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Ecological indicator values in the identification of peatland soils

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Abstract

Our research aimed to determine how Ecological Indicator Values (EIV) (W – soil moisture value; Tr – trophic value; R – soil acidity value; D – soil granulometric value) help identify forest type of soils formed in peatlands. In our research, we related EIV to various physicochemical characteristics of peatland soils. The research sites were established in selected peatlands throughout Poland and were characterized by the presence of Histosols. In each plot, a list of all ground vegetation was made using the Braun-Blanquet method. On this basis, EIV was calculated for each study plot. Basic physicochemical properties were determined in the soil samples, such as carbon (Corg) and nitrogen (N) content, pH, hydrolytic acidity (Ht) and the content of basic cations. The activity of urease and dehydrogenase were also determined. Ecological Indicator Values of trophic and acidity were characterized by a positive, statistically significant correlation between the following soil features: pH H_2O and pH KCl, N content, Ca^{2+} content, activity of urease and dehydrogenase and Mn content. For both indicators, a statistically significant negative correlation was found in the case of C content, C/N ratio, P content, exchangeable acidity (He) and Ht. The stocks of C, N, P, Ca, Mg, K were also calculated. The highest Ca stock was found in the Sapric Histosols. The highest average EIV was recorded in Sapric Histosols, while the lowest was in Hemic Histosols. Our research shows that EIV can help identify Histosols. EIV may be available in the condition of the peatland soil and described to determine the degree of degradation.

1. Introduction

Peatlands are valuable lands that can serve a number of important purposes, e.g. they store carbon, retain water, increase biodiversity and play a crucial role in regulating climate changes (Harenda et al., 2018; Makrickas et al., 2023). The ongoing climate warming and destructive human impacts cause peatlands to dry (Swindles et al., 2019; Karpińska-Kołaczek et al., 2022; Słowińska et al., 2022). Factors that have an adverse impact on peatlands include more and more frequent dry spells, decrease in rainfall, maintenance of ditches, forestry, agriculture and peat extraction (Glina et al., 2016a; Monteverde et al., 2022; Kilpeläinen et al., 2023, Szumińska et al., 2023). Decrease of water level in organic soils leads to changes in vegetation that are directly linked with the processes occurring within the upper layers of soil (Peltoniemi et al., 2009; Sun et al., 2016). The increased supply of oxygen to the upper, layers accelerates the mineralisation of organic matter accumulated throughout the peat formation process, which in turn results in the release of stored carbon from the soil into the atmosphere in the form of carbon dioxide (Glina et al., 2016b; Pinsonneault et al., 2016; Mpamah et al., 2017; Humpenöder et al., 2020; Łachacz et al., 2023; Mencel et al., 2024). The degradation of peatlands decreases the number of rare species of peat-forming and hygrophilous plants, which are replaced by species with less demanding requirements in terms of water – in many cases they are cosmopolitan species with widespread occurrence that can dominate whole communities (Grzybowski and Glińska-Lewczuk, 2020). Those include, e.g. the genera of grasses *Molinia*, *Calamagrostis*, *Deschampsia* as well as *Rubus* plants. Altered composition and structure of vegetation exacerbate changes within the soil. The growth of new species of vegetation causes different products of decomposition of organic matter to be supplied to soil along with detritus and root secretions (Staszel-Szlachta et al., 2024). The rhizosphere surrounding such new plants contains communities of microorganisms which are different from the original microorganisms that existed in symbiosis with the vegetation of natural peatland ecosystems (Marschner et al., 2001; Andersen et al., 2010). For many species of plants, animals, fungi and bacteria a sufficiently wet peatland is the only biotope they can inhabit (Peltoniemi et al., 2009; Kędzior et al., 2022; Sławski et al., 2022).

In geobotanical research, in addition to an analysis of species found in a plant community developed in a particular habitat, there are synthetic ecological indicator values that allow for identification of the vegetation's requirements for individual environmental parameters. The concept of Ecological Indicator Values (EIV) is one of the methods of phyto-indication used in ecology. A useful tool in such an analysis can be the EIV established for vascular plants or other life forms also (bryophytes, lichens). The pioneer of this system was Ellenberg et al. (1992). The comprehensive development of the EIV for Europe was carried out by Dengler et al. (2023). In the context of plant species found in Poland, the equivalent of those indicators are the ecological indicator values developed by Zarzycki et al. (2002). The synthetic numerical indicators, presented as an average value for an entire vegetation patch, enable comparison of diverse communities which differ in terms of naturalness, fertility variant or even the varieties living in particular geobotanical regions (Zarzycki et al., 2002; Czerepko et al., 2006; Alderson et al., 2019).

Our research aimed to determine how Ecological Indicator Values (EIV)(W – soil moisture value; Tr – trophic value; R – soil acidity value; D – soil granulometric value) help identify forest soils formed in peatlands. In our research, we related EIV to various physicochemical characteristics of peatland soils. We assumed that EIVs strongly correlate with the properties of the soils studied. Moreover, the paper considers the differences in the stocks of carbon (C), nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg) and potassium (K) depending on the soil type in order to define the potential for biogenic accumulation. The results of our research are an attempt to answer the question of whether EIV indices reflect the basic properties of soils; such studies have not been conducted so far, especially regarding organic soils. The presented results may have practical application in determining the condition of organic soils, which in recent years have been exposed to changes resulting from climate change.

