LANDUSE AFFECTED ORGANIC CARBON SATURATION OF THE PEDOSPHERE
(2017-2022)

Final report

The main research question: The pedosphere is one of the most important carbon reservoirs of the Earth, which significantly exceeds the total quantity of the carbon stocks of the atmosphere and the biosphere. Over the past century, human impacts (land use changes) have significantly reduced the amount of organically bound carbon in the pedosphere. The carbon sequestration potential of the pedosphere is fundamentally dependent on the particle size distribution of the minerals, which is the texture of the soils. The maximum (theoretical) carbon sequestration capacity determined by the particle size distribution is unused nowadays, therefore with the increase in the amount of the soil organic carbon, the decrease in the atmospheric CO_2 concentration (and its rate of growth) can be achieved, moreover, the fertility, water management, and stability against the erosion of the soils can be improved radically. This research seeks to answer the question of how it is possible to increase the amount of sequestered carbon in the uppermost, potentially tilled soil layers by changing land use structure.

The report provides the results as it was given as objectives of the research plan. The detailed results are available in the cited references.

1. What is the theoretical (max.) amount of soil carbon storage of various textural type soil layers on the surface?

1.1 Concept for determining and mapping SOC saturation

The approach we used in this study is based on the principle that topsoils under permanent forest land cover due to the unlimited plant residuum input can be practically considered as saturated in SOC. About 30% of the territory of Hungary is covered by forest on a wide range of soil types, including Luvisols, Podzols, Arenosols, Cambisols, and even Chernozems, among others. Theoretically, some permanent grassland sites may be saturated as well, their involvement, however, is neglected owing to the less reliable land-use history or the role of occasional hydric conditions that might happen on these lowland sites or the effect of grazing.
The quasi SOC saturated forest topsoils have high SOC concentration variance, and thus they are not suitable for a general reference group. Besides, various landscape positions or changes in topographical properties must also affect the way and threshold of SOC saturation for the local scale. Accordingly, only topsoils with similar physicochemical properties (e.g., texture, pH) and environmental conditions (e.g., topography, climate) are comparable directly in terms of SOC saturation. Our concept, therefore, focuses on the measured soil properties and environmental conditions and aims to find a relationship between them (i.e., fit a pedotransfer function (PTF)), which can be used to predict saturated SOC content at unvisited sites. Using the developed PTF, the theoretical (potential) SOC saturation value will be predicted across Hungary. Comparing the saturated SOC content with the actual SOC content, the saturation deficit can be determined and assessed (Szatmári et al. 2023).
We used the soil profiles of the Hungarian Soil Information and Monitoring System (SIMS), which is a country-wide soil monitoring system providing geographically referenced biological, physical and chemical information on the status and temporal change of Hungarian soils. Soil profiles placed in forests (183 profiles) have been specifically designed for providing spatio-temporal information on soils in the context of forest ecosystems and therefore they are appropriate for the objective of this study. According to the concept of determining SOC saturation, we could assume that the topsoils represented by these profiles are practically saturated in SOC and therefore they can be used as reference soil profiles for developing an empirical, data-driven predictive model between SOC saturation and further soil properties and environmental covariates (Szatmári et al. 2023).

1.2 Theoretical country-wide SOC saturation values

Table 1 summarizes the descriptive statistics of the harmonized data on saturated SOC content and further soil properties used as predictors in this study. The development of the cubist-based PTF was complemented with 5-times repeated 10-fold cross-validation. According to the results of cross-validation, an R-squared value of 0.56 was obtained, i.e., the developed PTF explained almost 60% of the total variation of the saturated SOC data. Table 3 presents the model structure of the PTF, which not just summarizes the conditions and the specific multivariate linear regression models fitted to the different subsets of saturated SOC content data partitioned in model fitting but also shows the hierarchy via the number of rules (Table 2, first column). Figure 1 presents the spatially exhaustive soil and environmental covariates, which were found to be significant in predicting the saturated SOC content in Hungary based on the fitted cubist-based PTF (Table 2).

Table 1. *Summary statistics of saturated soil organic carbon content (SOC_{sat}) and further soil properties harmonized for the topsoil (0–30 cm) at the reference soil profiles (n=183). Abbreviation: SD: standard deviation.*

Soil properties	Unit	Minimum	Maximum	Mean	Median	SD
SOC_{sat}	[%]	0.16	6.87	2.17	1.72	1.41
pH	[-]	3.73	8.09	5.72	5.35	1.18
Calcium carbonate	[%]	0.00	20.96	4.83	4.05	3.83
Sand	[%]	2	99	49	44	29
Silt	[%]	0	80	35	35	21
Clay	[%]	0	56	17	16	12

Table 2. *The model structure of the cubist-based pedotransfer function used for predicting the saturated soil organic carbon (SOC_{sat}) content in the topsoil (0–30 cm).*

Rules	Conditions	Specific multivariate linear regression models
1	IF *Sand* > 61.69	THEN SOC_{sat} = 0.58804 + 0.113 *Clay* – 0.0008 *Sand* – 0.02 *Temperature* + + 0.01 *pH*
2	IF *pH* ≤ 6.24 ***and*** *Sand* ≤ 61.69 ***and*** *Slope* ≤ 13.96	THEN SOC_{sat} = 7.6349 – 0.0087 *Evaporation* + 0.022 *LS factor* + + 0.0004 *Altitude* – 0.0013 *Sand* – 0.03 *Temperature* + 0.02 *pH*
3	IF *pH* > 6.24 ***and*** *Sand* ≤ 61.69	THEN SOC_{sat} = 31.6689 – 0.0217 *Evapotranspiration* – 0.8 *pH* – 0.139 *Slope*
4	IF *pH* ≤ 6.24 ***and*** *Sand* ≤ 61.69 ***and*** *Slope* > 13.96	THEN SOC_{sat} = 0.7695 + 0.0966 *Sand* + 0.27 *Topographic position index*

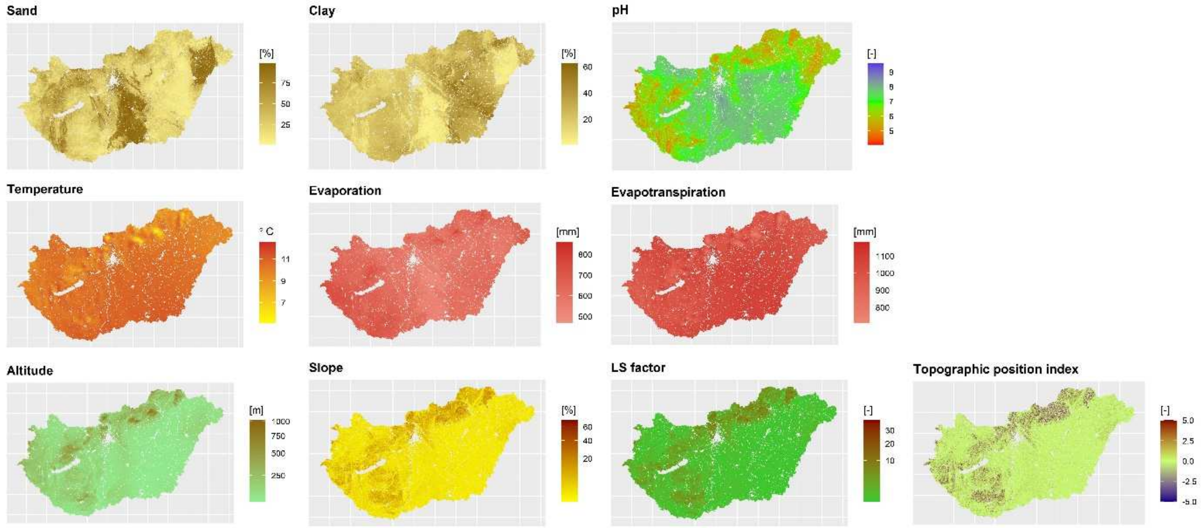

Figure 1: *Spatially exhaustive soil (first row) and environmental covariates (second row: climatic variables, and third row: geomorphological variables) found to be informative for predicting saturated soil organic carbon content in Hungary. Annotation: Settlements and open water bodies were left blank.*

