Original paper

NATIONAL CONTRIBUTION OF SLOVAKIA TO THE GLOBAL SOIL ORGANIC CARBON SEQUESTRATION POTENTIAL MAP

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Abstract

Soil organic carbon (SOC) is important component of soil which affects its properties and also is an important part of global carbon cycle. SOC was recognized as indicator of sustainable development in the frame of the UN Agenda 2030. In 2020 the first global topsoil SOC sequestration map has been established by the Intergovernmental Technical Panel on Soils (ITPS), the Global Soil Partnership (GSP), and the United Nations' Food and Agriculture Organization (FAO) from national contributions of its members. Contribution of Slovakia represents the implementation of selected national spatial data in terms of the methodology created by the above-mentioned organizations. National sources of climate, soil (clay content, initial SOC), and partly also land use data were used as inputs for the RothC model to estimate SOC sequestration potential in agricultural soils. According to the obtained results, the topsoil (0,0-0,3 m) annual sequestration potential of SOC in agricultural soils of Slovakia is in range from 0.01 to 0.14 Mt C yr^{-1}, depending on theoretical scenarios of soil carbon inputs. The current version of the SOC sequestration potential map for Slovakia still has got some limitations, mainly coming from the national data used, the methods of their processing, and it needs to be continuously updated.

Keywords: Global Soil Partnership, map of soil organic carbon sequestration, agricultural land, soil organic carbon modelling, RothC model, national soil inventory data, Slovakia

INTRODUCTION

Soil organic carbon (SOC) sequestration refers to the process of transferring carbon dioxide (CO_2) from the atmosphere into the soil as a land unit through plant residues and other organic materials which are stored or retained in the land unit as a part of the SOC with a long mean residence time so that it is not re-emitted back into the atmosphere" (Lal 2018). Alongside climate regulation and adaptation, maintaining or increasing soil organic carbon (SOC) stocks in agricultural lands is crucial to soil health (FAO & ITPS 2020), to secure the delivery of several ecosystem services and to enhance the resilience of the productive systems (Bossio *et al.* 2020, Smith *et al.* 2021). At the global or regional level estimates of the agricultural soils sequestration potential vary widely ranging between 0.1 and 3 Gt C yr^{-1} (e.g., Sommer & Bossio, 2014, Poeplau & Don 2015, Kämpf *et al.* 2016, Smith 2016, Conant *et al.* 2017, Minasny *et al.* 2017, De Vries *et al.* 2018; Fuss *et al.* 2018, Batjes *et al.* 2018, Paustian *et al.* 2019b, Bossio *et al.* 2020, Lessman *et al.* 2021, Janzen *et al.* 2022). For this reason, countries need standardized and evidence-based global and national procedures for carbon sequestration estimation to guide research, investments by the private sector, and public policies. Several different studies have combined empirical or process-oriented

SOC models with spatial datasets to project and map SOC dynamics and the SOC sequestration potential in agricultural lands at country, regional and global scales (e.g., Gottschalk *et al.* 2012, Wiesmeier *et al.* 2016, Morais *et al.* 2019). Also, in the conditions of Slovakia the modelling of SOC stock can be an effective way of estimating changes in SOC and can be used in the prediction of SOC stock at a national scale (Barančíková *et al.* 2011a; Barančíková *et al.* 2013). Several modelling systems were implemented in the conditions of Slovakia, linking the RothC model and geographical data on soil, climate, and land management. The results have proven usefulness of the modelling systems for estimating potential changes of SOC stock in Slovak agricultural soils and for analyzing SOC response to human driven changes in land use within different climate and other natural conditions (Barančíková *et al.* 2011a; Barančíková *et al.* 2013). Balanced or positive SOC stock dynamics is one of the primary pre-conditions of sustainable use of soils in Slovakia and SOC stock could be influenced positively or negatively by political measures set for the agricultural sector on the EU or national level (Barančíková *et al.* 2012).

