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Evaluation of Soil Organic Carbon Changes on Key Monitoring Sites

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Monitoring of soil organic carbon (SOC) is a part of the Partial Monitoring system – Soil (ČMS-P). ČMS-P consists of two subsystems. One of them is a subsystem of the key monitoring sites (16) in sampling repetition every year. The key monitoring localities cover all soil types, soil use (cropland, grassland) and a wide range of altitudes (111 – 975 m). In 16 key monitoring localities the content of SOC in topsoil is measured every year. This article shows the development of SOC content for a 30-year period on all key monitoring sites, separately on cropland, grassland and sites with land use changes, in lowland (< 300 m) and mountain soils (> 300 m). The 30-year monitoring period was divided into three time periods. On all key monitoring localities, separately on grassland and cropland and on lowland and mountain soils, the lowest median SOC content in the first time period was found. The reason could be substantial changes in Slovakia´s agriculture, mainly a sharp drop in organic fertiliser consumption on 90-ties. Between the first and second time period, SOC content is statistically significantly increased. We assume that it was caused by the state subsidy policy to increase the content of organic matter in the soil. Between the second and the third time period, changes of SOC content were negligible. Our results also show that the main driving forces affecting SOC content are altitude (statistically significantly higher SOC content on mountain soils compared to lowland), land use and land use changes (statistically significant higher SOC content on grassland compared to cropland).

Key words: soil organic carbon, monitoring, land use changes, altitude, cropland, grassland

Soil organic matter (SOM) represents a balance between inputs (plant and animal residues), on the one hand, and outputs such a mineralisation and leaching, on the other hand. In intensively used agricultural soils, mainly cropland, SOM is only a small percentage of soil mass; however, SOM impact on all soil ecosystem services, including soil fertility, regulating soil services such as water holding capacity and climate regulation, is crucial (Campbell & Paustian 2015; Srivasta *et al.* 2016; Kopittke *et al*. 2022). Depending on its use, soil can sequester or emit greenhouse gases and regulating these flows is extremely important for ongoing climate change. Soil organic carbon (SOC), as a basic element of SOM, is a key component of soil health and soil quality (Chevalier *et al.* 2016; Lal 2016; Razaghi 2022). Currently implemented strategies for global organic carbon sequestration are increasingly relevant for climate change mitigation as well as for improving food production (Moinet *et al.* 2023). The EU also supports the sequestration of organic carbon in soil through the Green Deal (2019), and SOC is included as one of the main soil descriptors in the proposal for a Directive of the European Parliament

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and of the Council on Soil Monitoring and Resilience, Soil Monitoring Law (Directorate-General for Environment 2023).

Soil organic carbon is affected by natural conditions and human activities (Eckelmann *et al.* 2006; Tayebi *et al.* 2021). The main natural factors affecting SOC dynamics are soil properties, climate characteristics and geographic factors (Poeplau & Don 2015).

As regards soil properties, important predictors of SOC can be parent material (Gray *et al.* 2016; Adhikari *et al.* 2019) and soil types (Mayes *et al.* 2014; Wiesmeier *et al.* 2014; Ottoy *et al*. 2022). The importance of parent material for SOC storage lies mainly in the silica content of the former due to weathering and geological source (Schulp *et al*. 2009). Soil type can be associated with SOC storage in the whole soil profile (Schulp *et al.* 2009; Wiesmeier *et al*. 2014) and can be a good indicator, which integrates with a wide range of soil properties that influence SOC stock formation (Wiesmeier *et al.* 2013; Mayes *et al.* 2014). In one of our previous studies (Barančíková *et al*. 2019a) on three soil types, it was found that across all evaluated ecosystems (cropland (C), grassland (G) and forest), the highest SOC content [%] was detected in Haplic Chernozem, followed by Eutric Cambisol and Luvic Stagnosol in decreasing order.

Next important soil parameters that influence the formation of SOC storage are soil texture (Wiesmeier *et al.* 2019; Ledo *et al*. 2020; Wyngaard *et al.* 2022, and many others). It can be said that the amount of SOC stock can be assessed from the fine fraction characteristic of soil texture, and many studies found a significant correlation between SOC stock and clay content (Arrouays *et al.* 2006; Tayebi *et al*. 2021; Skalský *et al.* 2024).

Climate conditions, in particular temperature and precipitation, are next to natural key factors controlling SOC content on global and regional levels through their impact on carbon input and its decay in soil (Jobagy & Jackson 2000; Allen *et al.* 2013; Doetterl *et al.* 2015; Hobley *et al*. 2015; Meersman *et al*. 2016; Koven *et al*. 2017; Yigini *et al*. 2017; Funes *et al.* 2019; Ledo *et al.* 2020). Humid conditions increase the formation of SOC, stabilising mineral surfaces by intensified weathering of the parent material (Doeterl *et al.* 2015). Temperature affects decomposition of SOM, and many studies indicated a decrease in SOM with increasing temperature (Jobbágy & Jackson 2000; Wei *et al.* 2014; Gray *et al.* 2016; Koven *et al.* 2017). Higher temperatures accelerate the decomposition of SOM; consequently, in soil, organic matter mineralisation processes predominate over humification processes (Webb *et al.* 2003). Some regional (Hobley *et al.* 2015) as well as global (Jobbágy & Jackson 2000; Koven *et al.* 2017) studies report a significant relationship between average annual precipitation and SOC stocks. Other studies report a stronger relationship between SOC supply and temperature (Allen *et al*. 2013; de Brogniez *et al.* 2014; Ledo *et al.* 2020). In general, the level of SOC accumulation is higher in colder and wetter regions, medium in warmer and wetter regions, and lowest in dry and hot regions (Wiesmeier *et al*. 2019).

