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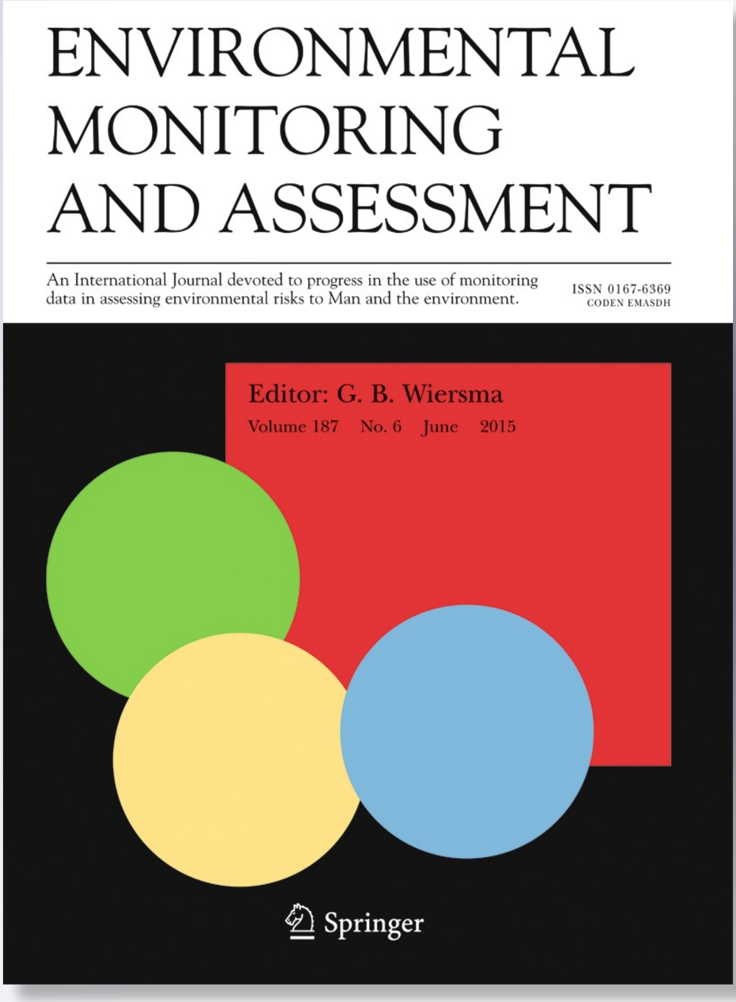

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Abstract Although several authors have suggested that the labile fraction of soils could be a potential soil quality indicator, the possibilities and limitations of using the dissolved organic matter (DOM) fraction for this purpose have not yet been investigated. The objective of this study was to evaluate the hypothesis that DOM is an adequate indicator of soil quality. To test this, the soil quality indices (SQI) of 190 arable soils from a Hungarian dataset were estimated, and these values were compared to DOM parameters (DOC and $SUVA_{254}$). A clear difference in soil quality was found between the soil types, with low soil quality for arenosols (average SQI 0.5) and significantly higher values for gleysols, vertisols, regosols, solonetzes and chernozems. The SQI-DOC relationship could be described by non-linear regression, while a linear connection was observed between SQI and SUVA. The regression equations obtained for the dataset showed only one relatively weak significant correlation between the variables, for DOC ($R^2 = 0.157^{***}$; $n = 190$), while non-significant relationships were found for the DOC and $SUVA_{254}$ values. However, an envelope curve operated with the datasets showed the robust potential of DOC to indicate soil quality changes, with a high R^2 value for the envelope curve regression equation. The limitations to using the DOM fraction of soils as a quality indicator are due to the contradictory processes which take place in soils in many cases.

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Keywords Arable soil · Dissolved organic matter · DOC · Soil quality · SQI · SUVA

Introduction

When investigating the agricultural sustainability and/or the environmental aspects of soils, there are needs to create precise and sensitive indicators for evaluating soil quality. However, these indicators are usually not well defined, so specifying soil quality is a continuously improving paradigm of soil sciences (Qi et al., 2009). Furthermore, the definition of soil quality raises so many difficulties that it would be better to talk about the "concept of soil quality" as stated by Bastida et al. (2008). However, despite the difficulties met in defining them, the use of soil quality indicators is critical for ensuring the sustainability of agricultural ecosystems (Arshad and Martin, 2002).

Soil quality is determined to a great extent by organic matter content and quality, which can be affected by changes in soil conditions (Haynes, 2005; Undurraga et al., 2009; Wang et al., 2011). Consequently, SOM is considered to be an important indicator of soil quality (Doran and Parkin, 1994). However, the generally large amount of soil organic matter and the soil variability make it difficult to measure the effect of changes in soil use management or agricultural practices in the short term (Gregorich et al., 1994; Fließbach et al., 2007). This means that it is difficult to measure changes in the SOM of the soils in a relatively short period (e.g. 1–5 years). Labile organic matter fractions (e.g. the light fraction of C, microbial biomass C, dissolved organic carbon), however, can respond rapidly to environmental changes (Haynes, 2000). The estimated DOM fluxes are 1–2 orders of magnitude smaller than the whole transfer of organic matter in ecosystems (Michalzik et al., 2001), so small changes in the organic carbon balance could result in large changes in DOM (Aitkenhead and McDowell, 2000). Because of this, it has been proposed that this labile fraction of the soil (quantified as DOC) could be used as an indicator of soil fertility, and consequently of soil quality (Haynes, 2000; Neff and Asner, 2001).

