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Regional topsoil organic carbon content in the agricultural soils of Slovakia and its drivers, as revealed by the most recent national soil monitoring data

Rastislav Skalský [a,b,*], Gabriela Barančíková [b], Jarmila Makovníková [b], Štefan Koco [b,c], Ján Halas [b], Jozef Kobza [b]

[a] Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis, Schlossplatz 1, Laxenburg A-2361, Austria
[b] National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Trenčianska 55, Bratislava 821 09, Slovakia
[c] Faculty of Humanities and Natural Sciences, University of Presov, 17. novembra 15, Prešov 080 01, Slovakia

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ABSTRACT

Soil organic carbon (SOC) is a primary constituent of soil organic matter and plays an important role in the regulation of many soil processes, including greenhouse gas emissions. Recently, SOC also became an indicator for monitoring climate change mitigation policies in the agricultural sector. The availability of up-to-date SOC inventories is thus crucial in terms of supporting SOC–related actions at country or sub-country scales. Currently, the National Monitoring System of the Agricultural Soils of Slovakia (CMS-P), whose network of 318 monitoring sites was last surveyed in 2018, is the only available source of up-to-date topsoil SOC data for agricultural land in Slovakia. Although very useful at the national scale, the number of CMS-P observations it contains is too limited for much needed sub-national SOC inventories. We hypothesized that with the aid of well-chosen macro-scale drivers of topsoil SOC accumulation in agricultural land in Slovakia, and by mapping those drivers geographically, we could upscale the CMS-P observations and produce a regional estimate of topsoil SOC. Altitude, land cover, topsoil texture, and soil type were assumed to be the key factors controlling topsoil SOC accumulation in Slovakia, and based on these, the country was classified into 14 macro-scale geographical regions. Typical ranges and mid-class values of 0–30cm topsoil SOC concentrations (%) and stocks (t ha^{-1}) were calculated for each macro-scale region from CMS-P data. The average topsoil SOC content in agricultural land was estimated to be 2.13% (72.9 t ha^{-1}). The highest topsoil SOC stock (> 90 t ha^{-1}) was estimated for the lowlands of Slovakia, and the lowest (< 50 t ha^{-1}) for the shallow and stony soils of mountain regions. When aggregated to 78 administrative regions at LAU1 level, the area-weighted averages ranged between 39.20 t ha^{-1} and 80.0 t ha^{-1}, with the highest values (> 65 t ha^{-1}) being in LAU1 regions in the south-west, south-east, and north of Slovakia where arable land is most prevalent. Total SOC storage in 0–30cm topsoil of agricultural land in Slovakia was estimated at 118.39 Mt, with two-thirds of this amount stored in arable soils in 33 south-west, south-east, and south LAU1 administrative regions. As there is no alternative and up-to-date dataset on topsoil SOC content in Slovakia, the upscaling algorithm presented in this study is an important step toward utilizing CMS-P data for sub-national SOC inventories. It may also offer a new way of providing inputs to help predict future or alternative regional topsoil SOC accumulation trajectories in Slovakian agricultural land using process-based or statistical models.

1. Introduction

Although soil organic matter (SOM) typically represents only a small fraction of the total soil mass in intensively used agricultural soils (1–5%), it is a key soil component in the delivery of many ecosystem services including biomass production, water and nutrient retention, and climate regulation via either positive or negative greenhouse gas emissions (Campbell and Paustian, 2015). The amount of organic matter in soils depends on inputs, such as plant and animal residues, and outputs, such as the decomposition, mineralization, and its loss through surface runoff or leaching. As a dynamic soil characteristic, SOM is often considered to be a primary indicator of soil health and quality (Chevallier et al., 2016) and is frequently used in definitions of ecosystem services (Banwart et al., 2015). SOM decline is also considered to be one

* Corresponding author at: Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis, Schlossplatz 1, Laxenburg A-2361, Austria.

E-mail address: skalsky@iiasa.ac.at (R. Skalský).

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of the major soil degradation processes. SOM is thus also an important element in the process of formulating and evaluating future national or regional environmental and climate change mitigation and adaptation policies for the land use and agricultural sectors (Jost et al., 2021; FAO/ITPS, 2021; Rodrigues et al., 2021).

The spatial and temporal dynamics of SOM are controlled by natural conditions and human activities (Eckelmann et al., 2006; Tayebi et al., 2021). Natural factors driving SOM balance include soil (parent material, soil type, soil texture, and stone content), climate (temperature, humidity), and other factors such as altitude or topography (Wiesmeier et al., 2019). Human factors impacting SOM include land cover type (arable land, grassland, forest), land use (including soil management), and land cover and land use change, for example, transitions from natural to semi-natural or managed ecosystems and transitions between main land cover types, which, together, are mainly responsible for the amount and quality of organic carbon inputs to soil (Guo and Gifford, 2002; Poeplau et al., 2011; Poeplau and Don, 2013; Wei et al., 2014; Maillard and Angers, 2014; Barančíková et al., 2019a).

Local combinations of natural and socioeconomic drivers at any site result in SOM accumulation or loss (Banwart et al., 2015); this, in the long term, gives rise to the typical spatial distribution patterns of SOM content in soil, which change according to geographical region and spatial scale (Lugato et al., 2014; Yigini et al., 2017; FAO, 2020). Knowing these spatial (as well as temporal) patterns at an appropriate level of detail is a necessary prerequisite for finding a practical solution to the accurate planning of sustainable land management and preservation of soil health across all scales (Paustian et al., 2019; Smith et al., 2012, 2020; Panagos et al., 2022). High quality, spatially detailed up-to-date information about topsoil SOM content is, however, not always available from existing datasets (Arrouays et al., 2017; FAO/IIASA/ISRI/ISSCAS/JRC, 2012; Cornu et al., 2023) and limited data availability could hamper efforts to obtain accurate and detailed regional or national evaluations of current and expected (or theoretical) topsoil SOM dynamics (IPCC, 2019).

As SOM itself represents a chemically diverse group of many organic compounds whose basic building elements (C, N, O, H, S, and others) are of varying stoichiometry, it is replaced in practically orientated research or environmental resources inventories by a single-element indicator of SOM content, soil organic carbon (SOC). SOC is easier to measure in a consistent way, as well as being more straightforward to interpret practically than SOM. SOC has been used as an indicator of (topsoil) SOM content in nearly all modern soil databases (Arrouays et al., 2017; FAO/IIASA/ISRI/ISSCAS/JRC, 2012; Tóth et al., 2013; Panagos et al., 2022). SOC content has also recently been endorsed and adopted by the international community as the official indicator for national greenhouse gas (GHG) inventories and reporting (IPCC, 2019; Panagos et al., 2020).

Slovakia has a tradition of collecting soil information (Bielek et al., 2005). The first systematic and country-wide inventory of agricultural soil resources (the National Agricultural Soil Inventory–KPP) dates to the 1960s (Němeček et al., 1967; Skalský et Vopravil, 2014). Many basic and interpreted soil maps have been published since the early 1970s based on KPP survey data and have been implemented for practical purposes, ranging from legal protection of agricultural soils to improving soil fertility and curbing soil degradation, for example, soil erosion. Starting in the early 1990s, this basic set of soil data, which consists of many thousands of measured soil profiles (17,741 in total) and soil maps at detailed spatial scales, has been further extended by new soil observation networks (Bielek et al., 2005). Perhaps, the most important of these is the National Monitoring System of Agricultural Soils (CMS-P), launched in 1993, with 318 permanent monitoring sites established in applicable regional settings in Slovakia that have since been revisited and resampled at regular 5-year intervals (Kobza, 1995, 2015; Linkeš et al., 1997; Bielek et al., 2005; Kobza et al., 2017, 2019).