Figure 2 (left map) presents spatial information on which of the rules and the associated multivariate linear regression model is appropriate for predicting the saturated SOC content in a particular area in Hungary. We should note that the rules identified notable geographical regions:

(i) Rule 1 covers the sandy areas of Hungary with low SOC content,
(ii) Rule 2 refers to the hilly and mountainous regions of Hungary with acidic soils,
(iii) Rule 3 relates to non-sandy lowlands with neutral or alkali soils,
(iv) Rule 4 is for the most elevated areas of Hungary with mostly acidic soils.

Increasing rule numbers predict an increasing SOC saturation value along the rules (Table 2). Rule 1 covers the sandy areas of Hungary (Figure 2), which have the lowest SOC storage capacity due to the lack of fine fraction. The clay content and the pH are directly connected, whereas the sand content and the mean annual temperature are inverse relationships with the predicted SOC saturation value. Rule 2 relates the acidic areas with lower sand content and slope steepness <14% (Figure 2). In this group, higher clay content, altitude, pH, slope angle, and length indicate higher predicted SOC saturation, while the higher evaporation, sand content and mean annual temperature triggers lower SOC saturation values. Rule 3 predicts the SOC saturation values for non-sandy sites with neutral or alkali conditions (Figure 2). This is the only group where sand content is not a predictor variable. In contrast, evapotranspiration, pH, and slope steepness all decrease the SOC saturation values. Rule 4 covers the acidic sites with high slope steepness (Figure 2), where both sand content and topographic position index increase the saturated SOC content.

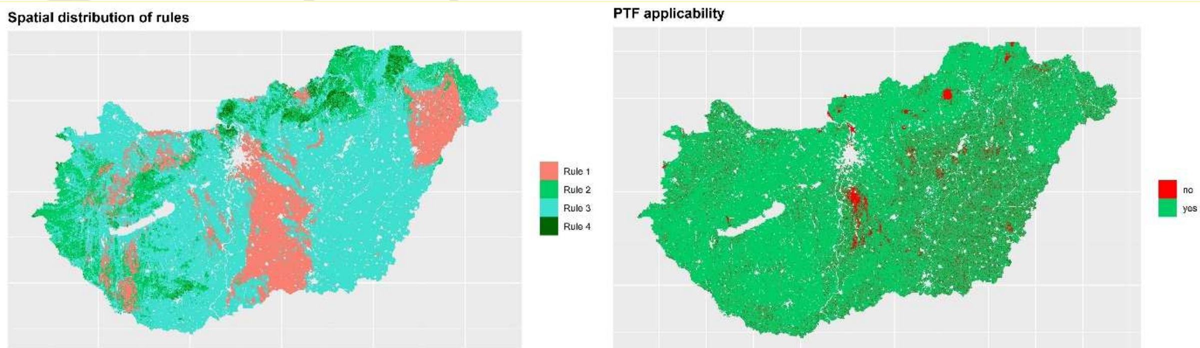

Figure 2: *Spatial distribution of the rules defined by the cubist-based pedotransfer function (left map) and the applicability of the pedotransfer function over Hungary (right map). Annotation: Conditions and multivariate*

linear regression models associated with the rules can be found in Table 3. Note that settlements and open water bodies were left blank.

The sand content was the most important predictor, which was included in three out of the four regression models. In two cases, it was inversely proportional with the SOC saturation value, even though in Rule 4, on the steepest parts sand content was proportional with SOC saturation (Table 2). This may result from the increased infiltration due to the coarser texture resulting in a lower amount of runoff and soil/carbon loss. The other general predictor is pH which regulates the predicted SOC saturation value in the Rules 1-3 (Table 2). It has a positive effect on sandy soils and under acidic and neutral conditions. In contrast, in the alkali range, pH has a very strong inverse relationship with SOC saturation. This may indicate the mitigated SOC saturation potential under sodic conditions even though in the current case, the prediction is uncertain for sodic soils. Regarding the climatic effects, both evaporation and evapotranspiration decrease SOC saturation on non-sandy and non-hilly fields. Mean annual temperature mitigates SOC saturation. Topography provided ambivalent results as slope steepness decreased SOC saturation values on the flat areas, but topographic position index and the LS factor were in direct linkage with the saturation. Taking the spatial resolution of the present study into account, the erosion and soil redistribution processes may result in a more detailed spatial pattern.

1.3 Applicability of the developed PTF

We should note that the fitted cubist-based PTF was elaborated on sampling points located in permanent forest in Hungary and therefore it is worth investigating whether there are areas where the applicability of the PTF is not recommended. As it was presented in Table 3, the fitted PTF is a set of specific multivariate linear regression models, each having a range within which the given regression model is reasonable to use for predicting the saturated SOC content. However, out of this range the applicability of the given regression model is definitely not recommended due to extrapolation. Therefore, we used the specific multivariate linear regression models (Table 2) to identify areas throughout the entire area of Hungary where extrapolation of the fitted PTF should be expected (Figure 2, right map). It was found that for 7922.7 km^2 the fitted cubist-based PTF cannot be used because of extrapolation. Considering the total area of Hungary (93,030 km^2) this means about 8%. Although the areas, where the application of the fitted PTF is not recommended, shows scattered pattern throughout the country, notable regions of Hungary can be identified. Almost 90% of the areas characterized by salt-affected soils (e.g., Danube-Tisza Interfluve, Hortobágy) are proved to be not suitable for the application of the fitted PTF, which can be attributed not just to their extreme sodicity, alkalinity or salinity but also to the fact that their formation is highly influenced by shallow groundwater, permanent or temporary waterlogging. Additionally, areas characterized by highly or moderately water-affected soils are also highlighted along the main rivers (e.g. Danube, Tisza, Dráva) and in the eastern part of the country, which is completely acceptable as the concept introduced above is referred to mineral soils and not to water-affected soils, where the balance between SOM accumulation and mineralization is strongly affected by surplus water. This also true for the peatlands, which can be easily identified on the map too (e.g. southestern part of Lake Balaton).

1.4 Spatial prediction of saturated SOC content with uncertainty propagation

Figure 3.A presents the spatial distribution of saturated SOC content over Hungary as a result of the application of the fitted cubist-based PTF (Table 3) on spatially exhaustive soil and environmental covariates (Figure 2). Next to this map we also presented its variance (Figure 3.B), as one of the main results of the uncertainty propagation analysis performed. This map can be interpreted as the uncertainty in the saturated SOC content spatial predictions. We found that higher uncertainty is associated with areas where extrapolation of the fitted PTF is expected (Figure 2, right map). We should also highlight that the final uncertainty associated with the saturated SOC content predictions takes into consideration not just the uncertainty associated with the fitted PTF but also the prediction uncertainty of the digital soil mapping products. The partitioning property allows to analyze how much each input contributes to the final uncertainty. Thus, we determined the contributions and relative contributions of the input soil

maps (Figure 3.C and E) and the cubist-based PTF (Figure 3.D and F) to the uncertainty in the saturated SOC content spatial predictions (Figure 3.B). As we had no information about the uncertainty of the environmental covariates (Figure 1, second and third row), we could not determine their contributions to the final uncertainty. However, their uncertainty contributes to the uncertainty in the fitted PTF (Figure 3.D and F). This is because the cubist-based PTF was elaborated on their uncertain data and not on measured ones as in the case of soil inputs, where we used actual measurements from SIMS. Hence, uncertainty in the environmental covariates (Figure 1, second and third row) is also represented in the PTF uncertainty. By comparing the relative contributions (Figure 3.E and F), it was found that the contribution of PTF uncertainty to the final uncertainty is much larger than the contribution of the soil maps uncertainty.