Globally, a strong divide exists between countries with enough resources and technical expertise to establish such modeling frameworks and those still lagging. In this sense, the Intergovernmental Technical Panel on Soils (ITPS), the Global Soil Partnership (GSP), and the United Nations' Food and Agriculture Organization (FAO) have established the GSOCseq initiative, working directly with nationally mandated institutions to model and map SOC sequestration potential in agricultural soils at a national scale (Peralta *et al.* 2020). At the core of this country-driven approach is the need to address extremely diverse and regional SOC dynamics by fostering and leveraging not only local data but also expertise.

The main goal of this paper is to describe Slovak national implementation procedures of quantifying SOC sequestration potential on a national basis for a global and official report and the resulting Slovak SOC sequestration potential of agricultural lands to global Global Soil Organic Carbon Sequestration map (GSOCseq).

MATERIAL AND METHODS

Characteristics of studied area

Slovakia is landlocked country in Central Europe. It is bordered by Poland to the north, Ukraine to the east, Hungary to the south, Austria to the west, and the Czech Republic to the northwest. Slovakia's territory spans 49,035 square kilometers, with a population of over 5.4 million. The territory of Slovakia is made up of lowlands (40%) and highlands and mountains (60%). The lowest point is located at 94 m above sea level (mouth of the river Bodrog from the territory of Slovakia). The highest point is Gerlachovský štít in the High Tatras mountains (2,655 m above sea level) (Michaeli 2008).

According to IPPC classification (IPCC 2006) most of the territory of Slovakia is in Cool Temperate Moist climate zone. Southern parts of national territory reach out to Cool Temperate Dry and Warm Temperate Dry zone. Average annual temperature ranges between -3 °C in high mountain positions to 11 °C in the lowlands. Average annual precipitation ranges from less than 500 mm in the lowland areas in the south to approximately 2,000 mm in the high mountain positions at the northern part of country (SHMU 2021).

According to national database of agricultural areas (Land Parcel Identification System – LPIS) the total agricultural area in 2020 was 1,913,341 ha. Of this, 1,344,660 ha was cropland, 547,782 ha permanent grassland, 13,290 ha vineyards, 7,469 ha orchards, and 140 ha hop gardens.

Cambisols are predominant soil type in Slovakia and cover almost 45% of the national territory. The second most abundant soil type is represented by Rendzic Leptosols with a share about 11%. More than 20% of the area of Slovakia is covered by Fluvisols, Chernozems, Planosols, and Molic Fluvisols (Granec & Šurina, 1999). Clay content in agricultural soils ranges between 6 to 65% (Balkovič *et al.* 2010) with the most of soil units having medium or medium fine texture.

Estimated topsoil SOC stock in soils of Slovakia ranges between 18 t $C.ha^{-1}$ and 655 t $C.ha^{-1}$ with its spatial pattern mainly determined by land cover (mosaic of agricultural areas and forests). The average SOC stock in topsoil layer of agricultural soils is 45.36 t $C.ha^{-1}$. The integral SOC stock in the 0,0 –0,3 m topsoil layer was estimated at 0.302 Pg, while the SOC stock is slightly lower in agricultural soils (0.113 Pg) than in forest soils (0.189 Pg) (Skalský *et al.*, 2017). However, these values are based on results from the National Agricultural Soil Inventory, the first systematic and country-wide inventory of agricultural soil resources in Slovakia dates to 1960-ies (Němeček *et al.* 1967, Skalský & Vopravil, 2014). On the other hand, the current National Monitoring System of Agricultural Soils (Kobza *et al.* 2019) values are higher.

SOC data requirements and spatial framework for data harmonization

FAO's effort was to create a global map of SOC sequestration from national contributions. For these purposes, a spatial framework (a regular grid of 1 × 1 km squares) and the content of the data that will be used in the evaluation of the sequestration potential were agreed upon. One or more national expert(s) were appointed directly by the national representative of the International Network of Soil Information Institutions (INSII) and by the GSP National Focal Point. The proposed approach was translated into scripts for open-source software (R, QGIS, Google Earth Engine) and is available in the following GitHub repository: https://github.com/FAO-GSP/GSOCseq-scripts. GSOCseq v1.1 was generated from the national submissions after a quality control/quality assessment procedure carried out by the GSP secretariat, ITPS and INSII, described in Peralta *et al.* (2022).

