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Research Article

A Properly Chosen Rate of NPK Fertilizers Has a Positive Effect on C Sequestration in Sandy Soils in the Conditions of a Changing Climate

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Soil organic carbon (SOC) plays a significant role in climate change. Its content can be modified by soil management practices, however, the effect of mineral fertilization on SOC is not clear. For this reason, a long-term effect of gradually increasing rates of NPK fertilizers on changes in soil organic carbon (SOC) in bulk soil and in water-stable aggregates (WSA) in soils with sandy loam and loamy sand texture at two experimental sites (Skierniewice, Poland, and Dražovce, Slovakia) was quantified. In both sites, soil samples were collected from the following treatments: NF – no fertilization, NPK1 and NPK2 – 1st level and 2nd level of NPK fertilization, respectively. The results showed that 100-year long application of NPK1 increased total carbon (TC) and SOC content by 24%, while NPK2 decreased it by 5% compared to NF at the Skierniewice site. The content of water-stable macroaggregates (WSAma) increased because of NPK application. In NPK1, the content of WSAma was higher and the content of water-stable microaggregates (WSAmi) was lower than in NPK2 or NF. However, as a result of NPK application, the content of agronomically favorable WSAma in size fraction 0.5–3 mm was reduced by 8 and 24% in NPK1 and NPK2, respectively, compared to NF. Overall, SOC in WSAma was lower than in bulk soil. The SOC in WSAma in NF, NPK1 and NPK2 treatments was 6.51, 7.77 and 5.89 g.kg^{-1}, respectively. Similar tendency of SOC in WSAma 0.5–3 mm was observed (NF: 6.12 g.kg^{-1}, NPK1: 7.35 g.kg^{-1}, and NPK2: 6.88 g.kg^{-1}). The SOC in WSAmi in NF, NPK1 and NPK2 was 8.33, 7.39 and 7.24 g.kg^{-1}, respectively. At Dražovce site, TC content decreased significantly due to the graded rates of NPK, not because of SOC mineralization but as a result of carbonate dissolution for a period of 14 years. The carbonate content decreased from 20 g.kg^{-1} in NF to 6.5 g.kg^{-1} in NPK1 and 3.0 g.kg^{-1} in NPK2, while SOC did not change significantly: (NF: 23.8 g.kg^{-1}, NPK1: 25.9 g.kg^{-1}, and NPK2: 23.4 g.kg^{-1}). In NPK1, the WSAma content was reduced significantly when compared to NPK2 and NF treatments. No significant difference was observed between NF and NPK2. On the contrary, the content of WSAma 0.5–3 mm significantly increased when compared to NF and NPK1. No difference was observed between NF and NPK1. Lower SOC content was found in WSA than in the bulk soil. Overall, higher SOC content was observed in WSAma when compared with WSAmi. The application of NPK1 and NPK2 increased SOC in WSAma as well as in WSAma 0.5–3 mm. The effect was more significant in NPK1 than NPK2 treatments when compared to NF.

Keywords: sandy soil, soil organic matter, water-stable aggregates, fertilization

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1 Introduction

Soil organic matter (SOM) plays a critical role in the carbon (C) cycle, which largely influences global climate change (Weil & Brady, 2017). Depending on the environmental conditions, SOM is more-less transformed/decomposed. The result is a whole range of products of its transformation. The essential factors influencing these processes are, among others, the temperature and precipitation, i.e. the most frequent factors linked with the climate change. The mineralization of SOM takes place more and more rapidly with increasing soil temperature (Kimble et al., 1998; Šimanský & Horváthová, 2010; Weil & Brady, 2017). The result can be reduced biomass production, and deterioration of physical properties of the soil (decline in soil structure, increase in soil compaction, and soil crust formation). On the other hand, primary production can be increased through the fertilizing impact of increasing CO_2 (Kimble et al., 1998). In the Slovak Republic, the

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average hectare of soil releases 4.2 t. CO_2 year^{-1}, which equals to 1.15 t. ha^{-1} C (Bielek, 2001). However, the results of Šimanský & Horváthová (2010) showed more intensive SOM mineralization due to higher temperature at the optimum soil moisture and thus higher CO_2 production from 1 hectare of soil. In arable soils, the soil type itself is a significant factor influencing SOM mineralization. More productive Chernozems with a higher C content and quality of humic substances produce smaller amount of CO_2 than soils with a relatively high C content but lower humus quality (Cambisols, Gleysols, Stagnosols, Planosols), as well as less productive soils with a low C content such as Regosols. It is assumed that the effect of increased temperature promotes the mineralization of mainly more labile forms of SOM in comparison to more stable forms (Semenov et al., 2008). Stable forms of SOM are protected in the soil by various mechanisms such as biochemical, physical and chemical stabilization (Six et al., 2002). An important tool to eliminate the negative consequences of rising temperature and extreme events linked with precipitation is C sequestration in the soil by the above-mentioned mechanisms. The sequestration capacity of soils is different and depends on the climate zone, soil type, but also soil management practices (Semenov et al., 2008). One of the important mechanisms of C sequestration and thus the elimination of SOM mineralization is the physical protection of SOM – incorporation of SOM into soil aggregates (Six et al., 2002), which has an impact on improving the soil structure (Bronick & Lal, 2005) and overall soil physical properties.