The sand content was the most important predictor, which was included in three out of the four regression models. In two cases, it was inversely proportional with the SOC saturation value, even though in Rule 4, on the steepest parts, sand content was proportional with SOC saturation (Table 2). This may result from the increased infiltration due to the coarser texture resulting in a lower amount of runoff and soil/carbon loss (Jakab et al., 2019a). The other general predictor is pH which regulates the predicted SOC saturation value in the Rules 1-3 (Table 2). It has a positive effect on sandy soils and under acidic and neutral conditions. In contrast, in the alkali range, pH has a very strong inverse relationship with SOC saturation. This may indicate the mitigated SOC saturation potential under sodic conditions even though, in the current case, the prediction is uncertain for sodic soils. Regarding the climatic effects, both evaporation and evapotranspiration decrease SOC saturation on non-sandy and non-hilly fields. Mean annual temperature mitigates SOC saturation. Topography provided ambivalent results as slope steepness decreased SOC saturation values on the flat areas, but the topographic position index and the LS factor were in direct linkage with the saturation. Taking the spatial resolution of the present study into account, the erosion and soil redistribution processes may result in a more detailed spatial pattern.

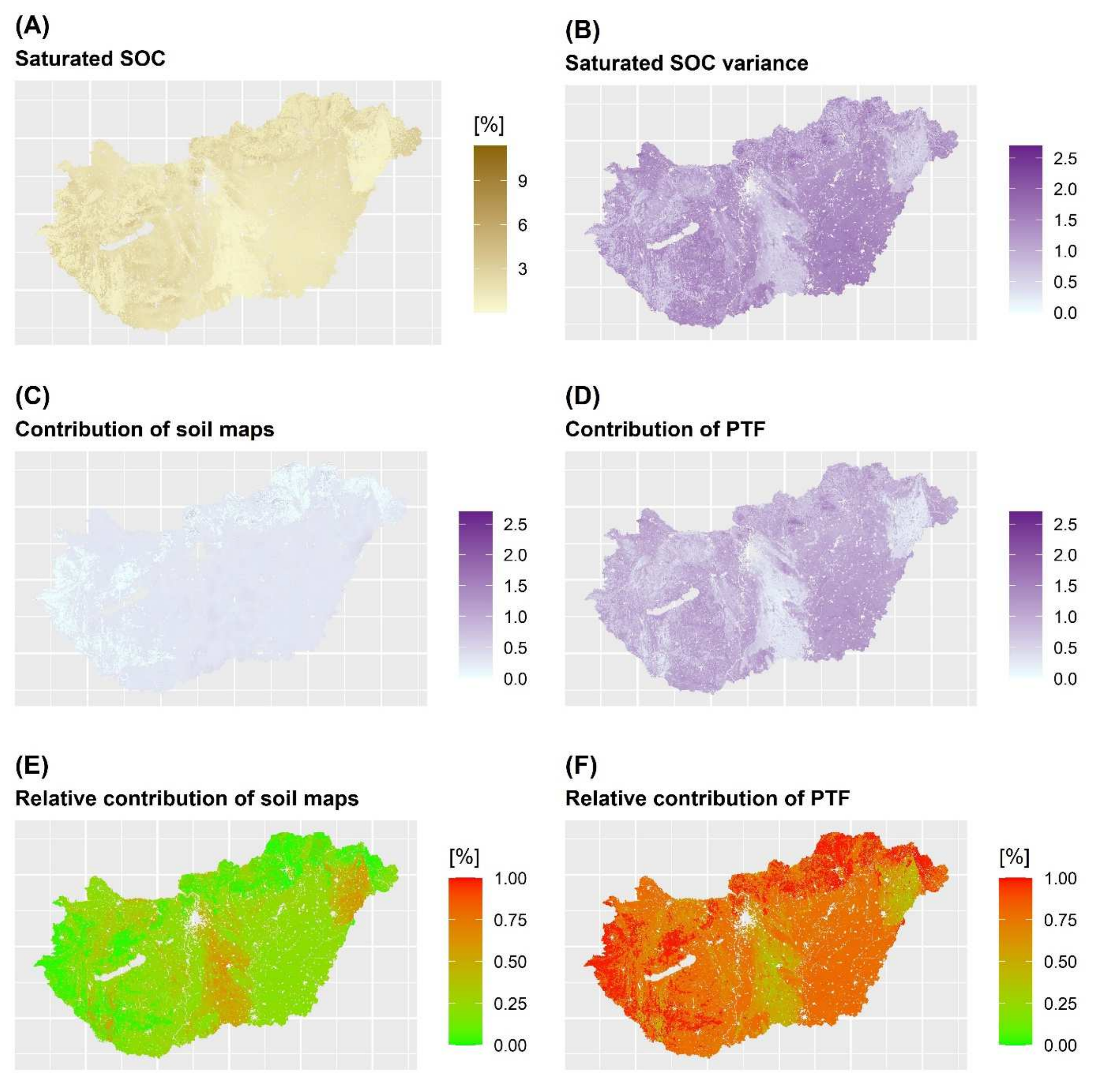

Figure 3: *Saturated soil organic carbon content for the topsoil (0-30 cm) (A) and its variance as a result of uncertainty propagation analysis (B). Contributions and relative contributions of the input soil maps (C and E) and the cubist-based pedotransfer function (D and F) to the uncertainty in saturated soil organic carbon content spatial predictions (B). Abbreviations: SOC: soil organic carbon, and PTF: pedotransfer function. Annotation: Settlements and open water bodies were left blank.*

2. What is the SOC saturation deficit in the uppermost 30 cm soil/sediment layers of the most typical soil profiles of Hungary?

We compared the saturated SOC content map with the actual SOC map of Hungary (Figure 4.A). In brief, the actual SOC map also refers to the topsoil (0–30 cm) and has been created by using a combination of geostatistics and advanced ML techniques. By subtracting the saturated SOC map from the actual SOC map, we compiled a difference map presenting the SOC deficit for the topsoil in Hungary (Figure 4.C). On the map, negative values (i.e., red colors) present areas with SOC deficit, whereas positive values (i.e., blue colors) show areas where soils are saturated or oversaturated in SOC. According to the compiled difference map, not just large parts of the country (ca. 80%) can be characterized by SOC deficit, but it also shows high spatial variability across Hungary. Note that the uncertainty in the spatial predictions of saturated SOC content (Figure 3.B) is an order of magnitude larger than the uncertainty in the spatial predictions of actual SOC (Figure 4.B). Because of this, the uncertainty in the SOC deficit map (Figure 4.C) must also be large, which does not allow to delimit areas with significant SOC deficit in the country.