In this context, it is clear that altitude may be a better indicator of SOC reserves than climate parameters alone are, as it integrates the effects of temperature and precipitation while reflecting erosion and accumulation processes that are important factors in the spatial distribution of soil types as well as soil depth (Leifeld *et al*. 2005; Barančíková & Makovníková 2013; de Brogniez *et al.* 2014; Kuhnel *et al.* 2019; Wiesmeier *et al.* 2019; Wust-Galley *et al.* 2019; Skalský *et al.* 2024).

In the present time, besides natural indicators impact of human activities represents a significant effect on SOC content, mainly coming land use (cropland, grassland, forest), changes in land use, and, in the case of intensively used agricultural soils, soil management (Guo & Gifford 2002; Poeplau *et al.* 2011; Maillard & Angers 2014; Wei *et al.* 2014; Barančíková *et al.* 2019a,b; Skalský *et al.* 2024). From the point of soil use, grassland (meadows, pastures) and forests have high SOC accumulation potential. On the other hand, SOC content in intensively used cropland is substantially low, and cropland can usually be a source of organic carbon (Schils *et al.* 2008).

Bensalma (2024) reports that, compared to soils under natural vegetation, under the same environmental conditions, intensively used cropland has a lower SOC content compared to grasslands/meadows/pasture and forest ecosystems. In our previous study, it was found that the same soil type under identical agroclimatic conditions contains the lowest SOC content on cropland, higher on grassland and the highest SOC content was found in forest (Barančíková *et al.* 2019a).

SOC content is mostly affected by land use changes (Seitz *et al.* 2025). Guo and Gifford (2002) based on meta-analyses, show that the conversion of pasture to arable land has decreased SOC by up to 59%. Loss of SOC content after conversion of natural ecosystems into agricultural land has been confirmed by many others as well (Poeplau *et al.* 2011; Wei *et al.* 2014; Barančíková *et al.* 2016; Meersman *et al.* 2016; Bouchmons *et al.* 2017; Ledo *et al.* 2020; Dou *et al.* 2025).

The main source of SOC in agricultural soils is decomposition of plant residues and application of manure (Schulp & Verbung 2009; van Wesemael *et al.* 2010; Wang *et al.* 2013; Banwart *et al.* 2015; Dechow *et al.* 2019). The substantial reasons of SOC loss in cultivated soils are erosion, lower C inputs in croplands, reduced stabilization of SOM due to deteriorated aggregation and following mineralisation stimulated by increased of soil temperature and aeration (Hamza & Anderson 2005). At present, due to the incorrect structure of the crop rotation system, reduction in the supply of exogenous organic matter and deterioration of the overall management of agricultural land lead to a gradual loss of organic matter on intensively arable soils. On the other side, many studies show that organic farming, sustainable land management practices, which including crop rotation diversity (Tiemann *et al.* 2015; Jimenez-Gonzáles *et al.* 2023; Guistiniani *et al.* 2024; Mavsar *et al.* 2025), mulching, supply of organic matter and organic fertilisers to the soil (Berti *et al.* 2016), crop rotation with inter-crops (Slepetiene *et al.* 2024), diversified crop rotation (Šimon *et al.* 2024), cover crops (Poeplau & Don 2015; Valkama *et al.* 2020; FAO 2021; Baartman *et al.* 2022; Seitz *et al.* 2023; Budai *et al.* 2024; Fohrafellner *at al.* 2024), soil fertility management, rotary grazing, cultivation of perennial crops with inter-crops (Ledo *et al.* 2020; Seitz *et al.* 2023), temporary grassland in rotation (Launay *et al.* 2021), control of wind and water erosion, the application of soil protection technologies (Jarecki & Lal 2003; Valkama *et al.* 2020), and external carbon input as compost (Banwart *et al.* 2015; Tifenbacher *et al.* 2021), manure (van Wesemael *et al.* 2010; Maillart & Angers 2014; FAO 2021; Tifenbacher *et al.* 2021; Liang *et al.* 2024; Šimon *et al.* 2024), straw (Wang *et al.* 2021; Lin *et al.* 2024), municipal waste (Kowalska *et al.* 2020), sewage sludge application (Lecciolle Paganini *et al.* 2024), biochar (Budai *et al.* 2024) or agroforestry (FAO 2021; Lesaint *et al.* 2023; Dmuchowski *et al.* 2024), together with changes in tree species (Francviglia *et al.* 2019) can significantly affect the dynamics of topsoil SOC accumulation in intensively used agricultural soils. A region-specific approach, including the importance of identifying and overcoming sociotechnical barriers, and accepting bio-physical limits that may be expanded by innovation should be considered (Heller *et al.* 2024).

Based on the mentioned facts, it can be concluded that altitude, as a natural factor and soil use, as an anthropogenic factor, can be two main driving forces affecting SOC content.