Some problems can occur in the case of coarse-textural soils which means in soils with Arenic and Loamic qualifier (IUSS Working Group WRB, 2015). Soils with dominant sand content in its texture has poorly developed soil aggregates and their stability is generally very weak (Šimanský et al., 2019). In general, coarse-textural or easy sandy soils are poor in nutrients and have low SOM contents and cation exchange capacity and exhibit low water holding capacity (Yost & Hartemink, 2019). If farmers want to use sandy soils to obtain sufficient yields, they must pay extra attention to its management, especially in the last decades, which is characterized by the changing climate. Rational mineral fertilization of these soils is a very important tool for increasing their productivity (Dong et al., 2014). As a result of the application of available nutrients, more biomass can be produced. There is an assumption that SOC will potentially increase (Tian et al., 2015), which has consequently a very close relationship with other soil properties, including soil structure (Bronick & Lal, 2005; Šimanský et al., 2019). On the other hand, very low mineral fertilization may not meet the expectation of sufficient crop yields and overall improvement of soil properties. For this reason, the issue of quantifying the optimal rate of mineral fertilization for coarse-textural soils is necessary. Therefore, the aim of this study was to quantify the extent of the effect of increasing rates of NPK fertilizers on changes in SOC bulk soil as well as in water-stable aggregates.

2 Material and methods

2.1 Study sites

Both experiments with graduated rates of NPK fertilization on sandy soils in central Poland and south-western Slovakia were carried out. In Skierniewice (51° 57′ 54.3″ N 20° 09′ 31.8″ E) locality, a randomized block design was applied, with plots measuring 4 × 9 m (36 m^2) along with a protective belt of 2 m left between individual plots (total 9 plots). The soil type classified according to WRB (IUSS Working Group WRB, 2015) was Arenic Planosols. It contained 72.9–81.5% of sand, 13.8–19.7% of silt, and 4.0–7.7% of clay (classified as loamy sand – sandy loam according to IUSS Working Group WRB, 2015), 3.79–11.79 g.kg^{-1} of SOC and 0.37–0.91 g.kg^{-1} of N, and soil pHH_2O ranged from 5.03 to 6.53 (Jonczak, 2021). The climate of the experimental site is temperate continental with an annual precipitation and mean annual temperature 530 mm and 8 °C, respectively. In Dražovce locality (48° 21′ 6.16″ N, 18° 3′ 37.33″ E), experiment with NPK fertilizers was located in experimental vineyard (northwest of Nitra city in the south-western foothills of Zobor Hill). The soil was classified as Rendzic Leptosol (IUSS Working Group WRB, 2015). Before the experiment, the soil contained 57% of sand, 33% of silt and 10% of clay on average (classified as sandy loam texture – IUSS Working Group WRB, 2015), 17.0 g.kg^{-1} of SOC, 1.07 g.kg^{-1} of N, and soil pHH_2O was 7.18. The average annual precipitation is about 559 mm and the mean annual temperature is about 10.8 °C (based on a 30-year climatic normal, 1991–2020).

2.2 Experimental setup in the fields

The treatments in the study consisted of two NPK levels (NPK1 and NPK2) and no fertilized control treatments (NF). All NPK fertilization levels in both experimental sites are summarized in Table 1. In Skierniewice locality, NPK fertilizers were applied into the soil to a depth of 15 cm by disk tillage in autumn every year from 1923. NPK fertilizers were applied in the forms of ammonium nitrate (34% N), triple superphosphate (46% P_2O_5) and potassium sulphate (50% K_2O). In Dražovce locality, NPK fertilizers were applied into the soil to the depth of 15–20 cm every year since 2006. Duslofert Extra was used as NPK fertilizer.

Table 1 Fertilization rates on both experimental sites

Soil/Site	Treatments	Crops	Fertilization ($kg.ha^{-1}$)		
			N	P_2O_5	K_2O
Sandy loam – Loamy sand	no fertilization (NF) as unfertilized control	cereals	0	0	0
Arenic Planosol	NPK1	cereals	75	50	100
Skierniewice, Poland	NPK2	cereals	150	100	200
Sandy loam	no fertilization (NF) as unfertilized control	vineyard	0	0	0
Rendzic Leptosol	NPK1	vineyard	100	70	145
Dražovce, Slovakia	NPK2	vineyard	125	115	225

2.3 *Experimental management*

In Skierniewice, the experiment was established in 2022. During the experiment, minimum tillage practice (the tillage by disking) was performed up to a depth of 15–18 cm. Wheat (*Triticum aestivum* L.) was grown in monoculture, therefore no crop rotation on the site was applied.

