Optimization of the large-scale mapping of salt-affected soils under different land uses

Salt accumulation and the related processes of sodification and alkalinization are one of the most characteristic features of the Hungarian lowlands (Tóth et al., 2002), and affects arable lands as well prove to be the most abundant chemical degradation form. Mapping of salt-affected soils is based on historical data or on recent but incomplete databases. Since soil/underground salinity – sodicity - alkalinity is continuously present in the landscape, showing specific depth distribution and temporal intensity in accordance with geomorphology and hydraulic conditions (Terres et al., 2016), there is a need to collect new information in an appropriate resolution and apply new methods in mapping salt affected soils (SAS) for ensuring the subsidies linked to agricultural areas with natural constraints of the European Union (CAP 2014-2020, CAP 2023-2027). In the frame of the K-124290 project, two land use types, a natural salt meadow and a moderately saline agricultural plot were investigated, and the three dimensional extent of soil salinity – sodicity - alkalinity was assessed with different proximal survey methods [electromagnetic conductivity measurement (EM), Electrical resistivity tomography - four-electrode geoelectric resistance measurement (ERT), Gamma spectroscopy, x-Ray Fluorescence Spectroscopy (xRf)]. Remote sensing techniques, as multicopter technique, multi/hyperspectral remote sensing and geostatistics combined with geographical information systems were also tested to ensure appropriate resolution.

Ground truth is provided by laboratory measurement data from the horizons of 1 m depth soil profiles (tube samples) in each hectare. The collected "profile" database is used for testing the accuracy of the prepared maps based on different survey strategies using metrics like mean error (ME), Root Mean Squared Error (RMSE), Lin's concordance correlation coefficient (CCC) and Nash–Sutcliffe model efficiency coefficient (NSE). Soil layers/horizons of the profiles were described for the purpose of identifying the presence and occurence depth of diagnostic horizons typical of salt affected soils (e.g. Salic, Natric) in the investigated soil classification systems (Soil Classification System of Hungary (HU), the World Reference Base for Soil Resources (WRB, 2015) and the USDA Soil Taxonomy (USDA ST)). Although the three different soil classification systems intend to describe the same phenomenon, there are differences between the definitions of the mentioned horizons, and between the approaches of the systems (genetical, diagnostical). As soil classes carry useful soil information, we aimed to compare the suitability of this three soil classification systems from the point of productivity estimation.

A summary of the project results - supported by related publications – is presented below.

I, **Testing alternative sampling strategies and new methods in mapping**:

We deviated from the planned survey strategy testing due to the experienced difficulties. Most of the **sampling strata** to be used for mapping (DTM, vegetation, EM transects) were surveyed, but (in Hortobágy sampling site) due to accessibility problems in the waterlogged parts of the site, and the difficulty of drilling through impenetrable hard near-surface layers on other parts of the site, 57 of the planned 100 points have been drilled, and data from four-electrode geoelectric resistivity (ERT) and natural gamma-ray spectrometry (TG) survey was largely incomplete - for the same reason -, making it unsuitable for testing the mapping strategy we planned. Manuscript produced by processing the measured data is under preparation with the title of "Indirect prediction of salt affected soil indicator through habitat types of a natural saline grassland using remotely sensed data".

Direct surface sodicity(/salinity/alkalinity) **prediction** based on SAS indices (SAR, EC, pH) was fulfilled at two different scales (1 km^2 and hectare resolution) and this topic has been one of the most influential publication results of the research. During the mapping work, data were processed using multivariate geostatistic methods, developing **new mapping strategy** that includes uncertainty map. Uncertainty map displays the expected accuracy of the predicted value of the variable (in our case, salinity indicator) at a given location of the thematic map. These objectives have been achieved for the Dunavecse sampling area (see publications and details in the report below).

I/1. Developing probability map for determining areas having unfavorable natural conditions in order to gain EU support

One of the project aims was to map the soil salinity/sodicity/alkalinity status and collect new information on these for ensuring the subsidies linked to agricultural areas with natural constraints of the European Union. An important practical aspect for applying European Union subsidies is the determination of the areas having unfavorable natural conditions. Sodicity creates unfavorable physical (swelling-cracking, plasticity, poor water and air regime) and chemical (Na^+ predominance over Ca^{2+}, poor utilization of nutrients) conditions in the soil that inhibit or make agrotechnic operations uneconomical and reduce crop yield within the given plot.

At global scale, Global Map of Salt-affected Soils (GSSmap) campaign was launched by the FAO, and in the frame of our work, the global and country-level information on salt-affected soils (SAS) were updated by preparing Hungary's own SAS maps with 1 km^2 spatial resolution using advanced digital soil mapping techniques. A combination of random forest and multivariate geostatistical techniques were tested for predicting the spatial distribution of pH, electrical conductivity (EC) and exchangeable sodium percentage (ESC), as SAS indicators, for the topsoil (0–30 cm) and subsoil (30–100 cm). A number of indices derived from remotely sensed images (Sentinel-2 satellite images) served as highly informative environmental covariates in digital mapping of SAS. Thus, in addition to climatic, geomorphic parameters and legacy soil information, image indices were the most important covariates. 10-fold cross validation was used to check the performance of spatial modelling. In addition to contributing to GSSmap, SAS mapping methodology in Hungary was also renewed with paying special attention to modelling and quantifying the prediction uncertainty that had not been quantified or even taken into consideration earlier. It was revealed that short-scale variability of salt-affected soils, which causes mosaic-like patches in field, can be appropriately captured and modelled via remote sensing indices.

At local scale, Hungary's largest (0.85 km^2), former salt-affected agricultural plot was surveyed in Dunavecse at a hectare resolution. A probability map for sodium adsorption ratio (SAR) was created (*Figure 1.*). SAR was used as an indicator for sodicity - represents sodic soils exceeding a threshold value of 13 -, where they are more likely to have the soil degradation problems resulting in a reduced average yield. The completed map gives a 90% probability of sodicity in the sample area. According to our results, 16.9 % of the test area was affected by sodicity. Due to the detailed spatial resolution of the completed map, the percentage of the area entitled to claim support can be specified with great accuracy.

