*,1984);
- content of inorganic forms of iron (Fe_{ac}) – as Fe_o - Fe_p;
- content of inorganic forms of aluminium (Al_{ac}) – as Al_o - Al_p;
- content of silicate forms of iron (Fe_{gk}) – as Fe_z - Fe_d;
- content of non-silicate crystalline forms of iron (Fe_{kr}) – as Fe_d - Fe_o.

4.3. Methods of analysis

The empirical results characterising different features of soil from the 39 study sites (soil profiles) were used as a basis for the determination of similarities using cluster analysis. The measure of non-similarity was Euclidean distance, while the grouping was achieved using Ward's method (Hill 1973; Degórski 1999). Following that, each of the groups shown to differ on a statistically significant basis was subject to calculations of selected parameters to describe similarity of the studied variables (soil properties), i.e. the arithmetic mean (n_m), the scope of variability (n_{min} – n_{max}) and the standard deviation (d).

Linkages between the different pedogenic factors and spatial differences in soil properties were in turn analysed multi-dimensionally and in terms of correlation (Sokal, Rohlf 1969). The relationships between geographical location and properties (as dependent variables) were determined on the basis of correlation and regression analysis for two groups, i.e. podzolic and rusty-podzolic soils, as well as two independent variables: latitude and longitude. In the case of research along the W-E line, the latter analysis was performed for factors located between $12^o25'$ and $32^o37'$ E, between 51^o and 52^o N. The N-S analysis in turn extended from $50^o28'$ to $69^o44'$ N, between 25^o and 28^o E. A regression equation was determined and correlation coefficients plus standard deviations were calculated. The optimal regression model was taken from the set of linear, power, exponential and logarithmic functions, the one adopted being that characterised by the minimum residual variance, as well as the lowest value for the standard deviation and the greatest value for the correlation coefficient (Pielou 1984**)**.

The soil characteristics not determined at all study sites (e.g. forms of iron and aluminium) were also not considered in the analysis of soil geographical variability. However, every effort was made to ensure that each of the groups obtained on the basis of cluster analysis and characterising the soil of the given spatial unit was represented by data on forms of iron and aluminium from a minimum of at least one profile. Mathematical analyses made use of calculation sheets from Excel, Quattro Pro, as well as the Bio Diversity, Tytan and Curve Expert statistical programs.

5. The time factor in the shaping of the studied soil cover

In the Quaternary Period, the area within which the research was carried out lay within the range of impact of the Scandinavian Ice Sheet (Mojski 1985). The time of cessation of the primary processes of the sedimentation of the geological material constituting the parent rock of the given soils is subject to marked spatial differentiation. The youngest sediments are those present in the north of Finland, associated with processes of accumulation taking place in the Neo- and Mesoholocene (Aartolahti 1977; Heikkinen, Kurimo 1977, Karczewski 1975; Koutaniemi 1987; Johansson 1995). This compares with an Eoholocene dating for sites in the central and southern parts of that country (Aartolahti 1972; Zilliacus 1987). The oldest rocks were in turn laid down in eastern Belarus, and are associated with deglaciation of the ice sheet of the Dniepr Stadial (Pietuchowa 1987). Those in Poland – in the north-eastern area of the Sandomierz Basin - are linked with the San II Glaciation (Maruszczak and Wilgat 1956). It can thus be stated that the sediments in the area of Lapland and Ostrobothnia were accumulated ca. 6–8,000 years BP (Hinneri 1974, 1975; Sepponen 1985; Koutaniemi *et al.*, 1988; Pietilainen 1999), while other ages are ca. 10,600 years BP in the Karelian Lakeland (Kontturi 1984), ca. 12,500 years BP in the Estonian Lowland (Liivrand 1984), ca. 14,000 BP in Lithuanian Lakeland (Ceponiene and Sablevicius 1997), ca. 150,000 years BP in the eastern parts of Berezina-Desna Lowland (Pietuchowa 1987), and ca. 400,000 BP in the Sandomierz Basin (Mojski 1985).

While the role of time in the development of soil is widely known, the development of palaeoenvironmental research allows for ever-more precise attempts at reconstructing the course of pedogenic processes, and for their treatment as a continuum functioning in varying space-time (Morozowa 1994; Kowalkowski 1994, 2001; Friedrich 1999; Manikowska 1999). In the case of the soils existing now, the duration of development is denoted by the point of initiation of soil-creating processes (Kowalkowski 1988, 1993; Kowalkowski *et al.*, 1994; Manikowska 1999). It is the view of many soil scientists (Kopp 1965, 1970; Kowalkowski 1988, 2001; Manikowska 1999; Blume *et al.*, 1998) that postglacial sites witnessed an initiation of the evolutionary development of soils while the cryogenic post-glacial and periglacial environment, conditions similar to Arctic tundra, was still in place. Their contemporary properties are thus the result of a whole complex of pedogenic and morphogenetic processes that have been ongoing until the present day. According to Manikowska (1999), the Warta Stadial to the Odra Glaciation was followed by three main pedogenic periods in Central Poland: the Eemian/Early Vistulian, the Central Plenivistulian and the Late Vistulian/Holocene. It is possible to link these periods with the onset of development of the studied soils in the central and southern parts of the region, albeit bearing in mind the two phases of surface denudation and destruction of soil cover that took place in the lower and upper Plenivistulian (Manikowska 1999). The development of soils should thus be looked upon as a mono- or polygenetic process (involving different pedogenic processes) taking place in a single phase or several phases, progressing under different habitat conditions (Aleksandrowski 1983; Catt 1988; Kowalkowski 1988; Bednarek 1991).

However, the most important pedogenic phase in the Central European region came in the Late Vistulian period, and in the Holocene (Kowalkowski 1990, 2001; Bednarek 1991; Nowaczyk 1994; Manikowska 1999), during which today's soil cover developed. The lack of accumulation of sediments characterizes today in Poland and ensured that the soil cover present today made use of resources of old soils in its development, ”coming together” with them in a single profile (Manikowska 1999). The succession of plant communities, particularly the appearance of forest vegetation, exerted a huge influence upon the direction of pedogenic processes (Catt 1988). For example, the expansion of Scots pine in Central Europe in the younger Dryas (11,900 years BP) and the pre-Boreal period (11,000 years BP) favored the podzolization process (Friedrich *et al.* 1999), which intensified up to the Atlantic Period (Manikowska 1999).

Some of the soils also arose in the period of the Late Vistulian and Holocene, from redeposited material brought in via fluvial or aeolian transport. In the area studied, the aeolian processes were also diverse in terms of the time of their depositiow as superficial layers of sediments. Aeolian phenomena first began in Lapland an estimated 4800 years ago, and they are thought to have persisted (via dune-formation) for 1300 years (Seppala 1995). In Poland, this event took place in the oldest Dryas, while the main dune-forming processes occurred in the older and younger Dryas, i.e. 12–10,200 years BP (Kozarski 1986; Bednarek 1991; Waga

1994; Janowska 2001). In the east of Belarus, aeolian processes were already very advanced in the oldest Dryas, some 14,000 years BP (Sańko 1987).

Data on the age of primary sedimentation of the substratum, assessment of the degree of development and the concept of macrostructural areal generation of soils (Kowalkowski 1988) were all used to divide the pedons by the time of origin:

- the Mesoholocene-Neoholocene; with sedimentation of soil material in the Mesoholocene and the main phase of pedogenic processes in the Neoholocene (last 3000 years) – in the case of the Lapland profiles (1 – 4),
- the Holocene; with sedimentation of soil material in the Eoholocene and the main phase of pedogenic processes in the Neoholocene – in the case of the Ostrobothnian and Finnish Lakelands profiles (5 – 10),
- the young-glacial and Holocene; with sedimentation of material in the Vistulian, pedogenic initiation in the late glacial and the main phase of pedogenic processes in the Neoholocene – as in the Baltic Coastland and Baltic Lakelands profiles (11 – 15 and 25 – 30);
- the old-glacial and Holocene; with sedimentation of material in the period of older glaciations, very much transformed in the Vistulian period and with Pleistocene pedogenic initiation and a Holocene main pedogenic phase – as with the Northern Podkarpacie profile (17), Podlasie-Byelorussian Plateaus (16, 18 and 19), Berezina-Desna Lowland (20-24), the Central Polish Lowlands (31 – 34, 38 and 39), the Central Małopolska Upland (35) and the Silesian-Cracovian Upland (36 and 37).

6. The geographical differentiation to pedogenic factors

6.1. Morpholithological conditions

The lithological material serving as the parent rock of soils is an important factor when it comes to the diversity and the spatial and temporal variability of the soil populations on Earth (Jenny 1980; Kowalkowski 2001). From the morphogenetic point of view, the study sites at which soil pits were dug are characterised by relative homogeneity of the geological material of the substratum - both in terms of sedimentation and lithology. This is because all of the soils emerged on redeposited, polygenetic glaciofluvial formations whose accumulation took place in the Pleistocene and Holocene (Kontturi 1984; Degórski 1998a). Because of the considerable differences in geographical locations of the analysed profiles in terms of both longitude and latitude, the covering lithological material has been and is subject to diversified processes of destruction (*i.e.* physical and chemical weathering) and transport that have exerted an influence on textural properties.The degree of transformation of the primary lithological material also results from the spatially-varied absolute age of the deglaciation (see Section 5), which *inter alia* influenced the course and duration of periglacial processes, and particularly cryogenic weathering in conditions of longlasting permafrost. While the southern regions of the research area were free of this type of phenomenon as early as in the Late Vistulian (Starkel 1977, 1986, 1988a and b, 1998; Kozarski 1986), the areas located to the north remain within the scope of their impact to this day. Cryogenic phenomena favor the emergence of profiled sequences of transformation (perstruction) that influence the properties of the soil substratum, as has been noted in many regions of central and northern Europe (Kopp 1965, 1970; Kowalkowski 1984, 2001; Degórski 1990; Blume *et al.*, 1998).

Also influencing the transformation of the primary lithological material was the spatial range of occurrence and intensity of transport of redeposited lithological material. For it was upon these processes that there depended, *inter alia*, the degree of mechanical processing of the primary material. The degree of abrasion of substratum grains, in turn, has an impact on, among other things, the ion-exchange properties of soils (Catt 1985, 1987).

In the Plenivistulian, the old-glacial areas were subject to strong surface denudation between periods of pedogenesis (Manikowska 1999). In turn, aeolian phenomena were present in the Late Vistulian and Holocene (Prusinkiewicz 1969; Konecka-Betley 1983; Bednarek 1991 and Waga 1994) – these also transforming the primary lithological material.

The diversified thermal-humidity conditions of the research area also influence the type weathering ongoing within the soil (Degórski 1995a, 1998a), the breakdown of silicates and aluminosilicates, and the rate at which alkaline components are washed through from the surface layers of weathering waste rock (Yaalon 1982; Catt 1988; Bednarek and Prusinkiewicz 1997 and Sandstrom 1997). In turn, the chemical composition of the residuum affects the synthesis of secondary clay minerals, among which, in the conditions of the Eurasian forest zone, there is an increase in the prevalence of illite as one moves from north to south (Bednarek and Prusinkiewicz 1997).

The multiplicity of factors impacting a primary sedimented material that was relatively uniform from a morphogenetic point of view ensured that a spatially diversified parent material was established, ultimately giving rise to the present soil cover. In the north of the study area, the lithological material that is young in sedimentary terms and less intensively redeposited, is characterised by a lower degree of transformation in comparison with the old-glacial sediments that have been subject to a range of destructive processes and intensive transport.

6.2. Climatic and aquatic conditions

Climate plays an exceptionally important role in soil-forming processes. It determines *inter alia* the type of weathering or the movement of soil solutions within the profile (Jenny 1941; Yaalon 1975; Catt 1988; Puchalski, Prusinkiewicz 1990 and Solantie 1992). From the point of view of the development of podzolic soils, the most important elements of the climate include air temperature and precipitation, and above all the inter-relationships between these two elements, which shape the aquatic and thermal conditions of the habitat. The intensity of climatic processes, as expressed in terms of basic climatic characteristics, has a major differentiating effect in the study area. Mean annual air temperature ranges from -1^{o}C in northern Finland (profiles 1, 2 and 3) and 4^{o}C in eastern Belarus (profiles 22, 23 and 24) to 8.5^{o}C in Brandenburg (profile 25). Considerable spatial variability is also shown by such thermal characteristics of the climate as annual amplitude in monthly mean values for air temperature (Ar) and the K index for the degree of oceanicity or continentality after Conrad-Pollak, with the difference that, from the point of view of continentality, the climatic conditions of northern Finland and eastern Belarus are very similar (Table2).

Table 2. Some climate characteristic of the research plot locations. Ar - annual amplitude of mean monthly temperature, A - the de Martone index of climatic dryness, H - Sielanin's Hygrothermal index, K - the Conrad-Pollak index of the degree of continentality

No.	Research plots	**Ar**	**A**	**H**	**K**
1	Kevo	28.8	51.1	2.61	36.00
2	Kessi	31.2	53.7	3.12	40.40
3	Oulanka	30.0	56.5	3.24	38.36
4	Tennila	29.1	48.2	2.37	37.17
5	Muhos	26.6	42.9	1.87	33.30
6	Luopioinen	26.1	50.3	1.80	32.80
7	Lammi	26.1	50.3	1.80	32.80
8	Hattula	26.1	50.3	1.80	32.80
9	Vitsiola	26.1	50.3	1.80	32.80
10	Punkaharju	26.4	43.6	1.75	33.00
11	Tipu	25.9	48.2	2.16	33.40
12	Jaunjelgava	24.2	44.2	1.75	30.86
13	Mincia	23.5	39.7	1.74	29.95
14	Strazdai	23.5	39.7	1.74	29.95
15	Płaska	23.0	36.1	1.57	29.54
16	Browsk	22.8	35.5	1.52	29.55
17	Józefów	22.2	34.7	1.49	29.38
18	Baranowicze	23.7	40.7	1.60	31.22
19	Krasna Swoboda	24.2	40.7	1.60	32.17
20	Soligorsk	24.8	40.6	1.60	33.32
21	Bychow	25.4	41.1	1.75	34.46
22	Słowgorod	25.8	41.9	1.76	35.10
23	Chotimsk	26.1	42.9	1.79	35.80
24	Uzłogi	26.1	42.9	1.79	35.80
25	Chrisdorf	18.5	29.6	1.30	21.30
26	Namyślin	19.4	28.2	1.27	23.18
27	Gościm	19.6	31.0	1.32	23.44
28	Krucz	20.2	30.9	1.28	24.58
29	Bobrowniki	21.1	30.1	1.30	26.30
30	Skrwilno	21.1	31.0	1.31	26.30
31	Glinojeck	21.8	30.1	1.28	27.64
32	Ceranów	22.3	30.8	1.33	28.72
33	Brok	22.2	32.4	1.32	28.79
34	Miedzierza	21.6	40.9	1.63	27.94
35	Tworóg	20.3	41.1	1.70	25.81
36	Nowe Miasto	21.7	32.4	1.36	28.02
37	Złoty Potok	20.7	39.4	1.66	26.33
38	Klucze	20.8	48.1	2.01	26.79
39	Kuźnia Raciborska	20.0	38.5	1.75	25.22

A second important climatic factor impacting the development of soil cover is air humidity. Like thermal relations, humidity is also characterised by marked differentiation across the study area. It is clear from curves for monthly precipitation totals and mean monthly air temperatures depicted on Walter climatic diagrams that the study area as a whole has very favorable hygrothermal conditions from the point of view of the development of podzolic soils. This is visible in the similar shape of the curves, typical for a humid climate (Fig. 3).

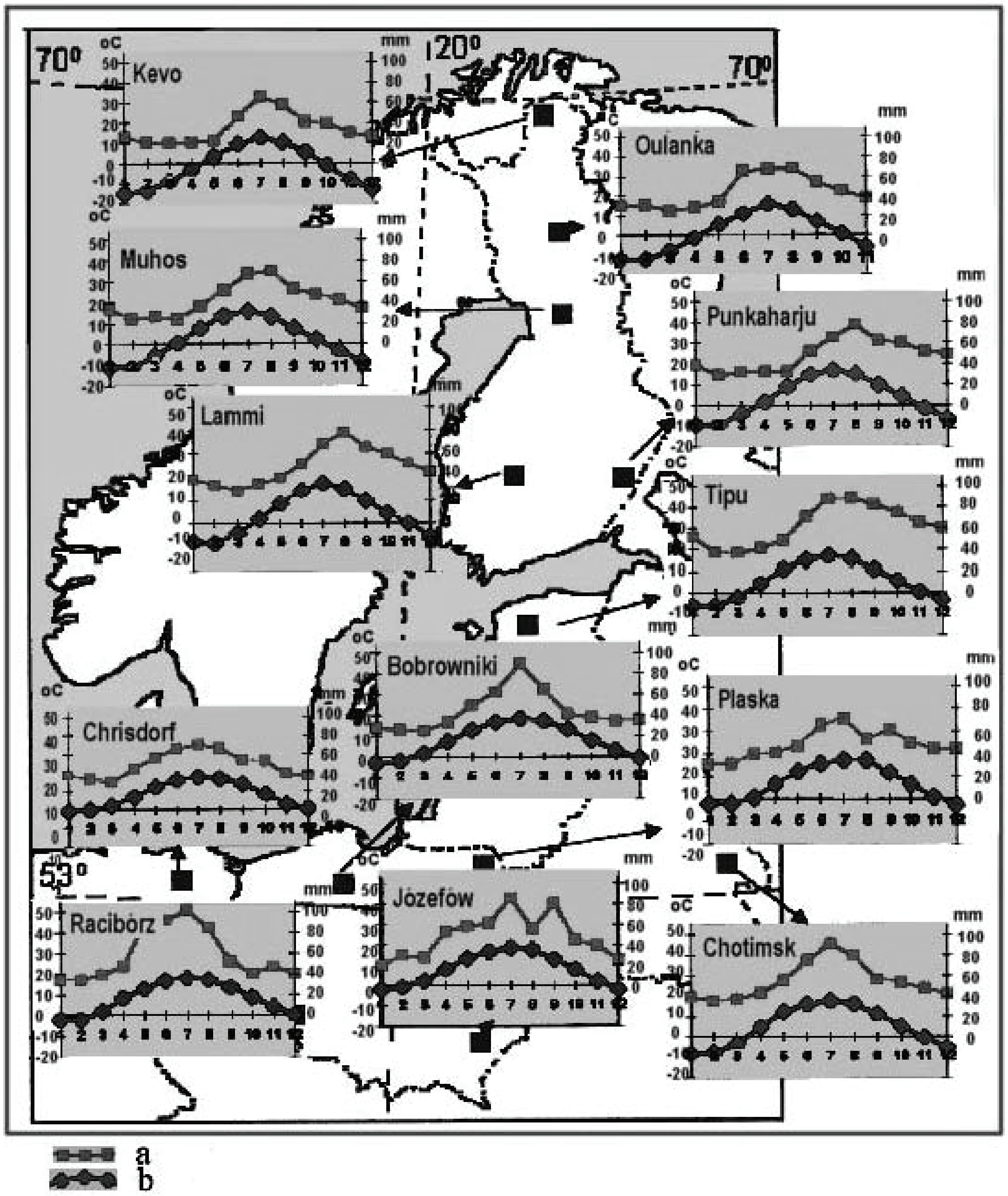

Figure 3. Climatic diagrams according to Walter. (a – distribution curve for the monthly sum of precipitation, b – distribution curve for the mean monthly temperature)

The moist nature of the climate is also confirmed by Sielanin hygrothermal indices determined for the warm (April-October) half of the year, albeit with their values ranging from 1.28-1.30 in the area of central Poland through to 3.24 in north-eastern Finland (Fig. 4). This points to the prevalence of precipitation over evapotranspiration, and thus to the highly moist state of habitat in both the north and south of the studied area. In addition, the northern regions are characterised by the longest persistence of snow cover - ca. 200-280 days a year on average (Dankers *et al.*, 2001), as well as the shortest growing season – lasting between 110 and 120 days (Solantie 1990). During the short warm period ablation takes place, as well as as a very intensive washing through of the soil profile due to both meltwaters and precipitation. The thermal and humidity-related relations prevailing in the entire study area ensure that all of the soils feature an endopercolative type of water economy.

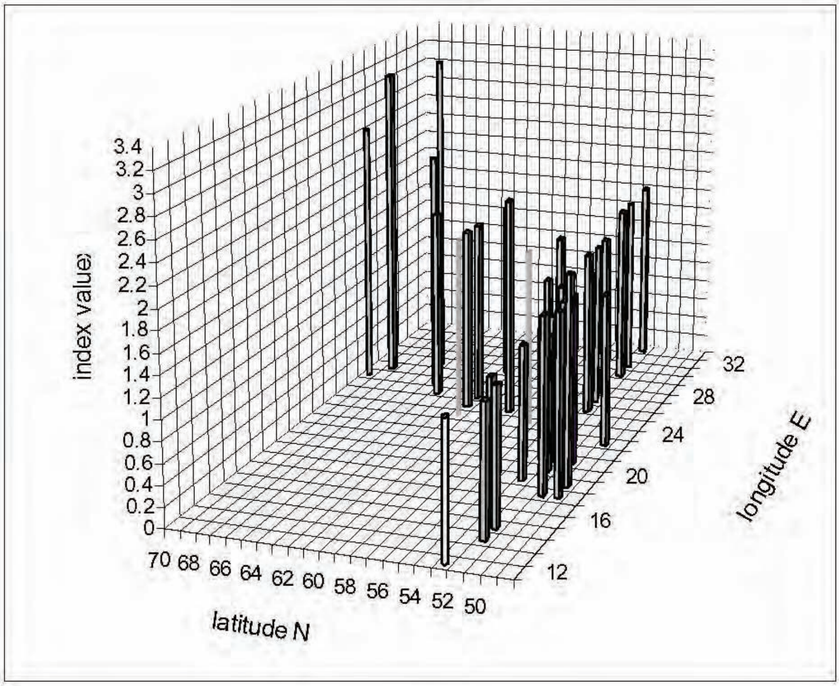

Fig. 4. Values of Sielaninov index determined for warmer part of the year (IV-X) as a function of geographical position

6.3. Plant communities

Vegetation plays one of the more important in the contemporary mosaic character of soils (Crocker 1952; Ugolini *et al.*, 1981; Puchalski, Prusinkiewicz 1990; Oksanen, Virtanen 1995 and Degórski 1996, 2001b).

Almost all the forest communities occurring at study sites (except for those in parts of northern Europe) are representative of the *Dicrano-Pinion* alliance. It was possible to identify two associations of fresh pine forest, i.e. *Leucobryo-Pinetum*, which is characteristic for the western regions of the study area, and *Peucedano-Pinetum*, which occurs in eastern parts thereof. As was noted in the introduction, the most northerly study sites (profiles 1 and 2) –

from the northern-boreal vegetation zone (Hamet-Ahti 1981) – are occupied by a community of the *Phyllodoco-Vaccinion* alliance (Bohn *et al.*, 1996).

In the north there are four study sites (numbers 1, 2, 5 and 10) which support a community of dry coniferous forest of the association *Cladonio-Pinetum boreale.* Though characteristic of what are locally the driest habitats, this community is characterised by high humidity. The presence/absence of this community is due to a biocoenotic factor, grazing of the herb layer by herds of reindeer (Matuszkiewicz *et al.*, 1994 b). All of the aforementioned communities of Scots pine forest overgrow the analysed podzolic soils.

The mixed coniferous forest community *Querco roboris-Pinetum* (Roo-Zielińska, Solon 1997, 1998) and the *Serratulo-Pinetum* (Matuszkiewicz *et al.*, 1994a)/*Dicrano-Pinion* alliance are associated with the occurrence of rusty-podzolic soils, except in three cases. These exceptions were noted beneath a vegetation of *Leucobryo-Pinetum* fresh pine forest, two growing on habitats for acid beech forest of the alliance *Luzulo-Fagion* (profiles 25, 27) and one on mixed/coniferous forest *Querco roboris-Pinetum* (profile 37) - Roo-Zielińska and Solon (1998). The dominant species of the tree layer in all the plant communities occupying the analysed soils is Scots pine (*Pinus sylvestris*). In fact this is the only component in most of the forests (Roo-Zielińska and Solon 1997, 1998).

Among the species occurring in the herb layer at almost all of the study sites are cowberry *Vaccinium vitis-idea* (except in the westernmost areas - profiles 25 and 26) and heather, *Calluna vulgaris,* which is absent from the northernmost study site (profile 1). Bilberry, *Vaccinium myrtillus*, is a species present at more than 90% of the study sites, being absent from just four (profiles 24, 26, 28 and 29).

The plant species richness of the herb layer increases from west to east (Nieppola and Carleton 1991; Roo-Zielińska and Solon 1998), as well as in Lapland moving towards Lithuania. However, species richness becomes lower further to the south of Poland (Solon and Roo-Zielińska 2001). The eastern part of the study area stands out in its maximally diverse herb layer, and possesses better habitat conditions for the development of the plant communities under discussion than do areas located in the marginal range of occurrence of Scots pine forests. It is worth emphasising that the forests of the most natural character are those in northern Europe.Those in the eastern part of the continent are now mostly stands of the third or second generation following earlier harvests (Degórski 1998a, Khotko 1998).

7. A characterisation of selected soil properties and their spatial variability

7.1. Morphological features

Podzolic soils

Podzolic soils (profiles 1-7, 10-13, 15-17, 19, 20, 22, 24, 26, 28, 29, 32, 35 and 38) occur within the study area in association with the territorial range of Scots pine forests. They are characterised by the following sequence of clearly-developed genetic horizons, i.e.: O – AEes – Ees – Bh – Bfe – C or O – A – Ees – Bh – Bfe – C, each of different thicknesses depending on geographical location (Fig. 5).

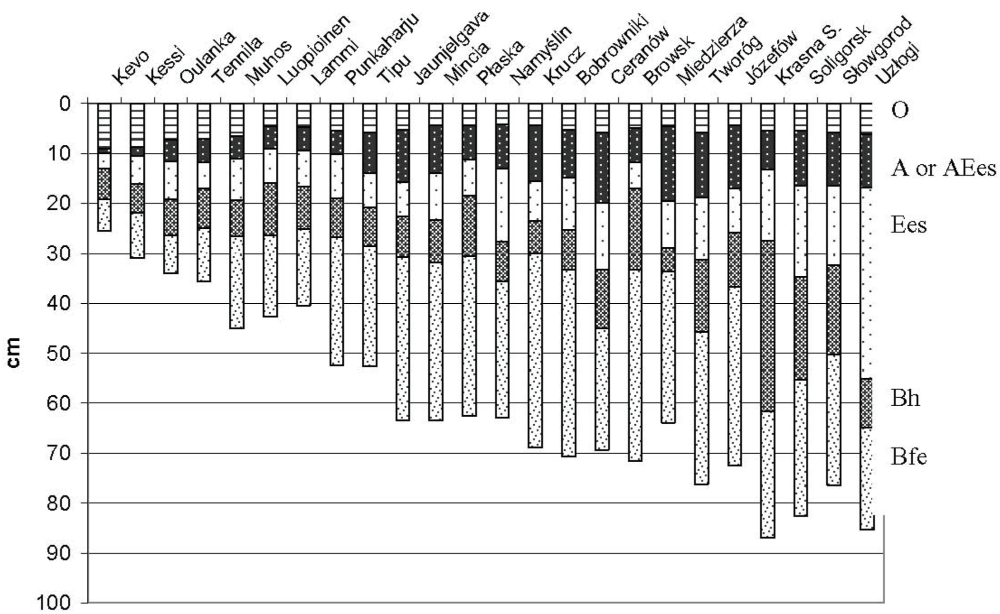

Figure 5. Thickness of genetic horizons in the studied podzolic soils

The mor-type humus, with the organic horizon assigned to three (litter, fermentative and epihumus) possible sub-horizons (Ol, Of and Oh respectively) is represented by two sub-types; the drosomor occurring in most of the studied profiles and the hygromor humus which is characteristic for northern Finland. The thickness of the organic horizon ranges from 4.4 cm in southern Poland (profile 17) [7] to 9.1cm in northern Finland (profile 1), while its spatial variability is associated with both longitude and latitude. This relationship is best described by regression models, inasuch as thicknesses are clearly greater at sites either further to the east or further to the north (Fig. 6).

[7] The values concerning the thickness of genetic horizons as given for each soil are the arithmetic means of 30 measurements made at the given study site.

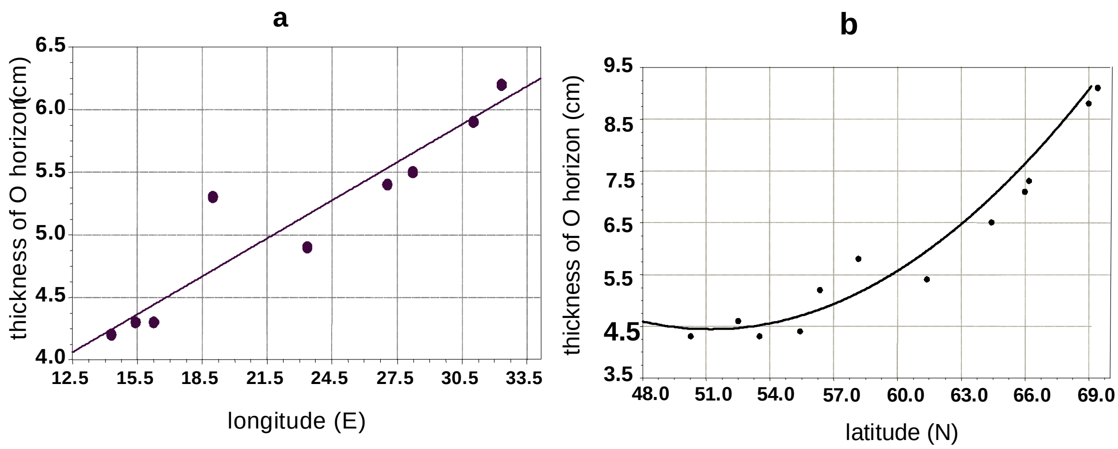

Figure. 6. Models of regression for the thickness of organic horizons (O) in podzolic soils on geographical coordinates. (a – longitude, Y = 2.792 + 0.101x, r = 0.951; b –latitude, Y = 40 + 1.38x +0.013x^2, r = 0. 981)

Similarity analysis shows that the spatial difference in the thickness of the organic horizon is divided into four significantly different groups. The first comprises the soils of northern Finland (profiles 1 and 2), in which the mean thickness of the ectohumus is 9.0 cm (d = 0.2 cm). The next group encompasses three profiles in southern Lapland (numbers 3, 4 and 5), in which the mean thickness of the O horizon is 7.0 cm (d = 0.4 cm). A further group includes soils of south-eastern Finland, Estonia, Latvia, Belarus and central and southern Poland (profiles 10, 11,12, 19, 20, 22, 24, 29, 32 and 38), and is characterised by a mean thickness of the organic horizon of 5.6 cm (d = 0.3 cm). The thinnest organic horizon is in southern Finland, west-central and eastern Poland (profiles 6, 7, 13, 15, 16, 17, 26, 28 and 35).

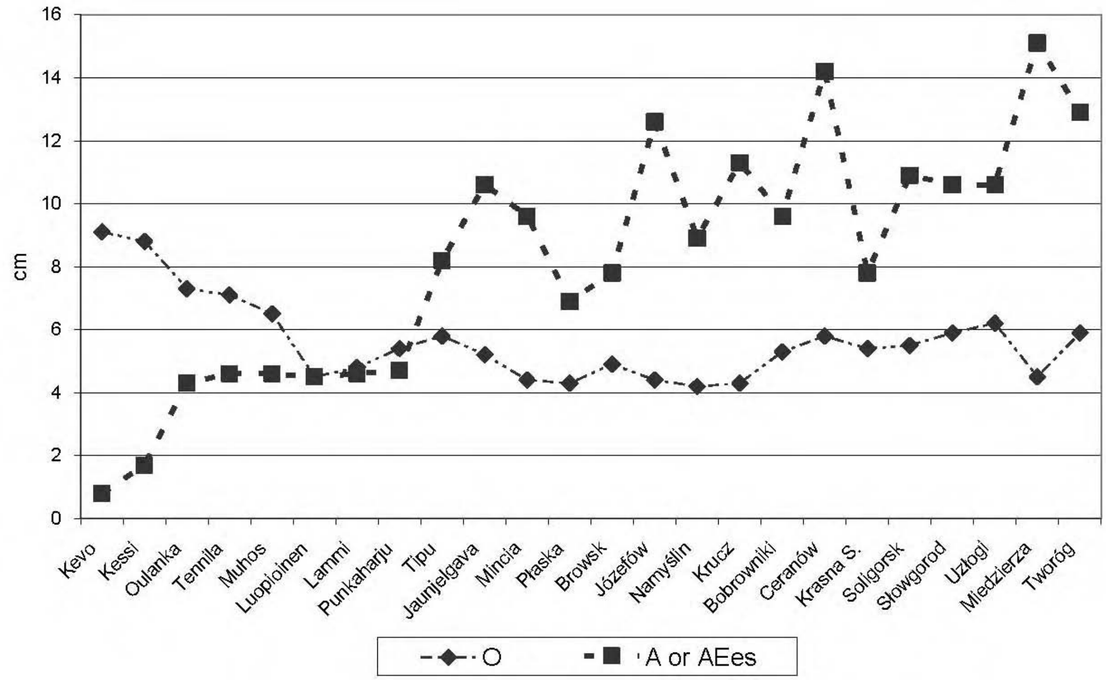

Figure 7. Thickness of organic and humus horizons in studied podzolic soils.

The humus (A) horizon is also characterised by spatial differences in thickness. In north Finland (profiles 1 and 2), it is only 1.2 cm (d = 0.6 cm), while in the central and southern parts of that country (profiles 3, 4, 5, 6, 7 and 10) it is 4.5 cm (d = 0.1 cm), and in other areas 10.4 cm (d = 2.4 cm). While the spatial variability in thickness of the humus horizon is characterised by a clear trend towards increase in the southerly and easterly directions, the difference within groups is sufficient to ensure that dependence on geographical location is of limited statistical significance (Fig. 7). The humus horizon is brown-grey in color (10YR 4/1), or beige-grey (7.5YR 4/1) where there are distinct traces of the podzolization process in the humus horizon.

The eluvial horizon, with its single-grain structure, is diversified in terms of thickness. It ranges from 3 cm in northern Finland (profile 1) to more than 38 cm in eastern Belarus (profile 24). While there is a tendency for the Ees horizon to be thicker with increasing latitude, it is difficult to determine if regional groups differ in a statistically significant manner because the complex of factors impacting the rates and course of the podzolization processes. The color of this horizon also differs, from grey-white (10 YR 7/1 – 5/1) and ash-grey (10YR 4/1) through to light ash (7.5YR 6/1 - 5/2), mainly in relation to local biotic conditions, *inter alia* the thickness of the O horizon, as well as the extent and rate of decay of the roots of herb-layer plants.

The enrichment horizon has developed beneath the eluvial horizon at depths of between 5 and 40 cm below the surface of the mineral part of the soil. The smallest distances between this and the surface of the mineral part of the soil found in the two profiles from northern Lapland. Profile 1 has a distance of 5 cm and profile 2 a distance of around 7.5 cm. According to criteria from WRB (1998), these soils do not meet the conditions for the minimum distance, 10 cm in the case of podzolic soils. Nevertheless, the configuration of genetic horizons is in line with the profile structure of this type of soil, while the transition point between the eluvial and illuvial horizons is sharp. These two horizons serve as a diagnostic spodic horizon and are divided morphologically into two sub-horizons: Bh – with the illuvial accumulation of organic matter and Bfe – with the illuvial accumulation of aluminium and iron.

The Bh sub-horizon is usually 6 – 10 cm thick, only reaching markedly greater thicknesses in eastern Poland and in Belarus (reaching 34 cm at profile 19). The thickness criterion from the WRB (1998) is thus met, since this defines the minimum value for the Bh sub-horizon of podzolic soils as 2.5 cm. The color in the pedons analysed is brownish-red, differing in lightness and degree of saturation. The hue ranging from 2.5YR-10YR is characterised by the greatest saturation of red in any of the soil mineral horizons, and this is strongest in the northern regions of Europe (at 2.5 YR). The paleness value for fresh samples ranges from 3 – 5 (most often 4), while the saturation with color (chroma) is in the range 2 to 6, falling to a value lower than for any other genetic horizons located below the Bh sub-horizon.

The Bfe sub-horizon attains thicknesses of between 6.5 and 9 cm in northern Finland (profiles 1-3), 10 - 25 cm in the southern parts of that country and 20-40 cm in the remaining area. It is most often orange-brown in color, with hues in the range 7.5 YR-10YR, a value of 5 and a chroma of 6. This sub-horizon is characterised by a much more limited spatial differentiation where changes in color parameters are concerned. The transition from the illuvial horizon to that of the parent rock is gentle in most of the profiles.The overall thickness of the solum[8] of podzolic soils is characterised by the higher values noted for sites increasingly far to the south or east. The parameters for the obtained linear regression ($Y = a + bx$) are as presented in Table 3

[8] The solum is understood as the mineral part of the soil profile, i.e. the A, E and B horizons, in line with the definition after Prusinkiewicz (1976, p. 137).

Table 3. Parameters to the regression and correlation coefficient determined for thickness of mineral horizons of podzolic soils in relation to its geographical location.

Independent variable	Parameters to the regression		Correlation coefficient
	a	b	r
longitude	40.491	1.191	0.930
latitude	200.179	-2.581	0.983

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Rusty-podzolic soils

The rusty-podzolic soils (profiles 8, 9, 14, 18, 21, 23, 25, 27, 30, 31, 33, 34, 36, 37 and 39) occur in the study area from central Finland to its south and east and are associated with the range of mixed/coniferous forests. The soils in question are characterised by the following sequence of genetic horizons: O - AEes - BfeBv - Bv - C or O - AEes - BfeBv – Bv - BvC - C.

Over most of the study area, the drosomor-type humus comprises the litter (Ol), fermentative (Of) and epihumic (Oh) sub-horizons of the organic horizons. However, in the southern part there is drosomoder/mor-type humus with two ectohumus sub-horizons: litter (Ol) and fermentative (Of). The weakly-humified Ol sub-horizon and strongly-humified Oh horizons are characterised by limited thickness (ca. 0.5 cm), while the fermentative sub-horizon represents ca. 75% of the total thickness of the overlying humus horizon. The mean thickness of the O horizon in all of the studied soils is 4.2 cm (d = 0.6 cm). Notwithstanding the limited differences to these values, the differentiation does reflect geographical variation, with a trend towards increased thickness in a northerly or easterly direction. In the case of latitude the relationship is a linear one ($Y = -3.749 + 0.135x$; $r = 0.939$), while that for longitude is described by a second-order polynomial ($Y = 6.802 – 0.31x + 0.008x^2$, $r = 0.772$).

The humus (A) horizon - very often with morphological traces of the leaching of iron and aluminium – is classified as an Aees humus-eluvial horizon, with a dark-grey color (10YR 4/1-4/2 in the wet state), with paler patches (10YR 5/1 in the wet state). Its thickness varies from 7 to 17 cm, the average for all of the profiles is 12.2 cm (d = 2.8 cm). The variation in the thickness of this horizon does not reveal any spatial patterns.

The transition from the AE horizon to the diagnostic sideric horizon is usually very gentle, while the thickness of the horizon varies from 34 to 61 cm (mean 55.1 cm; d = 9.8). In the north, this horizon may be only 36 cm as compared with a maximum in southern Poland of 61 cm. However, on account of the limited differentiation of its thickness over most of the studied regions, no statistically-significant linkage with geographical location could be reported.

The diagnostic sideric horizon of all the studied profiles comprised two genetic horizons: a rusty-illuvial BfeBv horizon and a rusty Bv horizon. The first of these is darker (10YR 5/4 – 5/6 in the wet state), and with a mean thickness of 19.1 cm (d = 3.3). The Bv horizon in turn has a mean thickness of 26.2 cm (d = 6.5 cm), and is characterised most frequently by a color of 10 YR 6/4 (in the fresh state). The color of the BfeBv and Bv horizons is almost identical throughout the study area. The transition from the Bv horizon to that of the parent rock C was a sharp one in 8 profiles, but a gentle one proceeding via a transitional BvC horizon in the remaining cases. The thickness of the solum of rusty-podzolic soils shows statistically significant linkage with geographical location, as characterised by greater values at sites further south or east. Parameters to the regression model for this relationship are presented in Table 4.

Table 4. Parameters to the regression and correlation coefficient determined for thickness of mineral horizons of rusty-podzolic soil in relation to its geographical location.

Independent variable	Parameters to the regression			Correlation coefficient
	a	b	c	r
longitude	-14.559	6.517	-0.123	0.832
latitude	2233.387	-73.885	0.623	0.996

7.2. Mineral material

7.2.1. Mineral composition

The podzolic and rusty-podzolic soils are mainly built from poor quartz sands. The quartz content of the parent rock ranges from ca. 50% in the soils of northern Finland to 98% in those of eastern Belarus. Feldspars account for up to 10+% of the mineral composition (maximally 15%), while the share of heavy minerals does not exceed 10% (Table 5). In the Finnish profiles this in large measure corresponds with the petrographic composition of the crystalline rocks of Fennoscandia (Lahtinen 1994; Simonen 1994). Since the analysis accounted for the organic components and these account for a major percentage of samples' overall composition in Northern Europe, the effect is to lower the absolute content of quartz (Table 5).

Characteristic of the spatial variation in mineral composition is the fact that the heavy (0.06-0.2 mm) fractions of the soils developed on the older sediments linked with the Odra

Table 5. Mineral composition of light fraction 0,5 - 0,8 mm (in weight %), in some soil profiles.

No. rpofile	Soil type	Genetic horizon	Quartz	Feldspars	Slivers of rocks	Micas	Carponates	Iron-humus aggregates	Organic components and parts of plants	Antropogenic components	Amphipoles	Pyroxynes
1	p	AEes	59	0	1	0	1	4	35	0	0	0
		C	69	0	1	0	1	2	27	0	0	0
3	p	AEes	43	0	0	0	1	8	48	0	0	0
		C	74	0	1	0	1	1	23	0	0	0
7	p	AEes	31	0	0	0	1	12	56	0	0	0
		C	77	0	1	0	1	1	20	0	0	0
11	p	AEes	20	0	1	0	1	24	54	0	0	0
		C	78	3	1	0	1	2	15	0	+	0
15	p	AEes	10	0	1	0	1	43	45	0	0	0
		C	85	1	1	+	1	1	10	0	1	0
16	p	AEes	80	0	0	0	1	2	17	0	0	0
		C	89	0	0	0	0	0	10	0	0	0
26	p	AEes	25	10	+	1	0	12	50	0	2	0
		C	44	5	4	1	0	4	33	1	8	0
29	p	AEes	19	0	0	0	0	10	70	1	0	0
		C	95	2	2	0	0	+	1	0	0	0
31	rp	AEes	50	15	18	15	0	0	0	0	2	0
		C	70	10	15	1	2	+	1	0	1	0
35	p	AEes	1	+	0	0	0	0	98	1	0	0
		C	85	0	4	0	1	0	10	0	0	0
39	rp	AEes	5	1	2	0	0	0	92	+	0	0
		C	84	2	2	0	0	0	10	0	0	2
20	p	AEes	84	2	1	0	0	3	10	0	+	0
		C	93	3	1	0	0	1	0	0	2	0
24	p	AEes	12	1	+	0	0	+	85	1	1	0
		C	98	+	2	0	0	0	0	0	0	0

p – podzolic soils,rp – rusty-podzolic soils

and San II Glaciations. They have greater contents of quartz and minerals resistant to exogenous factors (like granite and zirconium) and, simultaneously, lower contents of feldspars and non-resistant minerals (mainly amphiboles) (Fig. 8). The relationships reported may also result from the initial non-uniformity of the proportions of different minerals in temporally-diversified sedimentation cycles, as well as from the duration of processes of weathering and erosion of lithological material. It is possible to speculate that, as both fluvial and aeolian transport was taking place (in the period of the multiple redeposition of geological material), material less resistant to these processes (pyroxenes and amphiboles) were in part lost, leading to a relative enrichment in resistant minerals.

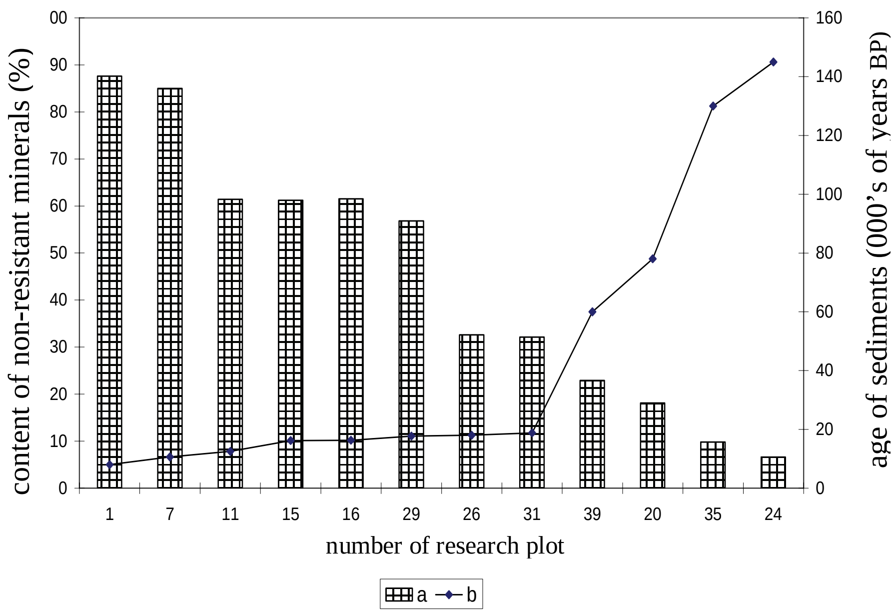


Figure 8. Age of soil sediments BP and content of non-resistant minerals in the heavy fraction (0.06 – 0.2 mm) on the parent rock of some soil profiles (a – proportional share of non-resistant minerals in heavy fraction (0.06 – 0.2 mm), b – age of sediments in 000's of years BP determined by C^{14} dating according data from other papers)

The values of the index for content of non-resistant minerals range from several percent in soils in the Podlasie-Byelorussian Plateaus and Berezina-Desna Lowland to more than 85% in the case of the northern Finnish soils, while the ratios of resistant to non-resistant materials are in the range 0.006 to 1.3 respectively (Table 6, Appendix B).

The geographical variation in the portion of non-resistant minerals in the overall content of heavy minerals is very clearly marked in both podzolic and rusty-podzolic soils. This relationship is best described by a linear regression model of longitude ($Y = 95.959 - 2.93x$), while the linear relationship with latitude is depicted using a second-order polynomial ($Y = -647.128 + 21.12x + 0.151x^2$) – (Fig. 9, below).

Mineral content of soil impacted by exogenous factors can be divided into four statistically-significant regions. These are related to the age of sedimentation. The first group encompasses Finnish profiles associated with accumulation in the late Vistulian and Holocene, while a second comprises soils developed in material of the Vistulian Glaciation, i.e. those in today's Estonia, Latvia, Lithuania and northern Poland. A third group is linked

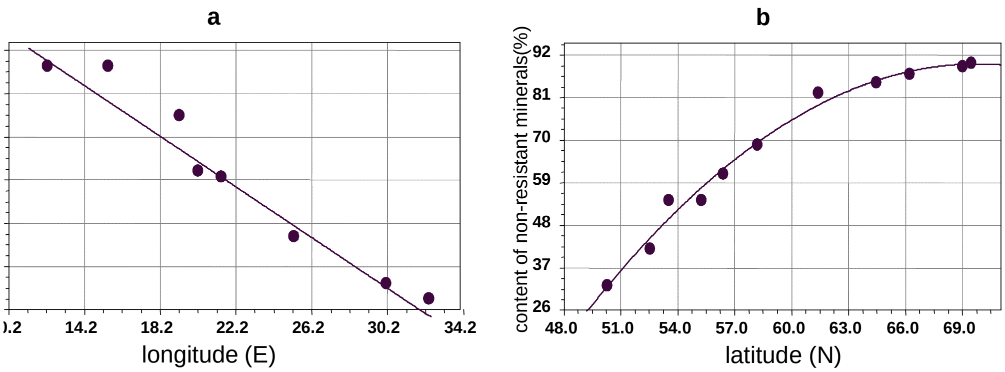


Figure 9. Some models of regression for the content of non-resistant minerals (MN) related to geographical coordinates.
a – MN in podzolic-rusty soils on longitude Y = 0.959 – 2.93x; r = 0.983;
b – MN in podzolic soils on latitude Y = -647.128 + 21.12x – 0.151x^2; r = 0.994

with soils developed in sediments of the Warta (Sož) stadial of the Odra (Dniepr) Glaciation, i.e. the profiles from central Poland and western Belarus. Finally, the fourth group comprises soils that arose on the oldest material from the Odra (Dniepr) Glaciation, in southern Poland and eastern Belarus (Fig. 10).

The data obtained for contents of non-resistant minerals do not depart from those in earlier research carried out in Poland in variously-aged soils developed in glaciofluvial sands shaped periglacially (Turnau-Morawska 1955; Degórski 1990 and Bednarek 1991).

