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The usefulness of the Munsell colour indices for identification of drained soils with various content of organic matter

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Abstract

Purpose The aim of the study was to determine the usefulness of the Munsell colour indices for identification of drained soils with various content of organic matter, developed on the sandy substrate.

Methods The analysed soils, according to the Polish Soil Classification (PSC 2019), belong to thin murshic soils (WRB 2022: Murshic Histosols/Histic Gleysols), typical semimurshic soils (Mollic/Umbric Gleysols (Arenic, Drainic, Mulmic)) and to postmurshic soils (Umbric Gleysols (Arenic, Drainic, Nechic)). The following dry colour indices: value (V), chroma (Ch), V+Ch, V+0.5Ch, V×Ch and V/Ch, were correlated with soil variables (LOI, $C_{org.}$, $N_{tot.}$, C:N and Fe_{HCl}, Mn_{HCl}—elements extracted with 0.5 M HCl).

Results The strongest correlation with the SOM content was displayed by the Munsell value, which allows one to estimate the SOM, $C_{org.}$, $N_{tot.}$ content in the soils studied. The classification and regression trees (C&RT) revealed that the analysed soil materials could be successfully divided based on the Munsell value alone. The V/Ch quotient demonstrated significant correlations with LOI, $C_{org.,}$ $N_{tot.}$, C:N, Fe_{HCl} and Mn_{HCl}. This quotient equalled 1–2 for murshic (≥ 12% $C_{org.}$) and semimurshic (≥ 6.0 $C_{org.}$ < 12.0%), but varied greatly (1–5) for postmurshic (≥ 0.6 $C_{org.}$ < 6.0% $C_{org.}$) soil materials.

Conclusion The analysed soil materials had the Munsell value differentiated enough to enable their identification. The V/Ch quotient can help to trace the origin of postmurshic soils. Its narrow value (1–2) indicates that the postmurshic soil developed through advanced transformation of murshic soil materials, whereas a broader value (2–5) indicates that the postmurshic soil originated from dewatered Gleysols.

Keywords Soil organic matter · Diagnostic soil horizons · Soil classification · Sandy post-bog soils · Histosols · Gleysols

1 Introduction

The colour of soils is an obvious morphological feature arising from the chemical composition of soils (Taylor 1981). Based on the colour, it is possible to estimate the content of some soil components, including humus or iron compounds, and—indirectly—nutrients. Field measurements of soil colour are essential for making an assessment of water relations, including the identification of redoximorphic features (Rabenhorst et al. 2014; Pretorius et al. 2017). Measurements of the soil colour can also be helpful in the monitoring of changes occurring in soil after a fire (Pereira et al. 2014). Colour serves to distinguish the horizons in a soil profile, and thus to determine the advancement of the soil formation process. As an important diagnostic feature, it is commonly used in descriptions of soil profiles (FAO 2006). Colour can also help to estimate the fertility of soils and their agricultural usefulness. This explains why so many names of soils are derived from the colour of their surface horizon.

Munsell soil colour charts are widely used for soil classification (Gobin et al. 2000; Pegalajar et al. 2020). Munsell soil colour parameters serve to define the soil features and diagnostic horizons in many soil classification systems, e.g. Soil Taxonomy (Soil Survey Staff 2014),

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World Reference Base for Soil Resources (IUSS Working Group WRB 2022), Polish Soil Classification—PSC 2019 (Kabała et al. 2019). In the Netherlands, the colour of soils has been employed to distinguish brown plaggen soils from black plaggen soils based on the value + chroma criterion (Pape 1970).

Many articles discuss dependences between the colour of soils and the content of soil organic matter (SOM) or organic carbon ($C_{org.}$) (Blume and Helsper 1987; Evans and Franzmeier 1988; Łachacz 1993; Schulze et al. 1993; Konen et al. 2003; Wills et al. 2007; Jorge et al. 2021), nitrogen (Qian et al. 1993; Moritsuka et al. 2014) and iron oxides (Leger et al. 1979; Torrent et al. 1983; Schwertmann 1993; Moritsuka et al. 2014). A rapid assessment of the SOM content using Munsell soil colour charts can help to determine trends and consequently the soil degradation state (Minh et al. 2020; Rubinić et al. 2021). Soil organic matter is the most important pigment that influences the soil colour. Typically, the SOM content is negatively correlated with soil hue, value and chroma (Ibáñez-Asensio et al. 2013). This is due to the fact that humus substances absorb most visible wavelengths of light (Vodyanitskii and Savichev 2017). The general relationship between SOM and soil colour is modified by the grain-size distribution, chemical and mineralogical composition, land use, climatic conditions and other factors (Franzmeier 1988; Schulze et al. 1993; Konen et al. 2003; Spielvogel et al. 2004; Wills et al. 2007; Pretorius et al. 2017). In some soils, the presence of dark minerals can strongly affect the relationship between organic matter and colour.

Many colour indices have been proposed in the literature to determine the SOM storage and to assess water conditions in soils (Evans and Franzmeier 1988; Thompson and Bell 1996; Gobin et al. 2000; Chaplot et al. 2001; Bravo et al. 2007; Pretorius et al. 2017). Because the composition of organic matter comprises different light-absorbing components, studies have been carried out on the effect of humic substances on the colour of soils (Schulze et al. 1993). These authors showed the dependence between the content of fulvic acids, humic acids and the Munsell value. They also concluded that the fulvic acid fraction isolated from Indiana soils displayed the Munsell value of 5.5, whereas the humic acid fraction had an average value of 2.1. The colour of soils is an outcome of interactions between pigmented mineral particles. Blume and Helsper (1987) demonstrated that the grouping of soils according to grain-size distribution greatly improved the correlation between the colour and content of SOM (humus) in soil. Leger et al. (1979) as well as Pretorius et al. (2017) found a stronger impact of organic matter on the colour of sandy soils than of clay ones. This is due to the smaller external surface area of sand grains than that of the clay fraction, hence the former require fewer organic colloids to be covered.

For decades now, standardized soil colour charts based on the Munsell colour system have been used in soil science field practice (Kirillova et al. 2018; Turk and Young 2020). Currently, they are available in different versions, depending on a producer. Studies have been completed to compare different versions of these charts (Thompson et al. 2013; Rabenhorst et al. 2015), and to find out to what extent an individual user is able to match soils to colour chips (Shields et al. 1966; Post et al. 1993, 2006). Results of these investigations indicate that an experienced soil scientist is able to interpolate determinations of soil colour to the nearest unit of hue and nearest half unit of both value and chroma (Pomerening and Knox 1962; Shields et al. 1966; Post et al. 1993; Rabenhorst et al. 2015). Although easy-to-use digital colorimeters have been made available (Kirillova et al. 2018; Moritsuka et al. 2019), colour charts continue to be used in soil science studies because of the rapidness and ease of determinations (Sugita and Marumo 1996).

Studies on colour are useful in the identification of post-bog soils developed on sandy substrate (Łachacz 1993). In the soil landscape, they constitute a transitional zone between organic soils (murshic soils), through soils with the decreasing SOM content, referred to as semimurshic and postmurshic soils in PSC 2019 (Kabała et al. 2019), to humose sands composing the top horizons of Arenosols. Semimurshic and postmurshic soils occur on the edges of peat bogs, and are particularly common on fluvioglacial plains, where they tend to cover large areas (Łachacz 2001). They develop in two ways: (i) directly from drained gley soils; (ii) as a result of prolonged intensive draining of shallow peat soils, which leads to a decrease in the SOM content below the lower threshold value set for organic soils, e.g. in PSC 2019 < 12% $C_{org.}$. An elevated content of mineral parts (sand and silt fractions) in these soils arises from: (i) input by flooding rivers, (ii) pedoturbation (mixing the surface soil layers with the mineral substrate) and (iii) aeolian supply from nearby sandy areas.

