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Practical evaluation of four classification levels of Soil Taxonomy, Hungarian classification and WRB in terms of biomass production in a salt-affected alluvial plot

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A R T I C L E I N F O

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We dedicate this paper to the memory of the two giants of post-war soil science in Hungary, Pál Stefanovits and István Szabolcs.

Keywords:
Goodness-of-classification criterion
Class separability
Correlation with environmental parameters
Parsimony of classes
Homogeneity
Electrical conductivity

A B S T R A C T

In a salt-affected alluvial plot, increased biomass is associated with increasing elevation and decreasing salt concentration. All four levels of three classification systems, the Soil Taxonomy (ST), the Hungarian classification (HU) and the WRB were evaluated in a 100 m regular grid of 85 profiles for their applicability for biomass estimation (using 10-year average NDVI as proxy) and their correlation with ground elevation. NDVI values reflecting soil formation chronology (from the least to the most developed soils) were found on the first (least detailed) level of the classification systems. By analyzing the aspects of *practical applicability*, mainly at the detailed levels 3 and 4, HU performed the best in terms of **class separability**, WRB showed the most **homogeneous classes**, HU provided the closest **correlation with** elevation; while ST operated with the lowest **number of classes**, and, consequently, had a lower level of homogeneity and weaker correlation with elevation. Both HU and WRB performed well in most aspects, but the latter showed greater homogeneity. WRB had twice as many classes as HU and four times as many compared to ST; thus, their homogeneity increased accordingly.

The implementation of a soil classification without profound tests might result in counterproductive classes in terms of class separability, homogeneity of classes, correlation with environmental parameters, and parsimony of classes.

1. Introduction

Soil science has been continuously gaining scientific and practical importance which triggers the emergence of novel methods. The development of remote/proximal sensing characterization and mapping of soils has been even more evident. Due to the availability of new instrumental analyses, quantitative soil properties can be visualized spatially which results in the increased availability of maps of soil properties, for example the recent Global Soil Maps by FAO (Szatmári et al., 2020). However, soil classes should carry useful soil information, and our study compares the suitability of three soil classification systems from the point of productivity estimation.

Classification is one of the main topics of soil science and has been one of the cornerstones of pedology since its emergence. Soil names and classes provide an overview of multiple soil properties (Kubiëna, 1953). Unlike in other disciplines (e.g., phyto- and zootaxonomy, mineralogy) many classification systems coexist globally in soil science (Krasilnikov et al., 2010) and their number has even been increasing. The type of classification system employed is often not based on multi-aspect analysis of the available classification systems, but rather influenced by legal actions, conventions, scientific trends, or the actual geopolitical atmosphere. Through the analysis of four practical criteria, this paper intends to show, how classifications can be evaluated systematically, as a first step for deciding on their practicability.

The study of classification systems and their comparison is a prime topic of pedology (Krasilnikov, 2009). Classification systems, with a special focus on Soil Taxonomy and World Reference Base for Soil Resources (Rossiter et al., 2017; Esfandiarpour et al., 2018; Salehi, 2018)

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have been compared according to parent material (Sorokin et al., 2021), levels of the classification, various physical and chemical properties and particular shortcomings. Other literary resources analyzed the applicability of classification systems to assess selected properties and primary production (Shrader et al., 1960; Webster et al., 1977; Allgood and Gray, 1978; Ogunkule and Beckett, 1988; Buol et al., 2011). In the latter case, practical applicability can be evaluated based on four criteria (class separability, homogeneity of classes, correlation to environmental parameters, and parsimony of classes, ranked in their order of importance (Fig. 1)). This paper follows this logic using 10-year average NDVI value as the target variable.

1.1. The four criteria tested in this paper

1.1.1. Class separability/Mutual exclusion of classes

According to the definition, it is an ideal, rarely realized situation when classes unequivocally refer to separate ranges of some property without overlap (Cline, 1949; Arnold, 2001). The more the classes are separated, the better the classification is. This criterion was assessed by the number of classes that showed significant differences in NDVI values pairwise, using ANOVA.

1.1.2. Homogeneity of classes

This criterion expresses the range of a property within the classes (Webster and Beckett, 1968). According to Beckett and Burrough, 1971, Webster, 1971"the uniformity of soil properties within mapping units" is quantified by 1-RV (the latter is the pooled within-class variance/total variance) in this study. Increasing 1-RV value indicates more precise classification. An alternative method is using CV% as done by Wilson and Giltrap, 1985.

1.1.3. Correlation with environmental parameters

Working with classification is facilitated by an environmental conceptual model that helps making inferences on the individual classes (Dotto et al., 2019). Hence, if a stronger correlation is found, the better the classification is. It was determined by the correlation between the proxy of productivity (10-year average NDVI values) and elevation in this study.

1.1.4. Parsimony of classes

Working with no more than just the necessary minimum number of classes in a given area, facilitates the practical decision (Ogunkule and Beckett, 1988). Therefore, the classification is better if there is a lower number of classes at one level.

Another criterion of classification is the indication of soil productivity which is the core concept of the current paper. Nonetheless, several other criteria exist for classification (undiscussed in this work), such as the availability of classification keys and the quick and unambiguous classification using the possible lowest number of laboratory parameters.

To achieve better compatibility with ST and WRB, updates of existing (national) soil classification systems are preferred today (Krasilnikov, 2010). Transitioning to a new system means significant changes in all databases, including GIS datasets which may trigger scientific disagreements (Bidló, 2019, Makó, 2019, Tóth, 2019a,b). In an ideal case, such transitions may be preceded by a thorough discussion revealing the pros and cons of the old and new systems concerning land use management and mapping. This justifies the current research and case study, where we aimed at comparing the applicability of three classification systems based on the criteria shown in Fig. 1 as suggested by Yost and Fox, 1981.

The Normalized Difference Vegetation Index is a universally applied remotely sensed indicator for the characterization of surface biomass (Pettorelli, 2013), calculated with spectral reflectance values as the ratio of the difference of near infrared and red reflectance to the sum of the same two parameters. Increasing NDVI indicates increasing biomass and typically larger yield (Marti et al., 2007). Based on previous experience, when very strong correlation between maximum NDVI values and cereal yield was obtained (Bussay et al., 2012, Table 1); 10-year average NDVI was selected as a proxy of soil productivity in this report.

Three soil classification systems were tested in the current study. Soil Taxonomy of the United States Department of Agriculture, Natural Resources Conservation Service was developed to have unique mnemonic system for naming soil classes, already has published its 12th edition and is widely applied all over the world (Soil Survey Staff, 2014). It is a hierarchical classification system using diagnostic horizons and features with a key, having six levels, such as order, suborder, great group, subgroup, family and series. Soil Taxonomy is widely used for mapping soils at every usual spatial scale.

The Hungarian Soil Classification System, a genetic and hierarchical classification system was developed in the 1960s (Szabolcs, 1966) continuing the Dokuchaev tradition for naming classes and was updated in 1989 (Jassó et al., 1989). It has four levels of classification, such as main type, type, subtype, variety, but does not have a taxonomic key to the classes. This classification system was developed to map the soils at detailed scale and is used on maps of 1:10,000 to 1:1,000,000 scales.

The World Reference Base for Soil Resources (WRB, 2015) was developed from the legend of the FAO-UNESCO Soil Map of the World (FAO-UNESCO, 1974). It is not employing a hierarchy for the reference soil groups, but under that has several hierarchical levels and uses

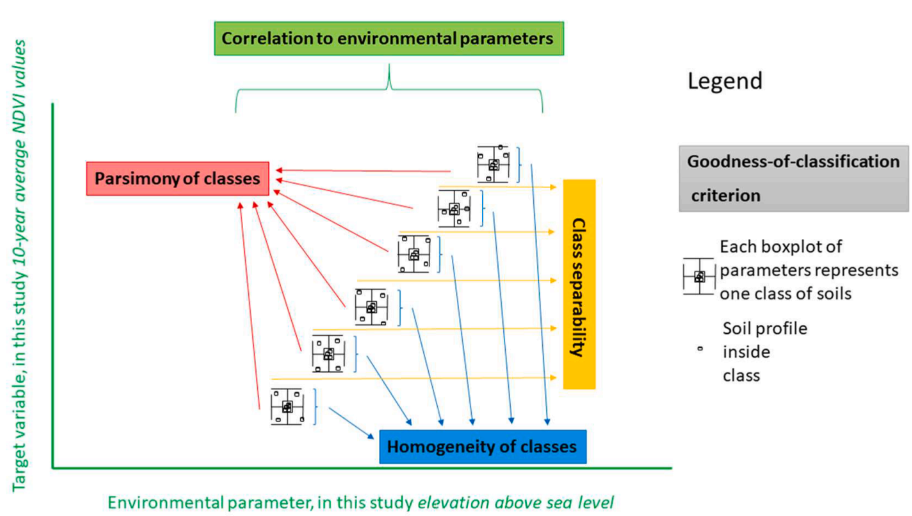

Fig. 1. Practical criteria for judging the performance of soil classification systems. See text for details.