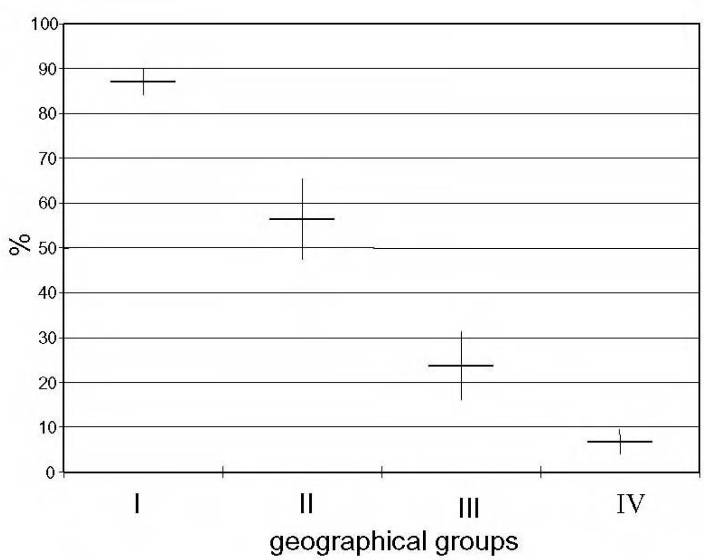


Figure. 10. Mean value and standard deviation obtained for the content of non-resistant minerals in statistical significance different group (group I - profiles:1,3, 7; II – profiles: 11, 15, 16, 26, 29; III – profiles: 20, 31, 35, 39; IV- profile 24)

7.2.2. Granulometric composition

Percentage shares of different grain classes in the mineral material of soils determine many of their physical and chemical properties (Królikowski *et al.*, 1968; Prusinkiewicz, Konys and Kwiatkowska 1994). In spite of the morphological differences among the sites studied, all the forms (eskers, outwash plains, accumulation plains and valley terraces) are associated genetically with glaciofluvial or fluvial processes. This is reflected in the similar shares of fractions in the fine earth parts of the studied soils, which is to say the dominance of the sandy fraction. In turn, the greatest differences in granular composition are in respect to the contents of skeletal parts.

A majority of the analysed geological formations sampled from their different genetic horizons are classified as loose sands (Table 7). What differences are observable in the granulometric compositions of soil substrata therefore result from: the lithological properties thereof, weathering processes (particularly those induced by frosts), processes shaping the relief of the studied site and pedogenic processes.The terraces of proglacial channels and rivers valleys are built of sands displaying a marked degree of sorting, as well as limited skeletal content (profiles 29 and 39), while the glaciofluvial material of outwash-plain areas and eskers is characterised by a greater share of grains of coarse sand and the marked presence of a gravelly-stony fraction of diameters reaching several centimeters (Table 7)[9]. This is particularly visible in material sampled in the north of Europe, where the content of the gravelly-stony fraction (>1 cm) in some genetic horizons is more than 50% of mineral material, while the dominant fraction of fine earth parts is coarse sand (up to 70% in the C horizon of profile 1).

The superficial soil horizons, especially those developed in older geological material, are characterised by minor increases in the shares of the clayey and dusty fractions within the granulometric composition, this being a consequence of their intensive frost weathering, as well as modelling by aeolian processes. During the Vistulian over central Poland, a period of the intensified impact of this type of process on waste rock/soil cover took place between 25,000 and 12,000 years BP (Goździk 1991).

An enrichment of material in the fine dusty-clay fraction may be influenced not only by frost weathering, but also by the phenomenon of corasion (Linde and Mycielska-Dowgiałło 1980). The most intensive exogenous processes took place in the upper zone of soils. The genetic horizons of the upper parts of certain soil profiles (e.g. nos. 11, 24, 26, 29 and 35) are also characterised by moderately good sorting, as manifested in a minimal (up to 5%) share for the skeletal fraction, as well as a very major content of the fractions of medium and fine sands (up to 90%).

[9] Documentation as regards granulometric composition in Poland is to be found in the studies Degórski (1994b, 1995b)

Table 7. Soil grain-size distribution and granulometric indices determined for some podzolic and rusty-podzolic soils.

No. profile	Genetic horizon	Content of fractions in %							GSS		GSD	GSK	GSP
		>1.0 mm	<1.0 mm	in 1-0.5	05 -0.25	0.25-0.1	0.1-0.02	<0.02	mm	w.w			
1	AEes	46.3	53.7	67.4	23.4	8.2	1	0	0.847	0.24	1.24	-0.14	1.36
	Ees	47.9	52.1	69.2	27.3	2.5	1	0	0.889	0.17	1.14	-0.23	1.22
	Bh	47.5	52.5	68.1	27.1	2.8	1	1	0.876	0.19	1.16	-0.21	1.24
	Bfe	56.7	43.3	69.2	27.0	2.8	1	0	0.880	0.18	1.14	-0.22	1.25
	C	62.3	37.7	70.4	27.3	2.3	0	0	0.862	0.21	1.08	-0.24	1.29
3	AEes	44.6	55.4	44.9	26.3	16.8	7	5	0.619	0.69	1.07	0.11	1.39
	Ees	41.4	58.6	46.0	24.1	16.9	8	5	0.589	0.76	1.91	0.13	1.45
	Bh	30.1	69.9	44.2	24.1	14.7	11	6	0.475	1.07	1.99	0.19	1.61
	Bfe	24.0	76.0	51.1	24.3	14.6	6	4	0.518	0.95	1.57	0.14	1.61
	C	19.7	80.3	41.4	21.6	24.0	8	5	0.341	1.55	2.05	0.28	1.31
7	AEes	45.6	54.4	44.2	32.2	13.6	7	3	0.673	0.57	1.69	0.03	1.33
	Ees	48.7	51.3	45.2	30.8	14.0	6	4	0.692	0.53	1.74	0.06	1.35
	Bh	44.6	55.4	42.3	26.4	17.3	8	6	0.589	0.76	2.00	0.14	1.43
	Bfe	49.2	50.8	52.2	16.2	19.6	8	4	0.644	0.63	1.89	0.13	1.37
	C	49.7	50.3	56.3	15.7	14.0	9	5	0.665	0.59	1.92	0.15	1.62
11	AEes	3.4	96.6	20.1	34.5	39.4	6	0	0.288	1.80	1.01	-0.02	0.97
	Ees	2.3	97.7	12.7	27.5	40.8	15	4	0.202	2.31	1.39	0.14	1.27
	Bh	2.5	97.5	15.6	20.9	41.5	16	6	0.188	2.41	1.69	0.18	1.43
	Bfe	4.5	95.5	25.3	20.5	42.2	10	2	0.263	1.93	1.27	-0.01	0.94
	C	8.9	91.1	28.3	28.7	36.0	6	1	0.332	1.59	1.25	-0.03	1.04
15	AEes	6.7	93.3	15.6	27.2	43.2	12	2	0.249	2.01	1.37	-0.01	1.24
	Ees	8.7	91.3	17.6	28.4	44.0	8	2	0.277	1.85	1.32	-0.11	1.17
	Bh	5.6	94.4	18.7	26.8	37.5	14	3	0.243	2.04	1.46	0.08	1.16
	Bfe	9.9	90.1	24.5	27.3	38.2	9	1	0.307	1.70	1.35	-0.07	1.06
	C	16.7	83.3	35.4	22.4	27.2	11	4	0.359	1.48	1.73	0.15	1.25
16	AEes	16.4	83.6	42.0	40.6	10.4	7	0	0.497	1.01	1.22	0.03	1.57
	Ees	15.2	84.8	39.5	43.4	12.1	4	1	0.485	1.04	1.14	-0.02	1.46
	Bh	12.2	87.8	28.0	48.4	15.6	6	2	0.399	1.33	1.27	0.03	1.60
	Bfe	20.6	79.4	27.1	48.9	16.0	6	2	0.452	1.15	1.41	-0.05	1.49
	C	21.8	78.2	26.6	50.0	15.4	6	2	0.464	1.11	1.43	-0.06	1.49
29	AEes	3.5	96.5	8.9	59.9	27.2	4	0	0.293	1.77	0.80	0.05	1.41
	Ees	3.3	96.7	5.6	62.1	26.3	4	2	0.276	1.86	0.86	0.15	1.63
	Bh	1.4	98.6	1.0	76.5	18.5	2	2	0.287	1.80	0.56	0.27	1.73
	Bfe	0.7	99.3	0.8	79.3	15.9	2	2	0.291	1.78	0.52	0.27	1.84
	C	0.6	99.4	1.3	81.2	15.5	1	1	0.306	1.71	0.44	0.20	1.56
26	AEes	2.0	98.0	45.6	27.7	20.7	3	3	0.381	1.39	1.11	0.38	1.26
	Ees	7.0	93.0	54.5	33.0	8.5	2	2	0.500	1.00	0.90	0.18	1.43
	Bh	7.6	92.4	42.5	41.4	10.6	3	3	0.459	1.12	0.97	0.10	1.42
	Bfe	6.6	93.4	48.7	40.6	6.7	2	2	0.490	1.03	0.86	0.14	1.41
	C	6.2	93.8	21.7	62.2	14.1	1	1	0.400	1.32	0.80	-0.06	1.48
31	AEes	12.4	87.6	40.1	26.9	25.0	8	0	0.398	1.33	1.34	0.11	1.15
	Ees	9.2	90.8	39.0	36.1	17.9	5	2	0.405	1.30	1.22	0.13	1.38
	Bh	4.6	95.4	37.1	46.4	12.5	3	1	0.406	1.30	0.92	0.16	1.13
	Bfe	5.2	94.8	37.8	41.2	17.0	4	0	0.426	1.23	0.85	0.13	1.23
	C	3.7	96.3	15.0	63.0	18.0	3	1	0.339	1.56	0.81	0.05	1.58
35	AEes	3.4	96.6	21.5	32.3	38.2	7	1	0.283	1.82	1.09	0.03	0.98
	Ees	2.3	97.7	19.3	36.3	34.4	8	2	0.271	1.88	1.15	0.14	1.13
	Bh	1.8	98.2	18.2	37.1	33.7	8	3	0.264	1.92	1.20	0.18	1.22
	Bfe	1.7	98.3	18.3	37.9	34.8	7	2	0.271	1.88	1.11	0.15	1.17
	C	1.1	98.9	14.6	43.4	37.0	2	3	0.273	1.87	0.94	0.12	1.50
39	AEes	5.6	94.4	29.3	43.2	15.5	12	0	0.331	1.59	1.20	0.20	1.35
	Ees	4.8	95.2	32.1	39.8	16.1	10	2	0.331	1.59	1.24	0.26	1.33
	Bh	4.2	95.8	28.2	37.4	25.4	7	2	0.320	1.64	1.16	0.18	1.11
	Bfe	3.2	96.8	26.7	36.1	29.2	7	1	0.310	1.69	1.12	0.15	1.07
	C	4.6	95.4	24.6	38.8	30.6	5	1	0.321	1.64	1.05	0.07	1.03
20	AEes	7.0	93.0	30.3	20.1	36.6	13	0	0.292	1.78	1.41	0.02	1.01
	Ees	14.3	85.7	34.2	21.4	34.4	9	1	0.358	1.48	1.49	0.04	1.10
	Bh	5.0	95.0	24.9	27.6	28.5	13	6	0.241	2.05	1.74	0.27	1.30
	Bfe	12.2	87.8	24.0	30.1	30.9	12	3	0.306	1.71	1.62	0.06	1.26
	C	16.7	83.3	37.2	34.2	24.6	4	0	0.440	1.18	1.25	-0.03	1.16
24	AEes	0.0	100.0	21.1	18.5	53.4	7	0	0.244	2.03	0.95	-0.10	0.80
	Ees	14.0	86.0	23.6	21.6	47.8	7	0	0.318	1.65	1.38	-0.22	1.03
	Bh	8.0	92.0	24.5	19.0	44.5	7	5	0.272	1.88	1.57	0.02	1.28
	Bfe	12.3	87.7	25.3	19.8	44.9	5	5	0.301	1.73	1.62	-0.02	1.31
	C	16.9	83.1	30.2	20.1	39.7	6	4	0.350	1.52	1.64	0.01	1.21

GSS – . mean grain diameter, GSO – standard deviation, GSK – co-factor of asymmetry, i.e. skewness, GSP – graphic curtosis

Enrichment of the soil substratum in the colloidal clay fraction can sometimes be associated with geochemical and pedogenic processes (Chorlery *et al.*, 1984). In the majority of the podzolic soils studied, there is an elevated share for the clay fraction (from 0.5 to 1%) in the sub-horizon of enrichment (Bh), as compared with the Bfe sub-horizon and eluvial horizon (E).The fluvial nature of sediments and their superficial aeolian transformations are also confirmed by calculated granulometric indices. Cumulative curves constructed on a Phi similarity grid characterise these two types of sediments (Fig. 11). The curves relating to the granulometric composition of fluvial sands are convex, clearly departing from the log-normal distribution (GSK >0). They are characterised by a leptokurtic or very leptokurtic distributions (GSP>1.2). Curves for blown sands are close to linearity, possessing a mesokurtic or platykurtic distributions (GPS <1.2). The characterisation of granular structure are similar to the results obtained by other authors for lowland Poland (Grzegorczyk 1970; Nowaczyk 1976; Bednarek 1991), Lithuania (Bauziene 1999) and Finland (Sepponen 1985), or from previous results of research (Degórski 1990, 1998a). Differences in the grain structure confirm statistically-significant spatial regularities in the coarser fractions - which show an age-related decline in the proportion of skeletal fractions and coarse sands. The remaining fractions show considerable local differences in their fraction of the granulometric composition but do not translate into statistically-significant geographical relationships.

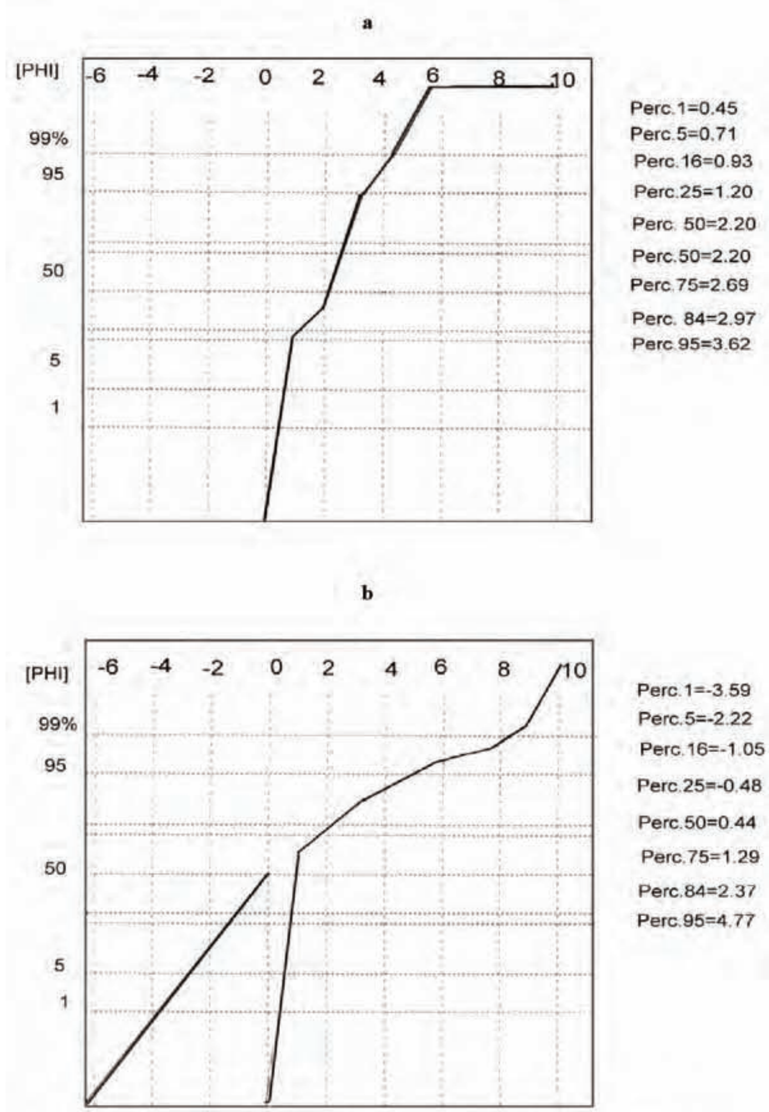


Fig. 11. Cumulative curves on the probability scale phi.(a –platycurtic distribution characteristics for the sample from A horizon in profile 24, b – leptocurtic distribution characteristics for the sample from C horizon, profile 7)

7.2.3. The degree of abrasion of quartz grains

Graniformametric analysis of the mineral material confirms the fluvial nature of the sedimentation of all the studied samples. This indicates what is typical of fluvial formations - the greatest content of grains of quartz rolling on the graniformometer with an incline of 12-16^{o}. However, as in the case of granulometric composition, the sandy parent formations differ in the abrasion of quartz grains. All the soils have a prevalence of semisharp grain edges (mature type - β), while their contents range from 52% in north Finland to more than 80% in southern Poland and Belarus. The largest shares are reported from sites at which the most marked impact of aeolian processes was observable (e.g. at profile 35). The northern profiles are characterised by the smallest content of abraded grains (long term abrasion type - γ) – amounting to between 1 and 9% while sharp edged grains (early stage of abrasion type - α) exceeded 40%. This shows primary weathering of the substratum, mainly of a cryogenic nature. The reverse applies to clearly windblown sands, in which the phenomena of corasion and deflation had an influence on the rounding of grains of quartz. The content of grains of the γ type amounts to 26% in these sediments (Table 8).

Table 8. Share of different types of grains γ, β, α [*long term abrasion type - γ, semisharp edges grain (mature type)- β, early stage of abrasion type - α*] and values of the grain abrasion index (Wo) and index of non-homogeneity (Nm) for some podzolic and rusty podzolic soils.

No profile	Genetic horizon	Content of grains			Wo	Nm
		γ	β	α		
1	AEes	1	53	46	839	2.8
	C	1	52	47	831	2.9
3	AEes	2	57	41	902	2.5
	C	3	77	20	923	2.6
7	AEes	9	53	38	994	3.2
	C	9	69	22	1020	3.6
11	AEes	16	66	18	1072	3.4
	C	11	68	21	1178	4.2
15	AEes	12	51	37	996	6.8
	C	19	50	31	1080	6.9
16	AEes	12	64	24	1012	4.4
	C	19	65	22	1010	3.8
29	AEes	12	68	20	1070	3.8
	C	14	70	16	1055	4.1
26	AEes	17	65	18	1096	3.6
	C	16	69	15	1078	3.9
31	AEes	19	74	7	1188	5.4
	C	19	76	5	1156	3.7
35	AEes	10	73	17	1125	4.1
	C	12	83	5	1196	3.5
39	AEes	19	70	11	1160	4.8
	C	19	73	8	1189	5.4
20	AEes	21	58	21	1178	7.2
	C	18	77	5	1224	5.7
24	AEes	26	64	11	1240	5.2
	C	24	65	11	1220	6.6

The *Wo* index of the grain abrasion attests to the different degrees of abrasion of the material. The lowest values of the index (of 800-1000) are those obtained for the youngest glaciofluvial sands in Finland, while the greatest (1200-1380) characterise the oldest sediments in central Poland and Belarus. Such high values for *Wo* are typical for lithological material that has been redeposited many times, mainly as a result of aeolian transport (Nowaczyk 1976; Degórski 1990; Bednarek 1991). At the same time, sands transformed as a result of the prolonged influence of exogenous processes are characterised by greater non-uniformity of the material. This is particularly true of profiles located in B-P (profile 20) and Berezina-Desna Lowland (profile 24), at which the index of non-homogeneity (*Nm*) attains values of 7.2 (Table 8). The locations of points characterising the inter-relationships of the two parameters (*Wo* and *Nm*), as presented in a rectangular configuration, point to their marked concentration at values of between 1000 and 1200 for the index of grain abrasion (*Wo*), as well as 4 – 6 for the index of non-uniformity of material (*Nm*). The breakdown obtained confirms the pedogenic maturity of the soils studied (Fig. 12).

The geographical variability in values of the indices of grain abrasion (*Wo*), and non-uniformity of material (*Nm*) is very clear. This relationship with both latitude and longitude in podzolic soils, as well as with longitude in rusty-podzolic soils, is characterised by a linear regression described by way of a second-order polynomial ($Y = a + bx + cx^2$). Only in the case of the relationship between latitude and the spatial differentiation of the *Wo* and *Nm* indices in rusty-podzolic soils is the best approximation a linear regression model ($Y = a + bx$) - Table 9.

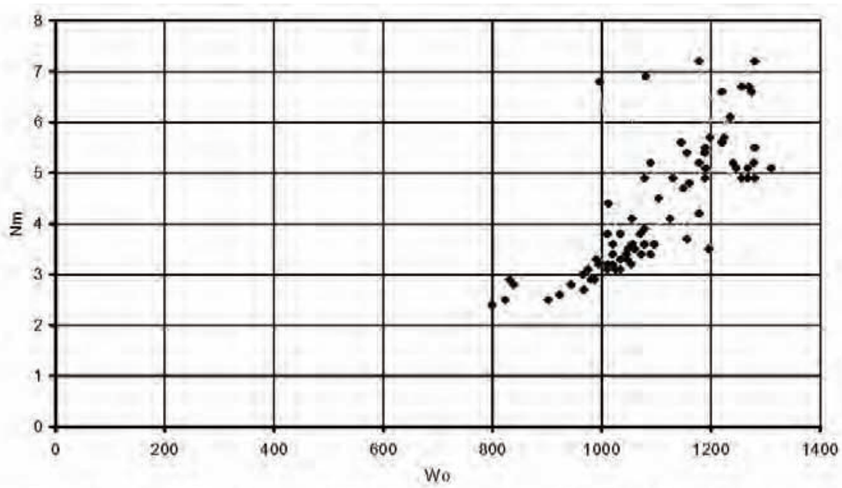


Figure 12. Location of quartz grains on the configuration of quartz grain abrasion index (Wo) - X axis and non homogenous index (Nm) – Y axis

Analysis of the similarity of distributions of the indices of non-uniformity and grain abrasion supports assigning the soils to six regional units statistically different from one another in various graniformametric properties (Fig. 13). (see Section 4.3, Methods of Analysis)

These are:

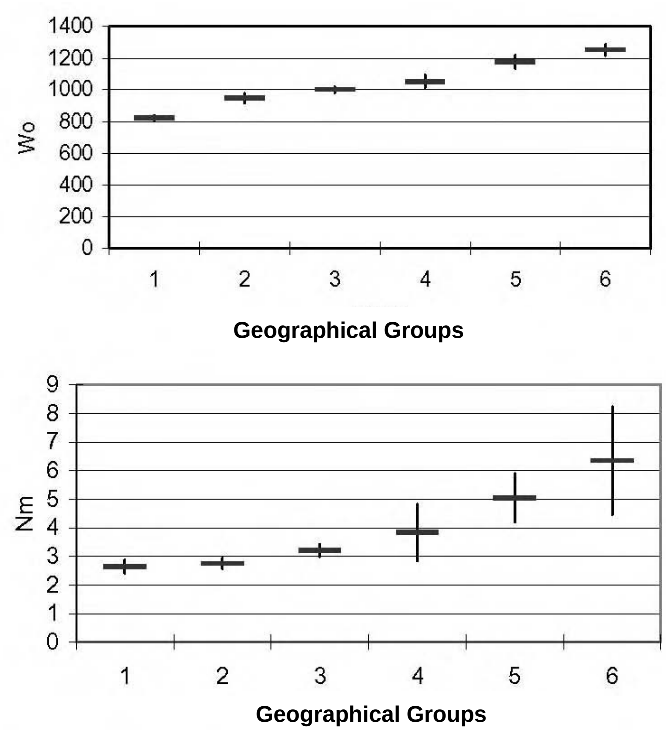


Figure 13. Mean value and standard deviation obtained for the quartz grain abrasion index (Wo) and non homogenous index (Nm) in statistical significance different group (groups: I – profiles 1-2, II profiles 3, 5, III – profiles 6-9, IV – profiles 10-16 and 25-29, V - profiles30-35 and 38-39, VI – profiles 17, 20-24, 36-37)

Group I, encompassing the two northernmost sites only, their soils having developed from the youngest glaciofluvial sediments NTof the Neoholocene (*Wo* < 900, Nm < 3);

Group II, encompassing three soil profiles in southern Lapland that have developed from Mesoholocene sediments (*Wo* ≈ 900, Nm < 3);

Group III, encompassing soils from the Hamme region developed from Eoholocene sediments (*Wo* ≈ 1000, 3 < Nm < 4);

Group IV, encompassing soils across a wide spectrum of geographical space;i.e., south-eastern Finland, Estonia, Latvia, Lithuania, Brandenburg, western Poland and north-eastern Poland, and associated in terms of their sedimentation with the Vistulian, (1000 < *Wo* < 1100, 4 < *Nm* < 6);

Group V, including the soils from central and eastern Poland, which developed from sediments of the Warta Stadial to the Odra Glaciation, (1100 < *Wo* < 1200, 4 < *Nm* < 6);

Group VI, encompassing soils of areas associated with the oldest sediments of the Odra Glaciation (in eastern Belarus and southern Poland), for which *Wo* > 1200, while the values of *Nm* fall within the range 5 to 8.

The graniformametric method of Krygowski (1964), elaborated on geomorphological bases, does not take account of the influence of soil processes on the shapes of quartz grains. For this reason it is hard to unambiguously assess which features are a consequence of pedogenic processes, and which are relief-forming processes, particularly in the so-called "young soils" (Rotnicki 1970). The supplementation of analytical methods using Krygowski graniformametry in the genetic classification of sediments, as well as in studies on pedogenesis, makes ever more frequent use of determinations based on very precise diagnostic techniques (Whalley 1979; Goździk 1991, 1995; Mycielska-Dowgiałło 1995). An electron microscope is very helpful in these studies (Whalley 1979; Kowalkowski 1984; Brogowski, Kocoń 1984; Kowalkowski, Brogowski, Kocoń 1986; Bednarek 1988, 1991; Kowalkowski, Kocoń 1998; Janowska 2001). The application of such techniques would have been helpful but were beyond the scope of the research presented.

7.3 Physical properties

The physical properties of the analysed soils were discussed within two main groups, in line with the division proposed by Uggli (1979). Presented in the first of these are primary physical properties mainly associated with the quality of soil material (bulk density, real specific gravity and porosity). Included in the second group are secondary (i.e. aquatic and aerial) properties that reflect the primary ones.

7.3.1 Primary physical properties

In spite of the diversity in textural properties of the mineral material, the primary physical properties are characterised by a limited variability, as well as by a lack of clear (statistically significant) regularities in the spatial distribution of certain features. The dominant (up to 98%) share accounted for by quartz, the limited (up to 10%) content of heavy minerals within the petrographic composition, and the vertical distribution of humus in profiles have a determining influence upon real specific gravity (RSG). Mean values range from 2.34 $g \cdot cm^{-3}$ in the humus horizon, to 2.60 $g \cdot cm^{-3}$ in the parent rock horizon. In the case of rusty-podzolic soils, the respective figures range from 2. 36 $g \cdot cm^{-3}$ in the humus horizon to 2.61 $g \cdot cm^{-3}$ in parent rock (Table 10). The greater differences in *RSG* values reported from humus horizons as opposed to mineral horizons emphasize the major significance organic matter has in shaping these features. The limited petrographic differentiation is also the cause of

Table 10. Mean (RSG_m) and extreme values (RSG_{nim}, RSG_{max}) of specific gravity and its standard deviation (d) determined for genetic horizons of podzolic and rusty-podzolic soils.

Genetic horizons	RSG_m	d	RSG_{min}	Profile no. with RSG_{min}	$RSGw_{max}$	Profile no. with RSG_{max}
	$g.cm^{-3}$				$g.cm^{-3}$	
podzolic soils						
AEes	2.34	0.11	2.02	29	2.51	7
Ees	2.53	0.07	2.42	38	2.65	24
Bh	2.46	0.06	2.32	24, 29	2.59	10
Bfe	2.59	0.06	2.47	38	2.69	1
C	2.60	0.05	2.51	38	2.69	4
rusty-podzolic soils						
AEes	2.36	0.11	2.21	34	2.53	25
BfeBv	2.51	0.08	2.35	37	2.61	25, 24
Bv	2.58	0.06	2.51	8, 34	2.66	25
BvC	2.60	0.03	2.56	36	2.67	24
C	2.61	0.06	2.55	8	2.67	18

small departures for extreme values of real specific gravity defined in the solum's different genetic horizons, these mean values range from 13.7% noted in the humus horizon to 3.5% in the parent rock (Table 10). All the profiles display an increase in real specific gravity with depth. Only in podzolic soils - because of the increased content of organic compounds in the spodic horizon - is its real specific gravity lower than those of adjacent horizons.
The spatial variability of real specific gravity precludes division of the soil profiles into statistically significant groups nor is there any linkage with geographical location. Thus, from the point of view of diagnosis of the geographical location of pedons, this variable should be regarded as neutral.

A rather different situation applies to the spatial variability where bulk density (*BD*) is concerned. This feature is not only influenced by lithogenic factors, since a major role is also played by local (above all biogenic) conditions (e.g. content of organic matter, distribution of plant roots, etc.). Bulk density has been thought of as one of the more important physical features of soils (Derone *et al.*, 1986; Alexander 1989; Manrique and Jones 1991; Tamminen and Starr 1994) and is treated by many researchers as the product of a series of other elements conditioning the soil development process (Alexander 1980; Strong and La Roi 1985; Huntington *et al.*, 1989; Hillel 1998).

The similar nature of both the litterfall (mainly comprising needles of Scots pine) and the group of hemicryptophytes dominating in the herb layer (Solon 1998) ensures that the sub-horizon of overlying humus is characterised by limited spatial differentiation in bulk-density. Average figures for the podzolic soils were of 0.152 g·cm^{-3} (d = 0.004) in the litter-humus sub-horizon, 0.195 g·cm^{-3} (d = 0.031) in the fermentative sub-horizon and 0.251 g·cm^{-3} (d = 0.017) in the epihumus. The values are higher at sites progressively further to the south, something that may be linked with the more rapid humification of organic matter in a warmer climate. In the case of rusty-podzolic soils, the bulk-density data for the organic horizon are still more uniform. The average for the litter humus at all sites was of 0.15 g·cm^{-3} (d = 0.012), cf. 0.216 g·cm^{-3} (d = 0.037) and 0.251 g·cm^{-3} (d = 0.004) for the fermentative and epihumus layers respectively. These values are not statistically significant..

In the horizons of the solum generated from sandy material, bulk density is greater at greater depth, ranging from ca. 1.05 g·cm^{-3} for the humus horizon (of profile 28) through to 1.76 g·cm^{-3} in the parent rock (of profile 18). The mean values for bulk density in the different genetic horizons of podzolic soils are between1.30 g·cm^{-3} in the AEes horizon and1.58 g·cm^{-3} in the C horizon. The corresponding range for rusty-podzolic soils is 1.24 to1.64 g cm^{3} (Table 11). The vertical and spatial variability of density in the profiles is related to the distribution of roots, as well as by the content of organic matter (r = - 0.522 for podzolic soils and r = – 0.557 for rusty-podzolic soils), granulometric composition (r = 0.376)[10], and the intensity of the podzolization process.

All the profiles from podzolic soils showed an increase in bulk density in the sub-horizon of enrichment (Bh) in comparison with the adjacent horizons (Table 11). The relatively low value for the correlation, though statisticallically significant, confirms the complex nature of the factors influencing bulk density. However, since the greatest value for this index was obtained in the case of organic matter, this may be regarded as one of the most important elements determining the vertical and spatial differentiation in bulk density.

Table 11. Mean (BD_m) and extreme values (BD_{nim}, BD_{max}) of bulk density and its standard deviation (d) determined for genetic horizons of podzolic and rusty-podzolic soils as well as for the obtained groups.

Genetic horizon	All analysed soils						Group I		Group II	
	BD_m	d	BD_{min}	no. of profile	$BD_{max.}$	no. of profile	BD_m	d	BD_m	d
	g cm^{-3}			with BD_{min}	g cm^{-3}	with BD_{max}	g cm^{-3}			
podzolic soils										
AEes	1.30	0.12	1.05	28	1.49	3	1.42	0.04	1.25	0.09
Ees	1.42	0.11	1.12	28	1.58	3, 4	1.52	0.05	1.38	0.10
Bh	1.59	0.09	1.34	28	1.69	22, 32	1.61	0.04	1.58	0.09
Bfe	1.48	0.08	1.29	28	1.59	3, 4, 22	1.54	0.05	1.46	0.08
C	1.58	0.09	1.47	29	1.74	5	1.67	0.07	1.55	0.08
rusty-podzolic soils										
AEes	1.24	0.12	1.10	8, 25	1.48	18	1.40	0.11	1.20	0.08
BfeBv	1.41	0.11	1.23	37	1.62	23	1.56	0.08	1.37	0.07
Bv	1.52	0.06	1.43	27	1.67	18	1.62	0.02	1.49	0.03
BvC	1.70	0.04	1.65	8, 21	1.74	18	1.72	0.02	1.65	0.01
C	1.64	0.1	1.52	8, 25	1.76	18	1.74	0.02	1.61	0.09

Podzolic soils: group I – (profiles 1-7); group II – rest of profiles
Rusty-podzolic soils: group 1 (profiles: 18,21,23); group 2 – rest of profiles

Statistical analysis of spatial differences in the variability of vertical distributions of bulk-density data resulted in the identification of two groups of podzolic soils in the study area that were different from each other. The first group encompasses soils in Lapland and Finnish Lakelands (profiles 1-7) while the second includes all remaining profiles (Table 11). The greatest differentiation occurs in the humus (A) and eluvial (E) horizons and the most limited differentiation is found in the sub-horizon of enrichment (Bh). In the case of rusty-podzolic soils the Podlasie-Byelorussian Plateaus and Berezina-Desna Lowland group is characterised

[10] the correlation between the GSS indicator and *BD* was determined for all genetic horizons of the studied soil profiles

by the greatest values for *BD* relative to any other soils. Nevertheless, when all the profiles studied are considered, there is no relationship between bulk density and geographical location.

Total porosity (*PT*) is also associated with the vertical and spatial distribution of structure-forming organic matter. The correlation coefficient between the porosity of all the genetic horizons and the content of organic matter therein is 0.613, while that between PT and the index of average grain diameter (GSS) – as determined for each genetic horizon – is 0.421. Porosity of the studied soils is greater with higher organic matter content in genetic horizons, as well as where the average grain size of the soil substratum is smaller.

In the analysed profiles at least, the value for total porosity grows smaller as one moves down from the humus horizon to the parent rock. In the case of podzolic soils this decline is from 52.7% in the *AEes* horizon of profile 28, to 34.1% in horizon C of profile 3. The respective figures for rusty-podzolic soils are 56.5% in profile 25 to 35.5% in profile 37 (Table 12).

Table 12. Mean (PT_m) and extreme values (PT_{nim}, PT_{max}) of total porosity and its standard deviation (d) determined for genetic horizons of podzolic and rusty-podzolic soils as well as for the obtained groups.

Genetic horizon	All analysed soils						Group I		Group II	
	PT_m	d	PT_{min}	no. of profile with PT_{min}	$n_{max.}$	no. of profile with PT_{max}	PT_m	d	PT_m	d
	%				%		%			
podzolic soils										
AEes	44.5	3.6	37.7	3	52.7	28	38.7	3.1	45.8	2.8
Ees	43.7	4.6	33.6	4	54.8	28	36.6	2.8	43.6	3.9
Bh	35.4	4.1	30.2	38	46.2	28	36.1	1.9	37.6	4.1
Bfe	42.9	3.1	36.7	4	46.1	29	40.1	2.9	43.6	2.7
C	41.4	3.0	34.1	3	45.3	32	37.9	2.3	42.3	2.5
rusty-podzolic soils										
AEes	47.4	6.1	36.8	18	56.5	25	39.5	3.4	49.4	4.5
BfeBv	43.7	4.4	34.7	18	48.3	27	37.5	2.6	45.3	3.1
Bv	41.3	2.9	35.0	18	45.6	27	37.4	2.2	42.2	2.1
BvC	37.1	1.2	35.7	34	38.7	21	35.7	0.1	37.0	1.2
C	39.1	3.3	35.5	37	44.3	27	36.1	0.4	40.0	3.2

Podzolic soils: group I - (profiles 1-5); group II – rest of profiles
Rusty-podzolic soils: group I – (profiles: 18,21,23); group II – rest of profiles

Even though substrata are similar in their petrographic and lithological properties, and the species structure of vegetation differs little, the data for total porosity are characterised by spatial differentiation. The main reason for this is variability in the hygrothermal factor that determines the processes by which organic matter is mineralised and humified.

The podzolic soils can be divided into two groups differing in terms of the spatial variability in values for total porosity. The first group comprises the soils of Lapland (profiles 1 – 5) and the second consists of the soils of the remaining study sites. The greater content of the skeletal and coarse-sand fractions within the granulometric composition of soils from northern parts of the research area, and above all the lower content of organic matter in the solum of these soils, are what determine the lower porosity of these pedons (Table 12). These soils are notable for the fact that differences in porosity between the sub-horizon of enrichment *Bh* (36.1%) and the eluvial horizon E (36.6%), as well as the enrichment (Bfe) horizon (40.1%) are smaller than is the case with the older soils of the Eastern European Soil Region. The soils of this part of the continent have a Bh sub-horizon characterised by greater compaction of material, as manifested in markedly lower porosity (37.6%) in comparison with the eluvial E horizon and *Bfe* enrichment horizon (43.6%).

As in podzolic soils, the spatial variability in values for porosity in the different profiles of rusty-podzolic soils permitted identification of two groups of soils. In this case, those clearly different are from profiles situated in eastern regions of the study area, i.e. on the Podlasie-Byelorussian Plateau and Berezina-Desna Lowland. In spite of the fact that the substrata of these soils were the most transformed by aeolian processes in the periglacial environment (and are thereby enriched in their dusty fractions), they are characterised by the lowest porosities of any of the studied rusty-podzolic soils. The reason is the low proportion of structure-generating organic matter in the solum of these soils – something that may be linked with intensive forestry management engaged in in the areas in question several decades ago (Jefremow, Degórski 1998). Thus, human activity may well have changed the primary properties of these soils.The results show that, where soils are of similar granulometric composition, a key role in the spatial diversification of their primary properties may be played by organic matter.

7.3.2 **Secondary physical properties**

It is primary physical properties, lithological properties of the substratum and the content of organic matter, that are the main factors shaping secondary physical properties of soil. The vertical differentiation of capillary capacity (KPW) and field capacity (PPW) in profiles of the podzolic and rusty-podzolic soils features a decline in values with depth (Table 13). The exceptions to this rule are the Bh enrichment sub-horizons in podzolic soils, as well

Table 13. Mean values ($KPW_{m,}$ PPW_m), extreme values (KPW_{nim}, KPW_{max}; PPW_{nim}, PPW_{max}) and standard deviation (d) of capillary capacity and field capacity in genetic horizons of studied podzolic and rusty-podzolic soils.

Genetic horizon	KPW						PPW					
	KPW_m	d	KPW_{min}	no. of profiles	$KPW_{max.}$	no. of profiles	PPW_m	d	PPW_{min}	no. of profiles	$PPW_{max.}$	no. of profiles
	weight %			with KPW_{min}	% wag.	with $KPW_{max.}$	weight %			with PPW_{min}	weight %	with $PPW_{max.}$
podzolic soils												
O	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	162.4	30.9	104.5	2	198.4	24
AEes	22.7	3.2	19.5	7	30.6	16	13.6	2.6	8.2	10	18.3	22
Ees	15.6	2.4	11.2	10	18.9	24	9.2	1.2	6.7	10	11.3	1
Bh	19.7	5.5	11.8	7	35.5	15	9.8	2.2	7.7	7	13.9	19
Bfe	11.8	2.2	9.7	2	17.6	24	7.6	1.1	6.1	35	10.3	22, 24
C	13.1	1.2	10.8	2	15.9	24	7.4	1.0	5.3	19	9.6	5
rusty-podzolic soils												
O	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	187.0	22.9	141.2	8	214.2	18
AEes	26.7	5.2	19.5	9	36.9	30	17.5	4.2	9.1	9	23.7	30
BfeBv	18.2	2.6	13.2	9	23.9	37	12.0	3.2	7.4	8	18.4	21
Bv	14.6	1.3	11.8	9	16.5	21	8.9	1.1	6.8	8	11.2	21
BvC	13.4	1.0	11.8	39	14.3	34	8.5	0.4	7.9	39	9.0	18
C	15.7	1.4	14.2	23	17.3	36	9.7	1.3	8.1	8	13.6	30

as the parent-rock horizon in both types of soil. The fact that both kinds of water capacity are once again higher when the parent-rock layer is reached may reflect, not only a different granular structure of the sediments, but also the fact that the impact of capillary forces is greater at depth (Birecki and Trzecki 1964; Degórski 1990).

Table 14. Mean values (MH_m), extreme values (MH_{nim}, MH_{max}) and standard deviation (d) of maximal hygroscopicity determined for genetic horizons of podzolic and rusty-podzolic soils.

Genetic horizon	MH_m	d	MH_{min}	no. of profiles with MH_{min}	MH_{max}	no. of profiles with MHmax
	%				%	
podzolic soils						
O	4.79	0.39	4.03	3	5.34	19
AEes	0.70	0.16	0.30	2	0.94	11
Ees	0.53	0.14	0.22	2	0.76	12, 28
Bh	0.56	0.14	0.24	2	0.79	12
Bfe	0.39	0.08	0.19	2	0.52	29
C	0.30	0.07	0.17	2	0.39	26
rusty-podzolic soils						
O	5.07	0.49	4.65	8	6.12	18
AEes	1.07	0.18	0.78	37	1.38	25
BfeBv	0.74	0.07	0.63	36	0.87	37
Bv	0.53	0.14	0.41	31, 36	0.84	23
BvC	0.37	0.05	0.32	36	0.45	39
C	0.31	0.05	0.22	36	0.43	33

Higher values of KPW and PPW are located in regions in old-glacial areas. The soils of these areas are developed from material with a greater share of the dusty fraction (more often than in other geographical regions), and are also characterised by a greater accumulation of organic matter (see Section 7.4.1). They also have higher soil colloids (mainly organic) that enhances their sorptive properties (see Section 7.4.6), as compared with the pedons of the remaining analysed regions. They also have greater capacity to adsorb water vapor than soils developed on younger geological material (Table 14). This results in the greatest values for maximal hygroscopicity (MH) in many genetic horizons of profiles in the Podlasie-Byelorussian Plateaus, Berezina-Desna Lowland and the Central Polish Lowlands. The causes underpinning differences in water capacity between the studied profiles need to be sought in local habitat conditions, and particularly in contents of organic matter in soils. In spite of the reported spatial differences, statistically significant regional groups could not be found.

Similar spatial trends in soil water retention water were found under different humidity conditions. The reserves of water in the capillary state (Z_{KPW}) or field state (Z_{PPW}) determined for the organic horizon, as well as a 100-cm layer of mineral soil, are characterised by higher values in geological material and soil of greater age. The lowest values occur in soils of the study area’s northern regions, as developed in lithological material with a considerable share of skeletal fractions. The greatest reserves are characteristic of soils whose parent rock has been subject to the most intensive disintegrative processes resulting in higher fractions of dusty and clayey granulometric composition. In the case of podzolic soils, the range of values for Z_{PPW} ranges from 114.4 mm in the Punkaharju profile (no. 10) to 206 mm in the Slavharad (profile no. 22). The mean value for all soils is 146.3 mm (d = 23.7). For rusty-podzolic soils, the range is from 147.9 mm in the Hatulla profile (no. 8) to 224 mm in the Skrwilno profile (no. 30), with a mean reserve defined for all soils of 184 mm (d = 22.2).

The regional differentiation in retention properties is revealed much more completely by data for the relationships between reserves of water or water capacity in the capillary state (Z_{KPW}), the field state (Z_{PPW}), the temporary moisture (Z_{WN}) state or the plant-inaccessible state (Z_{WTW}), than by data for the reserves as such (Fig. 14 - see Section 4.3, Methods of Analysis). Both the podzolic and the rusty-podzolic soils of old-glacial areas are characterised by the broadest ratios for reserves of water in the PPW state to reserves in the KPW state (Fig. 14). This confirms the greater retentiveness of soils with a greater share of fine capillaries (Rode 1956). The results obtained for Poland do not depart from those determined by other authors for soils developed from loose and weakly-clayey sands (Musierowicz, Królowa 1962; Królowa 1966; Prusinkiewicz *et al.*, 1981; Degórski 1990). The trends for greater

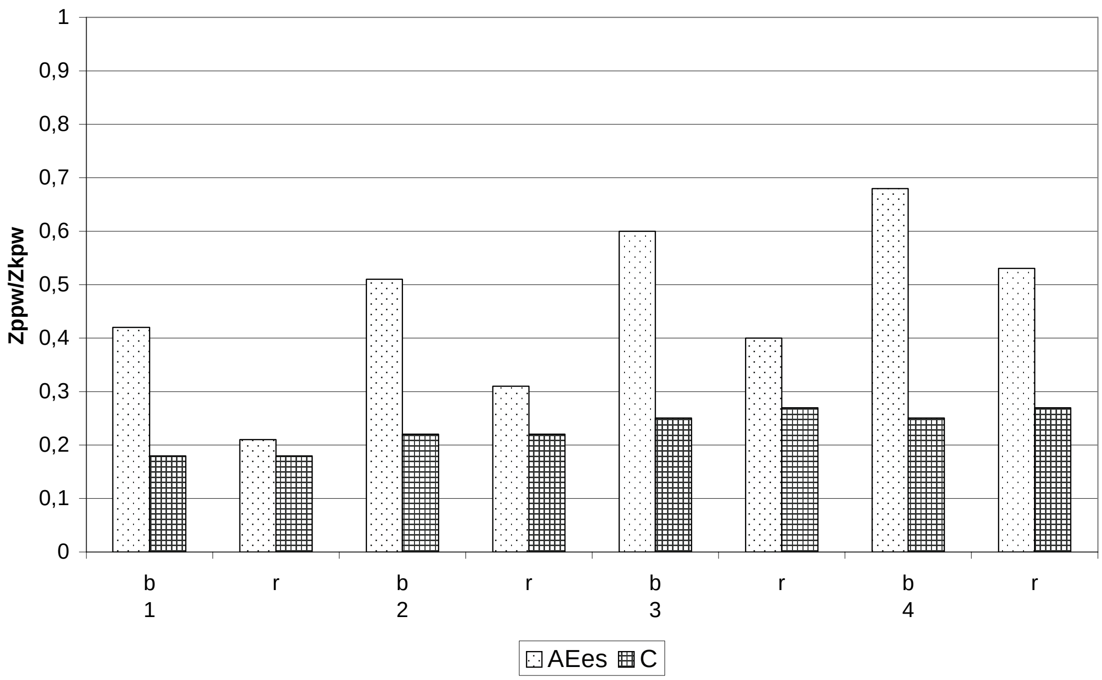


Figure. 14. Relationship between soil water stock in field capacity (Z_{ppw}) and soil water stock in capillary water capacity (Z_{kpw}) obtained for the humus-eluvial horizon (AEes) and parent rock horizon (C) in the regions with statistically significant distributions of features: b – podzolic and r – rusty-podzolic soils. The regions are; 1 – Lapland and the Firrrish Lackelands; 2 – Western, Southern, and Eastern Baltic Lakelands; 3 – Central Polish Lowlands and Silesion-Cracovian Upland; 4 – Podlasie-Byelorussian Uplands and Berezina-Desna Lowland

values of the Z_{PPW}/Z_{KPW} in more southerly or easterly sites area are confirmed by the regression functions obtained for this relationship in regard to geographical coordinates (Table 15).

Table 15. Parameters of the regression and correlation coefficient determined for relationships among reserves of water in the capillary state (Z_{KPW}) or field state (Z_{PPW}) as a dependent variable and longitude or latitude (independent variable).

Soil type	Independent variable	Parameters to the regresson			Correlation coefficient
		a	b	c	r
podzolic	longitude	0.346	0.012	–	0.701
	latitude	−0.371	0.035	−0.0003	0.469
rusty-podzolic	longitude	−0.010	0.032	−0.001	0.716
	latitude	4.272	−0.137	0.001	0.983

Spatial variation in soil properties dependent on the contemporary shaping of climatic conditions follows a different course. For example, soil moisture deficit shows a strong correlation with the Sielaninov hygrothermal index (r = 0.680). (Soil moisture deficit is the relation between field water capacity (Kowda 1984), defined as the percentage share of the reserve of water relative to the soil moisture state, compared to the reserves of water in the field capacity state.) Because of the large range of humidities shown by the different genetic horizons of the analysed soils (Degórski 1998c), this measure is also very labile. The mean value for it ranges from 50% in south-eastern parts of the study area to ca. 90 % in its northern regions (Fig. 15).

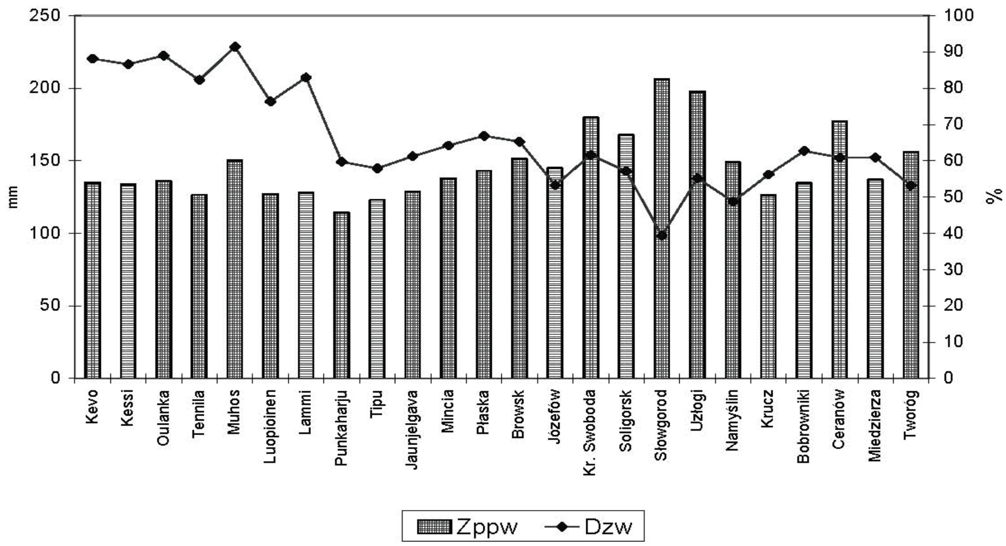


Figure 15. Soil water stock in field capacity (Z_{PPW}) and deficit of soil water stock (D_{ZW}) in relation to the soil water stock in field capacity (Z_{PPW}) in podzolic soils.