The approach was based on the studies by Smith *et al.* (2005; 2007b) and Gottschalk *et al.* (2012). In order to obtain repeatable, consistent, standardized and harmonized results, and allow comparisons between countries and regions, and due to differences in computational, technical capacities and data availability, the RothC model (Coleman & Jenkinson, 1996) was used as a standard SOC model. An R-language-based version of the RothC model included in the SoilR package (Sierra *et al.* 2012) of the R software (R core team 2020) was used to model SOC changes.

National data inputs

Final SOC sequestration outputs, including maps, tables, and graphs, as well as uncertainty assessment were produced according to guidelines from Technical Manual Global Soil Organic Carbon Sequestration Potential Map GSOCseq (Peralta *et al.* 2020). Slovak national sources of climate, soil (clay content, initial SOC), and partly also land use data were used as inputs for the RothC model. Other necessary input data were used from global sources following the recommendations from Peralta *et al.* (2020).

Daily climate data from the national network of 65 meteorological stations representative for agricultural areas were used for the model. Variables were interpolated to 10 x 10 km spatial resolution grid using CGMS version 9.2 (Baruth *et al.* 2007, Nováková 2007) and subsequently resampled to 1 km resolution. Data available at daily time step were aggregated to monthly values for the whole simulation period of 1980-2020 and all RothC mandatory variables included:

- monthly average of mean air temperature (°C)
- monthly sum of rainfall (mm)
- monthly sum of crop canopy transpiration (mm)

Existing dataset of clay (Ø < 0,002 mm) distribution in topsoil of agricultural soils of Slovakia was used as an input of clay content (%) data for the model. Model was calculated from soil profile records (clay contents, A horizons only) of National agricultural soil inventory (in total 16 264 georeferenced records). Final raster map at 1 km (30 arcsec) spatial resolution was validated only for agricultural soils (Balkovič *et al.* 2010). Initial SOC stocks in 0,0-0,3 m deep topsoil layer (t C ha^{-1}) was derived from the national contribution of Slovakia to FAO GSOCmap (national contribution to the topsoil SOC stock global map (Skalský *et al.* 2017, Yigini *et al.* 2017). Topsoil SOC content was estimated based on available point observations and soil map, and it brings comprehensive information both for agricultural and forest soils (Skalský *et al.* 2017). It reflects base year 1970 for agricultural land and base year 2000 for forests. Observed range of SOC stocks in cropland and grassland mineral soils according to national agricultural soil monitoring data is from 14 to 176 t C ha^{-1} (National Monitoring System of Agricultural Soils, Kobza *et al.* 2019). Initial SOC stock layer contains also values outside this range (up to 655 t C ha^{-1}) due to the fact, that areas of organic soil were also included.

The annual distribution of vegetation cover was derived from NDVI (normalized difference in vegetation index) values using time series of MODIS (MOD13A2) satellite images obtained via Google Earth Engine at 1 km spatial resolution. Time series represented period between 2000 and 2020. The NDVI threshold value for indicating active vegetation growth was set at 0.35 to best represent the local conditions of Slovakia. European Space Agency 2000 to 2018 (ESA CCI Land cover) data with land use change simulation was used as an input for land use change reconstruction. ESA CCI Land cover data at spatial resolution of 300 m in the agricultural land area were further refined with the data from national LPIS database available for all years between 2004 and 2020).