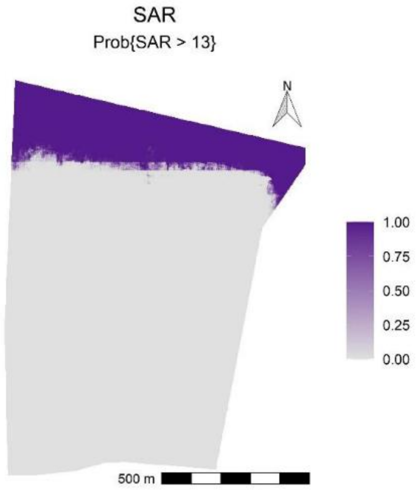

Figure 1. Map on sodium adsorption ratio (SAR) showing the probability that SAR is greater than the threshold value of 13.

Publications:

Hateffard Fatemeh, **Balog Kitti**, **Tóth Tibor**, Mészáros János, **Árvai Mátyás**, **Kovács Zsófia Adrienn**, Szűcs-Vásárhelyi Nóra, Koós Sándor, László Péter, Novák Tibor József, Pásztor László, Szatmári Gábor 2022. High-Resolution Mapping and Assessment of Salt-Affectedness on Arable Lands by the Combination of Ensemble Learning and Multivariate Geostatistics, AGRONOMY 12: 8 Paper: 1858 (2022), https://www.mdpi.com/2073-4395/12/8/1858, IF: 3,336, Q1

Szatmári, Gábor; Zsófia Bakacsi, Annamária Laborczi, Ottó Petrik, Róbert Pataki, **Tibor Tóth**, **László Pásztor**. 2020. Elaborating Hungarian Segment of the Global Map of Salt-Affected Soils (GSSmap): National Contribution to an International Initiative. Remote Sensing 12, 4073; doi:10.3390/rs12244073, IF=5,33, Q1

I/2. Proposal of a new methodology for mapping of salt affected soils (SAS) with different geostatistical estimations using SAS indicators

According to our project concept, the new mapping of SAS have to map the three chemical parameteres of salinity/sodicity/alkalinity status and collect new measured information according to international standard procedures in every typical land use types and describe the three dimensional extent of these degradation forms. Our objective was to map and assess salt-affectedness on an arable land in Dunavecse, Hungary, with high spatial resolution, using a **combination of ensemble machine learning and multivariate geostatistics**. Three SAS indicators (alkalinity: pH, electrical conductivity: EC, and sodium adsorption ratio: SAR) were modelled and mapped (n = 85 soil samples, Dunavecse, *Figure 2.*). Ensemble modelling with five **base learners** (i.e., **random forest, extreme gradient boosting, support vector machine, neural network, and generalized linear model**) was carried out and the results showed that **ensemble modelling outperformed the base learners for pH and SAR** with R^2 values of 0.43 and 0.96, respectively, while **only the random forest prediction was acceptable for EC**. Multivariate geostatistics was conducted on the stochastic residuals derived from machine learning modelling, as we could reasonably assume that there is spatial interdependence between the selected SAS indicators. We used **10-fold cross-validation** to check the performance of the spatial predictions and **uncertainty quantifications**, which provided acceptable results for each selected SAS indicator (for pH, EC, and SAR, the RMSE values were 0.11, 0.86, and 0.22, respectively). Our results showed that ensemble machine learning combined with multivariate geostatistics is efficient not just for jointly modelling and mapping the spatial distribution of different indicators of SAS at high spatial resolution (hectare), but also in assessing salt-affectedness on arable lands at the field scale. High-spatial-resolution mapping is important for farmers to indicate the part of the plot where reclamation/drainage works must be carried out and site-specific cultivation can be managed; and for decision-makers to help them decide the allocation of subsidies.

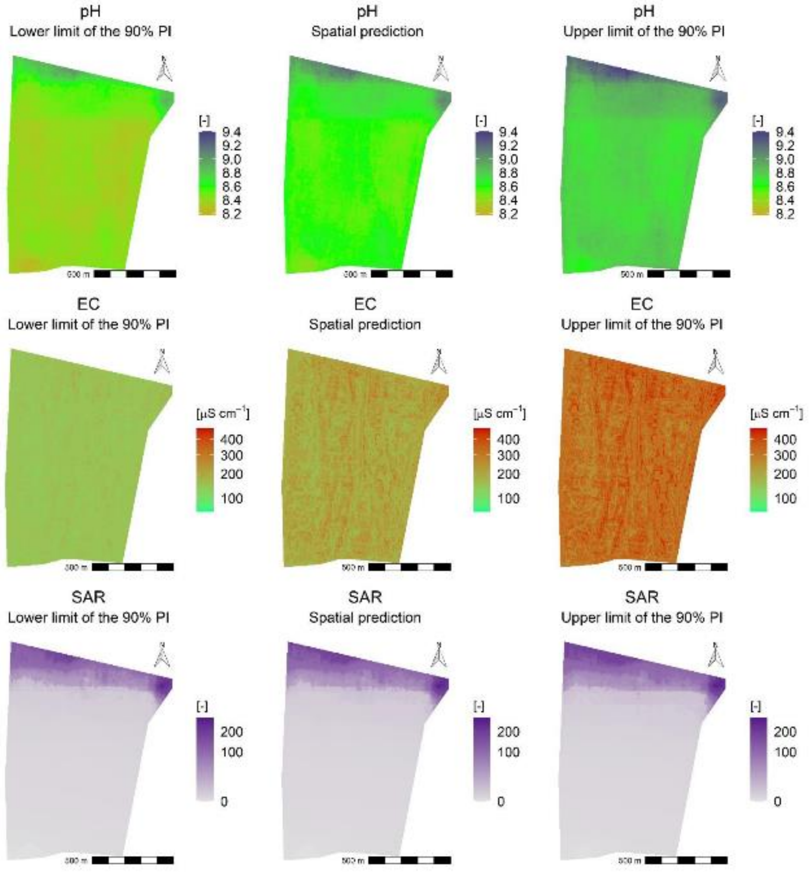

Figure 2. Spatial predictions (middle column) with the associated prediction uncertainty expressed by the 90% prediction interval (left and right column) for the indicators of salt-affected soils. Legend: EC: electrical conductivity, SAR: sodium adsorption ratio, and PI: prediction interval.