North to south differentiation in the soil moisture deficit shows that the mean annual reserve of water in the profiles in Lapland and Ostrobothnia is only some 10% lower than field-capacity state. In contrast, in the soils of the Northern Pre-Carpathians, the value ranges from 40 to 50%.

In contrast, where the E-W transect is considered, greater deficit occurs in Western Baltic Lakelands and Southern Baltic Lakelands in the west and Podlasie-Byelorussian Plateaus and Berezina-Desna Lowland in the east. The area of central Poland features the lowest moisture deficit in the soil, the mean annual reserve of soil water is less than 40% of field water capacity. However, the values for different profiles along the west-east line do not in fact vary greatly, their magnitudes being conditioned mainly by soil retention properties (obviously apart from hygrothermal conditioning). This is best seen in the area of the Podlasie-Byelorussian Plateaus and Berezina-Desna Lowland, where these soils are characterised by a greater moisture deficit on account of their maximal capabilities of holding soil water in the PPW state (notwithstanding the greater climatic humidity than in other areas of Poland, as well as greater past anthropogenic interference in forest ecosystems - Degórski 1998a; Khotko 1998). This is depicted by regression curves of moisture deficit over geographical coordinate (Fig. 16). Podzolic and rusty-podzolic soils resemble each other elative to the relationship between the soil moisture deficit and geographical location.

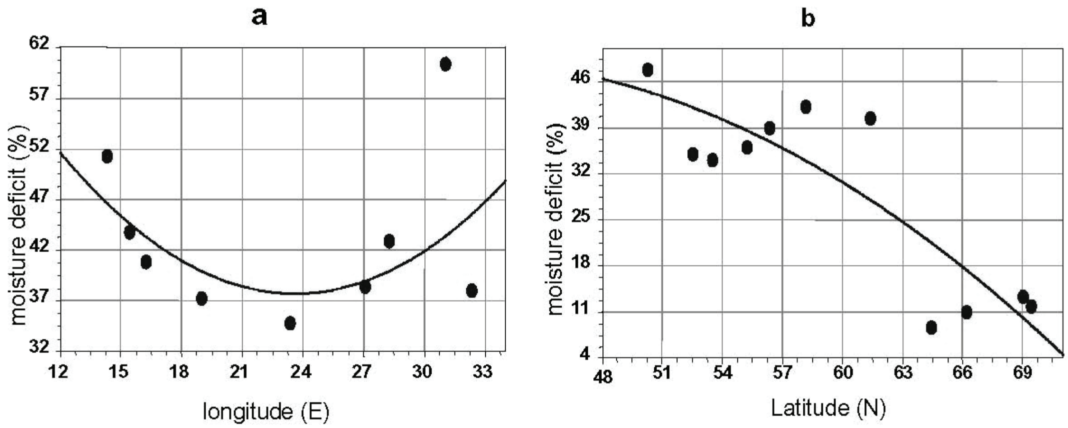


Figure 16. Regression curves for the water shortage in podzolic soils on geographical coordinates (a - longitude, $Y = 95,106 - 4,863x + 0,103x^2$, $r = 0,407$; b – latitude, $Y = -24,255 + 3,701x - 0,046x^2$, $r = 0,876$).

Only a small part of the total reserves of soil water are plant-inaccessible (in the Z_{WTW} form), which is to say very strongly associated by molecular forces with the soil's solid phase. In podzolic soils, the size of this reserve does vary – ranging from 5.0 mm in northern Lapland (profile 1) to 13.3 mm in the Podlasie-Byelorussian Plateau (profile 19). The average value is 9.8 mm (d = 1.9 mm). In the case of the rusty-podzolic soils, the differentiation is much more limited, ranging from 10.1 mm (profile 34) to 14.6 mm (profile 37), with a mean value of 12.2 mm (d = 1.1 mm). The reserves of soil water inaccessible to plants in rusty-podzolic soils also do not display spatially-determined regularities, something that may result from the greater uniformity of the geological material from which these soils developed, as well as the much less-diverse contents of organic matter (see Section 7.4.1). The Z_{WTW} values are 3 to 13% of the reserve of water in the field-capacity state in the case of podzolic soils, 6 to 20% in the case of rusty-podzolic soils. These values are similar to those determined in other soils developed from loose and weakly-clayey sands (Królowa 1963, 1966; Degórski 1990).

The variability in the total capillary and non-capillary air capacity in podzolic soils and rusty-podzolic soils varies spatially in a way similar to water properties. The greatest values for air capacity (Pp) were reported in soils from regions of northern Europe, the lowest from old-glacial areas of east-central Europe (Fig. 17). In the assessment of Kowda (1984), a higher value for capillary air capacity is associated with more difficult gaseous exchange between the soil and the atmosphere. In line with this assumption, the best conditions for the exchange of soil air with the atmosphere can be anticipated in soils situated where the cover is mature.

This would be true of both podzolic and rusty-podzolic soils. The eastern regions of the study area are characterised by the lowest values for capillary air capacity in any of the genetic horizons (Fig. 17- see Section 4.3, Methods of Analysis),

Data for air capacity in the soil profiles of Lapland and the Finnish Lakelands are distinctly different (in comparison with other physico-geographical units in which studies were carried out). The soils developed in the north of the continent have values for air capacity that decline with depth – as compared with the rise noted in the remaining profiles (Fig. 17). This difference may reflect three factors: the shallow rooting of plants, the low content of organic matter in the solum of soils and the marked impact of cryogenic weathering on the disintegration of the geological material of upper soil horizons (Liira and Hietaranta 1998).

Air capacity in the humus horizons of both podzolic and rusty-podzolic soils is characterised by relationships with profiles' geographical locations (Table 16). On the other hand, inter-regional differences in the courses noted for the feature in question become less distinct at increasing depth. This attests to the influence of other (not purely morpholithological elements) of the soil environment on its vertical course, especially in the upper part of profiles.

Table. 16. Parameters of regression and correlation determined for the relationships between air capacity in podzolic and rusty-podzolic soils (dependent variable) and longitude or latitude (independent variable).

Soil types	Independent variable	Regression parameters			Correlation coefficient
		a	b	c	r
podzolic	longitude	11.652	1.057	−0.027	0.442
	latitude	29.367	−0.127	−	0.449
rusty-podzolic	longitude	36.767	−0.767	−	0.796
	latitude	−1257.265	43.196	−0.361	0.991

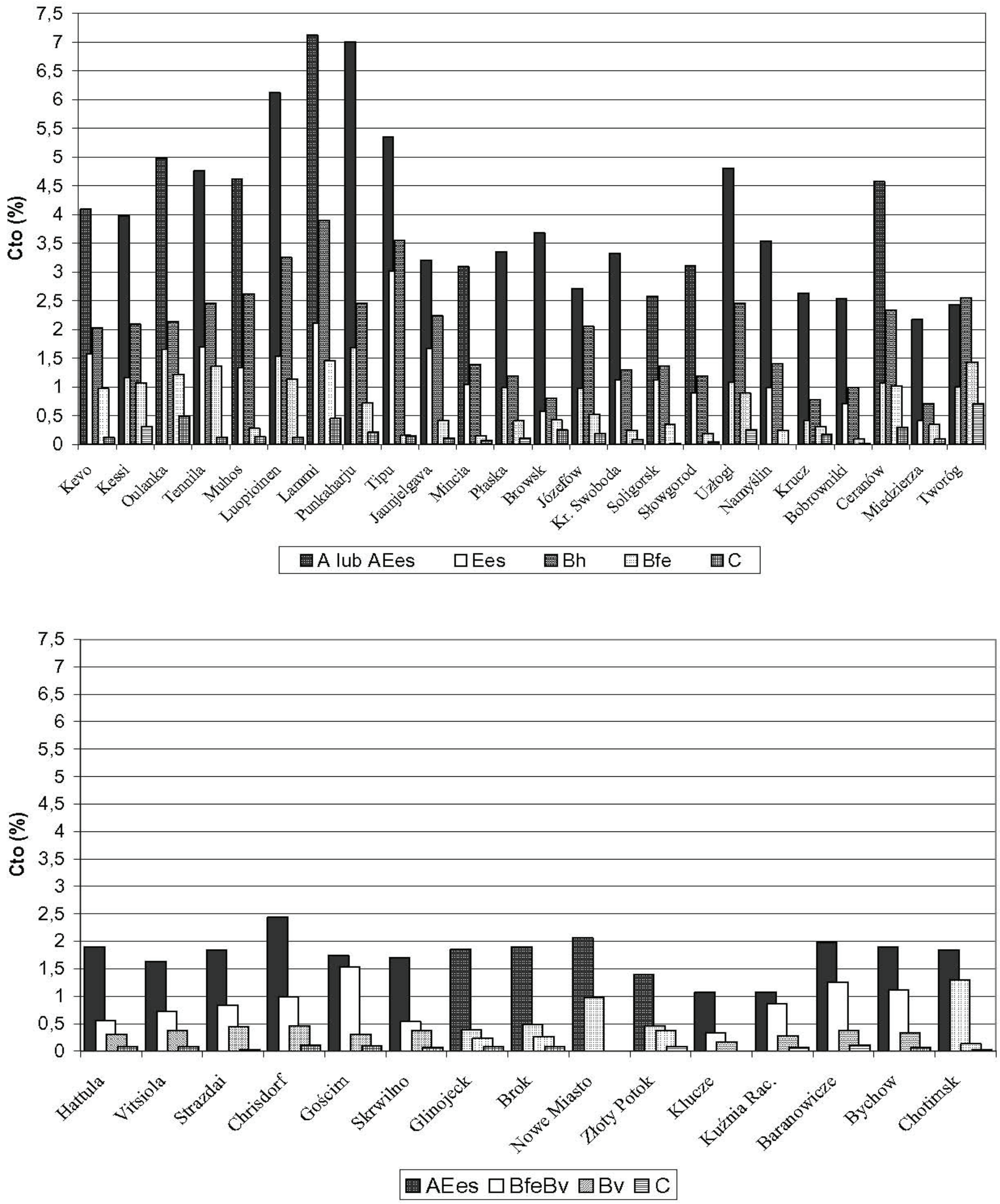
In the case of podzolic soils, the lowest absolute values and least varied values for air capacity are those of the Bh enrichment sub-horizons, ranging from 19.3 % by volume in soils of the northern regions to 14.0% in soils of Podlasie-Byelorussian Plateaus and Berezina-Desna Lowland.

7.4. Chemical and biochemical properties

7.4.1. Content and reserve of organic carbon

In both the analysed podzolic and rusty-podzolic soils, organic matter is mainly accumulated in sub-horizons of the organic horizon and in the humus horizons. The quantity of organic carbon (C_{to}) in the sub-horizons of the organic horizon declines with the degree of humification of organic matter, from the fermentative sub-horizon (49.1–54.8%) to that of the epihumus (21.3–42.8%). In the mineral parts of soil profiles (the solum), the content of organic carbon declines with depth, except in the diagnostic spodic horizon of podzolic soils. In the sub-horizon of enrichment (Bh) in particular, the illuvial accumulation of organic matter is associated with a significant increase in C_{to} as compared with the situation in adjacent genetic horizons (Fig. 18). Rusty-podzolic soils did not feature a rise in the content of C_{to} in the diagnostic sideric sub-horizon. Indeed, the situation is quite the reverse, as the content in the BfeBv and Bv horizons is markedly lower, amounting to between 0.5 and 1 % on average (Fig. 18). Shaped similarly in the profiles is the content of the organic carbon fraction extracted in 0.1 M sodium pyrophosphate (Cp) and forming part of iron- aluminium humus complexes, (complexes of organic carbon with sesquioxides of aluminium and iron).

a



b

Figure 18. Content of organic carbon (C_{to}) in particular genetic horizons of the mineral part of soil (a – podzolic soils, b – podzolic-rusty soils)

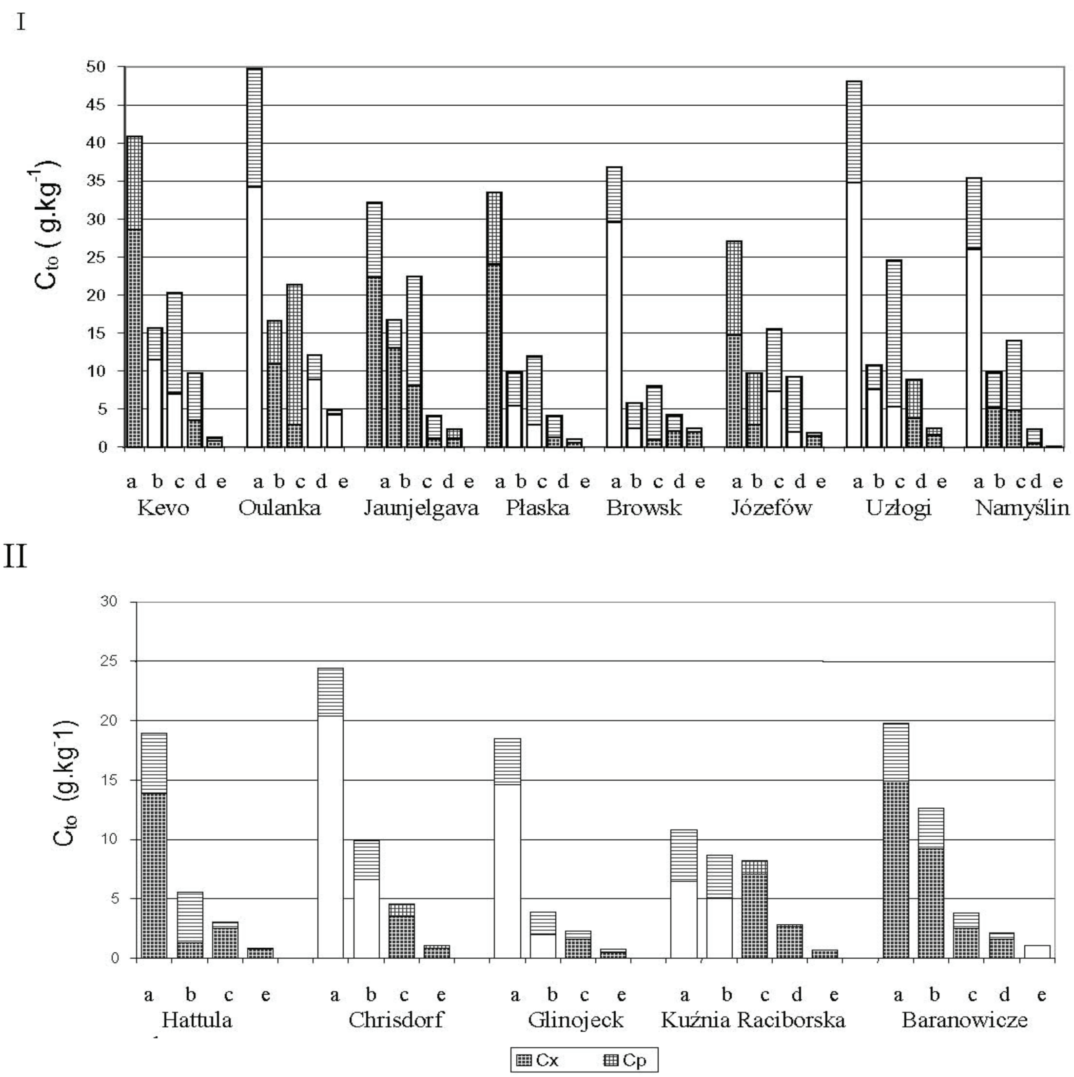


Figure 19. Content of organic carbon (C_{to}) as a C_x and Cp extracted by 0,1 M pyrophosphate in some pedons (I – podzolic soils; a-e genetic horizons: a – A or AEes, b – Ees, c – Bh, d – Bfe, e – C; II – podzolic-rusty soils; a-e genetic horizons: a – AEes, b – BfeBv, c – Bv, d – BvC, e –C). II – podzolic-rusty soils; a-e genetic horizons: a – AEes, b – BfeBv, c – Bv, d – BvC, e – C).

. In the mineral part of podzolic soils, the quantity Cp in the humus horizon is 11.1 $g \cdot kg^{-1}$ on average, i.e. 1.1%, beyond which there is a clear decline in the eluvial horizon, prior to a renewed rise in the sub-horizon of enrichment *Bh* – to 12.3 $g \cdot kg^{-1}$;i.e.; 1.2%; on average (Fig. 19). In contrast, in the rusty-podzolic soils, organic carbon associated in complexes with sesquioxides decline steadily from the top to the bottom of profiles. This attests to the weakly-advanced process of illuviation and the small content of organically-bound iron and aluminium in the diagnostic sideric horizon, as compared with the diagnostic spodic horizon of podzolic soils (Fig. 19).

However, there is a marked increase in the proportion C_p in C_{to} in their diagnostic horizons, as compared with the other genetic horizons, including the humus horizon. In the spodic horizons, the index $C_p/C_{to}x100\%$ ranges from 53 to 86%, cf. the humus horizons of podzolic soils that have proportions of C_p in C_{to} within the range 20-40%. In rusty-podzolic soils, there are much smaller differences between the humus and enrichment horizons in the index values. In the case of the AEes horizon, the content of C_p to C_{to} ranges from 16 to 40%, cf. 36-76% in the BfeBv horizon and 30-40% in the Bv horizon. These results emphasize the role of complexes of humus with iron or aluminium in the ongoing pedogenic processes.

The greatest contents of organic carbon, for both the C_p and C_{to} fractions, were reported in the Finnish Lakelands and Berezina-Desna Lowland profiles, attesting to the large accumulation of organic matter in these areas. These are today characterised by the least active soil environment, something that may reflect a climate in the area that is colder than any other, and a consequently short growing season.

Assessments of the variability in organic carbon in soils make more and more use of such measures as DC and MC, relating to density and resources (Liski 1995, 1997; Liski and Westman 1995, 1997). The distribution of organic carbon in the profiles of forest soils needs to be determined, in relation to the functioning not only of the given pedon, but the whole ecosystems. In the view of Post *et al.* (1990), around 2/3 of the reserve of carbon in forest ecosystems is in the form of soil organic matter. The spatial variability in reserves of organic carbon in the genetic horizons of soils is mainly determined in reference to their thickness, plus the density of organic carbon (DC).

When the vertical distribution of densities of organic carbon is considered, the greatest values are found to be those in the sub-horizons of the organic horizon. The carbon accumulated in the latter is younger and more uniform in terms of age than that in the mineral horizons (Liski *et al.* 1997). It is worth stressing here that, notwithstanding the influence of anthropogenic factors such as forest management, harvesting from the herb layer and forest fires (Liski and Westerman 1997), it is the organic horizon that shows the smallest spatial differences in the density by volume of organic carbon. In its sub-horizons, and most especially the litter sub-horizon, the densities of organic carbon are actually very uniform, amounting to between 75 and 83 $kg.m^{-3}$ in podzolic soils, and 75 – 77 $kg.m^{-3}$ in rusty-podzolic soils (Fig. 20 and 21). A rather greater diversity in density (90-110 $kg.\ m^{-3}$) arises in the Of and in the Oh sub-horizons comprising the humifying epihumus. A particularly significant increase in values is to be noted in the epihumus of the soils of northern Europe, i.e. Lapland, Ostrobothnia and the Finnish Lakeland (Fig. 20 and 21).

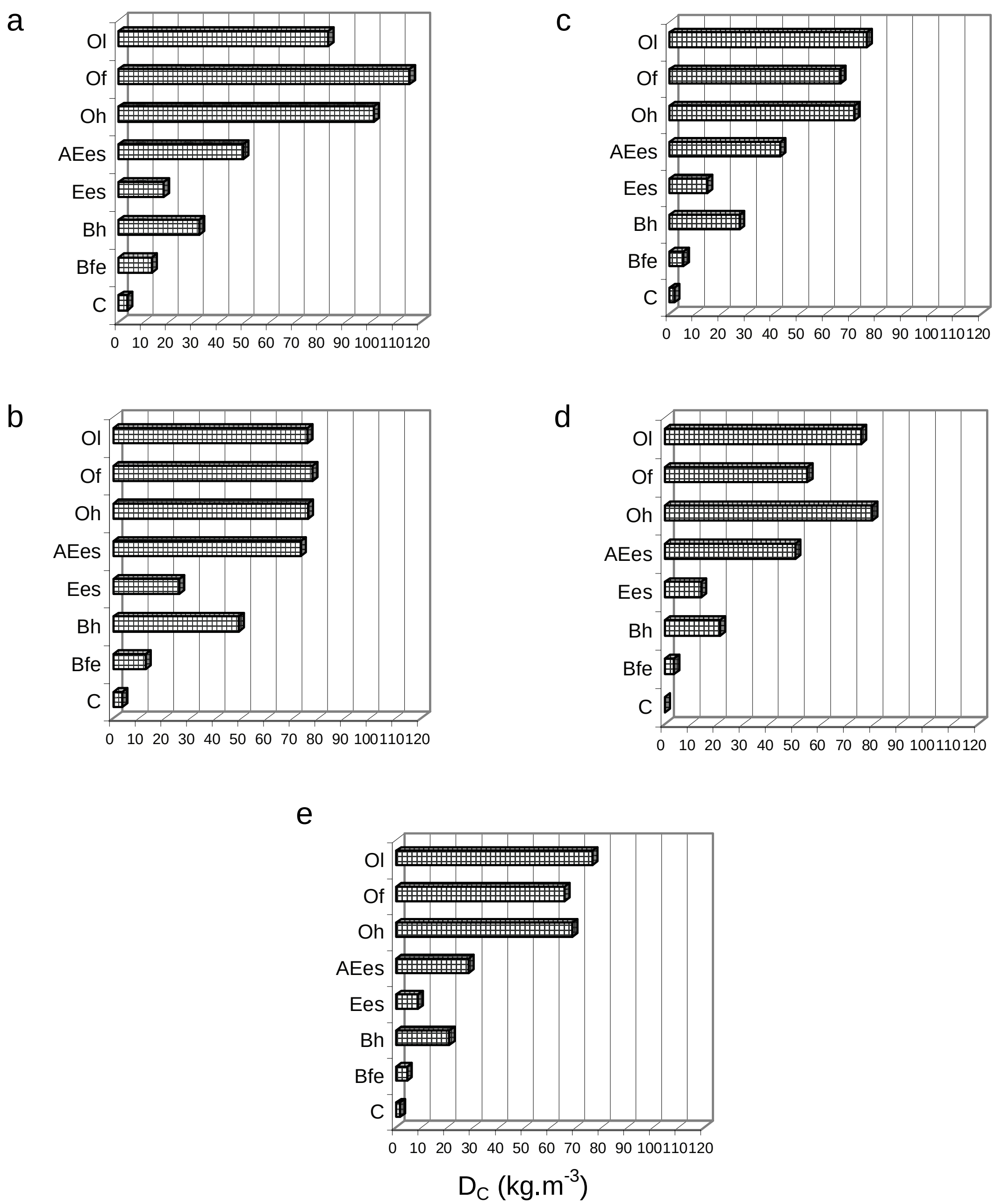


Figure 20 Carbon density (D_C) determined for the particular genetic horizons of podzolic soils in five geographical regions with differing distribution of features.-- a - Lappland and Ostro-Bothnia; b - Finnish Lakelands and Eastern Baltic Littoral Region; c - Eastern Baltic Lakelands, Podlasie-Byelorussian Uplands, Berezina-Desna Lowland, Northern Pre-Carpathian Uplands; d - Western Baltic Lakelands; e - Southern Baltic Lakelands, Silesian-Cracovian Upland and Central Malopolska Upland.

The solum has densities of organic carbon between 28.1 kg.m^{-3} (in the A-horizon of podzolic soils of the Silesian-Cracovian Upland and Central Małopolska, Poland) and 73.1 kg.m^{-3} (in the Finnish Lakeland). The respective values for the parent rock range from 1.5 to 3.5 kg.m^{-3} respectively. In rusty-podzolic soils, the respective values are in the range 7.8 to 23.4 kg.m^{-3} in the A-horizon, and 0.4 to 1.2 kg.m^{-3} in the parent rock. The results thus confirm ideas regarding an increase in the density of organic carbon in conditions of a cold and moist climate (Post *et al.* 1982; Liski 1997; Liski and Westman 1997).

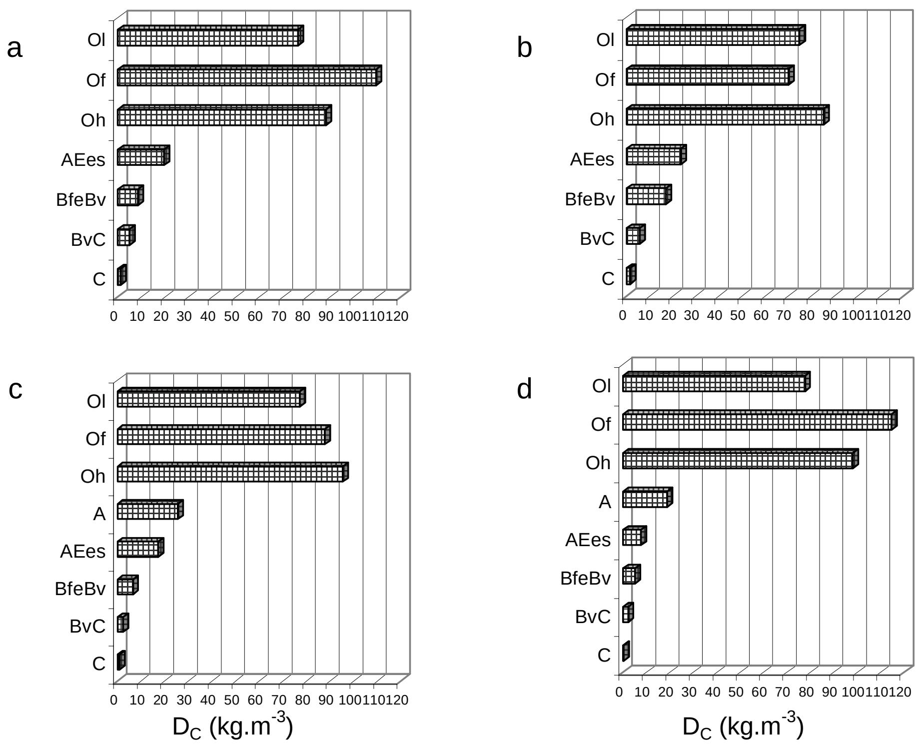


Figure 21. Carbon density (D_C) determined for the particular genetic horizons of podzolic-rusty soils in four geographical regions with differing distribution of features: a - Finnish Lakelands; b - Western and Southhern Baltic Lakelands; c - Eastern Baltic Lakelands, Podlasie-Byelorussian Uplands, Berezina-Desna Lowland; d - Central Polish Lowland and Silesian-Cracovian Upland.

The studies described here reveal marked differences in the resources of organic carbon (MC) determined for pedons of 1 m^2 area and containing the organic and mineral horizons down to a depth of 100 cm. Thus, the amount of carbon accumulated in pedons of podzolic soil is 16.4 kg on average (ranging from 9.7 kg in the Southern Baltic Lakeland – profile 29, to 23.5 kg in the Finnish Lakeland – profile 7). The mean value for rusty-podzolic soils is 12.3 kg (ranging from 9.2 kg on the Berezina-Desna Lowland – at profile 23, to 14.6 kg in the Eastern Baltic Lakeland - profile 14).

The much larger resources of organic carbon in podzolic soils probably reflect the lower trophic status and more limited biological activity of their soil environment as compared with that of rusty-podzolic soils. Podzolic soils also feature a greater diversity of values for the characteristic in question from profile to profile. In contrast, the small differences in resources of organic carbon in rusty-podzolic soils may reflect the more limited geographical range of these soils in the study area, as well as a greater uniformity of biotic and climatic conditions and less mosaic-like distribution. Also of importance is the level of transfer of humic compounds down the soil - weaker in rusty-podzolic than in podzolic soils (in which the diagnostic spodic horizon shows very significant elevations of organic carbon content). These factors ensure that podzolic soils have greater reserves of carbon overall than rusty-podzolic ones (Fig. 22), while the share of the organic horizon carbon in the total storage of organic carbon in podzolic soils is smaller than in the rusty podzolic soils.

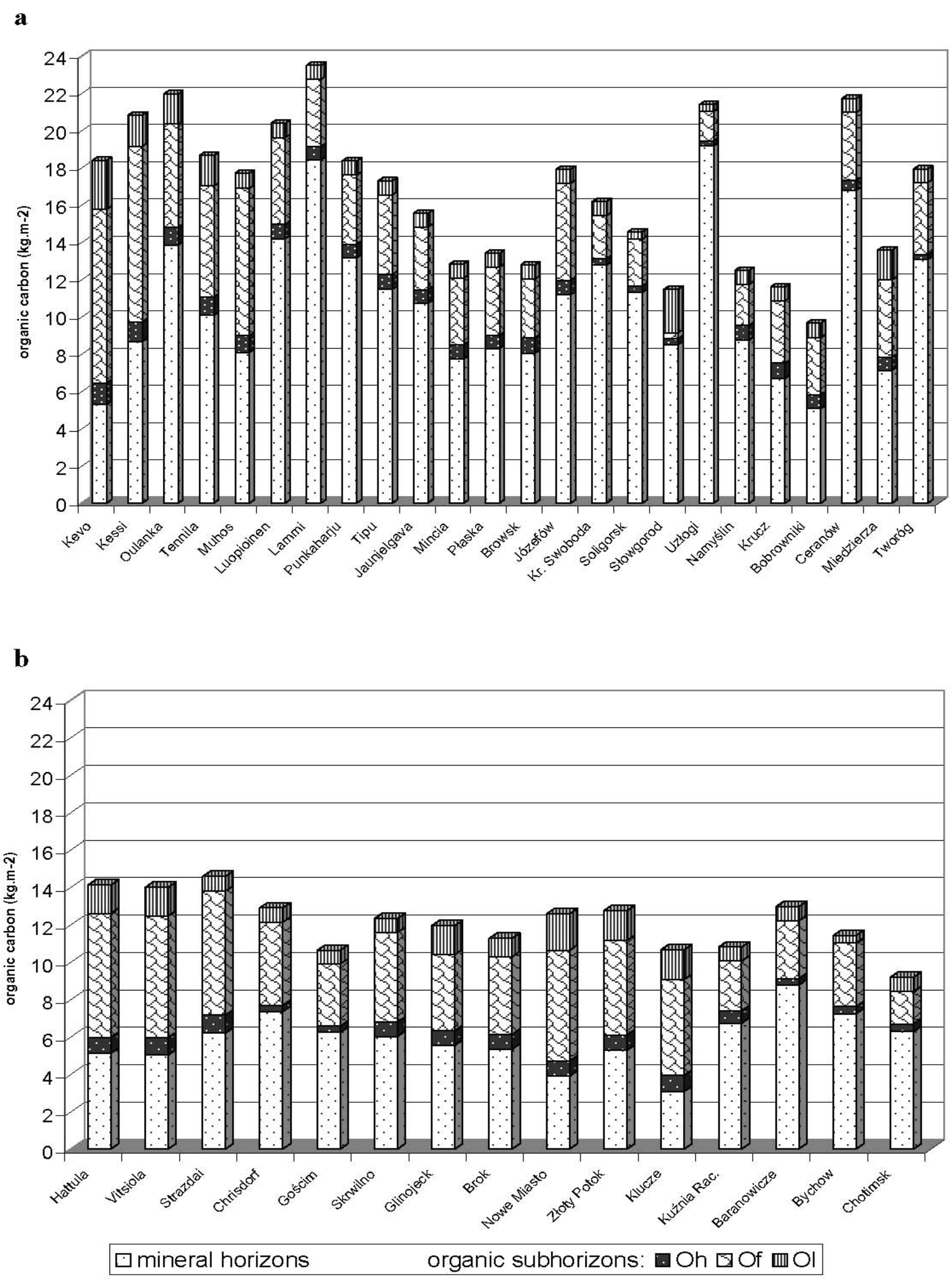


Figure 22. Carbon storage determined for the pedon about 1m^2 surface, contains organic horizon and mineral part to the 1 m deep. (a – podzolic soils, b – podzolic-rusty soil)

Table 17. Mean values of carbon storage (MC) determined for pedons about 1 m^2 contain organic horizon and mineral part of the profile to 1 m deep in statistically significant separation into geographical regions.

No. of group	Number of profile	Organic horizon		Mineral horizons to 1 m deep		Whole profile	
		MC_m	d	MC_m	d	MC_m	d
		$kg \cdot m^{-2}$					
podzolic soils							
I	5	10.3	3.2	9.2	3.4	19.5	5.4
II	4	5.6	0.5	14.3	4.0	19.9	5.9
III	10	4.3	1.2	11.5	4.3	15.8	4.5
IV	1	3.7	0.0	8.8	0.0	12.5	0.0
V	4	5.2	0.7	6.4	0.8	11.6	1.4
rusty-podzolic soils							
I	2	9.0	0.0	5.1	0.0	14.1	0.1
II	4	5.0	2.0	7.1	1.0	12.1	2.0
III	2	5.1	0.6	6.8	0.6	11.8	1.2
IV	6	7.0	1.5	5.1	1.2	12.0	0.8

Podzolic soils, groups:
I. Lappland (profiles: 1, 2, 3, 4, 5);
II. Finnish Lakelands (profiles: 6, 7, 10) and Eastern Baltic Coastland (profile 11);
III. Southern Baltic Lakelands (profile: 12, 13, 15), Podlasie-Byelorussian Plenteous (profile: 16, 19, 32), Berezina-Desna Lowland (profiles: 20, 22, 24), Northern Podkarpacie (profile 17);
IV. Western Baltic Lakelands (profile 26);
V. Eastern Baltic Lakelands (profiles: 28, 29), Silesian-Cracovian Upland and Central Małopolska Upland (profiles: 35, 38);
Rusty-podzolic soils, groups:
I. Finnish Lakelands (profiles: 8, 9);
II. Eastern Baltic Lakelands (profile 14), Podlasie-Byelorussian Plenteous (profile 18), Berezina-Desna Lowland (profiles: 21, 23),;
III. Central Polish Lowlands (profiles: 30, 31, 34, 39), Silesian-Cracovian Upland (profiles: 36, 37);
IV. Western Baltic Lakelands (profile 25), Eastern Baltic Lakelands (profile 27).

Nevertheless, the shares in both types are very high, ranging from 28 to 68% and from 41-64% in podzolic and rusty-podzolic soils respectively (Table 17.)

Analysis of the spatial distribution of resources of organic carbon in the soils studied reveals a statistically-significant relationship between these and the geographical coordinates of their profiles (as the independent variable). This confirms the trend for resources to increase towards the east and north, albeit with MC also being elevated in the south of the study area (Fig. 23). This result may point to the greater contemporary biological activity in the soil environment of Central Europe’s Lakeland areas.

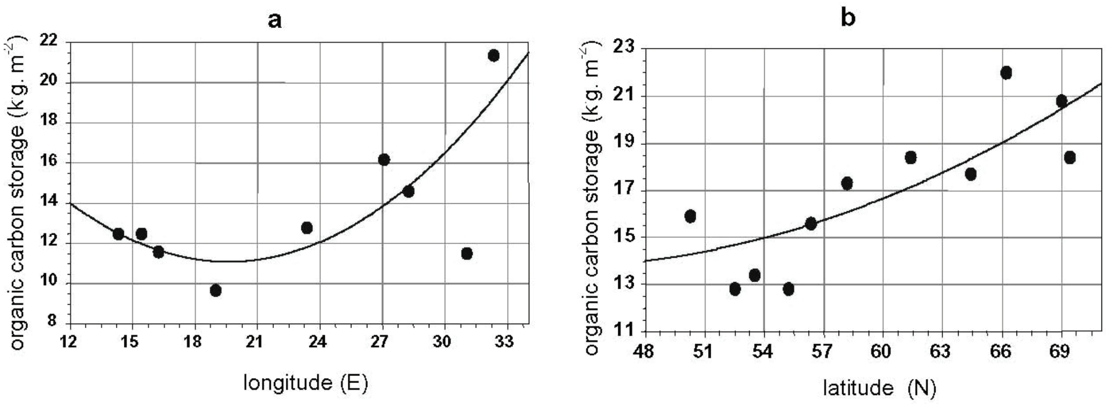


Figure 23. Regression curves for the carbon storage in podzolic soils on geographical coordinates (a - longitude $Y = 30,363 - 1,965x + 0,05x^2$, $r = 0,790$; b – latitude $Y = 31,217 - 0,822x + 0,01x^2$, $r = 0,802$).

To determine regional differences to the spatial variability of the study area's resources of organic carbon, spatial analysis found groups of geographical regions among the podzolic and rusty-podzolic soils identified. Among the five such groups of podzolic soils identified, those of Lapland have accumulated the greatest carbon resources in the O-horizon, while it is the mineral parts of the profile in the soils of the Finnish and Eastern Baltic Lakeland that are richest in carbon (Table 17). The greatest values of organic carbon in the organic and mineral parts of podzolic soils taken together are again those of the northern part of the study area.

Likewise, in the rusty-podzolic soils, the greatest carbon values in the organic horizon occur in the Finnish Lowland, while the greatest figures for the solum characterize the Eastern Baltic Lakeland, Podlasie-Belorussian Upland and Berezina-Desna Lowland. As with the podzolic soils, the rusty-podzolic soils in the northern regions have the greatest overall carbon. Differences between groups are nevertheless much more limited in these soils than in the podzolic soils (Table 17).

The results show that podzolic soils have much greater organic carbon than rusty-podzolic soils. This reflects the former's more limited biological activity and more intensive illuviation and transfer of humic compounds. The resources also tend to be greater in more humid climates, as indicated by their higher values in the northern and eastern parts of the study area. A similar conditioning of the spatial variability of resources of organic carbon has been reported for the podzolic earth in Scandinavia (Liski and Westman 1995), and northern parts of the USA (Michaelson *at al*., 1996).

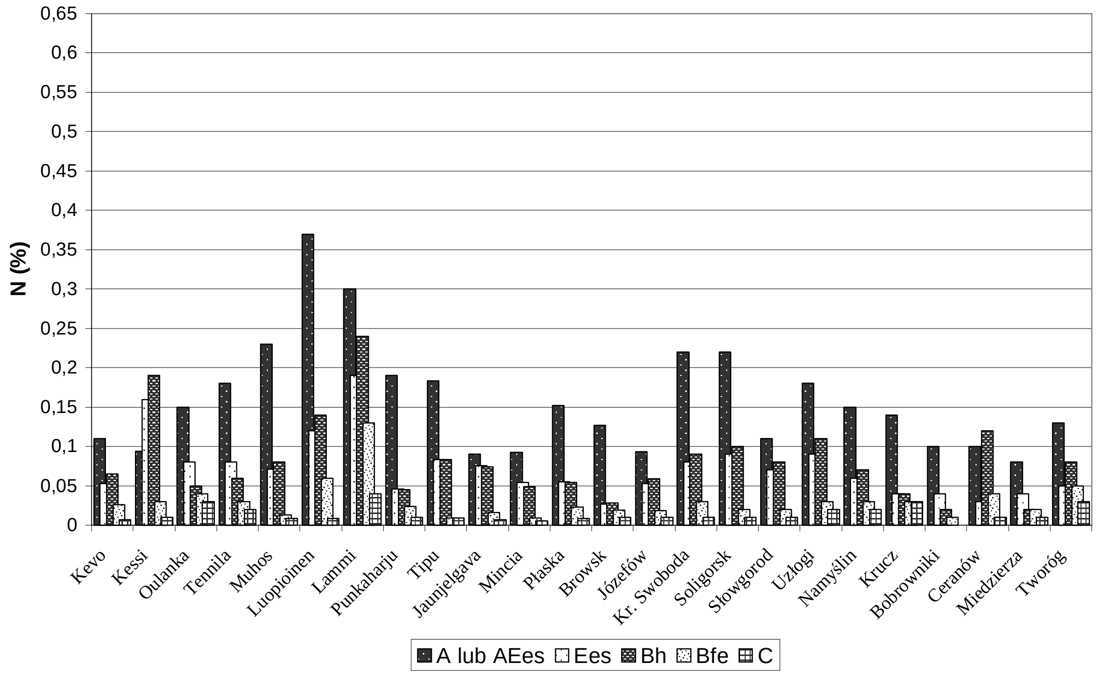
7.4.2. Nitrogen content and the C:N ratio

Alongside carbon, nitrogen is among the most important of the biogenic elements, for determining the level of activity of biochemical processes in soils. Its content in the analysed podzolic and rusty-podzolic soils does that noted by other authors (Białousz 1978; Sepponen 1985; Bednarek 1991; Raisanen 1996). In the epihumus (Oh) sub-horizon of podzolic soils, nitrogen ranges from 0.42 do 1.12 % (Table 18), wih a mean value of 0.64% (d = 0.16%). In the mineral horizons, the mean content of nitrogen was: in the A horizon – 0.16% (d = 0.07%), in Ees – 0.07% (d = 0.04%), then Bh – 0.08% (d = 0.05%), Bfe – 0.03% (d = 0.02%) and C – 0.01% (d = 0.01%). Rusty-podzolic soils had higher nitrogen with their mean values in different genetic horizons of: Oh – 0.93% (d = 0.23%), AEes - 0.19% (d = 0.18%), BfeBv – 0.09% (d = 0.06%), BvC 0.06% (d = 0.04%) and C – 0.02% (d = 0.02%). The standard deviations attest to the marked spatial differentiation. The greatest contents of nitrogen in either podzolic or rusty-podzolic soils were those reported the Finnish Lakelands profiles, while the lowest came from southern Poland (Fig. 24). Nevertheless, there is no statistically-significant relationship between the content of total nitrogen in the studied soils and geographical location. The only significant relationship was between the content of N and latitude in rusty-podzolic soils. This linkage was best depicted by a linear regression model in which Y = -2.262 + 0.047x (r = 0.984).

Table 18. Total nitrogen and its mineral forms ($N\text{-}NH_4^+$, $N\text{-}NO_3^-$) as well as organic carbon (C) and C : N ratio in epihumus subhorizon of podzolic soils.

No. of profile	C	N	C:N	NH_4^+	NO_3^-
	%			mg·100g^{-1}	
1	46.6	1.12	42	1.67	0.15
2	20.9	0.44	48	1.89	0.23
3	20.3	0.43	47	1.39	0.12
4	19.2	0.42	46	1.45	0.22
5	18.4	0.42	44	1.57	0.34
6	22.3	0.54	41	1.56	0.45
7	20.0	0.51	39	1.42	0.36
10	17.2	0.38	46	1.23	0.21
11	17.7	0.66	27	1.34	0.26
12	18.6	0.67	28	1.56	0.35
13	20.1	0.66	31	1.23	0.21
15	19.3	0.66	29	1.06	0.32
16	20.8	0.75	28	1.05	0.42
17	23.5	0.68	35	1.78	0.98
19	24.6	0.68	36	2.56	1.12
20	25.9	0.66	39	2.89	1.67
22	26.6	0.71	37	3.13	1.34
24	28.9	0.72	40	4.12	2.16
26	14.3	0.77	19	1.75	0.14
28	14.9	0.73	20	2.59	3.36
29	15.9	0.71	22	9.45	6.03
32	18.9	0.62	30	2.45	2.03
35	17.2	0.69	25	1.19	0.63
38	16.9	0.68	25	3.22	1.26

a



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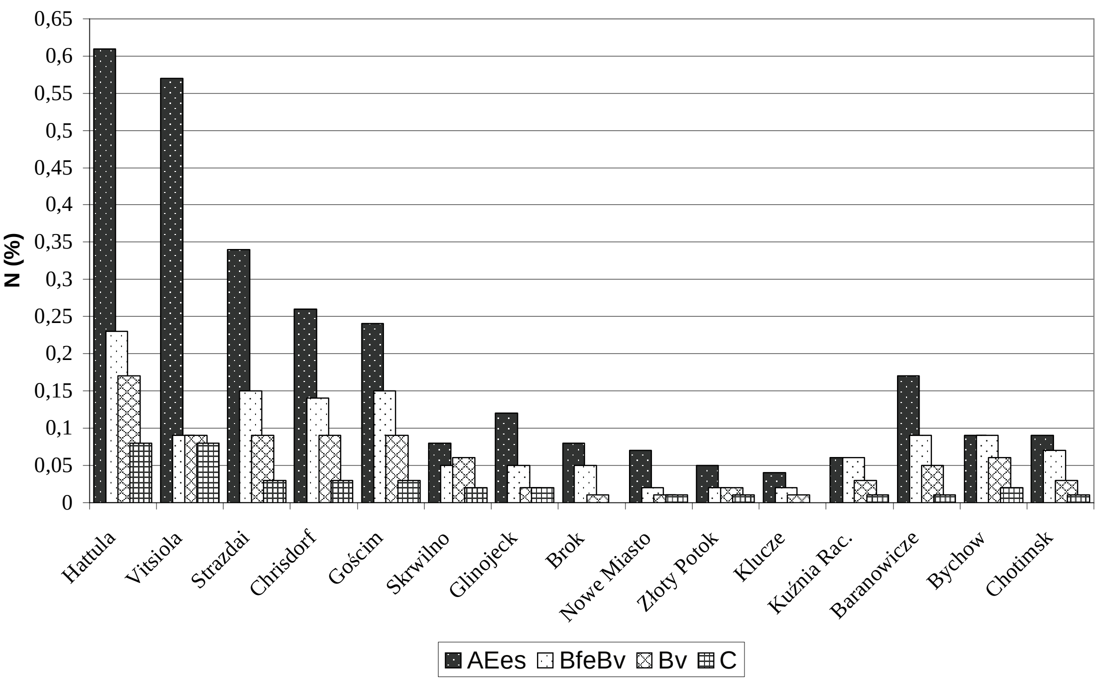


Figure 24. Content of total nitrogen in particular genetic horizons of studied soils (a - podzolic soils, b – podzolic-rusty soils).

Of significance to both the pedogenic process and the functioning of ecosystems are the transformations of organic forms of nitrogen into mineral forms, as well as the proportionality between nitrate and ammonium salts in the mineralized nitrogen. The literature draws attention to the more favorable influence of ammonium-nitrogen than nitrate-nitrogen with respect to the development of the Scots pine *Pinus sylvestris* (Łotocki, Żelawski 1973; Uggla and Uggla,1979), as well as other coniferous forest habitats (Brożek 1985). Of the total mineralized nitrogen, nitrates accounted for 24.7% on average and ammonium salts for 75.3% (d = 12.8%)[11]. Bearing in mind the high degree of variability among forms of nitrogen within a given year (Brożek 1985), these results should be treated only as a general indicator of the interrelationships between the nitrate and ammonium forms of nitrogen. The spatial variability in these relationships is characterised by a statistically significant separation into two groups of profiles. The first comprises the soils from Lapland, Finnish Lakelands and the Coast and Eastern Baltic Lakelands. Its distinguishing feature is a larger proportion of ammonium salts among the mineralized nitrogen (85.1%), when compared to the mean values determined for the podzolic soils as a whole. It is also characterised by a marked internal uniformity (d = 4.6%). The second group encompasses the remaining profiles of podzolic soil in the Central European Lowlands. The mean share of ammonium salts within the mineralized nitrogen of these soils is 67.0%. However, the values obtained for this group also differ markedly from one another (d = 11.4%).

In spite of such major differences in the proportions of the different forms of nitrogen, only in the case of $N\text{-}NH_4^+$ content in the epihumus of podzolic soils was there any statistically-significant link with longitude (Fig. 25). The different forms of nitrogen in rusty-podzolic soils relative to longitude and latitude were statistically significant, although the relationship is weak. The content of total nitrogen and of its mineral forms are presented for the epihumus of podzolic soils in Table 18.

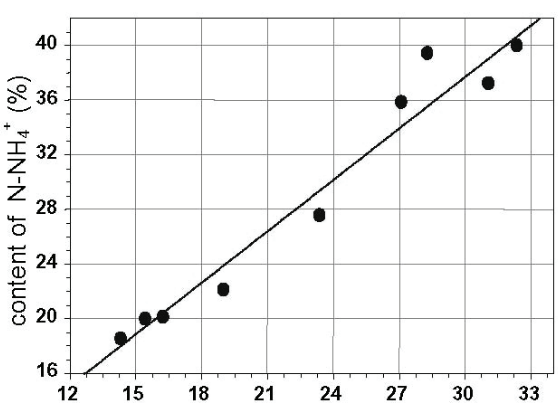
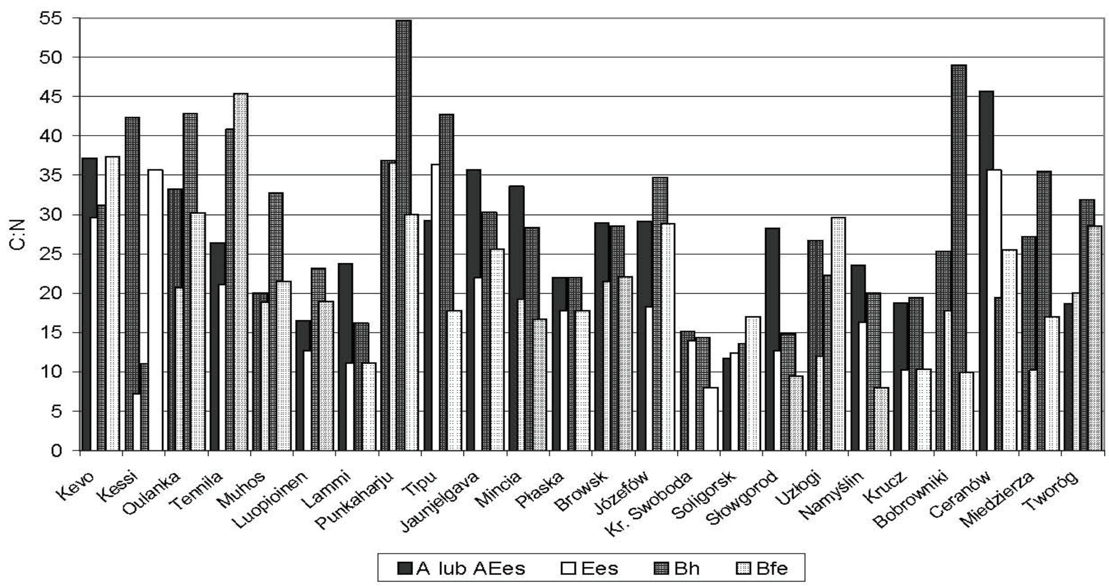


Figure 25. Regression line for the content of $N\text{-}NH_4^+$ in epihumus subhorizon of podzolic soils on longitude. (Y = 0,051 + 1,256x, r = 0,980).