The further evolution of organic soils after dewatering is called pedogenic transformation (mursh-forming process), which contributes to the depletion of SOM and a relative increase in the content of mineral matter (Łabaz and Kabala 2016; Kabała et al. 2019). In soil with a small thickness of the SOM rich horizon, ploughing also contributes to the formation of soil materials containing less than 12% $C_{org.}$. Organic matter in these soils is loosely attached to sand grains. It is composed of small granular aggregates (clusters) of coagulated humus, which are only partly enveloped in sand grains (Fig. 1). As a result of redoximorphic processes in the predrainage phase of these soils, a large amount of sand grains is devoid of any colour coatings. As SOM is being depleted, the share of black pigment (humic compounds) is decreasing, while a lighter in colour (whitish) sandy component (mainly quartz grains) is becoming

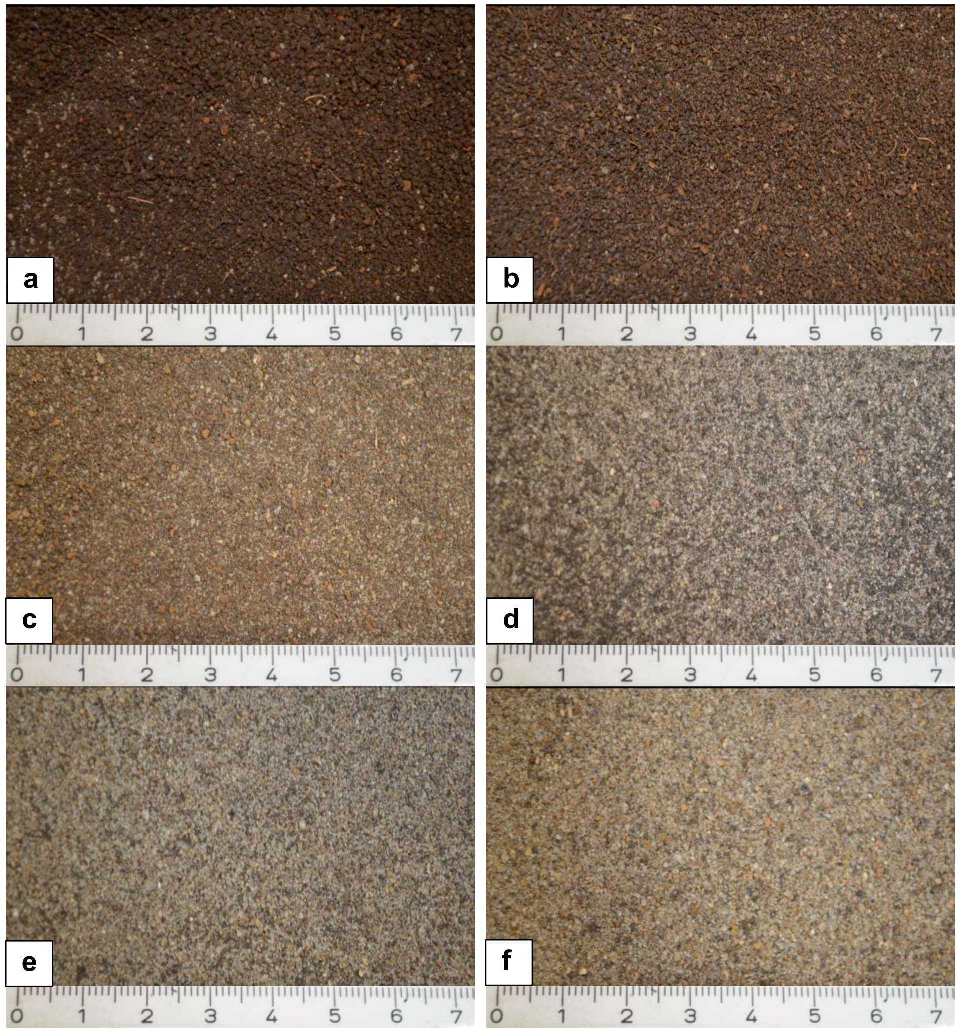


Fig. 1 Examples of soil materials studied: **a** murshic (20.26% $C_{org.}$, 40.9% LOI, 96,740 mg kg^{-1} Fe_{HCl}); **b** semimurshic (8.56% $C_{org.}$, 19.0% LOI, 44,000 mg kg^{-1} Fe_{HCl}); **c** semimurshic (6.88% $C_{org.}$, 14.5% LOI, 23,100 mg kg^{-1} Fe_{HCl}); **d** postmurshic (4.23% $C_{org.}$, 10.7% LOI, 16,800 mg kg^{-1} Fe_{HCl}); **e** postmurshic (2.68% $C_{org.}$, 6.1% LOI, 2000 mg kg^{-1} Fe_{HCl}); **f** postmurshic (1.06% $C_{org.}$, 2.6% LOI, 3420 mg kg^{-1} Fe_{HCl})

more visible. In outwash plains, a mosaic-like pattern of soils has developed with soils having a different content of organic matter, depending on the groundwater level (hydrotoposequences of soils). Different colours (shades of the grey colour) can be observed on the surface of a given area after ploughing or other soil tillage treatments, depending on small (up to 20–30 cm) differences in the elevation of the terrain (Łachacz 1993, 2001).

The Polish Soil Classification (Kabała et al. 2019), in accordance with the tradition of Polish soil science, distinguishes a diagnostic horizon in post-bog sandy soils called arenimurshic (Polish—*arenimurszik*) one, composed of semimurshic (6–12% $C_{org.}$) or postmurshic (0.6–6% $C_{org.}$) soil material. The World Reference Base for Soil Resources (IUSS Working Group WRB 2022) among diagnostic soil materials distinguishes mulmic one. It is a mineral material containing ≥ 8% $C_{org.}$ < 20% developed from organic material after drainage. This material may have varied grain-size distribution, not only sandy but also heavier, which enables the identification of a principal qualifier for Phaeozems, as well as a supplementary qualifier for Histosols and Gleysols. It should be underlined that the WRB classification does not distinguish soil materials which contain less than 8% $C_{org.}$ developed at a further stage in the pedogenic transformation of drained soils. In this classification, soils which represent further stages in the degradative depletion of SOM are most often classified as Gleysols, while the supplementary qualifiers (Arenic, Drainic, Humic, Mulmic, Nechic) allow more detailed characterisation of these soils. In our paper, we focused on post-bog soils with sandy texture containing less than 12% $C_{org.}$ There is an urgent need to develop methods for the assessment of the SOM content that will allow rapid and inexpensive evaluation of organic carbon resources over large areas of the globe. Despite the improvement of spectrophotometric and remote methods, the use of Munsell charts will remain the standard practice (Wills et al. 2007; Rabenhorst et al. 2015; Jorge et al. 2021; Schmidt and Ahn 2021).

The aim of the study was to answer the following questions: (1) can soil colour be a reliable proxy for soil organic matter, organic carbon and total nitrogen content in sandy post-bog soils and (2) to what extent can colour help to identify the following soil materials: murshic, semimurshic, postmurshic?

2 Materials and methods

2.1 Study area and soil sampling

The study covered soil samples collected from Mazury Plain and Kurpiowska Plain, NE Poland (Solon et al. 2018). These two physico-geographical regions in Poland embrace a plain formed from fluvioglacial sands (outwash plains). In the river valleys as well as in numerous terrain depressions, there are organic soils and accompanying mineral-organic soils (containing less than 12% $C_{org.}$). Usually shallow fens (alder and reed peats) were drained in the second half of the nineteenth century, and the drainage works continued in the first half of the twentieth century. The draining triggered changes of the soil mass, referred to as a mursh-forming process, and soil-degrading SOM depletion (Łabaz and Kabala 2016; Kabała et al. 2019). The soils studied were used as meadows and pastures as well as arable fields. To a certain extent, the type of land use depends on the SOM content, which in turn is dependent on the groundwater level. Thus, soils containing over 12% $C_{org.}$ in surface horizon are typically used as meadows, and those having less than 12% $C_{org.}$ are more often turned into arable fields. The type of land use is not constant over time, and therefore some arable fields are temporarily converted to grassland, while some grassland is converted into arable land. Ploughing deepens the surface layer and homogenises the soil material while the resulting aeration of the soil accelerates the mineralisation of SOM. It is only murshic soils used as permanent meadows that are sporadically ploughed in order to sow them with grass mixtures.

The analysed soils, according to the Polish Soil Classification (PSC 2019), belong to thin murshic soils (WRB 2022: Murshic Histosols/Histic Gleysols), typical semimurshic soils (Mollic/Umbric Gleysols (Arenic, Drainic, Mulmic)) and to postmurshic soils (Umbric Gleysols (Arenic, Drainic, Nechic)). Soil samples were taken from the surface layer (0–20(30) cm) ($n = 187$) and from the subsurface layer lying directly underneath (21(31)–60 cm) ($n = 139$). No samples were extracted from soil horizons below 60 cm because these were composed of fluvioglacial sand, not transformed by processes of pedogenesis. The surface layers represented mainly the mineral horizon A (Ah, Ap layer) and, less often, the organic H horizon. The subsurface layers represented mainly the mineral C horizon (Cr layer) and less often, the organic H horizon (IUSS Working Group WRB 2022). The soil sampling was based on the morphological differentiation visible in soil profiles, hence the lower threshold of the surface layer is not identical, varying from 20 to 30 cm in depth, which to some extent is associated with the depth of ploughing. The analysed soils are characterised by the topmost layer rich in organic matter, which is underlain either directly by fluvioglacial sand or an unploughed layer of organic or mineral-organic formation. The soil material taken from the depth of 21(31)–60 cm contains more of incompletely decomposed plant residues (peat-like) and sometimes has an addition of fine-grain (silt and clay) soil materials accumulated due to the alluvial activity of rivers (telmatic mud) (Długosz et al. 2018). The subsurface samples tend to contain less SOM than surface ones, which is typical feature of post-bog soils with a small thickness of the SOM abundant surface layer (Łachacz 2001). However, it is worth noting that a smaller content of SOM in the surface layer than in the deeper ones may indicate the prolonged draining of the soil and intensive SOM mineralisation. In the soils studied, this is associated with the degradation of fen soils caused by drainage.