Although simple soil quality indicators are easy to apply, the use of two or more parameters in a soil quality index makes it possible to give a better characterization of soil quality. Therefore, to obtain an index that provides and integrates more information on the quality of a given soil, multiparametric indices have been developed for agro-ecosystems and for non-agricultural soils (Bastida et al., 2008). In this case, the soil quality indicators should be a combination of chemical, physical and biological properties (Herrick et al., 2002; Aparicio and Costa, 2007) and the indicator values can be combined into a quantifiable soil quality index (SQI). A valid SQI would thus help integrate and interpret data from various soil measurements, and indicate whether the land use was having a desired effect on productivity, environmental protection and health (Granatstein and Bezdicek, 1992).

Although DOM is considered to be a potential quality indicator for arable soils (Haynes and Tregurtha, 1999; Haynes, 2000; Silveira, 2005) and an effort by Jones et al. (2014) to investigate whether different soil classes and vegetation cover types having different DOC concentrations, the evaluation and validation of DOM with a complex quality indicator has not yet been reported. In this paper, the dissolved organic matter in soils was evaluated as a potential soil quality indicator, and its limitations were shown on 190 Hungarian agricultural soils. Relationships between DOM parameters (DOC and $SUVA_{254}$) and a multiparametric soil quality index (SQI) were identified based on minimum data sets of the chemical, physical and biological parameters of soils. Two different approximations were applied to decide whether DOC and $SUVA_{254}$ are satisfactory soil parameters for use as soil quality indicators. First, a qualitative evaluation was done, including a comparison of the effect of different soil types on SQI values and DOC concentrations. Secondly, regression analysis was applied to give a quantitative approximation of the relationship between SQI values and DOM parameters.

Materials and methods

Soil characteristics

In this study, 190 samples were analysed from soil database for agricultural areas in Hungary. Hungary lies in the temperate zone and is situated at the convergence of three main climatic regions: the Oceanic, the Continental and the Mediterranean. The mean annual temperature of the country is 10 °C, while the annual average rainfall is about 600 mm (Ódor et al., 1998).

The arable soil samples were obtained from the Soil Monitoring System of Hungary (SMS; Várallyay, 1994). The soil samples were representative of the agricultural soils of Hungary, comprising 45 gleysols, 32 chernozems, 27 luvisols, 21 cambisols, 16 fluvisols, 11 greyzems, 10 arenosols, 8 phaeozems, 7 leptosols, 5 regosols, 4 solonetzes, 2 podzoluvisols and 2 vertisols. All samples were taken from the top 20 cm of the soils between 15th September and 15th October in 2004. All the samples were air-dried and sieved through a 2-mm stainless steel mesh.

The following soil parameters were determined: pH (measured in H_2O and KCl), soil organic matter (SOM), hydrolytic acidity (HAC), $CaCO_3$, particle-size fractions (sand, silt, clay), cation exchange capacity (CEC), electrical conductivity (EC), soil respiration (SR), cellulose digestion activity (CDA), dehydrogenase activity (DHA), dissolved organic carbon (DOC), total soluble N (TSN) and specific UV absorbance (SUVA) (Table 1).

Laboratory analysis

The soil pH was measured in 1:2.5 soil:water and soil:1M KCl suspensions 12 h after mixing (MSZ-08-0206/2:1978). The organic matter content was determined using the modified Walkley-Black method (Walkley and Black, 1934), digesting the soil organic matter with 5 % $K_2Cr_2O_7$ and cc. H_2SO_4 and analysing the colour of the suspension, which was related to the organic matter content of the samples, colorimetrically (MSZ-08-0452:1980). For the measurement of hydrolytic acidity (HAC), the soil samples were treated with 0.5 M Ca-acetate adjusted to pH 8.2, using a 1:2.5 soil/extractant ratio. The suspensions were then shaken for an hour and filtered. The filtrate was titrated with 0.1 M NaOH solution, and the hydrolytic acidity was calculated from the amount of base used (MSZ-08-0206/2:1978). The $CaCO_3$ content was measured with a calcimeter; the soil was mixed with diluted HCl solution