[11] Sampling done in the summer period

The C:N ratio in the different genetic horizons is characterised by great variability (Fig. 26). For podzolics the mean values and standard deviations calculated for different

a



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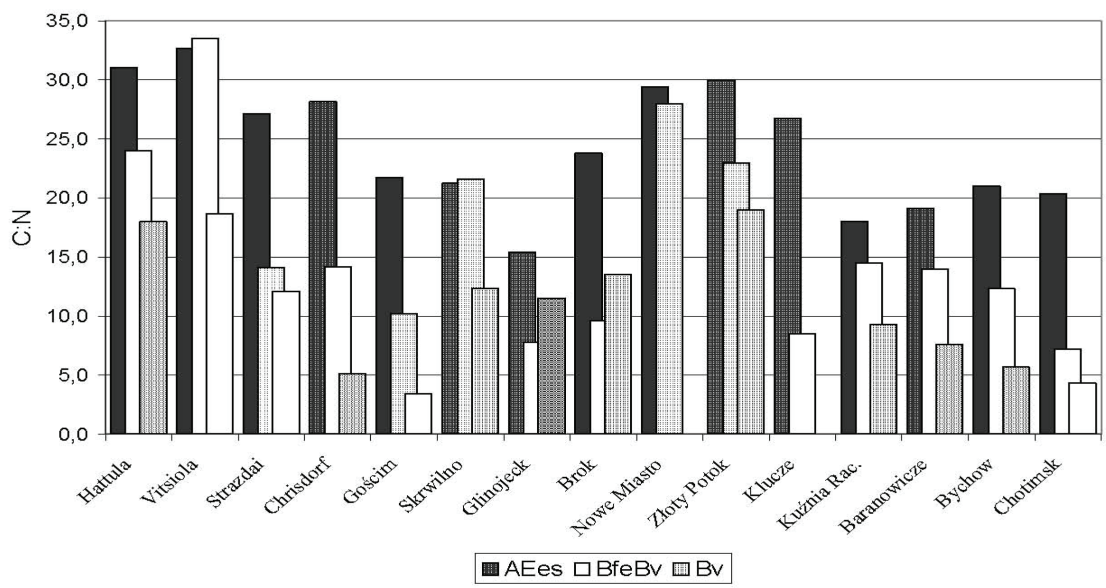


Figure 26. Carbon to nitrogen ratio (C:N) in particular genetic horizons of studied soils (a - podzolic soils, b – podzolic-rusty soils)

horizons were as follows: A – 27.3 (d = 8.5), Ees – 18.9 (d = 8.3), Bh – 28.3 (d = 11.8) and Bfe 21.8 (d = 10.1). In rusty-podzolic soils this ratio had rather lower values, 24.4 (d = 5.3) in the case of the AEes horizon, and in the cases of BfeBv – 16.2 (d = 8.0), BvC – 9.4 (d = 6.3), etc with a decline in values with depth. A majority of the profiles of podzolic soils display a slow mineralisation of organic matter, particularly in the north of the study area. The rusty-podzolic soils of the Central Polish Lowlands have the best bio-ecological properties. The factors influencing the efficiency of ecosystems in this physico-geographical province are a warm and sufficiently humid climate, as well as limited anthropogenic impact (Degórski 1998a). This favors the development of soil micro- and macrofauna, which in this area attain their greatest total biomass (Jefremow and Degórski 1998; Khotko 1998; Olechowicz 1998).

The latitudinal spatial variability in organic carbon to nitrogen ratio is characterised by a statistically-significant relationship for both podzolic and rusty-podzolic soils, while the longitudinal variability is shown to be weak and is confined to podzolic soils. In the former case, the relationship is approximated by a linear regression model, $Y = -29.425 + 1.101x$ ($r = 0.878$) for podzolic soils, and $Y = -45.804 + 247x$ ($r = 0.894$) for rusty-podzolic soils. The slope of the linear regression indicates that C:N ratios are significantly higher as one moves northwards, with all the influence this can be expected to have on soil biological activity.

7.4.3. Fractional composition of humus

As part of the research on soil cover, analysis of the fractional composition of humus showed common features that were either invariable over time or, at most, showing slight temporal change (Duchaufour 1964; Bednarek 1991). At the interface between the epihumus or fermentative organic sub-horizon (O) and the humus horizon (A), the fractional composition of the humus is dominated by light-fraction (F1 + F2) fulvic acids; i.e., free fulvic acids and those associated with R_2O_3 mobile forms. In quantitative terms, these account for between 4 and 18 % of the total content of carbon in the case of podzolic soils and from 4 to 19% of the C in rusty-podzolic soils. The group of humic acids is dominated by the light (H1 + H2) fraction. The difference between the light and heavy fractions is less for rusty-podzolic soils than podzolic soils. In the Silesian-Cracovian Upland there is a prevalence of humic acids of the heavy fraction of extraction 2 and 3. This points to greater polymerization of brown humic acids, leading to the emergence of a certain quantity of humic acids of greater speck, i.e. the so-called grey humic acids which are very important in the processes by which litter becomes mineralised. In comparison with fulvic acid, these are characterised by a greater sorption capacity and more favorable hydrophilous properties (Jefremow and Degórski 1998).

From the palaeopedological point of view, one of the most important features of humus is the ratio of carbon from humic acids - Ch to carbon from fulvic acids – Cf (Bednarek 1991). This ratio provides information on the direction the soil-generating process is taking, as well as the nature of transformations of organic matter and soil age (Skłodowski 1974; Bednarek 1991).

In the zone of contact between the organic horizon and the upper part of the humus horizon in the podzolic soils of Lapland (i.e. the youngest such soils), the ratio assumes the lowest values (0.33-0.36), compared with greatest values in the range 0.61-0.72 in the oldest soils of Eastern Europe. Greater values for the Ch : Cf ratio are linked with a greatrer degree of humification, as expressed in the total share of carbon from fulvic acids, humic acids, and humins as a percentage of the total carbon content. Its value in the soils of northern regions was 8.89-9.60%, cf. 24.47-33.85% in eastern and southern parts of the study area (Table 19). The Ch:Cf ratio, as well as the degree of humification, attest to enrichment of humus in the soils of old-glacial areas. These soils are also observed to have greater shares of non-hydrolising residues of the heavy fraction, i.e. the most durable humus compounds (mainly humins), as well as lower values for carbon in the residuum, something that can also be regarded as a diagnostic geographical soil indicator.

An analogous spatial variability was obtained for rusty-podzolic soils in that their Ch:Cf ratios were much higher – in the range from 0.26-0.30 in Western Baltic Lakelands to 0.92-0.96 in Podlasie-Byelorussian Plateaus, Berezina-Desna Lowland and Silesian-Cracovian Upland. The sub-provinces in Podlasie-Byelorussian Plateaus and Berezina-Desna Lowland were also seen to have the greatest degree of humification of organic matter, reaching 48.9-64.5% (see Appendix C, Table 19,).

The increase in values for the Ch: Cf ratio, as well as the degree of humification, as one moves south and east through the study area is confirmed by the relationships between these features and geographical coordinates. The relevant parameters for the regression functions and correlation coefficients are as presented in Table 20

.

Table 20. Regression parameters and correlation coefficients determined for the relationships between some features of fractional composition of humus in organic and humus horizons of podzolic and rusty-podzolic soils (dependent variable) and longitude or latitude (independent variable).

Soil types	Dependent variable	Independent variable	Parameters to the regression			Correlation coefficient
			a	b	c	r
podzolic	Ch:Cf	longitude	−44.524	5.597	−0.106	0.910
		latitude	1.090	−0.017	9.184	0.384
rusty-podzolic		longitude	−0.231	0.037	–	0.889
		latitude	27.625	_0.950	0.008	0.363
podzolic	degree of humification	longitude	0.362	0.009	–	0.414
		latitude	416.373	−12.371	0.094	0.870
rusty-podzolic		longitude	36.547	−1.992	0.078	0.720
		latitude	207.885	−3.090	–	0.642

All profiles for all soils in this study had values below 1 for the content of carbon in humic acids compared to that of carbon in fulvic acids, thereby corresponding to the type 1 humusclassification from Kononowa (1968), which is characterised by a limited degree of condensation of aromatic rings.

7.4.4. Biological activity

Biological activity plays a major role in the transformation of organic matter and is one of the most important elements to the functioning of the pedosphere (Kononowa 1968; Richards 1979; Puchalski, Prusinkiewicz 1990; Wood 1995; Breemen, *et al.*, 2000). As an ion-exchange substance of considerable sorption capacity, soil humus is of particular significance in the ecosystems developed on the biotopes of light soils otherwise characterised by a very limited sorption complex (Pokojska 1992; Berggren, Mulder 1995).

Microorganisms play a decisive role in the processes by which organic matter is humified and mineralised. The results of research to date show that a good surrogate indicator for the composition and activity of assemblages of microorganisms is the content of nucleic acids, as well as the ratio of the abundance of bacteria together with actinomycetes to that of fungi (Kosinkiewicz 1985; Myśków *et al.*, 1996; Jefremow 1999). On the basis of the microbiological research carried out by Jefremow and Degórski (1998) in 16 soil profiles (of the 39 referred to in this study - located between Western Baltic Lakelands and Berezina-Desna Lowland), differences in the biomass of microorganisms, as well as the contents of nucleic acids, depend in great measure on local habitat conditions and secondly on geographical location. The main microbiological characteristics determined for the 16 soil profiles are similar to those obtained previously for podzolic earths of the Central European Lowland (Jefremow 1998). The RNA/DNA ratio (indicative of the metabolic activity of the microbiological complex - Jefremow 1990) ranged from 0.75 to 0.92 in the organic horizons to 0.58 to 0.68 in the mineral horizons (Jefremow, Degórski 1998). The mass of microorganisms[12] in a 0.5 m layer of soil 1 m^2 ranged between 167g in podzolic soils to433g in rusty-podzolic soils. Nucleic acids ranged from 44 to 122g respectively, of which DNA accounted for 58-60%, and RNA for 40-42%. Within the overall biomass of microorganisms, bacteria accounted for 8-12%, and fungi for 88-92%.The ratio of bacteria to fungi had values of 1:7 and 1:12. The profiles were characterised by considerably shorter lengths of fungal hyphae in the humus horizon than in the organic. The differences were between 2.5-fold and 6-fold. Similar differentiation was obtained in the case of bacterial cells, though the figures were only between 43 and 80% as great. The strong development of fungi within and on the surface of the overlying humus (with its markedly acid reaction) is a natural phenomenon, but one that is not favorable from the point of view of the biological efficiency of ecosystems. Many species of fungi occurring at the sites studied display toxic properties (Smyk 1974; Vare *et al.*, 1996).

The vertical distribution of microorganisms in the profiles is related to the rate of decomposition of organic matter. Work carried out in the profiles located within Poland using cotton strips showed that, irrespective of the season of the year, the most rapid breakdown of cotton occurred at the point of contact between the epihumus sub-horizon and humus horizon (Degórski and Reed 1998).

According to Myśków *et al.* (1996), the metabolic activity of microorganisms is linked with their development. Assuming that the activity in question is manifested in enzyme activity, an indicator of the biological efficiency of soils is lactic dehydrogenase. Significant correlations were obtained for the relationship between the activity of lactic dehydrogenase in the humus horizon of the 16 studied soils and bacterial biomass (r = 0.821) or fungal biomass (r = 0.816). Unlike measuring populations of selected groups of microorganisms, the determination of enzymes is relatively simple, and it is easier to run in a series of analyses (Myśków *et al.* 1996). It was for this reason that the determination of biological activity made use of an analysis of lactic dehydrogenase activity.

[12] The abundance of bacteria, biomass of fungal mycelia, length of hyphae and content of nucleic acids were all determined at the Soil Enzymology Laboratory of the Belarussian Academy of Sciences in Minsk. A precise description of the methods of determination is included in Jefremow and Degórski (1998).

In podzolic soils, the mean amount of formazan indicative of dehydrogenase activity was 0.749 $mg \cdot g^{-1}$ of soil in the organic horizon and 0.865 $mg \cdot g^{-1}$ of soil in the humus horizon. In the rusty-podzolic soils, the respective figures were 0.441 and 1.211 $mg \cdot g^{-1}$. The spatial variability in lactic dehydrogenase activity in rusty-podzolic soils was much more uniform than for podzolic soils. The amounts of formazan obtained for the organic horizons of rusty-podzolic soils differ across an almost-threefold range - from 0.258 $mg \cdot g^{-1}$ of soil in profile 31 to 0.750 $mg \cdot g^{-1}$ of soil in profile 27. There was nearly a 39-fold range observable in podzolic soils, between 0.058 $mg \cdot g^{-1}$ of soil in profile 10 and 2.292 $mg \cdot g^{-1}$ of soil in profile 15. The range of values in the humus horizons of rusty-podzolic soils was nearly 6-fold (between 0.362 $mg \cdot g^{-1}$ in profile 27 and 2.078 $mg \cdot g^{-1}$ in profile 33) compared to a 25-fold range in podzolic soils (from 0.067 $mg \cdot g^{-1}$ of soil in profile 26 to 1.675 $mg \cdot g^{-1}$ in profile 20). In spite of the large differences in lactic dehydrogenase activity between the different soils, and between the fermentative sub-horizon and superficial parts of the humus horizon, the variability displayed may reflect geographically-diversified hygrothermal properties of the climate. As humidity and amplitudes of temperature decline, there is an increase in enzyme activity in the humus horizon, as well as a decline in activity in the fermentative sub-horizon of the organic horizon. The correlation coefficient determined for the relationship between the amplitude in annual temperature and dehydrogenase activity in the O horizon is of $r = -0.588$, cf. $r = 0.639$ for the humus (A) horizon.

Where the podzolic soils were concerned, those in the cool climatic conditions in the north of the study area have greater biological activity in the humus horizon (A). In the areas of central Europe with more moderate winters, it is the fermentative sub-horizon that is more biologically active (Fig. 27 a). In a cold climate, the organic horizon (O) plays the role of thermoregulator of the soil climate (Richards 1979), hence the greatest level of biological activity is concentrated in the upper parts of the humus horizon.

Where rusty-podzolic soils are characterised by the moder type of overlying humus (lacking an epihumus sub-horizon), and hence by a layer of more limited thickness than the mor type of overlying humus in podzolic soils there was a frequent shifting of the whole organic horizon during the growing season. This phenomenon may be the cause of another characteristic of the profiles in Poland - a higher level of lactic dehydrogenase activity in the humus horizon than in the organic horizon (Fig. 27b).

Lactic dehydrogenase is less resistant to exogenous hygrothermal factors than other enzymes (e.g. phosphatase) (Galstyan 1982; Lahdesmakki and Piispanen 1988, 1992). Relatively low correlation coefficients between climatic factors and dehydrogenase activity suggest that the spatial variability is under the direct or indirect impact of many other habitat and pedogenic factors such as the content of humus, occurrence of fungi, thickness of the organic horizon and intensity of podzolization processes. A major role is also played by such anthropogenic factors as type of forestry management pursued now or in the past in the given area (Jefremow, Degórski 1998).

In spite of the impact of a range of pedological and habitat factors, the activity of the dehydrogenase enzyme shows statistically significant spatial differences. These entail a difference in the intensity of lactic dehydrogenase activity in the humus or organic horizons of areas with a cool-temperate or warm-temperate climate. Table 21 presents regression parameters and correlation coefficients determined for formazan; i.e., lactic dehydrogenase activity in the humus or humus-eluvial horizons of podzolic and rusty-podzolic soils from sites of different geographical coordinates.

Table 21. Regression parameters and correlation coefficients determined for relation between dehydrogenase activity in humus horizons of podzolic and rusty-podzolic soils (dependent variable) and longitude or latitude (independent variable).

Soil types	Independent variable	RegressionParameters			Correlation coefficient
		a	b	c	r
podzolic	longitude	–0.659	0.059	–	**0.775**
	latitude	–12.960	0.414	-0.003	**0.749**
rusty-podzolic	longitude	–3.814	0.426	–0.080	**0.856**
	latitude	–0.577	0.042	–	**0.998**

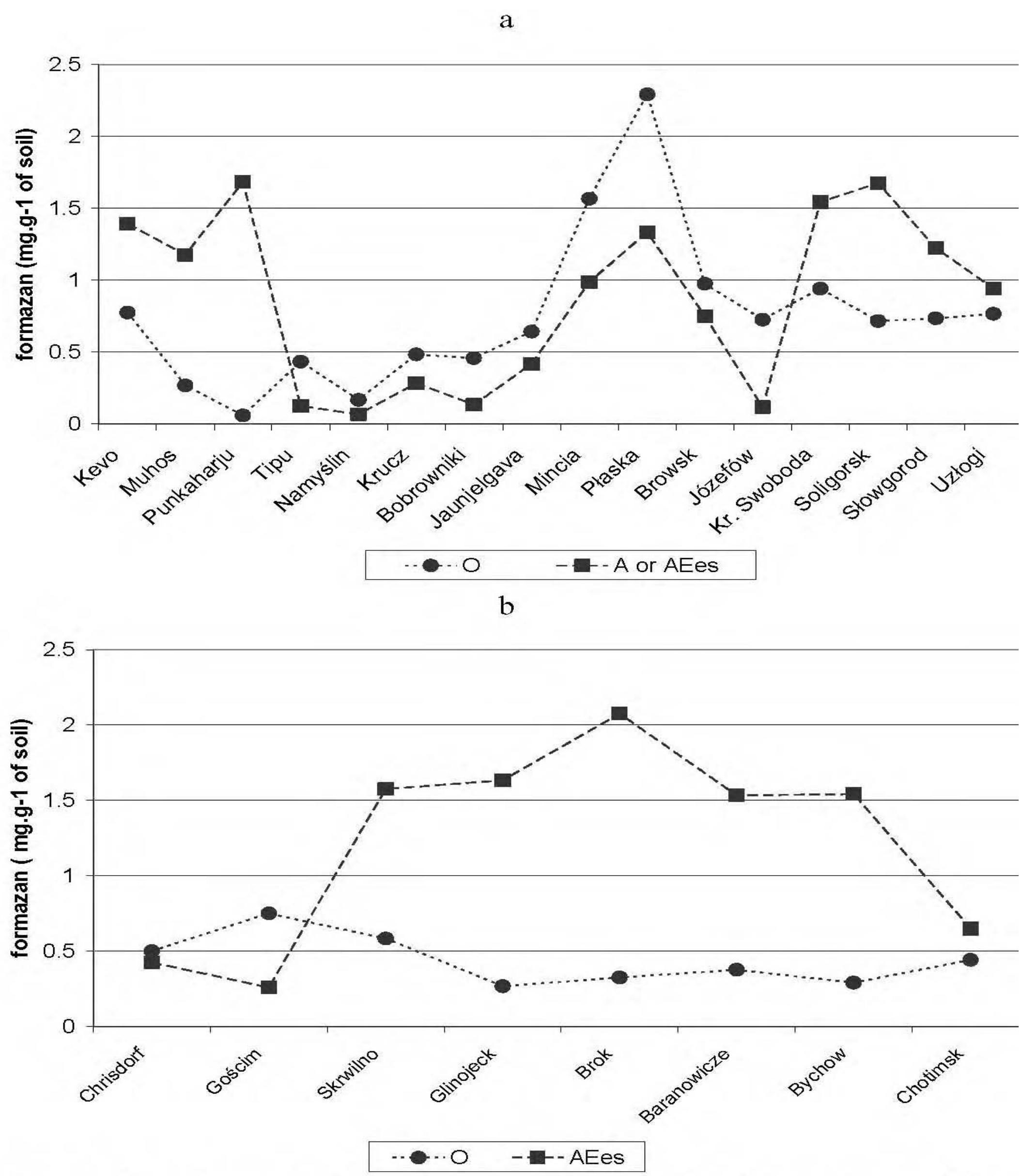


Figure 27. Value of formasan as an indicator of dehydrogenase activity in organic horizon (O) and humus horizon (A) or humus-eluvial horizon (AEes) of studied soils
(a - podzolic soils, b – podzolic-rusty soils),

7.4.5. Reaction

An acid reaction is one of the diagnostic features of podzolic earths. Both the podzolic soils and the rusty-podzolic soils were found to be similar ir their reaction to analogous ones in other regions of the Central European Lowland and Scandinavia. The lowest values for pH_{KCl} or pH_{H20} characterise the organic horizon, in which pH values were 0.1–0.3 units lower than in the A or AE horizons. In the soil solum, values for pH_{KCl} ranged from 3.1 in the humus horizons of podzolic and rusty-podzolic soils to 4.8 – 5.0 in parent rock. The lowest values for pH_{KCl} - noted in the enrichment sub-horizon Bhfe - were even in the range 2.6 – 2.8. Similar trends were obtained for pH_{H20}, except that the index had higher absolute values (Fig. 28)[13].

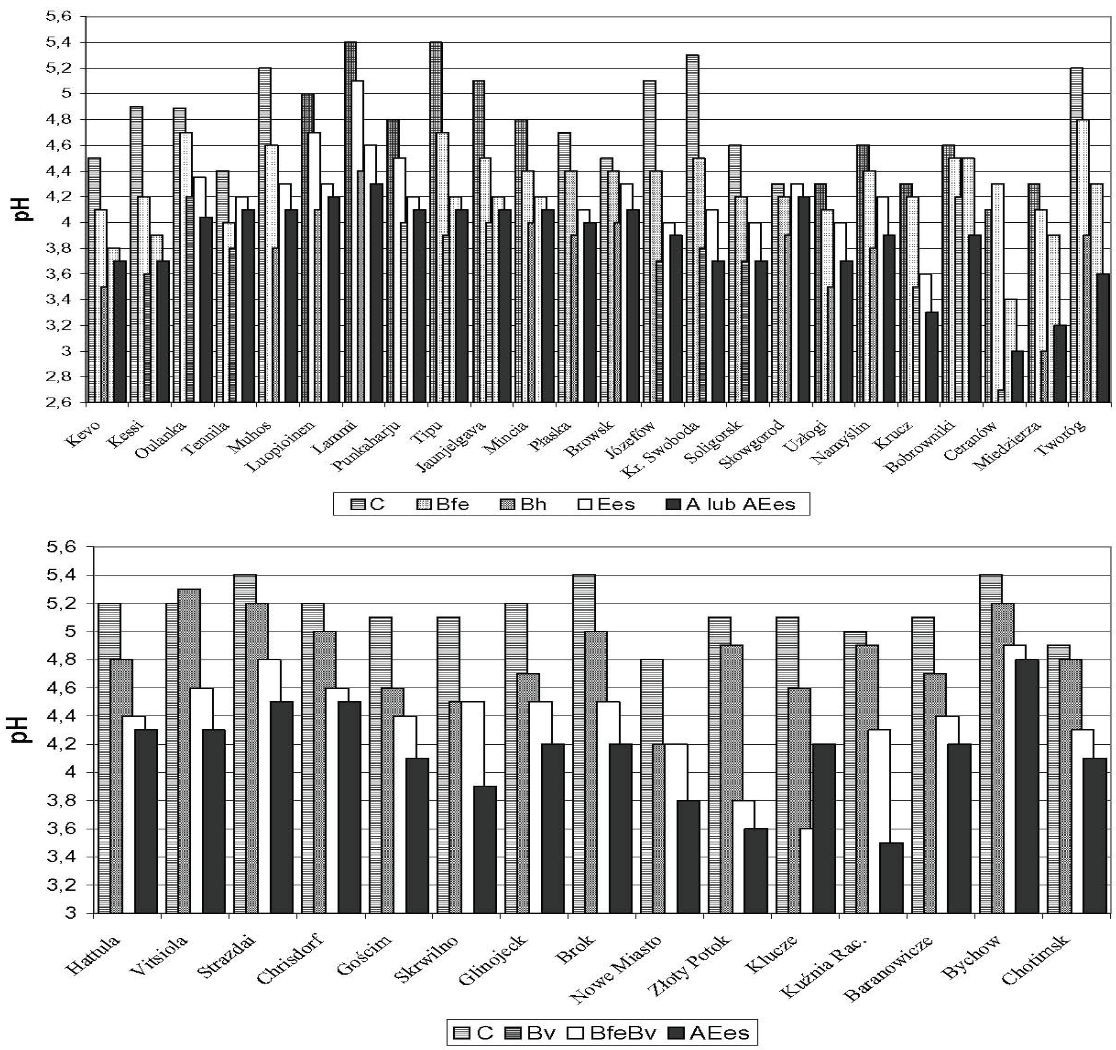


Figure 28. Reaction (pH_{H20}) of particular genetic horizons of studied soils
(a - podzolic soils, b – podzolic-rusty soils)

[13] The pH_{H20} values are the means of 10 measurements made in different seasons over 3 - 5 years.

While the spatial variability in the reactions of both podzolic and rusty-podzolic soils revealed no statistically-significant regional differences, certain tendencies were noted. In the case of podzolic soils, pH values tend to be higher at lower latitudes; i.e., towards Central Europe, irrespective of the genetic horizon being considered (Fig. 28a). In regions of Central Europe, differences in reaction between different profiles depend mainly on local habitat conditioning. The rusty-podzolic soils are characterised by a rather uniform spatial distribution of pH values. The greatest differences between profiles are characteristic of the humus horizon, with profiles assuming increasingly similar reactions at increasing depths below the surface (Fig. 28 b).

The results obtained also support the observations of Tamm and Hallbacken (1988) regarding the different degrees of impact of organic acids on the development of soil reactions in relation to geographical location. Compared with southern parts, northern regions of the study area displayed markedly smaller differences in pH between the humus horizons and parent rock of profiles. This indicates much more limited biological acidification of soils under the influence of the acidophilous vegetation present in regions with a short growing season, as well as the washing-through of humic acids beyond the relatively thin solum layer under the conditions of a wet climate. Soil age is significant. The young soils of northern Europe are still a very active pedogenic environment, in which contemporary soil-creating processes are proceeding very actively. A multiplicity of soil and non-soil factors influencing the development of soil reaction ensure that the spatial differentiation to in pH is only weakly associated with the geographical location of profiles.

Exchangeable acidity mainly reflects the presence of exchangeable aluminium ions, the mean content of which in the humus horizon is 3.1 cmol (+) kg^{-1} (d = 1.4) in the case of podzolic soils and 3.6 cmol (+) kg^{-1} (d = 2.8) for rusty-podzolic soils. The figure for the sub-horizon of enrichment (Bh) of the podzolic soils is 2.8 cmol (+) kg^{-1} (d = 2.5). The average share of Al^{3+} in total exchangeable acidity is 74.4% (d = 19.3) in the humus horizon of podzolic soils, 81% (d = 8.9) in the eluvial horizon and 83.9% (d = 8.7) in the enrichment sub-horizon Bh - Fig. 29. The rusty-podzolic soils were characterised by

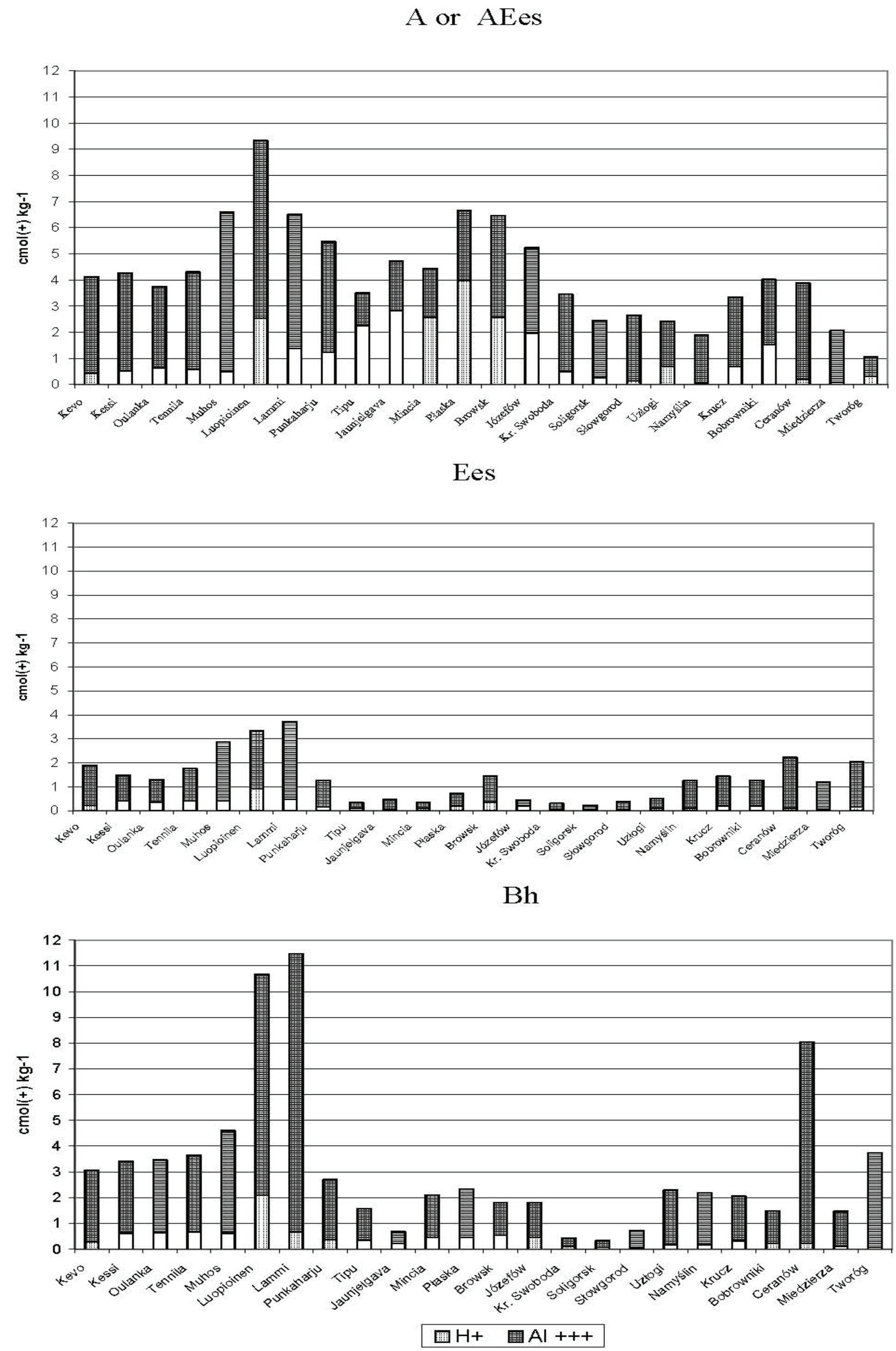


Figure 29. Exchangeable hydrogen (H^+) and exchangeable aluminium (Al^{3+}) as an exchange acidity in some genetic horizons of podzolic soils.

similar values throughout the profile; i.e., 84.7% (d = 16.8) in the humus horizon, 87.6% (d = 16.5) in the BfeBv horizon, and 89.6% (d = 13.5) in the BvC horizon (Fig. 30, below).

The spatial variability in the role aluminium plays in exchangeable acidity is related to the reactions of the different soil profiles. The relationships between contents of the different forms of aluminium (including exchangeable aluminium) and reaction, are known from the literature (Ulrich 1981, 1989; Berggren 1992, 1994; Sullivan 1994). H. Ulrich (1981) among others pointed to the rapid release of Al^{3+} ions where the pH of soils is in the range 3.8-4.2. The elevation of the share of exchangeable activity accounted for by exchangeable aluminium, as noted in profiles at intermediate latitudes, may point to the activity of non-soil-related factors. For example, certain authors attribute the increased content of exchangeable aluminium in the soils of Central Europe to environmental pollution (Filipek 1989, 1994).

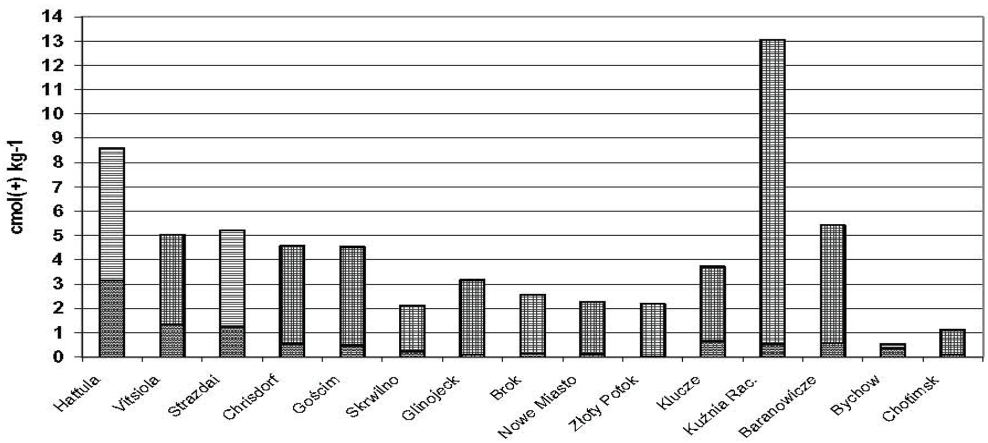
The geographical locations of profiles are statistically significanly different for exchangeable hydrogen, aluminium and acidity.These differences are clearly under the influence of many factors including local conditioning, soil age and the mechanisms and activity of the processes themselves. The regression functions approximating the relationship between each of the features and geographical coordinates emphasise the influence of the above factors (Table 22).

Table 22. Regression parameters and correlation coefficients determined for the relationship between exchangeable hydrogen (H^+), exchangeable aluminium ($Al.^{3+}$) and exchangeable acidity (H_w) in humus horizons of podzolic and rusty-podzolic soils (dependent variable) and longitude or latitude (independent variable).

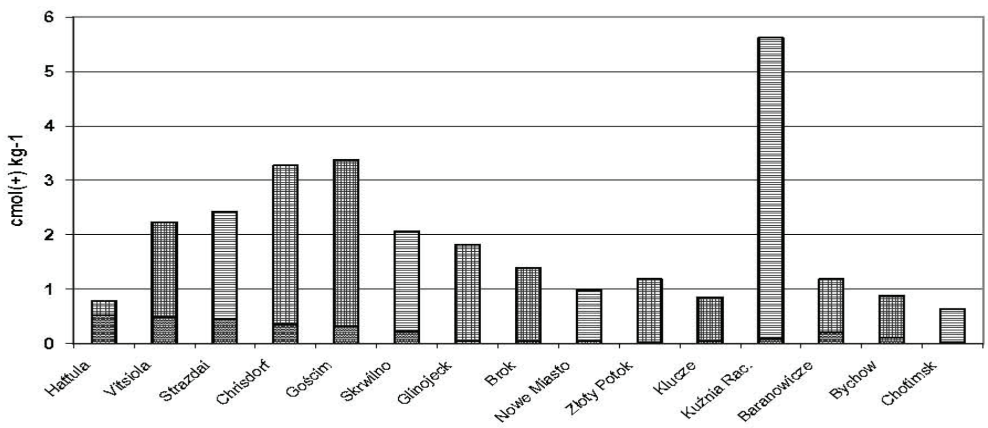
Dependent variable	Independent variable	Regression parameters			Correlation coefficient
		a	b	c	r
H^+	longitude	−6.388	0.676	−0.015	0.601
	latitude	−19.249	0.841	−0.008	0.839
	longitude	1.030	−0.053	0.001	0.536
	latitude	−9.715	0.196	−	0.821
Al^{3+}	longitude	−6.595	0.850	−0.018	0.838
	latitude	25.325	−0.814	0.007	0.419
	longitude	3.339	0.104	−0.006	0.716
	latitude	151.006	−5.246	0.047	0.459
H_w	longitude	−12.280	1.474	−0.032	0.768
	latitude	5.989	0.031	−0001	0.404
	longitude	4.369	0.051	−0.005	0.712
	latitude	151.467	−5.412	0.050	0.754

Figure 30. Exchangeable hydrogen (H^{+}) and exchangeable aluminium (Al^{3+}) as an exchange acidity in some genetic horizons of podzolic-rusty soils.

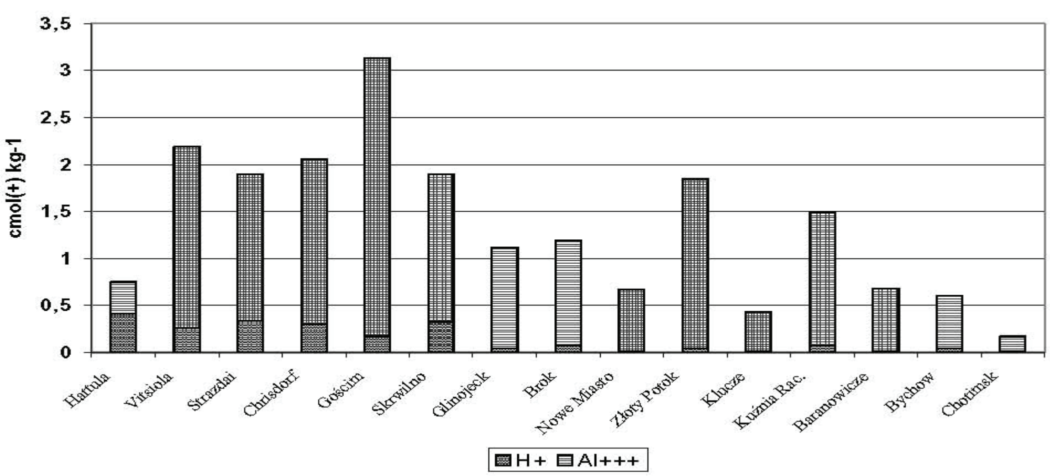
AEes



BfeBv



Bv



Exchangeable hydrogen, aluminium ions and exchangeable acidity show spatial differentiation in different genetic horizons. While absolute values for correlation coefficients are similar, the directions in the variability differ. For example, in the case of the AEes humus horizon of rusty-podzolic soils, the value of the correlation coefficient determined for exchangeable acidity relative to the location of a profile was 0.75. This compares with r = -0.70 for the BfeBv horizon. Note the reverse nature of the variability in these two genetic horizons. In the BfeBv horizon, exchangeable acidity is greater at lower latitudes of podzolic soils (Fig. 30). The humus horizon, however, in lower latitudes are associated with lower contents of exchangeable aluminium and hydrogen ions. For rusty-podzolic soils, spatially-related inter-profile differences observed for exchangeable acidity in the humus horizon may also reflect greater humidity of climate towards the east, as well as more intensive processes of leaching in pedons.

Habitat conditions manifested in features of biotopes in toposequences (*inter alia* moisture conditions, soil reaction, and the abundance and composition of organic matter), are also characterised by statistically-significant linkage with the vertical and spatial differentiation of exchangeable acidity. This indicates that geographical variation in H_w in the analysed soils is dependent on many local habitat factors. For example, greater organic matter content in the humus horizon of podzolic soils can be linked with greater exchangeable acidity in all the studied podzolic soils. The value of the correlation coefficient between content of organic matter and H_w value in all of the studied podzolic soils was 0.53. A still higher value for the correlation coefficient (r = -0.63) was obtained for an aggregated habitat index taking account not only of reaction and the content of organic matter in soils, but also their aerial and water-related properties, thereby confirming the complex nature of the relationship.In contrast, the greatest content of exchangeable aluminium, noted for the profile from Kuźnia Raciborska (profile 39), clearly points to its anthropogenic nature. The profile islocated in an industrialised region of Poland (Silesia) and thus within the zone of strong impact of pollution, which reaches the soil via wet and dry deposition (Degórski 1998d).

In spite of local factors influencing exchangeable acidity, we find a general regularity to the spatial variation regarding this feature. The humus horizons in the northern parts of the study area show higher exchangeable aluminium than those in the south. The reverse situation applies to exchangeable hydrogen ions, which tends to be higher in sites further to the south. Absolute differences in these exchangeable cations reveal different scopes of variability. Aluminium is much more uniform among sites along the N-S axis than are exchangeable hydrogen ions, whose levels grow greater in sites further south thus raising the overall level of exchangeable acidity.

The regression parameters and correlation coefficients for exchangeable acidity, exchangeable aluminium and exchangeable hydrogen ions in the humus horizon as against geographical coordinates are presented in Table 22.

7.4.6. The content of exchangeable base cations and sorption properties

Exchangeable cations in this study and for several tens of other profiles analysed previously from the macroregions of Hamme (Degórski 1994a) and Southern Lapland (Degórski 2001a), provided no basis for the identification of statistically-significant differences across space (See Appendix A). Each of the studied exchangeable cations is characterised by considerable spatial variability, the magnitude of which is linked with local habitat conditioning more than with geographical variability of pedogenic factors. The range of variability of the different exchangeable cations is very wide (Table 24).

Table 24. Mean values (Ca^{2+}_m, Mg^{2+}_m, K^+_m, Na^+_m), extreme values ($Ca^{2+}_{min} – Ca^{2+}_{max}$; $Mg^{2+}_{min} – Mg^{2+}_{max}$; $K^+_{min} – K^+_{max}$; $Na^+_{min} – Na^+_{max}$) and standard deviation (d) of exchangeable cations in each genetic horizons of studied soils.

Genetic horizon	Ca^{2+}			Mg^{2+}			K^+			Na^+		
	Ca^{2+}_m	d	Ca^{2+}_{min} - Ca^{2+}_{max}	Mg^{2+}_m	d	Mg^{2+}_{min} - Mg^{2+}_{max}	K^+_m	d	K^+_{min} - K^+_{max}	Na^+_m	d	Na^+_{min} - Na^+_{max}
	cmol(+).kg-1											
podzolic soils												
AEes	0.62	0.23	0.19 - 1.14	0.17	0.13	0.06 - 0.65	0.25	0.10	0.07 - 0.42	0.17	0.06	0.08 - 0.37
Ees	0.47	0.28	0.08 - 1.23	0.08	0.04	0.05 - 0.21	0.13	0.07	0.02 - 0.29	0.10	0.03	0.03 - 0.16
Bh	0.34	0.17	0.11 - 0.78	0.11	0.07	0.02 - 0.27	0.20	0.12	0.04 - 0.43	0.14	0.03	0.06 - 0.20
Bfe	0.41	0.29	0.11 - 1.09	0.10	0.06	0.03 - 0.25	0.18	0.12	0.03 - 0.40	0.13	0.04	0.03 - 0.20
C	0.37	0.29	0.03 - 1.02	0.09	0.06	0.01 - 0.25	0.16	0.13	0.02 - 0.39	0.12	0.06	0.01 - 0.26
rusty-podzolic soils												
AEes	1.12	0.71	0.29 - 2.83	0.36	0.36	0.11 - 1.34	0.30	0.26	0.07 - 1.11	0.21	0.14	0.08 - 0.68
BfeBv	0.40	0.24	0.12 - 0.89	0.16	0.12	0.05 - 0.44	0.13	0.09	0.02 - 0.31	0.14	0.05	0.07 - 0.27
Bv	0.30	0.15	0.13 - 0.51	0.11	0.06	0.05 - 0.26	0.13	0.13	0.02 - 0.59	0.11	0.03	0.05 - 0.18
BvC	0.28	0.13	0.09 - 0.43	0.07	0.03	0.03 - 0.11	0.05	0.01	0.04 - 0.06	0.07	0.04	0.03 - 0.12
C	0.25	0.19	0.05 - 0.57	0.09	0.03	0.04 - 0.13	0.13	0.12	0.01 - 0.44	0.10	0.06	0.03 - 0.26

The difference (R) between the noted maximum for a given cation (n_{max}) and the minimal (n_{min}), as defined for all the studied soil profiles, shows that in both the podzolic soils and the rusty-podzolic soils, the greatest spatial variability is that characterizing the horizon of parent rock (R = 26.1 and R = 16.8 respectively). In turn, the smallest differences in exchangeable cations were observed in the AEes and Bh horizons of the podzolic soils (R = 6.9 and 8.7 respectively), and in the BvC and Bv horizons of rusty-podzolic soils (R = 3.3 and 5.4 respectively). In contrast, when the R values determined for different cations were compared, the greatest differences in content in podzolic soils relate to exchangeable calcium, followed by potassium, magnesium and sodium (Ca > K > Mg > Na). The order in the rusty-podzolic soils is in turn: K >Na > Ca > Mg.

The vertical distributions of exchangeable base cations in podzolic soils follow different patterns depending on whether these are monovalent or divalent. Within-profile variability for monovalent exchangeable cations is characterised by markedly lower levels in the eluvial horizon, by higher values in the Bh sub-horizon, and then a decline in the deeper mineral horizons. The contents of both exchangeable calcium and magnesium decline with depth in most of the profiles. In the case of rusty-podzolic soils, all the exchangeable base cations are characterised by a steady decline in content with depth (See Appendix A).

The size of the change in content of the different exchangeable base cations between adjacent genetic horizons – as determined on the basis of the index of "loss of content"[14] (Bain *et al.*, 1993) – shows that, in podzolic soils, the sequence for cations from the one showing the greatest variability down through to the least diversified between genetic horizons is: Na>K>Mg>Ca. However, differences in values for the index defined for different cations are not large, and range from 62.5% do 75.5% (Table 25). Analogous results for chronosequences of Scottish podzolic soils were presented by Bain *et al.* (1993) in their work. A rather different ordering of cations in terms of the obtained indices was found for rusty-podzolic soils, in which the greatest "loss" between genetic horizons were noted in the case of exchangeable potassium. Cations may be arranged as follows: K > Na > Ca > Mg. The most even distribution in exchangeable cations is observed for magnesium, probably a result of its limited lability (Olsson and Melkerud 2000).

Table 25. Percentage changeability of the exchangeable cations between neighbor genetic horizons.

Podzolic soils					
cations	AEes/Ees	Bh/Ees	Bh/Bfe	Bfe/C	n_m
Ca^{2+}	99	55	56	40	62.5
Mg^{2+}	129	68	46	38	70.3
K^+	138	65	34	56	73.2
Na^+	119	72	38	73	75.5
Rusty-podzolic soils					
cations	AEes/BfeBv	BfeBv/Bv	Bv?BvC	BvC/C	n_m
Ca^{2+}	291	51	55	45	110.5
Mg^{2+}	145	35	42	30	63.0
K^+	142	52	69	368	157.8
Na^+	55	28	78	324	121.1

Values for the sum of base cations (S) are low in all the analysed soils and resemble base cations in that they decline down the profile to parent rock. In podzolic soils, S in the humus-eluvial horizon (AEes) ranges from 0.46 to 1.84 cmol (+) kg^{-1}. In many profiles, horizon C shows a slight increase. Certain of the soils also manifest an increase in the sum of base cations in sub-horizon Bh. Compared with podzolic soils, rusty-podzolic soils have greater values for the sum of base cations. For example, in the eluvial-humus horizon, these range from 0.46 to 5.97 cmol (+) kg^{-1} (Appendix A).

Similar vertical differentiation is shown by sorption capacity (T). The only difference in this case is a marked increase in its value in the sub-horizon of enrichment, Bh, when compared with adjacent genetic horizons.Frequently the degree of elevation in comparison with the eluvial horizon exceeds 50% (Appendix A).

[14] The index of the loss of content is defined as $[1 - x_a.x_b^{-1}]$, where x_a is the content of the given exchangeable cation in horizon a and x_b the content of the given cation in horizon b.

Of significance when it comes to assessing the functioning of pedons is the proportionality between the content of different cations in the sorption complex. Irrespective of geographical location, the dominant base cations are the divalent ones (Ca^{2+} and Mg^{2+}), and hence those of considerable exchange capacity. Their share of the total for base cations is 85% in podzolic soils and 95% in rusty-podzolic ones (Appendix A). Nonetheless, the sorption complex of the analysed soils is mainly saturated with hydrogen ions, which account for between 70 and 90+% of sorption capacity (Appendix A). The sum of base cations is most often between several and 10+ per cent of all cations in the sorption complex, maximally at or below 40%. Most common are calcium ions (maximally to more than 20%), magnesium (maximally 5%), potassium (to 10+%) and sodium (to 5%). These proportions increase with depth. The degree of saturation of the sorption complex with base cations in the analysed soils is thus very small, confirming the oligotrophic status (Fig. 31).