2.2 Laboratory analysis

Soil samples were air dried while being gently crushed and any live plant roots or iron concretions were removed manually. Afterwards, the samples were passed through a 2 mm mesh sieve. Soft (non-concretion) aggregations of iron and manganese oxides present in some soil samples, following the preparation of soil samples for analysis, were incorporated into the soil mass, thereby affecting its colour. The colour of air-dry soil samples was determined under diffused natural light with the help of Munsell charts (Munsell Color Company 1994). Two persons conducted the colour determination independently. In about 25% of the cases, there were differences, usually in the range of 0.5 value or chrome unit, which is when the Munsell colour notation is an average of the two determinations. A similar level of agreement for the two determinations is given by Post et al. (1993). The following determinations were made in air-dry soil samples: loss-on-ignition (LOI) after dry ashing for 6 h at a temperature of 550 °C, which approximates the amount of soil organic matter (SOM); total organic carbon ($C_{org.}$) and total nitrogen ($N_{tot.}$) contents, which were measured with a Vario Max Cube CN elemental analyser; and the content of iron (Fe_{HCl}) and manganese (Mn_{HCl}), after extraction with 0.5 M HCl measured with the ASA technique (Sapek and Sapek 1992). The results were converted to absolute dry matter (drying at 105 °C) and presented as an arithmetic mean from two parallel determinations.

2.3 Division of soil samples into groups

Soil samples were divided (stratified) into several groups. Considering the criteria provided in the PSC 2019 (Kabała et al. 2019), the surface soil samples were divided according to their $C_{org.}$ content into the following groups:

$\geq$ 12.0% $C_{org.}$—mursh (Polish–*mursz*),

$\geq$ 6.0–< 12.0% $C_{org.}$—semimurshic (Polish–*murszowaty*),

$\geq$ 0.6–< 6.0% $C_{org.}$—postmurshic (Polish–*murszasty*).

The subsurface samples were divided into the following groups:

$\geq$ 12% $C_{org.}$—peat (Polish–*torf*),

$\geq$ 6–< 12% $C_{org.}$—peaty sand (Polish–*torfiasty piasek*),

$\geq$ 0.6–< 6% $C_{org.}$—humose sand (sometimes with peat admixtures, especially when higher SOM content),

< 0.6% $C_{org.}$—sand (usually with some addition of humus substance of illuvial origin).

2.4 Statistical calculations

All statistical calculations were performed in STATISTICA 13.3 software (TIBCO Software Inc. 2017). The following colour indices found in the literature (Shields et al. 1966; Pape 1970; Blume and Helsper 1987; Chaplot et al. 2001; Bravo et al. 2007; Pretorius et al. 2017) were correlated with soil variables (LOI, $C_{org.}$, $N_{tot.}$, C:N, Fe_{HCl}, Mn_{HCl}): value of dry soil (V); chroma of dry soil (Ch); V+Ch; V+0.5Ch; V×Ch; V/Ch. Before making statistical evaluation of the strength of relationships between the aforementioned Munsell colour indices and soil variables, the ln(*x*) type logarithmic transformation was made. This transformation changes the natural, curvilinear dependence of the variables (Fig. S1) to a rectilinear one (Fig. 2). This enabled performing the Pearson correlation analysis with $p < 0.05$. The statistical significance of differences between soils materials was determined by the

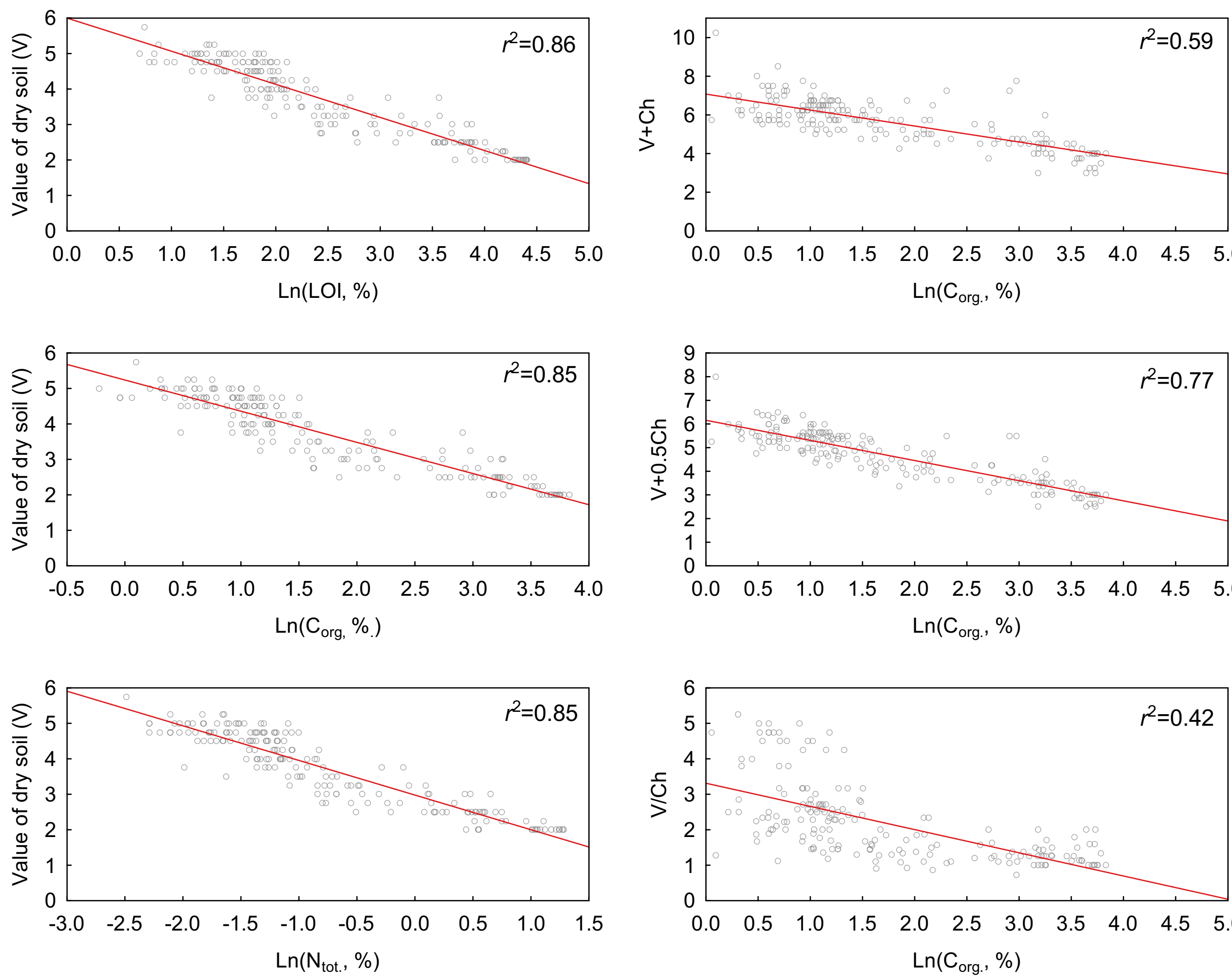


Fig. 2 Munsell colour indices versus organic matter parameters for surface soil samples (log-normal data transformation)