2. Materials and methods

2.1. Study area and experimental design

The analysis was based on data gathered by members of the Institute of Forest Soil Science in Krakow as part of the research project: "Development of soil quality indices for natural forest habitats of lowlands and uplands in Poland and its application in silviculture" (PNRF-2717/7/11). The data contained material taken from 30 typological forest sites set up in study plots of natural plant communities growing in Fibric Histosols (10), Hemic Histosols (6) and Sapric Histosols (9). The fourth group were comprised of modified communities that formed in drained soils modified as a result of mursh-forming process (Drainic Histosols: 5) (Fig. 1, Table 1). According to the Polish Soil Calssification (PSC) (Kabała et al., 2019) the soil types were: Fibric peat soils, Hemic peat soils, Sapric peat soils and Murshic peat soils. According to the IUSS-WRB soil Classification (IUSS Working Group WRB, 2022), the soils were classified as Fibric Histosols, Hemic Histosols, Sapric Histosols and Drainic Histosols. The analysis of soil from each plot involved digging a deep (150 cm) open pit in the centre of the study plots. Where it was not possible to dig a deep pit a Wardenaar'a peat corer was used. The C/N ratio was used as an indicator of the decomposition rate, which allowed for the classification of the tested soils.

2.2. Laboratory analysis

The chemical parameters were measured only for the upper layer of the soil (0–20 cm depth). After identification of genetic horizons within the profiles, samples were collected for the analysis of basic physical and chemical parameters according to the methodology by Ostrowska et al. (1991). The parameters analysed were: soil potentiometric pH (in water and 1 M KCl solution), hydrolytic acidity according to Kappen and exchangeable acidity determined by the Sokolov method. Total content of organic carbon (Corg) and total nitrogen were determined using the LECO CNS True Mac Analyzer (Leco, St. Joseph, MI, USA). Content of available phosphorus according to Bray-Kurtz method and total phosphorus (after mineralisation of samples in a mixture of nitric acid and perchloric acid) was measured with ICP EOS spectrometer with analysis of the content of microelements in the same solution. Exchangeable base cations were measured in 1M CH_3COONH_4 solution with pH of 7.0 using ICP-OES spectrometer (iCAP 6500 DUO, Thermo Fisher Scientific, Cambridge, UK). In addition, aggregate samples with natural moisture levels were collected from the upper horizons (up to 20 cm deep) of Histosols. The samples were transported to a laboratory, passed through a sieve with 2 mm mesh size and stored in temperature of 4°C. The samples were used to test the activity of two soil enzymes: dehydrogenase (Lenhard method modified by Cassidy) expressed in TFF/100g/24h, and urease expressed in µg $N\text{-}NH_4$/1g/1h (Alef and Nannipieri 1995). The bulk density was determined with the use of Kopecky rings with a volume of 250 cm^3, based on the dryer method (Ostrowska et al., 1991). The stocks of C, N, total P and the stocks of exchangeable forms of Ca, Mg and K were calculated as the sums of their total content within particular horizons of a soil profile with a cross section of 1 m^2 and depth of 100 cm:

$$N_{storage} = \frac{N \cdot D \cdot m}{10} \text{ [kg m}^{-1}\text{]}$$

$$C_{storage} = \frac{C \cdot D \cdot m}{10} \text{ [kg m}^{-1}\text{]}$$

$$P_{storage} = \frac{P \cdot D \cdot m}{100} \text{ [g m}^{-1}\text{]}$$

$$Ca_{storage} = \frac{Ca \cdot D \cdot m}{100} \text{ [g m}^{-1}\text{]}$$

$$Mg_{storage} = \frac{Mg \cdot D \cdot m}{100} \text{ [g m}^{-1}\text{]}$$

$$K_{storage} = \frac{K \cdot D \cdot m}{100} \text{ [g m}^{-1}\text{]}$$

where:
N – the nitrogen content in the next horizon [%]
C – the carbon content in the next horizon [%]
P – the total phosphorus conent in the next horizon [mg kg^{-1}]
Ca – the exchangeable calcium content in the next horizon [mg kg^{-1}]
Mg – the exchangeable magnesium content in the next horizon [mg kg^{-1}]
K – the exchangeable potassium content in the next horizon [mg kg^{-1}]
D – the soil bulk density at the appropriate horizon [g cm^{-3}]
m – the thickness of the next horizon [cm]

