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Morphology, properties and classification of folisols in the Tatra Mountains

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Abstract

The aim of the study was to present the diversity of folisols occurring in the Polish part of the Tatra Mountains. Morphology, basic properties and classification of the folisols were taken into consideration. The presented material was collected in a soil survey conducted on the forest research plots (regular grid 500×500 m) in the Tatra National Park. During this research, 22 folisols from a total of 668 soils were described. Typical pedons of folisols were selected for this study. The basic properties of soils were determined using standard laboratory methods. The studied folisols occurred at various altitudes and were covered with different vegetation (spruce forests, dwarf pine thickets, grasslands). The occurrence of these soils was associated with very specific locations, such as: (1) outcrops of various rock types with relatively high resistance to weathering – in such places rocky folisols (Leptic Folic Mawic Histosols) were formed, and (2) rock debris and slope cover consisting of large rock fragments – in such places mainly debris folisols (Skeletofolic Mawic Histosols) were formed. The properties of the studied folisols depended primarily on the bedrock. Vegetation affected morphology of the folisols but has no significant effect on their properties. These soils were acidic, but the occurrence of even a low amount of carbonate rock fragments (limestone, dolomite) caused soil alcalization. Therefore, the implementation of the subtype 'calcareous folisol' to the Polish soil classification is justified.

1. Introduction

Folisols ('litter organic soils') are specific soils, which are composed mainly of litter and are characteristic soils for mountain areas (Systematyka gleb Polski, 2019). The soils do not occupy large areas in Poland nor are of great economic importance (Systematyka gleb Polski, 2019) but are still interesting objects of research due to their important role in increasing bio- (Olleck et al., 2020) and pedodiversity (Kacprzak et al., 2006), carbon sequestration (Hoffmann et al., 2014), and sustaining highly vulnerable mountainous ecosystems (Skiba et al., 2011; Miechówka and Drewnik, 2018; Musielok et al., 2024).

Studies of folisols enable a better understanding of natural processes leading to the sequestration of soil organic carbon, which is one of the most crucial challenges of present-day soil science (Cotrufo and Lavallee, 2022). The potential of organic soils formed in mountain areas under the influence of hydrological factor (i.e. peat soils; histosols) to sequester SOC is relatively well known (Hribljan et al., 2015; Glina et al., 2019; Drollinger et al., 2020), while folisols are still poorly studied (Olleck et al., 2020). Mountain areas in mid-latitudes are particularly important in this context, because both histosols and folisols occur next to each other within different geoecological zones (Hoffman et al., 2014; Drewnik et al., 2015; Chimner and Cooper, 2024; Musielok et al., 2024).

The functioning of folisols in mountains differs significantly from adjacent mineral soils (Bojko and Kabała, 2017; Cotrufo et al., 2019). In the previous studies focused on folisols, it was found that soil material may move downward and laterally within pedon due to subsurface mechanical translocation (Skiba and Komornicki, 1983; Kacprzak et al., 2006; Musielok et al., 2013), and soil morphology strongly depends on both: local geomorphological conditions (Bojko and Kabała, 2017; Telega, 2022) and local vegetation (Vaughan and McDaniels, 2009; Rahman and Tsukamoto, 2013; Burgess-Conforti et al., 2019; Telega, 2022). In addition, the properties of soil organic matter (SOM) constituting the essence of folisols, depend in some extent on the properties of bedrock (Miechówka and Drewnik, 2018; Zanella et al., 2018; Telega, 2022). However, it should be noted that this relationship is still poorly understood (Kacprzak et al., 2006; Hackman et al., 2009; Vaughan and McDaniels, 2009). Finally, the habitat and hydrological functions of folisols in different environments are still not fully documented (Miechówka, 2000; Skiba et al., 2011).

Folisols are distinguished at a high-level unit in the Canadian soil classification (Agriculture Canada Expert Committee on Soil Survey, 1987) and in the Polish soil classification (Kabała et al., 2019), while in international soil classifications, they occur at a lower level as Lithic/Typic Udifolists in the US Soil Taxonomy (Soil Survey Staff, 2022) and as Folic (Rockic/Mawic) Histosols in WRB classification (IUSS Working Group WRB, 2022). It should be noted that classification of folisols poses several challenges. One of them is the criterion of organic material thickness that allows to distinguish these soils (Trowbridge, 1980; Vaughan and McDaniels, 2009). Additionally, the division into lower-level units of folisols is still under discussion (Miechówka and Drewnik, 2018).

The aim of this work is to present the diversity of folisols occurring in the Polish part of the Tatra Mountains considering their morphology and basic properties. Some crucial comments on the classification of these soils according to Polish soil classification (Systematyka gleb Polski, 2019) are also included.

2. Study area

The research was conducted in the Polish part of the Tatra Mountains (southern Poland), which are the highest part of the Carpathians (Gerlach 2655 m a.s.l.). The highest parts of the Tatra Mts. are composed of Paleozoic metamorphic rocks and granitoides forming a crystalline core (Piotrowska et al., 2015). The rocks of the crystalline core are covered on the northern side with Mesozoic sedimentary carbonate rocks such as limestones, dolomites, marls with a smaller share of non-carbonate rocks e.g. sandstone (Jach et al., 2014). The relief of the Tatra Mts. has an alpine character, which is mainly due to the high altitude and Pleistocene glaciations covering the higher part of the massif (Klimaszewski, 1988).