In Slovakia, information on the content and quality of SOM can be obtained from the Partial Monitoring System – Soil (ČMS-P) starting in 1993. ČMS-P consists of 2 basic subsystems:

- the basic network of monitoring sites (318) in a 5-year sampling repetition, mainly on agricultural soils,
- key monitoring sites (16) in sampling repetition every year.

On a basic network of monitoring sites, SOC concentration is determined on topsoil (0 – 0.1 m) and under the plough layer (0.35 – 0.45 m). In key monitoring localities, SOC concentration is measured only on topsoil (Kobza *et al.* 2024). In this paper, we will focus on the differences in SOC content on key monitoring localities and the development of SOC on these localities during a 30-year monitoring period.

The goal of this study is to find out:

a) if altitude as a natural factor and soil use as an anthropogenic factor can be considered as key driving forces affecting SOC content on key soil monitoring sites,

b) development of SOC content on key monitoring sites among three time periods.

MATERIAL AND METHODS

Key monitoring sites are in different agro-climate regions and cover all main soil types of agricultural soils of Slovakia (Figure 1). On soil types, with higher representation in Slovakia, there are more localities, on Cambisols and Stagnosols are 4 localities, on Fluvisols, three localities. On Chernozem, Phaeozem and Regosol is only 1 key monitoring locality. In the case of Stagnosol and Cambisol, key monitoring localities are located on cropland and grassland, on Fluvisol, Chernozem, and Phaeozem, which are used mainly for intensive cropland, key monitoring localities are only on cropland. The subsystem of key monitoring localities consists of 19 sites; however, SOC content is measured every year on 16 of them.

For the evaluation of SOC differences according to altitude and land use point of view and for the evaluation of the development of SOC content for 30 years, 15 key monitoring localities were selected. Locality Macov was the key monitoring locality only in the time period 1993–2015. In 2016, this locality was removed (this area was exempted from agricultural soils) and 2016 was replaced by the locality Veľký Lég. Because the localities Macov and Veľký Lég consist of significantly lower numbers of SOC values than other localities, these localities were not included in the evaluation. A detailed description of the 15 key monitoring localities is shown in Table 1.

In key monitoring localities, SOC concentration [%] is measured every year on topsoil, 0–0.1 m. From the period 1993–2007, SOC concentration according to the Tyurin method (wet way) was measured. From 2008–2024, SOC concentration was measured on an Elemental analyser (dry way) (Kobza *et al.* 2011). Up to an organic carbon value of 3%, both methods give comparable results. Above 3% the dry method gives slightly higher values, because in soil samples with a higher content of SOC, complete oxidation by the wet method (Tyurin method) does not occur. When comparing SOC values in soil samples higher than 3% of SOC determined by the wet and dry methods, the conversion pedotransfer equation is used (Barančíková & Makovníková 2015). From all key monitoring localities, only in locality Sihla, during all 30-year period, SOC content was higher than 3%.

At the beginning of monitoring, the SOC content was not determined every year. To be able to divide the 30 years into three equal time periods, with a comparable number of SOC values, the first time period takes years 1993–2004 and this time period contains, on almost all key monitoring localities, 10 values of SOC. One key monitoring lo-

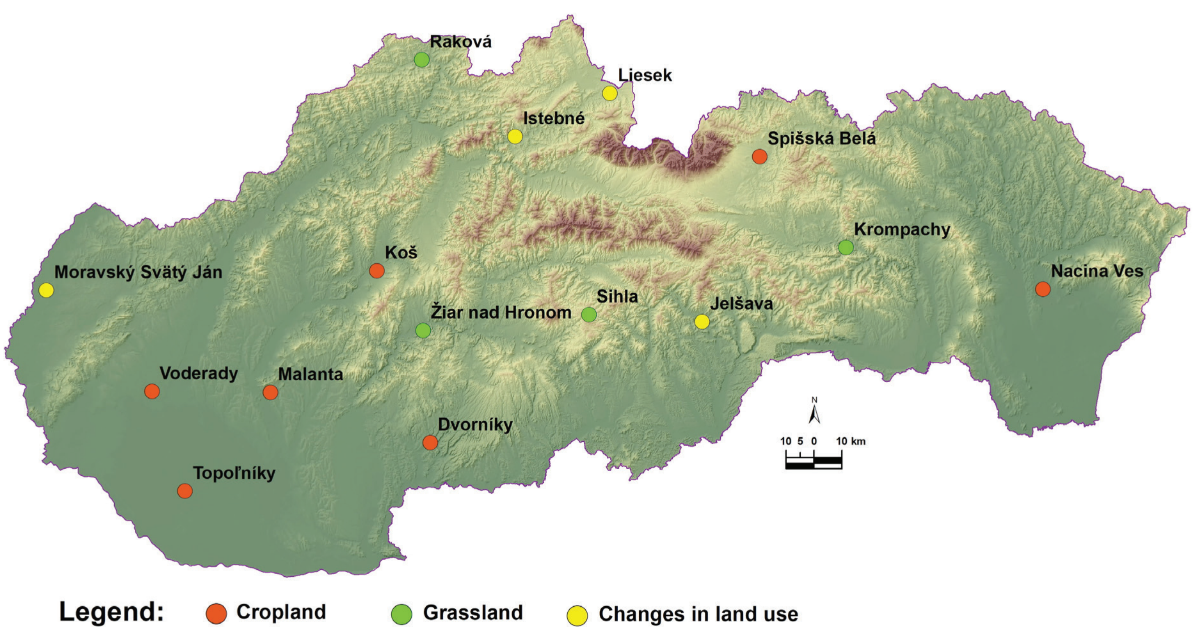

Figure 1. Rated key monitoring sites.

cality (Liesek) consists of 9 SOC values, and one key monitoring locality (Dvorníky) consists of 11 SOC values. The second time period (2005 – 2014) and the third time period (2015 – 2024) consist of 10 SOC values.