Table 1 Statistical properties of the soil parameters determined in the samples of Soil Monitoring System (SMS) of Hungary

	n	Min	Max	Mean[a]
pH (H_2O)	190	4.6	8.2	7.1 ± 0.85
pH (KCl)	186	3.6	8.1	6.3 ± 1.0
HAC (cmol kg^{-1})	188	0.00	35.2	4.5 ± 6.9
$CaCO_3$ (%)	184	0.00	20.0	2.5 ± 3.9
SOM (%)	190	0.52	5.3	2.2 ± 1.0
CEC (cmol kg^{-1})	186	3.4	61.7	22.5 ± 12.2
EC (dS m^{-1})	137	3.8	25.0	8.7 ± 3.6
Sand (%)	188	10.4	94.1	48.3 ± 21.3
Silt (%)	187	1.3	50.3	25.3 ± 11.0
Clay (%)	188	2.8	61.6	25.9 ± 12.7
TSN (mg kg^{-1})	188	2.39	166.1	32.4 ± 24.3
DHA (g kg^{-1} day^{-1})	174	0.00	0.49	0.11 ± 0.08
SR (mg CO_2 kg^{-1} h^{-1})	176	0.00	4.6	1.1 ± 0.79
CDA (%)	190	0.30	88.3	24.2 ± 21.2
DOC (mg kg^{-1})	189	25.1	364.9	100.9 ± 45.0
SUVA (l mg-C^{-1} m^{-1})	189	0.6	7.5	3.3 ± 1.1

[a] Mean ± standard deviation

and the volume of CO_2 released was determined (Loeppert and Suarez, 1996; MSZ-08-0206/2:1978). Particle-size distribution was determined by the pipette method. The soil:water suspension was mixed in a sedimentation cylinder, then sampled with a pipette to collect particles of a given size (MSZ-08-0215:1978).

The CEC of the soils was measured by the modified method of Mehlich (1948) (MSZ-08-0215:1978). Electrical conductivity was measured in soil saturated with water up to the upper limit of plasticity (MSZ-08-0206/2:1978). Soil respiration was determined as the CO_2 produced during 100 h of aerobic incubation at 18 °C. The CO_2 concentration was determined as methane by gas chromatography with an FID detector (ISO 16072, 2002). Cellulose degradation was measured in the laboratory as the decrease in weight of a Whatman No. 1 filter paper in the soil (MSZ-08-1931:1984). The determination of dehydrogenase activity was based on the reduction of 2,3,5-phenyl tetrazolium chloride as substrate. The triphenyl formazan formed in the enzyme-catalysed process was measured by spectrophotometry and expressed as formazan/1 g soil with original moisture/1 day (MSZ-08-1721-3:1986).

DOC was measured after extraction with 0.01 M $CaCl_2$ at a 1:10 soil:solution ratio for 2 h (Jászberényi et al., 1994) in a TOC/TN analyser (Tekmar Dohrmann Apollo 9000) using combustion (680 °C) with a platinum catalyst. Total soluble N (TSN) content was measured from the $CaCl_2$ extraction using Continuous Flow Analyzer (CFA). Specific UV absorption ($SUVA_{254}$) was calculated by dividing the absorption at 254 nm by the DOC value.

Data analysis

Outlier identification is important in many applications of multivariate analysis, so univariate outliers were removed by estimating the z-scores of the data using Eq. 1 and eliminating those with values between −3 and 3:

$$z_i = \frac{x_i - \mu}{\sigma}.$$

where μ and σ are the mean and standard deviation of the variable, and z_i and x_i the standard score and the value of the variable in sample *i*.

Differences in the SQI and DOC values of the soil types were tested by one-way ANOVA with Duncan's post hoc test ($p < 0.05$). Regression analysis was performed to quantify how the SQI of different sites influenced DOC and $SUVA_{254}$.

Soil quality index

Soil indicator scoring

Standard scoring functions (SSF) were determined (Andrews et al., 2002) to score the soil indicators (Table 2). Three types of SSFs are typically used for soil quality assessment: (i) 'More is better'; (ii) 'Less is better' and (iii) 'Optimum' (Liebig et al., 2001). The equation defines a 'More is better' scoring curve for positive slopes, a 'Less is better' curve for negative slopes and an 'Optimum' curve when a curve is reflected at the

Table 2 Score functions of soil parameters selected by PCA

pH	$f(x) = \begin{cases} \frac{e^x}{e^L} \\ x = 1 \\ \frac{(14-x)}{14-U} \end{cases}$	$x < 6.5$ $6.5 \le x \le 7.5$ $x > 7.5$	$L = 6.5$ $U = 7.5$
Sand	$f(x) = \begin{cases} x = 1 \\ \frac{(100-x)}{100-U} \end{cases}$	$x \le 65$ $x > 65$	$L = 65$
TSN	$f(x) = \frac{x}{x+M}$		$M = \frac{\text{max.}}{10}$
DHA	$f(x) = \frac{x}{x+M}$		$M = \frac{\text{max.}}{10}$

L lower limit

U upper limit

upper threshold value. 'More is better' curves score soil properties that are associated with improved soil quality at higher levels, e.g. CEC, SOM and DHA, so the highest observed value received a score of 1 while all others received a score of <1. 'Less is better' indicators (e.g. EC) are those that indicate poor quality at high levels. 'Optimum' curves score properties that have an increasingly positive influence on soil quality up to an optimal level beyond which their influence is detrimental. Soil quality indicators, such as pH, were rated using this curve.

The values of TSN, DHA were scored following the Michaelis-Menten kinetics, which is a combination of zero and first-order kinetics (Wagner, 1973) and reflects the nature of the biogeochemistry of these parameters.