Table 1 Chemical properties of soil materials studied

Soil materials	n	LOI (%)	$C_{org.}$ (%)	$N_{tot.}$ (%)	C:N	Fe_{HCl} (mg kg^{-1})	Mn_{HCl} (mg kg^{-1})
Surface							
Mursh	53	*53.6 ± 2.52	28.5 ± 1.31	2.03 ± 0.113	14.5 ± 0.311	5.41 ± 0.440 • 10^4	361 ± 25.3
Semimurshic	17	16.2 ± 0.823	8.02 ± 0.294	0.604 ± 0.0280	13.5 ± 0.492	4.17 ± 0.706 • 10^4	303 ± 43.9
Postmurshic	117	6.11 ± 0.226	2.85 ± 0.104	0.260 ± 0.0092	11.1 ± 0.212	0.789 ± 0.075 • 10^4	83.5 ± 4.82
Subsurface							
Peat	5	38.4 ± 8.32	19.5 ± 4.10	1.62 ± 0.49	13.4 ± 1.77	2.69 ± 1.00 • 10^4	255 ± 108
Peaty sand	12	13.4 ± 0.993	7.17 ± 0.576	0.464 ± 0.0350	15.8 ± 1.28	0.738 ± 0.254 • 10^4	93.3 ± 31.5
Humose sand	56	3.00 ± 0.275	1.59 ± 0.162	0.110 ± 0.0115	16.4 ± 1.28	0.476 ± 0.051 • 10^4	63.9 ± 5.73
Sand	66	0.567 ± 0.0249	0.287 ± 0.0131	0.0261 ± 0.0013	11.7 ± 0.654	0.265 ± 0.020 • 10^4	32.5 ± 3.91

*Mean ± SE

Dunn's test with Bonferroni correction with $p < 0.05$. Using classification and regression trees (C&RT), the Munsell colour indices that best classified the tested soil materials were selected. These analyses were made in two variants, i.e. for all (surface and subsurface) soil samples together, and separately for surface soil samples. The C&RT analysis enables constructing regression models, in which the dependent variable is a quantitative feature, and classification models, where the dependent variable is qualitative. Generally speaking, the objective of the analysis involving the algorithm for constructing trees is to find the set of logical conditions of the division of the type '*if* …, *then*', leading to an unambiguous classification of objects (Breiman et al. 1984; Ripley 2014).

3 Results

The basic chemical properties of the analysed soil materials are set in Table 1. The content of LOI as well as $C_{org.}$, $N_{tot.}$, Fe_{HCl}, Mn_{HCl} showed highly significant correlation with the Munsell value at $p < 0.001$ (Table 2). The correlation between the Munsell chroma and LOI, $C_{org.}$, $N_{tot.}$ turned out to be significant only in the group of subsurface samples. Munsell colour indices based on the inclusion of both value and chroma (V+Ch, V+0.5Ch, V×Ch) demonstrated strong correlation with LOI, $C_{org.}$, $N_{tot.}$ Among these indices, V+0.5Ch showed a slightly stronger relationship with SOM variables, while the relationship demonstrated by V×Ch was weaker. The V/Ch quotient showed a significant relationship with LOI, $C_{org.}$ and $N_{tot.}$ in the case of surface samples, and lower values of correlation coefficients for subsurface ones. The Munsell colour indices obtained for the group of surface soil samples showed a highly significant correlation with the content of Fe_{HCl} and Mn_{HCl} at $p < 0.001$, with the relationship determined for iron being stronger than for manganese. Similar relationships emerged in the groups of surface soil materials distinguished according to the $C_{org.}$ content (Table 3). As regards murshic soil materials, the strongest dependence with SOM variables was demonstrated by V and V + 0.5Ch. Also, chroma alone showed correlation

Table 2 Correlation coefficients between Munsell colour indices and soil variables for dry surface and subsurface soil samples

	LOI	C_{org}	N_{tot}	C:N	Fe_{HCl}	Mn_{HCl}
Surface soil samples (n = 187)						
V	−0.93***	−0.92***	−0.92***	−0.49***	−0.81***	−0.73***
Ch	0.10	0.09	0.08	0.11	0.36***	0.27***
V+Ch	−0.78***	−0.77***	−0.78***	−0.38***	−0.52***	−0.50***
V+0.5Ch	−0.89***	−0.88***	−0.88***	−0.45***	−0.69***	−0.63***
V×Ch	−0.48***	−0.49***	−0.49***	−0.23**	−0.22**	−0.24**
V/Ch	−0.66***	−0.65***	−0.65***	−0.33***	−0.71***	−0.57***
Subsurface soil samples (n = 139)						
V	−0.93***	−0.92***	−0.87***	−0.38**	−0.50***	−0.45***
Ch	−0.51***	−0.53***	−0.50***	−0.19*	0.10	0.11
V+Ch	−0.81***	−0.82***	−0.78***	−0.33**	−0.20*	−0.16
V+0.5Ch	−0.89***	−0.89***	−0.84***	−0.36**	−0.32**	−0.27**
V×Ch	−0.67***	−0.68***	−0.63***	−0.31**	−0.06	−0.05
V/Ch	0.19*	0.21*	0.21*	0.04	−0.28**	−0.19*

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 3 Correlation coefficients between Munsell colour indices and soil variables for dry surface soil samples divided into murshic, semimurshic and postmurshic materials

	LOI	C_{org}	N_{tot}	C:N	Fe_{HCl}	Mn_{HCl}
Murshic ($n=53$)						
V	−0.78***	−0.72***	−0.77***	0.41**	0.30*	0.11
Ch	−0.35*	−0.35*	−0.45**	0.39*	0.40**	0.13
V+Ch	−0.59***	−0.56***	−0.65***	0.44**	0.40**	0.13
V+0.5Ch	−0.67***	−0.63***	−0.71***	0.45**	0.38**	0.13
V×Ch	−0.52***	−0.50***	−0.59***	0.43**	0.37**	0.13
V/Ch	−0.12	−0.09	−0.02	−0.15	−0.31*	−0.05
Semimurshic ($n=17$)						
V	−0.17	0.16	−0.38	0.66**	−0.31	−0.02
Ch	0.29	0.15	0.20	−0.12	0.74***	0.84***
V+Ch	0.16	0.20	−0.01	0.21	0.46	0.68**
V+0.5Ch	0.06	0.20	−0.14	0.39	0.24	0.50*
V×Ch	0.23	0.19	0.09	0.08	0.57*	0.74**
V/Ch	−0.38	−0.04	−0.39	0.47	−0.90***	−0.79***
Postmurshic ($n=117$)						
V	−0.75***	−0.70***	−0.69***	−0.08	−0.63***	−0.34
Ch	0.21*	0.17	0.19	−0.04	0.41***	0.25**
V+Ch	−0.38**	−0.38**	−0.35**	−0.08	−0.12	−0.04
V+0.5Ch	−0.60***	−0.58***	−0.56***	−0.09	−0.38***	−0.19*
V×Ch	−0.12	−0.13	−0.11	−0.06	0.15	0.13
V/Ch	−0.50***	−0.44***	−0.48***	0.05	−0.51***	−0.23*

*$p<0.05$; **$p<0.01$; ***$p<0.001$

with SOM variables, but only at the levels of significance equal $\alpha=0.05$ and $\alpha=0.01$. Concerning the group of semimurshic soil materials, attention is drawn to the absence of significant correlations between the SOM variables and colour indices, but significant relationships at $p<0.001$ between Ch, V/Ch and Fe_{HCl}, Mn_{HCl}. The numerous group of postmurshic soil materials ($n=117$) in general showed a similar character of correlation that was determined for all surface soil materials in total.

The relationship between the Munsell value and LOI, $C_{org.}$, $N_{tot.}$ is curvilinear, well described with a logarithmic function (Fig. S1). The logarithmic transformation revealed a similar character of the relationship between the value and LOI, $C_{org.}$ and $N_{tot.}$, and a slightly better fit of the regression line for V+0.5Ch and for V+Ch, as well as the high variation of the V/Ch quotient for soil materials with a $C_{org.}$ content below 12% (Fig. 2). The surface soil materials are distinctly different in colour expressed as value (Fig. 3a). The median colour value is 2.5 for murshic soil materials, 3.0 for semimurshic and 4.5 for postmurshic ones. Based on the Dunn's test with Bonferroni correction with $p<0.05$, it was determined that the analysed soil materials composed homogenous groups in terms of the value parameter, which proves that this colour parameter can serve for their identification. A similar situation appears in the case of subsurface materials (Fig. 3b). The median Munsell value for peaty sands is slightly less than 3.5, slightly below 5 for humose sands and 6.5 for sands. The small population of samples denoted as peat create a homogenous group with peaty sands.

C&RT plotted for all samples (surface and subsurface) divided into groups according to their $C_{org.}$ content demonstrated that they could be successfully divided on the basis of the Munsell value alone (Fig. 4). Samples with 0.6 to 6.0% of $C_{org.}$ have value > 3.125. The value 2.625 splits the samples into two groups: those with ≥ 12% $C_{org.}$ have value ≤ 2.625, whereas samples with 6–12% $C_{org.}$ content have value > 2.625. However, unexpectedly, the best colour index for division of surface soil materials proved to be V+Ch (Fig. 5). The soil colour index V+Ch ≤ 4.875 was obtained by 52 murshic samples out of a total of 53 such samples. Another well-distinguished group, with V+Ch >5.125, comprised postmurshic samples. Semimurshic soils were relatively poorly distinguished (V+Ch ≤ 5.125), as nearly half of their samples were classified as postmurshic materials based on this colour index.