The created files did not meet the conditions of normality of the files; therefore, tests that work with the median of the files were used in further analysis and comparison of individual files across time periods. Kruskal-Wallis Test and Mood's Median Test were used for comparison between the three files. Wilcoxon W-test (to compare medians) and Kolmogorov-Smirnov Test (to compare the distributions of the two samples) were used to compare two files. The STATGRAPHICS CENTURION XV program for all statistical analyses was used.

RESULTS AND DISCUSSION

Overall Development of SOC Content on Key Monitoring Sites

On all 15 key monitoring sites, which included all main soil types on agricultural land of Slovakia,

Table 1

Detailed description of the evaluated key monitoring localities

Locality	Climate region	Altitude [m.s.l.]	Soil types (IUSS Working Group WRB 2015)	Soil use	Clay [%]
Žiar nad Hronom	warm, moderately humid, with mild winter	277	Luvic Stagnosol (Siltic, Albic)	G	18.37
Koš	warm, moderately humid, with mild winter	292	Haplic Planosol (Albic, Eutric, Siltic)	C	23.06
Jelšava	warm, moderately humid, with cool winters	289	Luvic Stagnosol (Albic, Siltic, Eutric)	C/G/C/G	17.01
Liesek	moderately cool	673	Haplic Stagnosol (Siltic, Eutric)	C/G/C/G	17.61
Raková	moderately warm, very humid, highlands	477	Haplic Cambisol (Skeletic, Dystric, Siltic)	G	16.48
Istebné	moderately warm, very humid, highlands	542	Stagnic Cambisol (Siltic, Eutric)	C/G	21.55
Sihla	moderately cool	975	Haplic Cambisol (Skeletic, Dystric, Siltic)	G	12.19
Krompachy	moderately warm, moderately humid, with a cold winter, valley/basin	390	Stagnic Cambisol (Siltic, Eutric, Skeletic)	G	15.96
Dvorníky	warm, moderately dry with mild winter	151	Gleyic Fluvisol (Anthric, Siltic, Calcaric)	C	18,.9
Topoľníky	warm, very dry, with mild winter	111	Haplic Fluvisol (Anthric, Calcaric, Siltic)	C	17.83
Nacina Ves	warm, moderately humid, with cool winters	121	Haplic Fluvisol (Enthric, Eutric, Siltic)	C	31.44
Spišská Belá	moderately cool	627	Haplic Phaeozem (Anthric, Eutric, Siltic)	C	18.56
Voderady	warm, very dry, with mild winter	134	Haplic Chernozem (Anthric, Siltic, Calcaric)	C	26.42
Malanta	warm, moderately humid, with mild winter	172	Cutanic Luvisol (Anthric, Siltic, Abruptic, Hypereutric)	C	27.54
Moravský Ján	warm, moderately dry with mild winter	170	Haplic Arenosol (Dystric)	C/G/C	5.55

C – cropland; G – grassland; WRB – World Reference Base for Soil Resources.

with different land use (cropland, grassland, localities with land use changes) and a wide range of altitude (111 – 975 m) median SOC content is the lowest in the first time period. Between the first and second time period, SOC content significantly increased, and this increase was statistically significant (Figure 2, Table 2). Negligible increase of SOC content was also detected between the second and third time period, but this increase was not statistically significant (Figure 2, Table 2). The same development of median SOC content, statistically significant increase between the first and second time period, was found on all key monitoring localities separately on cropland and grassland (Figure 2, Table 2).

Compared the second and third time period, median SOC content on cropland was at the same level and on grassland slight decrease was found. The changes between the second and third time period on all cropland and grassland were not statistically significant (Figure 2, Table 2).

In all three time periods, the SOC content on cropland was statistically significantly different, lower compared to grassland (Figure 2, Table 2). As it was mentioned above, higher input of plant and root residues in grassland soils stabilises the SOC content in the topsoil. Intensive agriculture, mainly lower input of organic matter, is a reason for substantially lower SOC content in cropland (Wiesmeier *et al.* 2019; Bensalma *et al.* 2024).

Also, when we divide key sites according to altitude, into lowland (<300) m a.s.l. and mountain soils (>300 m a.s.l.), a statistically significant difference was found, and an increase of SOC content between the first and second time periods was detected. SOC changes between the second and the third time periods were not statistically significant (Figure 2, Table 2). A gradual increase in median SOC content, in all time periods, was found only on mountain soils (Figure 2).

In all three time periods, the SOC content on the lowland was lower compared to mountain soils (Figure 2, Table 2). In the lowland temperature is higher compared to the mountain area. As reported by Wiesmeier (Wiesmeier *et al.* 2019), the level of SOC accumulation is higher in colder and wetter regions, which is characteristic of higher altitude, and lower in warmer and dryer regions, characteristic of areas of lower altitude. Higher median SOC content on key monitoring localities on mountain soils compared to lowland, agrees with many studies (Leifeld *et al.* 2005; Barančíková & Makovníková 2013; De Brogniez *et al*. 2014; Skalský *et al*. 2024).