Indicator selection

The identification of representative soil quality indicators is a key concern of soil quality evaluation. The data collected from the various soil analyses were reduced to a minimal data set (MDS) using principal component analysis (PCA) (Andrews and Carroll, 2001; Andrews et al. 2002) with the SPSS 16.0 program. The results of PCA (data not shown) on a given data set generate a number of principal components (PC), which are linear combinations of the variables that account for maximum variance. The PCs having high eigenvalues and comprising variables with high factor loading were assumed to be the variables that best represent the system attributes. Therefore, only PCs with eigenvalues >1.0 were selected (Brejda et al., 2000). Within each PC, variables with high factor loading (i.e. those with absolute values for factor loading within 10 % of the highest value) were retained for the MDS. To reduce redundancy of data, Pearson's correlation coefficients were used (Andrews and Carroll, 2001); if the highly weighted variables were not correlated (taken as a correlation coefficient of <0.60), then each was considered important and was retained in the MDS. Among the well-correlated variables within each PC ($r > 0.60$), the variable with the highest sum of correlation coefficients was chosen for the MDS (Andrews and Carroll, 2001; Karlen et al., 1997). The SQI was calculated for each treatment from the following:

$$\mathrm{SQI}_i = \sum_{i=1}^{n} W_i \times S_i$$

where W is the PC weighting factor, S is the indicator score for each variable i, and n is the number of variables in the MDS. In order to apply this equation, the values of S and W needed to be determined.

After calculating the S values for all the MDS variables, each property was weighted using the PCA results. Each PC explained a certain amount (%) of the variation in the total data set. This percentage, when divided by the total percentage of variation explained by all the PCs with eigenvalues <1.0, provided the weighting factor (W). Having determined the values of S and W, the SQI for each sample was then calculated using the equation above. Higher index scores mean better soil quality.

Results

SQI calculation

The indicators selected by PCA were transformed using scoring functions, and the SQI was calculated using weighting factors for each scored MDS variable. For the SMS database, the following formula was obtained:

$$\mathrm{SQI}_{\mathrm{SMS}} = \sum_{i=1}^{n} 0.36 \times S_{\mathrm{sand}i} + 0.26 \times S_{\mathrm{pH}i} + 0.22 \times S_{\mathrm{TSN}i} + 0.16 \times S_{\mathrm{DHA}i}$$

where S is the score for the subscripted variable and the coefficients are the weighting factors derived from PCA.

SQI values obtained for agricultural soils

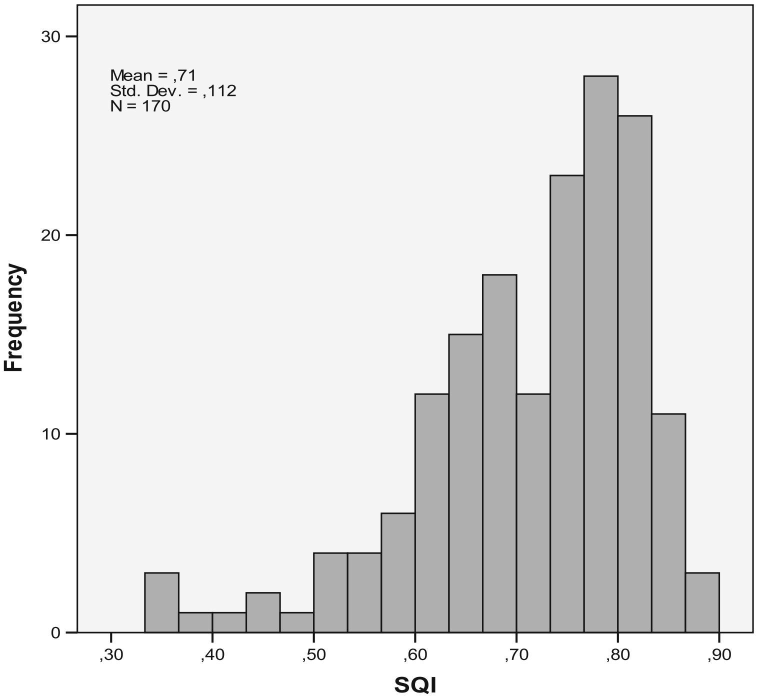
The SQIs obtained for agricultural soils have negatively skewed distribution, with a mean of 0.71 and a range of 0.34 to 0.90 for SMS database (Fig. 1). Qi et al. (2009) found that 431 samples of Cambisols and Anthrosols showed a symmetric, normal distribution, and 90 % of the samples were in the moderate quality category (between 0.68 and 0.78) according to their classification.

Variations between the SQI and DOC values of soil types

Figures 2 and 3 represent the values of SQI and DOC for the different soil classes. The DOC concentration varied from 58 to 156 mg kg^{-1}.

One-way ANOVA showed a clear difference in soil quality between the soil types (Fig. 2): low soil quality in arenosols with an average SQI of 0.5 and significantly

Fig. 1 Distribution of soil quality indices for agricultural soils of Hungary



higher soil quality for groups such as gleysols, vertisols, regosols, solonetzes and chernozems. Moderate soil quality indexes were found for leptosols, luvisols, cambisols, luvisols and greyzems.