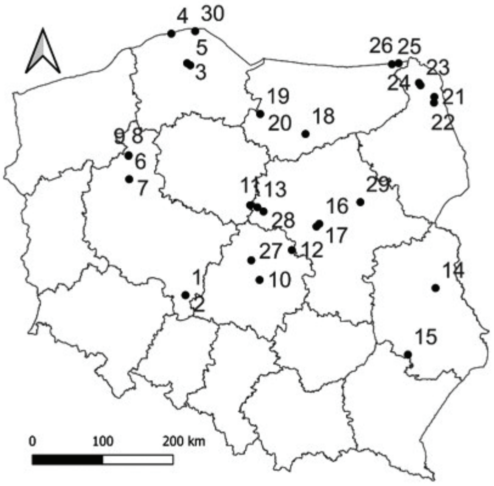

Fig. 1. Location of research sites

Table 1
Characteristics of the study plots

Plot number	Plant community	Soil type	Coordinates WGS 84 (N/E)	
1	*Molinio caeruleae-Pinetum*	Drainic Histosol	51°25’54.702”N	17°59’38.400”E
2	*Fraxino-Alnetum*	Drainic Histosol	51°25’51.864”N	17°59’50.118”E
3	*Vaccinio uliginosi-Pinetum*	Fibric Histosol	54°23’35.70”N	17°57’35.520”E
4	*Vaccinio uliginosi-Betuletum pubescentis*	Hemic Histosol	54°46’0.114”N	17°36’1.116”E
5	*Vaccinio uliginosi-Pinetum*	Fibric Histosol	54°22’1.560”N	18°1’48.732”E
6	*Sphagno squarrosi-Alnetum*	Hemic Histosol	52°53’41.460”N	16°46’14.000”E
7	*Molinio caeruleae-Pinetum*	Drainic Histosol	52°53’44.964”N	16°46’10.476”E
8	*Ribeso nigri-Alnetum*	Sapric Histosol	53°12’3.168”N	16°44’29.502”E
9	*Vaccinio uliginosi-Betuletum pubescentis*	Hemic Histosol	53°11’35.650”N	16°44’24.690”E
10	*Fraxino-Alnetum*	Sapric Histosol	51°37’45.540”N	19°30’53.298”E
11	*Ribeso nigri-Alnetum*	Drainic Histosol	52°35’2.772”N	19°19’43.26”E
12	*Sphagno squarrosi-Alnetum*	Fibric Histosol	52°0’20.376”N	20°11’19.614”E
13	*Sphagno squarrosi-Alnetum*	Fibric Histosol	52°33’26.334”N	19°28’41.844”E
14	*Vaccinio uliginosi-Pinetum*	Fibric Histosol	51°27’15.600”N	23°7’7.524”E
15	*Vaccinio uliginosi-Pinetum*	Drainic Histosol	50°37’26.628”N	22°29’19.320”E
16	*Vaccinio uliginosi-Pinetum*	Fibric Histosol	52°20’0.480”N	20°46’13.278”E
17	*Ribeso nigri-Alnetum*	Sapric Histosol	52°17’59.600”N	20°42’35.600”E
18	*Fraxino-Alnetum*	Sapric Histosol	53°29’4.374”N	20°31’16.944”E
19	*Sphagno squarrosi-Alnetum*	Fibric Histosol	53°44’54.972”N	19°33’7.236”E
20	*Vaccinio uliginosi-Pinetum*	Hemic Histosol	53°44’49.818”N	19°33’14.904”E
21	*Sphagno girgensohnii-Piceetum*	Sapric Histosol	53°53’20.466”N	23°19’42.768”E
22	*Querco-Piceetum*	Hemic Histosol	53°48’57.120”N	23°18’49.220”E
23	*Sphagno girgensohnii-Piceetum*	Sapric Histosol	54°2’53.142”N	23°2’38.148”E
24	*Ribeso nigri-Alnetum*	Sapric Histosol	54°4’44.400”N	23°0’42.702”E
25	*Sphagno girgensohnii-Piceetum*	Fibric Histosol	54°20’5.250”N	22°26’46.920”E
26	*Sphagno girgensohnii-Piceetum*	Hemic Histosol	54°20’37.656”N	22°35’41.208”E
27	*Fraxino-Alnetum*	Sapric Histosol	51°52’48.432”N	19°20’44.544”E
28	*Sphagno squarrosi-Alnetum*	Sapric Histosol	52°30’12.516”N	19°36’24.858”E
29	*Querco-Piceetum*	Fibric Histosol	52°35’39.918”N	21°38’40.116”E
30	*Vaccinio uliginosi-Betuletum pubescentis*	Fibric Histosol	54°48’10.700”N	18°7’43.000”E

2.3. Phytosociological relevés

On each site, a description of ground cover vegetation was carried out on a surface of 400 m^2 (a square measuring 20x20 m). In the central part of the surface, there was a soil pit. The vegetation list was made taking into account the spring aspect (May/June). For each plant, an appropriate degree of surface coverage was assigned according to the Braun-Blanquet scale. The scale includes the following degrees, along with a middle percentage range: 5 (87,5%), 4 (62,5%), 3 (37,5%), 2 (15%), 1 (below 5%), + (singly), r (rarely) (Braun-Blanquet, 1964). Then, in order to obtain the appropriate weight for each vascular plant, based on the degree of coverage, a weight was assigned according to the scale: 5 (5), 4 (4), 3 (3), 2 (2), 1 (1), r (0.5), + (0.1). Subsequently, for each vascular plants, the EIVs were read for a specific indicator according to Zarzycki et al. (2002). If the value of a selected indicators read from the table was expressed as a range, the middle value was used for calculations. On this basis, the values of selected indicators (trophic status, moisture, acidity and soil granulometric) were calculated for each studied area as a weighted average of the sum of EIV of all vascular plant species occurring in the area, divided by the sum of their weights (Braun-Blanquet, 1964; Zarzycki et al., 2002). The collected phytosociological relevés were assigned to the geobotanical classification approach (Matuszkiewicz, 2007).

2.4. Statistical analysis

The Spearman correlation coefficients for the soil characteristics and EIV were calculated. The Shapiro–Wilk test was used to assess normality. ANOVA test was used to assess significant differences between the mean values of soil types. HSD Tukey's post-hoc test was used to compare group differences. Principal component analysis (PCA) was used to interpret factors in particular data sets. The Statistica 13 software (StatSoft, 2013) was used for data analysis.