Climatic conditions vary greatly depending on altitude. The average annual air temperature ranges from –4°C in the highest part of the mountains to 6°C in their lowest part. The annual sum of precipitation ranges from 1100 mm to 1800 mm (Błażejczyk, 2019). The lowest parts of the Tatra Mts. are covered mainly with beech forest (*Dentario glandulosae–Fagetum*) or spruce forest (*Plagiothecio–Piceetum tatricum*) growing on granitoid moraines. The higher parts of the Tatra Mts. are covered with an upper montane spruce forest (*Plagiothecio–Piceetum tatricum*). Above the upper timberline, dwarf pine thickets (*Pinetum mughi*) prevail. In the alpine zone, there are mainly high-mountain meadows (mainly *Oreochloo distichae-Juncetum trifidi* on acidic soils and *Festuco versicoloris-Seslerietum tatrae* on alkaline soils), and the highest parts of the Tatra Mountains are characterized by very poor plant cover dominated by lichens and sporadic vascular plants (Piękoś-Mirkowa and Mirek, 1996). The soil cover of the Tatra Mts. is very heterogeneous, which results from the diversity of geological structure, relief, climatic and hydrological conditions and vegetation cover (Komornicki and Skiba, 1996). In the lower part of the Western Tatras various variants of rendzina and brown soils prevail. Podzols predominate on the weathered carbonate-free rocks in the upper montane zone covered with spruce forests and in the lowest zone in some cases (e.g. granitoide moraines). In the upper mountain forest belt Podzols and Leptosols dominate. In the highest part of the Tatra Mts., there are mainly initial and poorly formed soils such as Leptosols and Regosols (Komornicki and Skiba, 1996).

3. Materials and methods

The presented material was collected in a soil survey conducted on the forest research plots (regular grid 500×500 m) in the Tatra National Park (Drewnik et al., 2021, 2022). During this research, 22 folisols from a total of 668 soils (Drewnik et al., 2022 – classification corrected) were described (Fig. 1). Typical pedons of folisols were selected for this study (Tables 1–4; Figs. 2–6).

The studied soils were classified according to the Polish soil classification (Systematyka gleb Polski, 2019) and WRB classification (IUSS Working Group WRB, 2022). The soil color was determined in a dry state using the Munsell color chart (2018). Soil samples were collected from soil horizons. In the laboratory, the samples were dried at room temperature (~20°C). After removing living roots, they were gently crushed using a wooden roller and ground in a mill. Soil pH was determined via the potentiometric method in deionized water at a soil-to-water ratio of 1:2.5 (Thomas, 1996). Total nitrogen (TN) was measured using a Vario Micro Cube elemental analyzer. CO_2 content obtained from carbonates was determined using a volumetric calcimeter method and content of carbonates was calculated. Total carbon concentration (TC) was measured during combustion at 950°C with thermal detection on a Vario Macro Cube elemental analyzer. The concentration of soil organic carbon (SOC) was calculated by subtracting inorganic carbon (carbonate) from TC (Wasak and Drewnik, 2015). Carbon to nitrogen ratio was calculated as SOC to TN.

For determined soil properties, mean values and standard deviations of the mean were calculated and Shapiro-Wilk test was used to determine the normality of data distribution. Due to the lack of normal distribution, the non-parametric Mann-Whitney U test was employed to compare differences between the means. A significance level of $p < 0.05$ was adopted. All statistical analyses were conducted using Statistica 13 software.

4. Results

4.1. Occurrence, morphology and classification

The studied folisols occurred at various altitudes ranging from ca. 1000 m a.s.l. (profile No. 700) up to over 1600 m a.s.l. (profiles No. 116 and 253). They were covered with different vegetation (spruce forests, dwarf pine thickets, secondary shrubs, grasslands). The occurrence of these soils was associated with very specific locations, such as: (1) outcrops of various rock types with relatively high resistance to weathering (Fig. 2e–g, Fig. 3e–g) – in such places rocky folisols (Leptic Folic Mawic Histosols) were formed, and (2) rock debris and slope

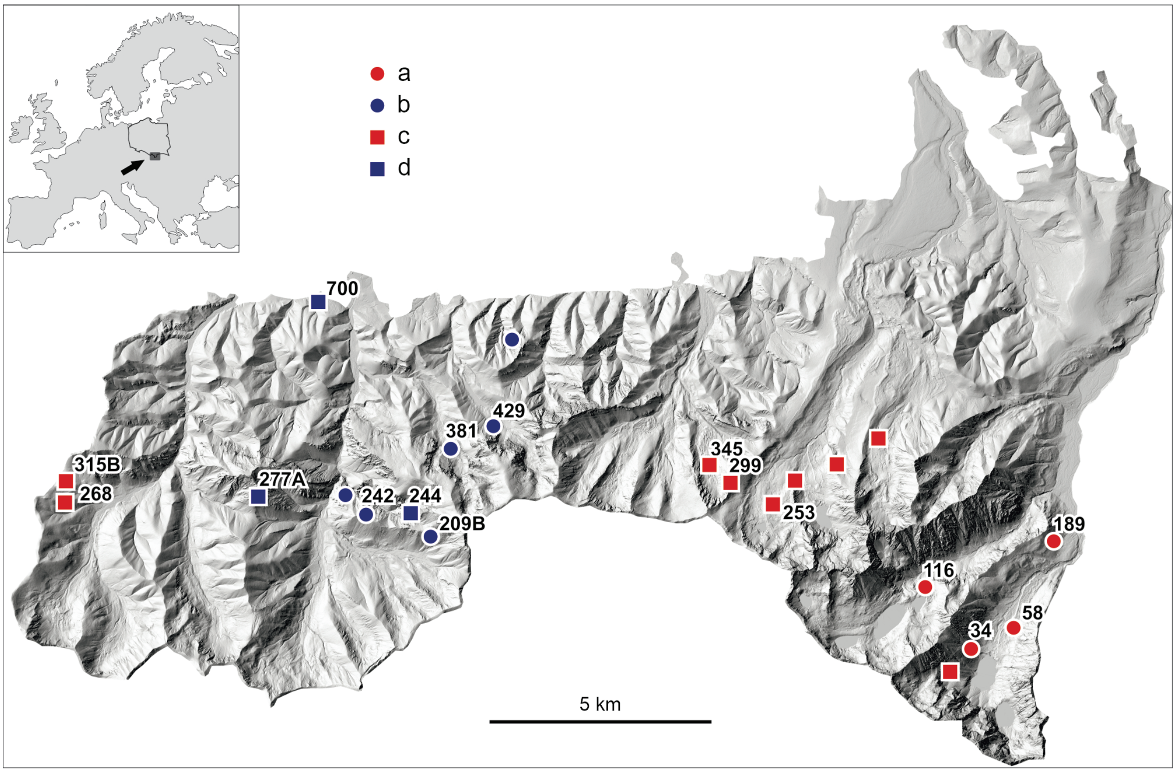

Fig. 1. Location of soils classified as folisols during a soil survey conducted on the forest research plots (regular grid 500×500 meters) in the Tatra National Park: a - rocky folisols, b - calcareous rocky folisols, c - debris folisols, d - calcareous debris folisols. Profiles included in this paper were marked with profile number (according to Tables 1–4)