Amongst the several country-wide soil datasets available for Slovakia (Bielek et al., 2005), the data on measured topsoil and subsoil SOC content are available only from KPP and CMS-P, with the former also serving as a primary data source for the most recent national contribution of Slovakia to the UN FAO Global Soil Organic Carbon map (Skalský et al., 2017; FAO/ITPS, 2018). The KPP, whose SOC measurements refer to the state of soils in the mid-1960s, has serious limitations in terms of providing the up-to-date information much needed by decision- and policy-makers at various levels. Several attempts at reconstructing the current topsoil SOC content in the agricultural soils of Slovakia from the KPP dataset using a historical time-series forcing process-based SOC turnover model (RothC) have not proven useful, as they have too many methodological caveats (Barančíková et al., 2010, 2012; Skalský et al., 2020). Currently, the most accurate, consistent, and up-to-date source of data on the SOC content of Slovakian agricultural land is the CMS-P. With six sampling campaigns completed to date up to 2018 then the seventh and most recent being in 2023 (with outputs of soil sample analyses becoming available throughout 2024 and 2025), the CMS-P provides a solid and robust basis for national-scale evaluations of the current topsoil SOC status and dynamics (Kobza et al., 2017, 2019; Barančíková and Makovníková, 2013; Barančíková et al., 2016). In this regard, the limited number of CMS-P monitoring sites in Slovakia (318 sites, 1 site per 7500ha of agricultural land in average) seems to be a major obstacle to deploying CMS-P measurements for more detailed regional (NUTS3) and sub-regional (LAU1) SOC inventories.

Relying on the widely accepted soil formation paradigm, originally formalized as the ClORPT function by Jenny (1941), and later adopted for wide range of modern soil mapping methods (e.g., McBratney et al., 2003), we hypothesize that if we are accurate in selecting the factors driving topsoil SOC accumulation, we can divide the agricultural land of Slovakia into a limited number of geographical regions that have homogenous conditions for SOC accumulation within their boundaries and hence typical ranges and middle values for the topsoil SOC content. We also assume that, if we do this, the CMS-P dataset, although limited in terms of the number of observations it has, will be able to provide a relevant basis for revealing the most prominent regional trends in topsoil SOC accumulation. We also expect that with the aid of a defined methodological framework of this kind, the most recent SOC data from CMS-P can be utilized to provide up-to-date and spatially regionalized information about the status of SOC in Slovakian agricultural land.

The goal of this study is to:

(i). Calculate the typical ranges and middle values of topsoil SOC content in agricultural land in Slovakia with measured SOC data coming from the 2018 CMS-P campaign after stratifying all monitoring sites according to predefined macro-scale stratification criteria; also analyse the regional trends of topsoil SOC accumulation in the conditions of Slovakia as controlled by the main soil forming factors;

(ii). Provide, firstly, an up-to-date regional estimate of the topsoil SOC content in agricultural soils in Slovakia via the linkage of typical regional topsoil SOC ranges and middle values calculated from 2018 CMS-P data to geographical regions interpreted from the available national-scale spatial data on topography, soil, and land use; and secondly, provide an estimate of integral topsoil SOC stock for administrative regions at NUTS4/LAU1 level (districts).

2. Material and methods

2.1. Study area

Slovakia is a landlocked country with an area of about 49,000 km^2 located in Central Europe (Fig. 1) roughly at latitude 16.85–22.57E, and longitude 47.78–49. Topographically, Slovakia is characterized by the mountain terrain of the Carpathian range, which covers nearly three-quarters of the national territory, while the rest is mainly flat or slightly undulating terrain of the Danube basin (Fig. 1). The Danube basin area, covering an altitude of 94–440m, is characterized by flat

Fig. 1. Geographical position and main topographical regions of Slovakia (1 Danube Basin; 11 river alluvia; 12 hilly land; 2 Carpathian mountains; 21 inner-Carpathian basins; 22 low- and mid-altitude mountains; and 23 high-altitude mountains).

alluvial plains along the Danube River, and surrounding hilly areas. The Carpathian mountains, with an altitude of 94–2655m, are characterized by high mountain ranges, lower mountains ranges with smoother, less rugged terrain, and lower-lying and flat inner-Carpathian basins.

The climate of Slovakia is temperate, with an average yearly temperature of 10°C; January is the coolest month is with an average temperature of −2°C, and July the warmest with a 20°C average. Total average yearly rainfall sum is 650mm, regularly distributed over the year. In the lowlands, total average yearly rainfall ranges from 500 to 650mm in the lowlands to more than 1000mm in high mountains regions (average yearly rainfall for mountain regions is 700–800mm). Average yearly temperature ranges according to altitude – from less than 6°C in the mountains to slightly above 11°C in the lowlands.

Soil cover in lowland areas is dominated by deep, loamy soils, with, to a lesser extent, sandy and clay soils; prevailing soil types, according to the World Reference Base (IUSS Working Group WRB 2015, further referred to as WRB), are *Fluvisols, Phaeozems, Chernozems* (*Haplic, Calcaric*, and *Gleyic*), and *Luvisols* (*Haplic*) developed from alluvial and loess sediments. The soil cover of the inner-Carpathian basins and the lower mountain positions are characterized by deep, loamy soils, and also locally by stony soils, with prevailing soil types being *Albic Luvisols* (*Retisols*) and *Stagnosols*. Mountain locations are characterized by shallow, stony soils with medium to coarse textures, where *Cambisols, Rendzinas, Litic Leptosols*, and *Podzols* are the prevailing soil types.

In 2021 most of the Slovakian land area (about 49,000 km^2) was used as agricultural land (48.4%), followed by forest land (41.4%), and the remainder (10.2%) under other use (urbanized areas, water bodies, and water streams). Agricultural areas are mainly located in the lower mountain ranges and lowlands. More than two-thirds of agricultural land is used for high-input farming of winter wheat, corn maize, rapeseed, barley, sunflower, sugar beet, and other crops, with croplands being situated in suitable lowland areas of Danube Basin and low-lying inner-Carpathian basins. Less suitable agricultural areas in mountain regions are used predominantly as managed grasslands.

2.2. Topsoil organic carbon data for Slovakia and calculation of the topsoil SOC stock

Currently, the most accurate, consistent, and up-to-date source of data on the topsoil SOC content in agricultural land of Slovakia is the National Monitoring System of Agricultural Soils (CMS-P) (Kobza et al., 2017, 2019). Since 1993, all permanent monitoring sites (N=318) have been revisited and resampled at regular 5-year intervals (six full sampling campaigns finished to date, with a seventh taking place in 2023) with both the sampling protocol and laboratory analysis for CMS-P (Fiala et al., 1999; Kobza et al., 2011) kept unchanged over the whole monitoring period. Samples for laboratory analysis have constantly been collected from predefined depth intervals of 0–10cm, 10–20cm (only in 1993), and 35–45cm, and topography, soil type, land cover and land use type information have been recorded during each visit.

Topsoil SOC concentration (%) data measured during the most recent CMS-P sampling campaign in 2018 were used in this study for a set of 306 CMS-P monitoring sites with accurate and consistent data records (Fig. A.1). A set of site and topsoil characteristics (site location, altitude, land use type, soil type, clay, silt, sand, and stone content) required for the topsoil SOC stock (t/ha) calculation and macro-scale stratification was also compiled from the CMS-P dataset for each monitoring site. SOC content was analysed by the Euro EA 3000 elemental analyser in CN configuration, and soil texture was determined by the pipetting method for all CMS-P sites used in this study (Kobza et al., 2011).