Table 1
Exemplary classification of the extreme soil profiles applying Soil Taxonomy (ST), Hungarian Soil Classification (HU) and World Reference Base for Soil Resources (WRB) at four levels.

Classification level and number of classes in this study	Abbreviation used in this report	Lowest NDVI and Elevation	Highest NDVI	Highest Elevation	Lowest ECe 0–100 cm	Highest ECe 0–100 cm
	Profile code	D6	B4	C5	D4	J8
Order/Suborder (3)	ST1	Mollisols/Ustolls	Mollisols/Ustolls	Mollisols/Ustolls	Mollisols/Ustolls	Mollisols/Ustolls
Main type (3)	HU1	Chernozem	Chernozem	Chernozem	Chernozem	Chernozem
Reference soil group (RSG) (7)	WRB1	Chernozem	Phaeozem	Kastanozem	Chernozem	Phaeozem
Great group (5)	ST2	Calciustolls	Haplustolls	Haplustolls	Calciustolls	Haplustolls
Type (7)	HU2	Meadow chernozem	Meadow chernozem	Calcareous chernozem	Calcareous chernozem	Meadow chernozem
RSG + principal qualifier (18)	WRB2	Katocalcic Chernozem	Chernic Phaeozem	Endocalcic Kastanozem	Amphicalcic Chernozem	Chernic Phaeozem
Subgroup (10)	ST3	Udic Calciustolls	Udic Haplustolls	Udic Haplustolls	Udic Calciustolls	Udic Haplustolls
Subtype (12)	HU3	Calcareous meadow chernozem	Calcareous meadow chernozem	Typical calcareous chernozem	Typical calcareous chernozem	Solonetz-like in deeper horizons meadow chernozem
RSG + principal&supplementary qualifier (49)	WRB3	Katocalcic Chernozem	Chernic Phaeozem	Endocalcic Kastanozem (Cambic)	Amphicalcic Chernozem	Amphifluvic Chernic Phaeozem
Family (17)	ST4	Loamy ,mixed, calcareous,mesic Udic Calciustolls	Sandy,mixed, mesic Udic Haplustolls	Loamy over sandy, mixed,calcareous, mesic Udic Haplustolls	Loamy ,mixed, calcareous,mesic Udic Calciustolls	Sandy,mixed,mesic Udic Haplustolls
Variety (26)	HU4	Calcareous meadow chernozem with medium humic horizon depth	Calcareous meadow chernozem with medium humic horizon depth	Typical calcareous chernozem with medium humic horizon depth, calcareous from surface	Typical calcareous chernozem with medium humic horizon depth, calcareous from surface	Solonetz-like in deeper horizons meadow chernozem with medium humic horizon depth, calcareous from surface
RSG + principal&supplementary qualifiers (59)	WRB4	Katocalcic Chernozem	Chernic Phaeozem	Endocalcic Kastanozem (Cambic)	Amphicalcic Chernozem	Pantocalcaric Amphifluvic Chernic Phaeozem

diagnostic horizons and features in a key. Its use is promoted by FAO as an „international classification" and is the generally accepted classification in the European Union (Tóth et al., 2008). Nevertheless, its use as a map legend is more widespread at less detailed scales, such as 1:1,000,000 and is just being introduced for detailed mapping (Schuler et al., 2006).

In agreement with many former literature (e.g., McBratney et al., 2003, Teal et al., 2006), our presumption was that time-averaged NDVI well correlates with soil productivity and yield of cereal crops. We hypothised that productivity adequately reflects the physical conditions of the area, and that was analyzed by correlating the various physical parameters by ignoring soil classification.

1.2. Soil class-specific hypotheses

i) When stacked in order, classes of ST, HU and WRB soil classification systems are applicable for the direct assessment of soil productivity which was calculated with ANOVA.
ii) The following hypotheses had been set up prior to our analyses of the classification systems.

In ST productivity increases with advancing pedogenesis at the level of soil orders (ST1) in the following order:
Mollisols > Inceptisols > Entisols

iii) In the Hungarian Soil Classification system (HU1) productivity increases with the depth of the humic layer, which is not affected by salinity and surplus water (either from the top or the bottom) at the level of the main types in the following order:

Chernozems > Alluvial soils > Meadow soils

iv) At the level of the Reference Soil Groups of the WRB (WRB1), soil productivity increases with increasing organic matter content (Chernic or Mollic horizons) and the depth of the topsoil while increasing carbonate content in the subsoil, surplus water (Gleyic properties) and the associated salinity (Alkalic, Salic, Sodic qualifiers) decrease soil productivity. As of the productivity, the following order was hypothesized at RSG level:

Chernozem > Kastanozem > Phaeozem > Calcisol > Gleysol > Cambisol > Regosol

v) Using the agronomic salinity classes (according to Richards, 1954, and using 2 and 4 dS/m threshold values) and considering the depths of 0–30 and 0–100 cm, the classes of the NDVI values can be separated. Testing was done with ANOVA.

For testing our hypotheses, a salt-affected plot with diverse morphology and soil properties was selected where the heterogeneity of yield reflects the differences in elevation (Tóth and Kertész, 1996, Tóth et al., 1998). Although, due to its alluvial origin and former mosaic-like land use, the study plot is pedologically rather heterogeneous and has numerous practical advantages for research. It is the largest contiguous salt-affected plot of Hungary, and as such, is best suited for a study of this sort, as it has been managed consistently during the past 50 years, thereby facilitating the collection of remote sensing data for NDVI calculations. Along with some barley and sunflower, mostly maize has been harvested there over the past years.

2. Materials and methods

2.1. Study plot

The study plot is located in the outskirt of the village of Dunavecse in the former (morphological) floodplain of the River Danube. The soils are slightly saline and have a sandy-silty texture, with increasing mean particle size along the profile depth. Groundwater table is shallow and groundwater is saline. Local depressions, formerly densely vegetated, are characterized by a higher silt fraction, organic matter and salt contents and lower carbonate concentrations. Elevation controls most soil properties. By comparing the delineated three elevation zones (see later) we revealed that with increasing elevation, average salt concentration at a depth of 0–1 m, pH, sodicity, clay content and organic carbon content monotonously decreased while $CaCO_3$ content increased.

At the study plot the annual precipitation totals average 530 to 550 mm (No. 1.1.22 Hungarian Geographical Microregion), annual solar radiation totals 2,000 – 2,020 h, whereas long-term mean annual temperature is 10.4–10.5 °C (Dövényi, 2010).

A digital elevation model with a 4 cm vertical resolution was obtained from UAV surveys using ground control points of known coordinates. NDVI values were calculated from NASA Landsat data. Yearly maximum NDVI values between 2010 and 2019 were averaged for the 85 profiles, while NDVI ranges showed the difference between the maximum and minimum values of the ten years studied.

The selected plot of 0.9 km^2 area has a rectangular form (corner coordinates (46° 55‘ 16″N 19° 01′ 37“E, 46° 55‘ 17”N 19° 02’ 12“E, 46° 55’ 55”N 19° 01’ 41“E, 46° 55’ 49”N 19° 02’ 12“E). Inside the plot 85 tube profiles of 1 m depth were deepened. At 10 locations profiles were obtained to the groundwater table which is found at 160 to 301 cm depth with a mean of 200 cm. The electric conductivity (EC) of the shallow groundwater varied between 2.4 and 6.1 dS m^{-1}, pH between 7.4 and 8.6 while SAR between 13 and 51 indicating saline-sodic alkaline conditions.

Tube profiles were vertically dissected at their centers for analysis. Soil profiles were described according to Szabolcs (1966). X-ray fluorescent spectroscopy analyses, EC and soil moisture, were also determined and samples were taken from each genetic horizon.

Parameters used for classification were obtained by analyzing one third of the samples, while others were assessed using morphological and measured data, including EC, pH, Na, SOC, $CaCO_3$ content and hygroscopicity. Hygroscopicity refers to water content retained in the soil at a tension of 1.6×10^6 H_2O-cm using the method of Di Gléria et al. (1962, p. 301) and Wuddivira et al. (2012). Its value is directly proportional to clay content. Relying on laboratory data and profile descriptions, soils were classified according to ST, HU and WRB in multiple iterations using the previously mentioned keys/guides/handbooks.