In Dražovce, the experiment with different doses of NPK started in 2006, however, experimental vineyard had been planted in 2001. Before experiment establishing, the area was intensively tilled due to weed removal in and between the rows of vines, and every autumn, between the rows, the soil was plowed down to 25 cm. In 2006, between rows of vines a mix of grasses (*Lolium perenne* L. 50% + *Poa pratensis* L. 20% + *Festuca rubra* subsp. *commutata* Gaudin 25% + *Trifolium repens* L. 5%) was sown in all treatments. Strip grass in vineyard was cut down during vegetation season of vines, on average three times, and no tillage system was applied. The aboveground biomass of the grass remained *in-situ* on the surface as a mulch layer. In NPK1 treatments, NPK fertilizer was divided as follows: 1/2 applied into the soil at bud burst growth stage (in March) and 1/2 at flowering growth stage (in May). In NPK2, 2/3 of fertilizer were applied into the soil at bud burst (in March) and 1/3 at flowering growth stage (in May).

2.4 *Soil sampling and analysis*

Soil samples at both experimental sites and in all treatments were taken from the depth of 25 cm in the spring of 2022. Soil analyzes were performed by using the standard methods described in Hrivňáková et al. (2011). In soil samples, size fractions of water-stable aggregates (WSA) were determined by wet sieving. These size fractions of aggregates represented macro-aggregates (>5, 5–3, 3–2, 2–1, 1–0.5, 0.5–0.25 mm) and micro-aggregates (<0.25 mm). Soil organic carbon content (SOC) was measured using the wet combustion method. Content of carbonates was determined by volumetric method using a Jankov calcimeter. For determination of total carbon content (TC) the Elementar Vario MacroCube analyzer was used.

The statistical analysis was performed using the Statgraphics Centurion XV.I (Statpoint Technologies, Inc., USA) software. The data were analyzed by utilization of one-way ANOVA, and the means (average values of soil properties) were compared with Tukey test at $p < 0.05$.

3 Results and discussion

3.1 *Carbon in bulk soil*

Soil is the largest carbon pool in terrestrial biosphere and includes SOC and soil inorganic carbon (SIC). There are two main types of SIC: lithogenic carbonates and pedogenic carbonates (Zamanian et al., 2016). Lithogenic carbonates originate from parent materials, mainly from limestone or other carbonate-containing minerals, whereas pedogenic carbonates are formed through the dissolution and reprecipitation of lithogenic carbonates. Usually, carbonates are found across the soil profiles of soils created on lithogenic carbonates which confirmed the results of this study (Table 2). The soil in the Dražovce vineyard was formed on Cretaceous, Triassic and Jurassic limestones (Jankowski et al., 2018). On the other hand, the Skierniewice site does not contain any carbonates (Chojnicki et al., 2016). In the Skierniewice site, the total carbon content (TC) was represented only by the SOC, while in the case of the Drážovce site, the TC was formed by the SOC and $CaCO_3$ content. In Skierniewice, SOC was statistically significantly increased due to long-term NPK1 fertilization (by 24%), while on the other hand, long-term NPK2 application reduced SOC by 5% compared to the unfertilized control (NF). Significant differences were found in TC depending on the intensity of NPK fertilization in the Dražovce site. In NPK2 and NPK1 treatments, TC was lower by 17.4 and 11.3 $g.kg^{-1}$, respectively, when compared to NF. A similar tendency was observed in the results for SOC. After 14 years of fertilization, SOC increased by 10% in NPK1 and did not change as result of NPK2 application when compared

Table 2 Carbon contents in studied soils in g.kg^{-1}

Treatments	**Skierniewice, Poland**			**Dražovce, Slovakia**		
	TC	**SOC**	**CO_3^{2-}**	**TC**	**SOC**	**CO_3^{2-}**
NF	5.06 ±1.40a	5.06 ±1.40a	n.d.	43.8	23.8	20.0
NPK1	6.28 ±2.36b	6.28 ±2.36b	n.d.	32.5	26.0	6.5
NPK2	4.82 ±1.56a	4.82 ±1.56a	n.d.	26.4	23.4	3.0