Also noteworthy is the limited range of proportionality values among cations. First calcium v magnesium followed by calcium v potassium and magnesium v potassium. The results obtained for this confirm earlier observations from Filipek (1990) and Szafranek (2000) relative to the direct proportional influence of active acidity on these relationships. It also confirms the inversely proportional relationship between reaction and the share of exchangeable potassium ions. The best relationship of this kind may be observed in podzolic soils, in which a decline in the pH of soils is associated with a narrowing of the ratios between exchangeable cations and an increase in the content of exchangeable potassium (Appendix A). Research by Reuss and Johnson (1986) shows that a relationship between the reaction of soils and the content of exchangeable cations is ongoing at pH values below 4.2 or above 5.6. In the analysed pedons, the strongest statistical link between pH and the content of exchangeable base cations are those reported in very acid organic, humus and enrichment horizons in podzolic soils – something that may confirm the thesis put forward by the aforementioned authors.

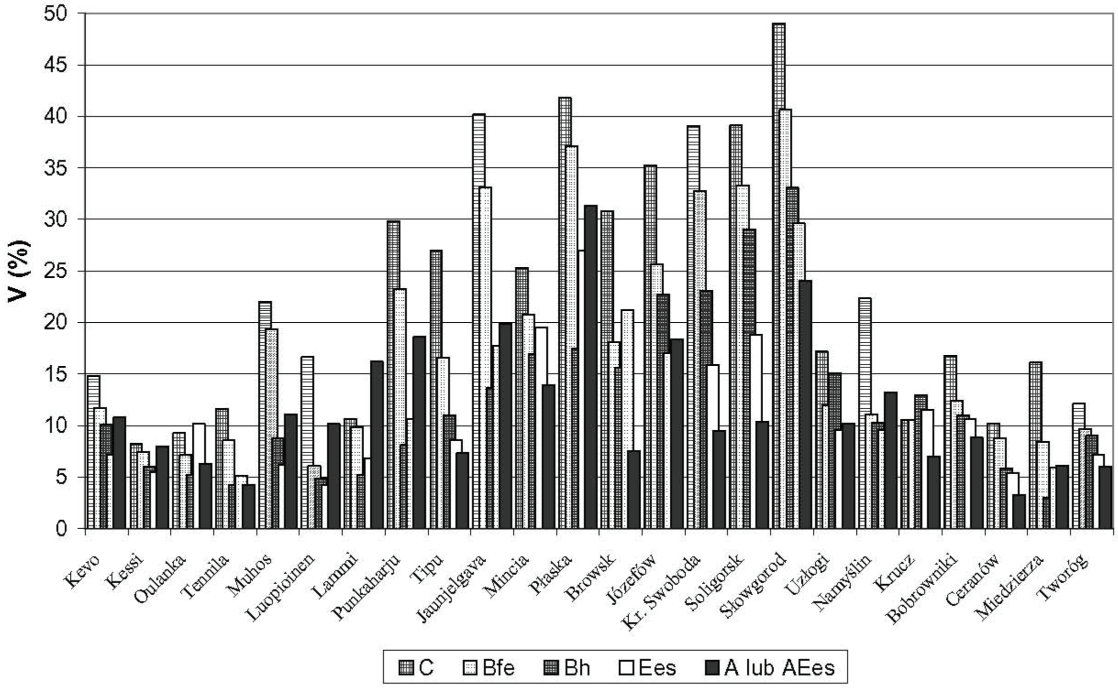
All of the studied soils (both podzolic and rusty-podzolic) are characterised by a low or average level of resistance to external (anthropogenic) factors. In most of the analysed profiles, the mean values for the index of elasticity (after Ulrich *et al.* 1984)[15] determined for the different genetic horizons are lower than 15, thereby qualifying these soils as being of limited stability where exogenous factors are concerned (Degórski 1990). Analysis of the spatial variabilityof the Ulrich index shows that this is the only sorptive characteristic of the

[15] The index of soil elasticity is defined as $\sum Ca^{2+} Mg^{2+} \cdot T^{-1}$ (Ulrich *et al.*,1984)

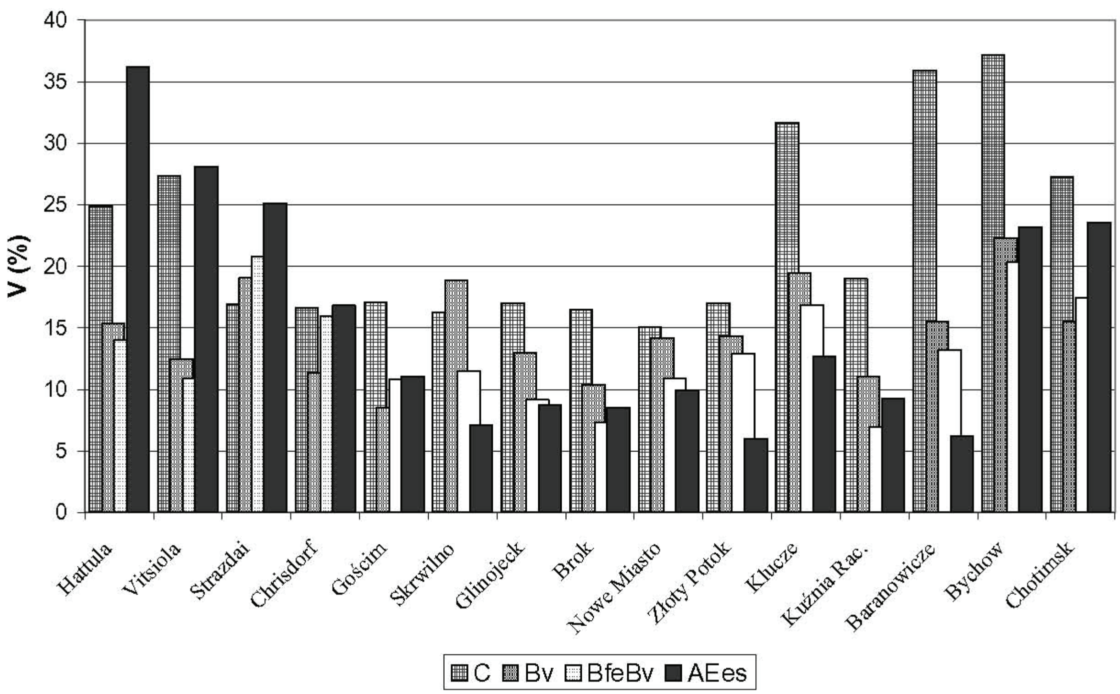
soils to allow for a significant differentiation of the studied profiles into two groups. It was reported that podzolic soils situated in eastern Poland as well as Belarus (profiles 15, 17, 19,

Figure 31. Degree of base saturation (V) particular genetic horizons of studied soils (a - podzolic soils, b – podzolic-rusty soils)

a



b



20 and 22) are characterised by much higher values for this index, - indicative of moderately resistant soils (values of the Ulrich index > 15). In the Bh sub-horizon (the main sorbent is organic matter) of the humus–eluvial horizon, the mean value for the index is 11.8, indicating the lesser resistance of these horizons to external factors (Table 26). In the case of rusty-podzolic soils, all the profiles represent one group - albeit one internally diverse as shown by the wide range of values for the index calculated for different genetic horizons (Table 26).

Table 26. Mean values (Ui_m), extreme values ($Ui_{min} – Ui_{max}$) and standard deviation (d) of Ulrich index determined for genetic horizons of all podzolic and rusty-podzolic soils.

Podzolic soils							Rusty-podzolic soils			
genetic	group I			group II			genetic	all profiles		
horizon	Ui_m	d	Ui_{min} - Ui_{max}	n_m	d	Ui_{min} - Ui_{max}	horizon	Ui_m	d	Ui_{min} - Ui_{max}
AEes	6.3	2.8	2.0 - 13.4	11.8	5.3	5.9 - 18.8	AEes	12.0	6.3	3.8 - 25.3
Ees	7.9	4.1	3.1 - 16.6	21.0	3.7	17.6 - 27.7	BfeBv	9.5	3.6	4.8 - 15.2
Bh	4.8	2.4	1.5 - 8.9	11.8	3.4	9.3 - 17.6	Bv	9.1	3.2	5.1 - 15.7
Bfe	9.0	4.4	3.8 - 20.0	21.5	4.8	13.6 - 28.5	BvC	11.2	4.6	5.9 - 19.6
C	10.6	4.8	5.1 - 21.3	25.2	5.0	18.4 - 33.7	C	14.5	4.3	9.0 - 22.8

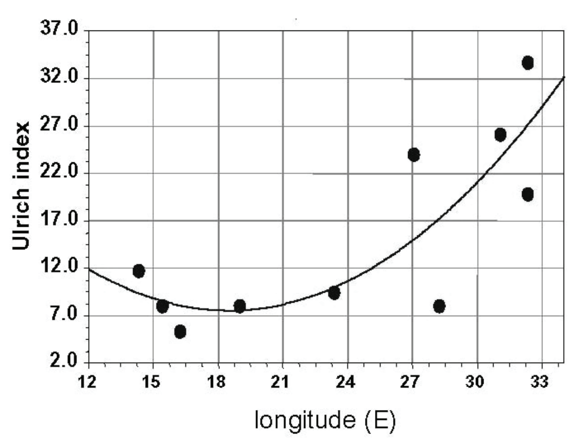
Group I - profiles of podzolic soils (without profiles of group II)
Group II – profiles: 15, 17, 19, 20, 22 (Eastern Poland and Belarus)

Few of the sorption properties show statistically significant linkage with geographical location. Very significant relationships were confined to the degree of saturation of the sorption complexes of rusty-podzolic soils with calcium and hydrogen ions. Latitudinal variability in $V_{Ca}2+$ is manifested by a decrease as one moves south.The relationship is described by the second-order polynomial $Y = -660.34 + 22.784x - 0.192x^2$; r = 0.951), where V_H+ increases markedly in that same direction. The mathematical formula for the regression model regarding the degree of saturation with hydrogen ions in relation to latitude has the form: $Y = 1966.257 – 64.523x + 0.547x^2$, (r = 0.971). Also emerging as significant is the longitudinal variation in the value of the Ulrich index in podzolic soils (Fig. 32).

7.4.7. Forms of iron and aluminium

The role of iron and aluminium as pedogenic elements in the emergence and development of podzolic earths is well-documented. Particularly important in podzolization process are the mutual relationships between the different forms of these elements. While the total content of

Figure 32. Regression curves for the values of Ulrich index in podzolic soils on longitude
$Y = 42,528 – 3,778x + 0,102x^2$, r = 0,819



iron and aluminium in soils results from the resources in the parent rock, it is the content of mobile (non-silicate) forms, as well as crystalline oxides, that determines the course and intensity of the soil-forming process (Fridland 1957; Konecka-Betley 1968; Petersen 1976; Pokojska 1979a; Mokma, Buurman 1982; Bednarek, Pokojska 1996; Melke 1997; Giesler *et al*., 2000; Lundström *et al*., 2000b).

The content of iron characterizing the resource in the habitat (Fe_z)

The amount of iron extracted in 20% HCl is taken by many authors to measure the overall resource of this element in a given habitat (Prusinkiewicz and Kowalkowski 1964; Białousz 1978; Szafranek 1990). It constitutes the reserve of iron that may be liberated steadily in soil from the primary and secondary minerals, as well as decomposing organic matter. In light soils this represents between 90 and 100% of the total content of the element (Gworek 1985; Szafranek 2000), as determined by the solution of samples in hydrofluoric and perchloric acid (Mocek 1988; Melke 1997; Szafranek 2000), or else alloy from Na_2CO_3 (Konecka-Betley 1968; Bednarek 1991). On account of the very poor mineral composition, the weathered parts of soils have iron contained in minerals of undisturbed crystalline structure (undeterminable by the above method) that represent only a tiny fraction (just several per cent) of the overall content of the element. Szafranek (2000) also pointed to the highly significant relationship between the content of iron determined in 20% HCl and the total content of Fe_t in the rusty soils of central Poland, showing that the increase in Fe_t and Fe_z is directly proportional.

The iron content (Fe_z) in podzolic soils ranged from 1.1 to 8.2 $g \cdot kg^{-1}$ in horizon A, and from 3.5 to 6.2 $g \cdot kg^{-1}$ in horizon C. In the rusty-podzolic soils, the range of variability is lower – amounting to between 6.5 and 10 $g \cdot kg^{-1}$ in horizon A, cf. 3 to 6 $g \cdot kg^{-1}$ in parent rock (Table 27). The higher content of iron (Fe_z) in the upper genetic horizons results from the stronger impact of weathering processes on the soil substratum, as well as the accumulation of organic matter. Differences in Fe_z content between the humus horizon and the ones underlying it do not exceed 1 – 2 $g \cdot kg^{-1}$ of soil (Table 27). On the other hand, the fact that Fe_z is greater in the diagnostic spodic horizon compared with the eluvial or parent-rock horizons, emphasises the trend towards the accumulation of iron. This occurs especially in the enrichment sub-horizon Bh, as well as the sub-horizon Bfe in the northern part of the study area. The latter area also features the most marked differentiation in content of Fe_z between the eluvial horizon and the diagnostic spodic horizon, 34-fold in profile 1 and 35-fold in profile 3. Across the European Lowland, these differences are much more limited, normally 2 to 3-fold. In certain profiles, a further factor which might encourage differentiation of contents of this form of iron is the sedimentary lamination of layers of lithological material with diversified Fe_z

Table 27. Content of different forms of iron and aluminum in some soil profiles.

No. of profile	horizon	Al_o	Al_{ac}	Al_p	Fe_z	Fe_d	Fe_{gk}	Fe_o	Fe_{kr}	Fe_{ac}	Fe_p
		g kg^{-1}									
podzolic soils											
1	**AEes**	**0.90**	**0.53**	**0.37**	**1.27**	**0.79**	**0.48**	**0.49**	**0.30**	**0.35**	**0.14**
	Ees	0.58	0.44	0.14	0.37	0.16	0.21	0.12	0.04	0.06	0.06
	Bh	3.98	2.85	1.13	5.45	2.69	2.76	2.12	0.57	1.87	0.25
	Bfe	5.65	3.99	1.66	12.06	6.03	6.03	4.43	1.60	3.79	0.64
	C	1.65	1.34	0.31	3.45	1.68	1.77	0.59	1.09	0.46	0.13
3	**AEes**	**1.46**	**1.16**	**0.30**	**1.10**	**0.68**	**0.42**	**0.47**	**0.21**	**0.21**	**0.26**
	Ees	0.46	0.39	0.07	0.44	0.26	0.18	0.20	0.06	0.09	0.11
	Bh	9.43	5.66	3.77	15.61	7.14	8.47	4.37	2.77	2.77	1.60
	Bfe	3.58	2.75	0.83	6.62	3.57	3.05	2.08	1.49	1.71	0.37
	C	1.35	0.98	0.37	4.60	1.05	3.55	0.59	0.46	0.47	0.12
12	**AEes**	**1.70**	**1.44**	**0.26**	**3.12**	**1.32**	**1.80**	**1.13**	**0.19**	**1.00**	**0.13**
	Ees	0.52	0.30	0.22	1.79	0.78	1.01	0.72	0.06	0.63	0.09
	Bh	3.75	1.03	2.72	8.21	3.88	4.33	1.53	2.35	0.93	0.60
	Bfe	2.54	0.90	1.64	1.57	0.85	0.72	0.28	0.57	0.17	0.11
	C	1.33	0.21	1.12	1.44	0.56	0.88	0.13	0.43	0.05	0.08
15	**AEes**	**1.79**	**1.37**	**0.42**	**5.23**	**2.56**	**2.67**	**1.46**	**1.10**	**0.97**	**0.49**
	Ees	0.93	0.69	0.24	3.40	0.62	2.78	0.26	0.36	0.16	0.10
	Bh	5.14	3.13	2.01	8.53	3.86	4.67	2.24	1.62	0.90	1.34
	Bfe	1.63	1.07	0.56	8.34	2.61	5.73	1.57	1.04	0.69	0.88
	C	0.98	0.75	0.23	3.53	1.24	2.29	0.78	0.46	0.24	0.54
16	**AEes**	**1.62**	**1.33**	**0.29**	**5.34**	**1.32**	**4.02**	**0.96**	**0.36**	**0.62**	**0.34**
	Ees	0.88	0.74	0.14	3.11	0.65	2.46	0.23	0.42	0.14	0.09
	Bh	2.98	1.19	1.79	9.08	2.68	6.40	1.68	1.00	0.45	1.23
	Bfe	1.72	1.17	0.55	4.57	1.97	2.60	1.24	0.73	0.26	0.98
	C	0.72	0.55	0.17	3.40	1.11	2.29	0.56	0.55	0.35	0.21
17	**AEes**	**1.70**	**1.29**	**0.41**	**5.12**	**2.06**	**3.06**	**1.77**	**0.29**	**1.49**	**0.28**
	Ees	0.46	0.31	0.15	2.06	0.33	1.73	0.24	0.09	0.09	0.15
	Bh	2.72	0.72	2.00	9.56	6.15	3.41	1.98	4.53	0.51	1.11
	Bfe	2.54	0.82	1.72	4.28	2.13	2.15	0.65	1.48	0.22	0.43
	C	1.33	0.39	0.94	1.11	0.58	0.53	0.28	0.30	0.07	0.21
24	**AEes**	**0.98**	**0.40**	**0.58**	**8.19**	**3.37**	**4.82**	**1.25**	**2.12**	**0.78**	**0.47**
	Ees	0.72	0.56	0.16	6.78	1.42	5.36	0.34	1.08	0.25	0.09
	Bh	6.78	2.22	4.56	11.97	7.39	4.58	2.96	4.43	0.39	2.57
	Bfe	3.77	0.98	2.79	10.42	6.05	4.37	2.07	3.98	0.99	1.08
	C	1.83	0.93	0.90	6.20	3.56	2.64	0.89	2.67	0.48	0.41
26	**AEes**	**1.89**	**1.51**	**0.38**	**4.31**	**2.34**	**1.97**	**1.45**	**0.89**	**0.93**	**0.52**
	Ees	0.89	0.62	0.27	3.09	1.11	1.98	0.61	0.50	0.56	0.05
	Bh	3.81	1.92	1.89	5.89	2.98	2.91	2.08	0.90	0.81	1.27
	Bfe	1.87	1.29	0.58	5.45	1.98	3.47	1.26	0.72	0.47	0.79
	C	0.89	0.87	0.02	4.18	0.93	3.25	0.34	0.59	0.31	0.03
rusty-podzolic soils											
8	**AEes**	**0.95**	**0.70**	**0.25**	**3.68**	**2.69**	**0.99**	**1.48**	**1.21**	**1.15**	**0.33**
	BfeBv	3.87	3.25	0.62	3.92	3.04	0.88	2.36	0.68	1.81	0.55
	Bv	1.12	0.99	0.13	3.45	1.36	2.09	0.85	0.51	0.76	0.09
	C	0.73	0.71	0.02	4.16	0.99	3.17	0.47	0.52	0.46	0.01
25	**AEes**	**0.69**	**0.42**	**0.27**	**6.52**	**1.56**	**4.96**	**0.98**	**0.58**	**0.64**	**0.34**
	BfeBv	1.56	1.13	0.43	5.60	2.43	3.17	1.66	0.77	1.26	0.40
	Bv	1.21	1.05	0.16	5.27	1.23	4.04	0.35	0.89	0.24	0.11
	C	0.28	0.24	0.04	5.71	0.87	4.84	0.23	0.64	0.20	0.03
31	**AEes**	**0.69**	**0.48**	**0.21**	**7.91**	**1.18**	**6.73**	**0.59**	**0.59**	**0.33**	**0.26**
	BfeBv	2.23	1.73	0.50	7.75	1.53	6.22	0.96	0.57	0.67	0.29
	Bv	1.15	0.85	0.30	6.20	0.97	5.23	0.41	0.56	0.26	0.15
	C	0.28	0.10	0.18	5.39	0.67	4.72	0.33	0.34	0.21	0.12
39	**AEes**	**0.76**	**0.50**	**0.26**	**5.79**	**1.89**	**3.90**	**0.98**	**0.91**	**0.69**	**0.29**
	BfeBv	1.33	0.97	0.36	9.71	2.79	6.92	1.46	1.33	0.95	0.51
	Bv	0.98	0.79	0.19	3.88	1.66	2.22	0.68	0.98	0.51	0.17
	BvC	0.78	0.70	0.08	2.76	0.86	1.90	0.39	0.47	0.36	0.03
	C	0.67	0.66	0.01	2.98	0.71	2.27	0.30	0.41	0.30	0.00
18	**AEes**	**0.54**	**0.35**	**0.19**	**7.78**	**1.76**	**6.02**	**1.06**	**0.70**	**0.81**	**0.25**
	BfeBv	1.46	0.99	0.47	8.52	2.98	5.54	2.08	0.90	2.39	0.59
	Bv	3.46	3.24	0.22	6.83	1.35	5.48	0.73	0.62	0.54	0.19
	BvC	0.92	0.85	0.07	7.09	1.07	6.02	0.35	0.72	0.28	0.07
	C	0.45	0.42	0.03	5.01	0.85	4.16	0.21	0.64	0.20	0.01

Al_o – amorphous forms of aluminium; Al_{ac} - inorganic forms of aluminium (Al_o – Al_p); Al_p – organic forms of aluminium; Fe_z - iron extracted in 20% HCl; Fe_d – free iron; Fe_{gk} – silicate forms of iron (Fe_z – Fe_d); Fe_o – amorphous forms of iron; Fe_{kr} – non-silicate crystalline forms of iron (Fe_d – Fe_o); Fe_{ac} – inorganic forms of iron (Fe_o – Fe_p); Fe_p – organic forms of iron.

content. An example of a manifestation of this is the greater amount of Fe_z in the parent-rock horizon (in profile 25) - Table 27.

In the case of the rusty-podzolic soils, profiles from the Finnish Lakelands area (profile 8), Silesian Lowland (profile 39) and Podlasie-Byelorussian Plateaus (profile 18) are characterised by an increase in the quantities of this form of iron in horizon BfeBv, in comparison with the humus horizon. In the remaining soils, the value for Fe_z declines between the humus horizon and the parent rock (Table 27).

The results obtained make it clear that the lithological material from which podzolic earths are developed is poor in metal sesquioxides, irrespective of geographical location. The low content of metal sesquioxides in podzolic earths of the different regions of Scandinavia and Poland were noted in earlier studies from Jauhiainen (1973), Bednarek (1991), Kowalkowski 1995; Szafranek (1998) and Melkerud *et al.*, (2000), as well as Janowska (2001).

Free iron (Fe_d)

The content of free iron, not in silicate form and not associated with the crystalline lattice of silicates, is indicative of the degree of weathering of primary minerals as well as the advancement of pedogenic processes (Kowalkowski 1968; Mokma and Buurman 1982; Bednarek 1991; Bednarek and Pokojska 1996; Melke 1997). The non-silicate part of soil is its most reactive component, formed from the three main types of linkage between organic substances and metals, of an amorphous nature or through crystalline non-silicate compounds (Melke 1997).

In all of the studied profiles, the greatest absolute contents of free iron were those observed in the spodic horizon of podzolic soils and the sideric horizon of rusty-podzolic soils (Table 27). Similarly, the percentage share of Fe_d in Fe_z is greatest in the diagnostic horizons of these soils (Table 28). In a profile from the Berezina-Desna Lowland area (profile 24), the sub-horizon Bh has a value for the Fe_d/Fe_z that exceeds 60%. Such a large share of this form of iron in Fe_z may be the result of a prolonged process of weathering of mineral material in soil, as well as a long period of accumulation of Fe_d as a consequence of the podzolization process. The profile in question represents the oldest podzolic soil of those studied (Table 28). High shares of Fe_d in Fe_z were also reported in very young soils from Lapland (profiles 1 and 3), where the enrichment horizon has figures in the range 46 to 54%. Such high proportions for the free form of iron within Fe_z and in young sedimented material may reflect very intensive cryogenic weathering of both a physical and chemical nature.of the parent rock -

found to be richest in aluminosilicates when compared with the substrata of the other studied soils. Below the diagnostic horizons, the contents of free iron and percentage share of Fe_d within Fe_z decline with depth. The parent rock of podzolic and rusty-podzolic soils has an absolute content of this form of iron of ca. 1 $g.kg^{-1}$ (Table 27), while the share of Fe_d in Fe_z is now at just 10-20% (Table 28).

Amorphous forms of iron (Fe_o) and aluminium (Al_o)

Amorphous or so-called weakly-ordered structures of iron and aluminium oxides extracted in oxalate reagent define the freshly lost oxides of these elements (Tamm 1922, 1932; McKeague *et al.*, 1971; Mokma and Buurman 1982; Bednarek 1991; Bednarek and Pokojska 1996; Melke 1997; Gustafsson *et al.*, 1998; Lundström *et al.*, 2000b; Hess *et al.*, 2000). As in the case of free iron, the greatest contents of Fe_o and Al_o, as well as percentage shares of Fe_o in Fe_z are characteristic of the Bh sub-horizons in all of the studied of podzolic soils, as well as the BfeBv horizons of the rusty-podzolic soils (Table 27). The soils reporting the greatest contents of amorphous forms of iron and aluminium are situated in the areas of occurrence of the youngest pedons, namely Lapland (profiles 1 and 3), the Finnish Lakelands (profile 8) and the Western Baltic Lakelands (profile 25). These are also characterised by the greatest shares for Fe_o in Fe_z (up to 45%). Such percentages fall in older soils (like profiles 18 and 24) to ca. 20-25% (Table 28).

Freshly-lost iron oxides, most often formless or weakly-crystalline, experience a gradual ageing process entailing dehydration and crystallisation (Bednarek and Pokojska 1996). One of the ways of assessing the state of advancement of these processes is via the index of activity after Schwertmann (1964), which defines the interrelationship between the most reactive, amorphous forms of iron (Fe_o), and the amorphous and crystalline non-silicate forms thereof (Fe_d). A higher value for the Fe_o/Fe_d ratio points to a lower degree of crystallization or iron compounds and greater activity of iron in the soil-formation process.

In the A horizons, the values for the Schwertmann index range from 0.4 to 0.7 in podzolic soils (other than profiles 1 and 3). The value is then lower in the eluvial horizons, but higher once more in the enrichment horizon (at up to 0.8). This confirms the hindered nature of the crystallisation process under conditions of an enhanced content of organic matter in the Bh enrichment sub-horizon. A very high Fe_o/Fe_d ratio is typical for the diagnostic spodic horizon of podzolic soils, the value often exceeding 0.6 (Schwertmann 1964; Blume and Schwertmann 1969; Pokojska 1976, 1979a). The value is lower in three profiles of the analysed soils.

Table 28. Relationship between different forms of iron and aluminium in some soil profiles.

No. of profile	Horizon	Percentage content								Fe_p/Fe_d	Fe_o/Fe_d	$C_p+Al_p+Fe_p$	C_p/Al_p+Fe_p	$Al_o+1/2F_o$
		Fe_d/Fez	Fe_{gk}/Fe_z	Fe_o/Fe_z	Fe_{kr}/Fez	Fe_{ac}/Fe_z	Fe_p/Fe_z	Fe_p/Fe_o	Al_p/Al_o			%		%
podzolic soils														
1	**AEes**	**62.2**	**37.8**	**38.6**	**23.6**	**27.6**	**11.0**	**28.6**	**41.1**	**0.18**	**0.62**	**1.27**	**62.7**	**0.11**
	Ees	43.2	56.8	32.4	10.8	16.2	16.2	50.0	24.1	0.38	0.75	0.43	55.0	0.06
	Bh	49.4	50.6	38.9	10.5	34.3	4.6	11.8	28.4	0.09	0.79	1.45	23.7	0.50
	Bfe	50.0	50.0	36.7	13.3	31.4	5.3	14.4	29.4	0.11	0.73	0.85	7.0	0.79
	C	48.7	51.3	17.1	31.6	13.3	3.8	22.0	18.8	0.08	0.35	0.08	2.2	0.19
3	**AEes**	**61.8**	**38.2**	**42.7**	**19.1**	**19.1**	**23.6**	**55.3**	**20.5**	**0.38**	**0.69**	**1.61**	**82.2**	**0.17**
	Ees	59.1	40.9	45.5	13.6	20.5	25.0	55.0	15.2	0.42	0.77	0.59	103.6	0.06
	Bh	45.7	54.3	28.0	17.7	17.7	10.2	36.6	40.0	0.22	0.61	2.38	9.1	1.16
	Bfe	53.9	46.1	31.4	22.5	25.8	5.6	17.8	23.2	0.10	0.58	0.44	7.1	0.46
	C	22.8	77.2	12.8	10.0	10.2	2.6	20.3	27.4	0.11	0.56	0.11	3.0	0.16
12	**AEes**	**42.3**	**57.7**	**36.2**	**6.1**	**32.1**	**4.2**	**11.5**	**15.3**	**0.10**	**0.86**	**1.02**	**68.0**	**0.23**
	Ees	43.6	56.4	40.2	3.4	35.2	5.0	12.5	42.3	0.12	0.92	0.39	30.9	0.09
	Bh	47.3	52.7	18.6	28.6	11.3	7.3	39.2	72.5	0.15	0.39	1.76	10.7	0.45
	Bfe	54.1	45.9	17.8	36.3	10.8	7.0	39.3	64.6	0.13	0.33	0.47	3.9	0.27
	C	38.9	61.1	9.0	29.9	3.5	5.6	61.5	84.2	0.14	0.23	0.24	2.4	0.14
15	**AEes**	**48.9**	**51.1**	**27.9**	**21.0**	**18.6**	**9.3**	**33.4**	**23.5**	**0.19**	**0.57**	**1.04**	**32.4**	**0.25**
	Ees	18.2	81.8	7.6	10.6	4.7	2.9	38.5	25.8	0.16	0.42	0.47	29.0	0.11
	Bh	45.3	54.7	26.3	19.0	10.6	15.7	59.8	39.1	0.35	0.58	1.23	7.6	0.63
	Bfe	31.3	68.7	18.8	12.5	8.3	10.5	55.9	34.4	0.34	0.60	0.42	6.4	0.24
	C	35.1	64.9	22.1	13.0	6.8	15.3	69.2	23.5	0.44	0.63	0.13	2.3	0.14
16	**AEes**	**24.7**	**75.3**	**18.0**	**6.7**	**11.6**	**6.4**	**35.4**	**17.9**	**0.26**	**0.73**	**0.78**	**35.5**	**0.21**
	Ees	20.9	79.1	7.4	13.5	4.5	2.9	39.1	15.9	0.14	0.35	0.35	40.2	0.10
	Bh	29.5	70.5	18.5	11.0	5.0	13.5	73.2	59.9	0.46	0.63	1.00	6.6	0.38
	Bfe	43.1	56.9	27.1	16.0	5.7	21.4	79.0	32.0	0.50	0.63	0.36	4.4	0.23
	C	32.6	67.4	16.5	16.2	10.3	6.2	37.5	23.6	0.19	0.50	0.08	3.7	0.10
17	**AEes**	**40.2**	**59.8**	**34.6**	**5.7**	**29.1**	**5.5**	**15.8**	**24.1**	**0.14**	**0.86**	**1.30**	**50.8**	**0.26**
	Ees	16.0	84.0	11.7	4.4	4.4	7.3	62.5	32.6	0.45	0.73	0.71	68.3	0.06
	Bh	64.3	35.7	16.9	47.4	5.3	11.6	68.5	73.5	0.18	0.32	1.13	7.2	0.35
	Bfe	49.8	50.2	15.2	34.6	5.1	10.0	66.2	67.7	0.20	0.31	0.93	8.4	0.29
	C	52.3	47.7	25.2	27.0	6.3	18.9	75.0	70.7	0.36	0.48	0.16	0.9	0.15
24	**AEes**	**41.1**	**58.9**	**15.3**	**25.9**	**9.5**	**5.7**	**37.6**	**59.2**	**0.14**	**0.37**	**1.44**	**37.0**	**0.16**
	Ees	21.0	79.0	5.0	15.9	3.7	1.3	26.5	22.2	0.06	0.24	0.34	34.7	0.09
	Bh	61.7	38.3	24.7	37.0	3.3	21.5	86.8	67.3	0.35	0.40	2.62	7.4	0.83
	Bfe	58.1	41.9	19.9	38.2	9.5	10.4	52.2	74.0	0.18	0.34	0.90	3.5	0.48
	C	57.5	42.5	14.4	43.1	7.7	6.6	46.1	49.2	0.12	0.25	0.22	1.8	0.23
26	**AEes**	**54.3**	**45.7**	**33.7**	**20.7**	**21.6**	**12.1**	**35.9**	**20.1**	**0.22**	**0.62**	**1.02**	**33.2**	**0.26**
	Ees	36.0	64.0	19.8	16.2	18.2	1.6	8.2	30.3	0.05	0.55	0.49	35.2	0.12
	Bh	50.6	49.4	35.3	15.3	13.7	21.6	61.1	49.6	0.43	0.70	1.22	8.2	0.49
	Bfe	36.4	63.6	23.1	13.2	8.6	14.5	62.7	31.0	0.40	0.64	0.33	4.4	0.25
	C	22.2	77.8	8.1	14.1	7.4	0.7	8.8	2.2	0.03	0.37	0.01	1.3	0.11
rusty-podzolic soils														
8	**AEes**	**73.0**	**27.0**	**40.2**	**32.9**	**31.2**	**9.0**	**22.3**	**26.3**	**0.12**	**0.55**	**0.57**	**29.4**	**0.17**
	BfeBv	77.6	22.4	60.2	17.3	46.2	14.0	23.3	16.0	0.18	0.78	0.53	10.7	0.51
	Bv	39.4	60.6	24.6	14.8	22.0	2.6	10.6	11.6	0.07	0.63	0.15	13.7	0.15
	C	23.8	76.2	11.3	12.5	11.1	0.2	2.1	2.7	0.01	0.47	0.02	4.6	0.10
25	**AEes**	**23.9**	**76.1**	**15.0**	**8.9**	**9.8**	**5.2**	**34.7**	**39.1**	**0.22**	**0.63**	**0.46**	**25.0**	**0.12**
	BfeBv	43.4	56.6	29.6	13.7	22.5	7.1	24.1	27.6	0.16	0.68	0.41	11.8	0.24
	Bv	23.4	76.6	6.5	16.8	4.5	2.1	31.9	13.2	0.09	0.28	0.14	22.8	0.14
	C	15.2	84.8	4.0	11.2	3.5	0.5	13.0	14.3	0.03	0.26	0.03	20.9	0.04
31	**AEes**	**14.9**	**85.1**	**7.5**	**7.5**	**4.2**	**3.3**	**44.1**	**30.4**	**0.22**	**0.50**	**0.43**	**25.9**	**0.10**
	BfeBv	19.8	80.2	12.4	7.4	8.7	3.7	30.2	22.4	0.19	0.63	0.27	6.8	0.27
	Bv	15.7	84.3	6.6	9.0	4.2	2.4	36.6	26.1	0.15	0.42	0.12	4.3	0.14
	C	12.4	87.6	6.1	6.3	3.9	2.2	36.4	64.3	0.18	0.49	0.06	2.9	0.04
39	**AEes**	**32.6**	**67.4**	**16.9**	**15.7**	**11.9**	**5.0**	**29.6**	**34.2**	**0.15**	**0.52**	**0.47**	**34.7**	**0.13**
	BfeBv	28.7	71.3	15.0	13.7	9.8	5.3	34.9	27.1	0.18	0.52	0.45	16.7	0.21
	Bv	42.8	57.2	17.5	25.3	13.1	4.4	25.0	19.4	0.10	0.41	0.25	15.6	0.13
	BvC	31.2	68.8	14.1	17.0	13.0	1.1	7.7	10.3	0.03	0.45	0.07	11.6	0.10
	C	23.8	76.2	10.1	13.8	10.1	0.0	0.0	1.5	0.00	0.42	0.01	2.2	0.08
18	**AEes**	**22.6**	**77.4**	**13.6**	**9.0**	**10.4**	**3.2**	**23.6**	**35.2**	**0.14**	**0.60**	**0.53**	**45.0**	**0.11**
	BfeBv	35.0	65.0	24.4	10.6	28.1	6.9	28.4	32.2	0.20	0.70	0.44	13.3	0.25
	Bv	19.8	80.2	10.7	9.1	7.9	2.8	26.0	6.4	0.14	0.54	0.17	16.2	0.38
	BvC	15.1	84.9	4.9	10.2	4.0	1.0	20.0	7.6	0.07	0.33	0.07	17.6	0.11
	C	17.0	83.0	4.2	12.8	4.0	0.2	4.8	6.7	0.01	0.25	0.03	11.6	0.06

The soils involved are among the oldest – in Berezina-Desna Lowland (profile 24) and the Sandomierz Basin (profile 17), as well as in the profile from the Courland Plain (profile 12) – Table 28. In rusty-podzolic soils, the greatest values for the Schwertmann index (in the range 0.5 to 0.8) characterise the horizons of enrichment, being above the values noted for the humus-eluvial horizon (which range from 0.5 to 0.6) - Table 28.

Organic forms of iron (Fe_p) and aluminium (Al_p)

Iron-aluminium-humus complexes are subject to transfer down the profiles of podzolic earths, and exert a direct influence on the sequences of genetic horizons, as well as their properties (Alexandrowa 1960; McKeague 1967; Mokma and Buurman 1982; Bednarek 1991; Bednarek and Pokojska 1996; Szafranek 1998; Mokma and Szafranek 2001). In all the studied podzolic soils, the greatest vaues for forms of iron and aluminium extractable in sodium pyrophosphate (Fe_p and Al_p) are characteristic of the spodic horizons - or the sideric horizons in the case of rusty-podzolic soils (Table 27). Most of the enrichment horizons have Al_p prevailing over Fe_p (in Bh) with the exception of the Bfe horizon where Fe_p dominates over Al_p. This is particularly true of profiles located on the Polish lowlands. In the case of rusty-podzolic soils, the greatest contents of Fe_p and Al_p always occur in the BfeBv horizon. In younger soils, the horizon of enrichment has a dominance of the Al_p form of aluminium (in profiles 8 and 25), while in older profiles it is the Fe_p form of iron (profiles 18 and 39).

Organic forms of iron account for 30-40% of Fe_o in the humus horizons of podzolic soils, as opposed to values as high as 80% in the enrichment horizons (profile 16). In the case of rusty-podzolic soils, the humus-eluvial horizon has Fe_p proportions of 30-40% Fe_o, cf. 24 – 34% in the enrichment horizon (Table 28).

When compared to the overall content of iron (Fe_z - as extracted in 20% HCl), the organic forms of the element account for between several per cent in the humus horizon of podzolic soils to more than 20 % in the Bh sub-horizon (Table 28). Below the spodic horizon, the proportion falls to 1-5% in the parent-rock horizon. While the soils from Lapland showed the greatest proportions of Fe_p in Fe_z in the eluvial horizon, the profiles from elsewhere had the greatest figures in their enrichment horizons. Such a differentiation may result from the impact of two factors. On the one hand, the very limited thickness of horizons and intense cryogenic weathering may affect the liberation of iron, while on the other, the very low pH may limit the rapid transfer through the profile of iron and aluminium in organic complexes. According to Sapek (1971), a highly acid soil reaction favors coagulation linkage between humus compounds and the metals.

Inorganic forms of iron (Fe_{ac}) and aluminium (Al_{ac})

The content of inorganic iron and aluminium reflect the differences between the amorphous content of organically-bound iron and aluminium (o), and the organic forms of these elements (p) and is a derivative of the oxalate and pyrophosphate forms.The forms of iron deriving from the difference between Fe_o and Fe_p are termed inorganic and non-crystalline iron (Bascomb 1968; McKeague *et al.*, 1971; Mocek 1988; Melke 1997). Their presence in the soil is important because of their high affinity for other organic and inorganic chemical compounds (mainly phosphates and silicates).

As in the case of inorganic iron, the difference between Al_o and Al_p is considered to be the content of inorganic aluminium Al_{ac}. In recent years, ever more attention has been paid to the different forms of aluminium in podzolic soils, and most especially to the inorganic forms. The interest results from a different way of looking at the process of podzolization. Certain soil-scientists (mainly Scandinavian) link the transfer through the profile of sols of aluminium with silicon (as proto-imogolite), while others link the transfer with the creation of soluble Fe-Al complexes (Farmer *et al.*, 1980; Farmer and Fraser 1982; Lumsdon and Farmer 1995; Gustafsson *et al.*, 1995, 1998, 1999; Lundström *et al.*, 2000b).

The variability in inorganic forms of iron and aluminium resembles the distribution of organic and amorphous forms. In podzolic soils, an elevation of their contents takes place in the diagnostic spodic horizon, while in the rusty-podzolic soils this occurs in the sideric horizon (Table 27). The greatest differences in contents of inorganic forms of iron and aluminium between the E and B_h horizons were those reported in the youngest soils in Lapland (profiles 1 and 3). These differences tend to become progressively smaller in older and older soils. Likewise, the greatest absolute contents of Fe_{ac} and the greatest shares of inorganic forms within total iron were reported in the soils from Lapland (profiles 1 and 3) - Table 28.

Silicate forms of iron (Fe_{gk})

The content of silicate forms of iron in the soil is calculated as the difference between the total content of the element, $Fe_{t,}$ and the content of free iron, Fe_d. The determination of this content in soils may be helpful in an assessment of the degree of weathering of material and the age of soils (Mokma and Buurman 1982; Mocek 1988; Bednarek and Pokojska 1996). Since the content of iron is limited to that extractable in 20% HCl (Fe_z) – the values of which are several percent lower than the true total Fe content in soils (Gworek 1985; Szafranek

2000), the results obtained for silicate forms of iron should only be treated as indicative of trends and spatial variability of Fe_{gk}.

In both podzolic and rusty-podzolic soils, the content of silicate forms of iron decrease down the profile, reaching lowest values in the parent-rock horizon. This is in line with the differentiated impact of processes of weathering on the different genetic horizons (Table 27). Data from other literature show that silicate forms of iron following weathering of the parent material do not move through a profile (Karltun *et al.*, 2000; Szafranek 2000).

The distribution of Fe_{gk} iron in profiles is the reverse of that of forms of free iron (Fe_d). This is best seen in the soils of old-glacial areas, in which the share of free iron is twice as high as that of silicate iron. The proportions in young-glacial areas are comparable.

Analysis of the spatial variation in values for Fe_{gk} shows that there is more of this form of iron in the youngest soils of Lapland (profiles 1 and 3), as well as Western Baltic Lakelands and Southern Baltic Lakelands (profiles 25 and 26), areas whose lithological material has greatest amounts of aluminosilicates (e.g. feldspars), or silicates (e.g. amphiboles) in its mineral composition. These regions are also characterised by considerable climatic humidity which accelerates processes by which primary geological material is weathered.

Non-silicate crystalline forms of iron (Fe_{kr})

Among the iron compounds in soil not associated with silicates, some are present in crystalline form (Mokma and Buurman 1982; Melke 1997; Kartlun *et al.* 2000). The non-silicate, crystalline form of iron is determined as the difference between the content of free iron (Fe_d) and that of amorphous and organic iron (Fe_o).

It is in the oldest soils that the share of total iron that is in crystalline form assumes its greatest values (in excess of 20% in profiles 24 and 39) - Table 28. The greater content of Fe_{kr} and greater share taken by this in Fe_z that characterise old-glacial areas may confirm earlier views of other authors concerning the role of the time factor relative to the course of the crystallization of iron in podzolic soils (Bednarek and Pokojska 1996). Apart from the age of soils as such, other influences on the content of crystalline forms of iron are exerted by climate and other factors that hinder crystallization including a high proportion of humus, phosphate ions, and silicates (Bednarek and Pokojska 1996). This may be explained by a large resource of Fe_{kr} in the parent-rock horizons of the analysed soil, especially in the northernmost profiles of limited thickness. Here the content of this form of iron in the C horizon amounts to more than 1 $g \cdot kg^{-1}$.

The most limited degree of crystallization of oxides of Fe, and greatest activity of this element in the processes shaping both podzolic and rusty-podzolic soils, are most characteristic of the humus horizons followed by the eluvial horizons of podzolic soils. Below these, in the diagnostic spodic horizons (of podzolic soils) or sideric horizons (of rusty-podzolic soils other than profiles 8 and 31) there is a greater portion of crystalline forms of iron (Table 27). While a greater content of organic matter in the Bh enrichment sub-horizon hinders crystallisation, the cumulation of this form of iron nevertheless does occur. Nevertheless, in almost all the spodic and sideric horizons, it is still the active forms of amorphous Fe that dominate. Exceptions are the oldest soils (profiles 17 and 24), which also show the greatest differences in content of Fe_{kr} between the humus and eluvial-humus horizons and the Bh enrichment sub-horizon.

7.4.8. Total and plant-accessible phosphorus

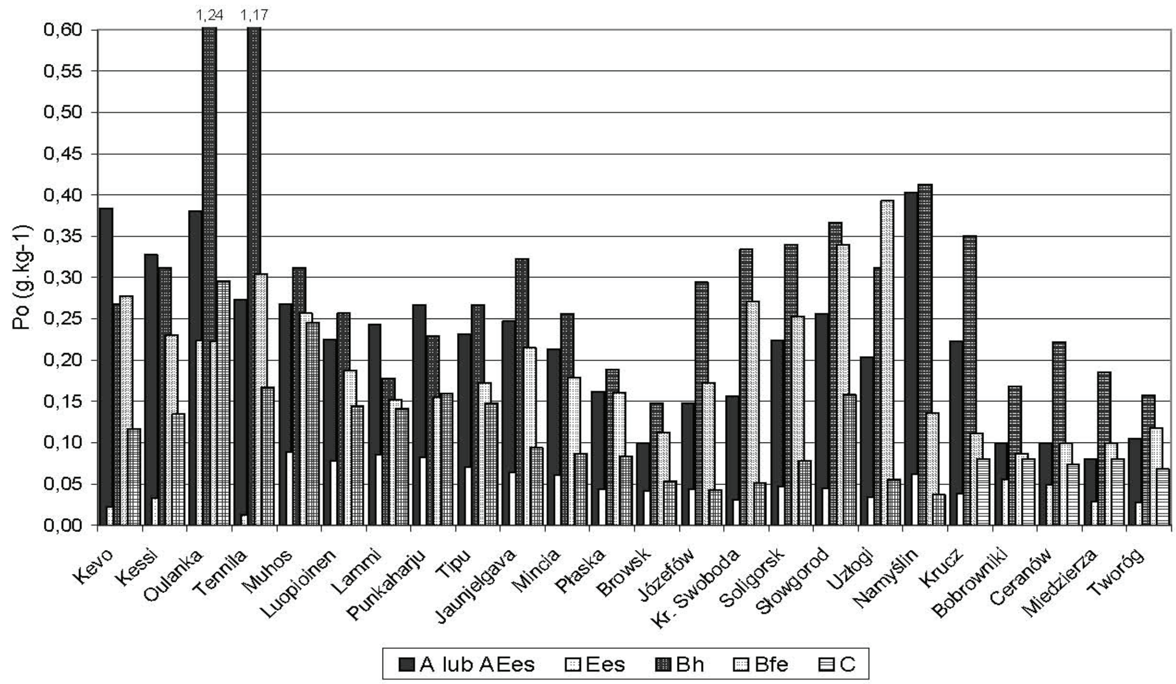
Phosphorus is present in different forms in the soil (Brogowski 1966a; Stewart and McKercher 1985; Czępińska-Kamińska 1992) and its distribution through profiles is regarded as a diagnostic feature of podzolization (Kundler 1956; Pokojska 1976, 1979c). It may also be suitable for estimating the age of soils in chronosequences (Bain *et al.* 1993). In this study, two forms of the element were determined. Phosphorus compounds soluble in 20% HCl represent the overall reserve of this element in the soil (Musierowicz 1955; Uggla, Uggla 1979; Sepponen 1985) and is only several per cent lower than the total content (Musierowicz 1955). In addition, there is the most active form of the element occurring in the soil solution as $H_2PO_4^-$ ions, a form available to plants (Musierowicz 1955; Chang and Jackson 1958).

The content of total P (P_o) in the studied podzolic and rusty-podzolic soils is low and is similar to results obtained for soils developed from fluvioglacial material across Poland (Brogowski 1966b; Czępińska-Kamińska 1992[16]) and Scandinavia (Sepponen 1985; Olsson and Melkerud 2000). In the parent-rock horizon the P_o content does not exceed 0.3 g kg^{-1}, while in the humus horizons the maximum level is 0.5 g kg^{-1} (Fig. 33).