2.2. Data analysis

All possible five soil classification levels of ST (order, suborder, great group, subgroup and family, but not series) were originally considered for the study area. As only one suborder belonged to each possible order (Mollisols, Inceptisols and Entisols) at the study plot, our study used only four levels (suborder, great group, subgroup and family. All four levels of HU were used for classification.

WRB classification was done at four levels. Reference soil groups (RSG) were determined, and all possible qualifiers were added. The number of applicable principal (princ) and supplementary qualifiers (suppl) ranged from 1 to 4, and 1 to 5, respectively. The number of all qualifiers varied between 2 and 6. Despite its non-hierarchical structure, soil classification was accomplished at levels 1, 2, 3 and 4. As our primary goal was the assessment of soil productivity, qualifiers were added according to their fixed order as required. Optional qualifiers were added according to the following approach.

- WRB1 level was RSG
- WRB2 level was RSG + 1princ
- WRB3 level was RSG + 2princ or RSG + 1princ + 1suppl
- WRB4 level was RSG + 3princ or RSG + 2princ + 1suppl or RSG + 1princ + 2suppl

The application of qualifiers according to the aforementioned principle is in harmony with the principles of name generation in WRB (WRB, 2015, p. 14–15, 3d-5.#) used for soil mapping. Those qualifiers that cannot be directly associated with productivity (textural supplementary qualifiers) were ignored.

The classification of profiles with extreme NDVI values, altitude or salinity are shown in Table 1.

Classification of saline soils (Richards 1954) was done for both the top 30 cm and 100 cm.

The analysis of the four criteria of Fig. 1. was carried out with the following tests at all four levels of classification based on the 10-year average maximum NDVI data of distinguished classes.

Class separability was characterized as the number of significantly different classes in single-factor ANOVA tests of 10-year average NDVI.

Homogeneity of classes for 10-year average NDVI, and as a reference, also for elevation, was analyzed at all four levels of classification. This was calculated by comparing the total and category averaged CV%. For the calculation of the weighted CV%, CV% was multiplied by the fraction of the total number of classes divided by the total number of samples (85) to avoid distortion by extreme class inhomogeneity.

Correlation to environmental parameters was analyzed by calculating the Pearson correlation coefficient between 10-year average maximum NDVI and elevation averaged for the distinguished classes at each level of classification, for example using the means of these two variables calculated for the 12 distinguished classes (n = 12) inside 3rd level of HU (Table 1).

Parsimony of classes was determined as the number of classes occurring within a classification scheme for the given level.

Due to space limitations, only one classification system was scrutinized at each level (1 to 4 from top to bottom) in the text but the results of all statistical analyses are shown in the summary tables and figures.

3. Results and discussion

In this section first (3.1.) the effect of elevation on soil formation and biomass production is described based on the results of this study, then (3.2.) the results of ANOVA on NDVI and elevation are presented. In the third part (3.3.) the results of the test of class-specific hypotheses are presented and discussed and in the last part of this section (3.4.) the fulfillment of the criteria set in Introduction (Fig. 1.) by the three classification systems are evaluated.

3.1. Elevation, biomass, salinity and soil formation based on the analytical results

Elevation was found to be the main influential factor, closely correlated with 10-year average NDVI, NDVI range, and salinity (Table 2).

Local topographic depressions of the study plot are characterized by increased infiltration and capillary action (from the shallow saline groundwater), increased salinity and, therefore, reduced productivity. With increasing elevation above the bottom of the depression, higher NDVI was found (correlation coefficient was 0.61^{**}). However, in the case of low 10-year average NDVI values, the NDVI range (R_NDVI) was higher in the depressions (correlation coefficient was -0.678^{**}). This is explained by the regularly occurring waterlogging. During wet springs and shallow groundwater table, biomass and NDVI were generally low and rather heterogeneous spatially. Biomass was larger and more homogeneous when spring was dryer and no waterlogging was observed when the groundwater table laid at a greater depth. At higher elevation, productivity proxy values were higher and more stable, not so much affected by year-to-year fluctuation of precipitation/waterlogging/shallow groundwater table. This situation is similar to that described for the “rangeland”, less saline/sodic habitat types on Fig. 1 of Tóth and Kertész, 1996, but due to lower clay content than in that study, in our plot salt concentration is lower, therefore, production is feasible.

Table 2
Pearson correlation matrix of the major variables ($n = 85$).

		10-year mean NDVI	10-year NDVI range	Elevation above sea level (m)	ECe (0–30 cm) dS/m	ECe (0–100 cm) dS/m
10-year mean NDVI value	Correlation	1	−0.678**	0.610**	−0.385**	−0.317**
	Sig. (2-tailed)	0.000	0.000	0.000	0.003	
10-year NDVI range	Correlation	−0.678**	1	−0.558**	0.327**	0.396**
	Sig. (2-tailed)	0.000	0.000	0.002	0.000	
Elevation above sea level (m)	Correlation	0.610**	−0.558**	1	−0.443**	0-0.328**
	Sig. (2-tailed)	0.000	0.000	0.000	0.002	
ECe (0–30 cm) dS/m	Correlation	−0.385**	0.327**	−0.443**	1	0.515**
	Sig. (2-tailed)	0.000	0.002	0.000		0.000
ECe (0–100 cm) dS/m	Correlation	−0.317**	0.396**	−0.328**	0.515**	1
	Sig. (2-tailed)	0.003	0.000	0.002	0.000	

**. Correlation is significant at the 0.01 level (2-tailed).

The combined influence of elevation and salinity to a depth of 100 cm, together with the agronomic salinity categories (Richards, 1954), are shown in Fig. 2. With some exceptions, saline profiles were found at the lowest points as expected. This is explained by the slope and the heterogeneous soil textural pattern of the plot both horizontally and vertically.

Mean NDVI values of the profiles, when categorized into three classes, were significantly different statistically, markedly demonstrating the effect of elevation (Fig. 3). Such relationships are well known from studies of natural plant communities, see for example Zalatnai et al., 2007, but also on croplands, such as the paper of Kitchen et al., 2003 who reported strong influence of elevation on yield on Kansas Haplustolls.

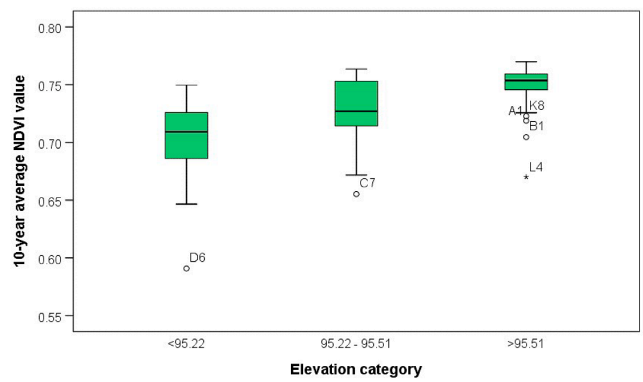

Fig. 3. Mean NDVI values of the three elevation classes (<95.22 m (n = 27), 95.22–95.51 m (n = 28) and > 95.51 m (n = 30)) are significantly different at a probability of ≤ 0.05. Profile codes identify the outliers (see Table 1).

3.2. *Performance of the classification systems to separate distinct ranges of NDVI and elevation values*

3.2.1. *Top (1) level classification using the example of HU1 main type*

NDVIs and elevations of the Chernozem and Meadow soils significantly differed. However, neither of them was statistically separable from the Alluvial soils. The mean values of the two variables changed similarly. The highest and lowest means were found for the Chernozems and the Meadow soils, respectively (Fig. 4).

3.2.2. *2nd level classification using the example ST2 great group*

No significant differences were found at the great group level of ST due to the great variability of elevation within each group (Fig. 5, right). The great groups of Haplustolls and Calciustolls were rather heterogeneous, their vertical variability of 0.31 to 0.36 m was twice as high as in the case of Usthorthents and Haplustepts (0.16–0.17 m).

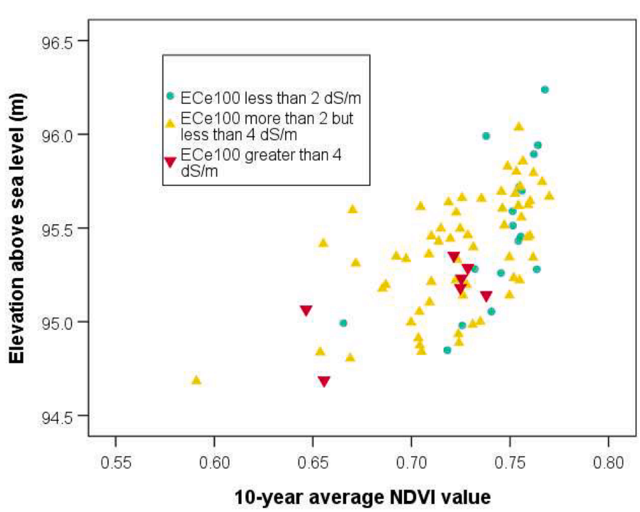

Fig. 2. Correlation between elevation and 10-year average NDVI values for the various salinity categories of 100 cm deep profile.