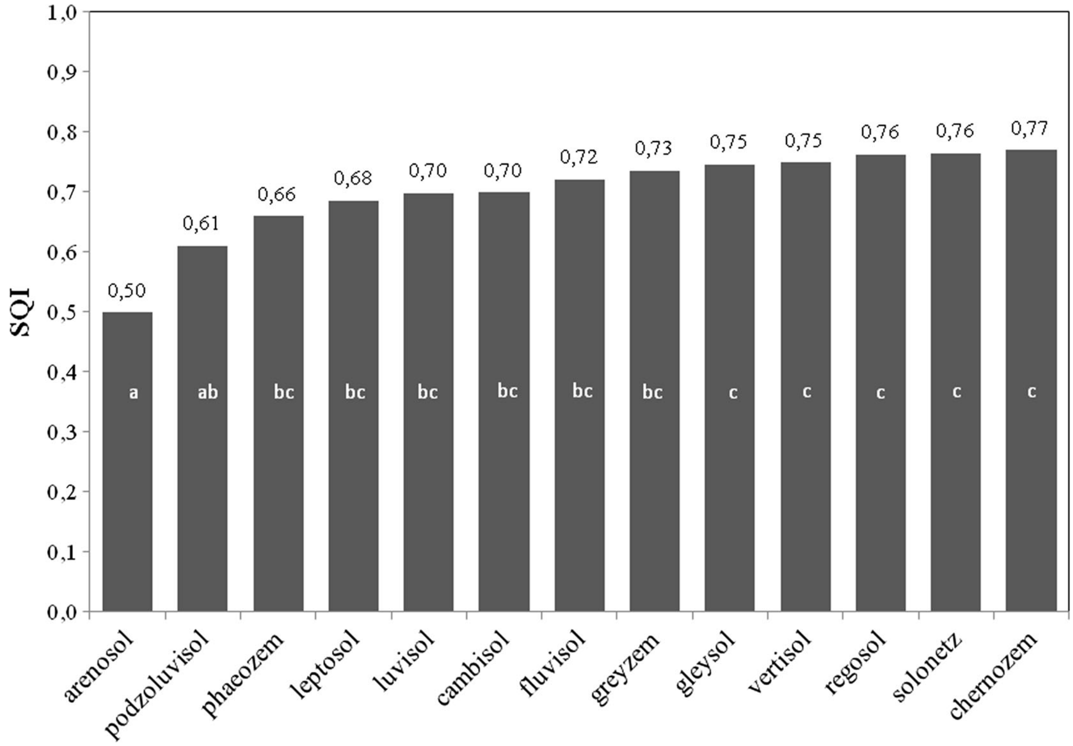


Fig. 2 Effect of soil type on the soil quality index (*a–c* indicates significant differences within each *bar* at the 5 % level of probability according to Duncan test)

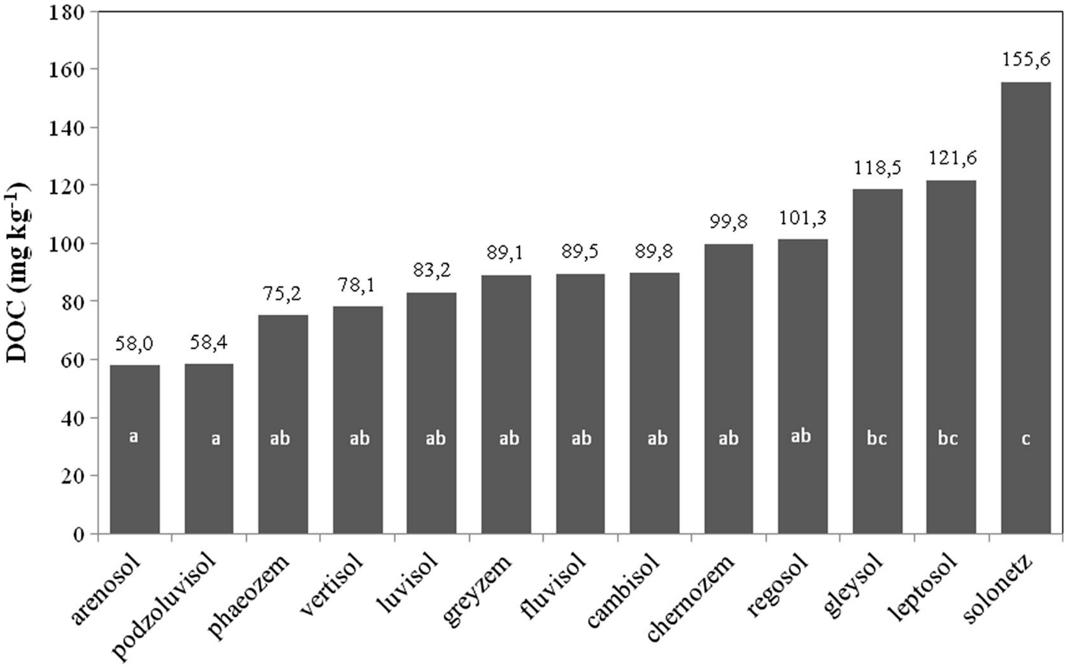


Fig. 3 DOC variations among soil classes (*a*–*c* indicates significant differences within each *bar* at the 5 % level of probability according to Duncan test)

The grouping of the soil types in terms of mean DOC values was similar to that obtained on the basis of SQI (Fig. 3), with the lowest DOC content for arenosols, podzoluvisols, phaeozems and vertisols, while solonetzes had the highest DOC value.