Modelling approaches

Final product constitutes national contributions for global map that depicts the average projected annual SOC changes from 2020-2040, for three sustainable soil management (SSM) scenarios that vary in the degree of carbon inputs to the soil compared to business as usual (BAU) carbon inputs, in global croplands and grazing lands, for the top 0,0-0,3 m of mineral soils, at 1 x 1 km spatial resolution. No climate change scenarios were projected (Peralta *et al.* 2020). The modeling approach consisted of three phases: long spin-up, warm-up and forward phases. In the spin-up phase RothC was run iteratively to equilibrium to calculate the amount of the annual carbon inputs (Ceq) required to reach initial SOC stocks (SOC stocks at year 2000) to initialize the model. Temporal harmonization of SOC stocks was performed as a second initialization step (warm up phase) to minimize differences between stocks from the GSOCmap and SOC stocks at year 2020 (i.e., initial SOC stocks in the simulations). SOC stocks from the GSOCmap were considered here to be representative of the stocks twenty years prior to the simulation start (t = -20 y; i.e., year 2000). A 20-year run was performed to adjust for major deviations among different measurement periods on the GSOCmap using monthly climatic conditions for the period 2001-2020, and land use during the 2000-2020 period. In a third phase (forward phase), SOC stock changes due to SSM practices were projected for 20 years, using average mean monthly climate variables (2001-2020), land use representative of year 2020 and C inputs estimated from the above-mentioned modeling phases. No land use change, or climate change scenarios were assumed. SOC stocks were simulated from 2020 (t=0) to 2040 (t = +20) for a business as usual (BAU) scenario and for three scenarios which represented a percent increase from BAU C inputs (5 % (SSM1), 10% (SSM2) and 20% (SSM3) increase in C inputs.)

RESULTS AND DISCUSSION

Slovakia participated as one of 49 countries which provided their national submission (representing 55 % of the global agricultural area). Other estimates generated by GSP Secretariat for countries that agreed to take part in the GSOCseq initiative but could not submit a national product in time (representing additional 37% of the global agricultural area) were also used in final global map. Considering both national submissions and GSP estimates, 92 % of global agricultural area was covered.

Figure 1 shows maps of the SOC stock ($t.ha^{-1}$) that depicts the average projected annual SOC changes from 2020-2040. Three SSM scenarios that vary in the degree of carbon inputs to the soil and business as usual (BAU) carbon inputs, in croplands and grazing lands of Slovakia were modeled. Result in topsoil (0,0-3 m) of mineral soils, at 0.0083° (~ 1 x 1 km) spatial resolution and was provided as a national input of the Slovak Republic for the compilation of the GSOCseq v1.1 global map. No climate change scenarios were used, assuming that major divergences in SSP-RCP (shared socioeconomic pathway-representative concentration pathway) scenarios are expected to occur only after 2050 (IPCC, 2018).

The obtained absolute sequestration rates values simulated with RothC for Slovakia territory are lower than the published data from experimental sites (Barančíková *et al.*, 2011b; Barančíková *et al.* 2014, Halas *et al.* 2018). In Slovakia observed sequestration potential ranges from 0.11 to 0.49 $tC.ha^{-1}.yr^{-1}$ with average value 0.30 $tC.ha^{-1}.yr^{-1}$ (GSOCseq v1.1) is still higher as SSM +20% scenario (Peralta *et al.* 2020) results (0.22 $tC.ha^{-1}.yr^{-1}$).