Topsoil SOC concentration (%) measured for the depth interval of 0–10cm was taken as a representative SOC concentration in the 0–30cm deep topsoil at all monitoring sites on arable land. We assumed that as moldboard tillage takes place on all crop fields at least once every several years, the top 25–35cm of soil is regularly mixed, and the 0–10cm topsoil thus accurately represents the SOC content in the entire ploughing layer.

Three separate topsoil layers (0–10cm, 10–20cm, and 20–30cm) were assumed for calculation of the 0–30cm topsoil SOC concentration (%) at all monitoring sites on grasslands (meadows, pastures). Topsoil SOC concentration (%) was directly measured during the CMS-P campaign for the 0–10cm depth interval and estimated on the basis of a set of soil type-specific taxo-transfer rules for the latter two (Table 1). Taxo-transfer rules for reducing the SOC content in the 10–20cm and 20–30cm depth intervals were derived from i) the additional SOC measurements available for the 20–30cm soil layer from the 1993 CMS-P sampling campaign (Linkeš et al., 1997) combined with ii) a set of SOC concentrations measured in 10cm depth increments up to 1m in soil profiles of selected soil types from Slovakian agricultural land (Barančíková et al., 2019b).

The SOC stock (t ha^{-1}) for the 0–30cm layer for all cropland sites plus the three separate layers (0–10cm, 10–20cm, and 20–30cm) for all grassland sites, was calculated as:

$$\boldsymbol{SOC} = \left(\boldsymbol{BD} * \boldsymbol{COX} * \left(\boldsymbol{d} * \left(1 - \frac{\boldsymbol{VS}}{100}\right)\right)\right) \quad (1)$$

where *SOC* is the SOC stock (t ha^{-1}), *BD* is soil bulk density (g cm^{-3}), *COX* is SOC concentration (%)*, d* is the depth of the layer (cm), and *VS* is volume of stones (%) in the soil layer. The SOC stock calculated for the three separate layers of grassland sites was then summed to give a total SOC stock for the whole 0–30cm topsoil layer. An alternative topsoil SOC stock with $VS = 0$ for all sites was also calculated and later used for estimating the topsoil SOC content in Slovakian agricultural soils with spatially explicit data on the volume of stones (see Section 2.4 for more details, Fig. A.3).

The topsoil bulk density values required for SOC stock calculation were for all CMS-P sites estimated with the regional pedo-transfer function derived and tested on the CMS-P dataset by Makovníková et Širáň (2011) to avoid any biases from uncertain outcomes of direct bulk density measurements:

$$\boldsymbol{BD} = 1.40779 + 0.00119072 * \boldsymbol{CS} - 0.0865001 * \boldsymbol{COX} \quad (2)$$

where *BD* is soil bulk density (g cm^{-3}), *CS* is the summed content (%) of clay and silt particle size fractions (i.e., the fraction < 0.05mm), and *COX* is topsoil SOC concentration (%).

2.3. Macro-scale stratification of Slovakia

Altitude, land cover, soil texture, and soil type were selected as stratification levels for a macro-scale regional classification aimed at evaluating regional specifics of topsoil SOC accumulation in agricultural soils in Slovakia. The number of classes defined within each stratification level and the class definition criteria described in Table 2 reflected both the availability of geographical datasets applicable for national-coverage geographical analyses (Table 3), and the content of the CMS-P dataset (number of sites, and site and soil descriptions).

The agricultural land of Slovakia was classified into 14 geographical macro-scale regions (Table A.1, Figs. A.1 and A.2). Four-level stratification (altitude class, land cover class, topsoil texture class, and soil type class) was used for all areas up to 600m resulting in 12 individual regions (LACH, LACO, LAMH, LAMO, LAFH, LAFO, LGCH, LGCO, LGMH, LGMO, LGFH, and LGFO). Due to the limited number of CMS-P sites in higher mountain positions with less agricultural land, two-level stratification (altitude class, land cover class) was used for all remaining areas (above 600m) resulting in two individual regions (HA00, HG00).

Table 1
Taxo-transfer rules for estimating SOC concentration in 10–20 and 20–30cm depth intervals from the SOC concentrations measured in 0–10cm depth interval; the rules were applied to all CMS-P sites located on grasslands.

Soil type (according to WRB)	SOC concentration in the 10–20cm depth interval	SOC concentration in the 20–30cm depth interval
Chernozems, Phaeozems	90% of the SOC concentration in the 0–10cm topsoil layer	80% of the SOC concentration in the 0–10cm topsoil layer
Luvisols, Fluvisols, Cambisols, Arenosols, Regosols	80% of the SOC concentration in the 0–10cm topsoil layer	70% of the SOC concentration in the 0–10cm topsoil layer
Rendzic Leptosols and *Rendzic Phaeozems, Podzols, Stagnosols*	60% of the SOC concentration in the 0–10cm topsoil layer	50% of the SOC concentration in the 0–10cm topsoil layer

Table 2
Class-definition criteria for a macro-scale stratification of agricultural land in Slovakia with respect to the main drivers of topsoil SOC accumulation.

Stratification level	Classification element	Class	Classification criteria
Altitude	Altitude (m)	L	Lower: < 600 m
		H	Higher: > 600 m
Land cover	Land cover class	A	Arable land: annual crops, perennial fodder crops and temporary grasslands, orchards, hop gardens, vineyards
		G	Grassland: permanent pastures, meadows, other agricultural land
Soil Texture	Content (%) of particle size fraction < 0.01mm, a sum of physical clay (fr. <0.001mm) and fine silt (fr. 0.001 – 0.01mm)*	C	Coarse: < 20%
		M	Medium: 20 – 60%
		F	Fine: > 60%
Soil Type	Soil type (according to WRB)	H	Humus-rich soil types: *Chernozems, Fluvisols, Phaeozems, Rendzic Leptosols, Mollic Gleysols,* and *Andosols*
		O	Other soil types: *Cambisols, Stagnosols, Luvisols, Podzols, Leptosols,* and *Regosols*

* the so-called "total clay" fraction used with the national agricultural soil inventory (KPP) and its practical interpretations (e.g., the land evaluation maps – BPEJ).

Table 3
List and identification of geographical datasets with country-wide coverage available for Slovakia from the public domain.

Dataset	Description	Source / download link
ZBGIS_DEM	DMR3.5 digital elevation model in 10, 25, 50, and 100m spatial resolutions.	Geoportal.sk / https://www.geoportal.sk/en/zbgis/download/
ZBGIS_OKRES	Boundaries of territorial and administrative arrangement and cadastral districts of the Slovak Republic, administrative units at LAU1 level (districts).	Geoportal.sk / https://www.geoportal.sk/en/zbgis/download/
LPIS	The National Land Parcel Identification System for Slovakia, provides boundaries of agricultural parcels and additional attributes including land use types.	data.gov.sk / https://data.gov.sk/en/dataset/system-identifikacie-polnohospodarskych-pozemkov-lpis
BPEJ	The National Land Evaluation Map for Slovakia, provides polygon boundaries and codes of land evaluation units, including attributes on soil types, soil texture, and volume of stones.	data.gov.sk / https://data.gov.sk/en/dataset/bonitovane-podnoekologicke-jednotky-bpej

2.4. Calculation of regional averages of SOC content from CMS-P data

Distributions of the calculated 0–30cm topsoil SOC content values (both concentrations and stock) along the main drivers of the topsoil SOC accumulation (Table 2) were analysed after all the CMS-P sites had been classified according to the macro-scale stratification criteria (Fig. A.1). The STATGRAPHIC CENTURION XV program was used to statistically test the differences between mid-class values (arithmetic mean, median), standard deviations, and sample distributions of the topsoil SOC concentration (%) and stock (t/ha) estimated for individual stratified classes with multiple statistical tests (F-test, *t*-test, Kolmogorov-Smirnov, and Wilcoxon test, all at $p < 0.05$), and hence the macro-scale stratification criteria tested for how appropriately they responded to the observed variability of topsoil SOC accumulation in Slovakia.