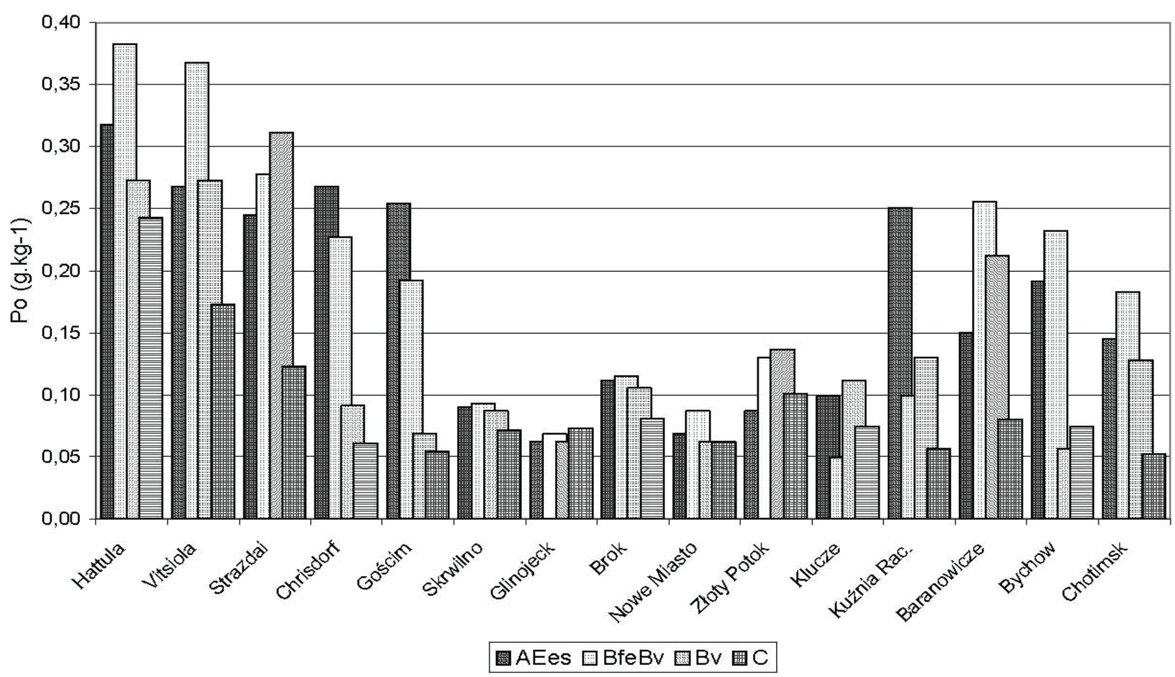
[16] The author referred to the total content of phosphorus

Figure 33. Content of phosphorus (Po) in particular genetic horizons of studied soils (a - podzolic soils, b - podzolic-rusty soils)

a



b



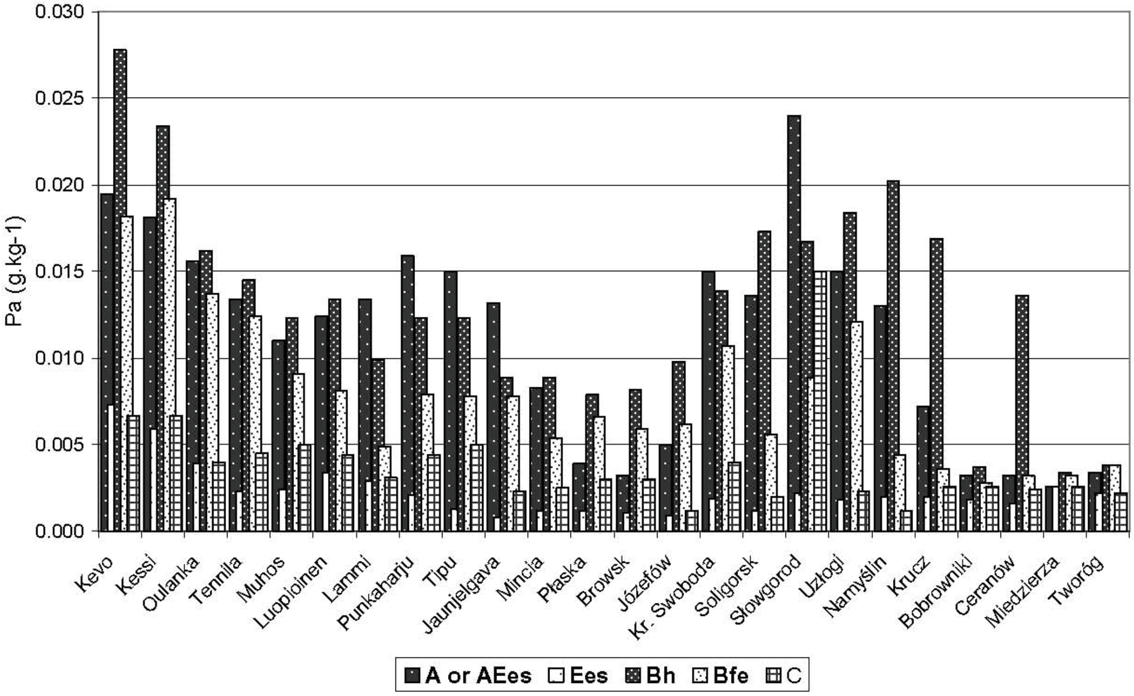
Where podzolic soils are concerned, the greatest values of P_o occur in the Bh sub-horizon, while the lowest values characterise the eluvial horizon, thereby indicating the transfer of this form of phosphorus through the profiles. Total P differs greatly between the eluvial and enrichment horizons – expressed via the ratio P_oB/P_oE, the value for this index ranging from 12.2 in profile 1 to 2.1 in profile 7. This index supported the division of the soils into three statistically-significant groups. The first group comprises the five northernmost profiles (numbers 1-5), with a mean value of the index equal to 9.3 (d = 2.7). The second group comprises profiles of soils developed from the oldest sedimented material in Northern Podkarpacie, Podlasie-Byelorussian Plateaus and Berezina-Desna Lowland (profiles 17, 19, 20, 22 and 24), and has a mean value for the index of 8.4 (d = 1.6). The remainder of the studied soils form the third group, in which the mean value equals 4.0 (d = 1.2).

Among the rusty-podzolic soils, 11 of the 15 studied profiles had greater content of total phosphorus in the enrichment horizon than in the eluvial-humus horizon. The differences were between ca. 10 and 40%. On the basis of the content of this form of phosphorus in the AEes and BvBfe horizons, the studied soils could be divided into three significantly-different groups. The first of these encompasses areas with the youngest soils, i.e., the Finnish Lakelands, Eastern Baltic Lakelands and Southern Baltic Lakelands (profiles 8, 9, 14, 25 and 27), in which the mean content of total P are: in the AEes horizon - 0.27 $g\cdot kg^{-1}$ (d = 0.03) and in the BvBfe horizon - 0.29 $g\cdot kg^{-1}$ (d = 0.08). The second group comprises the oldest soils; i.e., Podlasie-Byelorussian Plateaus, Berezina-Desna Lowland and the Silesian Lowland area (profiles 18, 21, 23 and 39), in which the mean contents of total P are in the AEes horizon – 0.18 $g\cdot kg^{-1}$ (d = 0.05) and in the BvBfe horizon – 0.19 $g\cdot kg^{-1}$ (d = 0.06). The remaining profiles situated in the east-central and southern parts of Poland form the third group, which shows a relatively high level of internal uniformity. The mean content of P_o in the AEes horizon is 0.09 $g\cdot kg^{-1}$ (d = 0.01) while that in the BvBfe horizon is 0.10 $g\cdot kg^{-1}$ (d = 0.03).

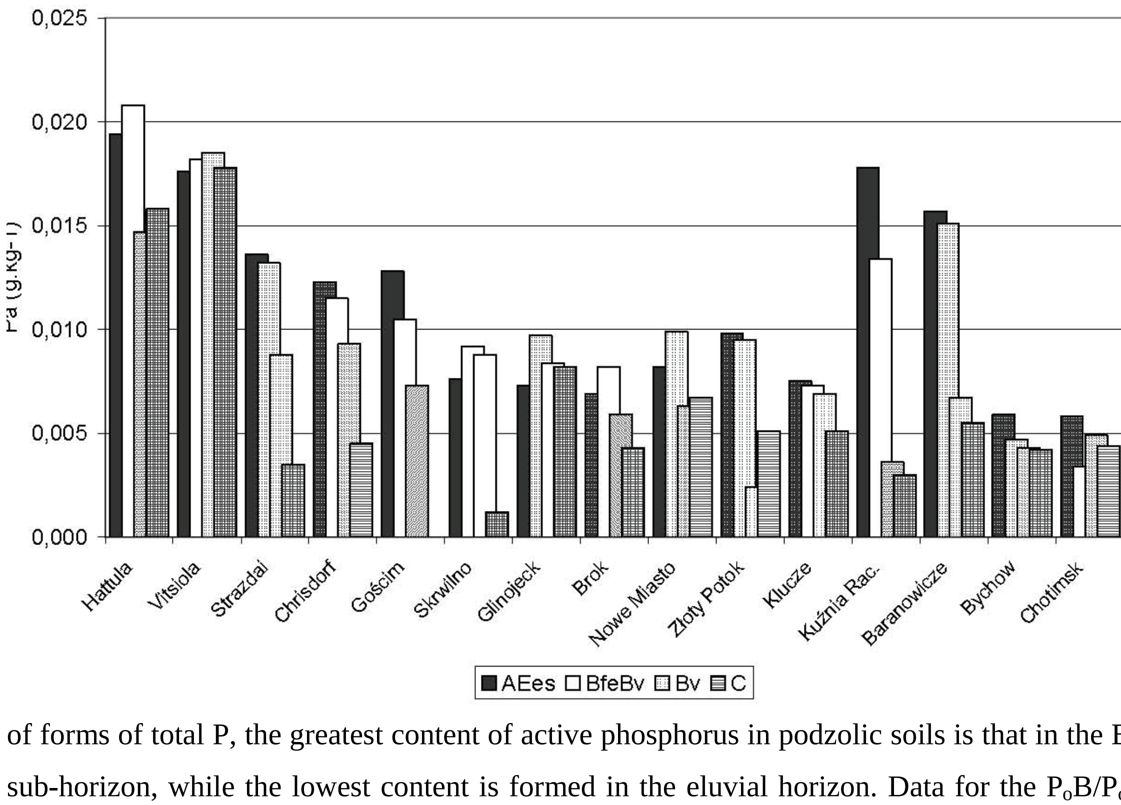
Plant-available phosphorus is a very labile form of the element mainly occurring in ionic form (Fotyma and Mercik 1995). Phosphate ions liberated both as minerals and weathered or mineralised organic matter are subject to relatively rapid “retrogradation” (Stewart, McKercher 1985). Their capacity to migrate therefore depends mainly on solubility of organometallically-linked forms (Pokojska 1976). On account of both the poor nature of the parent rock and the very acidic reactions, the studied soils have limited contents of plant-available phosphorus (Fig. 34). The humus horizons of the podzolic soils have 0.011 $g\cdot kg^{-1}$ (d = 0.006), the rusty-podzolic ones 0.011 $g\cdot kg^{-1}$ (d = 0.004).The respective figures for the parent-rock horizon are 0.004 $g\cdot kg^{-1}$ (d = 0.002) and 0.006 $g\cdot kg^{-1}$ (d = 0.003). As in the case

Figure 34. Content of phosphorus accessible to plants (Pa) in particular genetic horizons of studied soils (a - podzolic soils, b - podzolic-rusty soils)

a



b



of forms of total P, the greatest content of active phosphorus in podzolic soils is that in the Bh sub-horizon, while the lowest content is formed in the eluvial horizon. Data for the P_oB/P_oE

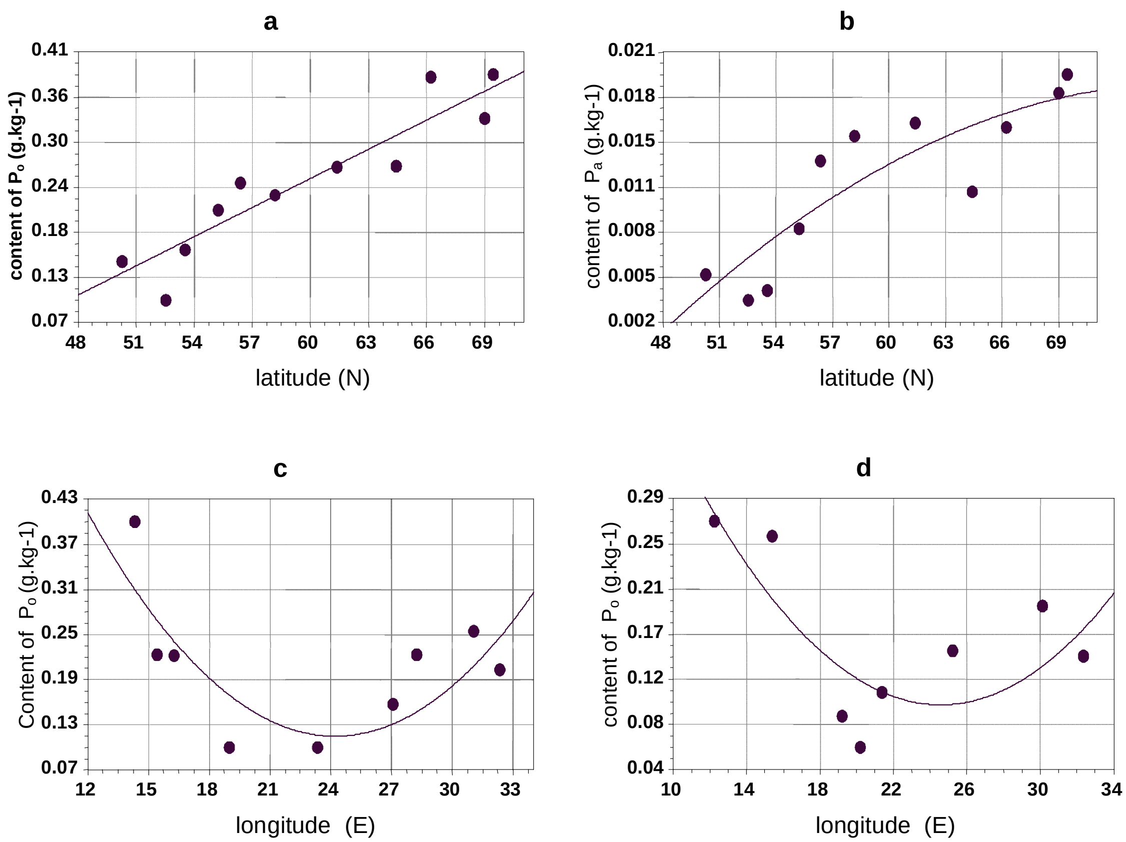
ratios separate the studied soils into two statistically different groups. The first of these comprises profiles from Finland (nos. 1, 2, 3, 4, 5, 6, 7 and 10), for which the mean value of the index is 4.6 (d = 1.0). The Finland profiles form the only statistically significant group. The mean value for the P_oB/P_oE index the remaining profiles is 8.6 (d = 2.9). In the rusty-podzolic soils, the content of active phosphorus is similar in humus-eluvial and rusty-illuvial horizons, while the P_oBvBfe/P_oAE ratio is 1.0 (d = 0.2), indicating that the soils in question have only very limited movement of plant-available phosphorus.

The relationships between content of total phosphorus (Po) and active forms of P (Pa) make it clear that the greatest proportion of total active P are in the eluvial horizon. The values here range from the 5 – 10 % in soils of the south-eastern parts of the study area to the ca. 30% characterizing the northernmost profile. In spite of the absolute increase in values for the two forms of phosphorus in the Bh sub-horizon, the Pa/Po index declines, indicating only a weak elevation of the content of phosphate ions in relation to total P in this sub-horizon. This is probably the result of the greater sorption of phosphate ions. In the very acidic podzolic soils, these ions react with aluminium and iron cations and their hydroxides.The iron forms are stronger sorbents than the different forms of aluminium (Sinha 1971; Pokojska 1976, 1979c; Czępińska-Kamińska 1992; Szafranek 2000). In the deeper mineral horizons, the share of plant-available phosphorus is at just 1-5% of the overall reserve of the element.

In rusty-podzolic soils, the share of P_a within P_o declines with depth through the profile. It is ca. 10% in the humus-eluvial horizons and declines to 1-5% in the parent-rock horizon. Several profiles had parent-rock horizons in which there is a slight renewed elevation of the share of all forms of plant-available phosphorus. This may indicate the transfer of this form of phosphorus down the profile or may be caused by the more limited uptake by plants in the lower parts of profiles.

In the humus horizons of both podzolic and rusty-podzolic soils, the content of total P and plant-available P show a statistically-significant linkage with geographical location. The content of these two forms of phosphorus is higher at more northerly sites (Fig. 35 a, b). Values trend lower from east to west in Polish territory. This is particularly true of total P – in both podzolic and rusty-podzolic soils (Fig. 35 c, d).

Figure 35. Regression models for content of total phosphorus (Po) and content of phosphorus accessible to plants (Pa) in humus horizon of studied soils as related to geographical coordinates:
a – phosphorus in podzolic soils on latitude, $Y = -0.483 + 0.012x$, $r = 0.934$;
b - phosphorus accessible to plants on latitude, $Y = -0.112 + 0.003x - 2.271x^2$, $r = 0.893$;
c – phosphorus in podzolic soils on longitude, $Y = 1.297 - 0.098x + 0.002x^2$, $r = 0.757$;
d – phosphorus in rusty-podzolic soils on longitude, $Y = 0.793 - 0.056x + 0.001x^2$, $r = 0.772$.



8. The spatial differentiation in selected diagnostic chemical pedogenic indicators of podzolic earths

The contents of different forms of iron and aluminium, as well as the relationships between them, are used to define both paleopedological criteria (see Section 7.4.8) and the degree of advancement of pedogenic processes in the development of a given soil. The relationships between different forms of iron and aluminium allow for the development of several quantitative indicators by which to assess the course of the process of podzolization (Konecka-Betley 1968; Mokma, Buurman 1982; Bednarek, Pokojska 1996). They also serve as diagnostic criteria by which to identify the spodic horizon in podzolic soils and the sideric horizon in rusty soils (Mokma and Buurman 1982; Mokma 1983; Bednarek 1991; WRB, 1998).

The content of amorphous iron and aluminium in the enrichment horizon was one of the criteria characterising the process of podzolization proposed for classifying a given pedon within the taxonomic unit of "podzol" - WRB (1998). In line with this criterion, the total for amorphous aluminium (Al_o) and ½ amorphous iron ought to constitute a minimum 0.5% of the soil mass. In the studied podzolic soils, the value varied from the level of 0.35% in profile 17 to 1.16% in profile 3 (Table 29). The respective figures for the rusty-podzolic soils were 0.21% (in profile 39) to 0.51% (in profile 8). Thus half of the analysed podzolic soils meet the above criterion (profiles 1, 3, 15 and 24). Only the rusty-podzolic soil profile from northern Finland has a value for the index in excess of 0.5%, pointing to a strong process of podzolization. However, a number of opinions recently circulating hold that the value for the index proposed by WRB (1998) is too high since many podzolic soils fulfilling the remaining morphological/chemical criteria have an index value below 0.5%.[17] It is also possible for a greater concentration of amorphous aluminium and iron to occur in the Bfe sub-horizon than the Bh sub-horizon, or in the Bv horizon in comparison with BfeBv. Such was the case in profiles 3 and 18.

Spatial variation in the index of the content of amorphous iron and aluminium in podzolic soils is higher in the diagnostic spodic horizon of the youngest soils.These are under the strongest impact from exogenous factors (profiles 1 and 3) as are the oldest profiles (profile 24). Similar observations may be found in a description of podzolic soils in Michigan, USA (Mokma 1991), in which the author draws the attention to the progressively higher contents of amorphous aluminium and iron that are present in the spodic horizon of older and older soils.

Another diagnostic criterion used in classifying podzolic earths as proposed by the WRB (1998) is the index of the transfer of amorphous forms of iron and aluminium. This is determined as the ratio of their value in the eluvial (diagnostic albic) horizon to their value in the enrichment (diagnostic spodic or sideric) horizon. It is expressed mathematically as: $(Al_o + 0.5\ Fe_oB)/(\ Al_o + 0.5\ Fe_oE)$. According to the proposal from WRB (1998), the minimal value for this index in the case of podzolic soils should be 2. This indicates that the diagnostic spodic horizon ought to contain at least twice as much of the amorphous forms of iron and aluminium as does the eluvial horizon. All the analysed podzolic soils meet this criterion, since values for this index are in the range from 3.8 (in profile 16) to 20.8 (in profile 3). The greatest values occur in soils of the northern regions (profiles 1 and 3), as well as in profiles

[17] *Inter alia*, such a suggestion was made during the Polish-German seminar held in 2000 (Bednarek – unpublished information)

located in eastern parts of the study area - in the Berezina-Desna Lowland (profile 24). The lowest values characterise the area of Poland (Table 29). In the rusty-podzolic soils, the greatest value for the index is in central Finland (profile 8). The values observed for the rusty-podzolic soils are much lower, between 1.6 for profile 39 and 3.0 for profile 8, in line with the WRB (1998) guidelines. Thus, only profile 39 is characterised by a more limited transfer of amorphous iron and aluminium than has been set as the classification of the process of podzolization. These results point to a quite strong process of illuviation of the kind ongoing in the analysed rusty-podzolic soils.

A similar spatial differentiation characterises the index of illuviation (Wi), as determined by Mokma (1983) via: $\sum_B C_p\ Al_p\ Fe_p$ - $\sum_A C_p\ Al_p\ Fe_p$. Among the podzolic soils, the greatest value,2.29, was obtained for the profile situated in the Berezina-Desna Lowland (profile 24), followed by soils in northern Lapland (profiles 1 and 3) where the respective figures are 1.03 and 1.79 (Table 29). Soils from Poland show limited variability (0.42 - 0.76). In rusty-podzolic soils, the values for the index of illuviation range from 0.02 do 0.16, and are thus only slighter greater than 0, which is characteristic for this type of soil (SGP 1989).

The index for the transfer of free iron Wp_{Fe}, proposed by Konecka-Betley (1968) and defined as the ratio of the F_d contents in two adjacent genetic horizons; e.g., humus-eluvial or eluvial-spodic horizons in podzolic soils and sideric horizons in rusty soils. In the analysed podzolic earths, the index assumes a wide range of values, from 2.7 in profile 26 to 27.5 in profile 3 (Table 29). This points to marked differences in the movement of free iron. The greatest values were found in the northern regions (profiles 1 and 3); i.e., the areas today subject to the strongest impact due to exogenous factors, and from profile 17, close to Józefów in southern Poland, which has the oldest sediments associated with the San II Glaciation. The other soils did not yield significant differences, the values obtained varying from 2.7 (profile 26) to 6.2 (profile 15). Similar results for Poland were obtained by Konecka-Betley (1968). Quite different values for the index are found in the rusty-podzolic soils (Table 29). Both the value of the index and the degree to which these differ between profiles are much lower, ranging from 1.1 in profile 8 to 1.7 in profile 18. Comparable results for the rusty-podzolic soils of northern Poland were presented by Bednarek (1991).

Table 29. Values of indices for characteristic of podzolization process criteria.

No. of profile	$Al_o+1/2Fe_oB$	$\frac{Al_o+1/2Fe_oB}{Al_o+1/2Fe_oE}$	$\frac{Fe_dB}{Fe_dE}$	W_i	$C_p+Al_p+Fe_pB$	$\frac{C_p+Al_p+Fe_pB}{C_p+Al_p+Fe_pA}$	$\frac{C_p}{Alp+FepB}$
	%				%		
	a	b	c	d	e	f	g
podzolic soils							
1	0.50	13.0	16.8	1.03	1.45	112	23.7
3	1.16	20.8	27.5	1.79	2.38	130	9.1
12	0.45	5.2	5.0	1.37	2.41	173	10.7
15	0.63	5.9	6.2	0.76	1.22	104	7.6
16	0.38	3.8	4.2	0.65	1.00	110	6.6
17	0.35	6.1	18.6	0.42	1.13	115	7.2
24	0.83	9.3	6.2	2.29	2.62	159	7.4
26	0.49	4.0	2.7	0.57	1.22	106	8.2
rusty-podzolic soils							
8	0.51	3.0	1.1	0.03	0.53	86	10.7
25	0.24	2.0	1.6	0.05	0.41	88	11.8
31	0.27	2.7	1.3	0.16	0.27	58	6.8
39	0.21	1.6	1.5	0.02	0.45	86	16.7
18	0.25	2.3	1.7	0.08	0.44	73	13.3

Explanatory:

a. content of amorphous iron and aluminium in the enrichment horizon, according to WRB (1998)
b. index of the transfer of amorphous forms of iron and aluminium, according to WRB (1998)
c. index for the transfer of free iron, according to Konecka-Betley (1968) and Bednarek (1991)
d. index of illuviation (Wi) according to Mokma (1983)
e. iron-aluminium-humus complexes in B horizon, according to Mokma (1983)
f. relationships ongoing between the contents of iron-aluminium-humus complexes in the humus horizon and the diagnostic spodic or syderic horizons according to Mokma (1983) and Bednarek (1991)
g. characteristics of immobile complexes according to Mokma (1983).

A further significant diagnostic criterion in the evaluation of processes of podzolization is the molar ratio of organic carbon to the sum of aluminium + iron determined in pyrophosphate extraction. This is very often used in identifying the diagnostic spodic and sideric horizons (Mokma and Buurman 1982; Bednarek 1991; Karltun *et al.* 2000). It is on these that many soil classifications are based, including also the one used in Poland (SGP 1989). According to Mokma (1983), the iron-aluminium-humus complexes are characterised by different degrees of mobility. This author established that, when the ratio exceeds 5.8 but is lower than 25, the complexes become immobile. In the diagnostic spodic horizons of all of the analysed podzolic soils, as well as the sideric horizons of the rusty-podzolic soils, the obtained molar ratios of Cp/(Alp+Fep) are in line with that criterion (Table 29). The values for this index are in the range from 6.6 in profiles 16 to 23, to 7 in profile 1. In eluvial horizons located above the spodic horizon the molar ratio was much greater, varying between 29 in profile 15 to 103.6 in profile 3. In humus-eluvial horizons of rusty-podzolic soils, the molar ratios were greater than 25 (Table 29). This attests to the mobility of iron-aluminium-humus complexes in the upper parts of the analysed soil profiles, as well as to their very limited mobility in the diagnostic spodic and sideric horizons.

Mokma (1983) proposed yet two more indices diagnosing podzolization. These are based on assessments of the contents of iron-aluminium-humus complexes in different genetic horizons. The index indicates that the diagnostic spodic horizon should contain more than 0.5% of the complexes linking humus with R_2O_3. It is based on results obtained in the course of sample extractions in sodium pyrophosphate. All of the studied podzolic soils meet this criterion, since values for the sum C_p,+Al_p+Fe_p range from 1.0% in profile 16 to 2.64% in profile 24. In the case of rusty-podzolic soils these values are much lower, between 0.27% in profile 31 and 0.53% in profile 8 (Table 29). These results also correspond to criteria for the classification of podzolic and rusty-podzolic soils proposed by Bednarek (1991) He defined a value for the index of 0.5% as borderline between the two types of soil. The content of iron-aluminium-humus complexes in the diagnostic spodic and sideric horizons is higher in soils located in the northern and eastern regions of the study area (profiles 1, 3 and 8 and profile 24 respectively).

A second index makes use of the relationships between the content of iron-aluminium-humus complexes in the humus horizon and the diagnostic spodic or sideric horizons. According to Mokma (1983), and then Bednarek (1991), the content of these complexes in the diagnostic spodic horizon is greater than in the humus horizon, while the share in the humus horizon of rusty-podzolic soils is greater than in the sideric horizon. In fact, all of the analysed profiles of both kinds of soil meet these criteria also (Table 29). In podzolic soils, the greatest difference between the contents of complexes in these horizons is present at profiles 12 (73%), 24 (159%) and 3 (130%). The most marked transfer of iron-aluminium-humus complexes have taken place in the oldest soils and those located in areas that today experience intensive leaching processes. In the rusty-podzolic soils, major differences between content of iron-aluminium- humus complexes in the humus and diagnostic sideric horizons are indicative of the weakest process of transfer. The result is that the decided majority of the chemical structures in question have accumulated in horizon A. The greatest differences in contents of the complexes were reported in the oldest soils, in B-P - profile 18 (73%) – Table 29.

9. Pedological properties as features diagnostic of the geographical diversity to podzolic earths

Significant spatial variation was found in certain soil properties based on correlation and regression analyses between the morphological, physical and biochemical properties of the humus, diagnostic and parent-rock horizons of podzolic and rusty-podzolic soils compared latitude and longitude (Section 6). These properties are recognised as diagnostic features where space-related pedological diversity is concerned.

Two geographic groups were identified using different combinations of analysis (types of soil – geographical coordinates), The first group included properties emerging as statistically significant in their association with geographical locations in all four analytical variants, i.e. for both podzolic and rusty-podzolic soils in relation to both longitude and latitude. These were termed universal diagnostic features. Those present in one type of soil or in relation to one or other of the sets of geographical coordinates were defined as specific diagnostic features.

Among the 51 soil properties[18] and four primary characteristics of soils[19] subjected to analysis in all profiles, only 24 could be considered diagnostic (Figs. 36 and 37), of which 17 were characterised by statistically-significant differences with all types of statistical analysis. These were thus regarded as universal features, and they are found to include two morphological, six physical and nine biochemical features (Table 30). The remaining seven are specific features, i.e., ones typical for just one systematic group of soils (podzolic or rusty-podzolic), or of the two geographical arrays (longitudinal or latitudinal) of study sites. Studying longitudinal and/or latitudinal variation in soil properties, the numbers of diagnostic features characterizing the different relationships were found to be as follows (Fig. 36, 37):

- rusty-podzolic soils in relation to latitude - 22 features, including 17 universal and 5 specific: the C:N ratio, $V_{Ca}2+$, V_H+, V and N;

[18] Thicknesses of the O, A and mineral horizons; colour of the diagnostic horizons; content of the skeletal, sandy, dusty fragments and silty and clay; content of non-resistant minerals; real gravity and bulk density; porosity; moisture; field and capillary water capacity; reserves of soil water in the field and capillary capacity states; maximal hygroscopicity; air capacity; contents: of organic carbon, total N, ammonium- and nitrate-nitrogen; C:N, Ch:Cf; degree of humification; content of exchangeable base cations (Ca, Mg, K, Na); sum of exchangeable base cations; sorption capacity; degree of base saturation with cations (V_{Ca}, V_{Mg}, V_K, V_{Na}, V_H); total for base cations; exchangeable hydrogen and aluminium ions; active, exchangeable and hydrolytic acidity; lactic dehydrogenase activity; total and plant-available P.

[19] The Nm, Wo, Z_{PPW}/Z_{KPW} and Ui indices.

- podzolic soils in relation to longitude - 20 features, including 17 universal and 3 specific: the Ulrich index of soil elasticity, C:N and $N\text{-}NH_4^+$;
- podzolic soils in relation to latitude - 19 features, including 17 universal and 2 specific color saturation of sub-horizon Bh and the C:N ratio;
- rusty-podzolic soils in relation to longitude - 17 features, universal only.

Diagnostic features could be divided into two groups.

Group I – geographical variation of a continuous nature decided mainly by factors on the supraregional scale, with the relationship between the feature and geographical coordinates expressed via linear regression models. This group includes the 3 identified diagnostic features of:

- thickness of the organic horizon (Fig. 6),
- content of non-resistant minerals (Fig. 9),
- content of $N\text{-}NH_4^+$ (Fig. 25)

Group II – geographical variation in features expressed by means of second-order polynomials (the remaining diagnostic features), based on the modifying influence of local or regional conditions.

Other analysed properties behaved neutrally as regards geographical location, denoting that their differentiation across space is more even than is the case for the diagnostic features or else presents major random variation. This latter situation results from the determining influence of local habitat factors in shaping the variability of a given feature in the soil profile – the reverse of diagnostic pedological features wherein influence is exerted by pedogenic factors, especially the age of sediments, hygrothermal conditions and plant cover. These relationships are discussed more widely in Section 11.

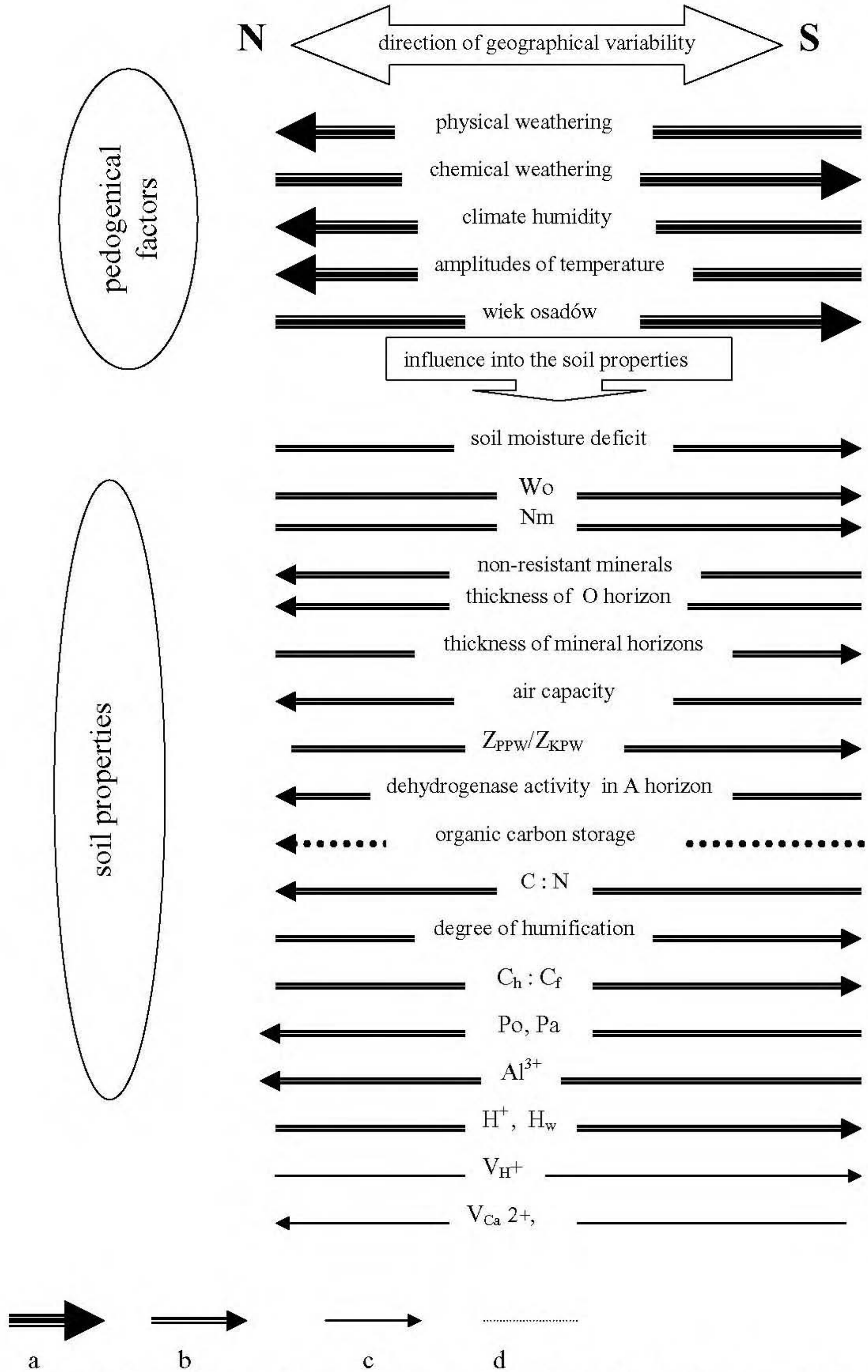


Figure 36. Directions of increase of some pedogenic factors into the studied soils and values of diagnostic feature along meridian
(a – lines of directions of increase of pedogenic factors, b – directions of increase of feature values in podzolic and podzolic-rusty soils, c – directions of increase of feature values only in podzolic-rusty soils, d – feature with strong influence of local conditions for its spatial variability)

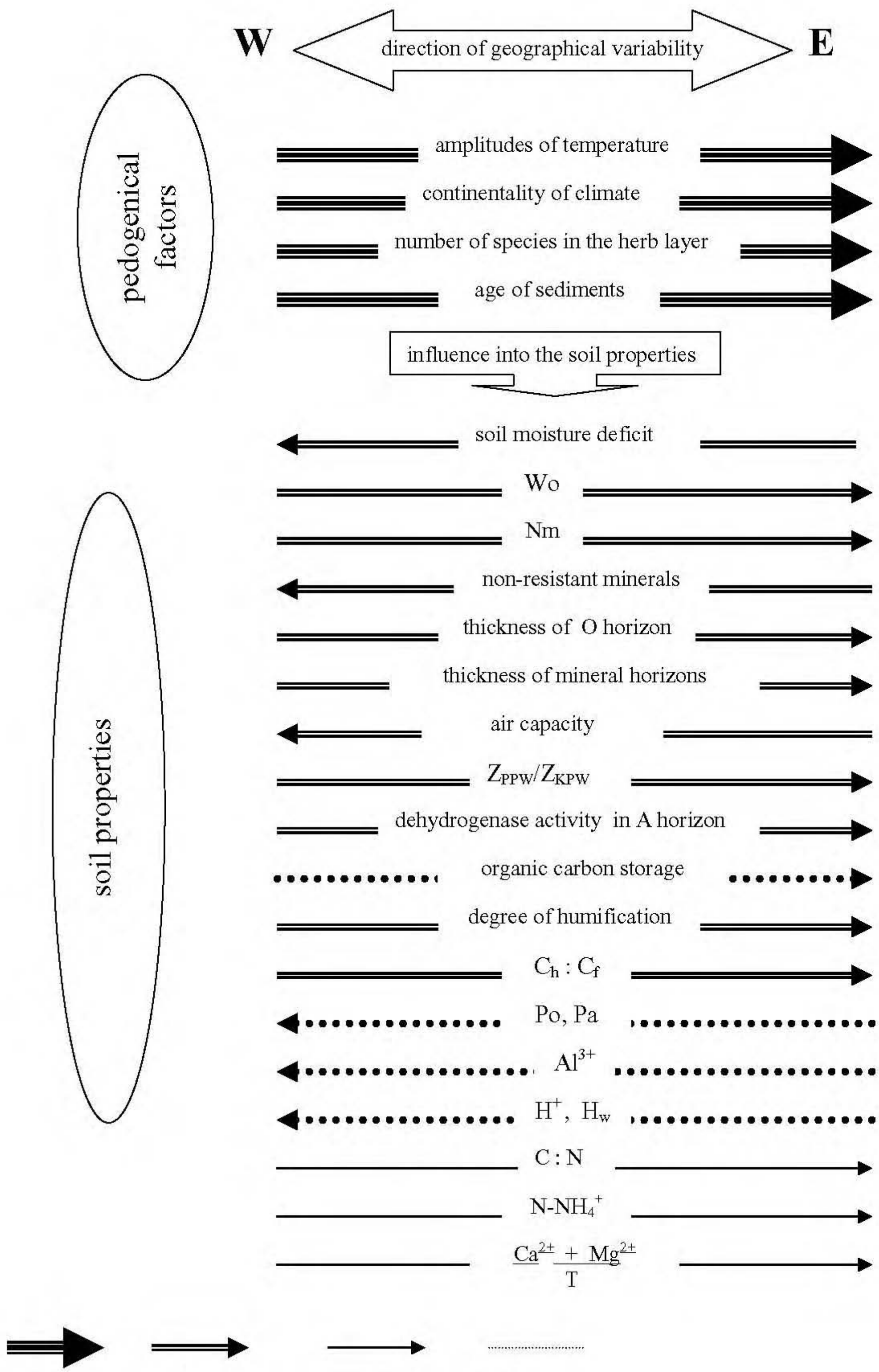


Figure37. Directions of increase of some pedogenic factors into the studied soils and values of diagnostic feature along parallel. (a – lines of directions of increase of pedogenic factors, b – directions of increase of feature values in podzolic and podzolic-rusty soils, c – directions of increase of feature values only in podzolic soils, d – feature with strong influence of local conditions for its spatial variability)

10 Regional differentiation of podzolic earths

10.1. Podzolic soils

Differentiation in soil properties in the humus horizon

All the studied profiles can be divided into two groups based on analyses of similarities in soil properties in humus horizons. The first mainly comprises soils of the Karelian Lakeland, Eastern Baltic Lakelands and western parts of the Podlasie-Byelorussian Plateaus (profiles 10. 11, 12, 13, 15 and 16). The second includes the remaining profiles. However, it needs to be made clear that the second group can be divided into four lower-rank units encompassing geographical regions as follows:

- Lapland (profiles: 1, 2, 3),
- Eastern Baltic Lakelands, Central Polish Lowlands, and Central Małopolska Upland (profiles: 26, 28, 29, 32, 35, 38),
- Ostro-Bothnia and the Finnish Lakelands (profiles: 4, 5, 6, 7),
- Northern Podkarpacie Podlasie-Byelorussian Uplands and Berezina-Desna Lowland (profiles: 17, 19, 20, 22, 24).

A noteworthy feature is that the properties of soils in northern Finland and western Poland are very similar (Fig. 38), these both being young pedons shaped under conditions of a wet climate.

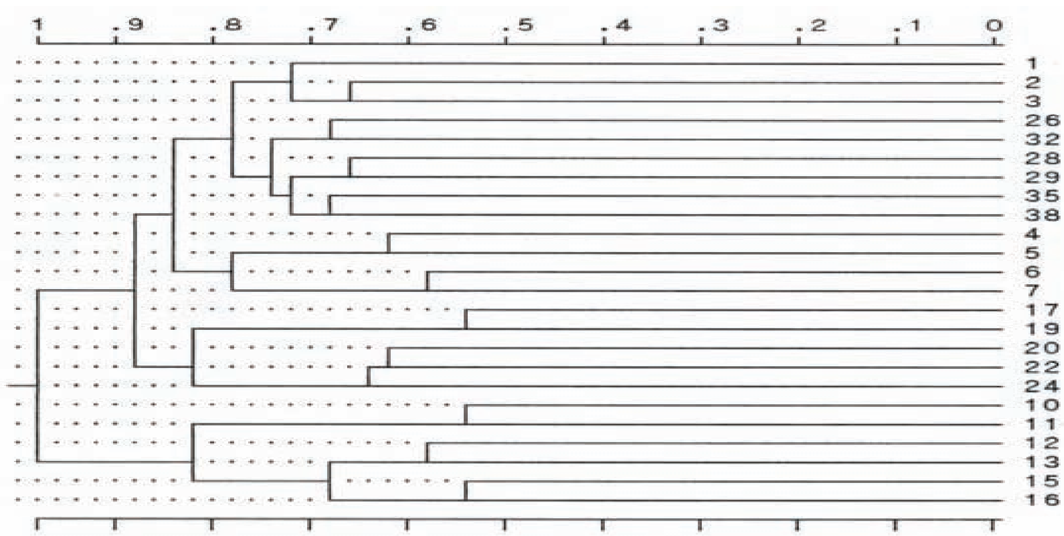


Figure 38. Dendrogram of similarity of humus horizon properties in studied podzolic soils (similarity determined on the basis of Euclidean distance and Wards method)

Differentiation of soil properties in the parent-rock horizon

Similarity analysis of different parent rocks of podzolic soils points to the much greater differentiation compared with the humus horizon. The division obtained encompasses eight primary units that are subject to further internal diversification (Fig. 39):

- Northern Lapland (profiles: 1, 2),
- Ostro-Bothnia, and the northern part of the Finnish Lakelands (profiles: 5, 6),
- the southern part of Finnish Lakelands and the Karelian Lakeland (profiles: 7, 10),
- the Eastern Baltic Coastland and Eastern Baltic Lakelands and (profiles: 11, 12, 13),
- the southern part of Lithuanian Lakeland, western part of Podlasie-Byelorussian Uplands and Northern Podkarpacie (profiles: 15, 16, 17),
- the Podlasie-Byelorussian Uplands and Berezina-Desna Lowland (profiles: 19, 20, 22),
- the eastern part of Central Polish Lowlands and Central Małopolska Upland (profiles: 32, 35).

The horizons of parent rock in the three profiles 1, 4 and 24 are one of the units differing from all the others.

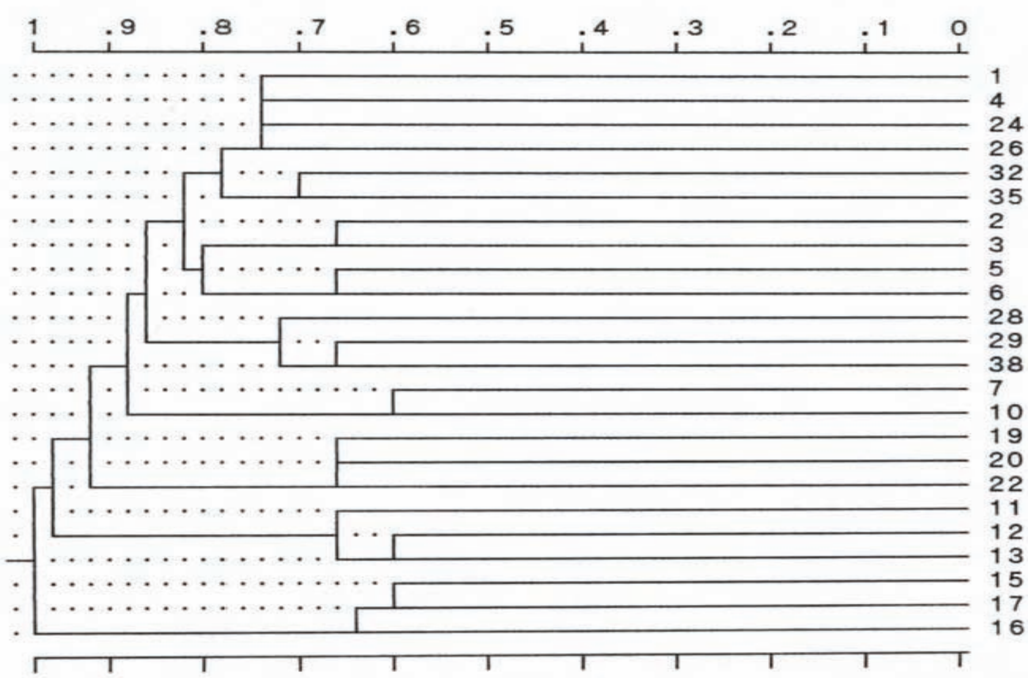


Figure 39. Dendrogram of similarity of parent rock horizon properties in studied podzolic soils. (similarity determined on the basis of Euclidean distance and Wards method)

The results obtained confirm two hypotheses advanced in the present work. The first of these concerns the influence of vegetation of similar species composition as a major element in the generation of humus, and the reduction or evening-out of spatial differences in the properties of soils in organic and humus horizons. The second hypothesis points to strong linkage between the age of a soil substratum and the associated soil and its properties. Attesting to this is the marked similarity between profiles in areas of Finland and northern-western Poland; i.e., between soils developed in material accumulated during the last stadial of the Vistulian or the Holocene, which differ significantly from the soils of the eastern part of the study area arising in material that accumulated during the Odra Glaciation.

The differentiation to the properties of soils in all genetic horizons

Analysis of all of the properties of podzolic soils determined for each profile (mineral and organic horizons) supports identification of similarities between the studied soils. These are differentiated into two large groups that separate the study area into a northern and a southern part (Fig. 40). Within each of these there are lower-order units of considerable internal cohesiveness. Overall, the podzolic soils are formed into six units in reference to the spatial differentiation of morphological, physical and biochemical properties. This division takes the following form:

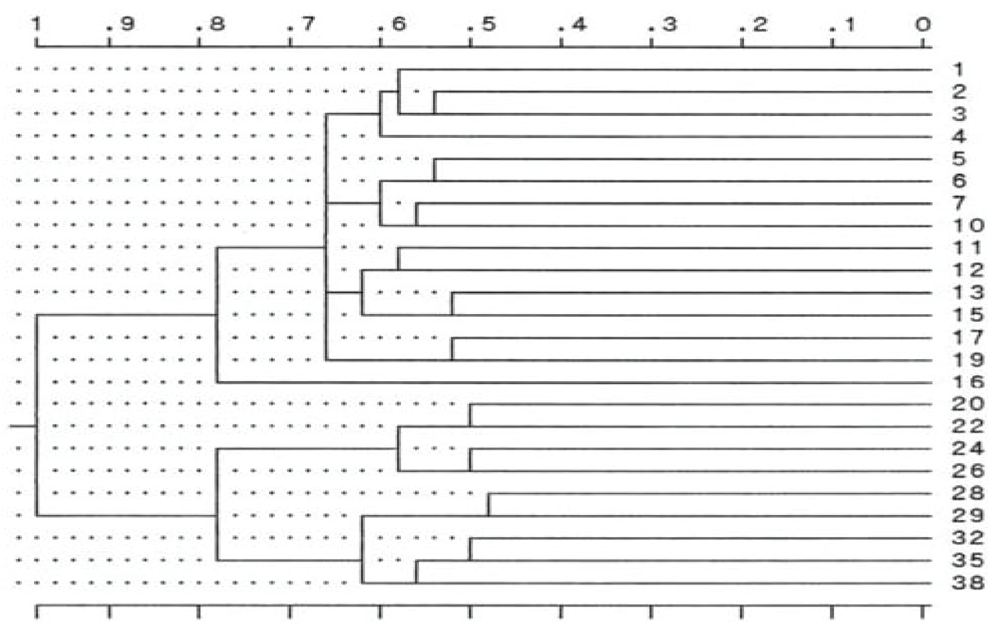


Figure 40. Dendrogram of similarity of properties in all genetic horizons in studied podzolic soils.(similarity determined on the basis of Euclidean distance and Wards method)

- Lapland (profiles: 1, 2, 3, 4),
- Ostro-Bothnia, the Finnish Lakelands and the Karelian Lakeland (profiles: 5, 6, 7, 10),
- the Eastern Baltic Coastland and Eastern Baltic Lakelands and (profiles: 11, 12, 13, 15),
- the Podlasie-Byelorussian Uplands and Northern Podkarpacie (profiles: 16, 17, 19)
- the Berezina-Desna Lowland (profiles: 20, 22, 24) and profile 26,
- the Southern Baltic Lakelands, Central Polish Lowlands and Central Małopolska Upland (profiles: 28, 29, 32, 35, 38),

The ordering identifies a profile from the western part of Southern Baltic Lakelands (profile 26) characterised by its marked similarity to the soils of Berezina-Desna Lowland. In spite of the considerable differences in morphological and petrographic composition, many physical and chemical properties of these soils show large similarities with one another, particularly in the superficial horizons. The results make it clear that stronger local habitat conditions may ”disturb” the geographical differentiation in soil properties that results from spatial variability to pedogenic factors – as the author has noted in previous work (Degórski 1998b).