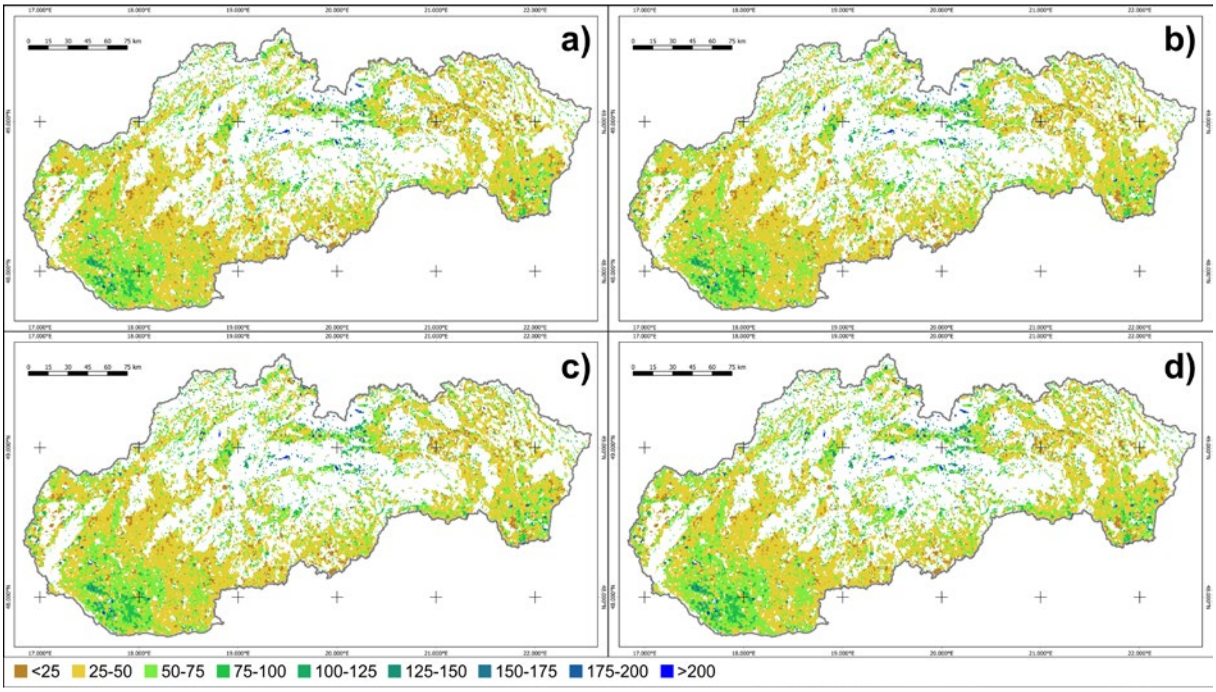

Figure 1 Final SOC stocks after 20 years with uncertainties (tC.ha^{-1}) in the top 30 cm, for business as usual (BAU; a) C input and after 20 years of increasing carbon inputs to soils by 5% (SSM1; b), 10% (SSM2; c) and 20% (SSM3; d), on agriculture land of Slovakia

Topsoil SOC stock in upper 0,3 m in mineral soils of Slovakia ranges from 14 to 176 tC.ha^{-1} (National Monitoring System of Agricultural Soils, Kobza *et al.* 2019). Initial total SOC stocks for running RothC model was derived from the national contribution of Slovakia to GSOCmap (30 arc seconds; ~ 1km x 1km resolution grid). This map also reports on organic soils (about 0.5% of the total number of 1km grid of agricultural land) with maximum SOC stock values up to 655 tC.ha^{-1} (Skalský *et al.* 2017). These spatial units outside the national range of SOC stock of mineral soils also exceeded the recommended range of output values according to Annex II Quality assurance and quality control of Technical Manual Global Soil Organic Carbon Sequestration Potential Map GSOCseq (Peralta *et al.* 2020). After excluding organic soils from the final quality control, all resulting ranges of values met the recommended limits according to Annex II Quality assurance and quality control of the Technical Manual Global Soil Organic Carbon Sequestration Potential Map GSOCseq (Peralta *et al.* 2020). The results reflect the natural conditions of Slovakia well. The highest average SOC stocks occur in the mountain regions, followed by mountain valleys. The smallest SOC stocks were found in the lowland, intensively agriculturally used areas of Slovakia (Table 1).

Table 1

Average annual SOC stock (on a per area basis in t.ha^{-1}) after 20 years of increased C inputs (SSM1: +5%; SSM2 +10%; SSM3: +20%), for elevation regions of Slovakia.