3.2.3. *3rd level classification using the example of WRB3*

In total, significant pairwise differences were found for mean NDVIs in 16 cases. The tendency of mean elevation was closely correlated with mean NDVIs (Fig. 6).

3.2.4. *Bottom (4) level classification using the example of ST4 families*

Six pairwise comparisons demonstrated significant differences for NDVI at the family level of ST (Fig. 7). The populous Loamy over sandy, mixed, calcareous, mesic Udic Haplustolls (n = 12) and Loamy over sandy, mixed, calcareous, mesic Udic Calciustolls (n = 28) families were rather heterogeneous. In these cases, the variability of elevation (0.37 to 0.38 m) was double compared to the Sandy, mixed, mesic Udic Calciustepts family of 3 profiles (variability = 0.20 m).

3.3. *Validation of the soil class-specific hypotheses*

Hypothesis i) has been entirely validated. Physical factors, primarily topography and salinity, markedly influenced NDVI (Table 2) as it was also proved by Kitchen et al. (2003), who found much lower correlation coefficient values between elevation and yield.

Hypothesis ii) was investigated at level 1 of the classification systems. It was partly validated for all three classification systems; however our findings were rather different due to the assumptions discussed in the Introduction.

iia) In ST, the NDVIs of Mollisols were greater than those of the Inceptisols, while the latter exceeded the same value of the single profile of Entisols. However, the differences were not significant. Similarly, significant yield differences were found between Entisols, Inceptisols and Vertisols by Kusumawati et al. (2021).

iib) The hypothesis was statistically validated for the Chernozems

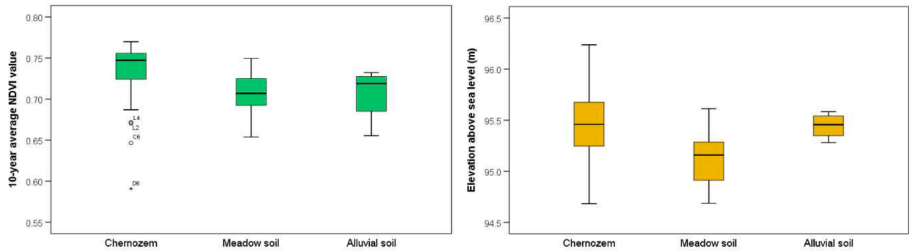

Fig. 4. Mean NDVI (left) and elevation (right) of Chernozem (n = 59), Meadow (n = 22) and Alluvial soils (n = 4) at the main type level (HU1) of the Hungarian Classification System.

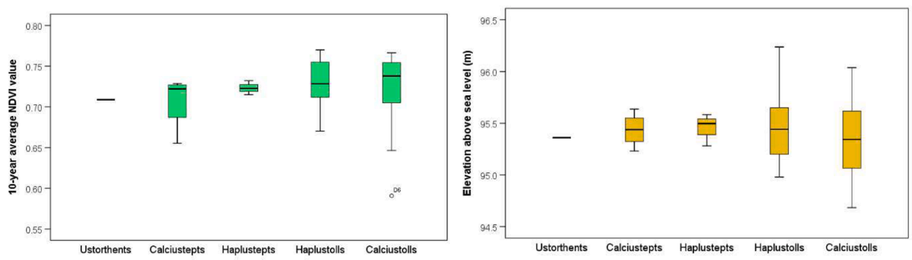

Fig. 5. Mean values of NDVI (left) and elevation (right) for Usthorthents (n = 1), Calciustepts (n = 4), Haplustepts (n = 3), Haplustolls (n = 24) and Calciustolls (n = 53) profiles at Great Group level (2nd level) of Soil Taxonomy (ST2).

and Meadow soils of HU (Fig. 4). Although the NDVIs of the Meadow soils were greater than that of the Alluvial soils, their differences were still insignificant. The differences in NDVI are explained by the saline subsoil (17 out of 22 profiles) of the Meadow soils, which profoundly reduced productivity. This observation clearly correlated with the elevation of the profiles. The relationship between soil classes and productivity is widely utilized in the Hungarian soil evaluation (Tóth et al., 2009) and forestry planning.

iic) With the exception of the low performance of Calcisols and Gleysols, WRB well reflected the presumed tendency. However, due to the heterogeneity of the classes, the differences were insignificant. The mean NDVIs were ranked in the following order

Chernozem ≫ Kastanozem ≫ Phaeozem ≫Cambisol≫ Calcisol ≫ Gleysol ≫ Regosol.

This ranking is explained by the salinity of the five Calcisol profiles, out of which three were salt affected. The limited productivity of the Gleysols is explained by the shallow groundwater table. Such linking of productivity of land and WRB soil classes was performed by Illés et al. (2011) in Hungarian forests.

Hypothesis iii) was validated. Mean NDVI values decreased with increasing ECe threshold values as 0.744 (n = 17), 0.724 (n = 61), 0.706 (n = 7) for classes "ECe<2", "ECe between 2 and 4" and "ECe>4 dS/m", respectively. The mean NDVI values of the two more saline classes did not show a significant difference, but other pairwise combinations did. These mean NDVI values showed an inverse, almost perfect linear relationship (r = -0.991) with mean ECe values of the three classes (1.77, 2.84, 4.4 dS/m). However, as only 3 classes (<2, 2–4 and > 4 dS/m) were possible the correlation was significant at p = 0.085. Butcher et al. (2018) also verified the effect of salinity and texture on maize and soybean yield in the Great Plains.

3.4. Results of the evaluation of four practical criteria

The evaluation of the four criteria expected to be fulfilled by any soil classification system is summarized as follows.

3.4.1. Class separability/Mutual exclusion of classes

Compared to the ideal case of complete separability (Fig. 1., Arnold 2001) we sought more realistic statistically significant differences between classes with ANOVA. In case of complete pairwise distinction when this ratio would be (n-1)/2, where n is the number of classes, only a fraction of the classes was separated in statistical terms (Fig. 8). At levels 1 and 3, HU demonstrated the best differentiation. The number of classes of statistically significant differences were only slightly higher for ST4 than for the other two classifications at level 4.

3.4.2. Homogeneity of classes

The calculated 1-RV values, i.e., the homogeneity of the classes, were comparable to those reported by Beckett and Burrough (1971) for soil properties. WRB performed the best at the more detailed levels of 3 and 4, which is explained by the flexibility provided by a large number of principal and supplementary qualifiers. The 1-RV of the WRB was about two and four times higher than the corresponding values of HU4 and ST4, respectively (Fig. 9). For HU the most detailed classification did not improve class homogeneity in terms of NDVI values.

The variability of the mean NDVIs was similar at level 1 of the three soil classifications (Fig. 10). HU showed consistent monotonously decreasing CV% for all levels. ST demonstrated the minimum CV% at great group level (ST2) but showed higher at subgroup level (ST3). It is in contrary to the findings of Wilson and Giltrap, (1985) for tropical Mollisols, who found a gradual increase of homogeneity for all studied chemical parameters between ST2 and ST3. The narrowest range of CV% was found for WRB2 (RSGs with principal qualifiers). The magnitude of variation reflected by NDVI was comparable to the least variable soil parameter, pH reported by Wilson and Giltrap (1985), showing 6,6,5,5 CV% for the levels ST1, 2, 3, 4 respectively. Overall there was not a great difference in the CV% values between the taxonomic levels, as shown also by Beckett and Burrogh (1971).

For the comparison of classes of greatly different profile numbers, mean CV% values were weighted according to their number of profiles (Fig. 11).

The weighted CV%s of the three classification systems were similar at level 4. Narrowest values were found for WRB while the broadest for ST, specifically at level ST2 (Fig. 11).