10.2. Rusty –podzolic soils

Differentiation of soil properties in the humus horizon

Two large groups resulted from similarity analysis of soil properties in the humus horizons of rusty-podzolic soils.The first of these comprises the soils of the northern and eastern regions of the study area and the second those of the remaining sites – i.e. in the south-west (Fig. 41). Each of these may subsequently be divided into two units of lower rank, giving four groups that are statistically different. These groups are:

- the Finnish Lakelands and Western Baltic Lakelands (profiles: 8, 9, 25),
- the Eastern Baltic Lakelands and Central Polish Lowlands (profiles: 27, 30,31, 33, 34),
- the Southern Baltic Lakelands, Podlasie-Byelorussian Uplands and Berezina-Desna Lowland (profiles: 14, 18, 21),
- the Silesian-Cracovian Upland and Silesian Lowland (profiles: 36, 37, 39).

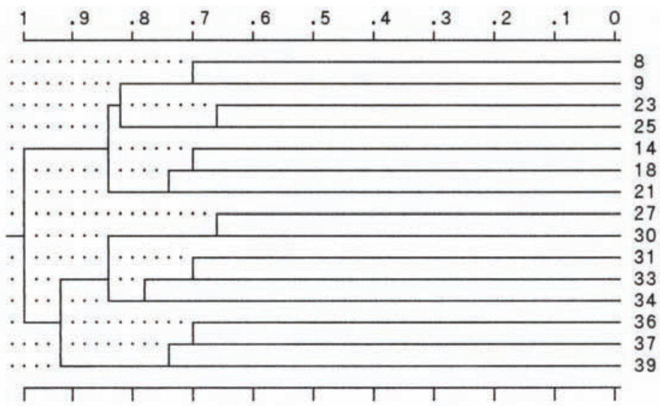


Figure 41. Dendrogram of similarity of humus horizon properties in studied podzolic-rusty soils.(similarity determined on the basis of Euclidean distance and Wards method)

The rusty-podzolic soils show major similarities in soil properties in profile 25, located in Western Baltic Lakelands, and profile 23 in Berezina-Desna Lowland. These pedons differ in terms of age.

Differentiation of soil properties in the parent-rock horizon

Three main groups were found based on the properties of the parent-rock horizon of the rusty-podzolic soils. These are the northern, south-eastern and western groups (Fig. 42). Further divisions into units of greater internal cohesion - thanks to similar shaping of soil properties in the analysed profiles - give rise to seven identifiable groups:

- the Finnish Lakelands (profiles: 8, 9),
- the Eastern Baltic Lakelands and Podlasie-Byelorussian Uplands (profiles: 14, 18),
- the Southern Baltic Lakelands (profiles: 27, 30),
- the Central Polish Lowlands (profiles: 31, 33, 34, 39),
- the Berezina-Desna Lowland (profiles: 21, 23),
- the Western Baltic Lakelands and Silesian-Cracovian Upland (profiles: 25, 36, 37).

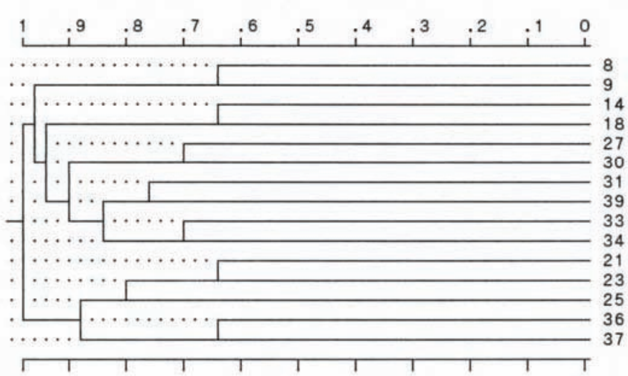


Figure 42. Dendrogram of similarity of parent rock horizon properties in studied podzolic-rusty soils.(similarity determined on the basis of Euclidean distance and Wards method)

Like the podzolic soils, the rusty-podzolic soils showed greater regional differentiation due to spatial variability in properties of their parent-rock horizons than in properties of more superficial layers.

Differentiation of the properties of soils in all genetic horizons

The rusty-podzolic soils differ from the podzolic in the more limited spatially-conditioned differentiation of their properties (Fig. 43). Two large groups result from similarity analysis of soil properties between different profiles. The first includes profiles of the northern part and the second the southern. The soils in the north in turn form three regional units, while the remaining soils are in one group demonstrating considerable internal uniformity (Fig. 43).

The division is as follows:

- the Finnish Lakelands and Eastern Baltic Lakelands (profiles: 8, 9, 14),
- the Western Baltic Lakelands and Southern Baltic Lakelands (profiles: 25, 27, 30),
- the Podlasie-Byelorussian Uplands and Berezina-Desna Lowland (profiles: 18, 21, 23),
- the Central Polish Lowlands and Silesian-Cracovian Upland (profiles: 33, 34, 36, 37, 39).

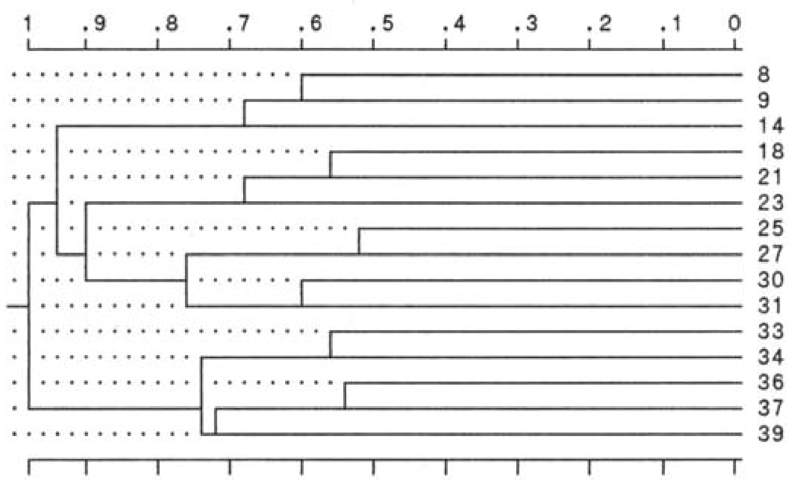


Figure 43. Dendrogram of similarity of properties in all genetic horizons in studied podzolic-rusty soils. (similarity determined on the basis of Euclidean distance and Wards method)

Differences among the properties of rusty-podzolic soils look much greater in the N-S configuration, between Finland and Central Europe, than when considered in the east-west dimension. This may suggest that it is the age of soils and the biotic-climatic element which are the pedogenic factors exerting the strongest influence on the spatial variability of properties of the analysed rusty-podzolic soils.

10. Discussion and summary of results

The analysis of the links between pedogenic factors and soil properties represents a major thrust to soil-science research, the origins of which are linked to the emergence of the scientific discipline as a whole (Glinka 1926; Yaalon 1997). The spatial scope to any studies that were carried out was mainly confined by technical opportunities. In work on soil geography, presenting spatial studies on a supraregional scale, both the description of the variability in soil cover and the analysis of linkage between pedogenic factors and properties of pedons made most frequent use of compilations of point results collected and processed by many scientific centers (Głazowska 1981; Boul *et al.*, 1989; Bednarek and Prusinkiewicz 1997). These studies are of cognitive value, but the non-uniformity of the material prevented any application of mathematical analyses of similarity in assessing the spatial variability in properties.

In contrast, the results presented here could be used in wide-ranging comparative analysis since the procedures adopted in the choice of research sites confined the potentially-distorting influence of many external factors that could impact the course of pedogenic processes (see Section 2). Also important was the application of uniform methods in field studies and analytical techniques. The data thereby obtained offers a valuable supplement to any previous work including knowledge of the geography of Europe’s podzolic earths and the inter-relationships between spatial variability of their properties and pedogenic factors resulting from conditioning in the natural environment.

The time factor is also of great importance in shaping soil features. I, along with many other soil scientists, adopted the assumption that the evolutionary development of soils in post-glacial areas was initiated and took place while conditions of arctic tundra and a cryogenic post-glacial and periglacial environment were still present (Kopp 1965, 1970; Catt 1988; Kowalkowski 1988, 2001; Manikowska 1999; Blume *et al.*, 1998). This assumption states that the dates of onset of morphogenetic and pedogenic processes vary from 6 – 8000 years BP in the north to ca. 400,000 years in the south of the study area. The factors that shaped the soils may thus be divided into the palaeopedogenic - initial development of soils - and the pedogenic – those occurring in the present. Irrespective of the genetic or temporal classification applied, the two groups of factors are directly dependent on two factors; one – the morphogenesis (morpholithological conditions) in the study area regarded by many soil scientists as the element conditioning the development of soil cover (Jenny 1961; Huggett

1975; Yaalon 1982; Catt 1988; Kowalkowski 1993, 2001; Janowska 2001) and, two, the temporally-variant biotic-climatic factors that determine the dynamics in and type of weathering, the quantity and quality of the organic matter and the cyclical development of whole ecosystems. These are regarded as elements steering the development of the pedosphere (Jenny 1961; Huggett 1975, 1985; Duchaufour 1982; Birkeland 1984; Kowalkowski 1988 and Lundström *et al,* 2000a). The functional interlinkages between pedogenic factors ensure that the podzolic earths have been subject to their synergistic impacts. As a result, it is hard to assess unambiguously which of the complex of factors is more important in the soil-forming process (Fig. 44).

A good example of the multi-factor impact on soil properties is provided by the degree to which substances wash through the profile, as expressed in terms of the index of illuviation ($\sum_B C_p\ Al_p\ Fe_p - \sum_A C_p\ Al_p\ Fe_p$) proposed by Mokma (1983). The value of this index is influenced by primary properties of the lithological material and by biotic-climatic features. The former are the primary source of nutrients and the latter determine the type and rate of weathering of the substratum, the species composition of the vegetation, the rate of decomposition of organic matter, and the processes of humification and mineralisation. The significance of the relationship between the amount of humus in soils and the intensity of the illuviation process is well documented in the literature (Konecka-Betley 1976, 1977; Catt 1988; Janowska 2001). In this study, the greatest value for the index of illuviation was obtained for pedons located in areas of the wettest climate and those wth the greatest reserves of organic carbon, those in northern Finland and eastern Belarus.

Another example of the joint impact of the pedogenic factors is the share non-resistant minerals within the heavy fraction of a soil’s mineral composition. The morphogenetic development has been determined by the mineral composition of the soil substratum, but also has been impacted by biotic-climatic factors through the type of physical, chemical and biochemical weathering. The degree of change induced by exogenous processes in primary soil properties also depends upon the length of time for which these processes persisted. Attesting to this is the fact that shares of non-resistant minerals in the substratum become progressively lower in a manner that is directly proportional with the age of the lithological

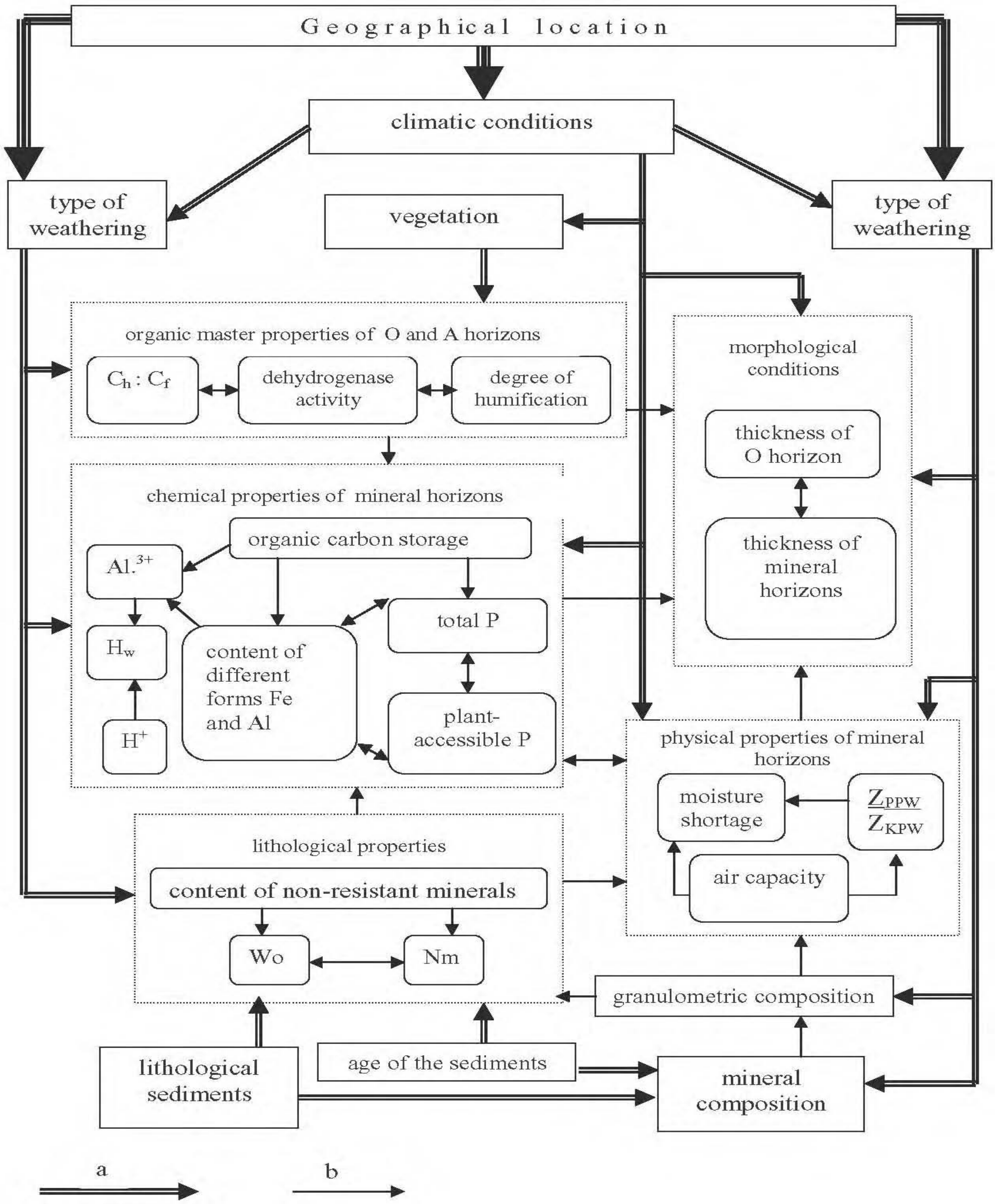


Figure 44. Relationship between pedogenic factors and diagnostic features of geographical variability of studied podzolic soils. (a – directions of influence of pedogenic factors into the soil properties, b – relationship between soil properties)

material. This is a result of the time and intensity of chemical or biochemical processes acting on primary minerals. The role of weathering in the formation of the residuum has already been commented on in the soil-science literature as has its influence on the synthesis of secondary clay minerals (Yaalon 1975; Whalley 1979; Duchaufour 1982; Catt 1988; Lahtinen 1994; Bednarek and Prusinkiewicz 1997). This literatures emphasizes the impact of these secondary minerals on the shaping of chemical properties of soils - particularly the proportions between exchangeable cations (Farmer, Fraser 1982) and the buffering of acids (Ulrich 1981, 1988). In the studies presented here, I observed higher proportions of divalent exchangeable cations in the sorption complexes of soils developed in regions further to the south and east. These soils are found in areas with the oldest soil cover characterised by the greatest contents of secondary clay minerals (Pietuchowa 1987).

The division of soils into regions via statistical analysis is associated with the mutual impacts of the morpholithological and biotic-climatic impacts on the shaping of properties of soil cover. Most of the soil profiles form into groups of regions designated on the basis of similarities in soil properties and referencing the extent of different glaciations, or stadials thereof – something that confirms the conditioning role of morpholithological factors in the process of pedogenesis. Sometimes, however, the strength of the relationship between properties of soils developed from formations of very different ages of primary sedimentation is greater than those in areas located within the same or neighbouring glacial periods. For example, the differences between properties of soils developed in the oldest sedimented material (Berezina-Desna Lowland, Northern Podkarpacie) and the youngest (Lapland) were, in the case of certain profiles of podzolic or rusty-podzolic soils, more limited than that between soils arising in formations of the Vistulian Glaciation (Southern Baltic Lakelands) and the Odra Glaciation (Podlasie-Byelorussian Plateau respectively). Hence they are less differentiated by the age of the sedimentation. In the case of properties of podzolic soils, no differences were reported among the profiles of the Southern Baltic Lakelands, the Central Polish Lowlands and the Central Małopolska Upland, i.e. between areas in which the soils developed in material accumulated in the course of two different Glaciations (of the Odra or Vistula). This emphasises the leading role biotic-climatic factors play in steering the development of soil cover – something that has been noted in many earlier studies on the geography of soils (Terlikowski 1951; Crocker 1952; Prusinkiewicz 1961a; Ugolini *et al.*, 1981; Degórski 1985; Huggett 1985; Catt 1988; Bednarek, Prusinkiewicz 1997; Liski *et al.*, 1997; Manikowska 1999).

The location of the study area within two physiognomic and ecological plant formations – mesophilic and hygrophilous coniferous forest and mesophilic broadleaved and mixed/coniferous forests (Bohn *et al.*, 1996) - has an influence in diversifying the biotic factors, and thus the current course of pedogenic processes. The courses of accumulation, decomposition, and the vertical distribution of organic matter in profiles are dependent on the geographical location of the pedon in the given spatial vegetational and ecological unit (Duchaufour 1982; Catt 1988).

The mutual impacts of these two groups of pedogenic factors (the morpholithological and the biotic-climatic) shaped the soils through the following kinds of spatial differentiation:

1. in Lapland, there are soils developed from the youngest glaciofluvial sediments of the Eoholocene that show strong contemporary processes of destruction of the soil substratum (very different from others);
2. in Ostrobothnia, the Finnish Lakelands, the Coastal Region and Eastern Baltic Lakelands, there are soils developed from glaciofluvial sediments of the Late Vistulian (which in the case of the rusty-podzolic soils show marked similarity to other sites as regards material accumulated during the Plenivistulian);
3. in Western Baltic Lakelands and Southern Baltic Lakelands, soils developed from glaciofluvial sediments of the Plenivistulian (in the case of podzolic soils of the western part of the study area not showing differences with others on material of the Warta Stadial to the Odra Glaciation)
4. soils developed from glaciofluvial sediments of the Odra Glaciation, divided into three geographical units located from east to west:
    - the Central Polish Lowlands and Central Małopolska Upland (western part of the study area) – with the greatest degree of oceanicity of climate and material accumulated mainly during the Warta Stadial of the Odra Glaciation;
    - the Podlasie-Byelorussian Plateaus, characterised by a transitional climate between the western and eastern parts of the area and associated with the accumulation of geological material during the maximal range of the Odra Glaciation;
    - the Berezina-Desna Lowland (eastern part of the study area), with the greatest continentality of climate, and material accumulated during the pre-maximal stadial of the Odra Glaciation.

In contrast, there were no differences reported between the profile developed in the oldest sediments associated with the San II Glaciation and the soils developed in sediments of the Odra Glaciation. The profile in question revealed many features in common with the soils in Podlasie-Byelorussian Plateau. The lack of significant differences between the properties of these soils could have been influenced by the superficial covering of the older sediments by younger ones (Maruszczak and Wilgat 1956; Buraczyński 1993; Maruszczak 2001). The development of soils in this region thus proceeded in lithological, biotic and climatic conditions similar to those developed in younger geological material.

There was a considerable degree of concordance between the arrangement of the studied profiles on the basis of analysis of similarities in the properties of pedons, as well as the adopted division to the macrostructural, superficial generation of soils (after Kowalkowski, 1988). Notwithstanding the more limited spatial range of rusty-podzolic soils (not shown to occur in Lapland), the remaining part of the study area was characterised by a significant statistical linkage between the two types of podzolic earths analysed even though there are great differences in their macrostructural, superficial generation. However, in comparison with podzolic soils, rusty-podzolic soils are characterised by a lesser strength of statistical linkage with lithological properties of the substratum.

Spatial categorization revealed the complex nature of the impact of pedogenic factors, which are in addition dependent on the time function in pedogenesis. Pedogenic processes – dynamic phenomena described by certain soil scientists as cyclical and pulsating (Jenny 1941; Kowalkowski 1988, 1993) – proceed in conditions of the natural environment that change over time (Yaalon 1975, Catt 1988; Manikowska 1999). In addition to the results of long-term research on the pedogenesis of soils in Central Poland (as carried out by Manikowska, 1999), this study shows that – following the Warta Stadial of the Odra Glaciation – the central and southern regions of the analysed area experienced three main pedogenetic periods: the Eemian/Early Vistulian, the central Plenivistulian, and the Late Vistulian/Holocene. The onset of development of the studied soils is linked with these periods. However, the most important pedogenic phase, in which the contemporary soil cover developed, is the period of the Late Vistulian and Holocene (Catt 1988; Kowalkowski 1990. 2001; Bednarek 1991; Nowaczyk 1994; Bronger, Catt 1998; Manikowska 1999). The concept of the development of spatio-temporal pedological systems (Jenny 1983, Kowalkowski 1993), treats soil cover as a continuum functioning in changing space-time (Morozowa 1994; Manikowska 1999; Friedrich 1999; Kowalkowski 2001). Following this concept, the podzolic and rusty-podzolic soils of central and northern Europe form a chronosequence (in the meaning of Vreeken 1975) characterised by the same direction of development. This was developed in geological material of a similar nature from the morphogenetic point of view (Aho 1979; Lahtinen and Korhonen 1996; Degórski 1998a) although with a different age of primary sedimentation and period of impact of exogenous processes on the substratumand resulting in a different duration of weathering processes. A lithological material comprises re-deposited, polygenetic formations of glaciofluvial sands that accumulated at different times. In spite of the similar morphogenesis of the studied areas (glaciofluvial accumulation of material), certain fundamental differences and spatial variability of textural properties of the soil substratum were noted. These related, not only to the age of sediments, but also to the type of exogenous process. The younger the sedimented material (characterised by a shorter period of disintegration and eluviation), the richer soils are in feldspars and non-resistant minerals in the heavy fraction,. The younger sediments, with a much shorter path of transport of sand grains, are also characterised by their weaker abrasion and much more limited non-uniformity of material as compared with older formations that were subject to processes of surface denudation at least twice – in the Lower and Upper Plenivistulian (Manikowska 1999). The material of the older formations was also transferred over longer distances, something which influenced the degree of abrasion of quartz grains. In contrast, in younger formations (Lapland), processes of frost-induced weathering promoted a greater share of grains with early stage of abrasion (α) in the graniformametric composition of the substratum. The elevated amounts of early stage abrasion of quartz grains (characteristic of the juvenile type of grain) in areas active contemporarily have been noted in studies by Whalley (1975); Yaalon (1975); Kowalkowski and Mycielska-Dowgiałło (1985); Catt (1988); Kowalkowski (1993); and Kowalkowski and Kocoń (1998).

Where the fine earth element in granulometric composition is concerned, the soils studied are not shown to differ significantly from one another. The glaciofluvial formations from which they developed represent loose sands, albeit ones of very different shares of the skeletal fraction. The greatest contents of this fraction characterise the soils of the northern part of the study area, confirming the existence there of a very active morphogenic and pedogenic environment, and pointing to the limited transport of lithological material.

An active morphogenetic environment causes the surface enrichment of soils in the northern regions of the dusty fraction. The augmentation of this fraction within the granular composition was also observed in soils associated with the formations of the Odra Glaciation during which they were transformed by periglacial processes - in the Vistulian, mainly. This is best seen in the soils of Belarus and southern Poland Melke (1997) has also noted similar granulometric composition of brown soils in northern and central Europe.

Granular composition is one of the factors influencing densities of the studied soils. In the northern parts of Europe, greater bulk densities also reflect a major content of organic carbon as well as a concentration of plant roots in the upper part of the profile. The influence of organic matter in developing the bulk density of podzolic soils has been demonstrated previously in other parts of the world by Alexander (1989), as well as Huntington *et al.*, (1989), among others.

Greater the impact of chemical weathering is found further south. This is a factor inducing enrichment with colloidal molecules. Nonetheless, in the acidic environment of podzolic earths, they are unstable, soluble, and washed out of soil to the extent that the correlations between geographical location of a profile and the content of colloidal molecules are not statistically significant. The augmentation of the clayey fraction in certain profiles is local in character. Nevertheless, it has an influence on the trophic status of habitats. In the nutrient-poor environment that podzolic earths represent, even very limited differences in the content of the clayey fraction, especially that of a colloidal nature, are of great significance in shaping physico-chemical properties (Adamczyk 1965; Białousz 1978; Catt 1988; Boul *et al.*, 1989; Degórski 1990, 1998a). Similarly, textural properties as regards quarts grains are important (Whalley 1979).

Irrespective of the geographical scale in differences in petrographic, granulometric and graniformametric properties, lithological material exerts an influence on the development of other physical and chemical properties of the studied soils (Fig. 44). A greater role of the fine fractions within the granulometric composition of podzolic and rusty-podzolic soils is one of the reasons for the more favorable water-related and aerial properties of the soils in the Podlasie-Byelorussian Plateau, Berezina-Desna Lowland, and Silesian-Cracovian; i.e., those developed in old-glacial lithological material subject to the most prolonged processes of weathering and combined with the high content and best quality of humus (greatest value of Ch : Cf). It is in their profiles that the greatest quantity of water is retained in the capillary water capacity (KPW) state, the greatest moisture maintained in the face of free gravitational flow of water (PPW), and maximal adsorption of water vapour (MH) takes place. This high water capacity occurs simultaneously with good aeration. This is also favored by greater porosity of these soils than of the remaining profiles studied.

The spatial variability in properties of the substratum also relates to the direction of the differences in biochemical soil properties that are most strongly associated with biotic-climatic elements like hygrothermal relations or the type of biochemical weathering. The shorter periods of biological activity in the environment occurring in northern and eastern regions limit the processes of humification and mineralization. This also favors the accumulation of organic matter, as is manifested in differentiation of the spatial reserves of carbon organic (Degórski 2001c). The literature tends to accept that regional differences in reserves of organic carbon result from the time of accumulation in soil horizons (Liski *et al.* 1997). In areas with slower processes of mineralisation and humification of organic matter, diagnostic horizons have older fractions of carbon than in areas of enhanced biological activity. On the basis of ^{14}C datings of organic matter done in different regions of Europe, the oldest fractions of carbon in the Bh horizon (assigned an age of 1942 years) occur in northern Sweden. There are 1260-year-old ones in central Sweden (Tamm and Ostlund 1960) and 560-year-old ones in France (Guillet 1979). The mineral parts of the profiles of northern regions have processes of the accumulation of organic carbon and then its mineralisation that have been proceeding at one-third or one-quarter of the speed characteristic for the soils in the southern part of the study area. The limited biological activity of soils located in the north and east of the research area is confirmed by the low activity of lactic dehydrogenase in the organic horizon. Low temperature, as well as the slowing of the uptake of nitrogen by microorganisms and even temporary immobilisation thereof, may be among the causes (Coleman, Crossley 1995; Robertson *et al.*, 1999). These areas are also characterised by a lower overall biomass of soil macro- and microfauna, in comparison with the south-western regions of the study area (Jefremow and Degórski 1998; Khotko 1998; Olechowicz 1998).

Bearing in mind the knowledge on geographical differences in reserves of organic carbon in podzolic earths, one of the factors determining the value thereof is the hygrothermal conditioning. This influences the rate of decomposition of organic matter (Prusinkiewicz 1961a; Kononowa 1968; Dziadowiec 1990; Breymeyer *et al.*, 1997, 1998; Breymeyer and Laskowski 1999), its humification and mineralisation (Volobuev 1964; Witkamp 1966; Lahdesmakki, Piispanen 1988; Dziadowiec 1990) and the cycling of carbon in the ecosystem as conditioned by habitat fertility and vegetational structure (Liski 1995).

The greatest total organic carbon (C_{to}) and of carbon extractable in sodium pyrophosphate (C_p) are present in the soils of southern Lapland and Finnish Lakelands with respect to a north-south distribution. These are greatest in soils of Berezina-Desna Lowland when it comes to the E-W dimension. Greater humidity and soil moisture as well as a shorter period of biological activity in the environment limit processes of mineralisation and favor the accumulation of organic matter in these regions.

Forest ecosystems – especially coniferous ones – provide specific conditions for the formation of soil humus. Its generation is favored by a continuous fall of litter with an acid reaction (Volobuev 1964; Puchalski, Prusinkiewicz 1990). As a rule, this is a humus saturated with a relatively large quantity of functional groups containing oxygen (Kononowa 1968 of the most mobile fractions. Humus of such a chemical composition shows an affinity for forming linkages with iron and aluminium (Dziadowiec 1976, 1990; Pokojska 1992; Bergelin *et al.*, 2000) that, in wet conditions, easily wash down through the profile (Lundström *et al.*, 2000b). The organic horizons of all of the podzolic earths are dominated by first-extraction fulvic acids. While shares of humic acids and humins were observed to be greater in older soils, all of those studied had ratios of humic acids to fulvic acids below unity (in the range 0.26 to 0.96), indicating that the humus has a limited degree of condensation of aromatic rings very typical of soils with advanced illuviation (Kononowa 1968).

Forms of iron (Fe_p) and aluminium (Al_p) are associated with organic matter and are linked to the geographical variability ino reserves of organic carbon. The greatest values were reported in soils of the northern and eastern parts of the study area. In the northern regions, the greater incidence of pedogenic linkages, especially with organic matter (p), show the greatest content of iron and aluminium in parent material to be found in any of the pedons studied. Here, the process of weathering of soil material is intensive and the aforementioned fractional composition of humus is characterised by a threefold prevalence of fulvic over humic acids. This dominance of acids of the first fraction is responsible for linkages with metals (Konecka-Betley 1968; Yaalon 1975; Bednarek 1991; Bergelin *et al.*, 2000; Lundström 2000b).

The northern part of the research area also reported the greatest concentrations of the forms of phosphorus (total and plant-available). Research carried out to date has noted the major affinity of the content of inorganic forms of iron (Fe_{ac}) and aluminium (Al_{ac}) for phosphates (Mc Keague *et al.*, 1971; Pokojska.1979c; Mokma 1991). The largest amounts of inorganic forms of iron and aluminium, as well as reserves of carbon, were reported in these very soils from Lapland. This may also link up with the higher content of phosphorus in these soils. Soil-science literature reports that the movement of phosphorus through podzolic soils takes place by way of three-component humic acid-metal-phosphate complexes (Sinha 1971; Pokojska 1976, 1979c; Czępińska-Kamińska 1992). The greatest differences in the vertical distribution of forms of phosphorus in pedons with the greatest contents of inorganic forms of iron and aluminium and humus were found in the northern and eastern sites in this study. Inorganic forms of iron and aluminium, as well as the content of organic matter, were higher than in the central part of the research area, on the Podlasie-Byelorussian Plateau and at Berezina-Desna Lowland. One of the reasons for the lower content of forms of inorganic iron (Fe_{ac}) and aluminium (Al_{ac}) in soils of this part of the continent may be the inhibitory influence of organic matter on the crystallisation processes for compounds of iron and aluminium (Schwertmann 1966, Pokojska 1979c). This is especially true of humic acids (Skłodowski 1974; Bergelin *et al.*, 2000). Their share in the fractional composition of the humus of Polish and Belarussian soils is greater than in the pedons of regions located in the north of the research area.

A greater content of humic acids in the fractional composition of humus from soils originating from old glacial material (as opposed to others) may also be a cause of the obstructed crystallisation of iron oxides in the southern and eastern regions of the research area. The role humus plays in slowing down the crystallisation of iron by organic matter and phosphate ions has been documented (Schwertmann 1964, 1966; Pokojska 1976; Bednarek, Pokojska 1996; Melke 1997). Although the studied soils display lower values for the Schwertmann index (Fe_o/Fe_d), in line with the age of sediments as well as soil, the differences in profiles are not statistically significant. The limited differentiation may be a consequence of the fact that active forms of humus increase in abundance as one moves to sites further to the south or east. The content of “young” oxides of iron is lowest the easternmost part of the area (profile 24), which developed on the oldest sedimentary material.

Many studies in the palaeopedological field have shown that, when it comes to soils developed from similar lithological material under similar topoclimatic conditions, greater age is associated with a higher degree of transformation of iron silicates into oxides of the element (Pokojska 1979a; Catt 1988; Arduino *et al.*,1986; Mokma 1991; Bednarek and Pokojska 1996). One of the manifestations of this is a greater proportion of free iron (Fe_o) within the total content of this element in the soil. These results are similar to the aforementioned thesis. The greatest content of Fe_o in $Fe_z$was generated over a very long period of time, mainly in periglacial conditions, in the profiles in Podlasie-Byelorussian Plateaus and Berezina-Desna Lowland; i.e., areas of markedly transformed lithological material,.

Moreover, high shares of Fe_d in Fe_z were also reported in the soils of Lapland, which have been shaped on the youngest geological material, but develop in conditions of ongoing severe weathering (mainly of a cryogenic nature) and very high levels of soil moisture. This points to a pedogenic environment that remains very active to this day. Similar observations have been presented for areas of northern Europe (Sweden and Spitsbergen) by Yaalon (1975); Catt (1988); Plichta and Kuczyńska (1991); Kowalkowski (1995, 1998) and Melke (1997), as well as for the Antarctic by Blume *et al.*, (1996) Here, emphasis is placed on the role a very active pedogenic environment plays in the transformation of silicates of iron into oxides of that element.

The differentiation in the climatic factors on weathering also influences the course of ongoing pedogenic processes and the shaping of soil properties (e.g. water relations, acidity, sorption properties, etc.) - Fig. 44. In the northern and eastern parts of the area studied, the weathering of rocks is great enough to ensure that the content of exchangeable base cations (above all magnesium) in the eluvial horizon is greater than that in the Bh sub-horizon. This occurs in spite of the fact that precipitation is much greater than evapotranspiration resulting in severe downwashing of these profiles. In contrast, in regions further to the south-west, we find ever-greater amounts of exchangeable cations (mainly divalent) in the enrichment sub-horizon Bh as compared with the eluvial horizon. This occurs in spite of the fact that conditions for sorption in this sub-horizon are unfavorable because of their acid reaction, while divalent cations are of limited lability. There is faster weathering in the north of the study area and extensive washing-through of the profile and eluviation of magnesium ions. Eluviation of exchangeable magnesium and other exchangeable base cations from the E horizon is frequently greater than the amounts liberated from weathering rock (Alexander *et al.*, 1994). This occurs even though the parent rock in this part of Europe is richer in this element than in other areas (Sairanen 1990; Lahtinen 1994). According to Jersak *et al.* (1995), the podzolic soils of Holocene origin in north-eastern regions of the USA have losses for the total mass of all exchangeable base cations are equal to $10^2 – 10^5$ $kg.ha^{-1}$. These losses are somewhat balanced by organic matter, which represents an important source of exchangeable base cations.

Spatial variability in chemical and physical properties in the different genetic horizons are greatest in the parent rock of the studied soils. Sands, being poor in chemical components and characterised by physical properties unfavorable relative to the functioning of the pedosphere, are a very dynamic element. They change their properties across a wide spectrum of values in the face of minor changes in pedogenic factors.As the author stressed in his previous studies (Degórski 2001b), the greatest heterogeneity is indeed characteristic of the organic horizon. Composition of the overlying humus was very limited because of the ”mixed sample” method used in collecting material and that the main components are pine needles and dead plants of the herb layer - be these hemicryptophytes, mosses or lichens – (Solon 1998). Organic matter was thus operating as a “leveling” factor evening out differences in the physico-chemical properties of the organic and humus horizons. This result confirms findings from earlier work by the author carried out in the soil catena in an area of central Poland (Degórski 1990). The greatest similarity between profiles was characteristic of the diagnostic sideric (Bv) horizon in rusty-podzolic soils, as well as the Bfe (enrichment) sub-horizon in the podzolic soils.

Vertical and horizontal variation in pedogenic factors was significantly linked to the geographical location of pedons in 47% of the features analysed (24 of the 51). Many of these factors are mutually synergistic (Fig. 44). These can therefore be considered diagnostic indicators of the geographical variability in pedogenic conditions. Local habitat is the decisive element shaping the remaining soil properties.

It is noteworthy that more than 70% (17 out of 24) of the properties shown to be of diagnostic value in respect to spatial differences (those showing statistical linkage with geographical location in the N-S or E-W directions) are present in both podzolic and rusty-podzolic soils. They are regarded as”universal” features for the geographical location of the two types of pedon. They include the following:

- thickness of the organic horizon,
- thickness of the soil solum,
- content of non-resistant minerals in the soil’s heavy fraction,
- the granulometric heterogeneity to the soil substratum,
- degree of processing of lithological material,
- deficit in moisture in relation to field capacity,
- the ratio between the reserve of soil water in the field-capacity state to that in the capillary capacity state,
- the air capacity,
- the reserve of organic carbon,
- the C_h to C_f ratio,
- the degree of humification,
- lactic dehydrogenase activity,
- total and plant-available P,
- exchangeable aluminium,
- exchangeable hydrogen,
- exchangeable acidity
- the relationship between different forms of aluminium and iron.

The high coefficients for the correlations between the spatial variability of universal soil features and indices characterising pedogenic factors offer support for the idea that a significant influence on the contemporary properties of soils has been exerted by the process of podzolization. This result is confirmed by the work of Manikowska (1999) and Janowska, which points to an optimum for the emergence of rusty soils in the pre-Boreal and Boreal periods, that is, an optimum for the origin of podzolic soils in the Atlantic period. It was the Late Vistulian/Holocene phase of development that gave rise to soil cover in central Poland. Podzolization is thus younger, and capable of transforming rusty soils into rusty-podzolic ones. The intensity of illuviation was great enough to ensure that. in all profiles but number 39, the values of the index for the transfer of amorphous forms of iron and aluminium [(Al_o + 0.5 Fe_oB)/(Al_o + 0.5 Fe_oE or AE)] met the requirements adopted by the WRB (1998) as one of the criteria by which to assess the presence of the podzolization process. This confirms the suitability of jointly considering the spatial variability of properties associated with podzolic and rusty-podzolic soils. It is the result of the impact of a similar set of geographically-diversified soil-forming factors, wether these are morpholithological or biotic-climatic.

A summary of the results supports the idea that the similarities among the analysed pedons allow for a geographically-based division of the studied podzolic eatrhs into two zones (I and II) and regional sub-zones (a, b, c).

1) Zone I – the podzolic earths of coniferous and mixed/coniferous forests within mesophilic and hygro-mesophilic vegetation formations of coniferous forests associated with a cool temperate climate.

   Sub-zones:

   a). Mesoholocene-Neoholocene illuvial-humus podzolic soils of coniferous forests within the regional vegetation formation of the North Boreal coniferous forests. These occur in conditions of a very humid climate in which there is a marked prevalence of precipitation over evaporation, in areas today characterised by very active pedogenic environments in which the soil substratum comprises the youngest Eoholocene sediments (as in Lapland). These soils are characterised by limited thickness, as well as intensive downwashing. These factors are favored by the glaciofluvial material with its typically large share of coarse-grained sands and a gravelly-stony fraction. Typical in such soils is a considerable accumulation of humus in the organic horizon, as well as greater biological activity in the upper parts of the humus horizon. The fractional composition of the humus is dominated by first-extraction fulvic acids associated with mobile R_2O_3 forms, while the ratio of fulvic to humic acids is below 0.4. The ratio of total organic carbon to total nitrogen (C:N) is greater in these soils than any of the others studied (Table 31). The ammonium form of nitrogen prevails, and this favors the development of ecosystems with Scots pine. The intensity of cryogenic weathering processes, be these physical or chemical or both, increases the rate of breakdown of aluminosilicates. The soils contain considerable amounts of free iron (Fe_d), as well as amorphous forms of the element (Fe_o).They also contain aluminium (Al_o), as well as the greatest contents of silicate forms of iron (Fe_{gk}). The podzolization process is very intensive, as is confirmed by the very high values obtained for indices of illuviation (determined in line with criteria from Mokma, 1983). Also confirming podzolization is the content of iron-aluminium-humus complexes in the enrichment horizon (C_p + Al_p + Fe_p), the transfer of amorphous iron and aluminium (Al_o + ½ Fe_o in the B horizon to Al_o + ½ Fe_o in the E horizon), and the transfer of free iron (Fe_d in horizon B to Fe_d in horizons E or AE) – Table 31.

b). Holocene podzolic and rusty-podzolic soils of coniferous or mixed/coniferous forests. These are developed from Late Vistulian sediments (in Ostrobothnia, the Finnish Lakelands and the Eastern Baltic Coastland and Lakelands), which occur in what are today conditions of a very humid climate, in the zone of the regional vegetational formation of the Central and Southern Boreal coniferous forests. In comparison with the soils of the Northern Boreal coniferous forests, these are characterised by greater thickness, as well as more favorable physical properties. They also contain much more organic matter. The fractional composition of their humus has a greater share of humic acids, although values for the ratio of fulvic to humic acids remain very low – in the range 0.4 to 0.6 (Table 31). The greatest biological activity is shown by the organic horizon, in which lactic dehydrogenase activity is greater than in the humus horizon.

2) Zone II – podzolic earths of coniferous (mostly pine) and mixed/coniferous forests of the vegetational formation of mesophilic broadleaved forests and mixed/coniferous forests in a warm temperate climate.

Sub-zones:

a). Late Vistulian/Holocene podzolic and rusty-podzolic soils of coniferous and mixed/coniferous forests developed from Plenivistulian sediments (Western and Southern Baltic Lakelands). They occur today in conditions of a temperate and humid climate of a lowland zone featuring the regional vegetational formation of beech forest and mixed/beech forest. As in the case of the soils of Lapland and the Finnish Lakelands, they are characterised by the greatest contents of amorphous forms of iron and aluminium, as well as a limited proportion of crystalline forms of Fe. This attests to their young age. The limited degree of weathering of soil material is also confirmed by the large shares of non-resistant minerals within the mineral composition of the heavier fraction, and silicate forms of iron (Fe_{gk}). They are also characterised by a very limited share of humic acids within the fractional composition of their humus. The

Ch:Cf ratio for rusty-podzolic soils of this sub-zone have lower values than in any of the other pedons (Table 31).

b). Neopleistocene/Holocene podzolic and rusty-podzolic soils of coniferous and mixed/coniferous forests, with a multiphasic cycle of development. These developed from sediments of the Warta Stadial to the Odra Glaciation (in the Central Polish Lowlands, Central Małopolska Upland and Silesian-Cracovian Upland). They now occur in conditions of an adequately humid climate, in the zone of the lowland form of the regional vegetational formation of mixed/oak-lime-hornbeam forests. The nature of the area as one of geographical transition exerts an influence on the soils as they develop. Values for properties tend to be intermediate between those characterizing areas of the youngest or oldest soil cover (Table 31).

c). Meso- and Neopleistocene/Holocene podzolic and rusty-podzolic soils of coniferous and mixed/coniferous forests, with a multiphasic developmental cycle. These developed from sediments of San II Glaciation and the pre-maximal and maximal stadials of the Odra Glaciation (Northern Podkarpacie, Podlasie-Byelorussian Plateau and Berezina-Desna Lowland). They occur today in conditions of a markedly humid climate, in a lowland zone featuring the regional vegetational formation of hemi-boreal and nemoral Scots pine forest. These are characterised by the most favorable physical properties of any of the studied pedons because they experienced the longest period of impact of exogenous factors on the soil substrata. Their granulometric composition features the greatest shares of the dusty and clayey fractions. They are also characterised by the greatest contents of organic matter, an aspect which combines with granular composition to make these soils the most porous. In the eastern part of the sub-zone, as in northern Scandinavia, there is greater biological activity in the upper part of the humus horizon as compared with the O horizon. The fractional composition of humus is dominated by first-extraction fulvic acids, as in the soils of the other geographical units, but the ratio of fulvic to humic acids is greatest for these soils amounting to between 0.6 and 0.7 in the podzolic soils, and 0.9-1.0 in the rusty-podzolic soils. The values for the ratio of total organic carbon to total nitrogen (C:N) are the lowest in this sub-zone (20), confirming the greatest level of biological activity and in lactic dehydrogenase activity these soils. The Bh enrichment sub-horizon has a value of 16 and the BfeBv enrichment horizon one of 11, as compared to the means for all podzolic soils of 27 in A, 28 in Bh, as well as for rusty-podzolic soils of 24 in A and 16 in BfeBv. These soils also differ in their greater shares of divalent cations in the sorption complex, as well as the degree of saturation of that complex in base cations. The greater shares of divalent cations are determined by amounts of secondary clay minerals that are higher in these soils than in the younger ones arising in other regional sub-zones. The prolonged impact of factors destructive of the soil substratum combined with the course of pedogenic processes is visible, not only in textural properties of sediments (e.g. very limited shares of non-resistant minerals in the fraction of heavier lithological material), but also in physico-chemical properties. This is best conveyed by the diagnostic chemical indicators. The soils of this sub-zone are also characterised by the greatest values for the Fe_d/Fe_z index. This confirms their greatest weathering (most silicates of Fe converted into oxides), as well as lowest values for the Fe_o to Fe_d ratio attesting to the "age" of the lost oxides of Fe and their crystallisation (Bednarek and Pokojska 1996. All this in spite of the fact that the extant climatic conditions do not favor these processes. The very longlasting and intensive process of podzolization in these pedons is confirmed by the greatest values for the index of illuviation ($\sum_B C_p Al_p Fe_p$ - $\sum_A C_p Al_p Fe_p$) according to Mokma (1983) criteria, as well as that of the contents of amorphous iron and aluminium (Al_o + ½ Fe_o in the B horizon to Al_o + ½ Fe_o in the Ees or AEes horizons) - Table 31

The proposed division could supplement existing divisions into soil-geographical regions (Głazowska 1981; Boul *et al.*, 1989). In comparison with these, the presented proposal for the geographical division of podzolic earths has combined within one spatial unit the sub-zones of the central and southern taiga. Differences in the analysed soil properties in these two sub-zones did not differ in a statistically significant manner. One of the main reasons for this could be the restricting of analyses to only forest soils. According to Russian researchers, deforested areas of the southern taiga very characteristically fall within the turf-podzolic soil category. The physical and chemical properties of this soil category represent a significant taxonomic factor in the division of the podzolic soils of the permafrost-free zone of the taiga (Głazowska 1981; Bednarek, Prusinkiewicz 1997). According to soil systematics in force in Poland, these would be closer to lessive soils.

The presented spatially-conditioned differentiation of the analysed soils suggests a division of the zone of podzolic earths in the warm temperate climatic belt into regional sub-zones. The spatial division of this area, reflecting soil properties that are statistically different is confirmed by the now-accepted concept for the spatial differentiation of the physiological-ecological vegetational formations of Europe (Bohn *et al.*, 1996 and in the variability in the morpholithological properties of the substratum from which they are developed.

The work presented has confirmed the many difficulties with methodology and interpretation that are inherent in the pursuit of research on the spatial differentiation of soil cover at a supra-regional level. Soil as a component of the landscape (Huggett 1975; Kowalkowski 1993, 2001; Degórski 2001b); i.e., as a spatial unit that is both a product of the natural environment and a shaper thereof (Terlikowski 1951; Catt 1988; Puchalski, Prusinkiewicz 1990; Szafranek 2000), and is characterised by great variability of properties, irrespective of the level of spatial organisation (Degórski 2001b). This interactive relationship between soil and the environment ensures that its properties are shaped by a set of pedogenic factors dependent on site morphology and lithology plus climatic conditions and factors created by the soil itself. There would thus seem to be every justification for the division of the properties of soils proposed by Głazowska (1981), envisaging "permanent" properties linked with pedogenesis of the given soil, as well as "supplementary" ones resulting from mutual dynamic interlinkage between the pedon and the natural environment.

In recent years, it has become particularly important to appreciate the interdependences governing the relationship between the pedosphere and the factors shaping it. In these days of intensifying population pressure and global changes in the natural environment, a precise knowledge of the relationship between spatial variability in soil properties and the geographical differentiation in pedogenic factors will be important in forecasting the directions to pedospheric change. For this reason, the many difficulties of both a methodological and technical nature and the necessarily long period of research, should not discourage continuation of this work and its extension of it into other types of soil and other regions.

Conclusion

The analysis conducted in this research supports several conclusions relative to the spatial differentiation in podzolic soil properties in northern and central Europe.

1. The time-dependent conditioning role of the morpho-lithological factor and the steering role of the biotic-climatic factor were confirmed where the process of pedogenesis in the studied podzolic soils was concerned.
2. The spatial division of the studied podzolic soils based on similarity analysis of properties defining the direction and type of pedogenic processes can be related to: the age of the original sediments expressed by reference to glaciation, the textural properties of the substratum from which the pedons are shaped, and the ecological and physiological plant formations and climatic (especially hygrothermic) conditions.
3. The soils present in similar hygrothermic conditions and shaped from lithological material of different geological periods have similar chemical properties, thereby attesting to the important influence of the biotic/climatic factor of the pedogenic process in relation to age.
4. Soils of similar granulometric composition do not merely differ in grain size. A large role in the spatial differentiation of primary and secondary physical properties (as well as some chemical properties) is played by the local environmental conditioning, and especially the organic-matter content.
5. Some pedogenic diagnostic features may be regarded as diagnostic indicators of the spatial variability of soils. These include:
   - the content of amorphic iron and aluminium (Al_o + ½ Fe_o) in the illuvial horizon (spodic and syderic),
   - the content of iron-aluminium-humus complexes (C_p + Al_p + Fe_p) in the enriched illuvial horizon, both spodic and sideric,
   - the magnitude of the index for the movement of free iron in profiles (ratio of Fe_d in B to Fe_d in E),
   - the degree of illuviation ($\sum_B C_p Al_p Fe_p - \sum_A C_p Al_p Fe_p$),
   - the molar ratio [$C_p/(Fe_p + Al_p)$] in the spodic and sideric zones of enrichment.
6. Among the properties of podzolic and rusty-podzolic soils, the universal diagnostic features of their differentiation; i.e., those showing statistically-significant relationships with geographical location, were:
   - thickness of the organic horizon,
   - thickness of the soil solum,

- non-resistant minerals in the soil's heavy fraction,
- granulometric heterogeneity of the soil substratum,
- degree of abrasion of lithological material,
- temporary soil moisture deficit in relation to field capacity,
- ratio of the stock of soil at field capacity to the stock in a state of capillary water capacity,
- air capacity,
- stock of organic carbon,
- ratio of the huminic to fulvic acid contents,
- degree of humification,
- lactic dehydrogenase activity,
- total phosphorus and plant-available phosphorus,
- exchangeable aluminium,
- exchangeable hydrogen ions,
- exchangeable acidity,
- the relationships between forms of aluminium and iron.