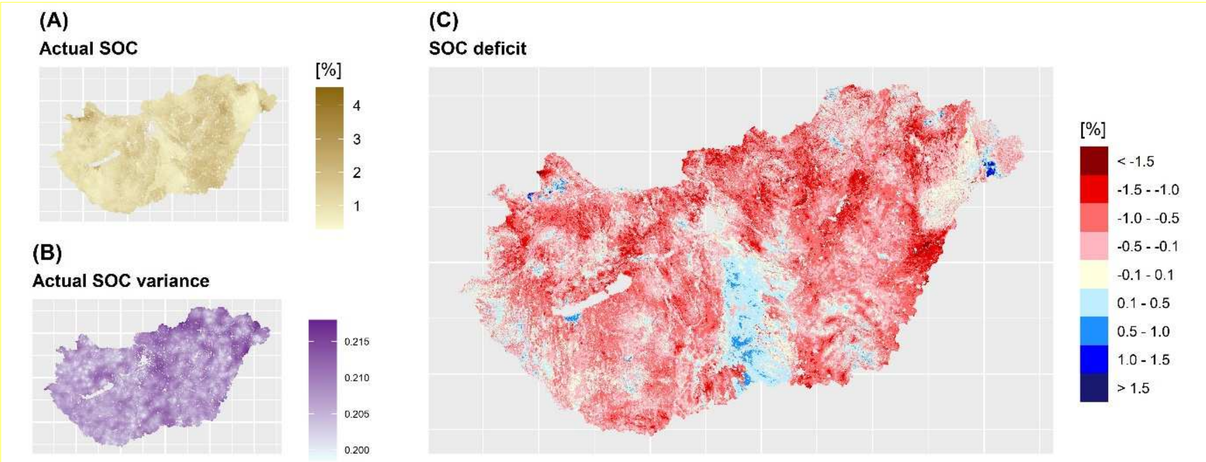

Figure 4: *Spatial distribution of the actual soil organic carbon (SOC) content (A) and the associated prediction uncertainty (B), and the map of SOC deficit (C). Annotation: Settlements and open water bodies were left blank.*

As a general trend in Hungarian topsoils, the highest SOC deficits (Figure 4.C) occur in areas with medium to high actual SOC content (Figure 4.A). Base saturated Chernozems and Kastanozems storing more than two percent of SOC have the capacity to sequester an additional one percent of SOC mainly on the plains of Hungary (Figure 4.C). In addition, the groundwater affected Phaeozems also have a high capacity to store additional SOC. The mountainous parts of the country as well as the acidic fields have lower capacity, however, it still means 0.1-0.5% additional SOC storage potential.
We should note that considerable parts of the country have been indicated as saturated or oversaturated (Figure 4). The highest values of oversaturation are mostly related to peatlands (e.g., southwestern part of Lake Balaton) and other water affected areas. As has already been mentioned in the introduction, on these sites, the temporal or former water coverage inhibited the mineralization of soil organic matter, which process cannot be captured by the fitted PTF since the approach used in this study based solely on forest sites. A further reason for (over-) saturation is related to the areas covered by Arenosols, especially in the Danube-Tisza Interfluve (Figure 4). These soils can be characterized by basically low SOC concentration, where low changes may trigger oversaturation. Under the above conditions, the role of particulate organic matter or fresh plant debris may cause increased variability in Arenosols resulting in oversaturation. Based on a case study carried out on an Arenosol, a considerable amount of SOC can be stored by the soil even during an extremely short period of fifty years. This highlights the role of (temporal) water saturation in organic matter stabilization in the soil (Szalai et al., 2021). Accordingly, for sites under hydromorphic conditions the above applied model is not applicable as they are able to store at least theoretically an unlimited amount of SOC (eg. Histosols) (Szatmári et al. 2023).

3. Does only specific surface area have an influence on organic carbon storage in the soils?

Based on the country-wide investigation of carbon saturated topsoils (SIMS, 183 profiles), soil texture in direct linkage to the specific surface area has a clear role in SOC storage. The sand content was found to be the most effective proxy for carbon content, indicating the role of silt fraction beyond the clay content. Consequently, the silt and clay fraction together affected the carbon holding capacity of the investigated soils the most. It is important to note that, unfortunately, no mineralogical composition was available for the investigated profiles (Szatmári et al. 2023).

In another approach based on own measurement, the specific surface area was predicted by hygroscopic measurements. In this case, we used 11 forest topsoil samples from Hungary. The highest correlation coefficient was found between the TOC content and the hygroscopy (R^2=0.64), and the texture has less importance. This suggests that beyond the particle size distribution, the mineral composition might also play a role (Unpublished yet).

4. Is it possible to identify mineral phases or specific soil organic matter (SOM) fractions for carbon sequestration?

Accordingly, additional topsoils of 13 permanent forest sites were investigated to estimate the role of mineralogy in SOC sequestration. The results indicated that the carbon mineralization was mainly reduced by the illite content (R2=0.797; p<0.001), Al-oxide content (R2=0,708; p<0,001), and clay content (R2=0.475; p<0.05) of the soils. Investigating the carbon release from the forest soils, the various soil carbon pools interacted differently with the soil properties. The recalcitrant, slow pool was only affected by the illite, and Al-oxide content, whereas the fast, mobile pool was also ruled by organic matter composition (aromaticity, C/N rato), the amount of Fe-oxides, and clay fraction beyond the pH. Thus, the specific surface area (directly related to the texture) definitely affects the carbon storage capacity of saturated soils even though the role of mineral composition (illite, Al-oxide, and Fe-oxide content) has a more important role under the investigated conditions (Zacháry, 2019)(Zacháry et al., 2022).

There is organic matter gain in both main SOC pools (fast and slow) in the soil due to tillage intensity drop or land use change. However, there were no distinct SOM fractions of highlighted importance found in terms of saturation (Rieder et al., 2018) (Jakab et al., 2023) (Masoudi et al., 2023) (Al-Graiti et al., 2022) (Dévény, 2022).

5. How do actual land-use types affect on SOC saturation deficit?

Based on the results of a case study carried out on a Luvisol, land use changes triggered significant differences in the SOC content of the bulk soil (Table 1) even in 15 years. The highest value was found under the natural forest (40.60 ± 0.61 mg g^{-1}), whereas under plowing tillage (PT), the SOC content decreased to 10.50 ±0.02 mg g^{-1}. Owing to 15 years of conservation (reduced) tillage (CT), the SOC increased to 13.70 ± 1.23 mg g^{-1}. In contrast to the traditional SOC dynamic models, the SOC content of the slow pools, such as the fine fraction associated pool and the recalcitrant pool, also decreased owing to cultivation. Then, the SOC content of these pools increased significantly because of reduced tillage during this short period. The highest SOC loss was in the occluded SOM within the aggregates, which decreased to 19% of the original content owing to PT. Shifting to CT in 2003 resulted in the current doubled volume of aggregate-occluded SOC. The highest SOC increase was detected in the rSOC fraction owing to CT, which exceeded the original values of rSOC under the NF. The reason for this phenomenon is not known; however, it suggested that the SOC saturation of soil was not directly related to the fine fraction (Jakab et al., 2019b).