3.4.3. Correlation with environmental parameters

Correlation between yield and environmental parameters is often

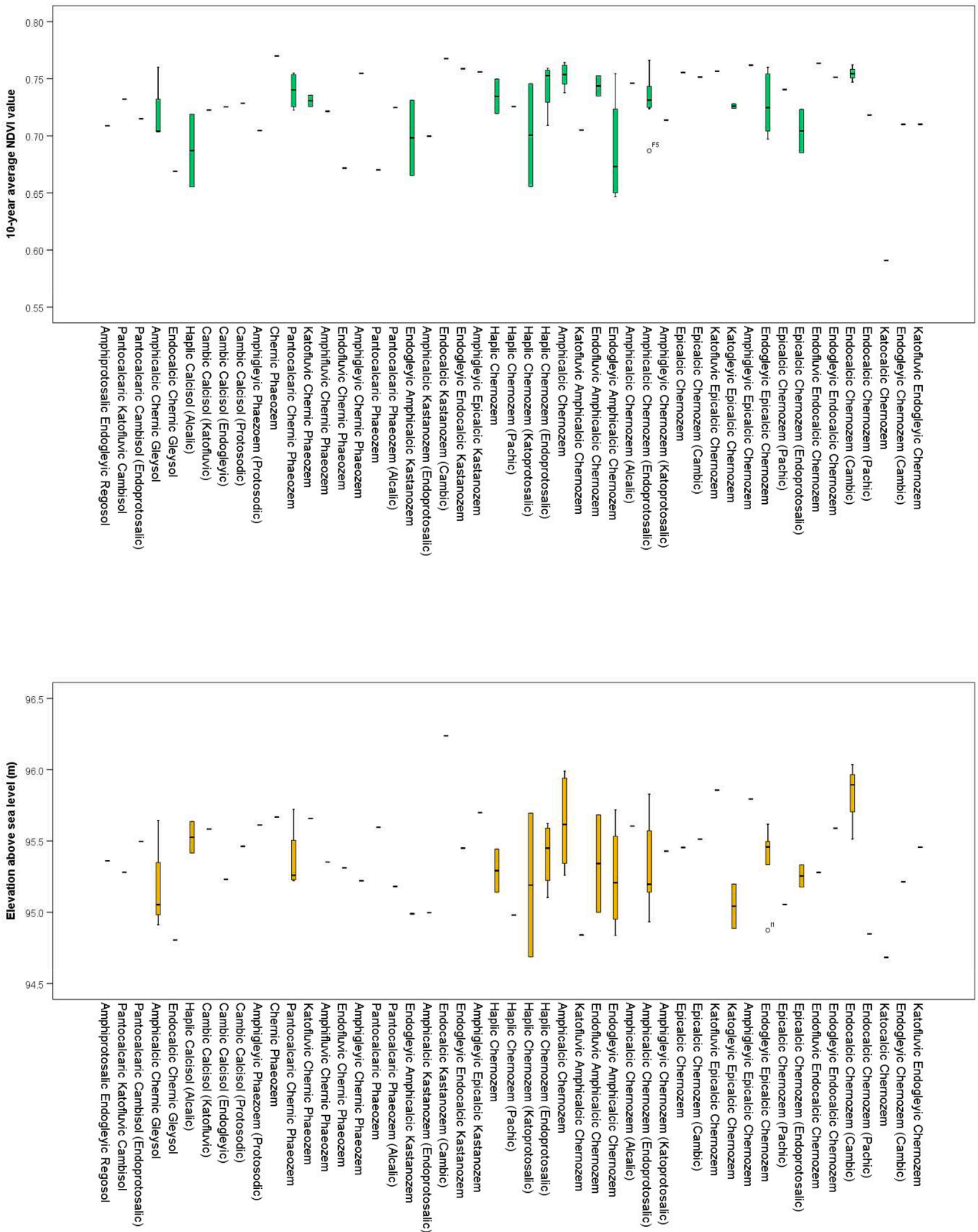

Fig. 6. Mean values of NDVI (top) and elevation (bottom) at level 3 of WRB (WRB3).

sought (McKenzie at al., 1999). High correlation of classes with mean NDVIs is amplified when classes closely correlate with elevation. In case of detailed levels HU3 ($r = 0.821^{**}$) and WRB3 ($r = 0.574^{**}$) were found more suitable for productivity estimation than ST at level 3. The same was found for level 4, where HU4 performed the best ($r = 0.707^{**}$) before WRB4 ($r = 0.562^{**}$) and ST4 ($r = 0.083$, insignificant). These correlation coefficients were much higher than those reported by Kitchen et al. (2003) in the Great Plains.

3.4.4. *Parsimony of classes*

Van Huyssteen et al. (2013) claimed that "the number of soil forms should further be limited. Humans do not possess the ability to comprehend a vast number of taxa." Therefore, we compared the number of classes at the four levels of the three classification systems as shown in column 1 of Table 1. The total number of classes ranged between 3 and 7, 5 and 18, 10 and 49, 17 and 59 for the four levels, respectively, ST showing the lowest and WRB showing the highest numbers consistently. WRB showed an excessive number of classes at levels 3–4 as 49–59 for a total set of 85 profiles. At level 1, the WRB distinguished twice as many, at level 2 thrice as many, and at level 3, four-five times as many classes as the other two classification systems. The same ratio remained at ST4, but the number of HU4 classes has

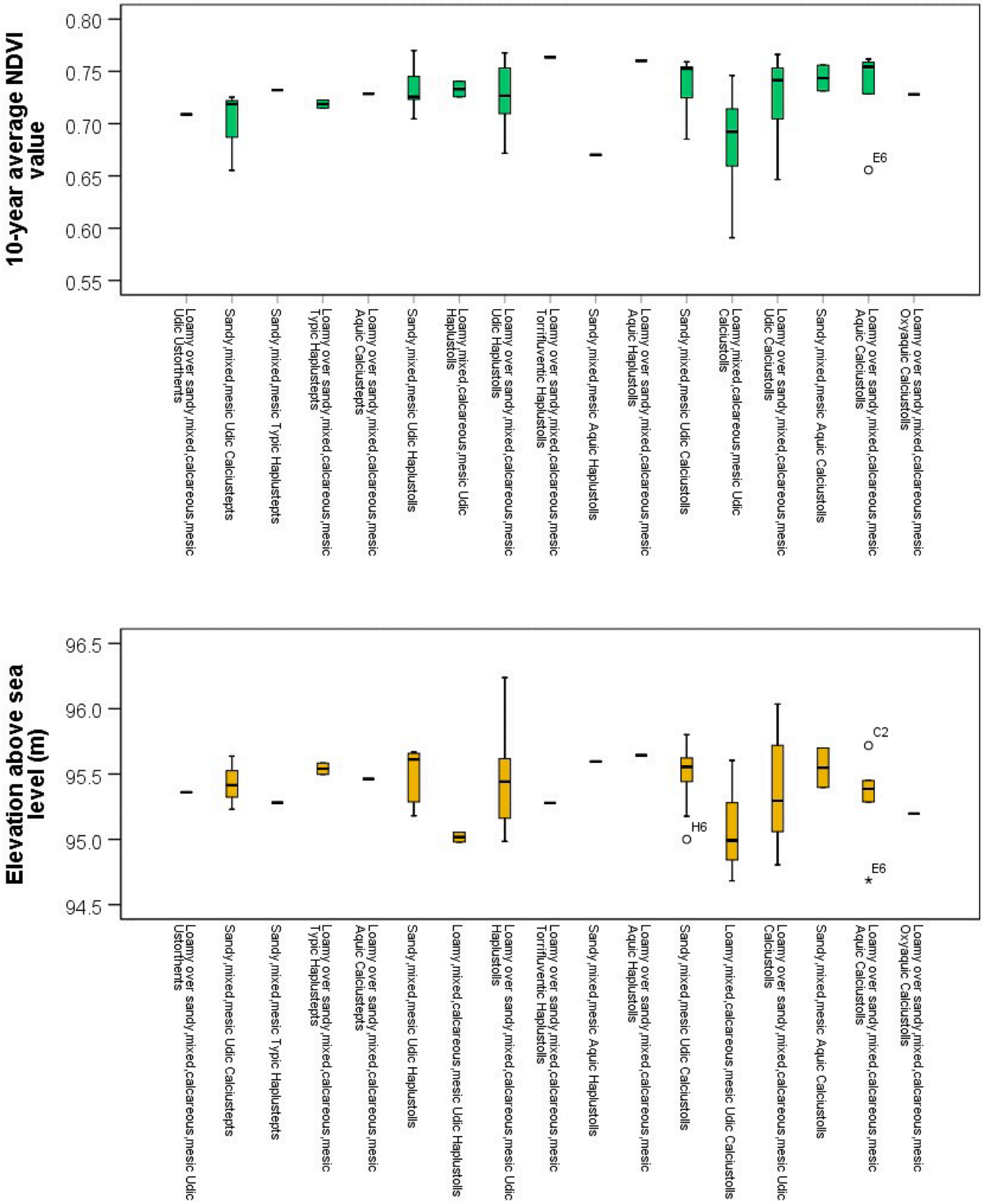

Fig. 7. Mean values of NDVI (top) and elevation (bottom) at family level (level 4) of Soil Taxonomy (ST4).

significantly increased at level 4, where the number of WRB4 classes twofold exceeded those in HU4. Statistical evaluation was challenging due to the large number of single-profile classes. ST had a single-profile ratio of 33, 20, 40 and 41%, HU had 0, 0, 8 and 54% and WRB had 14, 33, 67 and 78% at levels 1, 2, 3 and 4, respectively. HU had the lowest number of single-profile classes, while the WRB was the least manageable with the highest number. At level 4 all three systems had a large number of single-profile classes. WRB had the highest number with a single-profile ratio of 78% posing a difficulty for eventual digital mapping of the plot.