3. Results

3.1. Physical and chemical properties

The analysis of individual types of Histosols showed marked differences in terms of the analysed physical and chemical properties. Histosols with natural peat-forming vegetation in the upper horizons had different pH levels depending on their trophic status (Fibric Histosols: 3.70; Hemic Histosols: 4.20; Sapric Histosols: 5.82). As for Drainic Histosols the pH levels were highly variable and averaged 3.87. As the trophic status of peat soils increased, their acidity decreased (both for total acidity Ht and He). In the case of Fibric Histosols the acidity was Ht: 139.77 cmol kg^{-1}, He: 17.62 cmol kg^{-1}, in Hemic Histosols the acidity levels were slightly lower (Ht: 125.82, He: 6.14 cmol kg^{-1}) with the lowest acidity levels recorded in Sapric Histosols (Ht: 32.55 cmol kg^{-1}, Ha: 0.94 cmol kg^{-1}). The opposite was observed in terms of the content of exchangeable base cations. Their content was the lowest in Fibric Histosols (317.65 mg kg^{-1}), followed by Hemic Histosols (464.01 mg kg^{-1}) with the highest levels of exchangeable cations found in Sapric Histosols (1533.79 mg kg^{-1}). The soil in the murshic process exhibited a similar content of exchangeable cations to Sapric Histosols (480.14 mg kg^{-1}). The content of Corg was similar in the majority of analysed Histosols (Fibric Histosols: 41.85%; Hemic Histosols: 44.97%; Drainic Histosols: 43.28%). Hemic Histosols were an exception with a significantly lower content of 31.81%. Total N content was also similar in the analysed soil types (Fibric Histosols: 1.26%; Hemic Histosols: 1.64%; Drainic Histosols: 1.72%). Sapric Histosols had a significantly lower content of N compared to the other soil types. The C/N ratio ranged from 15.29 for Sapric Histosols to 35.68 for Fibric Histosols. The lowest C/N ratio was recorded in the Hemic Histosols (15.29). The lowest mean P content was observed in Sapric Histosols (7.26 mg kg^{-1}) and the highest in Hemic Histosols (12.38 mg kg^{-1}). The highest dehydrogenase activity was observed in the Hemic Histosols (18.99 mgTFF/100cm^3/24h). On average, the activity of those enzymes in the O horizon of the peat soils was 3–4 times lower (5.7 and 4.5 mgTFF/100cm^3/24h respectively). In Drainic Histosols there was a tendency for the activity of dehydrogenase to be even lower (on average, 3.1 mgTFF/100cm^3/24h). The highest urease activity was observed in the Hemic Histosols (1.63 µg N-NH_4/1cm^3/1h). The activity of those enzymes was 5 times lower in Drainic Histosols (on average, 0.30 µg N-NH_4/1cm^3/1h). The activity of urease in the O horizon was the lowest in Hemic Histosols and Fibric Histosols (0.07 and 0.06 µg N-NH_4/1cm^3/1h respectively) (Table 2). Sapric Histosols had a significantly highest content of Mn compared to the other soil types (201.63 mg kg^{-1}). The contents of other chemical elements did not differ significantly in the soil types examined (Table 3). As for non-drained Histosols, the calculated indicators of trophic status and acidity increased with the increase in the trophic status of Histosols.

3.2. Ecological indicator values (EIV)

The lowest values were observed in study plots of vegetation growing in Fibric Histosols (Tr: 2.5, R: 2.72). The indicators were slightly higher in study plots of vegetation in Hemic Histosols (Tr: 2.72, R: 2.94), and the highest values were recorded in Sapric Histosols (Tr: 3.6, R: 3.83). The Tr and R values for study plots of vegetation growing in Drainic Histosols were spread across a broad range with mean values of 2.91 and 3.21 respectively. In terms of the EIV of moisture (W) in study plots of vegetation in Histosols with diverse trophic levels, the range of values was similar and averaged from 3.92 to 4.21. There was a tendency for the indicator concerning plants in Drainic Histosols to decrease (mean value: 3.92), however, the difference was not statistically significant compared to the W indicator concerning study plots of naturally moist soils with no evidence of murshic process (Fig. 2). The broadest range and the lowest mean value of the floristic indicator of soil granulometric value (D) were observed in the study plots of vegetation growing in Hemic Histosols. As for the study plots of vegetation in Fibric Histosols and Sapric Histosols, the range was narrower and the mean values slightly higher (3.40 and 3.74 respectively). The lowest variation of the D indicator was recorded for vegetation growing in Drainic Histosols, with a mean value of 3.66.

Table 2
Basic chemical properties in the upper soil layer in different soils

Soil	pH_{H2O}	pH_{KCl}	C	N	C/N	Ca	**K**	**Mg**	**Na**	**P**	**He**	**Ht**	**U**	**DH**
Drainic H.	3.87±0.53^{b}	2.96±0.71^{b}	43.28±1.28^{a}	1.72±0.42^{ab}	26.54±7.21^{a}	408.96±405.07^{b}	25.24±5.44^{ab}	39.04±33.78^{a}	6.90±5.57^{a}	11.98±3.95^{a}	16.25±9.84^{a}	130.54±36.78^{a}	0.30±0.21^{a}	3.07±3.92^{b}
Fibric H.	3.70±0.25^{b}	2.78±0.23^{b}	41.85±5.52^{a}	1.26±0.43^{b}	35.68±10.52^{a}	244.63±137.62^{b}	33.13±15.64^{a}	28.74±9.16^{a}	11.15±7.78^{a}	11.54±4.82^{a}	17.62±6.54^{a}	139.77±20.37^{a}	0.06±0.04^{a}	4.53±3.79^{b}
Hemic H.	4.20±0.46^{b}	3.23±0.41^{b}	44.97±2.29^{a}	1.64±0.25^{ab}	27.98±5.37^{a}	405.41±323.75^{b}	18.71±12.58^{ab}	34.32±12.31^{a}	11.65±9.62^{a}	12.38±5.71^{a}	6.14±4.26^{b}	125.82±28.73^{a}	0.07±0.04^{a}	5.72±3.61^{ab}
Sapric H.	5.82±0.69^{a}	5.26±0.87^{a}	31.81±11.37^{b}	2.09±0.80^{a}	15.29±2.53^{b}	1462.78±769.60^{a}	12.90±7.12^{b}	53.05±50.46^{a}	5.06±3.05^{a}	7.26±2.95^{a}	0.94±1.36^{b}	32.55±25.00^{b}	1.63±2.60^{a}	18.99±15.74^{a}

Mean ± SD; C – content of carbon (%), N – content of nitrogen (%), Ca – calcium cation content (mg kg^{-1}), K – potassium cation content (mg kg^{-1}), Mg – magnesium cation content (mg kg^{-1}), Na – sodium cation content (mg kg^{-1}), P – phosphorus content (mg kg^{-1}), He – exchangeable acidity (cmol kg^{-1}), Ht – hydrolytic acidity (cmol kg^{-1}), U – urease activity (μg N-NH_4/1cm^3/1h), DH - dehydrogenase activity (mg TFF/100cm^3/24h); small letters in the upper index of the mean values mean significant differences between soils