Region	**BAU**	**SSM1**	**SSM2**	**SSM3**
Lowlands	46.4	47.2	47.9	49.6
Valleys	47.5	48.2	48.6	50.4
Mountains	54.4	55.3	56.1	57.8

SOC sequestration (t C ha^{-1} yr^{-1}) was evaluated as the average annual difference in SOC stocks under increased carbon inputs (SSM scenarios) with respect to BAU projections in the same time frame. Considering the estimates from all the represented agricultural land in GSOCseq v1.1 for Slovakia, increasing C inputs by 5% (SSM1), 10% (SSM2) and 20% (SSM3) during the next 20 years could lead to an additional SOC sequestration of 0.20, 0.39 and 2.71 Mt C, compared to BAU practices. This would represent an annual sequestration potential from 0.01 to 0.14 Mt C yr^{-1} (Table 2).

Table 2

SOC sequestration potential in Slovakia agricultural lands according to the GSOCseq v1.1 at year 2040 and after 20 years of increased C inputs scenarios (SSM1: +5%; SSM2 +10%; SSM3: +20%).

Scenario	**Total SOC sequestered (SSM vs BAU)**	**Annual SOC sequestration rates (SSM vs BAU)**		**Annual SOC sequestration rates per area (SSM vs BAU**
	Mt C	*Mt C yr^{-1}*	*% yr^{-1}*	*t C ha^{-1} yr^{-1}*
SSM1	0.20	0.01	0.02	0.004
SSM2	0.39	0.02	0.05	0.008
SSM3	2.71	0.14	0.32	0.057

Figure 2 depicts the distribution of the expected annual SOC sequestration rates under the three SSM scenarios is Slovakia. In comparison with the business of usual scenario, the soils of the mountainous regions of Slovakia have the highest sequestration potential. Lowland soils have also got high sequestration potential (Table 3). However, these are agriculturally intensively used areas and for this reason it is necessary to focus on the implementation of sustainable agricultural management practices in these regions, which will support the increase of carbon sequestration into the soil in these territories of Slovakia such as suitable crop rotation and addition of external carbon input (manure/compost) on arable land and optimal grazing capacity on pasture.