Other important pigments in soil, apart from organic matter, were iron and manganese oxides determined as forms extracted by 0.5 M HCl. Both showed highly significant correlations with the content of $C_{org.}$ at $p<0.0001$ (Fig. 6) as well as a mutual correlation. However, it is worth underlining that the content of manganese in the analysed soils was approximately 150-fold lower than the content of iron, while manganese oxides are black

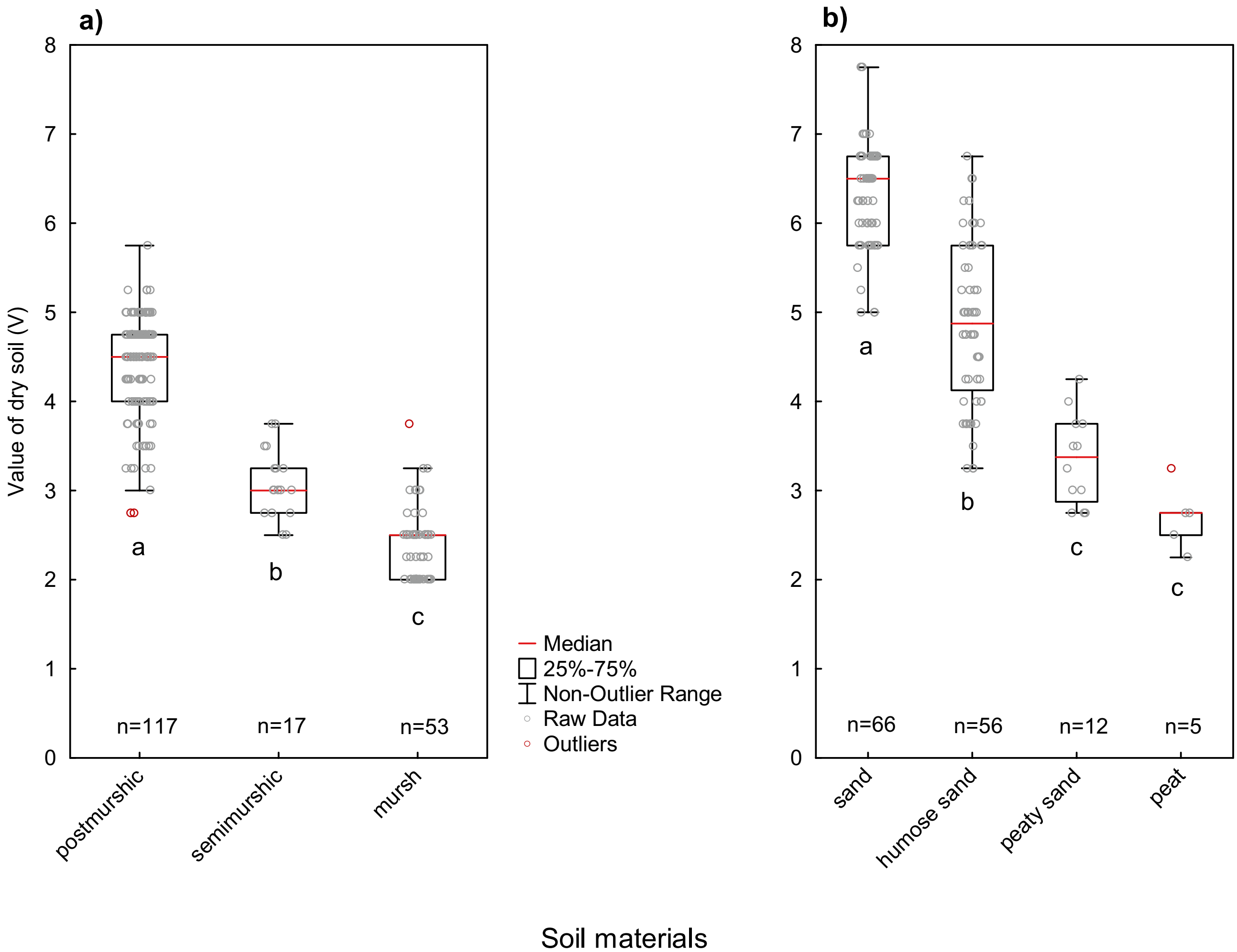


Fig. 3 Munsell value of **a** surface soil samples and **b** subsurface soil samples. Different letters below columns indicate significant differences ($p<0.05$) among different soil materials

in colour, same as humus. Despite the overall increasing trend concerning the content of iron and manganese oxides alongside an increase in the $C_{org.}$ content, a high degree of dispersion of the results needs to be noted. The V/Ch quotient showed a curvilinear dependence on the $C_{org.}$ content (Fig. 7a) as well as on the content of Fe_{HCl} (Fig. 7b). It should be emphasised that it falls in the range of 1 to 2 for murshic soil materials (> 12% $C_{org.}$). It appears in a similar although slightly broader range for semimurshic materials (6–12% $C_{org.}$). In turn, postmurshic materials (0.6–6% $C_{org.}$) are characterised by this quotient falling within the range of 1 to over 5. The diagram shows that the V/Ch quotient depends on the presence of colour iron compounds in the soil, represented by Fe_{HCl}.

4 Discussion

In our study, air-dry samples were analysed because the drying of soil enlarges the span of both value and chroma (Pretorius et al. 2017; Rubinić et al. 2021). Of the three colour variables, value and chroma show to be strongly dependent on the SOM content (Konen et al. 2003; Pretorius et al. 2017; Jorge et al. 2021). In turn, the relationship between SOM and hue is weak (Pretorius et al. 2017; Jorge et al. 2021). Hue was not discussed in this study because over 90% of the samples had the same notation (10YR) while the remaining hue notations (7.5YR, 2.5Y, 5YR) were mainly obtained in subsurface samples. Blume and Helsper (1987), as well as Fernandez et al. (1988) and Franzmeier (1988)