Table 3
Content of selected elements in the upper soil layer in different soils

	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn	Al	Fe	Mo
Drainic H.	0.703±0.341^{a}	1.652±0.832^{a}	58.690±61.906^{a}	13.242±9.319^{a}	92.784±56.994^{b}	39.990±39.420^{a}	71.368±38.696^{a}	46.398±20.520^{a}	3290.060±1078.726^{a}	3297.260±762.108^{a}	6.634±7.808^{a}
Fibric H.	1.193±0.798^{a}	1.768±1.819^{a}	67.784±40.413^{a}	11.102±10.397^{a}	49.656±32.708^{b}	44.274±27.159^{a}	81.976±118.089^{a}	50.044±66.566^{a}	3629.160±2717.519^{a}	7839.170±11686.442^{a}	7.759±4.922^{a}
Hemic H.	0.843±0.649^{a}	2.733±3.702^{a}	61.767±35.653^{a}	6.450±2.949^{a}	63.453±62.688^{b}	44.267±23.143^{a}	29.878±22.237^{a}	14.065±7.884^{a}	2512.717±912.596^{a}	3710.900±2501.923^{a}	7.633±4.772^{a}
Sapric H.	1.047±0.668^{a}	1.779±1.330^{a}	43.389±36.806^{a}	8.886±4.832^{a}	201.634±97.383^{a}	28.466±21.394^{a}	40.302±19.797^{a}	54.130±54.709^{a}	5453.667±2175.837^{a}	8734.133±5564.851^{a}	5.451±3.884^{a}

Mean ± SD; Cd – total cadmium, Co – total cobalt (mg kg^{-1}), Cr – total chromium (mg kg^{-1}), Cu – total copper (mg kg^{-1}), Mn – total manganese (mg kg^{-1}), Ni – total nickel (mg kg^{-1}), Pb – total lead (mg kg^{-1}), Zn – total zinc (mg kg^{-1}), Al – total aluminium (mg kg^{-1}), Fe – total iron (mg kg^{-1}), Mo – total molybdenum (mg kg^{-1}); small letters in the upper index of the mean values mean significant differences between soils;

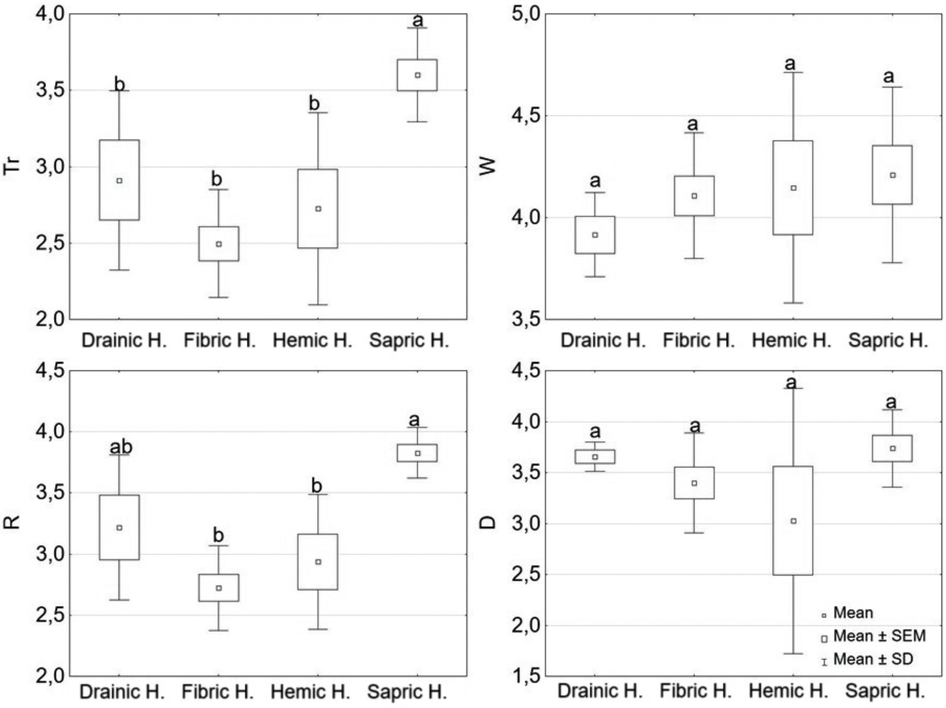

Fig. 2. Average value of floristic indicators depending on soil; Tr – trophy value, W – soil moisture value, R – soil acidity value, D – soil granulometric value

3.3. Relationship between ecological indicator values and chemical properties of soils

The statistical analyses demonstrated a positive correlation between the EIV of trophic status (Tr) and acidity (R) and the properties of the upper layers of the analysed Histosols and Drainic Histosols. The indicators correlated positively with pH H_2O and pH KCl, total N content, content of exchangeable Ca^{2+} cations, urease and dehydrogenase activity (Table 4). In terms of chemical elements, the indicators were found to correlate with Mn content (Table 5). A negative correlation was found between the indicators and Corg content, C/N ratio, total P content, He and Ht. The soil granulometric value showed a positive correlation with the activity of urease and a negative correlation with C/N ratio, total P content and He. The analyses did not reveal any significant correlations between the moisture indicator and the parameters of the analysed soils (Table 4 and 5). The projection of variables on a plane, clearly shows a strong correlation between the EIV of trophic status and acidity, while the proximity of the vector assigned to Hemic Histosols indicates that this is where the indicators reach the highest values. 42.18% of the variance was explained by Factor 1 and 12.21% of the variance was

Table 4
Spearman's correlation coefficient between floristic indicators and soil chemical properties (statistically significant correlations are bold – **p < 0.05***)

Variable	Trophy value Tr	Soil moisture value W	Soil acidity value R	Soil granulometric value D
pH H2O	**0.667***	0.252	**0.705***	0.231
pH KCl	**0.745***	0.289	**0.769***	0.324
C	**–0.582***	–0.010	**–0.583***	–0.241
N	**0.623***	0.019	**0.661***	0.271
C/N	**–0.788***	–0.076	**–0.821***	**–0.440***
Ca	**0.738***	0.090	**0.762***	0.354
K	–0.308	–0.249	–0.346	–0.220
Mg	0.197	–0.040	0.247	–0.266
Na	–0.248	–0.091	–0.275	–0.304
P	**–0.452***	–0.210	**–0.460***	**–0.503***
He	**–0.797***	–0.221	**–0.812***	**–0.366***
Ht	**–0.616***	–0.230	**–0.617***	–0.151
U	**0.672***	–0.061	**0.681***	**0.444***
DH	**0.569***	0.095	**0.504***	0.335