ST had the lowest number of classes at all four levels when multiple-profile classes were considered. Following the findings of Schuler et al. (2006), WRB had the highest number of classes (Fig. 12). Nevertheless, due to the larger number of environmental factors, any global classification system is likely to have a higher number of classes than the local (national) ones. In HU, environmental factors are closely correlated with the specific morphological, sedimentological, and climatic conditions of the Pannonian Basin reflected in specific soil development features. These specifics have determined the intensity of soil forming factors and processes, resulting in site-specific organic matter and $CaCO_3$ accumulation, water budget and rate of leaching. The site-specific pedogenetic processes indicate enhanced profile development over the Quaternary. The deposition of loess and hence the general presence of $CaCO_3$ (Stefanovits, 1963) coupled with the alluvial character of the landscape and the ubiquitous shallow groundwater table, have markedly influenced the physico-chemical soil properties (Arany, 1956).

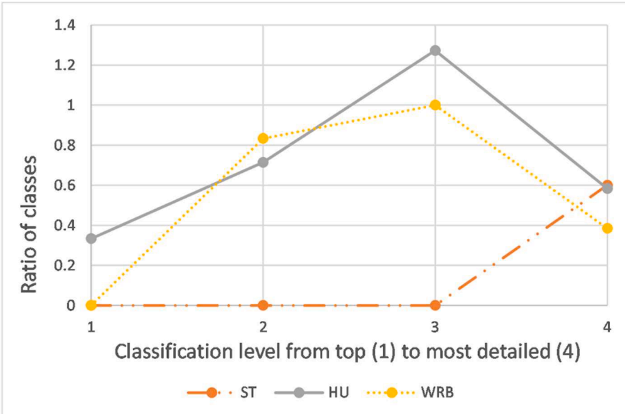

Fig. 8. The ratio of significantly different classes compared to the total number of classes at the four levels of the three studied classification systems (ST: Soil Taxonomy, HU: Hungarian Classification, WRB: World Reference Base). Classes with only one profile were not considered. Levels are shown in Table 1.

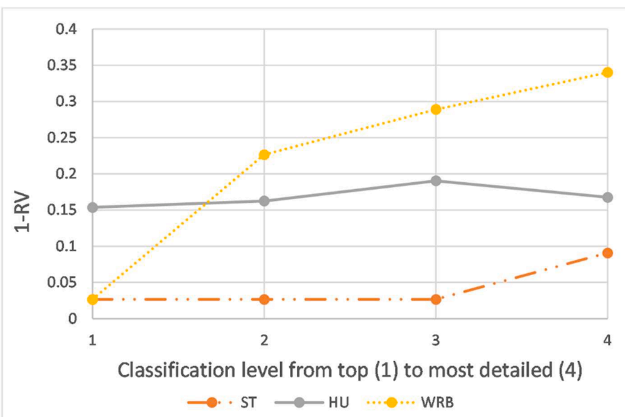

Fig. 9. 1-RV values (RV is the fraction of within-class variance/total variance) calculated with NDVI for the four levels of the three classification systems. (ST: Soil Taxonomy, HU: Hungarian Classification, WRB: World Reference Base). Levels are shown in Table 1.

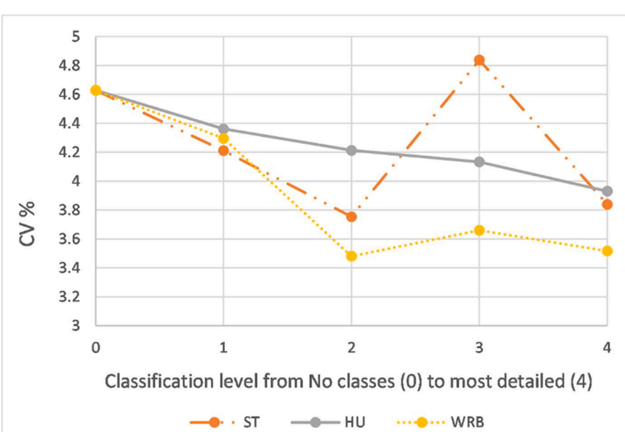

Fig. 10. The NDVI based mean CV%s per class at the four levels of the three soil classifications. (ST: Soil Taxonomy, HU: Hungarian Classification, WRB: World Reference Base). Levels are shown in Table 1.

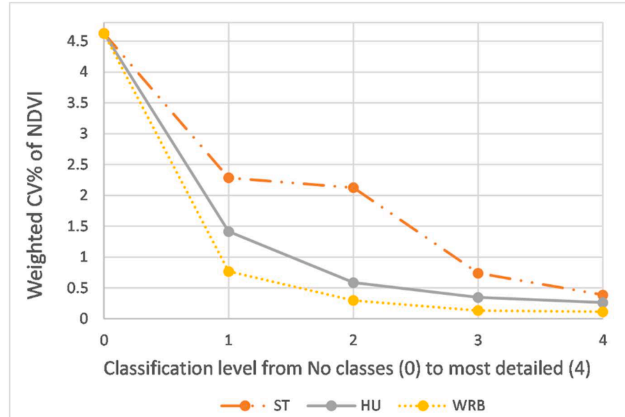

Fig. 11. Mean NDVI-based weighted mean CV%s by number of profiles per class at the four levels of the three soil classifications. (ST: Soil Taxonomy, HU: Hungarian Classification, WRB: World Reference Base). Levels are shown in Table 1.

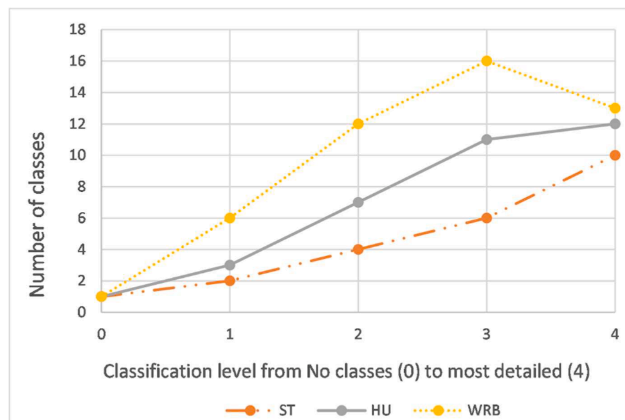

Fig. 12. Number of classes with more than one profile at the four levels of the 3 soil classifications. (ST: Soil Taxonomy, HU: Hungarian Classification, WRB: World Reference Base). Levels are shown in Table 1.

Our results might guide the developers of numerical soil classification systems that attract large attention recently (Hughes et al., 2014, Maynard et al., 2020, Flynn et al., 2021). There are several expectations regarding soil classifications (Simfukwe et al., 2011) and numerical classifications might be designed to fit user requirements better. In a numerical classification it is possible to define the importance of the individual properties and to provide a hierarchy based on those as having primary, secondary etc. importance (Grigal et al., 1969). We suggest conceiving biomass production as a primary soil-related ecosystem service (Brevik et al., 2016, Simfukwe et al., 2011) and very important soil-forming factors such as elevation as dominant primary factors (Lagacherie et al., 2000), so classes should be associated with these. Very desirable characteristics of new classification systems are homogeneous, well separated classes which are not too numerous (see Fig. 1). Such classification systems might provide classes that are more easily interpreted for land evaluation and agronomical purposes than the existing ones (Lóczy et al. 2020).

4. Conclusions

The classes of the three classification systems had different levels of homogeneity and **class separability**. In terms of class separability, the studied soil classifications were ranked as HU3 > WRB3 > ST3 and ST4 > HU4 > WRB4 with only slight differences (Fig. 8).

Regarding **class homogeneity**, WRB was the best, i.e., had the narrowest range of the classes, followed by the HU and ST according to both the 1-RV (Fig. 9), the non-weighted CV%s (Fig. 10) and the weighted CV%s (Fig. 11).