In another case study, we investigated the total organic C (TOC) and total nitrogen (TN) contents of the bulk soil in a base-saturated Endocalcic Chernozem. Both TOC and TN were higher in the 0–10 cm layer and differed significantly (p<0.05) between the tillage systems in the order of no tillage (NT)>deep cultivation (DC)>plowing tillage (PT). In the 30–40 cm layer, there were no differences in the TOC and TN contents of the bulk soil. Consequently, the C/N ratios did not differ between tillage systems and soil depths for bulk soils. The highest SOC stock was found in the 0–10 cm layer under NT followed by DC and PT, respectively. Due to higher bulk densities in the 30–40 cm deep layers SOC stock revealed less difference between the layers than that of SOC concentration, resulting in similar values for the PT 0–10 cm and the CT 30–40 cm layers. The particulate organic matter (POM) fraction had the highest TOC content, followed by the aggregate fraction, whereas the fine fraction had the lowest value;

however, the POM fractions accounted for a minimal proportion of the bulk soil and were not further analyzed. The TOC concentrations in both aggregates and fine fraction followed the same distribution as that of the bulk soil. Accordingly, because of the tillage intensity drop in the 0–10 cm layer, the TOC gain did not manifest primarily as POM but, via microbiological contribution, equally increased the amount of aggregate occluded OM (fast pool) and mineral phase associated OM (slow pool). The true aggregate-occluded OM ($AAOM_{net}$) amount varied among tillage systems and depths. In the 0–10 cm layer of plowing tillage, 22% of the total TOC was stored as physically occluded OM in the aggregates. In the subsoil of plowing tillage, it was only 12%. Shifting to deep cultivation did not affect $AAOM_{net}$ in the topsoil but increased the ratio of occluded OM in the subsoil to 24%. No tillage resulted in an increase in the amount and ratio of $AAOM_{net}$ in the topsoil (36%) but not in the 30–40 cm layer (15%) (Jakab et al., 2023).

On the same site, we compared the cropfield's OM concentrations to a nearby treeline with a grass understorey planted over forty years before. Here we detected almost three times higher value (9.3%) under the tree line compared to the average of the cropfield cultivated with various conservation technics (3.1%) (Masoudi et al. 2023).

In a third case study, we also compared the OM concentration and composition of a neighboring permanent grassland, cropland, and cropland turned to grassland twelve years before on a base saturated soil next to the village Battonya. These twelve years significantly increased the TOC content of the uppermost 10cm soil layer of the degraded cropfield (1.8%) to 2.2% in the grassland. However, this is still far beyond the value of the permanent grassland (3.8%). In this case, the fast (aggregate occluded) carbon pool increased significantly during the twelve years; nevertheless, the size of the slow pool did not change. (Dévény 2022) (Not published yet).

Accordingly, land use change generally results in a rapid and significant increase of SOC even though reaching the saturation value would take a long time and therefore does not seem reasonable.

6. How do actual land-use types affect on SOM compound?

In a case study comparing tillage systems with a native forest under Luvisol the most aromatic SOM was identified in the restricted fraction under all land uses and tillage systems. Tillage intensity seemed to be the driver of increasing aromaticity in the aggregate-occluded SOM.

The aggregates and the recalcitrant OM fractions of both cultivations were characterized by the lack of aliphatic SOM components (Figure 5). On the other hand, the fine fractions and bulk samples were rich in aliphatic SOM. The forest aggregates and recalcitrant OM fractions were situated in the middle with moderate aliphatic SOM. The clear difference between all aggregates and bulk samples was presumed to be due to the absence/presence of clay minerals (Jakab et al., 2019b).

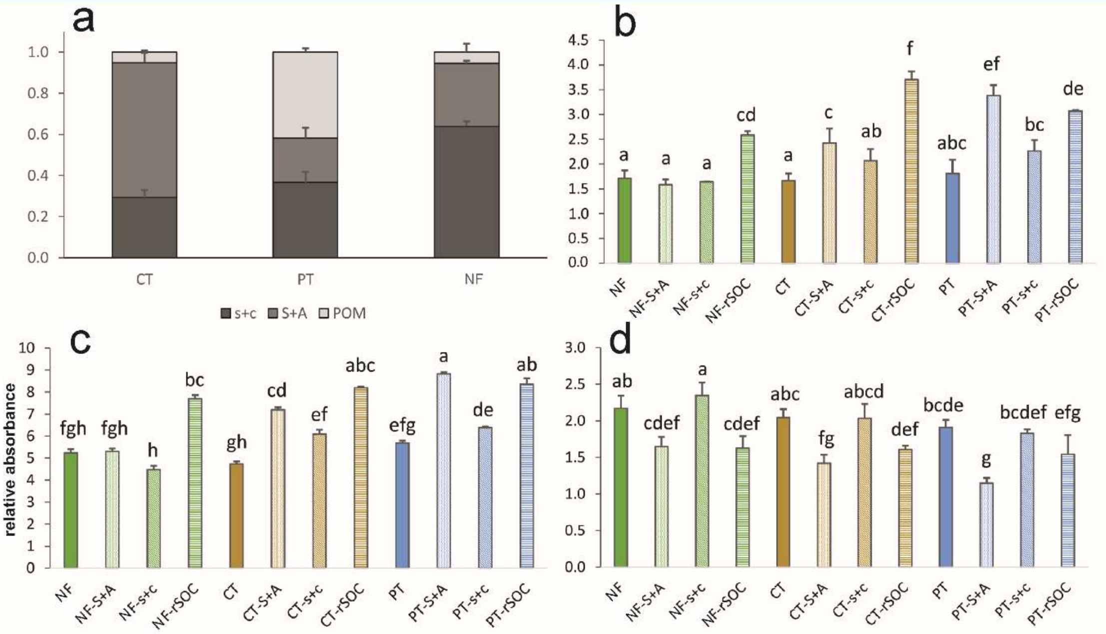

Figure 5. *Total organic carbon distribution of the investigated Luvisol under various land uses (**a**). The aromaticity index (**b**), the relative absorbance at 1794 cm^{-1} referring to the oxidation degree (**c**), the clay/quartz index (**d**), and values of the fractions. Different letters above the bars indicate the significant difference at $p < 0.05$ (CT: conservation tillage; PT: plowing tillage; NF: native forest; S+A: sand and aggregates; s+c: fine fraction (<20 µm); POM: particulate organic matter; rSOC: resistant part of organic carbon attached to s+c).*

In another case study under a base-saturated Endocalcic Chernozem we found that the tillage intensity drop induced surplus SOM, which was stabilized in the soil, did not affect the existing SOM composition difference between the depths and fractions (Figure 6). This suggests preferential binding of the more aromatic and less complex OM to the fine fraction, even for the surplus OM in recent years. This fractionation maintains or even increases the difference between organic carbon pools (soil fractions) in OM composition. In addition, vertical differentiation due to tillage intensity mitigation was established by an increase in the stratification of aromaticity. These results may indicate the role of dissolved OM movement in the profile as a potential driving force for the differentiation of aromaticity with depth. The results also emphasize the role of local conditions in OM composition changes (Jakab et al., 2023).