That are many reasons for the low SOC content in the first time period on key monitoring sites. It could be intensive conventional soil cultivation (Aranda *et al.* 2011), deep ploughing (Causarano *et al.* 2006; Dou & Hons 2006), incorrect crop rota-

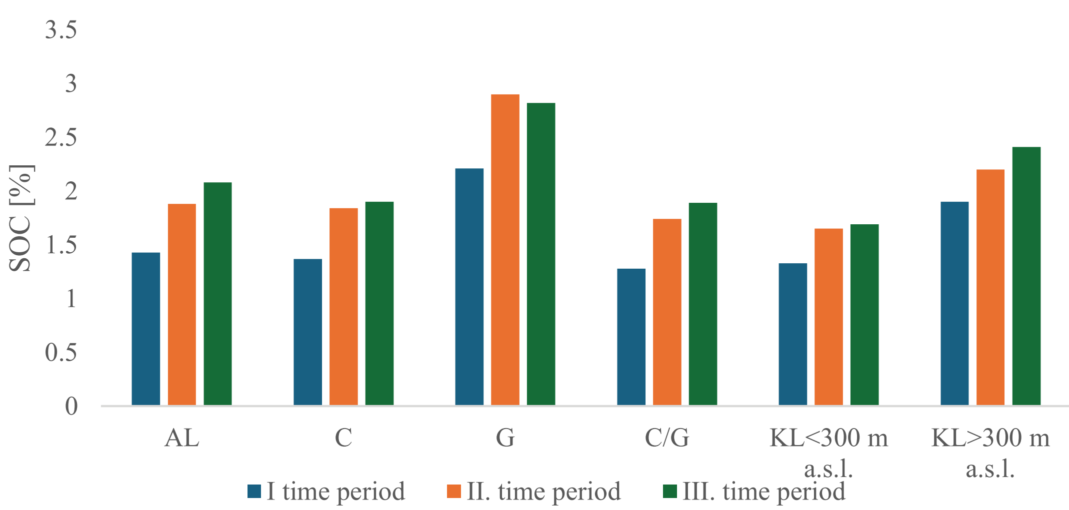

Figure 2. Development of median SOC [%] values during 3 time periods.
Note: C; G – see Table 1; AL – agricultural land; SOC – soil organic carbon; KL – key localities.

I.	time period: 1993 – 2004	AL – agricultural land
II.	time period: 2005 – 2014	C – cropland
III.	time period: 2015 – 2024	G – grassland

tion (Machado *et al.* 2006) or insufficient supply of quality organic matter (Stetson *et al.* 2012). In Slovak agriculture, the reason for the low SOC content in the first time period (1993 − 2004) on cropland could be conventional soil cultivation, monoculture cultivation on large agricultural areas and above all sharp drop in organic fertiliser consumption mainly on 90-ties (Bielek 2017). On grassland/pasture, low SOC content may be caused by inappropriate mowing time and grazing intensity (Soussana *et al.* 2006; Ward *et al.* 2016; Whitehead *et al.* 2018; Abdalla *et al.* 2021).

An increase in SOC content in the second time period can have multiple causes. An increase of SOC content on cropland can be achieved by crop rotation diversity (Abdalla *et al.* 2013; Tiemann *et al.* 2015), mulching, supply of organic matter and organic fertilisers to the soil (Tifenbacher *et al.* 2021; FAO 2021; Liang *et al.* 2024), soil fertility management, agroforestry, rotary grazing, cultivation of perennial crops (Ledo *et al*. 2020; Seitz *et al.* 2023; Dmuchowski *et al.* 2024), the application of soil protection technologies (Jarecki & Lal 2003; Valkama *et al.* 2020), and application of biowastes (Kowalska *et al.* 2020).

In Slovakia, after 2000 year the situation in Slovak agriculture partially stabilised since one of the priorities of the state subsidy policy was to increase the content of organic matter in the soil through organic fertilisation or the share of arable land on which soil protection technology is applied, which included incorporating post-harvesting residues (Kováč *et al.* 2010). The post-harvesting residues and root mass play an irreplaceable role in enriching the soil by SOM and is one of the key measures to achieve carbon sequestration identified in the Carboseq project (Seidel *et al.* 2025). Benslama (Benslama *et al.* 2024) and Mavsar (Mavsar *et al.* 2025) state that post-harvesting residues as one of the main measures to increase SOC content.

T a b l e 2

Comparison of SOC changes among individual time periods

Localities	I. – II.	II. – III.	I. – III.
KL total	+	0	+
KL C	+	0	+
KL G	+	0	+
KL <300 m a.s.l.	+	0	+
KL>300 m a.s.l.	+	0	+
KL C/KL G	+	+	+
KL <300 / m >300 m	+	+	+

KL – key localities + – statistically significant difference
C – cropland the 95% significance level
G – grassland 0 – statistically insignificant difference
Note: SOC – see Figure 2.