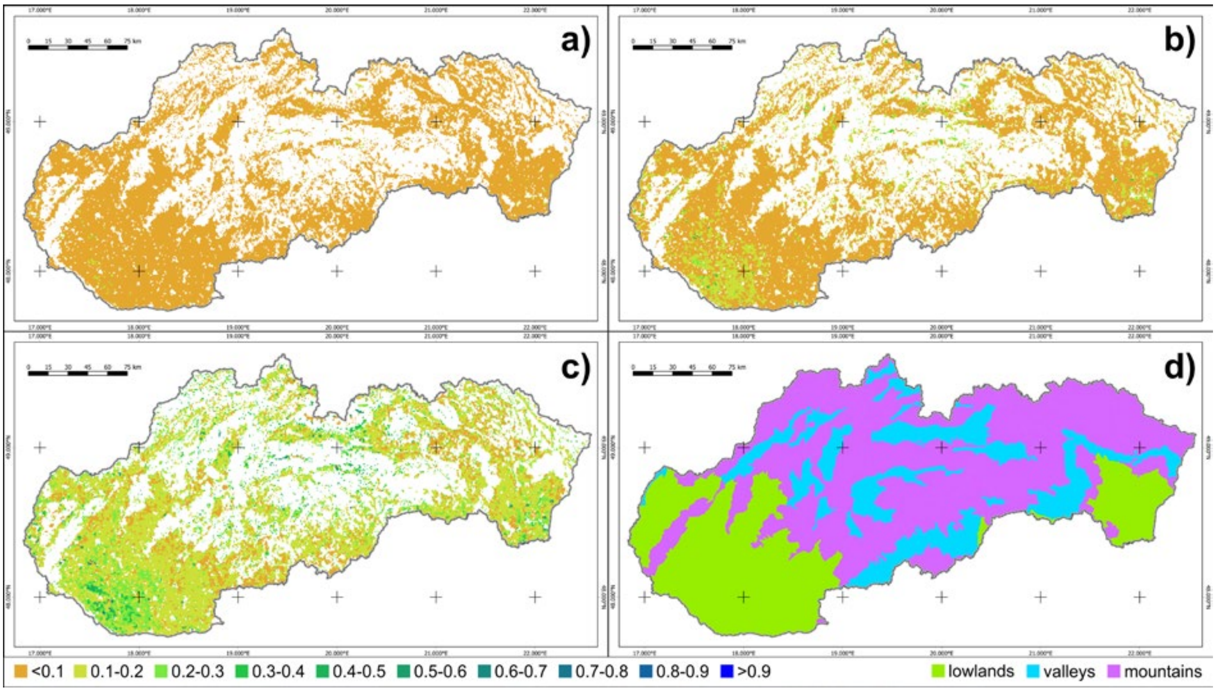

Figure 2 Annual average soil organic carbon sequestration rates (tC.ha^{-1}.yr^{-1}) in the top 30 cm, after 20 years of increasing carbon inputs to soils by 5% (SSM1; a), 10% (SSM2; b) and 20% (SSM3; c), on agriculture land of Slovakia. Elevation regions of Slovakia (d).

Table 3
Average annual SOC sequestration (on a per area basis in t.ha^{-1}yr^{-1}) after 20 years of increased C inputs (SSM1: +5%; SSM2 +10%; SSM3: +20%), for elevation regions of Slovakia.

Region	SSM1	SSM2	SSM3
Lowlands	0.04	0.07	0.15
Valleys	0.03	0.06	0.13
Mountains	0.05	0.09	0.16

The map of SOC sequestration (Fig. 2) represents a potentially very important piece of information that can form the starting point for carbon emission monitoring within international activities aimed at monitoring development and combating climate change (e.g., UNFCCC, UNCCD, SDG). It is therefore important to be aware of the limitations and uncertainties that the current version of the estimate brings. In conditions of Slovakia, the important uncertainty of the estimate is that the observations of SOC stocks on agricultural land come from the 1961-1970 period. It is known that there has been a development in the last 50 years and these values may be higher or lower today depending on the type of soil (Barančíková *et al.* 2010). It is therefore necessary to devote further attention to the inventory of current SOC stocks within the territory of Slovakia, both at the level of collecting new up-to-date data from actual soil sampling of soil monitoring (Kobza *et al.*, 2019), as well as to methods for processing the resulting spatial estimate, such as digital soil mapping methods with an aid of remote sensing data (Skalský *et al.* 2017), or process modeling of the of SOC stock dynamics over time (e.g., Barančíková *et al.* 2010, 2012, 2013). Such an approach is currently being solved within the URANOS project, and the first preliminary results on SOC sequestration on agricultural soils in Slovakia will be available in 2024.

CONCLUSION

GSOCseq constitutes the first global participatory effort to assess the SOC sequestration potential and associated GHG mitigation in global agricultural lands following a country-driven, gridded, model-based approach. The process encouraged countries (including Slovakia) to gather information that was in many cases scattered, to generate national spatial layers which will be useful for other projects, promoted inter-institutional interaction within each country, and created a favorable environment for experts around the world to exchange knowledge on SOC sequestration.

Based on the FAO methodology for determining SOC sequestration (Peralta *et al.*, 2020), national contribution of Slovakia to the GSOCseq v.1.1 was processed and presented in this study. National sources of climate, soil (clay content, initial SOC), and partly also land use data were used as inputs for the RothC model which was utilized for estimating SOC sequestration potential in agricultural soils of Slovakia.

According to the obtained result annual sequestration potential of agricultural soils in Slovakia is in range from 0.01 to 0.14 Mt C yr^{-1}. Agricultural soils in mountainous areas have the highest sequestration potential. The agriculturally most used lowland areas in the south-west and south-east of Slovakia were also found having high sequestration potential, but in these areas the sequestration of carbon into the soil must be supported by appropriate land management practices.

Current version of the national contribution of Slovakia into GCOCseq v1.1 map still has limitations coming from the national data used, as well as the methods of data processing, and it will be necessary to devote further attention to SOC inventory at national scale.

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