Publication:

Hateffard Fatemeh, **Balog Kitti**, **Tóth Tibor**, Mészáros János, **Árvai Mátyás**, **Kovács Zsófia Adrienn**, Szűcs-Vásárhelyi Nóra, Koós Sándor, László Péter, Novák Tibor József, Pásztor László, Szatmári Gábor 2022. High-Resolution Mapping and Assessment of Salt-Affectedness on Arable Lands by the Combination of Ensemble Learning and Multivariate Geostatistics, AGRONOMY 12: 8 Paper: 1858 (2022), https://www.mdpi.com/2073-4395/12/8/1858, IF: 3,336, Q1

I/3. Testing geostatistical approaches for mapping highly structured patterns in SAS

An important characteristic of SAS is their structured spatial pattern, which pose a real challenge for geostatistical mapping. This is because most geostatistical applications rely on the multivariate normal distribution, which maximizes spatial disorder. Our objective was to propose two geostatistical approaches, namely the **indicator approach and multiple-point geostatistics** (MPS). **Indicator kriging** (IK) and **single normal equation simulation** (SNESIM) were tested in a pilot area (190.4 km^2) on Hungary, where a digitized legacy soil map was available. The upper half of the legacy map was retained as training image in order to retrieve multiple-point statistics for SNESIM, whereas the lower half was used as study area and it was virtually sampled by spatial coverage sampling with various sample sizes for SAS mapping. Our study illustrated that **both techniques can capture and assess the highly structured SAS pattern**. Although the validation showed that IK slightly outperformed SNESIM, the MPS approach can provide a new perspective on the use of legacy soil maps in digital soil mapping. It was also found that the predictive performance of both techniques cannot be arbitrarily improved by solely increasing the number of sampling points, which needs further investigation.

Publication under review:

Gábor Szatmári and **László Pásztor** 2023. Geostatistical assessment of the highly structured spatial pattern of salt-affected soils, Arid Land Research and Managemenet, IF= 1.955, Q2 (under revision for second round of review)

I/4. Field testing of proximal soil sensing techniques (EM, ERT, gamma spectroscopy)

The purpose of geophysical measurements as **proximal soil sensing techniques** is to contribute to soil mapping, and **help the extension of the results of point-based surveys to 2 or even 3 dimensions**. Furthermore to detect important pedologic and agricultural properties (as groundwater depth, textural differentiation of soil) that influence the salinization process.

In Dunavecse pilot area, multi-electrode resistivity measurement, ground penetrating radar and seismic measurements (with P and S waves) was completed by Geomega Ltd.

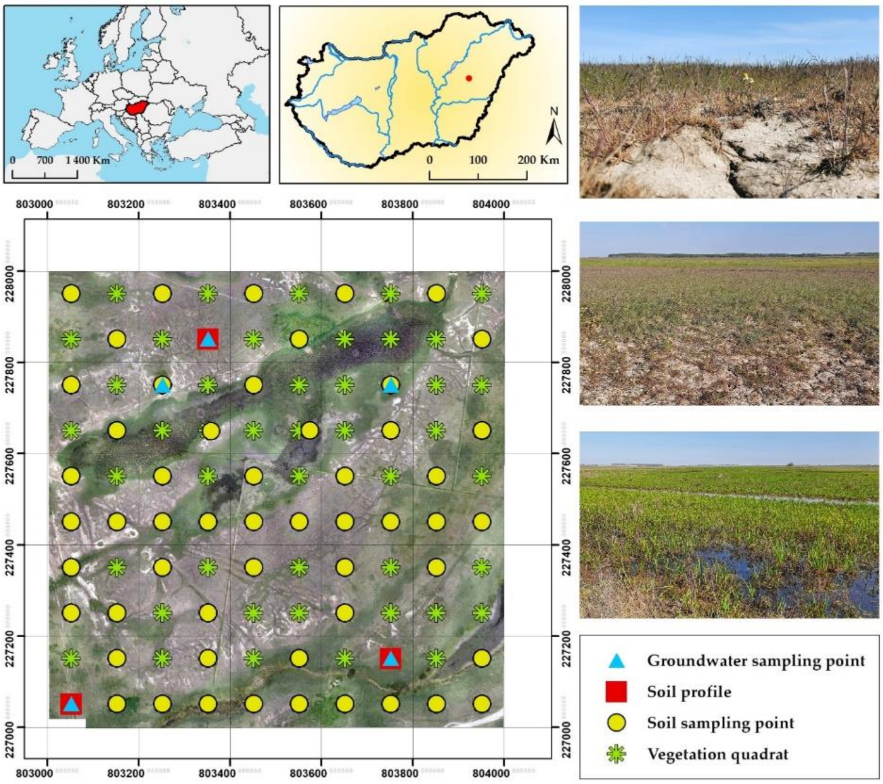

Figure 3. Location of the sampling site and type of the collected samples

With **specific resistance measurement** we were able to **separate sandy and clayey areas** of the pilot area. Measured specific resistance values less than 20 ohm-m are caused by clayey sediments, while greater than 40 ohm-m are caused by the higher resistivity of sand. The values determined by geophysical measurements correlate well with the conductivity measured in soil tests and therefore represent an **excellent opportunity for extending point measurements in digital mapping**.

Ground-penetrating radar measurements were not suitable for detecting the ground water table. Compared to our other measurements, clayey areas can be indirectly distinguished from sand bodies: in the former, the radar waves show only 1 m penetration, whereas in sandy sediments penetration reaches up to 3 m depth.

The **depth of groundwater level could be detected with seismic measurements**, as **P-wave velocity** suddenly increased from 250 to ~1500 m/s as reaching groundwater level.

In Hortobágy pilot area, a protected semi-arid salt meadow and steppe with 100 ha area– being the part of Hortobágy National Park - was surveyed (Molnár et al., 2008) (*Figure 3*) with the same geophysical measurements (Geoelectro Ltd) as in Dunavecse.