The physical environment was best reflected by the HU3 and HU4 with the highest **correlation between elevation and mean class NDVI values**. WRB3 and WRB4 had only slightly lower correlations than HU3 and HU4. On the contrary, correlation coefficients were slightly higher of the WRB2 than at HU2. ST did not correlate well with physical parameters at any level.

When the **number of classes** was considered, the highest number of classes was found in WRB, while ST was the most favorable with lowest number of classes (Fig. 12).

Our findings revealed that, none of the classification systems performed either excessively poorly or outstandingly, when only levels 3 and 4 were considered. WRB3-4 and HU3-4 performed slightly better than ST, however, with different strengths. An advantage and, at the same time, a drawback of WRB is that it considers many aspects using a plethora of physical and chemical parameters (Krasilnikov et al., 2009). The good performance of the HU may be explained by the excessive experience on alluvial, floodplain and saline soils. This knowledge has been soundly integrated into the current soil classification from the former Hungarian classification systems (Treitz, 1924, de Sigmond 1927, 1938).

At the final comparison of the three classification systems, their pros and cons were evaluated. ST employs a relatively low number of classes; hence its weakness is the lower homogeneity of classes formerly also pointed out by Hughes et al. (2017, 2018). The low correlation with physical parameters, specifically with elevation in the current study, is in correspondence with the findings of Webster (1968). At level ST4 (family level), however, ST performed similarly to the other two classification systems. HU performed well in all aspects, slightly surpassing the other two classification systems in terms of class separability and correlation with elevation. However, in terms of the homogeneity of classes, it was found inferior to WRB. While WRB performed similarly to HU in almost all respects, its weakness was the large number of classes, 2 and 4 times as many as HU and ST, respectively. Such large number of classes and, above all, of the single-profile classes seems to be a severe limitation for the digital mapping of WRB soil classes. However, these classes showed four times higher homogeneity than ST and HU.

This work will be followed by a digital mapping exercise in the same plot to test the performance of the three classification systems at the same levels.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Allgood, F.R., Gray, F., 1978. Utilization of soil characteristics in computing productivity ratings of Oklahoma soils. Soil Sci. 125, 359–366.

Arany, S. 1956. Salt affected soils and their reclamation. Mezőgazda Kiadó. Budapest. p. 407. (in Hungarian).

Arnold, R.W. 2001. Soil classification principles. In Soil classification 2001: contributions to the International symposium “Soil Classification 2001”, 8-12 October 2001, Velence, Hungary (pp. 3-8).

Beckett, P.H.T., Burrough, P.A., 1971. The relation between cost and utility in soil survey: IV. Comparison of the utilities of soil maps produced by different survey procedures, and to different scales. J. Soil Sci. 22 (4), 466–480. https://doi.org/10.1111/j.1365-2389.1971.tb01631.x.

Bidló, A. 2019. Invited commentaries to „Michéli Erika, Fuchs Márta, Szegi Tamás, Csorba Ádám, Dobos Endre, Szabóné Kele Gabriella: “Diagnostically renewed Hungarian soil classification: principles, structure, rules of classification” (2018.10.10.). *Agrokémia és Talajtan,* 68 (2), 345-354. DOI: 10.1556/0088.2019.00055 (in Hungarian).

Brevik, E.C., Calzolari, C., Miller, B.A., Pereira, P., Kabala, C., Baumgarten, A., Jordán, A., 2016. Soil mapping, classification, and pedologic modeling: History and future directions. Geoderma 264, 256–274.

Buol, S.W., Southard, R.J., Graham, R.C., McDaniel, P.A., 2011. Soil genesis and classification. John Wiley & Sons.

Bussay, A., Tóth, T., Juskevicius, V., Seguini, L., 2012. Evaluation of aridity indices Using SPOT Normalized Difference Vegetation Index Values calculated over different time frames on Iberian rain-fed arable land. Arid Land Res. Manage. 26, 271–284.

Butcher, K., Wick, A.F., DeSutter, T., Chatterjee, A., Harmon, J., 2018. Corn and soybean yield response to salinity influenced by soil texture. Agron. J. 110 (4), 1243–1253.

Cline, M.G., 1949. Basic principles of soil classification. Soil Sci. 67 (2), 81–92.

de Sigmond, A. 1938. The principles of soil science. London.

de Sigmond, A., 1927. Hungarian alkali soils and methods of their reclamation. Special publication issued by the California Agricultural Experiment Station. University of California, Berkeley.

Di Gléria, J., Klimes-Szmik, A., Dvoracsek, M., 1962. Bodenphysik und Bodenkolloidik. Akadémia Kiadó, Budapest.

Dotto, A.C., Demattê, J.A., Viscarra, R.R., Rizzo, R., 2019. Soil classification based on spectral and environmental variables. Soil Discuss. 1–20.

Dövényi, Z. (ed.) 2010. Inventory of microregions in Hungary, Second edition, Hungarian Academy of Sciences, Geographical Research Institute, Budapest. p. 876. (in Hungarian).

Esfandiarpour, I., Mosleh, Z., Farpoor, M.H., 2018. Comparing soil taxonomy and WRB systems to classify soils with clay-enriched horizons (A case study: arid and semi-arid regions of Iran). Desert 23 (2), 315–325.

Fao–unesco., 1974. Soil map of the world, 1. Legend, Paris.

Flynn, T., Triantafilis, J., Rozanov, A., Ellis, F., Lázaro-López, A., Watson, A., & Clarke, C. 202). Numerical soil horizon classification from South Africa’s legacy database. *CATENA*, 206, 105543.

Grigal, D.F., Arneman, H.F., 1969. Numerical classification of some forested Minnesota soils. Soil Sci. Soc. Am. J. 33 (3), 433–438.

Hughes, P.A., McBratney, A.B., Minasny, B., Campbell, S., 2014. End members, end points and extragrades in numerical soil classification. Geoderma 226, 365–375.

Hughes, P., McBratney, A.B., Minasny, B., Huang, J., Michéli, E., Hempel, J., Jones, E., 2018. Comparisons between USDA soil taxonomy and the Australian Soil Classification system II: Comparison of order, suborder and great group taxa. Geoderma 322, 48–55. https://doi.org/10.1016/j.geoderma.2018.02.022.

Hughes, P., McBratney, A.B., Huang, J., Minasny, B., Michéli, E., Hempel, J., 2017. Comparisons between USDA Soil Taxonomy and the Australian Soil Classification System I: Data harmonization, calculation of taxonomic distance and inter-taxa variation. Geoderma 307, 198–209. https://doi.org/10.1016/j.geoderma.2017.08.009.

Illés, G., Kovács, G., Heil, B., 2011. Comparing and evaluating digital soil mapping methods in a Hungarian forest reserve. Can. J. Soil Sci. 91 (4), 615–626.

Jassó, F., Horváth, B., Izsó, I., Király, L., Parászka, L., Kele, G., 1989. Guidelines to large-scale soil mapping, 2nd Ed. Agroinform, Budapest (in Hungarian).

Kitchen, N.R., Drummond, S.T., Lund, E.D., Sudduth, K.A., Buchleiter, G.W., 2003. Soil electrical conductivity and topography related to yield for three contrasting soil–crop systems. Agronomy J. 95 (3), 483–495.

Krasilnikov, P., Arnold, R.W., Ibáñez, J.J. 2010. Soil classifications: their origin, the state-of-the-art and perspectives. In Proceedings of the 19th World Congress of Soil Science: Soil solutions for a changing world, Brisbane, Australia, 1-6 August 2010. Symposium 1.4. 2 Soil classification benefits and constraints to pedology (pp. 19-22). International Union of Soil Sciences (IUSS), c/o Institut für Bodenforschung, Universität für Bodenkultur.

Krasilnikov, P., Marti, J.J.I., Arnold, R., Shoba, S. (Eds.), 2009. A handbook of soil terminology, correlation and classification. Routledge.

Kubiëna, W.L. 1953. Bestimmungsbuch und Systematik der Böden Europas.

Kusumawati, A., Hanudin, E., Purwanto, B.H., Nurudin, M., 2021. Sugarcane growth and yields in response to long-term monoculture practices under different soil orders, 1. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing, p. 012007.

Lagacherie, P., Voltz, M., 2000. Predicting soil properties over a region using sample information from a mapped reference area and digital elevation data: a conditional probability approach. Geoderma 97 (3–4), 187–208.