7. The following groups of regions were obtained based on the statistical similarity of all of the studied pedogenic and pedological properties:
   - 6 groups of podzolic soils:
     - Lapland,
     - Ostro-Bothnia and the Finnish Lakelands,
     - Eastern Baltic Coastland and Eastern Baltic Lakelands,
     - Podlasie-Byelorussian Uplands and Northern Podkarpacie,
     - Berezina-Desna Lowland,
     - Southern Baltic Lakelands, Central Polish Lowlands and Central Małopolska Upland.
   - 4 groups of rusty-podzolic soils:
     - Finnish Lakelands and Eastern Baltic Lakelands,
     - Western and Southern Baltic Lakelands,
     - Podlasie-Byelorussian Uplands and Berezina-Desna Lowland,
     - Central Polish Lowlands and Silesian-Cracovian Upland.
8. The spatial variability in pedogenic factors and the properties of the pedons studied showed geographical differences in podzolic soils that were divided into two zones and five regional sub-zones:

- The Holocene and Late Vistulian-Holocene podzolic soils of pine and mixed/pine forests in the vegetation formation of mesophilic and hygromesophilic coniferous forests of the cool-temperate climate:
  - meso-Holocene/eo-Holocene illuvial-humic podzolic soils of pine forests within the north-Boreal coniferous forest regional vegetation formation, in conditions of a highly humid climate, in areas characterised today by a very active pedogenic environment in which the soil substrata are meso-Holocene or youngest eo-Holocene sediments,
  - Late Vistulian-Holocene podzolic and rusty-podzolic soils of pine and mixed/pine forests, developed from eo-Holocene and Late Vistulian sediments, occurring today in conditions of a highly humid climate, in the zone of the Central and Southern Boreal coniferous forest regional vegetation formation,
- Pleistocene-Holocene podzolic soils of pine and mixed/pine forests of the vegetational formation of mesophilic deciduous and coniferous forests in the zone of warm-temperate climate:
  - Plenivistulian-Holocene podzolic and rusty-podzolic soils of pine and mixed/pine forests, developed from Plenivistulian sediments and occurring today in the conditions of a humid temperate climate within the zone of the regional form of the beech and mixed/beech vegetation formation,
  - Neo-Pleistocene-Holocene podzolic and rusty-podzolic soils, developed from sediments of the Warta stage of the Odra Glaciation, occurring today in conditions of a sufficiently humid climate, in the zone of the lowland form of the mixed oak-lime-hornbeam forest regional vegetation formation,
  - Meso- and Neopleistocene-Holocene podzolic and rusty-podzolic soils of pine and mixed/pine forests, developed from the sediments of the San II Glaciation and the pre-maximal and maximal stages of the Odra Glaciation, occurring today in conditions of a highly humid climate, in the lowland zone of the hemi-boreal and nemoral pine forest regional vegetation formation.

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Appendix A. Table 23. Some sorption properties of studied soils.

No. of profile	horizon	H^+	Ca^{2+}	Mg^{2+}	K^+	Na^+	S	T	V	V_H	V_{Ca}	V_{Mg}	V_K	V_{Na}	Ca:Mg	Mg:K	$\frac{Ca+Mg}{K+Na}$	$\frac{Ca+Mg}{T}$ 100%
		cmol(+).kg^{-1}							%									
a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	r	s	t
podzolic soils																		
1	AEes	9.19	0.53	0.09	0.30	0.19	1.11	10.30	10.8	89.2	5.15	0.87	2.91	1.84	5.9	0.3	1.3	6.0
	Ees	6.23	0.45	0.07	0.16	0.04	0.72	6.95	10.4	89.6	6.47	1.01	2.30	0.58	6.4	0.4	2.6	7.5
	Bh	8.72	0.38	0.06	0.27	0.20	0.98	9.70	10.1	89.9	4.64	0.62	2.78	2.06	7.5	0.2	1.1	5.3
	Bfe	4.22	0.32	0.06	0.09	0.09	0.56	4.78	11.7	88.3	6.69	1.26	1.88	1.88	5.3	0.7	2.1	7.9
	C	4.08	0.49	0.08	0.06	0.08	0.71	4.79	14.8	85.2	10.23	1.67	1.25	1.67	6.1	1.3	4.1	11.9
2	AEes	12.34	0.61	0.14	0.19	0.13	1.07	13.41	8.0	92.0	4.55	1.04	1.42	0.97	4.4	0.7	2.3	5.6
	Ees	7.12	0.53	0.07	0.14	0.05	0.79	7.91	10.0	90.0	6.70	0.88	1.77	0.63	7.6	0.5	3.2	7.6
	Bh	9.34	0.34	0.07	0.19	0.16	0.76	10.10	7.5	92.5	3.37	0.69	1.88	1.58	4.9	0.4	1.2	4.1
	Bfe	4.11	0.17	0.04	0.12	0.20	0.53	4.64	11.4	88.6	3.66	0.86	2.59	4.31	4.3	0.3	0.7	4.5
	C	3.23	0.15	0.03	0.03	0.08	0.29	3.52	8.2	91.8	4.26	0.85	0.85	2.27	5.0	1.0	1.6	5.1
3	AEes	23.50	0.52	0.65	0.24	0.18	1.58	25.08	6.3	93.7	2.06	2.58	0.97	0.70	0.8	2.7	2.8	4.6
	Ees	3.45	0.18	0.07	0.03	0.12	0.39	3.84	10.2	89.8	4.56	1.74	0.73	3.14	2.6	2.4	1.6	6.3
	Bh	6.47	0.13	0.05	0.04	0.13	0.35	6.82	5.2	94.8	1.95	0.77	0.52	1.95	2.5	1.5	1.1	2.7
	Bfe	3.90	0.11	0.05	0.04	0.10	0.30	4.20	7.1	92.9	2.62	1.19	0.95	2.38	2.2	1.3	1.1	3.8
	C	2.89	0.11	0.05	0.02	0.11	0.30	3.19	9.3	90.7	3.52	1.60	0.73	3.42	2.2	2.2	1.2	5.1
4	AEes	22.45	0.58	0.15	0.12	0.15	1.00	23.45	4.3	95.7	2.47	0.64	0.51	0.64	3.9	1.3	2.7	3.1
	Ees	2.78	0.08	0.08	0.02	0.03	0.21	2.99	7.0	93.0	2.68	2.68	0.67	1.00	1.0	4.0	3.2	5.4
	Bh	6.32	0.11	0.02	0.06	0.06	0.25	6.57	3.8	96.2	1.67	0.30	0.91	0.91	5.5	0.3	1.1	2.0
	Bfe	2.78	0.16	0.03	0.04	0.03	0.26	3.04	8.6	91.4	5.26	0.99	1.32	0.99	5.3	0.8	2.7	6.3
	C	1.37	0.14	0.01	0.02	0.01	0.18	1.55	11.6	88.4	9.03	0.65	1.29	0.65	14.0	0.5	5.0	9.7
5	AEes	12.90	0.62	0.20	0.42	0.37	1.61	14.51	11.1	88.9	4.27	1.38	2.89	2.55	3.1	0.5	1.0	5.7
	Ees	5.32	0.12	0.06	0.09	0.08	0.35	5.67	6.2	93.8	2.12	1.06	1.59	1.41	2.0	0.7	1.1	3.2
	Bh	6.23	0.24	0.08	0.16	0.12	0.60	6.83	8.8	91.2	3.51	1.17	2.34	1.76	3.0	0.5	1.1	4.7
	Bfe	6.12	0.92	0.15	0.25	0.15	1.47	7.59	19.4	80.6	12.12	1.98	3.29	1.98	6.1	0.6	2.7	14.1
	C	5.14	0.82	0.14	0.29	0.20	1.45	6.59	22.0	78.0	12.44	2.12	4.40	3.03	5.9	0.5	2.0	14.6
6	AEes	15.59	0.85	0.40	0.29	0.22	1.76	17.35	10.1	89.9	4.90	2.31	1.67	1.27	2.1	1.4	2.5	7.2
	Ees	8.89	0.31	0.07	0.03	0.10	0.51	9.40	5.4	94.6	3.30	0.74	0.32	1.06	4.4	2.3	2.9	4.0
	Bh	10.40	0.21	0.03	0.04	0.11	0.39	10.79	3.6	96.4	1.95	0.28	0.37	1.02	7.0	0.8	1.6	2.2
	Bfe	6.49	0.26	0.04	0.03	0.09	0.42	6.91	6.1	93.9	3.76	0.58	0.43	1.30	6.5	1.3	2.5	4.3
	C	1.00	0.15	0.02	0.02	0.01	0.20	1.20	16.7	83.3	12.50	1.67	1.67	0.83	7.5	1.0	5.7	14.2
7	AEes	9.10	0.69	0.40	0.41	0.26	1.76	10.86	16.2	83.8	6.35	3.68	3.78	2.39	1.7	1.0	1.6	10.0
	Ees	5.20	0.56	0.10	0.12	0.10	0.88	6.08	14.5	85.5	9.21	1.64	1.97	1.64	5.6	0.8	3.0	10.9
	Bh	12.23	0.27	0.12	0.15	0.14	0.68	12.91	5.3	94.7	2.09	0.93	1.16	1.08	2.3	0.8	1.3	3.0
	Bfe	4.12	0.14	0.07	0.12	0.12	0.45	4.57	9.8	90.2	3.06	1.53	2.63	2.63	2.0	0.6	0.9	4.6
	C	1.09	0.03	0.05	0.02	0.03	0.13	1.22	10.7	89.3	2.46	4.10	1.64	2.46	0.6	2.5	1.6	6.6
10	AEes	6.53	0.74	0.15	0.34	0.26	1.49	8.02	18.6	81.4	9.23	1.87	4.24	3.24	4.9	0.4	1.5	11.1
	Ees	5.11	0.48	0.08	0.11	0.10	0.77	5.88	13.1	86.9	8.16	1.36	1.87	1.70	6.0	0.7	2.7	9.5
	Bh	10.41	0.32	0.12	0.16	0.16	0.76	11.17	6.8	93.2	2.86	1.07	1.43	1.43	2.7	0.8	1.4	3.9
	Bfe	4.39	0.67	0.23	0.23	0.20	1.33	5.72	23.3	76.7	11.71	4.02	4.02	3.50	2.9	1.0	2.1	15.7
	C	3.86	0.81	0.25	0.34	0.24	1.64	5.50	29.8	70.2	14.73	4.55	6.18	4.36	3.2	0.7	1.8	19.3
11	AEes	15.60	0.63	0.10	0.32	0.18	1.23	16.83	7.3	92.7	3.74	0.59	1.90	1.07	6.3	0.3	1.5	4.3
	Ees	5.51	0.46	0.05	0.10	0.11	0.72	6.23	11.6	88.4	7.38	0.80	1.61	1.77	9.2	0.5	2.4	8.2
	Bh	10.34	0.28	0.09	0.34	0.17	0.88	11.22	7.8	92.2	2.50	0.80	3.03	1.52	3.1	0.3	0.7	3.3
	Bfe	5.78	0.56	0.09	0.30	0.20	1.15	6.93	16.6	83.4	8.08	1.30	4.33	2.89	6.2	0.3	1.3	9.4
	C	3.00	0.46	0.09	0.30	0.26	1.11	4.11	27.0	73.0	11.19	2.19	7.30	6.33	5.1	0.3	1.0	13.4
12	AEes	6.45	0.84	0.24	0.33	0.19	1.60	8.05	19.9	80.1	10.43	2.98	4.10	2.36	3.5	0.7	2.1	13.4
	Ees	5.23	0.76	0.21	0.24	0.12	1.33	6.56	20.3	79.7	11.59	3.20	3.66	1.83	3.6	0.9	2.7	14.8
	Bh	8.43	0.65	0.22	0.31	0.15	1.33	9.76	13.6	86.4	6.66	2.25	3.18	1.54	3.0	0.7	1.9	8.9
	Bfe	2.34	0.57	0.13	0.30	0.16	1.16	3.50	33.1	66.9	16.29	3.71	8.57	4.57	4.4	0.4	1.5	20.0
	C	1.43	0.43	0.08	0.27	0.18	0.96	2.39	40.2	59.8	17.99	3.35	11.30	7.53	5.4	0.3	1.1	21.3
13	AEes	8.32	0.73	0.18	0.28	0.16	1.35	9.67	14.0	86.0	7.55	1.86	2.90	1.65	4.1	0.6	2.1	9.4
	Ees	4.29	0.76	0.16	0.20	0.12	1.24	5.53	22.4	77.6	13.74	2.89	3.62	2.17	4.8	0.8	2.9	16.6
	Bh	6.12	0.31	0.18	0.23	0.13	0.85	6.97	12.2	87.8	4.45	2.58	3.30	1.87	1.7	0.8	1.4	7.0
	Bfe	2.98	0.34	0.15	0.19	0.10	0.78	3.76	20.7	79.3	9.04	3.99	5.05	2.66	2.3	0.8	1.7	13.0
	C	2.01	0.31	0.14	0.14	0.09	0.68	2.69	25.3	74.7	11.52	5.20	5.20	3.35	2.2	1.0	2.0	16.7
15	AEes	2.85	0.64	0.14	0.35	0.17	1.30	4.15	31.3	68.7	15.42	3.37	8.43	4.10	4.6	0.4	1.5	18.8
	Ees	2.76	0.66	0.12	0.23	0.11	1.12	3.88	28.9	71.1	17.01	3.09	5.93	2.84	5.5	0.5	2.3	20.1
	Bh	5.68	0.34	0.18	0.27	0.15	0.94	6.62	14.2	85.8	5.14	2.72	4.08	2.27	1.9	0.7	1.2	7.9
	Bfe	1.78	0.53	0.09	0.28	0.15	1.05	2.83	37.1	62.9	18.73	3.18	9.89	5.30	5.9	0.3	1.4	21.9
	C	1.31	0.45	0.07	0.28	0.14	0.94	2.25	41.8	58.2	20.00	3.11	12.44	6.22	6.4	0.3	1.2	23.1
16	AEes	15.00	0.69	0.13	0.18	0.22	1.22	16.22	7.5	92.5	4.25	0.80	1.11	1.36	5.3	0.7	2.1	5.1
	Ees	3.45	0.61	0.11	0.10	0.16	0.98	4.43	22.1	77.9	13.77	2.48	2.26	3.61	5.5	1.1	2.8	16.3
	Bh	5.67	0.56	0.14	0.12	0.18	1.00	6.67	15.0	85.0	8.40	2.10	1.80	2.70	4.0	1.2	2.3	10.5
	Bfe	5.11	0.41	0.10	0.11	0.17	0.79	5.90	13.4	86.6	6.95	1.69	1.86	2.88	4.1	0.9	1.8	8.6
	C	2.62	0.23	0.07	0.10	0.16	0.56	3.18	17.6	82.4	7.23	2.20	3.14	5.03	3.3	0.7	1.2	9.4

Appendix A continued

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	r	s	t
17	AEes	4.39	0.49	0.09	0.28	0.13	0.99	5.38	18.4	81.6	9.11	1.67	5.20	2.42	5.4	0.3	1.4	10.8
	Ees	3.11	0.64	0.07	0.14	0.07	0.92	4.03	22.8	77.2	15.88	1.74	3.47	1.74	9.1	0.5	3.4	17.6
	Bh	4.12	0.56	0.11	0.30	0.16	1.13	5.25	21.5	78.5	10.67	2.10	5.71	3.05	5.1	0.4	1.5	12.8
	Bfe	2.67	0.41	0.08	0.27	0.16	0.92	3.59	25.6	74.4	11.42	2.23	7.52	4.46	5.1	0.3	1.1	13.6
	C	1.58	0.39	0.06	0.27	0.14	0.86	2.44	35.2	64.8	15.98	2.46	11.07	5.74	6.5	0.2	1.1	18.4
19	AEes	12.56	0.80	0.11	0.28	0.13	1.32	13.88	9.5	90.5	5.76	0.79	2.02	0.94	7.3	0.4	2.2	6.6
	Ees	3.76	0.78	0.08	0.13	0.08	1.07	4.83	22.2	77.8	16.15	1.66	2.69	1.66	9.8	0.6	4.1	17.8
	Bh	4.67	0.42	0.11	0.32	0.19	1.04	5.71	18.2	81.8	7.36	1.93	5.60	3.33	3.8	0.3	1.0	9.3
	Bfe	2.51	0.66	0.10	0.31	0.15	1.22	3.73	32.7	67.3	17.69	2.68	8.31	4.02	6.6	0.3	1.7	20.4
	C	1.84	0.65	0.10	0.27	0.16	1.18	3.02	39.1	60.9	21.52	3.31	8.94	5.30	6.5	0.4	1.7	24.8
20	AEes	8.18	0.48	0.06	0.29	0.12	0.95	9.13	10.4	89.6	5.26	0.66	3.18	1.31	8.0	0.2	1.3	5.9
	Ees	3.11	0.89	0.05	0.18	0.08	1.20	4.31	27.8	72.2	20.65	1.16	4.18	1.86	17.8	0.3	3.6	21.8
	Bh	4.21	0.41	0.21	0.43	0.19	1.24	5.45	22.8	77.2	7.52	3.85	7.89	3.49	2.0	0.5	1.0	11.4
	Bfe	3.45	1.03	0.15	0.39	0.15	1.72	5.17	33.3	66.7	19.92	2.90	7.54	2.90	6.9	0.4	2.2	22.8
	C	2.66	0.93	0.21	0.39	0.18	1.71	4.37	39.1	60.9	21.28	4.81	8.92	4.12	4.4	0.5	2.0	26.1
22	AEes	5.81	1.14	0.18	0.35	0.17	1.84	7.65	24.1	75.9	14.90	2.35	4.58	2.22	6.3	0.5	2.5	17.3
	Ees	3.09	1.23	0.11	0.29	0.12	1.75	4.84	36.2	63.8	25.41	2.27	5.99	2.48	11.2	0.4	3.3	27.7
	Bh	4.29	0.78	0.27	0.43	0.19	1.67	5.96	28.0	72.0	13.09	4.53	7.21	3.19	2.9	0.6	1.7	17.6
	Bfe	2.79	1.09	0.25	0.40	0.17	1.91	4.70	40.6	59.4	23.19	5.32	8.51	3.62	4.4	0.6	2.4	28.5
	C	1.86	1.02	0.21	0.39	0.17	1.79	3.65	49.0	51.0	27.95	5.75	10.68	4.66	4.9	0.5	2.2	33.7
24	AEes	9.69	0.50	0.11	0.30	0.19	1.10	10.79	10.2	89.8	4.63	1.02	2.78	1.76	4.5	0.4	1.2	5.7
	Ees	7.19	0.52	0.09	0.23	0.12	0.96	8.15	11.8	88.2	6.38	1.10	2.82	1.47	5.8	0.4	1.7	7.5
	Bh	8.45	0.31	0.23	0.40	0.16	1.10	9.55	11.5	88.5	3.25	2.41	4.19	1.68	1.3	0.6	1.0	5.7
	Bfe	9.34	0.55	0.21	0.37	0.14	1.27	10.61	12.0	88.0	5.18	1.98	3.49	1.32	2.6	0.6	1.5	7.2
	C	5.40	0.47	0.17	0.28	0.20	1.12	6.52	17.2	82.8	7.21	2.61	4.29	3.07	2.8	0.6	1.3	9.8
26	AEes	3.47	0.23	0.06	0.09	0.15	0.53	4.00	13.3	86.8	5.75	1.50	2.25	3.75	3.8	0.7	1.2	7.3
	Ees	5.87	0.31	0.07	0.10	0.14	0.62	6.49	9.6	90.4	4.78	1.08	1.54	2.16	4.4	0.7	1.6	5.9
	Bh	8.48	0.58	0.11	0.12	0.16	0.97	9.45	10.3	89.7	6.14	1.16	1.27	1.69	5.3	0.9	2.5	7.3
	Bfe	3.12	0.15	0.04	0.08	0.12	0.39	3.51	11.1	88.9	4.27	1.14	2.28	3.42	3.8	0.5	1.0	5.4
	C	1.53	0.17	0.06	0.08	0.13	0.44	1.97	22.3	77.7	8.63	3.05	4.06	6.60	2.8	0.8	1.1	11.7
28	AEes	21.98	1.05	0.21	0.23	0.16	1.65	23.63	7.0	93.0	4.44	0.89	0.97	0.68	5.0	0.9	3.2	5.3
	Ees	4.45	0.36	0.08	0.11	0.15	0.70	5.15	13.6	86.4	6.99	1.55	2.14	2.91	4.5	0.7	1.7	8.5
	Bh	5.30	0.24	0.11	0.15	0.17	0.67	5.97	11.2	88.8	4.02	1.84	2.51	2.85	2.2	0.7	1.1	5.9
	Bfe	4.24	0.18	0.06	0.11	0.15	0.50	4.74	10.5	89.5	3.80	1.27	2.32	3.16	3.0	0.5	0.9	5.1
	C	4.06	0.18	0.06	0.10	0.14	0.48	4.54	10.6	89.4	3.96	1.32	2.20	3.08	3.0	0.6	1.0	5.3
29	AEes	12.30	0.73	0.15	0.16	0.15	1.19	13.49	8.8	91.2	5.41	1.11	1.19	1.11	4.9	0.9	2.8	6.5
	Ees	3.54	0.21	0.05	0.10	0.06	0.42	3.96	10.6	89.4	5.30	1.26	2.53	1.52	4.2	0.5	1.6	6.6
	Bh	4.86	0.27	0.06	0.11	0.16	0.60	5.46	11.0	89.0	4.95	1.10	2.01	2.93	4.5	0.5	1.2	6.0
	Bfe	2.82	0.16	0.05	0.09	0.10	0.40	3.22	12.4	87.6	4.97	1.55	2.80	3.11	3.2	0.6	1.1	6.5
	C	2.28	0.15	0.07	0.09	0.15	0.46	2.74	16.8	83.2	5.47	2.55	3.28	5.47	2.1	0.8	0.9	8.0
32	AEes	13.62	0.19	0.09	0.07	0.11	0.46	14.08	3.3	96.7	1.35	0.64	0.50	0.78	2.1	1.3	1.6	2.0
	Ees	4.92	0.12	0.04	0.04	0.08	0.28	5.20	5.4	94.6	2.31	0.77	0.77	1.54	3.0	1.0	1.3	3.1
	Bh	6.26	0.13	0.06	0.09	0.11	0.39	6.65	5.9	94.1	1.95	0.90	1.35	1.65	2.2	0.7	1.0	2.9
	Bfe	3.12	0.11	0.04	0.05	0.10	0.30	3.42	8.8	91.2	3.22	1.17	1.46	2.92	2.8	0.8	1.0	4.4
	C	2.29	0.10	0.03	0.04	0.09	0.26	2.55	10.2	89.8	3.92	1.18	1.57	3.53	3.3	0.8	1.0	5.1
35	AEes	7.08	0.19	0.06	0.09	0.12	0.46	7.54	6.1	93.9	2.52	0.80	1.19	1.59	3.2	0.7	1.2	3.3
	Ees	4.78	0.12	0.04	0.05	0.09	0.30	5.08	5.9	94.1	2.36	0.79	0.98	1.77	3.0	0.8	1.1	3.1
	Bh	12.82	0.15	0.05	0.07	0.13	0.40	13.22	3.0	97.0	1.13	0.38	0.53	0.98	3.0	0.7	1.0	1.5
	Bfe	2.71	0.09	0.04	0.04	0.08	0.25	2.96	8.4	91.6	3.04	1.35	1.35	2.70	2.3	1.0	1.1	4.4
	C	1.25	0.08	0.03	0.04	0.09	0.24	1.49	16.1	83.9	5.37	2.01	2.68	6.04	2.7	0.8	0.8	7.4
38	AEes	10.81	0.40	0.10	0.11	0.08	0.69	11.50	6.0	94.0	3.48	0.87	0.96	0.70	4.0	0.9	2.6	4.3
	Ees	5.99	0.24	0.07	0.07	0.08	0.46	6.45	7.1	92.9	3.72	1.09	1.09	1.24	3.4	1.0	2.1	4.8
	Bh	6.24	0.22	0.05	0.07	0.08	0.42	6.66	6.3	93.7	4.72	1.07	1.50	1.72	4.4	0.7	1.8	4.1
	Bfe	4.11	0.24	0.05	0.07	0.08	0.44	4.55	9.7	90.3	5.27	1.10	1.54	1.76	4.8	0.7	1.9	6.4
	C	1.67	0.09	0.03	0.04	0.07	0.23	1.90	12.1	87.9	4.74	1.58	2.11	3.68	3.0	0.8	1.1	6.3
rusty-podzolic soils																		
8	AEes	10.52	2.83	1.34	1.11	0.68	5.97	16.49	36.2	63.8	17.14	8.15	6.75	4.15	2.1	1.2	2.3	25.3
	BfeBv	5.60	0.18	0.24	0.23	0.27	0.91	6.51	14.0	86.0	2.81	3.62	3.50	4.08	0.8	1.0	0.8	6.4
	Bv	2.96	0.06	0.13	0.17	0.18	0.54	3.50	15.4	84.6	1.69	3.83	4.77	5.09	0.4	0.8	0.6	5.5
	C	1.35	0.05	0.11	0.14	0.14	0.45	1.80	24.9	75.1	2.84	6.12	7.90	8.01	0.5	0.8	0.6	9.0
9	AEes	7.95	1.44	0.82	0.54	0.31	3.11	11.06	28.1	71.9	13.00	7.39	4.90	2.80	1.8	1.5	2.6	20.4
	BfeBv	4.58	0.14	0.17	0.11	0.13	0.56	5.14	10.9	89.1	2.80	3.35	2.18	2.57	0.8	1.5	1.3	6.2
	Bv	2.93	0.13	0.11	0.07	0.10	0.42	3.34	12.5	87.5	3.98	3.38	2.12	2.99	1.2	1.6	1.4	7.4
	C	1.13	0.12	0.13	0.08	0.10	0.42	1.55	27.3	72.7	7.43	8.14	5.10	6.65	0.9	1.6	1.3	15.6
14	AEes	7.34	1.12	0.65	0.42	0.27	2.46	9.80	25.1	74.9	11.43	6.63	4.29	2.76	1.7	1.5	2.6	18.1
	BfeBv	6.24	0.73	0.43	0.31	0.17	1.64	7.88	20.8	79.2	9.26	5.46	3.93	2.16	1.7	1.4	2.4	14.7
	Bv	4.12	0.45	0.24	0.19	0.09	0.97	5.09	19.1	80.9	8.84	4.72	3.73	1.77	1.9	1.3	2.5	13.6
	C	1.91	0.12	0.11	0.09	0.07	0.39	2.30	17.0	83.0	5.22	4.78	3.91	3.04	1.1	1.2	1.4	10.0
25	AEes	11.93	1.42	0.45	0.33	0.21	2.41	14.34	16.8	83.2	9.90	3.14	2.30	1.46	3.2	1.4	3.5	13.0
	BfeBv	9.54	0.89	0.44	0.30	0.18	1.81	11.35	15.9	84.1	7.84	3.88	2.64	1.59	2.0	1.5	2.8	11.7
	Bv	8.12	0.45	0.26	0.19	0.14	1.04	9.16	11.4	88.6	4.91	2.84	2.07	1.53	1.7	1.4	2.2	7.8
	C	2.11	0.20	0.09	0.08	0.05	0.42	2.53	16.6	83.4	7.91	3.56	3.16	1.98	2.2	1.1	2.2	11.5
a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	r	s	t

Appendix A continued

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	r	s	t
27	AEes	16.64	1.39	0.31	0.21	0.16	2.07	18.71	11.1	88.9	7.43	1.66	1.12	0.86	4.5	1.5	4.6	9.1
	BfeBv	8.85	0.64	0.14	0.14	0.15	1.07	9.92	10.8	89.2	6.45	1.41	1.41	1.51	4.6	1.0	2.7	7.9
	Bv	6.59	0.29	0.08	0.10	0.14	0.61	7.20	8.5	91.5	4.03	1.11	1.39	1.94	3.6	0.8	1.5	5.1
	C	2.38	0.20	0.06	0.09	0.14	0.49	2.87	17.1	82.9	6.97	2.09	3.14	4.88	3.3	0.7	1.1	9.1
30	AEes	12.38	0.51	0.14	0.15	0.14	0.94	13.32	7.1	92.9	3.83	1.05	1.13	1.05	3.6	0.9	2.2	4.9
	BfeBv	4.79	0.29	0.08	0.11	0.14	0.62	5.41	11.5	88.5	5.36	1.48	2.03	2.59	3.6	0.7	1.5	6.8
	Bv	4.53	0.25	0.07	0.59	0.14	1.05	5.58	18.8	81.2	4.48	1.25	10.57	2.51	3.6	0.1	0.4	5.7
	C	2.11	0.16	0.09	0.09	0.07	0.41	2.52	16.3	83.7	6.35	3.57	3.57	2.78	1.8	1.0	1.6	9.9
31	AEes	10.14	0.64	0.14	0.04	0.15	0.97	11.11	8.7	91.3	5.76	1.26	0.36	1.35	4.6	3.5	4.1	7.0
	BfeBv	4.67	0.22	0.08	0.02	0.15	0.47	5.14	9.1	90.9	4.28	1.56	0.39	2.92	2.8	4.0	1.8	5.8
	Bv	3.08	0.18	0.10	0.03	0.15	0.46	3.54	13.0	87.0	5.08	2.82	0.85	4.24	1.8	3.3	1.6	7.9
	C	1.51	0.13	0.10	0.03	0.05	0.31	1.82	17.0	83.0	7.14	5.49	1.65	2.75	1.3	3.3	2.9	12.6
33	AEes	10.76	0.64	0.15	0.05	0.16	1.00	11.76	8.5	91.5	5.44	1.28	0.43	1.36	4.3	3.0	3.8	6.7
	BfeBv	4.44	0.18	0.05	0.02	0.10	0.35	4.79	7.3	92.7	3.76	1.04	0.42	2.09	3.6	2.5	1.9	4.8
	Bv	3.45	0.18	0.06	0.02	0.14	0.40	3.85	10.4	89.6	4.68	1.56	0.52	3.64	3.0	3.0	1.5	6.2
	C	1.32	0.15	0.04	0.01	0.06	0.26	1.58	16.5	83.5	9.49	2.53	0.63	3.80	3.8	4.0	2.7	12.0
34	AEes	8.36	0.62	0.11	0.10	0.09	0.92	9.28	9.9	90.1	6.68	1.19	1.08	0.97	5.6	1.1	3.8	7.9
	BfeBv	3.02	0.12	0.05	0.06	0.14	0.37	3.39	10.9	89.1	3.54	1.47	1.77	4.13	2.4	0.8	0.9	5.0
	Bv	1.83	0.09	0.03	0.05	0.11	0.28	2.11	13.3	86.7	4.27	1.42	2.37	5.21	3.0	0.6	0.8	5.7
	BvC	1.76	0.09	0.03	0.05	0.12	0.29	2.05	14.1	85.9	4.39	1.46	2.44	5.85	3.0	0.6	0.7	5.9
	C	1.47	0.10	0.06	0.06	0.04	0.26	1.73	15.0	85.0	5.78	3.47	3.47	2.31	1.7	1.0	1.6	9.2
36	$AEes_1$	7.23	0.25	0.06	0.07	0.08	0.46	7.69	6.0	94.0	3.25	0.78	0.91	1.04	4.2	0.9	2.1	4.0
	$AEes_2$	2.37	0.15	0.05	0.05	0.10	0.35	2.72	12.9	87.1	5.51	1.84	1.84	3.68	3.0	1.0	1.3	7.4
	BfeBv	2.92	0.17	0.05	0.06	0.09	0.37	3.29	11.2	88.8	5.17	1.52	1.82	2.74	3.4	0.8	1.5	6.7
	Bv	2.21	0.18	0.05	0.05	0.09	0.37	2.58	14.3	85.7	6.98	1.94	1.94	3.49	3.6	1.0	1.6	8.9
	C	1.12	0.10	0.06	0.04	0.03	0.23	1.35	17.0	83.0	7.41	4.44	2.96	2.22	1.7	1.5	2.3	11.9
37	AEes	3.71	0.29	0.06	0.10	0.09	0.54	4.25	12.7	87.3	6.82	1.41	2.35	2.12	4.8	0.6	1.8	8.2
	BfeBv	2.07	0.22	0.05	0.06	0.09	0.42	2.49	16.9	83.1	8.84	2.01	2.41	3.61	4.4	0.8	1.8	10.8
	Bv	1.49	0.15	0.05	0.06	0.10	0.36	1.85	19.5	80.5	8.11	2.70	3.24	5.41	3.0	0.8	1.3	10.8
	C	0.69	0.19	0.04	0.05	0.04	0.32	1.01	31.7	68.3	18.81	3.96	4.95	3.96	4.8	0.8	2.6	22.8
39	AEes	32.81	2.30	0.56	0.33	0.16	3.35	36.16	9.3	90.7	6.36	1.55	0.91	0.44	4.1	1.7	5.8	7.9
	BfeBv	7.22	0.31	0.08	0.06	0.09	0.54	7.76	7.0	93.0	3.99	1.03	0.77	1.16	3.9	1.3	2.6	5.0
	Bv	9.69	0.51	0.10	0.07	0.10	0.78	10.47	7.4	92.6	4.87	0.96	0.67	0.96	5.1	1.4	3.6	5.8
	BvC	3.31	0.20	0.06	0.06	0.09	0.41	3.72	11.0	89.0	5.38	1.61	1.61	2.42	3.3	1.0	1.7	7.0
	C	1.45	0.18	0.06	0.04	0.06	0.34	1.79	19.0	81.0	10.06	3.35	2.23	3.35	3.0	1.5	2.4	13.4
18	AEes	18.34	0.64	0.11	0.30	0.16	1.21	19.55	6.2	93.8	3.27	0.56	1.53	0.82	5.8	0.4	1.6	3.8
	BfeBv	5.12	0.54	0.09	0.06	0.09	0.78	5.90	13.2	86.8	9.15	1.53	1.02	1.53	6.0	1.5	4.2	10.7
	Bv	3.65	0.45	0.08	0.06	0.08	0.67	4.32	15.5	84.5	10.42	1.85	1.39	1.85	5.6	1.3	3.8	12.3
	BvC	2.99	0.34	0.11	0.04	0.03	0.52	3.51	14.8	85.2	9.69	3.13	1.14	0.85	3.1	2.8	6.4	12.8
	C	2.66	0.74	0.15	0.34	0.26	1.49	4.15	35.9	64.1	17.83	3.61	8.19	6.27	4.9	0.4	1.5	21.4
21	AEes	3.68	0.57	0.09	0.29	0.16	1.11	4.79	23.2	76.8	11.90	1.88	6.05	3.34	6.3	0.3	1.5	13.8
	BfeBv	3.25	0.51	0.11	0.12	0.09	0.83	4.08	20.3	79.7	12.50	2.70	2.94	2.21	4.6	0.9	3.0	15.2
	Bv	2.98	0.48	0.10	0.08	0.05	0.71	3.69	19.2	80.8	13.01	2.71	2.17	1.36	4.8	1.3	4.5	15.7
	BvC	2.02	0.43	0.08	0.04	0.03	0.58	2.60	22.3	77.7	16.54	3.08	1.54	1.15	5.4	2.0	7.3	19.6
	C	1.91	0.49	0.07	0.44	0.13	1.13	3.04	37.2	62.8	16.12	2.30	14.47	4.28	7.0	0.2	1.0	18.4
23	$AEes_1$	5.25	1.08	0.13	0.29	0.12	1.62	6.87	23.6	76.4	15.72	1.89	4.22	1.75	8.3	0.4	3.0	17.6
	$AEes_2$	4.12	0.57	0.12	0.11	0.07	0.87	4.99	17.4	82.6	11.42	2.40	2.20	1.40	4.8	1.1	3.8	13.8
	BfeBv	3.96	0.42	0.12	0.09	0.06	0.69	4.65	14.8	85.2	9.03	2.58	1.94	1.29	3.5	1.3	3.6	11.6
	Bv	3.28	0.41	0.10	0.06	0.03	0.60	3.88	15.5	84.5	10.57	2.58	1.55	0.77	4.1	1.7	5.7	13.1
	C	2.96	0.57	0.09	0.29	0.16	1.11	4.07	27.3	72.7	14.00	2.21	7.13	3.93	6.3	0.3	1.5	16.2

Appendix B.

Table 6. Mineral composition of heavy fraction 0,06 -0,2 mm (in weight %), in some soil profiles.

							Transparent minerals (sum to 100%)															Content in %			Relationship between minerals			
No. of profile	genetic horizon	Weighing %	Number of analysed grains	Non-transparent minerals in%	carbonates %	Transparent minerals in %	amphiboles	andalusite	apatite	biotite	chlorite	cyrconite	dystenite	epidote	granet	pyroxynes	rutyl	staurolite	sylimanite	topaz	turmaline	tytanite	MN	MS	MO	MO/(MN+MS)	MN/MO	MS/MO	MN/MS
1	AEes	10.12	352	4.6	1.2	92.1	88.9	0	0.1	4.6	1.1	0	0	3.3	0.6	1.2	0	0	0	0	0.1	0.1	90.1	9.7	0.2	0.002	450.5	48.5	9.3
	C	7.96	344	1.4	0.6	98.0	85.2	0	0.3	5.6	1.2	0	0	4.4	0.3	2.4	0	0	0	0	0.3	0.3	87.6	11.8	0.6	0.006	146.0	19.7	7.4
3	AEes	11.24	367	4.7	2.4	91.3	87.4	0	0.1	3,2	1,2	0	0	4,6	1,2	1,7	0	0,3	0	0	0,3	0,3	89,1	10,3	0,6	0,006	148,5	17,2	8,7
	C	12.34	336	3.6	1.7	90.5	83.9	0	0.3	1,2	1,2	0	0	8,9	0,9	3,2	0	0	0	0	0,4	0	87,1	12,5	0,4	0,004	217,8	31,3	7,0
7	AEes	10.33	318	9.7	3.1	87.2	85.3	0	0	0.7	1.4	0	1.1	4.7	2.5	3.6	0	0.7	0	0	0	0	88.9	9.3	1.8	0,020	49.4	5.2	9.6
	C	6.54	349	5.7	2.6	91.7	80.9	0	0.3	0.6	0.3	0	0.3	11.5	1.7	4.1	0.3	0	0	0	0	0	85.0	14.4	0.6	0.006	141.7	24.0	5.9
11	AEes	10.47	347	9.6	1.9	88.2	63.2	0	0.3	0.9	1.1	0.8	0.3	6.5	16.2	5.6	0	4.3	0	0	0.6	0.2	68.8	25.0	6.2	0.090	11.1	4.0	2.8
	C	11.11	330	7.6	1.5	90.9	55.4	0	0.3	1.0	1.3	0.6	0.3	8.7	18.7	6.0	0	5.7	0	0	1.7	0.3	61.4	30.0	8.6	0.1	7.1	3.4	2.0
15	AEes	8.75	339	8.2	1.7	84.4	49.2	0.7	0.3	1.1	0.9	0.8	1.1	12.9	20.5	5.4	0.9	3.7	0	0	2.1	0.4	54.6	35.7	9.7	0.1	5.6	3.7	1.5
	C	4.23	337	6.1	2.8	90.5	52.3	1.1	0.3	0.9	1.2	0.9	0.6	11.6	16.0	8.9	0	0.4	0	0	4.8	1.0	61.2	30.0	8.8	0.1	6.9	3.4	2.0
16	AEes	0.64	332	13.6	3.3	83.1	33.7	0	0	0	0.4	1.8	1.1	18.5	27.9	8.2	0	0	0.8	0	7.2	0.4	41.9	47.6	10.5	0.1	4.0	4.5	0.9
	C	0.75	337	5.3	1.5	93.2	49.0	0.3	0.3	1.3	2.5	1.0	0.6	9.9	15.9	12.5	0.3	0	0	0.3	5.1	1.0	61.5	29.9	8.6	0.1	7.2	3.5	2.1
29	AEes	0.77	339	14.7	7.1	78.2	34.0	0	0	0.8	2.3	0	1.1	18.1	26.4	11.3	0	0	0	0	4.9	1.1	45.3	47.6	7.1	0.1	6.4	6.7	1.0
	C	0.05	373	15.3	0.5	84.2	46.6	0.3	0	1.9	1.6	3.8	1.6	13.4	14.6	10.2	0.3	0.6	0.3	0	4.5	0.3	56.8	31.8	11.4	0.1	5.0	2.8	1.8
26	AEes	1.34	390	25.4	1.3	73.3	26.9	0.4	0	0.6	1.4	2.4	0.4	14.0	43.0	2.8	1.4	0.4	0	0.4	5.9	0	29.7	59.0	11.3	0.1	2.6	5.2	0.5
	C	2.02	379	20.4	1.8	77.8	28.2	0.7	0	0	0.3	2.0	4.1	13.9	38.6	4.4	0	1.4	0.3	0.3	5.1	0.7	32.6	53.1	14.3	1.2	2.3	3.7	0.6
31	AEes	1.16	330	16.4	7.0	76.6	23.7	0	0	1.2	0	3.2	2.4	19.8	37.2	1.2	2.4	0.7	0.7	1.2	6.3	0	24.9	58.9	16.2	1.2	1.5	3.6	0.4
	C	1.36	339	20.4	1.8	77.8	27.6	0	0	0.4	0.4	4.5	0.8	19.8	31.8	4.5	0.4	1.1	0.4	0	7.2	1.1	32.1	52.8	15.1	0.2	2.1	3.5	0.6
35	AEes	0.49	376	10.4	5.6	84.0	5.4	0.3	0	0	1.3	1.9	1.3	26.5	45.6	1.9	0.6	5.1	1.3	0.6	8.2	0	7.3	74.7	18.0	1.2	0.4	4.2	0.1
	C	0.73	322	8.4	8.7	82.9	4.9	1.1	0	0.7	0	3.0	0.7	13.8	53.3	4.9	0.7	2.6	0.7	3.0	10.6	0	9.8	68.5	21.7	1.3	0.4	3.2	0.1
39	AEes	0.13	510	28.2	9.2	62.6	8.5	0.6	0	1.9	0.3	10.3	1.3	26.7	27.0	3.1	4.7	3.4	1.3	0.3	7.8	2.8	11.6	51.2	29.2	0.5	0.4	1.7	0.2
	C	0.38	421	21.6	3.8	74.6	16.2	2.9	0	1.9	1.6	4.5	1.3	19.6	29.0	6.7	2.9	1.9	0	1.3	8.9	1.3	22.9	52.1	25.0	0.3	0.9	2.1	0.4
20	AEes	0.60	330	17.0	0.6	82.4	16.2	0.4	0	0.4	1.1	1.5	0.7	12.1	61.3	1.1	0	1.1	0.7	0	3.4	0	17.3	75.6	7.1	0.1	2.4	10.6	0.2
	C	0.56	325	13.2	1.5	85.3	17.0	1.1	0	0.4	0.7	2.9	1.1	15.5	50.5	1.1	0	2.5	0	0.7	6.1	0.4	18.1	67.1	14.8	0.2	1.2	4.5	0.3
24	AEes	0.21	346	12.4	1.4	86.2	1.3	1.7	0	0	0	1.0	0.3	10.4	62.1	1.7	0.3	9.1	0.7	0.7	10.7	0	3.0	73.2	23.8	0.3	0.1	3.1	0.04
	C	0.25	321	9.3	0.9	89.8	2.4	0.3	0	0	0	3.5	0.3	11.1	72.7	4.2	0.3	2.1	0	0	3.1	0	6.6	83.8	9.6	0.1	0.7	8.7	0.1

MN – non-resistant minerals, MS – medium-resistant minerals, MO – resistant minerals.

Appendix C

Table 19. Total content of different forms of organic compounds in separate fractions of the humus and some characteristics of organic matter humification in epihumus subhorizon.

No.of profile	C total %	C of fulvic, humic acids and humins in total C (%)					Ch:Cf	Degree of humi-fication	Percentage content of C in each fraction in relation to the mass of the sample					
		light fraction		heavy fraction					light fraction			heavy fraction		
		F1+F2	H1+H2	F3+F4 +F5	H3+H4 +H5	humins			R	F1+F2	H1+H2	F3+F4 +F5	H3+H4 +H5	humins
podzolic soils														
1	29.12	6.34	2.05	0.14	0.12	0.95	**0.33**	**9.6**	26.321	1.849	0.598	0.041	0.035	0.276
2	26.53	4.42	1.47	0.18	0.17	2.65	**0.36**	**8.9**	24.170	1.173	0.389	0.049	0.045	0.703
5	25.68	5.00	2.50	0.18	0.17	1.55	**0.64**	**9.4**	23.264	1.284	0.642	0.046	0.045	0.399
7	19.12	4.84	1.63	0.28	0.25	4.75	**0.37**	**11.8**	16.873	0.925	0.312	0.053	0.048	0.909
10	12.15	5.74	1.93	0.55	0.58	7.84	**0.40**	**16.6**	10.126	0.698	0.234	0.067	0.070	0.952
11	9.24	3.87	1.45	0.77	0.80	7.49	**0.48**	**14.4**	7.911	0.358	0.134	0.071	0.074	0.692
13	7.23	6.31	2.17	1.16	1.02	7.11	**0.42**	**17.8**	5.945	0.456	0.157	0.084	0.074	0.514
15	15.91	4.12	1.71	0.43	0.47	4.17	**0.47**	**11.0**	14.166	0.660	0.270	0.070	0.076	0.664
16	4.88	12.79	2.22	3.48	0.69	14.67	**0.18**	**33.9**	3.228	0.624	0.108	0.170	0.034	0.716
17	3.72	10.27	4.81	2.93	2.69	12.34	**0.57**	**33.0**	2.491	0.382	0.179	0.109	0.100	0.459
19	4.12	6.92	4.05	2.26	2.16	11.87	**0.68**	**27.3**	2.997	0.285	0.167	0.093	0.089	0.489
20	3.79	7.36	3.56	3.27	2.88	12.27	**0.61**	**29.3**	2.678	0.279	0.135	0.124	0.109	0.465
22	6.24	6.33	4.31	2.45	1.71	9.66	**0.69**	**24.5**	4.713	0.395	0.269	0.153	0.107	0.603
24	4.98	6.00	3.59	1.14	1.59	14.74	**0.72**	**27.1**	3.632	0.299	0.179	0.057	0.079	0.734
26	7.27	3.00	2.35	0.64	1.37	8.58	**0.60**	**15.9**	6.111	0.221	0.168	0.046	0.098	0.624
28	4.85	4.43	1.69	1.14	0.93	9.07	**0.47**	**17.3**	4.013	0.215	0.082	0.055	0.045	0.440
29	5.38	3.87	1.80	1.97	1.54	11.62	**0.57**	**20.8**	4.261	0.208	0.097	0.106	0.083	0.625
32	3.26	7.42	4.08	7.32	4.38	6.99	**0.57**	**27.2**	2.275	0.242	0.133	0.239	0.143	0.228
35	2.15	11.63	4.19	4.00	4.97	8.23	**0.59**	**33.0**	1.440	0.250	0.090	0.086	0.107	0.177
38	2.86	8.84	3.32	7.65	4.72	8.95	**0.49**	**26.5**	1.902	0.253	0.095	0.219	0.135	0.256
rusty-podzolic soils														
9	15.34	8.75	6.40	2.84	1.23	3.80	**0.66**	**23.0**	11.809	1.342	0.982	0.435	0.189	0.583
14	6.23	9.10	6.60	2.68	1.88	2.83	**0.72**	**23.1**	4.792	0.567	0.411	0.167	0.117	0.176
18	3.49	18.88	17.16	3.55	3.50	21.43	**0.92**	**64.5**	1.238	0.659	0.599	0.124	0.122	0.748
21	3.89	17.43	14.58	2.80	2.75	11.31	**0.86**	**48.9**	1.989	0.678	0.567	0.109	0.107	0.440
25	5.31	11.13	1.71	2.01	1.74	13.01	**0.26**	**29.6**	3.738	0.591	0.091	0.107	0.092	0.691
27	5.37	9.06	2.27	2.14	1.05	11.51	**0.30**	**26.0**	3.972	0.486	0.122	0.115	0.057	0.618
30	10.30	7.98	2.61	1.43	0.58	5.77	**0.41**	**16.7**	8.584	0.647	0.269	0.147	0.059	0.594
31	5.55	6.84	1.59	2.74	1.29	7.86	**0.30**	**20.3**	4.422	0.380	0.088	0.152	0.072	0.436
33	9.18	6.34	5.04	1.29	0.92	5.69	**0.80**	**19.1**	7.425	0.582	0.463	0.104	0.084	0.522
36	1.68	3.39	2.09	4.76	5.71	14.50	**0.96**	**18.6**	1.168	0.057	0.035	0.080	0.096	0.244
37	2.81	3.88	3.74	10.29	4.34	8.50	**0.57**	**30.8**	1.946	0.109	0.105	0.289	0.122	0.239
39	5.86	7.36	2.32	2.49	1.34	11.52	**0.37**	**25.0**	4.393	0.431	0.136	0.146	0.069	0.792

C – organic carbon

C_h – carbon of humic acids

C_f – carbon of fulvic acids

R – residuum

F(1..n) – fraction of separate extraction

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