The minimum, maximum, arithmetic mean, median, 25th, and 75th percentile of the 0–30cm topsoil SOC stock (t ha^{-1}) were calculated from the same pre-stratified set of CMS-P data with the goal of providing a direct input to upscaling of CMS-P point measurements to the macro-scale and the administrative regions of Slovakia using available geographical data (Table 3). In this step, topsoil SOC stock (t ha^{-1}) was also calculated without assuming a stone content in order to avoid multiple reduction estimated SOC stock values with volume of stones during the upscaling and to keep the volume of stones as an independent and spatially explicit predictor (see Section 2.5 on SOC stock calculations for more details).

2.5. Upscaling regional averages of topsoil SOC stock to macro-scale geographical regions

Geographical datasets with country-wide coverage for Slovakia from the public domain, listed and described in Table 3, were processed, and then used for geospatial stratification of Slovakian agricultural land into predefined number of macro-scale geographical regions (Table A.1). All input geospatial data were first converted into raster coverages with spatial resolution of 100m and then subsequently classified according to the macro-scale stratification criteria shown in Table 2. Elevation (m) from the 100m spatial resolution raster of ZBGIS_DEM was directly used for classifying altitudes into two classes. Land use types available for each agricultural parcel from the LPIS dataset were aggregated into two classes. Three soil texture classes and two soil type classes were interpreted from the BPEJ dataset based on the land-evaluation code attributed to each BPEJ map polygon (Linkeš et al., 1996).

Pre-classified raster coverages of altitude, land cover, soil texture, and soil type classes were overlaid with two additional raster coverages with i) administrative district identification number (NUTS4/LAU1; ii) administrative region from the ZBGIS_OKRES dataset); and iii) stoniness class with associated mid-class values of the volume of stones (%) in topsoil (interpreted from the BPEJ dataset based on the land-evaluation code attributed to each BPEJ map polygon; Linkeš et al., 1996). This yielded the final geospatial coverage of macro-scale regions that was later used for upscaling topsoil SOC content and calculating integral SOC stock in agricultural soils in Slovakia.

Regional SOC averages calculated from the CMS-P data for pre-stratified combinations of altitude, land use, soil texture, and soil type (Table 2, Table A.2) were mapped to geospatial coverage of macroscale regions and topsoil SOC stock (t ha^{-1}) subsequently reduced by volume of stones as:

$$\boldsymbol{SOC_{reg}} = \boldsymbol{SOC} * (1 - \left(\frac{\boldsymbol{VS}}{100}\right) \quad (3)$$

where SOC_{reg} is the final topsoil SOC stock (t ha^{-1}) for the geographical region, *SOC* is a regional value of the topsoil SOC stock (t ha^{-1}) calculated from pre-stratified CMS-P data which was not reduced by volume of stones (median, 25th percentile, and 75th percentile), and *VS* is a mid-class value of volume of stones (%) attributed to each stoniness class (Fig. A.3) as follows: 0% for class 0 (no or some stones), 15% for class 1 (few stones), 35% for class 2 (frequent stones), and 65% for class 3 (prevalence of stones).

Integral topsoil SOC stock (Mt) was calculated for each administrative region at LAU1 level (administrative district), for arable land and grasslands separately, by summing SOC_{reg} values for all pixels having the same combination of administrative unit (LAU1) and land cover class.

3. Results

3.1. Macro-scale drivers of the topsoil SOC content in agricultural soils in Slovakia

The average topsoil concentration of SOC in agricultural soils in Slovakia calculated from the 2018 CMS-P site data is 2.13%; 90% of the measurements ranged between 0.98% and 4.25%, with extreme values being 0.56% and 9.0% at the low and high end, respectively. The average topsoil stock of SOC in agricultural soils in Slovakia calculated from the 2018 CMS-P site data is 72.9 t ha^{-1}, with 90% values ranging between 35.2 t ha^{-1} and 117.0 t ha^{-1}, and extreme values being 18.7 t ha^{-1} and 191.5 t ha^{-1} at the low and high end, respectively.

Distributions of the topsoil SOC concentration (%) and the topsoil SOC stock (t ha^{-1}) calculated from the 2018 CMS-P site data across all individual macro-scale stratification levels are plotted in Fig. 2. Statistical significance of differences between mid-class values (arithmetic mean, median), standard deviation, and sample distributions of the classes, separately for each macro-scale stratification level, are listed in Table 4.

The average topsoil SOC content in agricultural soils in Slovakia at altitudes below 600m is 1.97% (70.2 t ha^{-1}), with 90% of measurements ranging between 0.87% (33.5 t ha^{-1}) and 3.67% (113.9 t ha^{-1}). The average topsoil content of SOC at altitudes above 600m is 2.92% (86.6 t ha^{-1}), with 90% of measurements ranging between 1.43% (54.1 t ha^{-1}) and 5.76% (133.1 t ha^{-1}). Topsoil SOC content at higher altitudes (above 600m) is generally shifted toward higher SOC content values, compared to lower altitudes (below 600m), with differences in arithmetic means, medians, standard deviations, and sample distributions found to be statistically significant (Table 4). Altitude also shows itself to be a strong SOC accumulation driver if analysed separately for arable land and grasslands (Fig. A.4), and repeats the same pattern as observed for agricultural land. If also analysed together with soil type class (Fig. A.4), the impact of altitude seems to be less obvious, suggesting that in arable soils in particular, soil type can locally prevail over the general macro-scale impact of altitude.

The average topsoil SOC content in arable land in Slovakia is 1.84% (68.5 t ha^{-1}), with 90% of measurements ranging between 1.0% (36.2 t ha^{-1}) and 2.87% (102.7 t ha^{-1}). The average topsoil SOC content in Slovakian grasslands is 2.65% (80.9 t ha^{-1}), with 90% of measurements ranging between 0.87% (34.6 t ha^{-1}) and 5.30% (131.9 t ha^{-1}). Topsoil SOC content in grasslands is generally shifted toward higher SOC content values, compared with arable soils, with differences in arithmetic means, medians, standard deviations, and sample distributions found to be statistically significant (Table 4).

The average topsoil SOC content in medium-textured soils in Slovakia is 2.12% (72.5 t ha^{-1}), with 90% of measurements ranging between 0.99% (36.0 t ha^{-1}) and 4.20% (118.7 t ha^{-1}). Average topsoil SOC content in coarse-textured soils in Slovakia is 1.94% (63.4 t ha^{-1}), with 90% of measurements ranging between 0.65% (25.3 t ha^{-1}) and 3.74% (106.9 t ha^{-1}). The average topsoil SOC content in fine-textured soils in Slovakia is 2.44% (86.0 t ha^{-1}), with 90% of measurements ranging between 1.84% (63.3 t ha^{-1}) and 2.91% (109.9 t ha^{-1}). Topsoil SOC content increases from coarse-, through medium-, to fine-textured soils, with differences in arithmetic means, medians, standard deviations, and sample distributions all found to be statistically significant, except between coarse- and medium-textured soils (Table 4). When