The area is characterized by deep saline, sodic soils, which forms a mosaic structure with diverse saline soil complexes. Largest area is dominated by meadow solonetz soils with a clay loam mechanical composition utilized as saline pasture. Smaller areas are covered with deep meadow solonetz soil and solonetz meadow soils as well (Dövényi, 2010). Groundwater level is between 2 and 4 m, chemically rich in sodium, which has contributed to the salinization of the soil in the sample area. Salt- and drought-tolerant plant communities live on this salt affected soils, forming extremely diverse flora of the landscape. Summarising the sedimentological, pedological, and water-holding conditions of the sample area, it can be stated that **this area presents a very diverse, mosaic picture, where the vegetation zones on saline soils reflect the spatial variation of soil salinity and moisture in correlation with the surface elevation.** The purpose of the performed **geophysical measurements** is to provide an aid to **soil mapping for the economic survey of large areas**. In situ measurements included electromagnetic conductivity measurement (EM) and ERT four-electrode geoelectric resistance measurement (ERT) of soils. These non-destructive methods can be applied on soil surface of protected nature saline areas. In total, 16997 soil apparent **electrical conductivity data** were derived from the 1 km^2 study area, which is an **important parameter for** describing the spatial variability of physical and chemical attributes of the soil and **outlines the spatial variability of the salt accumulation zones** (Figure 4.), which **shows a correlation with salt-tolerant vegetation pattern** (Figure 5.).

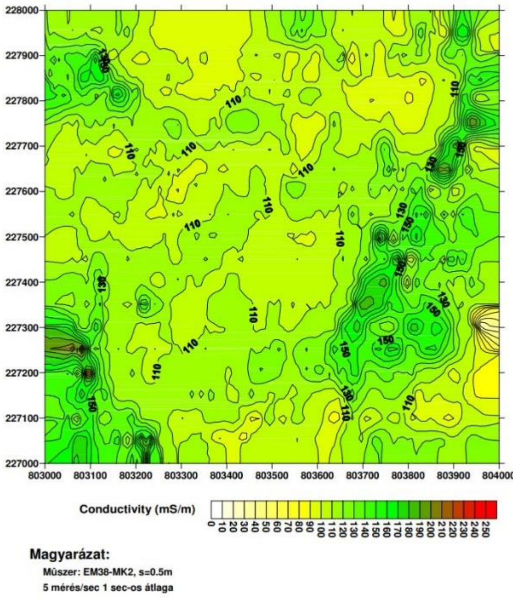

Figure 4. Soil apparent electrical conductivity map – Hortobágy (penetration depth 0,5 m) measured by László Vincze, 2022. 05. 31.

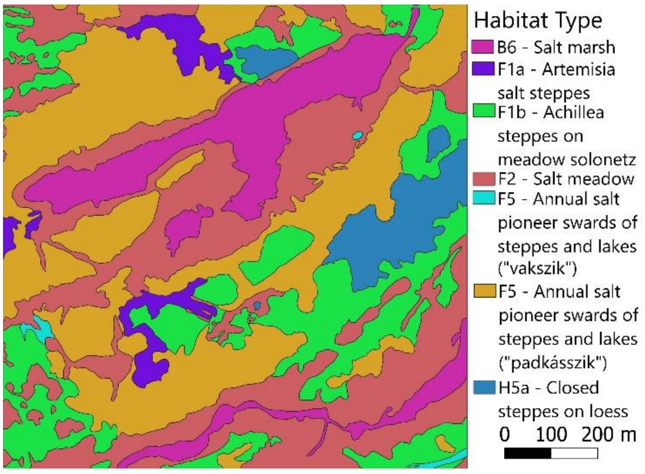

Figure 5. Habitat type map according to the nomenclature of the General National Habitat Classification System (Bölöni, Molnár and Kun, 2011)

Soil properties are important for the occurrence of vegetation categories. **Soil properties classify vegetation categories** nearly as well as plant covers (Tóth, 2002). Thus, **soil property estimation based on vegetation categories** is the subject of our forming study. The **highest values of electrical**

conductivity are associated with the Annual salt pioneer swards of steppes and lakes and Artemisia salt steppes (*Figure 6.B*). While **the maximum of soil moisture value is associated with the salt marsh, followed by salt meadow and Annual salt pioneer swards of steppes and lakes**.

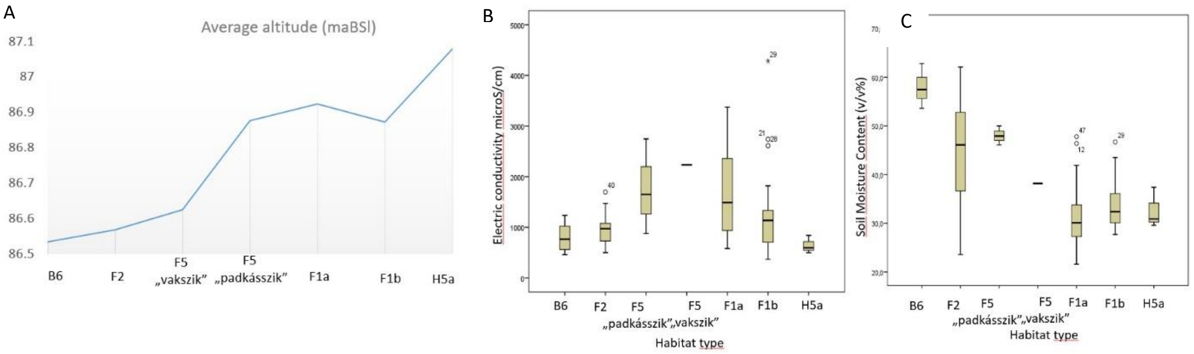

Figure 6. A, Distribution of habitat types by surface elevation, Legend: B6: salt marsh, F2: salt meadow, F5: Annual salt pioneer swards of steppes and lakes („vakszik”, „padkásszik”), F1a: Artemisia salt steppes, F1b: Achillea steppes on meadow solonetz, H5a: Closed steppes on loess., B, distribution of habitat types according to Electric conductivity, C, distribution of habitat type according to Soil Moisture Content

Accordig to Tóth (2002), the **vegetation categories** - due to the extreme values of all plant cover **- can be separated with** the help of data derived from reflectance measurements, comparable to the scale of the **satellite image**. Furthermore, a significant difference can be seen between each category of soil chemistry. In areas with natural vegetation, it is recommended to carry out a salinity assessment using space imagery in early spring season, if vegetation types and soil hydrology are reflected in the image as in case of this pilot area.