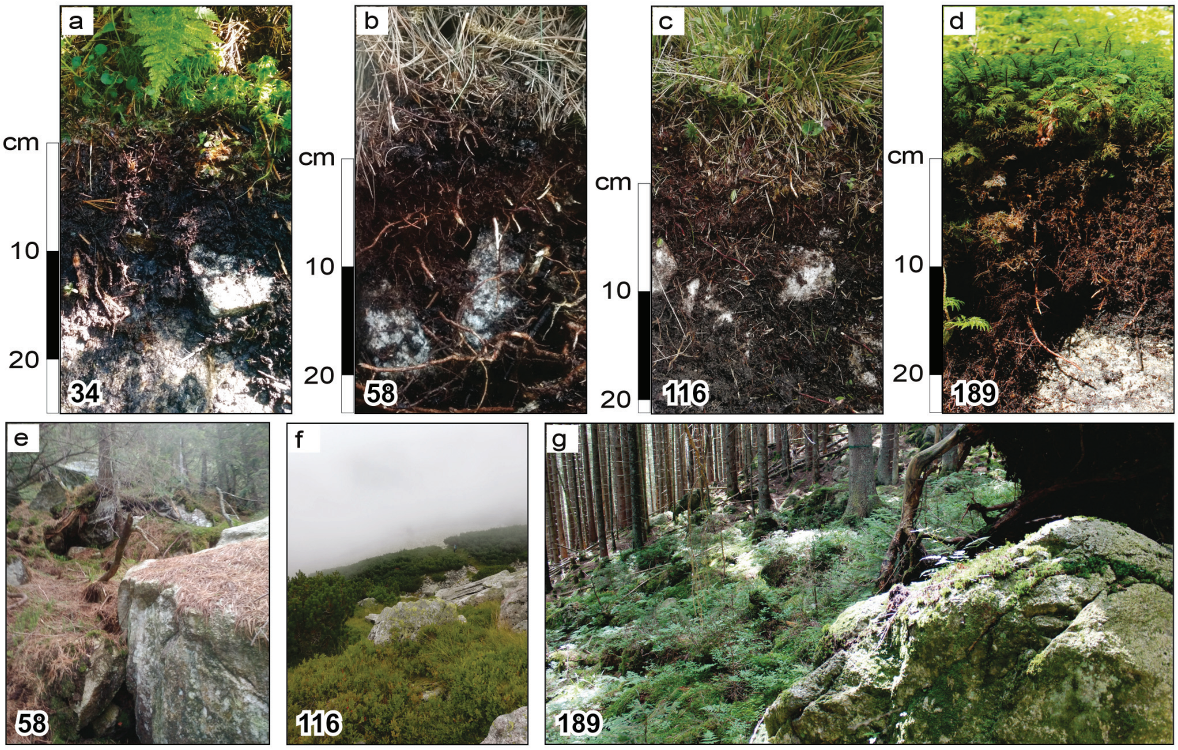

Fig. 2. Profiles of the studied rocky folisols and their location; a – profile 34, b – profile 58, c – profile 116, d – profile 189, e – surroundings of profile 58, f – surroundings of profile 116; g – surroundings of profile 189

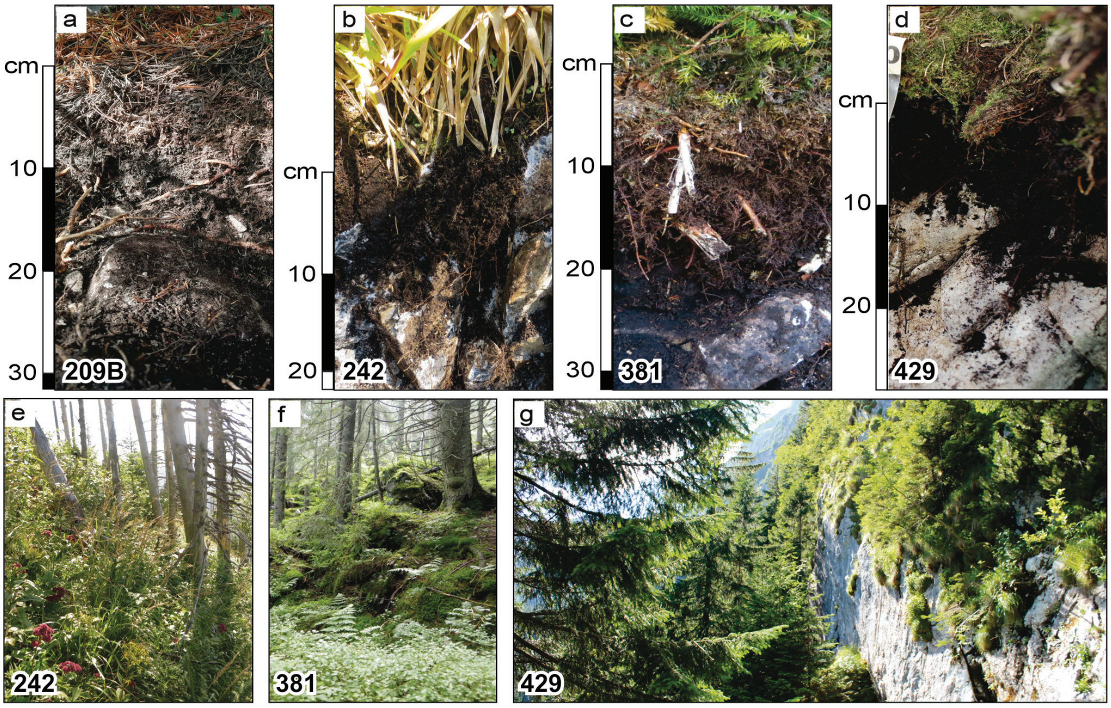

Fig. 3. Profiles of the studied calcareous rocky folisols and their location; a – profile 209B, b – profile 242, c – profile 381, d – profile 429, e – surroundings of profile 242, f – surroundings of profile 381; g – surroundings of profile 429