Table 5
correlation coefficient between floristic indicators and micronutrient (statistically significant correlations are bold – **$p < 0.05$***)

Variable	Trophy value Tr	Soil moisture value W	Soil acidity value R	Soil granulometric value D
Cd	–0.183	0.150	–0.147	–0.221
Co	0.136	0.296	0.089	0.050
Cr	–0.136	0.232	–0.155	–0.039
Cu	0.034	0.008	0.006	0.148
Mn	**0.642***	0.260	**0.670***	0.282
Ni	–0.151	0.300	–0.184	–0.101
Pb	–0.106	–0.284	–0.091	0.038
Zn	0.071	–0.112	0.120	0.140
Al	0.337	–0.092	0.339	0.236
Fe	0.313	–0.046	0.341	0.283
Mo	–0.198	0.308	–0.212	–0.244

explained by Factor 2. The projection of variables demonstrates the existence of relationships between the content of exchangeable K$^+$ cations, He and C/N ratio. In Fibric Histosols the values of those parameters were higher. The content of exchangeable cations of Ca^{2+}, Mg^{2+}, Na$^+$ and pH levels were higher in the Hemic Histosols (Fig. 5).

In terms of the mean stock of C in the analysed soils there were no statistically significant differences. The greatest stock was found in Drainic Histosols and Hemic Histosols (81.46 kg m^{-2} and 75.61 kg m^{-2}). The lowest mean stock of C was found in Fibric Histosols at 50.66 kg m^{-2}. Hemic Histosols displayed the highest mean stock of N (4.39 kg m^{-2}), followed by Drainic Histosols, Hemic Histosols and Fibric Histosols at 2.69 kg m^{-2}, 2.13 kg m^{-2}, 1.37 kg m^{-2} respectively. The highest mean stock of total P was found in the Hemic Histosols (150.58 g m^{-2}) and the lowest in the Hemic Histosols (41.55 g m^{-2}) (Fig. 3). The highest mean stocks of exchangeable Ca and Mg were found in the Hemic Histosols (5940.40 g m^{-2} and 206.04 g m^{-2}). In terms of calcium (Ca), its content was significantly different from the stock of exchangeable Ca found in other soil types. The lowest mean stocks of Ca and Mg were found in the Fibric Histosols (578.27 g m^{-2} and 85.47 g m^{-2}). The highest mean stock of K was found in Drainic Histosols (247.66 g m^{-2}) and the lowest in the Fibric Histosols at 123.12 g m^{-2} (Fig. 4).

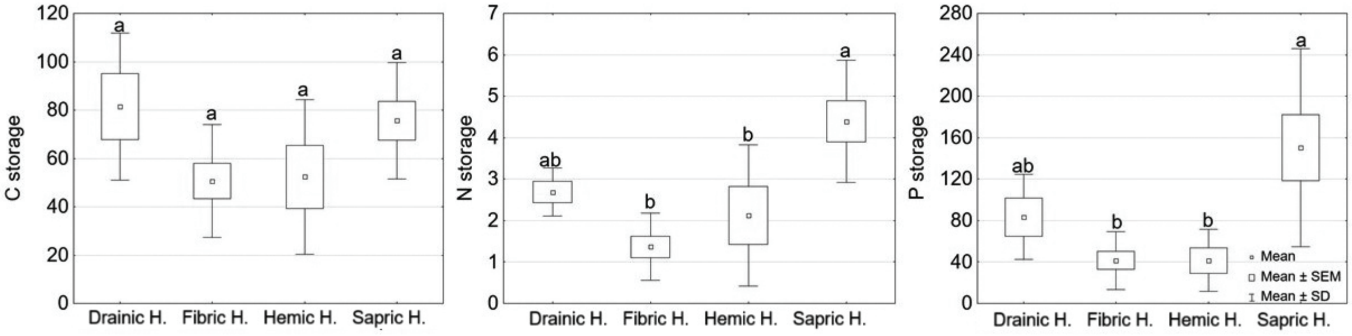

Fig. 3. Average storage of C, N (kg m^{-2}), total P (g m^{-2}) depending on the soil; C – carbon, N – nitrogen, P – total phosphorus

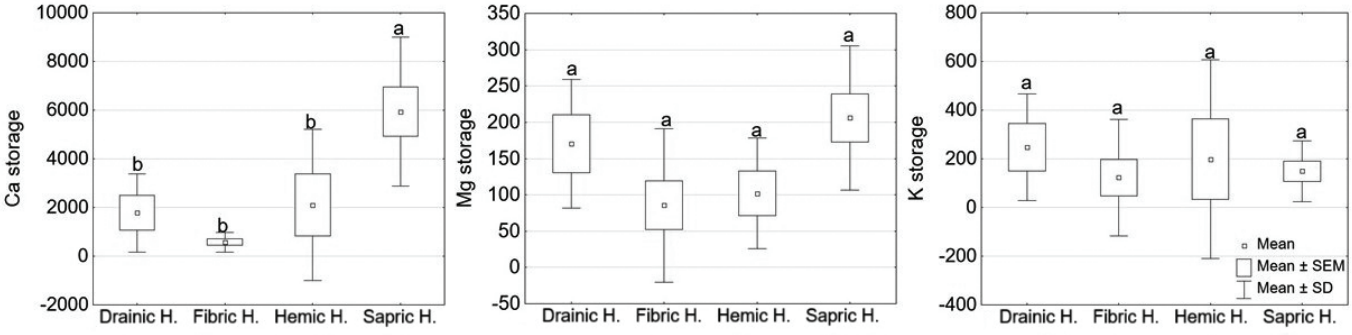

Fig. 4. Average storage of Ca, Mg, K (g m^{-2}) depending on the soil; Ca – calcium, Mg – magnesium, K – potassium