Geoelectric resistivity (ERT) measurements were performed at and between the sampling points in a 50x50 m raster. Due to accessibility problems in the waterlogged parts of the study site, and the difficulty of electrode insertion through impenetrable hard near-surface layers on other parts of the site, measurements were performed only at 128 points of the pilot area, thus in the central parts of the map, the estimation is subjected to large errors (*Figure 7*). In natural saline areas, the feasibility of geophysical measurements is highly questionable due to appearance of technical and practical problems.

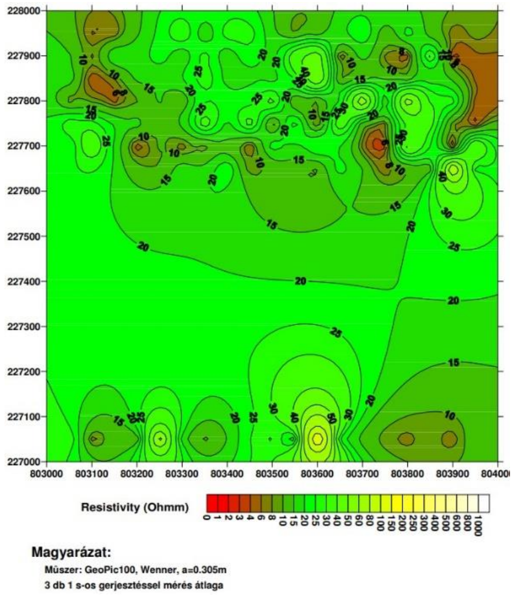

Figure 7. Geoelectrical resistivity map – Hortobágy (penetration depth 0,3 m) Measured by László Vincze, 2022. 05. 31.

Publications:

Matula Ramóna, **Tóth Tibor** 2019. Talajok agyagtartalmának becslése gamma-spektroszkópiai mérésekkel, Agrokémia és Talajtan 68, 2. p. 367-383 DOI: 10.1556/0088.2019.00034

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Tóth, Tamás ; Hámori, Zoltán ; Hermann, Tamás ; Kovács, Gábor ; **Kovács, Zsófia Adrienn** ; **Pásztor, László** ; Sisák, István ; **Tóth, Tibor** ; Wórum, Géza 2022. Modern geofizikai módszerek alkalmazási lehetőségei a talajtani vizsgálatokban (előadás), Talajtani Vándorgyűlés, Szegedi Tudományegyetem–Mezőgazdasági Kar, Hódmezővásárhely, 2022. szeptember 1-3.

László Pásztor, Katalin Takács, János Mészáros, Gábor Szatmári , **Mátyás Árvai, Tibor Tóth**, Gyöngyi Barna, Péter László, **Kovács Zsófia Adrienn**, Sándor Koós, **Kitti Balog** 2023. Spatial prediction of salt affected soil indicators for habitat types of a natural saline grassland using near surface remotely sensed data, Land, "Salinity Monitoring and Modelling at Different Scales" Special Issue, forming manuscript, abstract is accepted

I/5. Using XRF-measured rubidium concentration as best predictor for estimating the soil clay content and salinity of semi-humid soils in two catenas

When salts are present in considerable but not too large amounts, differentiating between soil clay content and salinity with electric/electromagnetic methods is not possible (Sudduth et al., 2005). In this case, the 0.3-0.4 dSm^{-1} bulk soil electrical conductivity (ECa) values (*Figure 8*) could be the result of the clay content being larger than 30 percent, or because of the low level of salinity. Such thresholds depend on all other affecting factors, such as soil moisture content, cation exchange capacity, texture, etc. (Rhoades et al., 1976; Friedman, 2005). Our objective was **to find a quick field method capable of predicting the soil salinity and soil clay content independent of instantaneous moisture content**.

The **two** studied, 70-70 m long transects (Sand dune-Valley transect at Kiskunlacháza, Sodic transect at Apaj) (**catenas**) were previously **analysed for salinity and clay content** and are routinely used as **test sites of electric and electromagnetic instrumental measurements** (Ristolainen et al., 2009). As *Figure 8* shows, an increase in soil clay content is indicated by larger ECa values in both transects. **After a threshold value — ca 0.3 dS m^{-1} in this particular case — no longer the increase in the clay content, but the presence of soluble and adsorbed salt ions will result in very large conductivity values.**

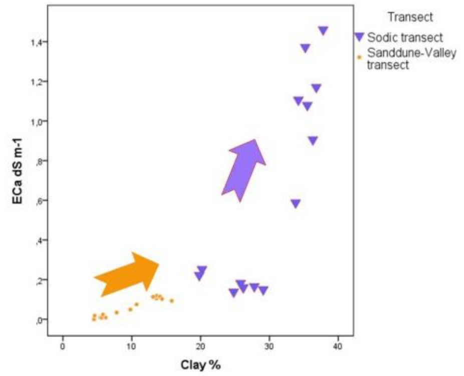

Figure 8. Relationship between field-measured bulk soil electrical conductivity and soil clay content in the two studied transects. Arrows show the topographic descent direction of the respective transects.

We checked the **relationship between gamma dosimetry and XRF** since potassium-40 is the most common radioactive isotope in typical soils; therefore, the major source of natural background soil gamma radiation. The theoretical relationship **was proven by the case of the Sanddune-Valley transect because the Pearson correlation coefficient between dose rate and potassium concentration was 0.893** (** denotes p<0.01), while in the case of Sodic transect it was 0.647**.**

The three-minute-gamma-dose-rate was a good indicator of the laboratory-measured clay content inside the Sanddune-Valley transect (Pearson correlation coefficient 0.889**). However, the opposite was obtained in the Sodic transect, where the same Pearson correlation coefficient was -0.769**. This relationship is caused by the differences in mineral composition and the antagonism of sodium and potassium in sodic soils.