A clear similarity was revealed between the effect of the soil classes on the soil quality index and the DOC concentration (Figs. 2 and 3). For most of the soil types, e.g. arenosols, phaeozems, luvisols, solonetzes etc., the ranking of the soil types was similar on the basis of SQI and DOC.

Relationships between SQI and DOM parameters

Correlation between DOC and SUVA$_{254}$

It is important to know how the dissolved organic matter parameters (DOC and SUVA$_{254}$) are correlated with each other. There was a significant correlation between DOC and SUVA$_{254}$ (with a Pearson's coefficient of −0.549, $p < 0.001$); however, regression between these parameters was not linear (Fig. 4). A non-linear, exponential function was obtained for the DOC-SUVA$_{254}$ relationship in the present study, as also reported in a study on extracts from composts (Zmora-Nahum et al., 2007).

SQI vs. DOC and SUVA

After showing the considerable agreement between the SQI and DOC scales, regression analysis was performed to reveal quantitative relationships, since the correlation analysis can only be used to investigate linear relationships.

Regression analysis showed a non-linear relationship between DOC and SQI and a linear correlation between SUVA and SQI (Fig. 5). Clear trends emerged for the SQI-DOC and SQI-SUVA regressions in the SMS dataset; however, the regression equations obtained for the dataset, displayed in Table 3, showed that there was only one significant relationship between the variables: a relatively weak, but significant correlation for DOC ($R^2 = 0.157$), while the remainder were not significant, with R^2 values of 0.021for SUVA$_{254}$.

Discussion

Qualitative approximation: effect of soil type on SQI and DOC concentration

Figures 2 and 3 indicate that there is a match between DOC and SQI regarding the soil types. In general, the

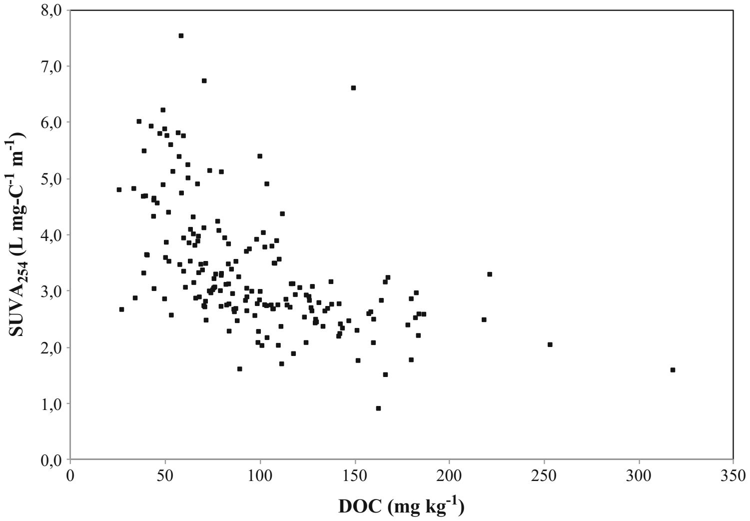


Fig. 4 Relationship between DOC and SUVA$_{254}$ based on Soil Monitoring System of Hungary (SMS)

most dominant factor explaining the DOC concentration of soils is the SOM content (Filep and Rékási, 2011). Chernozem and gleysol soils had the highest SOM values in this study (2.98 and 2.76 %, respectively), while arenosols had the lowest one (0.97 %). This is in agreement with present knowledge on the limited formation of well-humified soil organic matter and stable organo-mineral complexes in coarse soils. In addition, it is known that a rapid turnover of organic matter exists in coarse-textured soils in arid and semiarid regions (Quiroga et al., 1999), so most plant and animal residues incorporated into the soil will be mineralized (Gregorich et al., 1994).

The pattern based on the SOM content of soil is modified by the mineralization rate of the soil and the aggregate size (Zech et al., 1997). In the case of vertisols, there is a mismatch; vertisols may have high denitrification potential, allowing easily decomposable organic material to be leached from the top soil. Moreover, many studies have shown that organic C mineralization increases and C/nutrient ratios decrease with decreasing aggregate size (Chichester, 1969; Anderson et al., 1981).