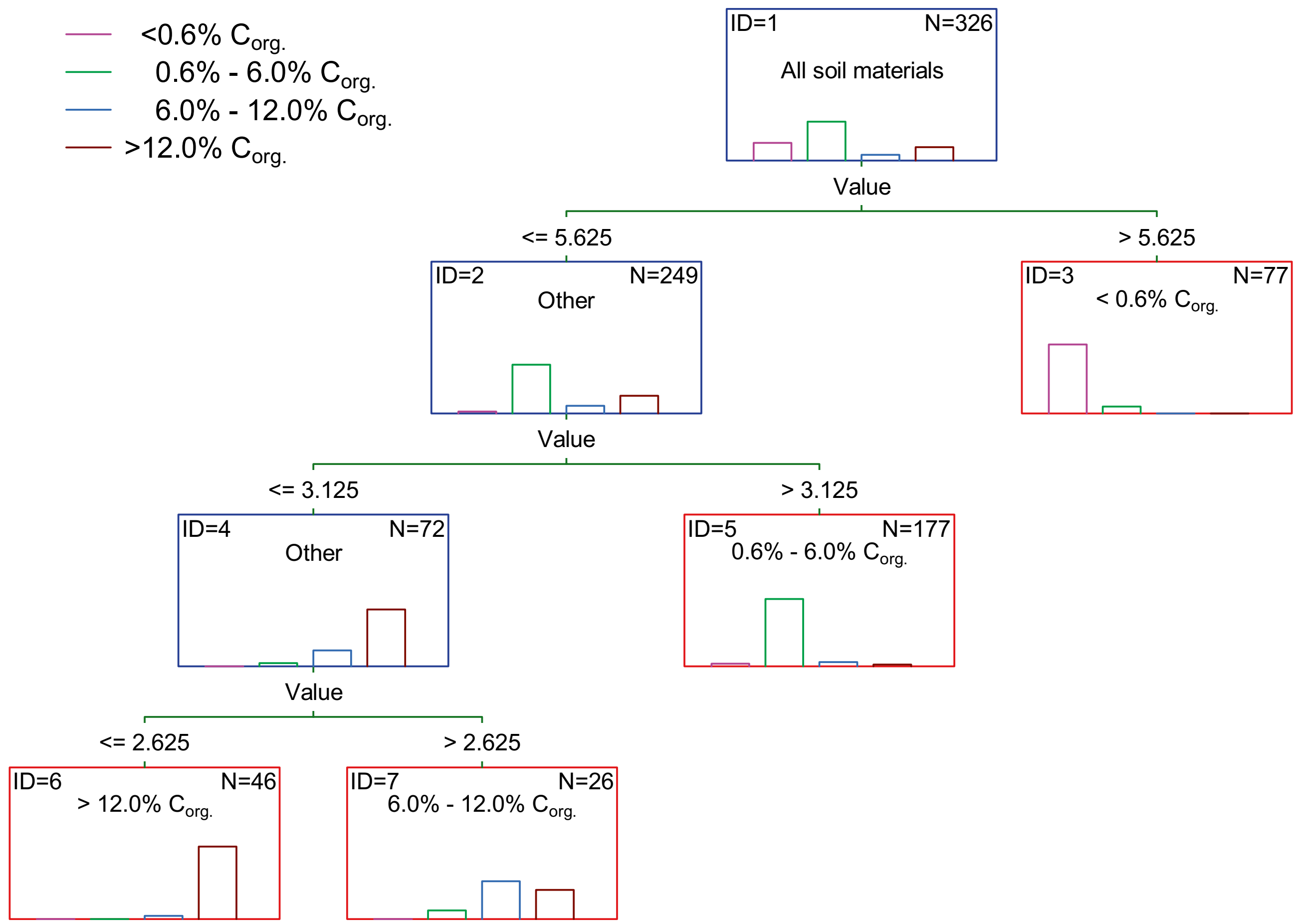


Fig. 4 Classification and regression tree (C&TR) for all soil materials (surface and subsurface) distinguished according to organic carbon content

or Wills et al. (2007), showed that it was necessary to use both the Munsell value and chroma in order to predict the organic matter content in soil. However, Jorge et al. (2021) claim that all the three colour components (value, chrome and hue) should be included in such assessments because the organic carbon content affects both value (lightness) as well as other colour pigments (e.g. red, yellow and green). Some researchers (Rubinić et al. 2021) concluded that the relationship between the SOM content in dry samples was stronger for chroma than for value. Likewise, Konen et al. (2003) maintain that chroma can be a good predictor of the SOM content. Based on the classification and regression trees for surface samples (Fig. 6), we stated that despite the low values of correlation coefficients between chroma and organic matter variables (Table 2), value plus chroma could be useful in the identification of the analysed soils.

High values of correlation coefficients between the Munsell value and the LOI, $C_{org.}$ and $N_{tot.}$ content in soil (Tables 2 and 3) indicate that the content of organic matter in the analysed soils can be estimated based on this colour parameter. In our study, the correlation strength was also tested for chroma (saturation or intensity) because this colour parameter also depends on the presence of the black pigment; additionally, the following colour indices were applied: V+Ch, V+0.5Ch, V×Ch, V/Ch. Other scholars (Pretorius et al. 2017) used only the value component of the Munsell system, as this showed the best correlation with SOM. Statistically significant correlations ranging from −0.92 to −0.93 were found between the Munsell value and LOI, $C_{org.}$ $N_{tot.}$ ($p < 0.001$) (Table 2). The results obtained in our study concerning the relationships between the Munsell value and organic matter variables were in agreement with the data given in the literature (Schulze et al. 1993; Chaplot et al. 2001; Konen et al. 2003; Bravo et al. 2007). The correlation coefficients calculated for the organic matter variables versus V×Ch were lower (albeit still statistically significant) than for the Munsell value alone (Table 2). A similar relationship was determined by Bravo et al. (2007). Generally, based on the achieved research results, the analysed colour indices can be ordered in terms of their usefulness for estimating the SOM content, and therefore for identification of soil horizons. The

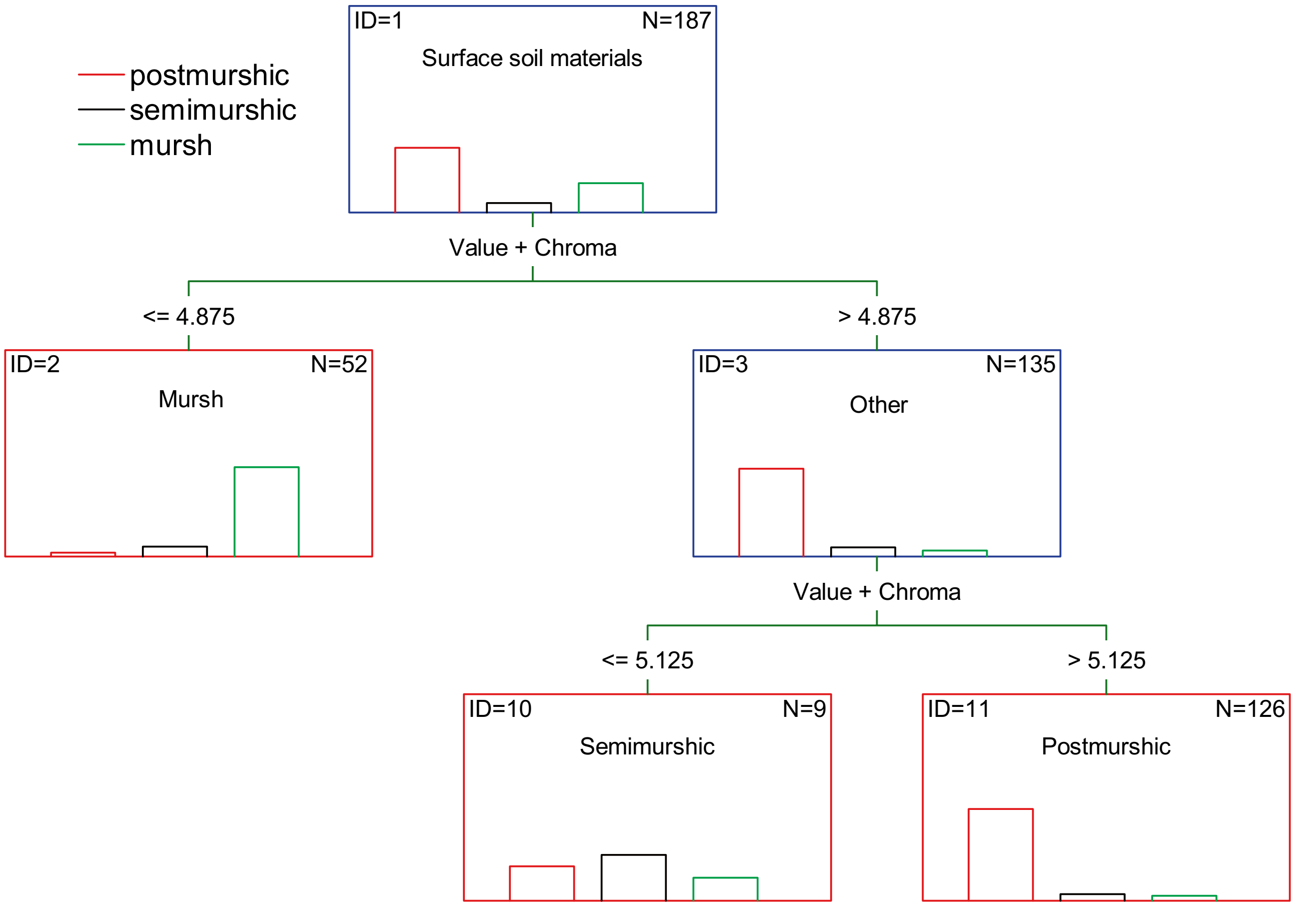
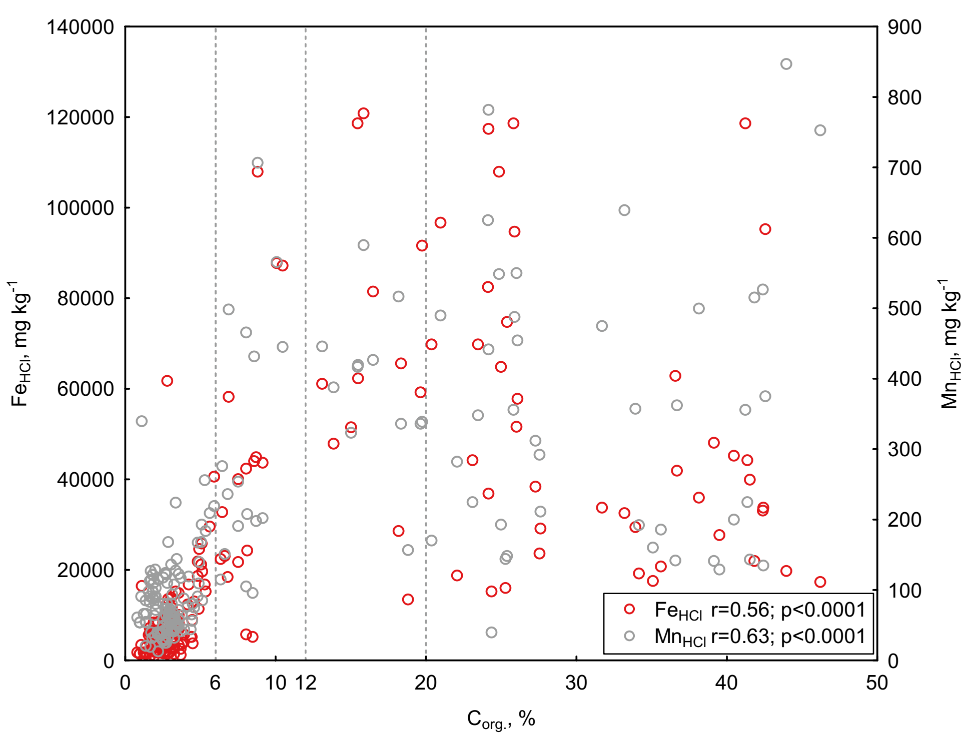