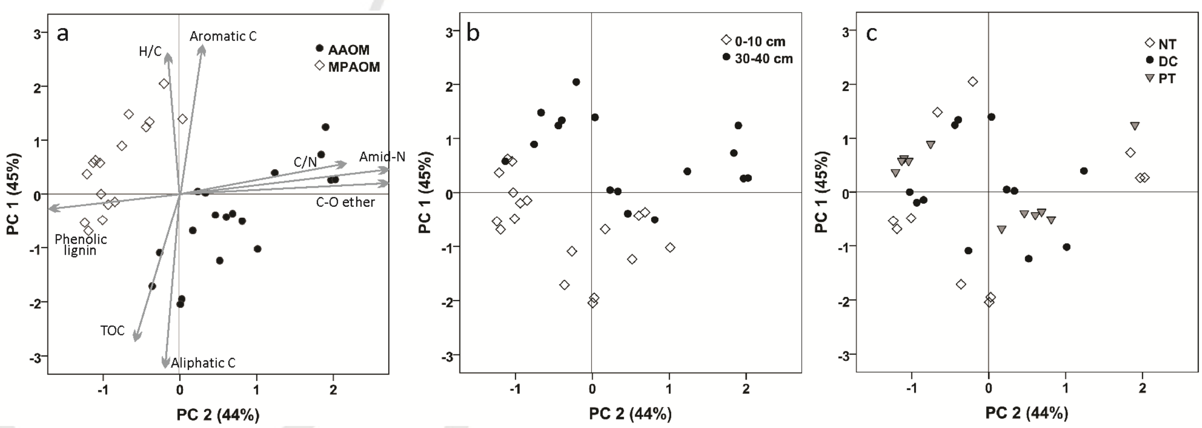

Figure 6. Principal component analysis results of the SOM composition across soil fractions (a) depth (b) and tillage (c); AAOM: aggregate-associated organic matter, MPAOM: mineral-phase-associated organic matter, NT: no tillage, DC: deep cultivation, PT: plowing tillage.

At the Józsefmajor site, we also investigated the OM composition under the tree line. Compared to the arable fields' averages, the OM under the tree line is much more aromatic and has a higher C/O functional groups ratio. This suggests that, however, the changes indicated by the conservation agriculture, tillage intensity drop, and mulch application are significant they remain on a lower level compared to the results of land use change (Masoudi et al., 2023).

In the third case study at the Battonya site, there was no difference among the organic matter composition (predicted by using the C/N ratio) of the fine fraction related SOC pools of the grassland, cropfield, and the cropfiled turned to grassland 12 years ago. In contrast, the lowest C/N values were found in the aggregates of the cropfield (11.1±0.32) followed by the historic grassland (11.6±0.32) and the "new" grassland (11.8±0.44). This underlines that the new land use affects the OM composition of the fast pool first, and in the present case, 12 years after the shift was not enough to change the composition in the slow pool as well (Dévény 2022) (Not published yet) (Figure 7).

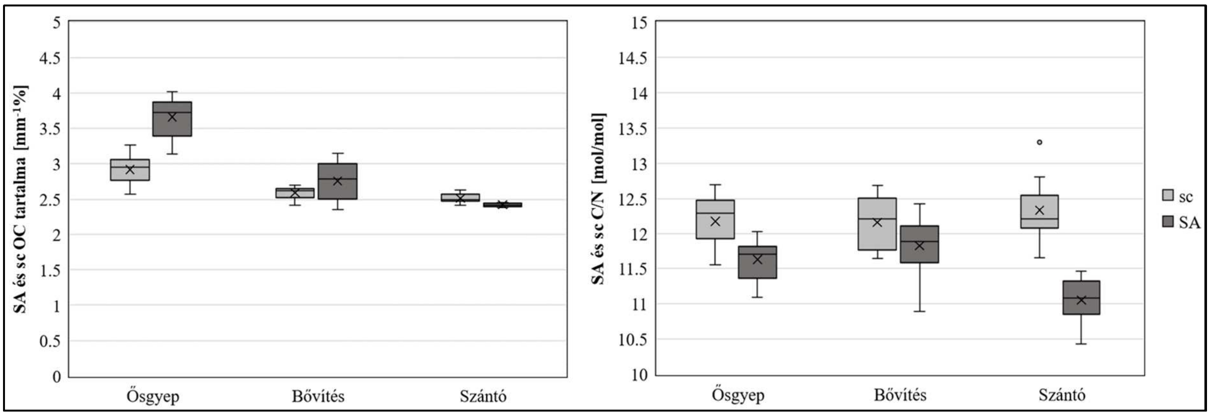

Figure 7. *Soil organic carbon concentration and C/N ratio of the aggregates (fast pool; SAnad the fine fraction (slow pool; sc) under various land uses. Ősgyep: permenent grassland; Bővítés= cropfield turned to grassland 12 years ago; Szántó: cropfield*

Accordingly, the cropfield has the more transformed OM in the fast pool, and the grasslands seem to be characterized more by fresh organic matter. In contrast, taking the Fourier Transform Infrared Spectroscopy results into account, the more transformed, aromatic components dominated OM was found in the aggregates independently of land use, and the abundance of aliphatic components were found in the slow pool (Dévény 2022) (Figure 8).

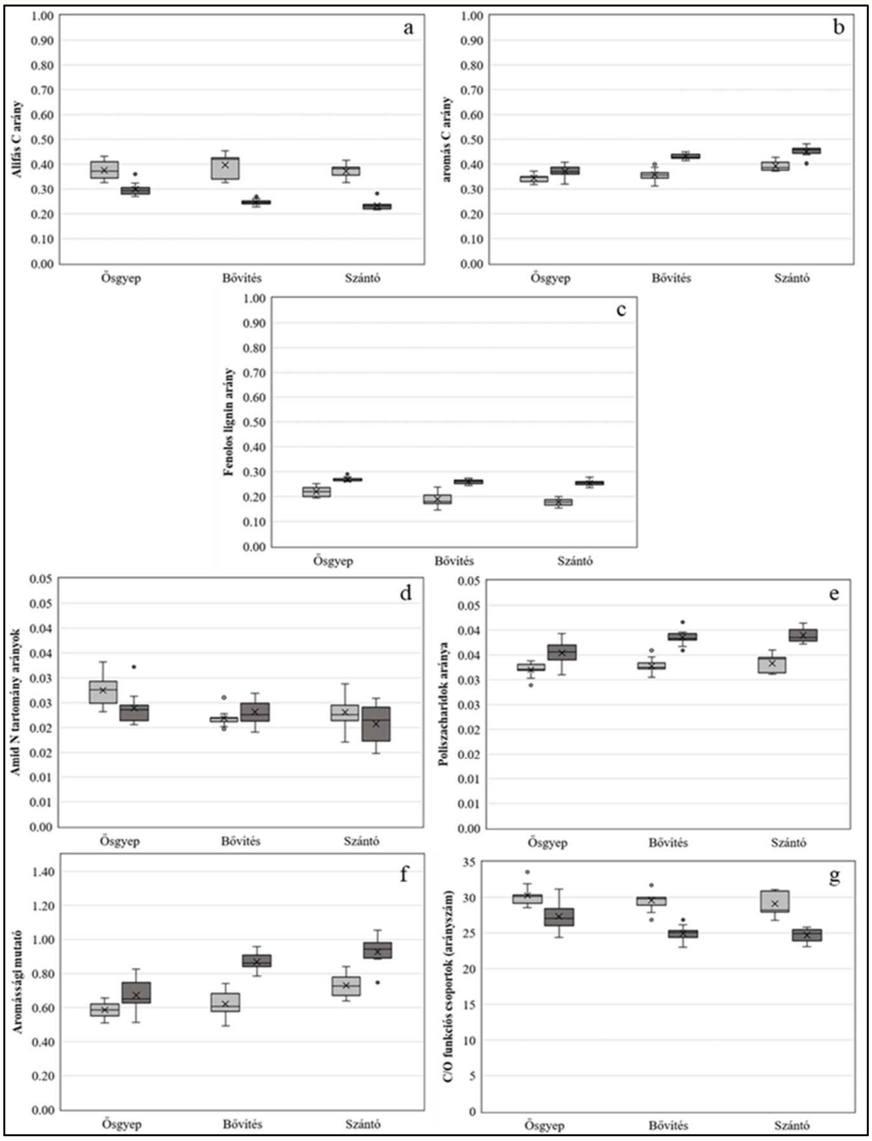

Figure 8. *The organic matter composition of aggregates (fast pool) and the fine fraction (slow pool) at Battonya under different land uses measured by Fourier Transform Infrared Spectroscopy. Ősgyep: permanent grassland; Bővítés= cropfield turned to grassland 12 years ago; Szántó: cropfield*

Consequently, the results found at Szentgyörgyvár (Jakab et al., 2019b) and Battonya (Dévény 2022; not published yet) agree with each other but contradicts those revealed by at Józsefmajor (Jakab et al., 2023) and the mainstream of the literature. As a preconception, we suspected the role of lime in aggregation and organic matter stabilization to rule OM composition in different pools. However, the present results do not support this theory, as only the Battonya and Józsefmajor sites are calcaric. Further investigations are needed to clarify the varying OM composition in the slow, and fast pools of the soils under different land uses and tillage systems.