cover consisting of large rock fragments (Fig. 4b, 4d, 5b, 5d, 5f) – in such places mainly debris folisols (Skeletofolic Mawic Histosols) were formed.

The folisols were characterized by occurrence of thick organic horizons formed from litter at various stages of transformation (Tables 1–4): from Ol horizon (weakly decomposed and non-decomposed foliar residues and, in some cases, woody debris; colour in dry state 5–10YR 2.5–4/2–6), through Of horizon (more or less fragmented residues of foliar origin recognizable with the naked eye; colour in dry state 7.5–10YR 2–4/1–4) to Oh horizon (homogeneous organic matter with no recognizable plant structure; colour in dry state 7.5–10YR 2.5–4/1-3). Ol hori-

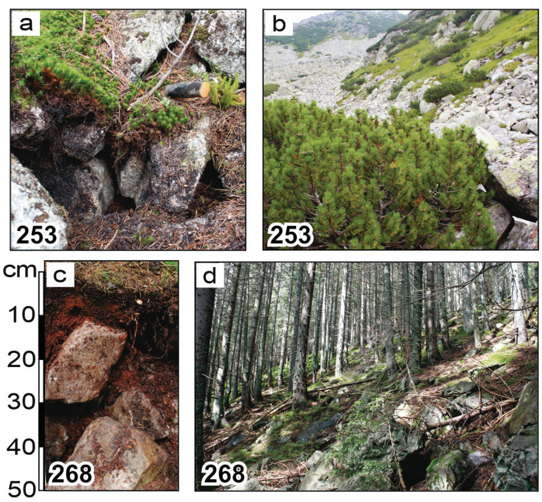

Fig. 4. Profiles of the studied debris folisols and their location (part 1); a – profile 253, b – surroundings of profile 253, c – profile 268, d – surroundings of profile 268

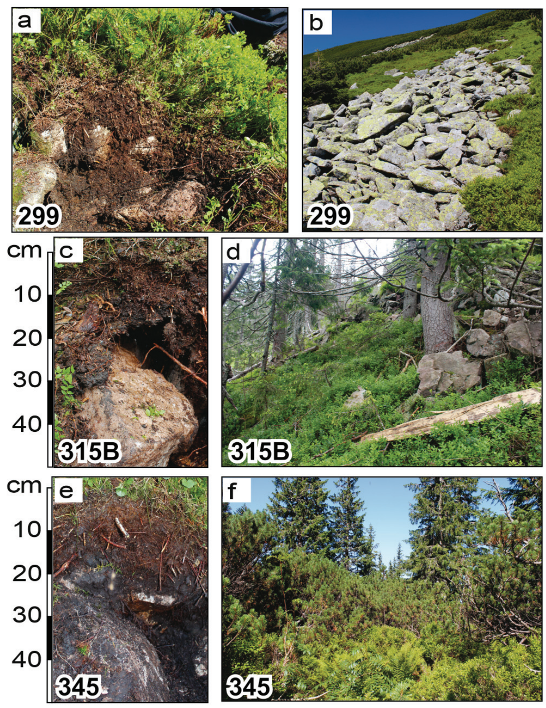

Fig. 5. Profiles of the studied debris folisols and their location (part 2); a – profile 299, b – surroundings of profile 299, c – profile 315B, d – surroundings of profile 315B, e – profile 345, f – surroundings of profile 345

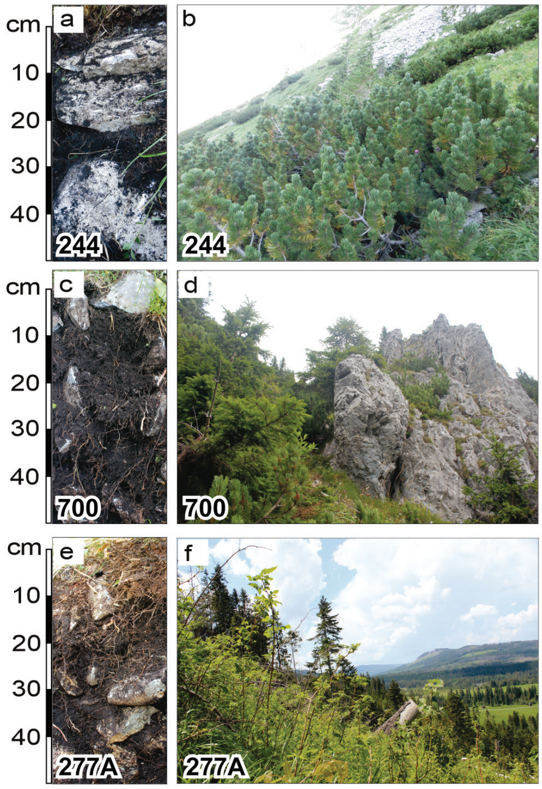

Fig. 6. Profiles of the studied calcareous debris folisols and their location; a – profile 244, b – surroundings of profile 244, c – profile 700, d – surroundings of profile 700; e – profile 277A; f – surroundings of profile 277A

zons did not occur in soils covered with grass vegetation (Tables 1, 2, 4: profiles No. 116, 242, 244, 700, 277A). The uppermost part of these soils was composed of the Of horizon (Figs. 2c, 3b, 6a, 6c, 6e).