Lóczy, D., Tóth, G., Hermann, T., Rezsek, M., Nagy, G., Dezső, J., Salem, A., Gyenizse, P., Gobin, A., Vacca, A., 2020. Perspectives of land evaluation of floodplains under conditions of aridification based on the assessment of ecosystem services. Hungarian Geogr. Bull. 69 (3), 227–243. https://doi.org/10.15201/hungeobull.69.3.1.

Makó, A. 2019. Invited commentaries to „Michéli Erika, Fuchs Márta, Szegi Tamás, Csorba Ádám, Dobos Endre, Szabóné Kele Gabriella: “Diagnostically renewed Hungarian soil classification: principles, structure, rules of classification” (2018.10.10.). *Agrokémia és Talajtan, 68* (2), 323-332. DOI: 10.1556/0088.2019.00052 (in Hungarian).

Marti, J., Bort, J., Slafer, G.A., Araus, J.L., 2007. Can wheat yield be assessed by early measurements of Normalized Difference Vegetation Index? Ann. Appl. Biol. 150 (2), 253–257. https://doi.org/10.1111/j.1744-7348.2007.00126.x.
Maynard, J.J., Salley, S.W., Beaudette, D.E., Herrick, J.E., 2020. Numerical soil classification supports soil identification by citizen scientists using limited, simple soil observations. Soil Sci. Soc. Am. J. 84 (5), 1675–1692.
McBratney, A.B., Santos, M.M., Minasny, B., 2003. On digital soil mapping. Geoderma 117 (1–2), 3–52.
McKenzie, N.J., Ryan, P.J., 1999. Spatial prediction of soil properties using environmental correlation. Geoderma 89 (1-2), 67–94.
Ogunkunle, A.O., Beckett, P.H.T., 1988. Combining soil map and soil analysis for improved yield prediction. Catena 15 (6), 529–538. https://doi.org/10.1016/0341-8162(88)90004-5.
Pettorelli, N., 2013. The normalized difference vegetation index. Oxford University Press.
Richards, L.A. 1954. Diagnosis and improvement of saline and alkali soils (No. 60). Soil and Water Conservative Research Branch, Agricultural Research Service, US Department of Agriculture.
Rossiter, D.G., Zeng, R., Zhang, G.L., 2017. Accounting for taxonomic distance in accuracy assessment of soil class predictions. Geoderma 292, 118–127. https://doi.org/10.1016/j.geoderma.2017.01.012.
Salehi, M.H., 2018. Challenges of Soil Taxonomy and WRB in classifying soils: Some examples from Iranian soils. Bull. Geogr. Phys. Geogr. Ser. 14 (1), 63–70. https://doi.org/10.2478/bgeo-2018-0005.
Schuler, U., Choocharoen, C., Elstner, P., Neef, A., Stahr, K., Zarei, M., Herrmann, L., 2006. Soil mapping for land-use planning in a karst area of N Thailand with due consideration of local knowledge. J. Plant Nutr. Soil Sci. 169 (3), 444–452. https://doi.org/10.1002/jpln.200521902.
Shrader, W.D., Schaller, F.W., Pesek, J.T., Slusher, D.F., & Riecken, F.F.1960. Estimated crop yields on Iowa soils. U. S. Dept. Agr . and Iowa Agr . Expt . Sta . Special Rpt. 25 , April 1960.
Simfukwe, P., Hill, P.W., Emmett, B.A., Jones, D.L., 2011. Soil classification provides a poor indicator of carbon turnover rates in soil. Soil Biol. Biochem. 43 (8), 1688–1696.
Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.
Sorokin, A., Owens, P., Láng, V., Jiang, Z.D., Michéli, E., Krasilnikov, P., 2021. "Black soils" in the Russian Soil Classification system, the US Soil Taxonomy and the WRB: Quantitative correlation and implications for pedodiversity assessment. Catena 196, 104824. https://doi.org/10.1016/j.catena.2020.104824.
Stefanovits, P. 1963: Soils of Hungary. Akadémiai Kiadó, Budapest, Hungary (in Hungarian).
Szabolcs, I. (Ed.), 1966. Handbook of the large-scale genetic soil mapping.. OMMI Genetikus Talajtérképek. Ser. 1. No. 9. Budapest. (In Hungarian).
Szatmári, G., Bakacsi, Z., Laborczi, A., Petrik, O., Pataki, R., Tóth, T., Pásztor, L., 2020. Elaborating Hungarian Segment of the Global Map of Salt-Affected Soils (GSSmap): National Contribution to an International Initiative. Remote Sensing 12 (24), 4073.
Teal, R.K., Tubana, B., Girma, K., Freeman, K.W., Arnall, D.B., Walsh, O., Raun, W.R., 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98 (6), 1488–1494. https://doi.org/10.2134/agronj2006.0103.
Tóth, G. 2019a. Invited commentaries to „Michéli Erika, Fuchs Márta, Szegi Tamás, Csorba Ádám, Dobos Endre, Szabóné Kele Gabriella: "Diagnostically renewed Hungarian soil classification: principles, structure, rules of classification". *Agrokémia és Talajtan, 68* (2), 333-344. (in Hungarian) DOI: 10.1556/0088.2019.00053.
Tóth, G., Montanarella, L., Stolbovoy, V., Máté, F., Bódis, K., Jones, A., Panagos, P., Van Liedekerke, M. 2008. Soils of the European union. JRC Scientific and Technical Reports, Office for Official Publications of the European Communities, Luxembourg.
Tóth, G., Makó, A., Máté, F., 2009. Designation of local varieties in the Hungarian soil classification system: Remarks from a viewpoint of land evaluation application. Eurasian Soil Sci. 42 (13), 1448–1453.
Tóth, T. 2019b. Invited commentaries to „Michéli Erika, Fuchs Márta, Szegi Tamás, Csorba Ádám, Dobos Endre, Szabóné Kele Gabriella: "Diagnostically renewed Hungarian soil classification: principles, structure, rules of classification" . *Agrokémia és Talajtan, 68*(2), 315-321. (in Hungarian) DOI: 10.1556/0088.2019.00051.
Tóth, T., Kertész, M., 1996. Application of soil-vegetation correlation to optimal resolution mapping of solonetzic rangeland. Arid Land Res. Manage. 10 (1), 1–12.
Tóth, T., Kertész, M., Pásztor, L., 1998. New approaches in salinity/sodicity mapping in Hungary. Agrokémia és Talajtan. 47, 76–86.
Treitz, P. 1924. The nature and properties of salt-affected soils. Budapest.
Van Huyssteen, C.W., Le Roux, P.A.L., Turner, D.P., 2013. Principles of soil classification and the future of the South African system. S. Afr. J. Plant Soil 30 (1), 23–32.
Webster, R., 1968. Fundamental objections to the 7th approximation. J. Soil Sci. 19 (2), 354–366. https://doi.org/10.1111/j.1365-2389.1968.tb01546.x.
Webster, R., 1971. Wilks's criterion: A measure for comparing the value of general purpose soil classifications. J. Soil Sci. 22 (2), 254–260. https://doi.org/10.1111/j.1365-2389.1971.tb01612.x.
Webster, R., Beckett, P.H.T., 1968. Quality and Usefulness of Soil Maps. Nature 219 (5155), 680–682. https://doi.org/10.1038/219680a0.
Webster, R., Hodge, C.A.H., Draycott, A.P., Durrant, M.J., 1977. The effect of soil type and related factors on sugar beet yield. J. Agric. Sci. 88 (2), 455–469. https://doi.org/10.1017/S0021859600034973.
Wilson, A.D., Giltrap, D.J., 1985. Effectiveness of " Soil Taxonomy" for prediction of soil chemical properties on Mollisols under a shifting cultivating system in the Ha'apai group, Kingdom of Tonga. South Pacific J. Nat. Sci. 7, 45–57.
WRB, IUSS Working Group. 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. Food and Agriculture Organization of the United Nations, Rome. p. 192.
Wuddivira, M.N., Robinson, D.A., Lebron, I., Bréchet, L., Atwell, M., De Caires, S., Oatham, M., Jones, S.B., Abdu, H., Verma, A.K., Tuller, M., 2012. Estimation of soil clay content from hygroscopic water content measurements. Soil Sci. Soc. Am. J. 76 (5), 1529–1535. https://doi.org/10.2136/sssaj2012.0034.
Yost, R.S., Fox, R.L., 1981. Partitioning variation in soil chemical properties of some Andepts using Soil Taxonomy. Soil Sci. Soc. Am. J. 45 (2), 373–377. https://doi.org/10.2136/sssaj1981.03615995004500020029x.
Zalatnai, M., Körmöczi, L., Tóth, T., 2007. Community boundaries and edaphic factors in saline-sodic grassland communities along an elevation gradient. Tiscia 36, 7–15.