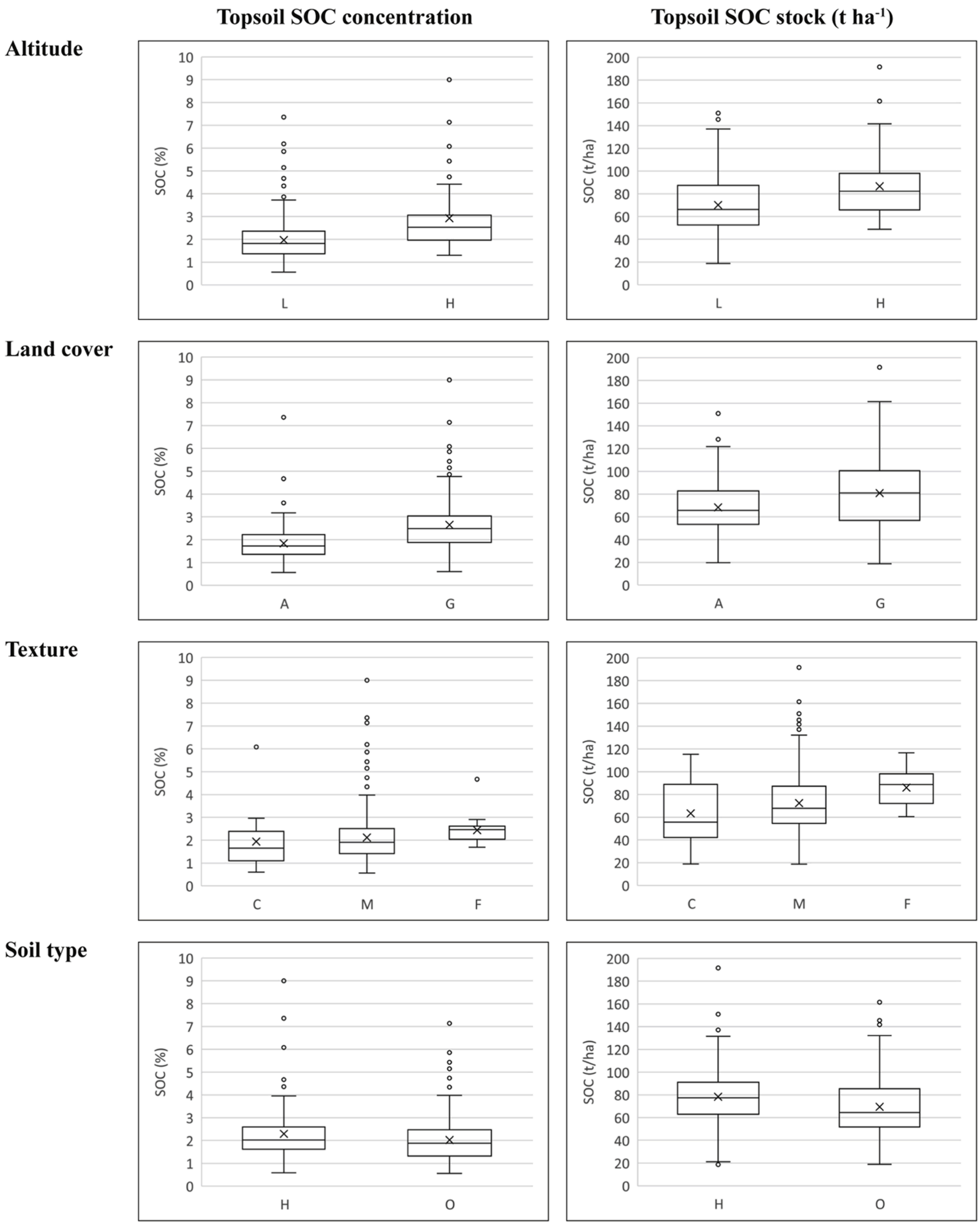

Fig. 2. Distribution of the topsoil SOC concentration (%) and the topsoil SOC stock (t/ha) in agriculture land of Slovakia for individual macro-scale stratification levels: altitude class (L—below 600m, H—above 600m), land cover class (A—arable land, G—grassland), topsoil texture class (C—coarse, M—medium, and F—fine textured soils), soil type class (H—humus rich soils, O—other soils).

analysed together with altitude and land cover (Fig. A.4), observed soil texture-driven gradient of topsoil SOC content is also visible within individual altitude and land cover classes, with a slightly less obvious trend for grasslands.

The average topsoil SOC content in humus-rich soil types in Slovakia is 2.29% (78.3 t ha^{-1}), with 90% of measurements ranging between 1.0% (36.5 t ha^{-1}) and 4.36% (116.8 t ha^{-1}). The average topsoil concentration (stock) of SOC in other soil types of Slovakia is 2.02% (69.5 t ha^{-1}), with 90% of measurements ranging between 0.87% (35.2 t ha^{-1}) and 3.92% (117.0 t ha^{-1}). Topsoil SOC content in humus-rich soils generally shifted slightly toward higher SOC content values, compared to other soil types, with differences in arithmetic means, medians, standard deviations, and sample distributions all found to be statistically significant, except for standard deviations of SOC stock and for SOC concentrations (Table 4). The difference between the topsoil SOC content distributions analysed separately for SOC concentration (%) and stock (t ha^{-1}) could be explained by the stone content, with the areas of stony soils corresponding geographically to areas of other soil types

Table 4
Statistical significance of differences between arithmetic means (*t*-test), medians (Wilcoxon test), standard deviations (F-test), and sample distributions (Kolmogorov-Smirnov test) of the topsoil SOC concentration (%) and stock (t/ha) between individual classes within the macro-scale stratification levels, 1—statistically significant difference at $p < 0.05$, 0—no statistically significant difference.

Measure	Stratification level	Arithmetic mean	Median	Standard deviation	Sample distribution
SOC concentration (%)	Altitude	1	1	1	1
	Land cover	1	1	1	1
	Topsoil texture 1*	0	0	0	0
	Topsoil texture 2*	0	1	1	1
	Topsoil texture 3*	0	1	1	1
	Soil type	0	0	0	0
SOC stock (t ha^{-1})	Altitude	1	1	0	1
	Land cover	1	1	1	1
	Topsoil texture 1*	0	0	0	0
	Topsoil texture 2*	1	1	1	1
	Topsoil texture 3*	1	1	1	1
	Soil type	1	1	0	1

* Due to the difference in the number of observations in the topsoil texture classes (coarse, medium, and fine) the statistical significance was tested separately for coarse and medium soils (Topsoil texture 1), medium and fine soils (Topsoil texture 2), and coarse and fine soils (Topsoil texture 3).

(Figs. A.2 and A.3).

3.2. Topsoil SOC stock in agricultural land in Slovakia

Topsoil (0–30cm) SOC stock estimated for macro-scale regions from the 2018 CMS-P data (Table 5) varies across a range of 18.70 t ha^{-1} to 191.53 t ha^{-1}, with the majority of values being between 43.59 t ha^{-1} and 90.61 t ha^{-1} (10th and 90th percentile). The median and arithmetic mean of topsoil SOC stock for overall agricultural land soils in Slovakia are 69.35 t ha^{-1} and 72.93 t ha^{-1}, respectively. Both medians and arithmetic means of topsoil SOC stock estimated for individual macro-scale geographical regions generally follow the trends observed in the gradients of individual SOC accumulation drivers (Fig. 2). Some observed exceptions that do not follow the expected topsoil SOC content along the elevation and land cover gradients can be attributed to specific soil conditions (e.g., extreme soil texture in case of LGCO, LACO, LAFH, and LAFO regions), or as in case of LAFO, LGCH, LGFH, or also LGFO to very limited number of CMS-P observations for these regions giving in a result biased estimate.