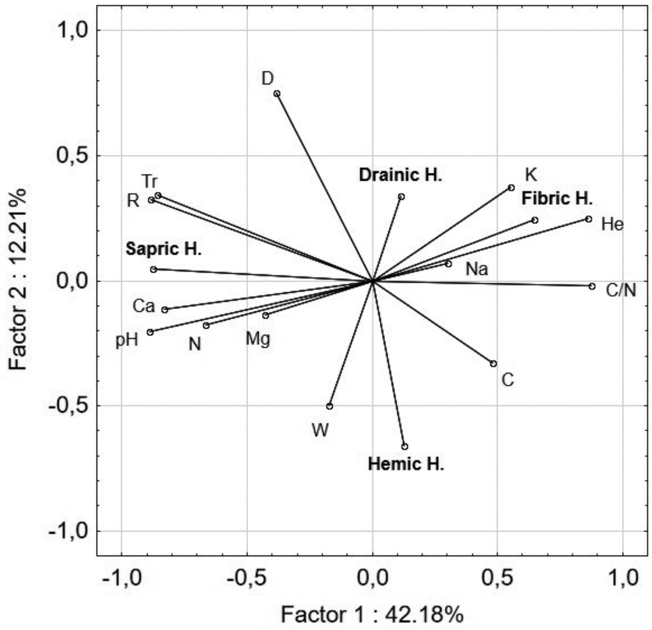

Fig. 5. The projection of variables on a plane of the first and second PCA factor; Tr – trophy value, W – soil moisture value, R – soil acidity value, D – soil granulometric value, C – carbon content (%), N – nitrogen content (%) , P – total phosphorus, Ca – calcium cation content, Mg – magnesium cation content, K – potassium cation content, Na – sodium cation content, He – exchangeable acidity (cmol kg^{-1})

4. Discussion

4.1. Physical and chemical properties

In our research, the EIVs of trophic status and acidity status showed the strongest correlations with the properties of the upper horizons of the analysed Histosols associated with their trophic status. These parameters include, in particular, pH H_2O and pH KCl, total N content and content of exchangeable cations of Ca^{2+}. What this means is that these indicators could potentially be used for vegetation differentiating and soil formations with different trophic levels. This potential has already been discussed in earlier studies by Wiecheć (2020), who conducted his research in Czarna Rózga in central Poland, and Gaura (2022), who conducted his research in the Gorce National Park (southern Poland). In their research, they successfully distinguished the studied vegetation areas with different trophic levels. In both cases, the Tr and R indicators showed significant positive correlations with soil pH, exchangeable Ca content, total content of exchangeable cations, saturation of the complex with cations. Concurrently, there was a significant negative correlation with soil acidity, Corg content, C/N ratio and, interestingly, exchangeable K content. Similar observations were made for the Histosols and Drainic Histosols analysed in this study. A significant negative correlation was found between the two indicators and Corg content, C/N ratio, total P content, He and Ht. Czerepko (2006) reported similar findings. It points to the existence of a repeatable correlation between certain soil parameters and selected EIVs. In Czerepko (2006) there was a significant positive correlation between trophic and acidity and pH KCl, the content of exchangeable cations of calcium (Ca^{2+}) and magnesium (Mg^{2+}), and iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), nickel (Ni), sulphur (S), phosphorus (P) content. A significant negative correlation was found between the indicators of trophic status and acidity, and C/N ratio, He, aluminium (Al) and lead (Pb) content.

4.2. Ecological indicator values (EIV)

In this study no correlation was identified between the moisture indicator and any parameters of the upper horizons of the Histosols and Drainic Histosols under analysis. In addition, no significant difference was found in the EIV of moisture between study plots Drainic Histosols and Histosols with active peat formation. There was a tendency for lower mean values of the W indicator, however, the degree of its variation was so high that a statistically significant difference could not be confirmed. It should be noted that the moisture indicator determined on the basis of existing vegetation may fail to reach the anticipated results, indicative of permanent drainage of a specific peatland. A possible explanation for that could be that depending on the degree of drainage and the rate of murshic process, covered with or shadowed by trees, may continue to host specific plant species a long time after it is drained (Koskinen et al., 2017; Lubińska-Mielińska et al., 2023). In the aforementioned research of Wiecheć (2020) and Gaura (2022) the authors analysed the potential of the EIV of moisture in the evaluation of microhabitats with different moisture levels within study plots of three different plant communities, and in the distinction between separate formations of fertile beech forests of the Carpathians. In both cases the results were positive. In Wiecheć (2020) the floristic indicator of moisture was closely linked with groundwater level and a number of parameters of the topsoil. In Gaura (2022) the indicator differentiated formations of beech forests of the Carpathians with different water content. The EIV of moisture was also analysed by Czerepko (2006). He confirmed the existence of correlations with the content of Ca, Mn, Pb and groundwater level. However, these correlations were very weak. The fourth floristic indicator, i.e. soil granulometric value, was not found to differentiate study plots of vegetation growing in the Histosols and the Drainic Histosols under analysis. It is not surprising that the soil granulometric value is not suitable for differentiating various types of Histosols as the soils under examination have characteristics of typical organic soils and the indicator categories (scale of 1 to 5) fail to consider any preferences in terms of organic substrate (without mineral components). What may be surprising here is the broad range of values obtained for study plots of vegetation growing in Hemic Histosols. It suggests that the plant communities found in these soils feature species with high tolerance of soil substrate, which may grow in mineral substrates and substrates rich in rock debris. As for plant communities growing in Drainic Histosols, due to the presence of grass species with greater tolerance in terms of substrate types (grain parameters) it was reasonable to expect slightly different results for this indicator. That, however, was not the case. On the contrary, in this group the range of values of the soil granulometric value indicator was very narrow (3.5–3.8) pointing to the dominance of species linked with mineral formations from somewhere between sandy and clay formations.