The total thickness of litter horizons reached up to 30 cm in rocky folisols (Tables 1 and 2), and it might reach at least 100 cm in the form of organic material filling the spaces between stones and/or boulders (both in open work and non-open work slope covers) in debris folisols (Tables 3 and 4). The organic material showed no evidence of development under water saturation conditions, as indicated by lack of peat material in the studied folisols and *Sphagnum* sp. was not observed at the soil surface.

Table 1
Selected properties of rocky folisols

Horizon	Depth	Color (Munsell, dry)	Coarse fragments >2 mm	Soil structure	pH	$eqCaCO_3$	SOC	TN	C/N
	(cm)		(% vol.)			(% w.)			
Profile No. 34; WRB2022: Leptic Skeletofolic Mawic Histosol (Dystric); 1488 m a.s.l.; bedrock: granitoide (outcrop); vegetation: dwarf pine thickets (*Pinetum mugo carpaticum*)									
Ol/Of	0–2	7.5YR 4/4	0	tw	4.52	nd*	48.1	1.06	46
Of	2–12	7.5YR 3/4	10	tw	3.57	nd	42.3	2.10	20
Oh	12–27	7.5YR 3/2	70	zn, oa	3.73	nd	21.0	1.53	14
R	27+	–	–	–	–	–	–	–	–
Profile No. 58; WRB2022: Leptic Folic Mawic Histosol (Dystric); 1459 m a.s.l.; bedrock: granitoide (rock debris); vegetation: spruce forest (*Plagiothecio-Piceetum tatricum*)									
Ol	0–3	7.5YR 3/4	0	tw	4.99	nd	45.6	2.70	17
Of	3–13	7.5YR 3/3	0	tw	3.61	nd	44.2	2.64	17
Oh	13–23	7.5YR 3/3	50	zn	3.44	nd	40.7	2.33	17
R	23+	–	–	–	–	–	–	–	–
Profile No. 116; WRB2022: Leptic Skeletofolic Mawic Histosol (Dystric); 1664 m a.s.l.; bedrock: granitoide (rock debris); vegetation: grassland (*Nardetalia*)									
Of	0–7	10YR 3/3	20	tw	4.08	nd	39.1	2.04	19
Oh	7–20	7.5YR 4/1	60	zn, os	4.13	nd	21.4	1.41	15
R	20+	–	–	–	–	–	–	–	–
Profile No. 189; WRB2022: Leptic Folic Mawic Histosol (Dystric); 1192 m a.s.l.; bedrock: granitoide (rock debris); vegetation: spruce forest (*Plagiothecio-Piceetum tatricum*)									
Ol/Of	0–12	7.5YR 4/4	0	tw	3.43	nd	45.7	1.52	30
Of	12–18	7.5YR 3/4	0	tw	3.05	nd	46.6	1.62	29
Oh	18–22	10YR 3/2	30	zn	3.45	nd	32.2	1.58	20
R	22+	–	–	–	–	–	–	–	–

Abbreviations: tw – fibrous, zn – granular, oa – angular blocky, os – subangular blocky.
* not detected

Table 2
Selected properties of calcareous rocky folisols

Horizon	Depth	Color (Munsell, dry)	Coarse fragments >2 mm	Soil structure	pH	$eqCaCO_3$	SOC	TN	C/N
	(cm)		(% vol.)			(% w.)			
Profile No. 209B; WRB2022: Leptic Skeletofolic Mawic Histosol (Eutric); 1576 m a.s.l.; bedrock: limestone (outcrop); vegetation: dwarf pine thickets (*Pinetum mugo carpaticum*)									
Ol	0–2	5YR 4/6	0	tw	4.35	nd*	48.7	1.48	33
Of	2–4	7.5YR 4/4	0	tw, tg	4.77	nd	47.0	1.45	32
Oh	4–14	10YR 3/2	5	zn	7.29	8.915	27.4	1.48	19
Oh	14–30	7.5YR 2.5/2	80	zn	7.50	12.668	22.2	1.50	15
Rca	30+	–	–	–	–	–	–	–	–
Profile No. 242; WRB2022: Leptic Skeletofolic Mawic Histosol (Eutric); 1546 m a.s.l.; bedrock: dolomite (outcrop); vegetation: secondary shrubs (*Epilobietea angustifolii*)									
Of	0–3	7/5YR 3/3	0	tw	5.05	nd	45.7	1.05	43
Oh	3–15	7.5YR 2.5/2	50	zn	6.92	5.026	32.9	2.11	16
Rca	15+	–	–	–	–	–	–	–	–
Profile No. 381; WRB2022: Leptic Folic Mawic Histosol (Dystric); 1348 m a.s.l.; bedrock: dolomite (rock debris); vegetation: spruce forest (*Polysticho-Piceetum tatricum*)									
Ol	0–5	7.5YR 4/4	0	tw	4.11	nd	48.0	1.70	28
Of	5–17	7.5YR 3/4	0	tw	3.78	nd	47.6	1.71	28
Oh	17–26	7.5YR 2.5/3	0	zn	3.91	nd	44.2	2.04	22
Oh	26–30	7.5YR 2.5/3	40	zn, os	6.10	nd	41.2	1.91	22
Rca	30+	–	–	–	–	–	–	–	–
Profile No. 429; WRB2022: Leptic Folic Mawic Histosol (Dystric); 1340 m a.s.l.; bedrock: limestone (outcrop); vegetation: spruce forest (*Polysticho-Piceetum tatricum*)									
Ol	0–4	10YR 3/2	0	tw	4.67	nd	45.6	1.23	37
Of	4–8	10YR 2/2	0	tw	5.01	nd	42.3	1.64	26
Oh1	8–10	10YR 2/1	0	tg, tw	5.18	nd	37.1	2.01	18
Oh2	10–15	10YR 4/1	5	gr	7.09	4.435	34.8	2.40	14
Rca	15+	–	–	–	–	–	–	–	–

Abbreviations: tw – fibrous, tg – spongy, zn – granular, os – subangular blocky, gr – crumby.
* not detected

In the studied soils, extremely high content of coarse rock fragments was found, starting from different depths. In folisols developed on the slope cover formed from quartzite sandstone, large pores between rock fragments (open work) occupied up to 20–30% of the soil volume (Figs. 4a, 4c, 5c; profiles No. 253, 268, 315B). Transitions between soil horizons usually were smooth and wavy, while where coarse fragments were present (stones, boulders), the transition was irregular or broken. In the case of open work cover type, mechanical translocation of soil material was observed (Figs. 4c, 5c).