The reason for negligible changes in SOC content between the second and the third time periods could be climate change, mainly the increase in temperature and long dry periods predominantly in the lowland between the second and third time periods. In Slovakia, a significant increase in temperature, mainly in the lowland, especially after 2010, was detected (Barančíková *et al*. 2020). As reported by Webb (Webb *et al.* 2003), higher temperatures accelerate the decomposition of SOM; consequently, in soil organic matter mineralisation processes predominate over humification processes. Wiesmeier (Wiesmeier *et al.* 2019) states, the lowest SOC accumulation occurs in dry and hot regions.

The reason for the gradual increase of SOC content during all monitoring period on key monitoring sites of higher altitude could be lower temperature and higher humidity on mountain soils compared to the lowland (Leifeld *et al.* 2005; Barančíková & Makovníková 2013; de Brogniez *et al.* 2014; Skalský *et al.* 2024).

Development of SOC Content on Individual Key Monitoring Sites

a) Individual key monitoring sites on cropland and grassland

Most of the key monitoring sites (7) are located on cropland, and median SOC content on these localities is in a quite narrow range from 1.1 to 2.5% (Figure 3). The individual key monitoring localities represent different soil types (Koš – Haplic Planosol, Dvorníky – Gleyic Fluvisol, Spišská Belá – Haplic Phaeozem, Voderady – Haplic Chernozem), and only two of them (Topoľníky and Nacina Ves) are on the same soil type (Haplic Fluvisol).

On the grassland are only 4 key monitoring localities, and three of them are Cambisols (Raková and Sihla are Haplic Cambisol, Krompachy is Stagnic Cambisol) and one locality, Žiar nad Hronom,

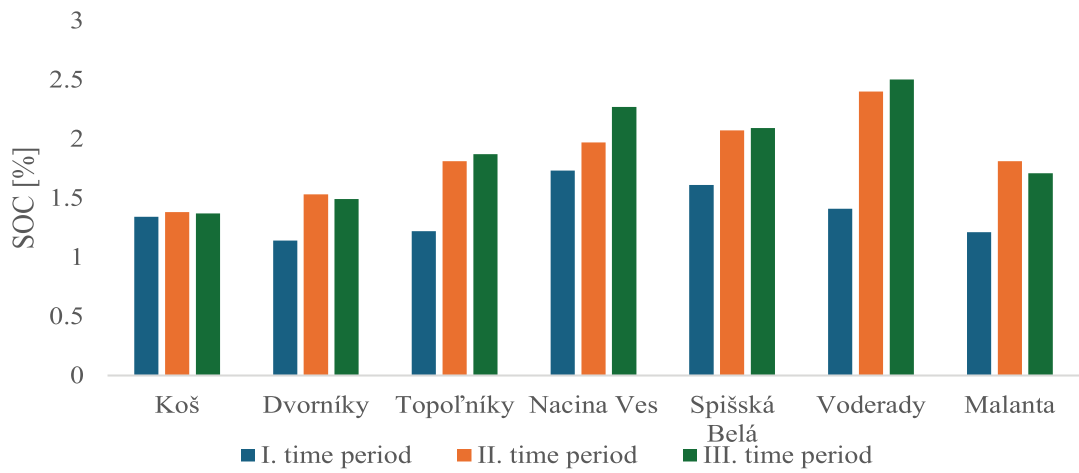

Figure 3. Development of median SOC [%] values on individual key monitoring localities on cropland.
Note: SOC – see Figure 2.

is Luvic Stagnosol. Cambisols are the most widespread soil type in Slovakia (Bielek 2017), and the largest number of monitoring localities are on Cambisols (Kobza *et al.* 2024). Cambisols are infertile soils located mainly at higher altitudes and are predominantly used as grassland/pasture (Bielek 2017). Median SOC content on grassland key monitoring localities is higher compared to cropland, and is in quite a wide range, 1.5 – 4.9% (Figure 4). The highest SOC content is in locality Sihla, which is located at the highest altitude (975 m a.s.l.).

Except for locality Koš (Haplic Planosol), at all other key monitoring localities on cropland, between the first and second time periods, development of SOC content has the same trend as overall SOC development, an increase of SOC content, and on 4 localities (Dvorníky, Topoľníky, Voderady and Malanta) this increase was statistically significant (Figure 3, Table 3). In the locality Koš, SOC content was stable during all monitoring period (Figure 3).

Between the second and the third time periods, SOC changes in individual localities were different. In three localities increase was detected, in two decrease and in two, no changes were detected (Figure 3). A statistically significant change was detected between the second and third time periods, an increase in the organic carbon content (SOC), at the Nacina Ves site (Figure 3, Table 3).

On all key monitoring sites on grassland-as on cropland, between the first and second time periods, SOC increases. Statistically significant difference, increase of SOC between the first and second time periods, was found on two localities, Žiar nad Hronom a Sihla (Figure 4, Table 4). The changes of SOC content between the second and third time periods on individual grassland key monitoring localities were negligible (Figure 4).

Only in the locality Raková gradual increase of SOC content, during all monitoring period, was found. In three key monitoring localities on grassland, statistically insignificant changes were detected (Figure 4, Table 4).