The XRF-measured rubidium concentration, was the overall best predictor variable in both transects of the bulk soil electrical conductivity and 0-20 cm soil clay content. The Pearson correlation coefficient between Rb and soil clay content was 0.974 in the Sanddune-Valley transect and -0.895** in Sodic transect** (*Figure 9.*). **The same coefficient between Rb and ECa was 0.926** in the Sanddune-Valley transect, and a correlation coefficient with similar statistical significance, but with an opposite sign of -0.925** was calculated in the Sodic transect.**

XRF works through the excitation of the atoms and hence overperformed the short-time passive gamma dosimetry. Longer periods of measurement or larger detector volume (Triantafilis et al., 2013) could provide better results with the gamma dosimetry. The Rb concentration can be a good predictor since it is less affected by plant uptake and agronomic practice compared to K (e.g., when the latter is applied as a fertilizer).

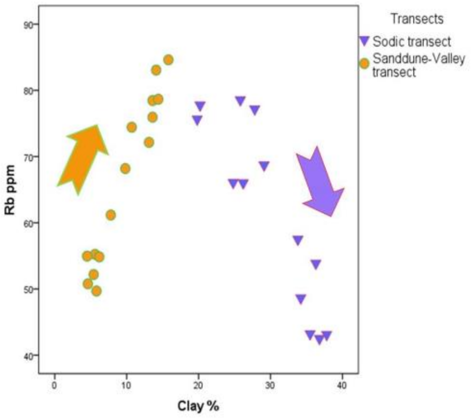

Figure 9. Scattergram of soil clay content and XRF-measured rubidium concentration in two surface transects. Arrows show the topographic descent direction of the respective transects.

Publication:

Tóth, T, Zs A Kovács, M Rékási. 2019. XRF-measured rubidium concentration is the best predictor variable for estimating the soil clay content and salinity of semi-humid soils in two catenas.Geoderma. 342 (2019) 106–108.)

I/6. Multiregional correlations between XRF and gamma spectroscopic data measured on soil profile wall and important parameters in the Pannonian Plain

Since the studied soils and tools used in different papers are different, the equations set up thus far have limited validity; that is, the predictive relationships change from place to place and by distinct sets of instruments (Hartemink and Minasny, 2014). There is a need to have relationships that cover a wide range of parameters and soil depths. The investigation focused on **several types of soil**, ranging from soil formed on clay deposit in deep-lying areas and soils formed on loessic materials in intermediate elevations to high lying soils formed on acidic sand, thereby representing most soil types on the Pannonian Plain. Therefore, the study covered alluvial and aeolian landscapes, and all soils were formed on variants of Quaternary clay/loess/sand, which are affected by the shallow water table to varying degrees. Three saline/sodic profiles formed under the influence of saline water table were studied, but another one also showed salinity in a deeper layer. The range of every parameter (see *Figure 10*) was wide in both the surface and depth layers.

The objective of the study was to **set up equations to predict important parameters in a full region covering several different soil types and representing a wide range of soil parameters.**

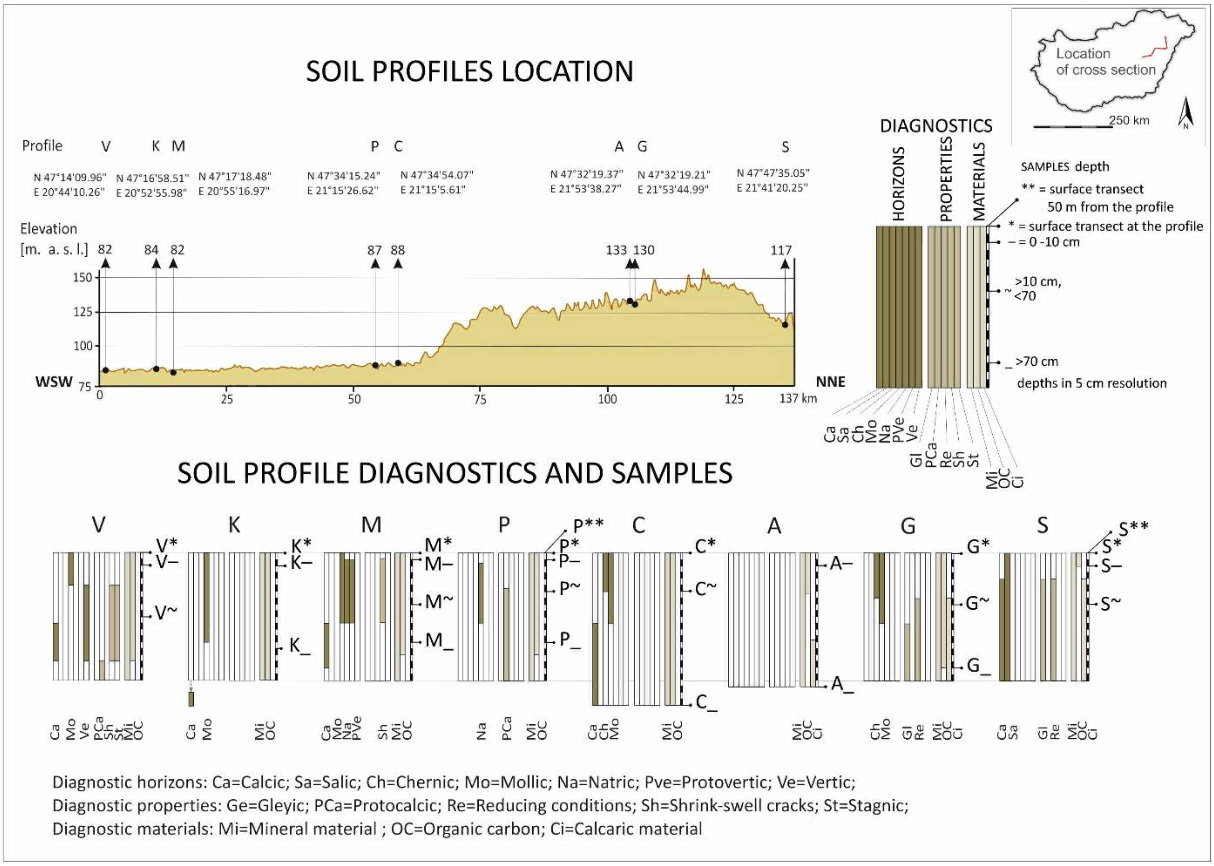

Figure 10. The location of profiles inside Hungary, and the WRB diagnostic features of the profiles along the studied transect