The soil structure was related to the degree of litter transformation. Ol, Of and Ofh horizons were dominated by a fibrous structure, while in Oh horizons the structure was usually granular, in some cases also subangular blocky (Tables. 1–4).

4.2. Chemical properties

The studied soils showed a very wide range of pH values (from 3.05 to 7.92) and a clear dichotomy in terms of reaction depending on the type of bedrock reflected by the soil subtype (rocky folisols and debris folisols on non-carbonate rocks vs. calcareous rocky folisols and calcareous debris folisols on carbonate rocks). Rocky folisols and debris folisols, regardless of the vegetation, had a very strong acidic reaction (pH < 4.00) or a strong acidic reaction (pH ≥ 4.00 and < 5.00) (Tables 1 and 3). In the calcareous rocky folisols, regardless of the vegetation, the uppermost part of the soil (Ol, Of horizon) had a strong acidic (pH ≥ 4.00 and < 5.00) or acidic (pH ≥ 5.00 and <6.00) reaction, while from the depth of the occurrence of rock fragments (even in low amounts, such as 5% vol. in profile No. 209B) the

Table 3
Selected properties of debris folisols

Horizon	Depth	Color (Munsell, dry)	Coarse fragments >2 mm	Soil structure	pH	eqCaCO$_3$	SOC	TN	C/N
	(cm)		(% vol.)			(% w.)			
Profile No. 253; WRB2022: Skeletofolic Mawic Histosol (Dystric); 1659 m a.s.l.; bedrock: granitoide (rock debris – open work); vegetation: dwarf pine thickets (*Pinetum mugo carpaticum*)									
Ol	0–3	5YR 4/4	0	tw, tg	4.07	nd*	48.4	0.89	54
Of	3–6	7.5YR 3/3	10	tw	3.78	nd	33.2	1.91	17
Of	6–60+	7.5YR 3/2	65	zn	3.98	nd	21.1	1.34	16
Profile No. 268; WRB2022: Skeletofolic Mawic Histosol (Dystric); 1346 m a.s.l.; quartzite sandstone (slope cover – open work); vegetation: spruce forest (*Plagiothecio-Piceetum tatricum*)									
Ol	0–2	7.5YR 4/4	0	tw	5.00	nd	49.9	2.03	25
Of	2–6	7.5YR 3/4	70	tw. tg	3.98	nd	49.8	2.09	24
Of	6–80	7.5YR 3/3	70	tw. tg	3.18	nd	47.3	1.71	28
Oh	80–100+	7.5YR 2.5/3	70	tw. tg	3.48	nd	34.8	1.21	29
Profile No. 299; WRB2022: SkeletofolicMawic Histosol (Dystric); 1773 m a.s.l.; bedrock: granitoide (slope cover – open work); vegetation: blueberry shrubs (*Vaccinietum myrtilli*)									
Ol	0–2	7.5YR 3/4	0	tw	4.77	nd	46.6	2.57	18
Of	2–15	7.5YR 3/2	0	tw	3.89	nd	32.6	1.57	21
Of	15–40	10YR 4/1	70	zn	4.06	nd	25.3	1.31	19
Ah	40–70+	7.5YR 4/1	70	zn	4.37	nd	17.2	0.96	18
Profile No. 315B; WRB2022: Skeletofolic Mawic Histosol (Dystric); 1368 m a.s.l.; bedrock: quartzite sandstone (slope cover – open work); vegetation: spruce forest with blueberry shrubs (*Plagiothecio-Piceetum tatricum*)									
Ol	0–4	5YR 3/4	0	tw	4.25	nd	51.0	2.00	25
Of	4–12	7.5YR 4/3	0	tg, tw	3.32	nd	47.4	1.58	30
Of	12–60+	10YR 2/2	50	tg, tw	3.30	nd	47.6	2.07	23
Profile No. 345; WRB2022: Skeletofolic Mawic Histosol (Dystric); 1546 m a.s.l.; bedrock: granitoide (moraine); vegetation: dwarf pine thickets (*Pinetum mugo carpaticum*)									
Ol/Of	0–3	7.5YR 4/4	0	tw	4.67	nd	47.5	2.32	20
Of	3–18	7.5YR 3/4	0	tw	3.84	nd	44.6	2.11	21
Oh	18–25	7.5YR 2.5/3	0	zn, os	3.43	nd	35.2	1.75	20
Oh	25–50+	7.5YR 3/2	70	os	3.71	nd	26.9	1.07	25

Abbreviations: tw – fibrous, tg – spongy, zn – granular, os – subangular blocky.
* not detected

reaction became neutral (pH ≥ 6.80 and < 7.40) or alkaline (pH ≥ 7.40) (Table 2). In the calcareous debris folisols in the uppermost part of the soil (Ol, Of, Ol/Of, Oh horizon) the reaction was slightly acidic (pH ≥6.10 and <6.80) or acidic, but deeper it changed to neutral or alkaline (Table 4). It should be noted that all calcareous debris folisols were covered with non-forest vegetation. Also, in this case, the lack of rock fragments within uppermost part of the soil (profile 700) resulted in acidification of this part of the soil (Table 4).