7. How do actual land-use types affect on SOM turnover time?

The particulate organic matter (POM) fraction in the investigated Luvisol was the most labile C pool, with easily degradable chemical structures (e.g., aliphatic, O-alkyl, and polysaccharides), depleted ^{13}C values, the highest proportion of new C, and the fastest turnover rate, confirming that this fraction contained non-stabilized organic matter which was easily available for decomposition. The analysis of the POM, aggregates and fine fractions showed that, in general, with decreasing grain size distribution: (1) the C/N ratio decreases; (2) the aromaticity increases; (3) the $\delta^{13}C$ value increases; (4) the proportion of new maize-derived C decreases; (5) the proportion of bomb-derived ^{14}C decreases; and (6) the mean residence time of C increases, suggesting an increasing degree of mineral–organic association, leading to decreased degradability and greater resistance to decomposition. Therefore, the hypothesis that the smallest fraction is the most stable was confirmed. In addition, the fact that the recalcitrant SOC fraction represents a relatively inert C pool was also demonstrated by the much smaller proportion of maize-derived C and bomb-derived ^{14}C and by far the longest mean residence time, confirming the ability of NaOCl oxidation to separate a C fraction which is less transformed by microorganisms in the native forest soil investigated. Nevertheless, the fact that the rSOC fractions unexpectedly had the widest C/N ratio, a decrease in relative aromaticity, and the most negative $\delta^{13}C$ value, regardless of incubation or maize addition, highlighted the effect of chemical oxidation by NaOCl (Zacháry et al., 2020) (Zacháry, 2019).

7. What is the specific resistance degree of various SOM compounds against distinct environmental effects?

Describing the SOM composition with analytical accuracy is still not a solved issue. We tried to compare different approaches in parallel to consider their advantages and disadvantages and conclude the comparability of the results. The traditional method was alkali extraction, which recently received much criticism (Jakab et al., 2018). Therefore we compared the results of the alkali extraction of SOM to that of water extraction. Compared to the alkali-extracted fulvic acid fraction, in the present case, the water-extracted OM was a better indicator of organic matter composition changes due to land use shift, providing an economical and fast method for routine soil organic matter characterization (Jakab et al., 2022). Consequently, we continued to study the water-extractable OM as a proxy of the whole SOM (Al-Graiti et al., 2022). However, most studies used the Fourier Transform Infrared Spectroscopy, which investigates the in situ soil organic matter. Still, the absorption of the mineral components of the soil may obscure the results. This tool was found to be applicable even though, in some soils, the OM absorbance of one or two wavenumber ranges remained hidden due to unknown mineral compounds (Masoudi et al., 2023) (Jakab et al., 2023) (Jakab et al., 2019b) (Dévény, 2022).

Even though some OM compounds are believed to be more recalcitrant against decomposition, our results suggest that each OM pool contains all types of organic molecules. The ratio among them may vary, but basically, we did not find relevant differences among OM compounds in terms of decomposition (Masoudi et al., 2023) (Jakab et al., 2023) (Jakab et al., 2019b) (Dévény, 2022) (Al-Graiti et al., 2022).

8. To identify hotspots for additional carbon sequestration on the basis of the physical and human point of view

The estimated SOC saturation deficit value is rather theoretical with practical applicability. The saturated forest sites used as references have no tillage but practically unlimited organic matter input. On cropfields, however, a considerable amount of organic matter is gathered as yield and straw thus, the OM input is limited. Moreover, tillage increases SOM mineralization. Consequently, the theoretically calculated saturation value is hardly available for the practice without land use change. To ensure food security, most cropfields must be kept as arable land in the long run, accordingly, loading the total amount of calculated SOC deficit is unlikely. Nevertheless, the application of conservation agriculture technics is believed to relevantly increase the SOC content under cropfields (Masoudi et al., 2023)(Jakab et al., 2022; Madarász et al., 2021). Thus the amount of SOC saturation deficit may be an efficient indicator to identify hot spots where cultivation shift would benefit most, independently of the theoretical amount of SOC saturation.

On the other hand, we also should note that considerable parts of the country have been indicated as saturated or oversaturated (Figure 5.C). The highest values of oversaturation are mostly related to peatlands (e.g., the southwestern part of Lake Balaton) and other water affected areas. As has been already mentioned in the introduction, on these sites, the temporal or former water coverage inhibited

the mineralization of soil organic matter, which process cannot be captured by the developed PTF (Figure 2, right map) since the approach used in this study was based solely on forest sites. A further reason for (over-)saturation is related to the areas covered by Arenosols, especially in the Danube-Tisza Interfluve (Figure 4). These soils can be characterized by basically low SOC concentration, where low changes may trigger oversaturation. Under the above conditions, the role of particulate organic matter or fresh plant debris may cause increased variability in Arenosols resulting in oversaturation.
In this approach, we used the monitoring points of SIMS located in permanent forests as reference soil profiles, which is a coherent dataset because the description of soil profiles, field sampling, and laboratory analyses have been carried out according to a predefined protocol based on the Hungarian Standards. We should note that only a limited number of soil profiles located in permanent forests are available (n=183), therefore, more effort should be made in the future to collect additional soil samples from permanent forests across Hungary. The age of these permanent forests may also affect the current saturation degree if they were afforested in the recent past; thus, the age of forests would be useful to include in further studies.
The uncertainty associated with the saturated SOC content spatial predictions was larger than the uncertainty of the actual SOC content by order of magnitude (Figure 3.B and 4.B), which made it impossible to delimit areas with statistically significant SOC deficit in Hungary. Note that this is not unique in the literature, a number of papers have demonstrated that large prediction uncertainty can put a restraint to digital soil assessment. However, the methodology presented in this study and the compiled maps provided useful preliminary results on identifying and delimiting areas with SOC deficit in Hungary, which should be fine-tuned in the future with probably more additional observations on saturated SOC content. As was pointed out by the results of uncertainty propagation analysis, this large amount of uncertainty can be mostly attributed to the fitted PTF (Figure 4.D and F). This is of great importance, as it basically gives the direction on how to design the additional sampling campaign to successfully improve the cubist-based PTF and, at the same time, reduce its uncertainty. Besides, the cubist algorithm also proved to be an efficient machine learning technique not just for developing PTF but also for making the resulting PTF more transparent for users, an issue frequently addressed in recent studies. The transparency of the model structure can help us not just to better understand soil and environmental conditions affecting SOC saturation but also to optimize the number and location of additional sampling points making the additional soil survey more cost-effective

9. Try to discover elementary processes (erosion, leaching out, mineralogical, and SOM quality) of correlation between SOC and texture.