Topsoil (0–30cm) SOC stock in macro-scale geographical regions of Slovakia was also estimated without assuming the volume of stones (Table 5). The volume of stones is a soil-related factor which can affect SOC stock and assumes that stones are an inert volume without any accumulated SOC, which also makes SOC stock (t ha^{-1}) partly independent from SOC concentration (%) measured in fine-earth soil samples. Regional figures show that topsoil stoniness is mainly of importance in macro-scale geographical regions in grasslands, where differences between reduced and non-reduced SOC stocks could be as high as 7–20 t ha^{-1}, compared with arable land regions where differences range between only 0–2 t ha^{-1}.

Topsoil SOC stock (t ha^{-1}) upscaled to geospatial coverage of macro-scale regions of Slovakia (Fig. 3a) shows the highest values (> 90 t ha^{-1}) in lowland regions (river alluvia) of south-east Slovakia, south-west Slovakia, and also locally in the north of country, all characterized by fine-textured, deep soils, and/or soils with high soil organic carbon content (Fig. A.2). Carbon-rich and medium-textured soils mainly in hilly locations in the lowland region had topsoil SOC stock ranging from 70 to 90 t ha^{-1}, whereas a topsoil SOC stock of only 50–70 t ha^{-1} spatially corresponded to soil types not rich in carbon and to mountain regions with higher topsoil stone content (Figs. A.2 and A.3). The lowest (< 50 t ha^{-1}) topsoil SOC stock was estimated for the shallow and stony soils of the mountain region and also locally in the coarse-textured or stony soils of the lowland region (Figs, A.2 and A.3). The geospatial pattern of topsoil SOC stock observed with median values was also preserved with the topsoil SOC stock estimates using the SOC stocks for 75th percentile, but it was less obvious with the estimates using 25th percentile topsoil SOC stock values (Fig. A.5), pointing to the uncertainty associated with regional estimates based on a limited number of observations.

3.3. Current topsoil SOC stock in administrative regions of Slovakia

Obtaining a regional estimate of topsoil SOC stock (t ha^{-1}) or storage (Mt) for a combination of administrative regions (LAU1, administrative districts) and a macro-scale stratification region could provide a very useful and practical overview of which carbon-related policies and/or

Table 5
Topsoil (0–30cm) SOC stock (t ha^{-1}) in agricultural land of individual macro-scale geographical regions of Slovakia calculated from CMS-P data; values in brackets were not reduced by the volume of stones in a topsoil layer and were used for regional topsoil SOC stock estimate with spatially explicit stoniness data.

Region	MIN	Q25	MEDIAN	MEAN	Q75	MAX	Count
HA00	48.92 (54.35)	61.03 (76.00)	76.57 (77.99)	77.39 (88.03)	85.13 (95.34)	121.85 (152.31)	12
HG00	48.86 (54.29)	67.09 (79.60)	85.02 (102.63)	89.39 (106.85)	102.25 (119.51)	191.53 191.53)	39
LACH	50.83 (56.48)	53.77 (57.34)	71.48 (72.92)	70.75 (72.88)	88.45 (88.45)	89.20 (89.20)	4
LACO	40.48 (42.61)	44.03 (45.09)	47.58 (47.58)	47.15 (47.86)	50.48 (50.48)	53.39 (53.39)	3
LAMH	21.25 (25.67)	61.54 (62.94)	70.28 (73.14)	72.90 (76.89)	86.76 (90.42)	150.98 (188.72)	81
LAMO	19.69 (24.44)	49.42 (50.39)	58.07 (60.02)	59.18 (61.89)	68.16 (70.36)	117.05 (117.05)	81
LAFH	69.43 (69.43)	78.13 (81.07)	89.86 (90.88)	89.65 (93.81)	98.68 (98.81)	116.67 (155.56)	14
LAFO	–	–	109.93 (109.93)	109.93 (109.93)	–	–	1
LGCH	–	–	104.13 (104.13)	104.13 (104.13)	–	–	1
LGCO	18.95 (25.27)	27.45 (27.45)	32.23 (32.23)	44.63 (45.89)	69.90 (69.90)	74.59 (74.59)	5
LGMH	18.70 (33.72)	70.16 (77.96)	90.70 (111.53)	86.34 (109.51)	113.58 (137.10)	137.10 (174.74)	9
LGMO	33.05 (33.05)	52.47 (63.65)	80.11 (87.25)	77.40 (88.84)	100.55 (108.46)	145.49 (169.85)	52
LGFH	60.53 (99.20)	61.51 (99.62)	62.50 (100.04)	62.50 (100.04)	63.49 (100.46)	64.48 (100.88)	2
LGFO	63.32 (84.42)	71.71 (87.54)	80.10 (90.65)	80.10 (90.65)	88.49 (93.77)	96.88 (96.88)	2
Slovakia	18.70 (24.44)	54.84 (58.77)	69.35 (77.01)	72.93 (80.53)	88.38 (97.35)	191.53 (191.53)	306