Fig. 5 Classification and regression tree (C&TR) for surface soil materials

Fig. 6 Content of iron and manganese soluble in 0.5 M HCl extract versus organic carbon content in surface soil samples



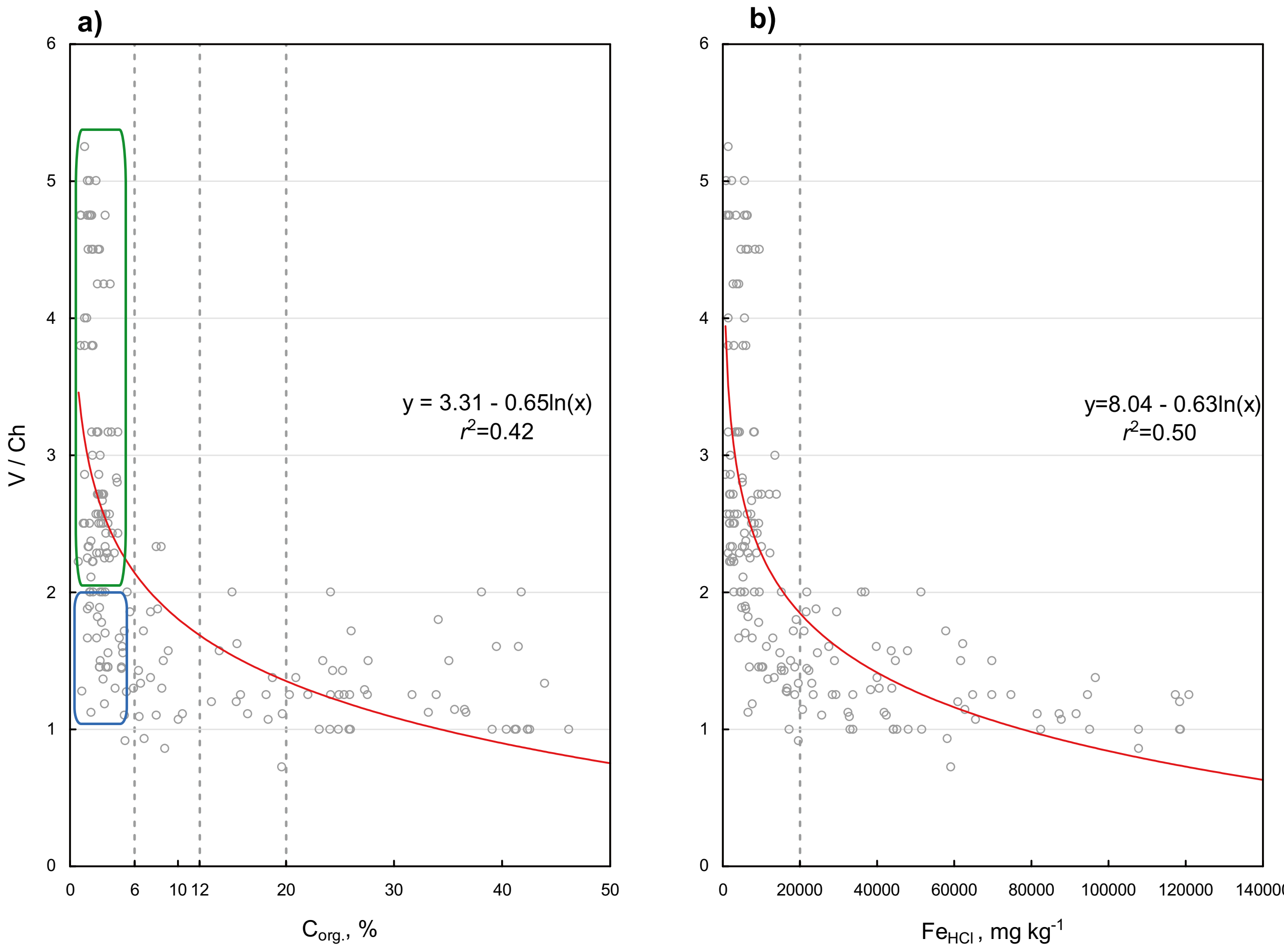


Fig. 7 Relationship between V/Ch quotient and **a** organic carbon content and **b** content of Fe soluble in 0.5 M HCl extract for surface soil samples. Green colour indicates postmurshic soil materials of gleyic origin, blue colour indicates postmurshic soil materials of subsequent degradation of murshic and semimurshic soil materials

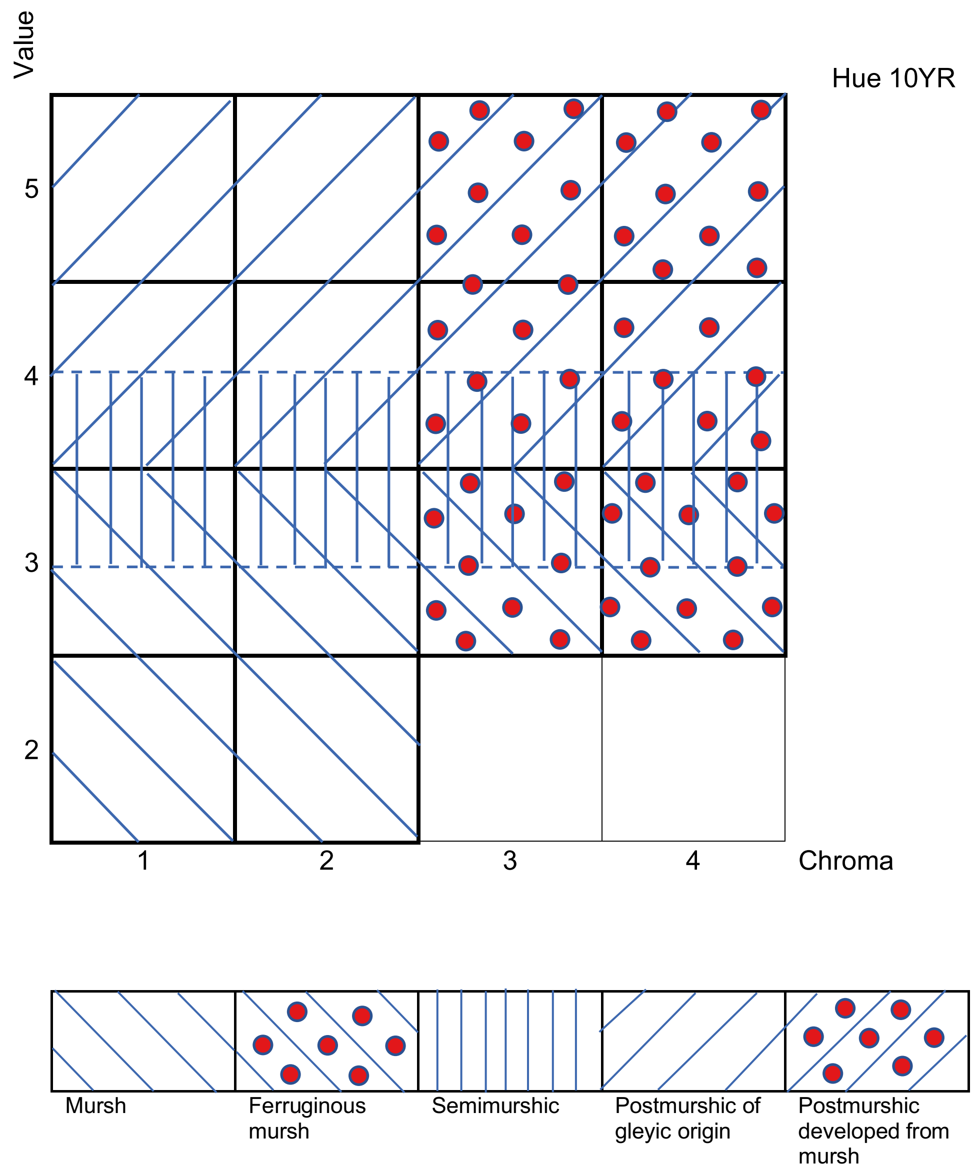
Munsell value alone proved to be the best in this respect, followed by V+Ch and V+0.5Ch, ensuring approximately the same estimation success. Chrome alone and V+Ch were determined to be much less useful for the above purpose.