The content of SOC in the studied soils was very high and decreased with soil depth from 40–50% in the uppermost part of the soil (Ol, Of horizons) to 20–30% in the Oh horizons (Tables 1–4). Similarly, a high TN content was found in the studied soils – from ~1% to ~3%. The range of the C/N ratio was very large – from values exceeding 50 to values of ~15. Generally, the C/N ratio value decreased with depth. There was no expected clear dependence of the C/N ratio on the type of vegetation, but only a general tendency of a slightly lower C/N ratio in the case of soils covered with non-forest vegetation.

A significant difference between folisols formed on different bedrock (non-carbonate rocks vs. carbonate rocks) in the case of mean soil pH and the mean C/N ratio was found (Table 5). Considering all soil horizons together, calcareous folisols (both rocky and debris folisols) showed a higher mean pH than folisols found on non-carbonate rocks (pH 6.04 vs. pH 3.90, respectively) and had a lower mean C/N ratio (21 vs. 25, respectively). No statistically significant differences were found in the content of both SOC and TN in this respect (Table 5).

Table 4
Selected properties of calcareous debris folisols

Horizon	Depth	Color (Munsell, dry)	Coarse fragments >2 mm	Soil structure	pH	$eqCaCO_3$	SOC	TN	C/N
	(cm)		(% vol.)			(% w.)			
Profile No. 244; WRB2022: Skeletofolic Mawic Histosol (Eutric); 1543 m a.s.l.; bedrock: limestone (slope cover); vegetation: grassland (*Festuco versicoloris-Seslerietum tatrae*)									
Of/Oh	0–6	7.5YR 2.5/2	5	tw. zn	6.75	nd*	37.2	2.52	15
Oh	6–50+	10YR 2/2	60	zn	7.07	nd	33.0	2.52	13
Profile No. 700; WRB2022: Skeletofolic Mawic Histosol (Eutric); 1031 m a.s.l.; bedrock: limestone (rock debris); vegetation: secondary shrubs (*Epilobietea angustifolii*)									
Of	0–10	7.5YR 3/4	0	tw	5.42	nd	44.2	2.07	21
Oh1	10–20	7.5YR 2.5/2	70	gr, zn	6.41	nd	32.8	1.86	18
Oh2	20–55+	7.5YR 2.5/2	70	gr, zn	7.92	3.844	25.3	1.27	20
Profile No. 277A; WRB2022: Skeletofolic Mawic Histosol (Eutric); 1577 m a.s.l.; bedrock: limestone (slope cover – open work); vegetation: grassland (*Festuco versicoloris-Seslerietum tatrae*)									
Of	2–0	7.5YR 2.5/3	20	tw	6.43	nd	37.9	2.35	16
Of	0–10	10YR 2/2	40	zn, os	7.57	0.364	34.5	2.35	15
Oh1	10–35	7.5YR 2.5/2	70	ko, gr	7.67	3.639	32.7	2.04	16
Oh2	35–60+	7.5YR 2.5/2	70	zn, gr	7.90	6.664	29.9	1.64	18

Abbreviations: tw – fibrous, zn – granular, gr – crumby, os – subangular blocky, ko – coprolitic.
* not detected

Table 5
Mean soil pHw, content of SOC and TN as well as C/N ratio in folisols developed on non-calcareous and calcareous bedrock. Values in parentheses are standard deviations. For a given column, mean values with different letters significantly differ at $p < 0.05$ based on non-parametric Mann-Whitney U test

Bedrock	N	pH	SOC (% w.)	TN (% w.)	C/N
Granitoide. quartzite sandstone	63	3.90 (0.12) a	38.24 (1.41) a	1.64 (0.06) a	25 (1) a
Limestone. dolomite. calcareous conglomerate	35	6.04 (0.30) b	35.87 (1.54) a	1.80 (0.07) a	21 (1) b

5. Discussion

The diversity of the studied folisols can be explained by the heterogeneity of soil-forming factors. First of all, an important factor differentiating the studied folisols was the type of bedrock (Drewnik et al., 2021, 2022). In terms of soil morphology, the folisols developed on the extremely resistant to weathering quartzitic sandstone stood out. In these soils, a significant volume of the soil profile was occupied by voids, which favour subsurface mechanical translocation of soil material that are easy to detect with the naked eye. Similar effects of subsurface soil material translocation were described by Skiba and Komornicki (1983) in soils on isolated patches of washed granitoid moraine in the Polish Tatra Mts. and by Schaetzl (1991) in soils developed on gravelly dolomitic parent materials on Bois Blanc Island on the Lake Huron (USA). In our study, such folisols occupied extensive areas on the slope, which is not easily noticeable in the field (Figs. 4d, 5b).

The influence of the lithological factor on diversity of the studied folisols is also clearly visible in the mineral composition of the bedrock. The presence of carbonates in coarse fragments (even in when the coarse fragments constitute as little as e.g. 5% vol. – see: profile No. 209B in Table 2) is sufficient to reduce the acidity of the soil, which would be natural in humid climate and in the case of organic material, which constitutes an essential part of the soil. Similar effects of carbonate-bearing (< 6.2% of $CaCO_3$) parent materials on biogeochemistry and properties of mineral soils were described by Rowley et al. (2020) in Swiss Alps. As a result of carbonates weathering in a humid climate, soil pH rise significantly but also high amount of extractable Ca is released to soil solution (Rowley et al., 2018) affecting plants growth (Jobbágy and Jackson, 2001).

The diversity of the studied folisols was also related to the type of vegetation, which was reflected in the lack of Ol horizon in the soils covered with non-forest vegetation (grassland such as *Festuco versicoloris-Seslerietum tatrae*, *Carici-Festucetum tatrae*, and *Nardetalia*). However, it should be emphasised that vegetation not significantly affects the C/N ratio, which confirms the findings of Telega (2022) in the Sudetes Mts. (Poland). This is an issue that certainly requires further research.