Although Myers and McGarity (1971) reported appreciable denitrification activity in solonetzic subsoils enriched by DOC leaching from the surface horizons, such enriching of the DOC content of the topsoil was not observed in this study, resulting in the highest DOC values (156 mg kg^{-1}) for solonetz soils. The differences in respiration between chernozem and solonetz suggested that the higher carbon turnover rates in the chernozem soils could explain the differences observed between the rankings obtained with the SQI and DOC scales. Although podzolization typically caused a mobilization of

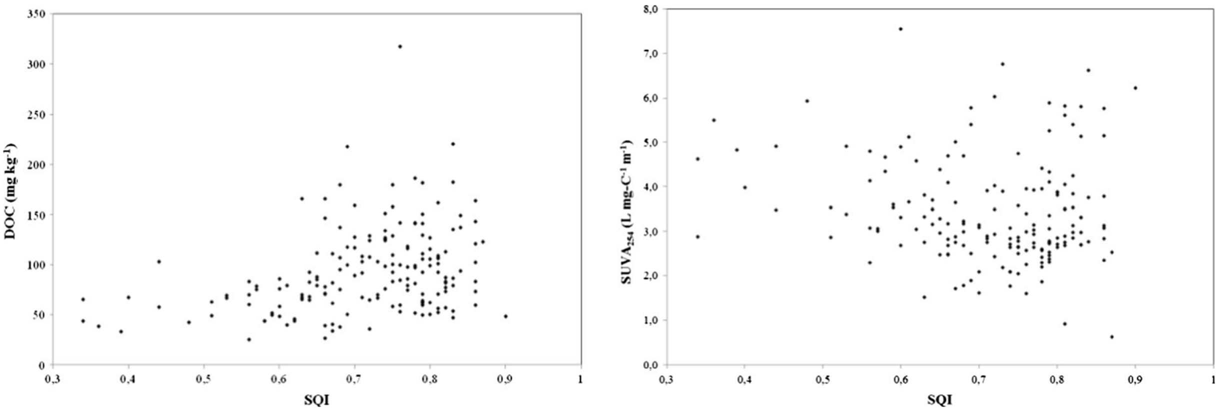


Fig. 5 Relationships for soil quality index (SQI) and DOM parameters

Table 3 Regression equation for DOC and $SUVA_{254}$ with soil quality index (SQI) in the SMS dataset ($n = 190$)

Equation	Coefficient of determination	Probability
$SQI = 27.2e^{1.6DOC}$	$R^2 = 0.157$	$p < 0.001$
$SQI = -1.5\ SUVA + 4.5$	$R^2 = 0.021$	$p = 0.057$

DOC, mature spodosols might be a net DOC source (McClain et al., 1997), explaining why podzoluvisols had a DOC value of only 58.4 mg kg^{-1} in this study.

Quantitative evaluation: relationship of SQI with DOC and $SUVA_{254}$

The fundamental aim of soil quality research is to discover single soil parameters which are largely determined by soil attributes, so that variation in these parameters would reflect changes in soil quality in response to treatments or natural processes. Since the DOC concentration was greatly influenced by soil parameters such as pH, SOM content and texture, it has the potential to indicate changes in soil quality. In previous studies (e.g. Kalbitz et al., 2000; Filep and Rekasi, 2011), significant relationships were found between the DOC concentration of the soil and fundamental parameters.

As reported above, the pH, sand content, total soluble N (TSN) and dehydrogenase activity (DHA) were selected by MDS for creating SQI values for the SMS dataset, which involves 190 soils from agricultural areas. It was interesting to note that the Mg content of soil was highly correlated with the soil texture. The correlation between these factors and dissolved organic matter will be discussed below.

Soil acidity, measured as the pH of the soil, has a substantial but contradictory influence on DOM dynamics through abiotic and biotic parameters (Kalbitz et al., 2000; Ji et al., 2014). Almost all laboratory studies revealed that DOC release was in positive correlation with soil pH (Curtin and Smillie, 1986; You et al., 1999). Various mechanisms have been suggested to explain this phenomenon, such as an increase in organic matter solubility (Erich and Trusty, 1997; Tombácz and Rice, 1999), increased microbial activity, an increase in the production of soluble molecules (Guggenberger et al., 1994) due to the decrease in biologically toxic Al at higher pH (Castro Filho and Logan, 1991), and the displacement of the previously adsorbed DOM by other mobilized anions (Vance and David, 1992). However, other mechanisms, such as the microbial consumption of DOM (Kemmitt et al., 2006) and DOM flocculation or adsorption by cation bridging due to higher Ca^{2+} concentrations (Römkens and Dolfing, 1998), might also decrease the DOC concentration.

The positive relationship between organic matter and silt + clay (or the negative correlation with sand) can be attributed to the existence of organo-mineral complexes, the amount of which increases parallel with that of the fine fraction (Nichols, 1984; Sollins et al., 1996). It is likely that the changing organic matter content of the soils with alterations in soil texture had an effect on the DOC concentration.

The effect of the N status of the soils on DOC has not yet been clearly established (Chantigny, 2003). For arable soils, decreasing mineral N content was related with an increase in DOC concentration (Chantigny et al., 1999). However, Rochette and Gregorich (1998) found no effect of N addition on the DOC content of arable soils. Soil N may simultaneously stimulate DOC production and consumption processes, so the net effect is hard to predict under field or even laboratory conditions.