The lack of a significant correlation between chroma and SOM in surface soil materials (Table 2) should be linked to the diversified content of coloured iron compounds in mursh materials and a typically small content of such compounds in postmurshic soil materials (Table 1, Fig. 6). Before drainage, large oscillations of the groundwater table had been characteristic for semimurshic and postmurshic soils. Hence, semimurshic and especially postmurshic soil materials contain numerous whitish quartz grains completely devoid of goethite coatings, which is referred to as redox depletions (Soil Survey Staff 2014). Quartz grains affect the resultant colour of post-bog soils with sandy texture. Due to the smaller specific surface area of sand than that of silt or clay, smaller amounts of pigment (humus substances) are needed to cover sand grains (Leger et al. 1979). Noteworthy is also the fact that quartz grains are rarely covered by dyeing substances entirely because of the low reactivity of their surface (Spielvogel et al. 2004). These authors conclude that sandy soils are significantly darker than finer textured soils and have only slightly lower values than Histosols with a much higher $C_{org.}$ content.

Numerous researchers emphasise that models for soil carbon estimation from soil colour measurements should be constrained to specific mineralogical and physiographic settings (Schulze et al. 1993; Wills et al. 2007; Ibáñez-Asensio et al. 2013; Moritsuka et al. 2014; Schmidt and Ahn 2021). Grouping soils according to their texture improves the regression dependence between SOM and colour indices (Blume and Helsper 1987; Evans and Franzmeier 1988). In order to classify the surface soil materials sampled in this study, the criteria included in the Polish Soil Classification (Kabała et al. 2019) were applied, which take into account the degrading depletion of SOM in drained organic soils, and the specific features of post-bog soils developed from sand. The diagnostic horizon distinguished in the PSC 2019 called arenimurshic, despite having a similar SOM content as found in the mollic and umbric horizons, differs from these two by its sandy texture. The arenimurshic horizon does not form permanent clay-humic bonds because of the lack or very small amount of the clay fraction. Humus is mostly composed of chelated macromolecular complexes, which appear as grains of the size corresponding to the sand or silt fractions, with sharp or rounded edges (Fig. 1). The PSC 2019 (Kabała et al. 2019) assumes that the arenimurshic diagnostic horizon contains at least 10% of sand grains without the humus coating. The colour of such materials is the result of the light colours of sand and silt (quartz) grains and dark colours of granular aggregations of humus. The colour of some arenimurshic horizons, especially postmurshic materials (Fig. 1d, e), is referred to as lead-black or greyish, because it had low chroma (< 2) due to the small amount of coloured iron oxides.

The analysed soil materials demonstrated a different character of the dependence of the V/Ch quotient on the SOM content than soils from Croatia (Rubinić et al. 2021), which should be linked to the different conditions of their pedogenesis. The analysed soils show large differences in the content of Fe and Mn soluble in 0.5 M extract of HCl (Fig. 6). Further, 0.5 M HCl extract is commonly used in Poland for determination of the content of nutrients potentially available to plants in organic and in mineral-organic soils (Sapek and Sapek 1992). Amorphous forms of iron and other metals enter 0.5 M HCl extract. In organic soils with the sandy texture, the amount of iron in aluminosilicates is extremely small, and most of iron appears in non-silicate (amorphous) forms, because this element originates from mineralisation of plant residues and capillary supply from groundwater (Okruszko 1993). Hence, in post-bog soils, the content of iron extracted with 0.5 M HCl can serve as a

Fig. 8 Munsell colours of surface materials of post-bog soils



measure of amounts of amorphous forms, that is coloured iron oxides. In these soils, more than 50% of total iron enter this extract (Okruszko 1993). Rubinić et al. (2021) found a significant positive correlation between the V/Ch quotient and the SOM content in soil. In our study, only surface soil materials demonstrated a significant ($p < 0.001$) albeit negative correlation between V/Ch and all soil variables studied (Table 2). Among all surface soil materials, postmurshic ones showed an exceptionally wide V/Ch quotient (Fig. 7a). This ratio can be useful in determination of the origin of postmurshic soils. Postmurshic soil materials with a narrow V/Ch quotient (1–2) originated as a result of advanced transformation of murshic soils, which contained larger amounts of iron because of the mineralisation of plant residues and particularly the capillary ascension of waters abundant in Fe^{2+}. Postmurshic materials with a broad V/Ch quotient (2–5) originated mostly from the draining of Gleysols, which due to the redox depletions were almost completely devoid of iron compounds. As shown in Fig. 7b, all soil materials, regardless of the $C_{org.}$ content, which contained over 20,000 mg kg^{-1} Fe_{HCl} achieved the V/Ch quotient ≤ 2.

The pattern of the colours of surface soil materials is presented in Fig. 8. It can be helpful in identification of these soil materials in field conditions. Soil materials demonstrating the chroma ≥ 3 were denoted as ferruginous ones. They are characterised by a higher than 20,000 mg kg^{-1} Fe_{HCl} content (Fig. 6) and a narrow V/Ch quotient (1–2) (Fig. 7a). It is worth noting that in Poland, murshic soils which contain over 4.2% of total iron are known as ferruginous murshes (Okruszko 1993), and the 20,000 mg kg^{-1} Fe_{HCl} content approximately corresponds to this threshold value. It should be noted that the dominance of the Munsell chroma < 3 is also a consequence of the strong colouring effect of humus, masking the effect of iron oxides by dark soil components. General darkening also occurs when iron oxides (goethite) undergo cementing, i.e. compacting into hard mass (Schwertmann 1993). Chroma ≥ 3 indicates that post-bog soils contain large amounts of coloured iron oxides, which become more visible when the black pigment (humus) is being depleted. Schwertmann (1993) presented a change in colour of various iron oxides after the removal of humic substances with the H_2O_2 treatment.

5 Conclusions

Among the analysed Munsell colour indices (V, Ch, V+Ch, V+0.5Ch, V×Ch, V/Ch), value alone showed the strongest correlation with the content of soil organic matter. Less satisfactory estimates of the SOM content were achieved by employing the V+Ch and V+0.5Ch. Chroma alone and V×Ch proved to be far less useful. It is possible to estimate the content of $C_{org.}$ and $N_{tot.}$ in the soils studied based on the Munsell value. The analysed surface and subsurface soil materials had the Munsell value differentiated enough to enable their identification. The median Munsell value for murshic soils was 2.5, while being 3 for semimurshic and 4.5 for postmurshic soils. Classification and regression trees (C&TR) showed that the analysed surface and subsurface soil materials together can be effectively divided on the basis of value alone. Materials containing < 6.0% $C_{org.}$ have value > 3.125. Materials with the content ≥ 12.0% $C_{org.}$ have value ≤ 2.625. However, the best division for surface soil materials achieved with C&RT was obtained for value plus chroma. For murshic soils, it reached ≤ 4.875, and for postmurshic ones > 5.125. The V/Ch quotient showed highly significant correlations with LOI, $C_{org.}$, $N_{tot.}$, C:N, Fe_{HCl}, Mn_{HCl} in the group of surface soil materials. This quotient equals 1–2 for murshic and semimurshic soil materials, but is much more varied (1–5) among postmurshic materials. The V/Ch quotient may serve to trace the origin of postmurshic soils because its value within the range of 1–2 indicates its origin due to highly advanced transformation of murshic and semimurshic soil materials, whereas the range from 2 to 5 suggests it originated directly from surface layers of drained Gleysols.

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Author contribution Andrzej Łachacz: conceptualisation, methodology, laboratory analyses, writing—original draft, writing—review and editing, supervision. Dariusz Załuski: conceptualization, methodology, statistical analyses, writing—original draft, visualisation.

Data availability Data will be made available from the corresponding author on request.

Declarations

Conflict of interest The authors declare no competing interests, and the manuscript is approved by all the authors for publication. The authors would like to declare that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part.

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