We assume that the increase of SOC content on all individual cropland between the first and sec-

Table 3

Comparison of SOC changes among individual time periods on individual key monitoring localities on cropland

Localities	I. – II.	II. – III.	I. – III.
Koš	0	0	0
Dvorníky	+	0	0
Topoľníky	+	0	+
Nacina Ves	0	+	+
Spišská Belá	0	0	0
Voderady	+	0	+
Malanta	+	0	0

+ – statistically significant difference the 95% significance level
0 – statistically insignificant difference
Note: SOC – see Figure 2.

ond time periods may be caused incorporation of post-harvesting residues on soils, or the application of external organic matter. These two measures are the most widespread on Slovak arable soils and can increase SOC content (Kováč *et al.* 2010; Sainju *et al.* 2012; Berti *et al.* 2016; Valkama *et al.* 2020; Bensalma *et al.* 2024; Mawsar *et al.* 2025). Decrease of SOC content between the second and the third period on Sihla locality (Figure 4) can be caused by ploughing the pasture in 2019 and then restoring the pasture in the next years. As reported by Guo and Gifford (2002), ploughing rapidly decreases SOC content, and after restoring SOC content can slowly increase.

b) Key monitoring localities with land use changes

During the 30-year monitoring period on 4 localities was found land use changes, while these changes in individual localities were different. Locality Jelšava (Luvic Stagnosol) in the period 1993 – 2003 was cropland, in the period 2004 – 2011 abandoned land, 2012 – 2018 again cropland and from 2019 until 2024 is pasture. Locality Liesek (Haplic Stagnosol) in the period 1993 – 1999 was cropland, 2000 – 2015 was sown clover grass mixture, 2016 – 2018 cropland, and from 2018 – 2024 again was sown clover grass mixture. Locality Istebné (Stagnic Cambisol) was cropland only at the beginning of the monitoring period (1993 – 1999), and from 2000 until 2024, on this site clover grass mixture is sown. The locality Moravský Ján (Haplic Arenosol) in the period 1993 – 2004 was cropland, in the period 2005 – 2011 was abandoned land, 2012 – 2016 cropland, 2017 – 2018 fallow and from 2018 is again cropland.

In key monitoring localities, with land use changes, SOC content, during all monitoring period, was the lowest in locality Moravský Ján (Figure 5). Soil type in this locality is Haplic Arenosol with very low clay content (Table 1), and among soil types of Slovak agricultural soils, this soil type has the lowest content of SOC. Quite low SOC content was found on locality Jelšava, soil type Luvic Stagnosol. Also, this soil type, mainly on cropland, is characteristic by low SOC content (Kobza *et al.* 2024).

The lowest average SOC content, on all localities with land use changes, just like on the other key monitoring localities, was found in the first period (Figure 5).

T a b l e 4

Comparison of SOC changes among individual time periods on individual key monitoring localities on the grassland

Localities	I. – II.	II. – III.	I. – III.
Žiar nad Hronom	+	0	0
Raková	0	+	+
Sihla	+	0	0
Krompachy	0	0	0

+ – statistically significant difference the 95% significance level
0 – statistically insignificant difference
Note: SOC – see Figure 2.

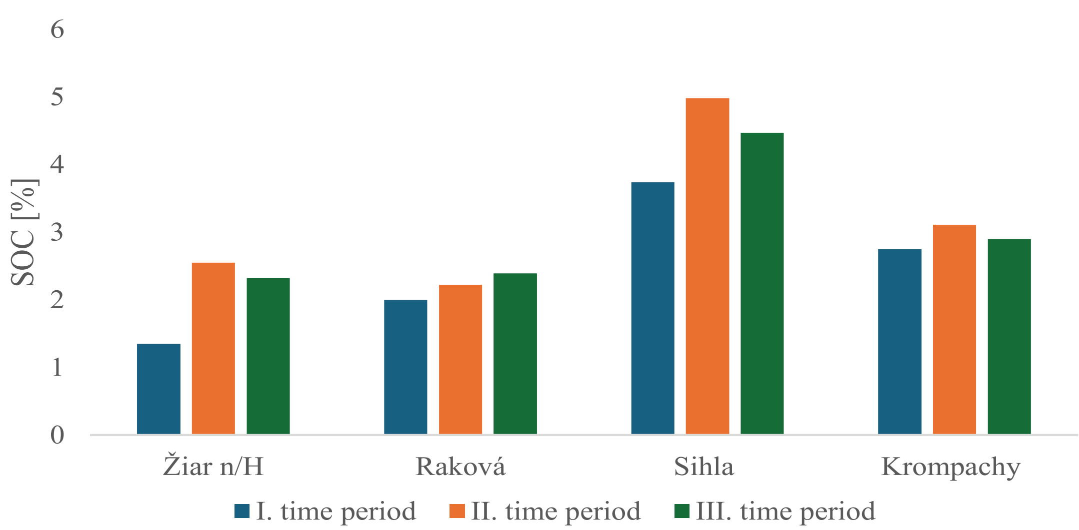

Figure 4. Development of median SOC [%] values on individual key monitoring localities on grassland.
Note: SOC – see Figure 2.

In locality Istebné, when cropland was only in the first period, SOC content gradually increased, mainly in the third period, and this increase was statistically significant (Figure 5, Table 5). In locality Jelšava, when land use was changed several times, and since 2019, it has been pasture, SOC low increase and changes between individual decades were not statistically significant (Figure 5, Table 5).