Dissolved organic compounds are the primary substrates for microorganisms (Jones et al., 2005). DHA, commonly used as an index to describe the microbial activity of soils, is related to soil respiration and thus to the decay and formation of DOC compounds (van Hees et al., 2005).

UV spectroscopy can provide valuable structural information about dissolved organic matter structure (Weishaar et al., 2003), because the absorbance of a molecule depends on the electron structure of the molecule. The UV spectrum, therefore, indicates the presence of specific bonding arrangements in the molecule. In the case of absorption in the near UV range (200–380 nm), conjugated systems, such as those in aromatic molecules, generally have the greatest absorptivities (Silverstein et al., 1974). Therefore, the SUVA value, calculated by dividing the absorbance at 254 nm by the DOC concentration, is indicative of the aromaticity of dissolved organic matter. This means that high SUVA values indicate a relatively high proportion of aromatic carbon in the DOC fraction. Furthermore, an extract with a high DOC concentration and a low value of SUVA would be expected to be rich in aliphatic components (e.g. soluble sugars, fatty acids).

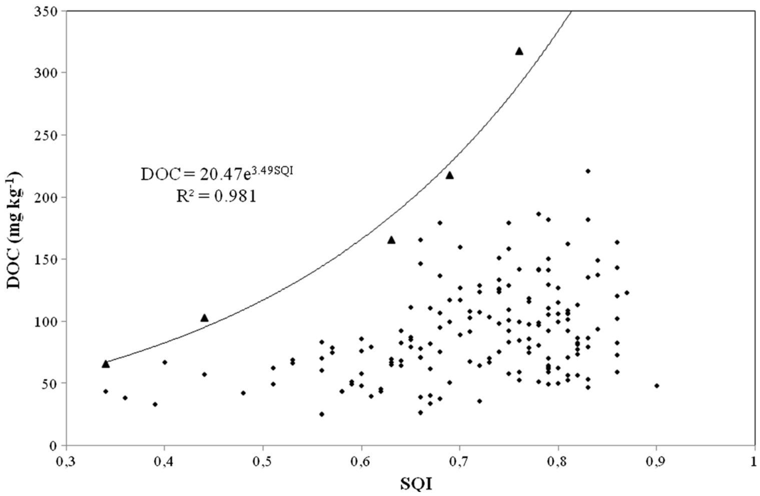


Fig. 6 Envelope curve for SQI-DOC function based on a trend line through the points identified by triangles

Although there was weak correlation between the SUVA values of DOC and SQI, the trend is clear; lower SQI values were associated with high SUVA values, while soils with high SQI had relatively low SUVA values. The metabolism of aromatic carbon is very different from that of aliphatic carbon. The aromatic rings of the organic compounds are generally very recalcitrant, so mineralization is limited. Previous studies showed that management practices can affect DOC properties, e.g. long-term manure input increased the aromaticity of DOC (Marschner and Kalbitz, 2003). This may cause a dysfunction in microbial activity and consequently in the nutrient status of the soil.

Estimation of the potential of DOC as a soil quality indicator

Although a weak correlation was obtained between SQI and DOC, the tendency of the relationship is unambiguous. In many soil samples, low DOC concentrations were measured at high SQI values; however, high concentrations of DOC were all associated with high values of SQI (from 0.60). A high value of DOC can thus be assumed to indicate a high SQI value, and consequently high soil quality. On the other hand, a low DOC concentration does not necessarily signify that the given soil has low quality.

In many cases, envelope curves have been used for evaluating the relationships between plant characteristics and meteorological properties. Because envelope curves provided supplementary tools to assess the potential of indicators for ecological systems (Stockle and Debaeke, 1997), such functions were used to reveal the potential of DOM for use as a soil quality indicator. Instead of the standard minimisation of the sums of squares, an upper envelope curve was fitted to the data (Fig. 6).

The envelope curve shows the robust potential of DOC to indicate changes in soil quality, as the regression equation had a high R^2 value. Points below the envelope curve may indicate the soil quality of a given sample, but there are some limitations due to the contradictory processes often taking place in the soil. As discussed above, the soil pH and the N status or texture of the soil not only have a direct effect on DOM but also indirectly control the DOC concentration. In general, the DOC concentration of a given soil is the result of numerous, often contradictory processes, leading to a wide scattering of the data.

Conclusions

The DOC concentration was greatly influenced by the physical and chemical processes taking place in different soil types. The similar trends observed for the soil quality index (SQI) and DOC in different soil types showed the possibility of using DOC as a soil quality indicator. The dynamic nature of dissolved organic matter makes it a plausible soil quality indicator. Despite the weak correlation detected between SQI and DOC, the tendency was unambiguous; although low DOC concentrations were measured in many soil samples at high SQI values, high DOC concentrations were always associated with high values of SQI (from 0.60).

High values of DOC are thus a clear indication of high SQI values and consequently of high soil quality, while low DOC concentrations do not necessarily signify that the given soil has low quality. Thus, a clear tendency was illustrated using an envelope curve, which showed the robust potential of DOC to indicate changes in soil quality. This indicates that the dissolved organic matter fraction could be applied for evaluating soil quality, with some limitations which can be eliminated by the simultaneous use of other indicators.

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