The presented examples of folisols from the Tatra Mts. allow to some comments regarding classification of the soils. First of all, it should be stressed that the implementation of the 'calcareous folisol' subtype to the Polish soil classification (Systematyka gleb Polski, 2019) for folisols developed on carbonate parent material was justified, which is confirmed by the above-mentioned differences in soil properties (soil pH, C/N ratio). In addition, it should be noted that among presented folisols from the Tatra Mts., subtype 'typical folisol' was not found (Tables 1–4). The occurrence of such soils was confirmed by Telega (2022) in the Stołowe Mts. (Poland, Sudetes Mts.), who however did not find these soils in the Karkonosze Mts. (Poland, Sudetes Mts.). From the comparison of the above data, a preliminary conclusion can be drawn that 'typical folisols' occur rather in areas that strongly favours local accumulation of litter in traps between boulders and stones without its downward or lateral translocation through slope covers – which is a peculiarity of the extraordinary rock relief of the Stołowe Mts. (Telega, 2022). The case of the folisols in the Karkonosze Mts. (Telega, 2022) and the Tatra Mts. (this study) is different in relation to folisols in the Stołowe Mts. Apart from the local traps, specific and relatively extensive areas of both stony and boulder slope covers and moraines as well as rock walls favours the formation of folisols. This conclusion is supported by the fact that out of over 660 studied soils in the Tatra Mts., 22 soils were classified as folisols (Drewnik et al., 2022). Considering both geometric location (regular grid) and large number of the research plots, this gives a roughly approximated ratio of about 3.5% of all soils in the Polish part of the Tatra Mts.

A comparison of studied soils classification according to the Polish soil classification (Systematyka gleb Polski, 2019) and WRB classification (IUSS Working Group WRB, 2022) revealed a few important differences between these systems. The first one concerns the definition of 'Rockic' principal qualifier (WRB classification) which excludes folisols with even low amount of coarse fragments (Tables 1–4). In the result, all the studied soils were classified according to WRB classification as Mawic Folic Histosols (Tables 1–4). In the Polish soil classification (Systematyka gleb Polski, 2019) no folisols subtype is completely equivalent to 'Mawic' principal qualifier. Only if the presence of coarse fragments filled with organic material exceeds 60% vol. (with at least 35% of stone fraction) soil can be classified as debris folisols (Tables 3 and 4). Despite occurrence of coarse fragments coated with organic matter and large voids filled with organic matter in between the soil surface and continuous rock the other soils were classified as rocky folisols according to the Polish soil classification (Systematyka gleb Polski, 2019).

Another difference was related to the trophic status of folisols. In WRB classification (IUSS Working Group WRB, 2022) soil organic material in Histosol needs to have a specific range of soil pH in its major part to be classified either by 'Dystric', 'Eutric' or 'Alcalic'. On the other hand, in the Polish soil classification (Systematyka gleb Polski, 2019) the only subtype referring to soil trophy (calcareous folisols) is dependent on the mineralogy of bedrock, namely the presence of carbonate bedrock in the form of continuous rock or coarse-skeletal cover. Thus, using the principal qualifier 'Eutric' was not consistent with classifying as 'calcareous folisol' (see: profiles No. 381 and 429, Table 2).

6. Conclusions

1) In the Polish part of the Tatra Mts. folisols can be found relatively often, covering up to 3.5% of the soil cover in the studied area (i.e. without the highest part of the Tatra Mts.). The occurrence and the properties of these soils depend primarily on the bedrock. Vegetation affects the morphology of folisols but has no significant effect on their properties.
2) In the humid and cool climate, folisols are acidic, but the occurrence of even a low amount of carbonate rock fragments (limestone, dolomite) causes soil alkalization. Therefore, the implementation of the subtype 'calcareous folisol' to the Polish soil classification (Systematyka gleb Polski, 2019) is justified.

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Morfologia, właściwości i klasyfikacja gleb ściółkowych Tatr

Słowa kluczowe

Gleby ściółkowe
Folic Histosols
Klasyfikacja gleb
Glebowy węgiel organiczny
Obszary górskie

Streszczenie

Celem pracy było przedstawienie zróżnicowania gleb ściółkowych (folisoli) występujących w polskiej części Tatr. Uwzględniono morfologię, podstawowe właściwości i klasyfikację tych gleb. Prezentowany materiał został zebrany w trakcie badań przeprowadzonych na leśnych powierzchniach monitoringowych (regularna siatka punktów 500×500 m) na terenie Tatrzańskiego Parku Narodowego. W trakcie badań opisano 22 gleb ściółkowych na łącznie 668 badanych profili. Do niniejszej publikacji wybrano typowe profile gleb ściółkowych. Podstawowe właściwości gleb zostały oznaczone standardowymi metodami laboratoryjnymi. Badane gleby ściółkowe występowały na różnej wysokości bezwzględnej i były porośnięte różną roślinnością (lasy świerkowe, zarośla kosodrzewiny, zbiorowiska naskalne, murawy). Występowanie tych gleb wiązało się z bardzo specyficznymi lokalizacjami, takimi jak: (1) wychodnie różnych typów skał o stosunkowo dużej odporności na wietrzenie – w takich miejscach utworzyły się gleby ściółkowe skaliste (Leptic Folic Mawic Histosols wg WRB 2022), oraz (2) rumosz skalny i pokrywy stokowe składające się z dużych okruchów skał (kamienie, bloki, głazy) – w takich miejscach utworzyły się głównie gleby ściółkowe rumoszowe (Skeletic Folic Mawic Histosols wg WRB 2022). Właściwości badanych gleb ściółkowych zależały przede wszystkim od podłoża skalnego. Roślinność wpływała na morfologię tych gleb, ale nie miała istotnego wpływu na ich właściwości. Gleby ściółkowe były kwaśne, jednak występowanie nawet niewielkiej ilości fragmentów skał węglanowych (wapieni, dolomitów) powodowało ich alkalizację. Z tego powodu wprowadzenie podtypu „gleba ściółkowa rędzinowa” do Systematyki gleb Polski jest uzasadnione.