In locality Liesek, the lowest SOC content was detected in the first period. Most of the years of this period locality was cropland. In the second period locality was a clover grass mixture, and between the first and second time periods statistically significant increase of SOC on this locality was found. In the third period, 2 years were cropland and another year's grassland, while average SOC content remained at the level of the second time period (Figure 5). In locality Moravský Ján, SOC content increased between the first and second time periods, because in most years of the second time period, this site was abandoned land, and in the third time period, SOC content decreased, since 2018, this locality has again been cropland. SOC changes in this locality among individual time periods were not statistically significant (Figure 5, Table 5).

On all key monitoring sites, with land use changes, it is clearly visible that SOC content on topsoil is very sensitive to soil use. In natural conditions, SOC dynamics are affected by soil properties, climate characteristics and geographic factors (Poeplau & Don 2015), but due to anthropogenic interferences in the soil ecosystem, SOC content is largely influenced by land use (Bensalma *et al.* 2024). The effect of land use changes on SOC content was confirmed by many authors (Guo & Gifford 2002; Poepau *et al.* 2011; Poeplau & Don 2013; Maillard & Angers 2014; Wei *et al*. 2014; Barančíková *et al.* 2016; Barančíková *et al.* 2019b; Seitz *et al.* 2025). Guo and Gifford (2002) based on meta-analyses show that the conversion of pasture to arable land has decreased SOC by up to 59% and when converting cropland to pasture, SOC content will increase by 19%. Poeplau and Don (Poeplau & Don 2013) in their analysis of land use changes in Europe found that average SOC stock at the depth of 0.3 m increased by 18 Mg/ha when changing cropland to grassland. However, it should be noted that while the reduction in SOC

T a b l e 5

Comparison of SOC changes among individual time periods on individual key monitoring sites with land use changes

Localities	I. – II.	II. – III.	I. – III.
Jelšava	0	0	0
Istebné	+	+	+
Liesek	+	0	+
Moravský Ján	0	0	0

* – statistically significant difference the 95% significance level
0 – statistically insignificant difference
Note: SOC – see Figure 2.

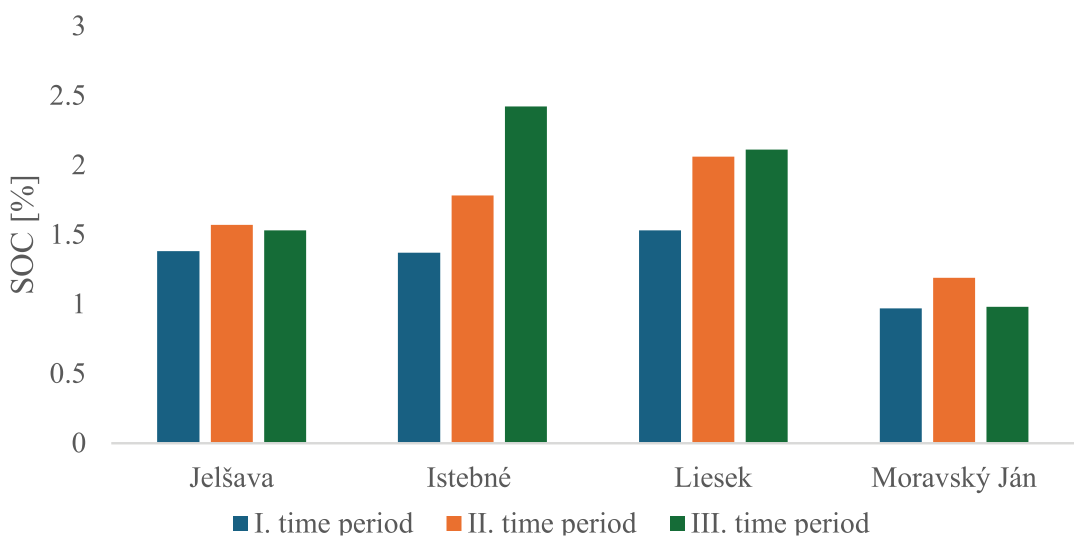

Figure 5. Development of median SOC [%] values on individual key monitoring localities with land use changes.
Note: SOC – see Figure 2.

content occurs very quickly when changing grassland to cropland, the opposite change, cropland to grassland, requires a significantly longer time for the change to be significant, as confirmed by our results.

CONCLUSIONS

Evaluation of SOC development on key monitoring sites clearly showed that SOC content of topsoil on intensively used agricultural soils is affected by land use and land use changes. It was confirmed that one of the main driving forces affecting SOC content is land use, since substantially higher SOC content on grassland compared to cropland was found. It was also clearly shown that, among natural factors, we can assume, the altitude is another driving force affecting SOC content. Based on our results, the SOC content seems to be higher at higher altitudes, with colder and more humid conditions, compared to the lowland with higher temperatures and dry conditions. The development of SOC content over 30 years, divided into three time periods, was different. The lowest SOC content at the beginning of the monitoring period (90s) could have been caused by strong changes in Slovak agricultural management. Between the first and second time periods, median SOC content increased. We assume that it was caused by the state subsidy policy to increase the content of organic matter in the soil. Between the second and the third time periods, negligible changes in SOC content were detected, which could be the consequence of a gradual increase in temperature and long dry periods, and despite better agricultural management, SOC content did not increase. Our results also show that if we want to increase SOC content in Slovak agricultural soils, we need to increase the input of organic matter into the soil mainly by measures as grassing of part of arable land, improving crop rotation systems (inclusion of cover crops in the crop rotation system) and sufficiently high doses of manure. All these measures are supported by the EU (Green Deal).

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