The selected soil profiles (*Figure 11.*) represented the soil types and ranges of important parameters of the Pannonian Plain. Except for the lowest-lying Vertisol, formed on acidic clay, and the highest lying Arenosol, formed on acidic sand, most soils had somewhat reworked calcareous loess as soil-forming material under the Gleysol, Chernozem, Kastanozem, Solonetz and Solonchak profiles. This homogeneous, genetically linked (Thamó-Bozsó et al., 2014) soil-forming material, together with the similarity of the climate, resulted in similar soil formation in the topsoil. Differences in the deeper layers of the soil profiles were the result of the fluctuation depth and salinity of the water table.

LABEL IN SCATTERGRAMS

V	K	M	P	C	A	G	S
Endocalcic – Pellic	Endocalcic	Mollic – Endocalcic – Protovertic	Protocalcic – Gleyic	Endocalcic	Lamellic – Endocalcaric	Chernic – Oxigleyic – Calcaric	Katogleyic – Sodic – Katocalcic
VERTISOL	**KASTANOZEM**	**SOLONETZ**	**SOLONETZ**	**CHERNOZEM**	**ARENOSOL**	**GLEYSOL**	**SOLONCHAK**
(Aric, Mollic, Humic, Amphistagnic)	(Aric, Pantoclayic, Pachic)	(Epiloamic, Amphiclayic, Humic, Hypernatric)	(Episiltic, Katoloamic, Ochric, Hypernatric)	(Pantoloamic, Pachic)	(Ochric, Nechic)	(Episiltic, Endoarenic)	(Alcalic, Epiarenic, Ochric, Endosiltic)

Figure 11. Photos of V, K, M, P, C, A, G, and S profiles from left to right.

Based on the Adjusted R^2, accurate multiple linear regression equations were set up for particle fractions (clay [1], silt [2] and sand [3]) that had a high degree of accuracy for $CaCO_3$ content and salinity (EC).

[1] $Clay\_pct = 24.886+0.119*Ba\_S-1846/LE$; *Adjusted* R^2*=0,935*

[2] $Silt\_pct = 0.00168*Tot\_3*Tot\_3-189.539/Pb\_S+12.602/K\_G-0.15506/K\_3-85.533$; *Adjusted* R^2*=0,934*

[3] $Sand\_pct=48.147-23.158*\ln(Ba\_S)+99630.589/Ca\_S-23.394/K\_G-25.265*\ln(K\_3)+579.095/Rb\_S-14.833/Ca\_G+0.2165/Nb\_G+0.00808*Pb\_S*Pb\_S$; *Adjusted* R^2*=0,996*

where LE: concentration of Light Elements = Mg+Al+Si+P+S , Tot: total count rate over 3 minutes, Ba_S, , Ca_S, Pb_S, Rb_S, K_G, Ca_G, Nb_G: element concentrations, where S means the XRF measurement with Soil mode, G means the XRT measurement with geochemistry mode, K_3 : ^{40}K concentration measured with gamma spectroscopy over 3 minutes

Utilizable equations were obtained to predict the organic carbon content (SOC) [4] and pH value [5] of the soil.

[4] $SOC\_pct = 7.458E-5*Mn\_S*Pb\_S+6.109-4*LE*LE-70.461*Sr\_G+3.334/U\_3 -14.155/Pb\_S-1.035$; *Adjusted* R^2*=0,803*

[5] $pH\_2.5 = 16.92+2.181*\ln(Sr\_G)+189.5/Mn\_S+2252*K3m*K3m-0.100*Rb\_S+822.6*Rb\_G$; *Adjusted* R^2*=0,755*

where LE: concentration of Light Elements = Mg+Al+Si+P+S, pH_2.5: pH determined in 1:2.5 soil:distilled water suspension, Mn_S, Pb_S, Rb_S, element concentrations, where S means the XRF measurement with Soil mode, Sr_G, Rb_G, G means the XRT measurement with geochemistry mode, U_3: ^{238}U concentration measured with gamma spectroscopy over 3 minutes, K3m: ^{40}K concentration measured with gamma spectroscopy over 3 minutes

Na concentration and Na ratio were not predicted accurately with the equations; however, these are easily predicted with salinity and pH values, and there is a wide variety of other field devices, such as EC/pH/Na sensors for this purpose.

The two applied instruments (xRf, gamma spectroscope) are well fitted for the prediction of the important parameters of these soil profiles. Accuracy of predicting equations and the values of the regression coefficients depend on the particular instruments; therefore, the equations are not directly utilizable in other settings. Based on the reported correlations of the predicting elements, the most promising elements for new equations can be easily selected. In very different climatic, geologic and hydrologic conditions, the equations could be very different. Nevertheless, it was promising to see the overlap in the predicting equations of organic carbon and pH with those of O'Rourke et al. (2016), which were developed from the Australian database.