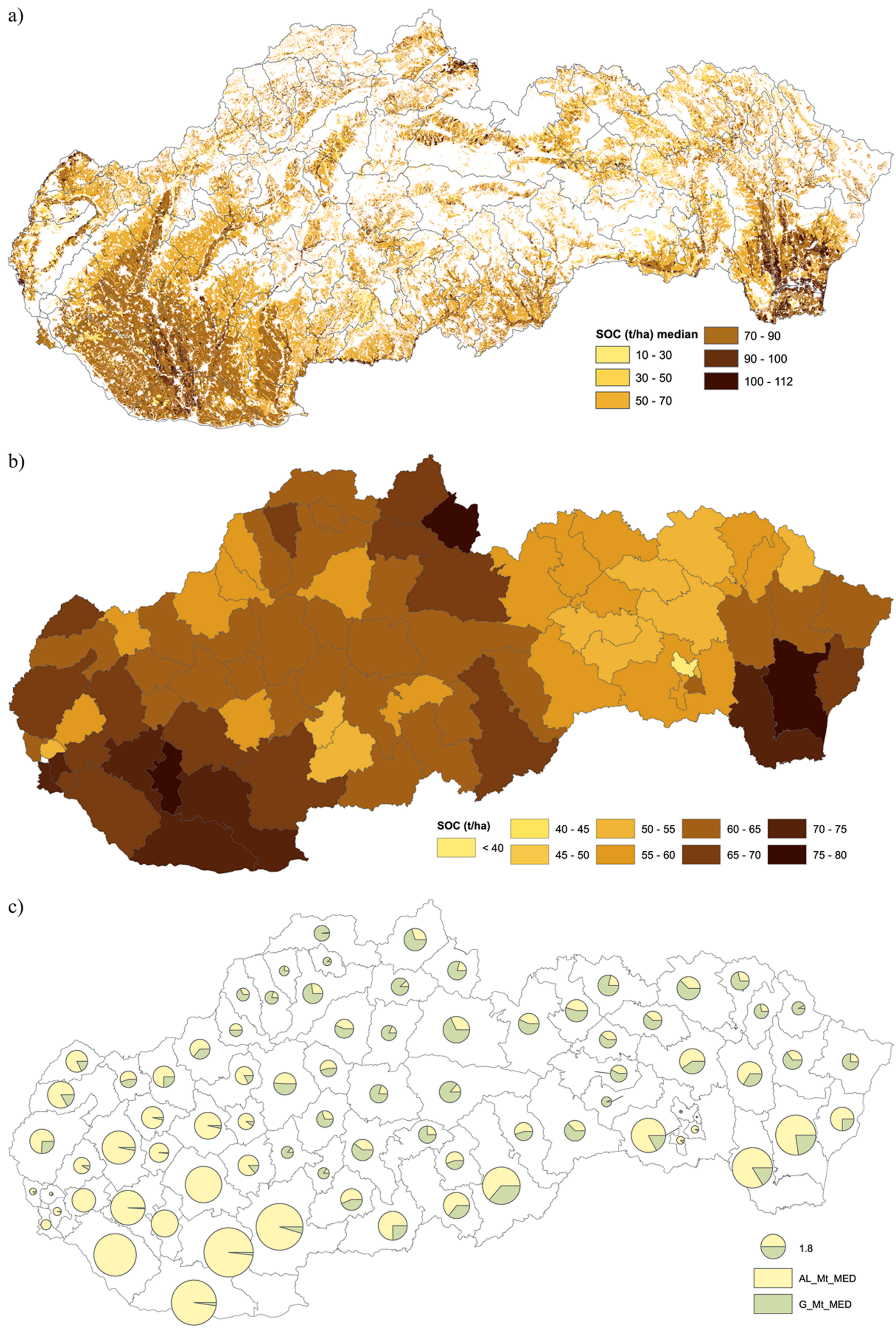

Fig. 3. Topsoil (0–30cm) SOC content in the agricultural soils of Slovakia, estimated from the 2018 CMS-P data for macro-scale geographical regions: a) spatial pattern of the topsoil SOC content (t ha^{-1}) for macro-scale geographical regions (median estimate) reduced by volume of stones; b) as (a) but aggregated as area weighted mean value for LAU1 administrative regions (administrative districts); c) as (a) but aggregated separately for arable land (AL) and grassland (G) as total topsoil SOC stock (Mt) for LAU1 administrative regions (administrative districts).

targeted soil and land use management measures should be prioritized during their implementation and also where.

Aggregated across the agricultural land of the LAU1-level administrative regions (administrative districts, Fig. 3b), the highest average topsoil SOC stock (> 65 t ha^{-1}) was estimated for the administrative districts located in south-west and south-east Slovakia, corresponding mainly to lowland regions with humus-rich soil types. The average regional topsoil SOC stock of 50–60 t ha^{-1} was estimated for most of the administrative districts of mountain regions and lowland regions where soils without a high humus content are prevalent. Only a few administrative districts showed average regional topsoil SOC stocks of lower than 50 t ha^{-1}. A similar geospatial pattern was also observed when topsoil SOC stock was analysed separately for arable land and grassland, and with the alternating use of median, 25th, and 75th percentile values for regional estimates (Fig. A.6).

The total storage of topsoil SOC in Slovakian agricultural soils was estimated at 118.39 Mt and ranged between 0.1 and 7.0 Mt for individual LAU1 regions, with an average LAU1-level topsoil SOC storage estimated to be 1.8 Mt (Fig. 3c). Two-thirds of total topsoil SOC in agricultural soils in Slovakia is stored in the (mainly) arable soils of 33 south-west, south, and south-east lowland LAU1 regions (Fig. 3c).

Regional topsoil SOC storage gradually decreases toward the LAU1 regions in the north of the country, with a slight east–west gradient of decreasing in regional topsoil SOC storage also visible. The proportion of topsoil SOC stored in grasslands also increases toward the north and north-east, with grasslands contributing to total regional topsoil SOC storage by 0–5% in LAU1 regions in the Danube lowlands in the south-west of the country to 70–98% in LAU1 regions in the Carpathian mountains in the north of country (Fig. 3c). Use of the 25th and 75th percentile values of topsoil SOC stock to calculate total topsoil SOC storage shows a similar pattern to median topsoil SOC values (Fig. A.7). However, using the 25th and 75th percentile input values respectively, the amount of topsoil SOC estimated for Slovakia is 1.5 Mt (97.96 Mt) and 2.1 Mt (142.33 Mt), and compared to the median value of 1.8 Mt and the country total of 118.39 Mt), it also indicates an uncertainty range of +/- 20%.

4. Discussion

4.1. Evaluation of the CMS-P data representativity for robust topsoil SOC estimates

The topsoil SOC storage estimates for macro-scale geographical regions (or administrative regions) of Slovakia presented in this study are based on a limited number (N=306) of CMS-P point observations (Fig. A.1). The CMS-P monitoring network sites selection in early 1990s followed soil–landscape representativity rules in the sense that the number and location of monitoring sites were supposed to represent all the major soil–landscape types of Slovakia (Kobza, 1995, 2015; Linkeš et al., 1997; Bielek et al., 2005; Kobza et al., 2017, 2019). Nevertheless, the primary purpose of CMS-P at that time was the monitoring of soil contamination and the hygiene status of the soils, and this could have biased the final selection of monitoring sites.

Only slight differences (both positive and negative) were observed in the distribution of CMS-P site numbers (relative to total%) when compared to the distribution of agricultural land area (relative to total %) in individual macro-scale geographical regions (Fig. 4). This suggests that CMS-P monitoring sites offer good representativity of general macro-scale conditions for topsoil SOC accumulation captured by the macro-scale geographical regions. A possible limitation of CMS-P data utilization for robust regional estimates of topsoil SOC content could, however, be the insufficient total number of CMS-P sites available for individual macro-scale geographical regions, with some represented by as little as one (LAFO, LGCH), two (LGFH, LGFO), or up to five (LACO, LACH, LGCO) CMS-P monitoring sites (Table 5).

4.2. Importance of assumed drivers for SOC accumulation in SLOVAKIA

Altitude was selected in this study as a proxy for climate drivers of topsoil SOC content (both concentration and stock) and proved to be a statistically significant predictor (Fig. 2, Table 4). A comparison of long-term temperature and precipitation and corresponding altitudes for a set of 10k spatial resolution climate grids from Slovakia (Nováková, 2007) at approximate locations of climate stations representative of agricultural land (Fig. A.8), demonstrates the very close relationship between yearly average temperature and yearly precipitation sum, and altitude. The large volume of published research shows that in many other regions of the world, altitude is also a better indicator of SOC accumulation than climate parameters alone, as it integrates the effects of temperature and precipitation while also reflecting other important site-specific effects on topsoil SOC accumulation (Leifeld et al., 2005; Barančíková and Makovníková, 2013; De Brogniez, et al., 2014).

The impact of major land use types on topsoil SOC content (both concentration and stock) was also proven to be statistically significant according to our results, showing land cover to be an important macro-scale topsoil SOC predictor for Slovakia. This applies both when individual land cover types were analysed alone (Fig. 2), and when a land cover class was combined with other assumed drivers (altitude, topsoil texture, soil type). In the latter case, the topsoil SOC content observed for grasslands was, in most cases, higher than that in arable soils found

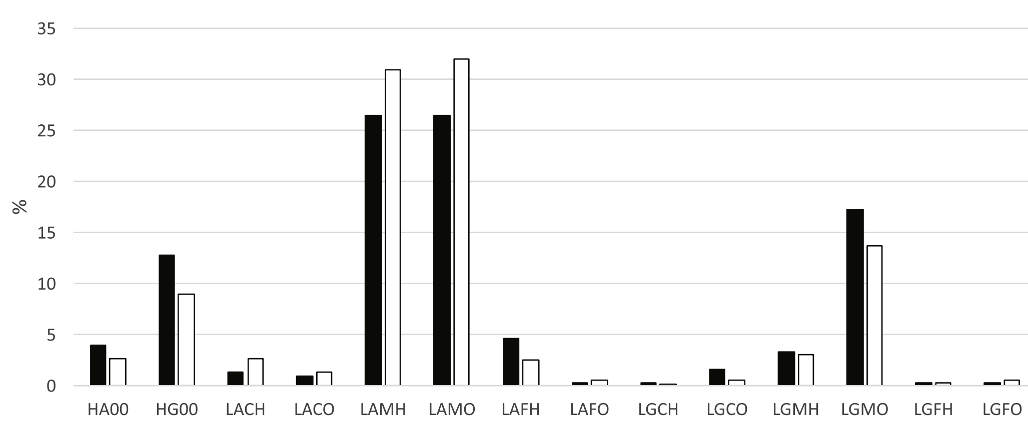

Fig. 4. Representativity of the CMS-P data, distribution of the relative number of CMS-P monitoring sites (%), and the relative area of agricultural soils (%) across the macro-scale geographical regions of topsoil SOC accumulation (as a percentage of total number of CMS-P sites or a percentage of total area of agricultural land in Slovakia).

in the same site conditions (Table 5). Moreover, other published research demonstrates that human activity has an important effect on topsoil SOC accumulation in, for instance, managed landscapes (arable land, grassland, forest), with still more pronounced effects of human activity in intensively managed agricultural soils (Guo and Gifford, 2002; Poeplau et al., 2011; Poeplau and Don, 2013; Maillard and Angers, 2014; Wei et al., 2014; Barančíková et al., 2019a). Meadows, pastures, and forests have a high SOC accumulation potential, whereas in intensively used arable soils, topsoil SOC content is usually low (Schils et al., 2008; Barančíková et al., 2019a,b).