4.3. Relationship between different soil types and their chemical properties

Our research showed that the mean stock of carbon throughout the entire soil profile up to the depth of 100 cm may vary depending on the type of Histosols. Within the Fibric Histosols and Hemic Histosols the mean stock was 55.66 and 52.34 kg m^{-2} respectively, whereas within the Hemic Histosols it was 75.61 kg m^{-2}. The Drainic Histosols had the highest stock of C at a mean level of 81.46 kg m^{-2}. This may be due to the intensity of peat dehydration. The highest the long-term lowering of groundwater levels, the faster the release of carbon in the form of carbon dioxide into the atmosphere from the topsoil layers. The research by Kiryluk (2020) showed that as a result of dehydration, the bulk density of the soil increases and in addition into a decrease in soil porosity and water capacity. The dehydrated murshic layer can be decrease in thickness. However, the lower peat layers can still store significant amounts of carbon (Kiryluk, 2014; Jarnuszewski, 2017). The Hemic Histosols held over twice as much N, total P and Ca compared to the other examined soil types. The higher content of these elements within the Hemic Histosols may be due its origins. These soils form within Sapric Histosols which rely on waters such as rivers and lakes for their normal function and are fed by them. The waters of rivers and lakes carry deposits rich in organic and mineral matter and increase the trophic status of the soils, e.g. when the water levels surge (Lemkowska, 2016; Solovey et al., 2021; Watmough et al., 2022). The research by Łabęda and Kondras (2020) showed that the mean stock of organic carbon in agricultural soils was 55.53 Mg ha^{-1}, while in mineral forest soils its content was higher at a mean level of 101.23 Mg ha^{-1}. Łabęda and Kondras (2020) noted that the higher content of organic carbon in the forest soils was the result of good forest management and changes in growing practices, i.e. introduction of beech trees. Organic soils, which are the subject of this study, accumulate significantly more Corg depending on the depth of the O horizon, its structure, addition of mineral components and the degree of compaction of the peat substance that determines the bulk density of organic horizons. Within the deep Histosols of lowlands and highlands the mean stock of Corg usually oscillates between 550 and 750 Mg·ha^{-1} (Lasota and Błońska, 2021).

5. Conclusions

The conducted analyses confirmed the possibility of using EIV in determining soil conditions. Out of the analysed EIVs, mainly trophic value (Tr) and soil acidity value (R), can be helpful in differentiating Fibric Histosols, Hemic Histosols, and Sapric Histosols.

The EIV of moisture does not unequivocally differentiate between study plots of vegetation growing in Drainic Histosols formed as a result of drainage, and Histosols. However, there is a tendency for the values to decrease, which may indicate degradation and dehydration of the study plots.

The values of the soil granulometric value (D) are similar for all types of Drainic Histosols and Histosols. Hence, it is not possible to make any distinction between them. The values of this indicator are the result of the specificity of Histosols.

Certainly the most effective in differentiating Histosols with different trophic status levels were pH, content of exchangeable calcium, exchangeable acidity and C/N ratio.

Out of the analysed types of Histosols, the highest potential for the accumulation of C, N, total P, Ca, and Mg is exhibited by the Sapric Histosols.

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Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Andrzej Szlachta – Data curation, Investigation, Visualization, Writing – original draft, Writing – review & editing). **Jarosław Lasota** – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Ewa Błońska** – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

All authors read and approved the final manuscript.

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Wskaźniki ekologiczne w identyfikacji gleb torfowych

Słowa kluczowe

Właściwości gleb
Torfowisko
Zmiany klimatyczne
Zapas węgla

Streszczenie

Celem naszych badań było określenie, w jaki sposób wskaźniki ekologiczne (W – wskaźnik wilgotności gleby; Tr – wskaźnik trofizmu; R – wskaźnik kwasowości gleby; D – wskaźnik granulometryczny) mogą pomóc w identyfikacji gleb torfowych. W naszych badaniach powiązaliśmy wskaźniki ekologiczne z różnymi właściwościami fizykochemicznymi gleb torfowych. Powierzchnie badawcze założono na wybranych torfowiskach na terenie całej Polski, które charakteryzowały się obecnością torfu. Na każdym poletku wykonano spis florystyczny metodą Brauna-Blanqueta. Na tej podstawie dla każdej powierzchni badawczej obliczono wskaźniki ekologiczne. W próbkach gleby oznaczono podstawowe właściwości fizykochemiczne, takie jak zawartość węgla i azotu, pH, kwasowość hydrolityczną oraz zawartość kationów zasadowych. Oznaczono także aktywność ureazy i dehydrogenazy. Ekologiczne wskaźniki trofizmu i kwasowości charakteryzowały się dodatnią, istotną statystycznie korelacją pomiędzy następującymi cechami gleby: pH H_2O i pH KCl, zawartością N, zawartością Ca^{2+}, aktywnością ureazy i dehydrogenazy oraz zawartością Mn. Dla obu wskaźników stwierdzono istotną statystycznie ujemną korelację w przypadku zawartości C, stosunku C/N, zawartości P, kwasowości wymiennej i kwasowości hydrolitycznej. Obliczono także zawartość C, N, P, Ca, Mg, K. Najwyższą zawartość Ca stwierdzono w glebach torfowych torfowisk niskich. Najwyższe średnie wartości wskaźników ekologicznych odnotowano w glebach torfowych torfowisk niskich, a najniższe w glebach torfowych torfowisk przejściowych. Nasze badania pokazują, że wskaźniki ekologiczne mogą być pomocne w identyfikacji gleb torfowych. Wskaźniki ekologiczne mogą być przydatne do oceny warunków środowiskowych i stopnia degradacji gleb torfowych.