Publication under preparation:

Tóth Tibor, Molnár Sándor, Rékási Márk, Novák Tibor, **Balog Kitti**, Makó András: Multiregional correlations between XRF and gamma spectroscopic data measured on soil profile wall and important parameters in the Pannonian Plain

II, Comparsion and evaluation of three different Soil Classification Systems for the purpose of selecting the optimal classification in terms of their practical applicability and correlations with elevation and biomass production in a salt-affected alluvial plot

The other part of the project, which has an outstanding achievement in terms of publications, was the comparison of **three soil classification systems: the Soil Classification System of Hungary (HU), the World Reference Base for Soil Resources (WRB, 2015) and the USDA Soil Taxonomy (USDA ST).**

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). Soil classes carry useful soil information. The WRB and USDA ST systems use **diagnostic soil horizons** for identifying characteristics describing salinity and sodicity, which determines presence and depth occurrence of the horizon. There is overlap between the criteria of these diagnostic levels in the two systems, while the Hungarian system is based on **genetic** instead of diagnostic **horizons**, using processes as identification. The investigated horizons were **solonetz B and solonchak near surface horizon** (Jassó, 1989) according to HU, **natric and salic horizons** according to WRB (IUSS, 2015) and natric and salic horizons according to Soil Taxonomy [ST] (Soil Survey Staff, 2014). The comparison of the systems was made at all **four hierarchical levels of classification systems** in terms of four **practical criteria: class separability (Cs), parsimony (PoC) and homogeneity of classes (HoC)**, **correlation to biomass (NDVI).** We investigated, **which one, and in which level has the strongest correlation with elevation and vegetation index** (10 years average Normalized Difference Vegetation Index, NDVI) **characterizing biomass production**, and thus which one is most suitable for productivity estimation on slightly saline agricultural plots. **Class separability** shows the 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. **Parsimony of classes** describes that 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. **Homogeneity of classes** expresses the range of a property within the classes. The uniformity of soil properties within mapping units is quantified by 1-RV (Beckett and Burrough, 1971, Webster, 1971). Homogenity of classes 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.

Our study plot was a previously salt affected arable land with the area of 0,85 km^2, located in the outskirt of the village of Dunavecse in a 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. The groundwater is saline with shallow level. Survey was carried out in a 100 m regular grid with 85 soil profiles to be able to estimate biomass (using 10-year average NDVI as proxy) and investigate the correlation with elevation. Meadow Chernozem, Calcareous Chernozem, Solonetz-like deeper horizon Meadow Chernozem soils were identified according to HU, Chernozem, Kastanozem, Phaeozem, Calcisol, Gleysol, Cambisol, Regosol Reference Soil Groups according to WRB and Mollisols/Ustolls, Haplustolls, Calciustolls according to USDA ST. Inside the studied plot, further specification of soils was also carried out and all four levels of the classification systems were compared in terms of Cs, PoC and HoC. Furthermore **correlation to biomass** was also tested by establishing the correlation between elevation and mean class NDVI values.

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 (at third level) and ST4 > HU4 > WRB4 (at fourth level) with only slight differences. 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, the non-weighted CV%s and the weighted CV%s. 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**. 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.

Considering the correlation between the elevation and biomass in this salt-affected alluvial plot, increased biomass was associated with increasing elevation and decreasing salt concentration. Elevation controls most soil properties on the sample plot also. By comparing three delineated elevation zones, 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.** The combined influence of elevation and salinity to a depth of 100 cm, together with the agronomic salinity categories (Richards, 1954), are shown in *Figure 12.* 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.

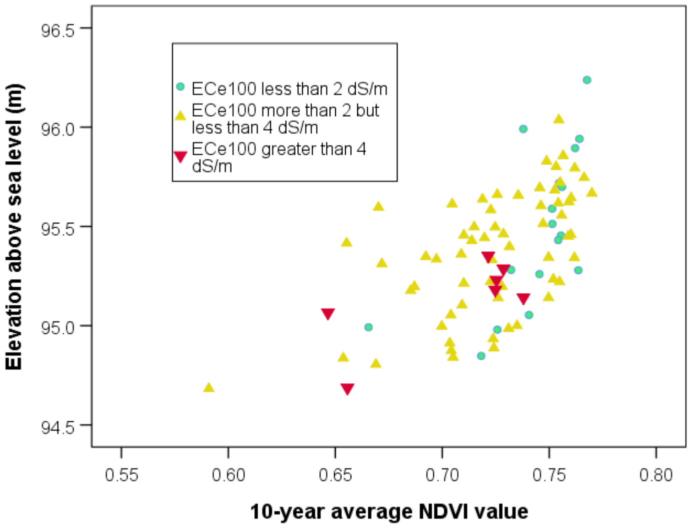

Figure. 12 Correlation between elevation and 10-year average NDVI values for the various salinity categories of 100 cm deep profile

Mean NDVI values of the profiles, when categorized into three classes, were significantly different statistically, markedly demonstrating the effect of elevation (*Figure 12*). 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. NDVIs and elevations of the investigated Chernozem and Meadow soils (according to WRB, 2015) significantly differed. However, neither of them was statistically separable from the alluvial soils.

Comparing the Soil Classification Systems, it can be stated that **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.** WRB surpassed HU in terms of the very important HoC only, but HU performed better in terms of Cs, correlation to biomass and PoC. With many possible classification units WRB categorized the soil into a large number of classes, but 67 % and 78 % of them were single-profile classes at levels 3 and 4, respectively. In case of **the third levels HU** (r = 0.821**) and WRB (r = 0.574**) **were found more suitable for productivity estimation** than ST. The same was found for fourth level, where HU performed the best (r = 0.707**) before WRB (r = 0.562**) and ST. **NDVI values reflecting soil formation chronology were found on the first 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 Cs, 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.

These research results will be tested further on the applicability in the creation of maps for precision agriculture. (Article under preparation: Tibor Tóth, András Makó, Mihály Kocsis, Kitti Balog et al…Soil polygons at four classification levels of Soil Taxonomy, Hungarian classification and WRB in a salt-affected alluvial plot)

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Tóth, Tibor; Gallai, Bence; Novák, Tibor; Czigány, Szabolcs; Makó, András; Kocsis, Mihály; **Árvai, Mátyás**; Mészáros, János; László, Péter; Koós, Sándor, **Balog, Kitti**. 2022. Practical evaluation of four classification levels of Soil Taxonomy, Hungarian classification and WRB in terms of biomass production in a salt-affected alluvial plot, GEODERMA 410 Paper: 115666 , 11 p. (2022), IF: 6,114, Q1

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