The increased SOC content due to tillage activity drop also played an important role in other soil properties' improvement. Our data showed that soil organic matter, water-stable aggregates, and earthworm abundance increased significantly in the soil in conservation tillage plots after 16 years compared to plowing. This improved soil structure and quality, and a stable gallery network was developed, facilitating water infiltration and decreasing erosion. A stable soil structure is more resistant to erosion by raindrops during storms and less prone to crust development. A large abundance of macropores reduced the likelihood of blockage of the network of channels. The crop residues left on the surface, together with the more rugged soil surface, resulted in a lower rate of runoff on conservation tillage plots, leaving more time for infiltration. Thus, runoff declined by 75 %, and soil loss declined by 95 % on conservation tillage plots. Therefore the increasing OM content due to tillage intensity drop as positive feedback may indicate further OM sequestration via the improvement of soil health and ecosystem services (Madarász et al., 2021). Erosion was investigated with different approaches and devices to study the comparability of the results (Szabó et al., 2020a). Results indicated that aggregate associated organic matter stability might vary highly even within a single arable field due to different aggregate stability (Jakab et al., 2019a). Splash erosion induced aggregate breakdown, and the consequent SOM release results in a new SOM-clay composition on the soil surface. As a methodological issue, we tested the applicability of rare earth oxides as tracers of selective erosion. Results provided a colloid phase independent mobility of tracers, indicating a moderate linkage between the SOM content and rare earth oxide concentration (Szabó et al., 2020b).

The results are published in articles with a cumulative impact factor >43 so far, and two additional D1 journal publications are in the second review phase (IF 6.28+4.98).

References for detailed results:

Al-Graiti, T., Jakab, G., Ujházy, N., Vancsik, A., Fodor, N., Árendás, T., Madarász, B., Barcza, Z., Márialigeti, K., Szalai, Z., 2022. The Composition of Dissolved Organic Matter in Arable Lands: Does Soil Management Practice Matter? Agronomy 12, 2797. https://doi.org/10.3390/AGRONOMY12112797/S1

Jakab, G., Dobos, E., Madarász, B., Szalai, Z., Szabó, J.A.J.A., 2019a. Spatial and temporal changes in infiltration and aggregate stability: A case study of a subhumid irrigated cropland. Water (Switzerland) 11. https://doi.org/10.3390/w11050876

Jakab, G., Filep, T., Király, C., Madarász, B., Zacháry, D., Ringer, M., Vancsik, A., Gáspár, L., Szalai, Z., 2019b. Differences in Mineral Phase Associated Soil Organic Matter Composition due to Varying Tillage Intensity. Agron. . https://doi.org/10.3390/agronomy9110700

Jakab, G., Madarász, B., Masoudi, M., Karlik, M., Király, C., Zacháry, D., Filep, T., Dekemati, I., Centeri, C., Al-graiti, T.A.J., Szalai, Z., 2023. Soil organic matter gain by reduced tillage intensity : Storage , pools , and chemical composition 226. https://doi.org/10.1016/j.still.2022.105584

Jakab, G., Rieder, Á., Vancsik, A.V., Szalai, Z., 2018. Soil organic matter characterisation by photometric indices or photon correlation spectroscopy: Are they comparable? Hungarian Geogr. Bull. 67. https://doi.org/10.15201/hungeobull.67.2.1

Jakab, G., Vancsik, A., Filep, T., Madarász, B., Zacháry, D., Ringer, M., Ujházy, N., Szalai, Z., 2022. Soil organic matter characterisation using alkali and water extraction, and its relation to soil properties. Geoderma Reg. 28, e00469. https://doi.org/10.1016/J.GEODRS.2021.E00469

Madarász, B., Jakab, G., Szalai, Z., Juhos, K., Kotroczó, Z., Tóth, A., Ladányi, M., 2021. Long-term effects of conservation tillage on soil erosion in Central Europe: A random forest-based approach. Soil Tillage Res. 209, 104959. https://doi.org/10.1016/J.STILL.2021.104959

Rieder, Á., Madarász, B., Szabó, J.A.J.A., Zacháry, D., Vancsik, A., Ringer, M., Szalai, Z., Jakab, G., 2018. Soil organic matter alteration velocity due to land-use change: A case study under conservation agriculture. Sustain. 10. https://doi.org/10.3390/su10040943

Szabó, J.A., Centeri, C., Keller, B., Hatvani, I.G., Szalai, Z., Dobos, E., Jakab, G., 2020. The use of various rainfall simulators in the determination of the driving forces of changes in sediment concentration and clay enrichment. Water (Switzerland) 12. https://doi.org/10.3390/w12102856

Szabó, Judit Alexandra, Király, C., Karlik, M., Tóth, A., Szalai, Z., Jakab, G., 2020. Rare earth oxide tracking coupled with 3D soil surface modelling: an opportunity to study small-scale soil redistribution. J. Soils Sediments. https://doi.org/10.1007/s11368-020-02582-7

Szalai, Z., Ringer, M., Németh, T., Sipos, P., Perényi, K., Pekker, P., Balázs, R., Vancsik, A.V., Zacháry, D., Szabó, L., Filep, T., Varga, G., Jakab, G., 2021. Accelerated soil development due to seasonal water-saturation under hydric conditions. Geoderma 401, 115328. https://doi.org/10.1016/J.GEODERMA.2021.115328

Zacháry, D., 2019. Az ásványi fázis hatása a talaj szervesszén forgalmára. ELTE Eötvös Loránd University, Budapest, PhD thesis, In Hungarian.

Zacháry, D., Filep, T., Jakab, G., Molnár, M., Kertész, T., Király, C., Hegyi, I., Gáspár, L., Szalai, Z., 2020. Carbon Isotope Measurements to Determine the Turnover of Soil Organic Matter Fractions in a Temperate Forest Soil. https://doi.org/10.3390/agronomy10121944

Zacháry, D., Filep, T., Jakab, G., Ringer, M., Balázs, R., Németh, T., Szalai, Z., 2022. The effect of mineral composition on soil organic matter turnover in temperate forest soils. J. Soils Sediments. https://doi.org/10.1007/S11368-022-03393-8

Studies within the publication process:

Dévény Z. 2022. A művelés elhagyásának hatása a talaj szerves anyagára. TDK dolgozat, ELTE, TTK, Földrajz- És Földtudományi Intézet, Környezet- és Tájföldrajzi Tanszék, Budapest, p. 47 – In Hungarian https://drive.google.com/file/d/17g-iXlhx_xYBFlxE3qygwDUOLFnEQlK6/view?usp=sharing

Masoudi, M., Centeri, Cs., Karlik, M., Jakab, G. 2023. Extracted and in-situ soil investigations to assess the effects of different land use and tillage management practices on soil organic matter composition, Land Degradation and Development, Revision submitted: 20/12/22

https://drive.google.com/file/d/1SMdZ0Ldgqr6Lb4l7wJWiVDkC7KcFQaY7/view?usp=sharing

Szatmári, G., Laborczi, A., Balkacsi, Zs., Pásztor, L., Zacháry, D., Filep, T., Szalai, Z., Jakab G. 2023. Country-wide mapping and assessment of organic carbon saturation in the topsoil using machine learning-based pedotransfer function with uncertainty propagation, Catena, Revision submitted: 10.May.2022

https://drive.google.com/file/d/1d6sARQaD-pSsCWoNk3FIrawf44_pWgO1/view?usp=sharing