Regional differences in topsoil SOC content (both concentration and stock) in Slovakian agricultural soils are also well explained by topsoil texture alone (Fig. 2), or in combination with other drivers (altitude, land cover, soil type) (Table 5). Topsoil SOC content increases from coarse through medium to fine textured soils, namely that an increasing proportion of clay and fine silt particle size fractions in fine earth provides better conditions for SOM stabilization, as also suggested by other authors (Arrouays et al., 2006; Zinn et al., 2007; Tayebi et al., 2021). Soil type also proved to be a good and significant predictor of topsoil SOC stock in Slovakia (Fig. 2)—a soil type that also integrates factors other than humus content, such as stones, might also affect the amount of SOC storage in topsoil. A given soil type, even in the absence of other soil characteristics, can still be an effective predictor of SOC accumulation (Mayes et al., 2014; Wiesmeier et al., 2013; Barančíková et al., 2019a). Topsoil stone content, which is included in spatial analyses, but not directly assumed in macro-scale stratification, proved to be an effective predictor in terms of improving local estimates, as it showed consistently lower estimates of topsoil SOC stock (t ha^{-1}) for grassland and higher-altitude regions (i.e., above 600m), where topsoil was assumed to include stones, as compared with estimates that did not assume stones in topsoil (Table 5). This is in line with Barančíková et al. (2019b) for selected sites and soil types in Slovakia.

4.3. Caveats and outlook

The methodological approach to mapping topsoil SOC presented in this study is somewhat simplistic, as it follows very straightforward assumptions about the relationship between topsoil SOC accumulation and its long- and short-term regional drivers. The simple class-area map quantification used for the CMS-P data upscaling algorithm relies purely on broad and well-known relationships between topsoil SOC accumulation and its drivers and is implemented using pre-classified spatial data on topography, soil, and land cover.

The selection of a simplistic method for the algorithm was due in part to the limited number of available CMS-P observations—there are only 318 observation sites for whole of Slovakia (i.e., one site per 7500ha of agricultural land). We contend that this seriously limits any successful utilization of the more formalized and quantitative algorithms for digital soil mapping that are available and widely used for SOC mapping (McBratney et al., 2003; Brus et al., 2017; Hengl et al., 2017). Even if only four environmental predictors are considered, each with two or three individual classes, some combinations of predictors were represented by as few as one, two, or three observations from the CMS-P dataset. These shortcomings must be taken into consideration before any practical utilization can take place or when the results are interpreted. Even though the final estimates of topsoil SOC content are representative of the major soil–landscape regions of Slovakia (or administrative regions at LAU1 level) and indicate general trends of regional potentials or limits of topsoil SOC accumulation, they are unlikely to be indicative of any particular location/site, as the algorithm widely neglects the short-distance variability of the topsoil SOC accumulation (e.g., topographic position, ground water table presence, fine-scale soil type, soil texture, and land use patterns) which at a local level could outweigh the impacts of the assumed macro-scale drivers.

Regardless of above-mentioned caveats, the regional estimates of the topsoil SOC stock in Slovakian agricultural soils and the methodological framework presented in this study represent an important step toward practical utilization of the national monitoring data for national and regional SOC inventories. In the absence of other relevant and up-to-date data on topsoil SOC content, CMS-P will serve, at least until new and better targeted SOC monitoring programs are launched, as a basic source of official SOC-related information for Slovakia.

The temporal record of topsoil SOC content is available in 5-year intervals starting in 1993 for all CMS-P monitoring sites (Kobza, 1995, 2015; Linkeš et al., 1997; Bielek et al., 2005; Kobza et al., 2017, 2019). This record can be processed effectively using the methodological framework presented in this study, with macro-scale geographical regions serving as a robust basis for analysis of the drivers of the short-term temporal dynamics of topsoil SOC accumulation as controlled over the last 30 years by land cover and land use change.

Several previous published research papers from Slovakia show that the RothC model can be successfully combined with national-, regional-, or local-scale input data on initial topsoil SOC stock, clay content, organic carbon input to the soil, and monthly climate data; it can be utilized as a tool for historical analysis or future prediction of climate change and management impacts on spatio-temporal dynamics of topsoil SOC stock in agricultural soils (Barančíková et al., 2010, 2012; Skalský et al., 2020). The macro-scale geographical regions and estimated topsoil SOC content presented in this study can be directly utilized as inputs for simulation of historical or future trajectories of topsoil SOC stock in regions of Slovakia.

5. Conclusions

A regional estimate of the topsoil SOC stock (t ha^{-1}) and integral topsoil SOC (Mt) using the stratified predictors and 2018 CMS-P data was conducted for the 78 LAU1 regions of Slovakia and provided the most up-to-date regional figures on the state of the topsoil SOC in agricultural soils of Slovakia.

The data from the most recent monitoring cycle of the CMS-P (year 2018) suggest that topsoil SOC accumulation in agricultural soils in Slovakia is controlled by altitude, soil types, soil texture, and land cover.

The highest topsoil SOC stock (> 90 t ha^{-1}) was estimated in lowland alluvial positions in south-east Slovakia, the central part of Danube lowland in south-west Slovakia, and locally also in the north of country; the lowest (< 50 t ha^{-1}) topsoil SOC stock was found to be in shallow and stony soils of hillslope positions of the Carpathian mountains. Total SOC storage in 0–30cm topsoil of agricultural land in Slovakia was estimated to be118.39 Mt. Two-thirds of this amount is stored in arable soils of south-west, south, and south-east LAU1 administrative regions, and only one-third in arable or grassland soils in the LAU1 administrative regions in the north of the country.

Without any alternative, up-to-date dataset for topsoil SOC in Slovakian agricultural land, an effective and reliable upscaling algorithm employing the CMS-P for regional topsoil SOC inventory is of crucial importance (at least for the time being) for informing land sector policies and their implementation. Moreover, the regional averages (or distributions) of the topsoil SOC content that were produced based on the most recently available CMS-P data could become a direct input (mainly, but not only) for predicting the region-specific future or alternative topsoil SOC accumulation trajectories under a variety of assumed scenarios of climate change, and/or land cover and land use change using process-based or statistical modelling.

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CRediT authorship contribution statement

Rastislav Skalský: . **Gabriela Barančíková:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Jarmila Makovníková:** Writing – original draft, Writing – review & editing, Investigation. **Štefan Koco:** Investigation, Writing – original draft, Writing – review & editing. **Ján Halas:** Investigation, Writing – original draft, Writing – review & editing. **Jozef Kobza:** Investigation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2023.100816.

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