NF – no fertilization, NPK1 – 1st level of NPK rates, NPK2 – 2nd level of NPK rates, TC – total carbon, SOC – soil organic carbon, CO_3^{2-} – carbonates, n.d. – no detected
Means and standard deviations for the treatments are presented. In Skierniewice site, different letters within rows indicate significant differences between treatments – based on Tukey's test at 0.05 significance level. In Dražovce site, without statistical evaluation

to the NF treatment. In Dražovce site, a significant effect of graduated NPK fertilization rates on the carbonate content was observed. The higher was the NPK rate, the more intense decrease in $CaCO_3$ was detected. Mineral fertilization can affect TC in the different ways – by higher formation of biomass (positive effect) or by salinization of soils (negative effect). After applying NPK fertilization to the soil, the content of available nutrients increases. Due to the higher content of available nutrients more biomass is produced, microbial activity increases, higher rhizodeposition occurs, etc. The result of this process is an increase in SOM. On the other hand, high concentrations of NPK cause salinization of the soil solution with a negative impact on the soil microflora (Ratzke & Gore, 2018). The negative effect can also be related to the priming effect, which means that NPK fertilization will cause an increase in the biomass of microorganisms and an increase in SOM. Subsequently, after the depletion of labile sources of SOM by soil microorganisms, SOM is attacked and decomposed by increased abundance of soil microorganisms, which results in a decrease of SOC. Such effects could be related to changes primarily in SOC in the Skierniewice site. At the Dražovce site, as a result of increasing doses of NPK, a significant reduction of SIC in the form of $CaCO_3$ was observed. Acidification induced by mineral fertilizer greatly accelerates SIC dissolution and thus SIC losses (Bughio et al., 2016).

3.2 Water-stable aggregates

The content of WSA and especially the size fraction of water-stable macroaggregates (WSAma) 0.5–3 mm is an important indicator of soil structure. Soil structure is affected by soil management practices, including mineral fertilization (Bronick & Lal, 2005; Kobierski et al., 2018; Šimanský et al., 2019). The application rate and type of fertilizer play a crucial role. Adding monovalent cations to the soil promotes clay dispersion. On the contrary, the application of divalent cations improves soil aggregation (Bronick & Lal, 2005). Divalent Ca^{2+} and Mg^{2+} cations form cationic bridges between SOC and clay and result is a stable soil aggregate (Kobierski et al., 2018). In the Skierniewice site, NPK1 had a positive effect, while NPK2 had no effect on WSA (Table 3). NPK1 primarily promoted the formation of large WSAma fractions >3 mm. However, WSAma 0.5–3 mm content was reduced compared to NF due to both NPK rates – more for NPK2 than NPK1. In Dražovce, NPK1 decreased WSAma and increased WSAmi content, while no difference was observed for NPK2. The differences between the treatments were not found even in the case of WSAma 0.5–3 mm. NPK1 fertilization promoted the breakdown of large WSAma >3 mm and the formation of WSAma <0.5 mm.

3.3 Soil organic carbon in water-stable aggregates

As reported by Šimanský et al. (2017), WSA are an important SOC sequester because inside these water-stable aggregates SOC can be physically protected

Table 3 Content of water-stable aggregates in studied soils in %

Treatments	**Skierniewice, Poland**			**Dražovce, Slovakia**		
	WSAmi	**WSAma**	**WSAma 0.5–3**	**WSAmi**	**WSAma**	**WSAma 0.5–3**
NF	10.8 ±0.69b	89.2 ±0.69a	62.3 ±3.53b	11.3	88.8	45.0
NPK1	5.17 ±3.20a	94.8 ±3.20b	56.7 ±10.6b	26.1	78.3	41.9
NPK2	8.20 ±2.07ab	91.8 ±2.07ab	45.8 ±2.95a	12.7	87.2	45.3

NF – no fertilization, NPK1 – 1st level of NPK rates, NPK2 – 2nd level of NPK rates, WSAmi – water-stable micro-aggregates, WSAma – water-stable macro-aggregates, WSAma 0.5–3 – water-stable macro-aggregates in size fractions 0.5–3 mm
Means and standard deviations for the treatments are presented. In Skierniewice site, different letters within rows indicate significant differences between treatments – based on Tukey's test at 0.05 significance level. In Dražovce site, without statistical evaluation

Table 4 Soil organic carbon in water-stable aggregates in studied soils in g.kg^{-1}

Treatments	Skierniewice, Poland			Dražovce, Slovakia		
	SOC in					
	WSAmi	WSAma	WSAma 0.5–3	WSAmi	WSAma	WSAma 0.5–3
NF	8.33 ±0.08b	6.51 ±0.02a	6.12 ±0.01a	14.2	16.6	16.4
NPK1	7.39 ±0.06a	7.77 ±0.02b	7.35 ±0.05c	13.4	19.5	21.3
NPK2	7.24 ±0.09a	5.89 ±0.84a	6.88 ±0.03b	16.7	19.2	19.5

NF – no fertilization, NPK1 – 1st level of NPK rates, NPK2 – 2nd level of NPK rates, SOC in WSAmi – soil organic carbon in water-stable micro-aggregates, SOC in WSAma – soil organic carbon in water-stable macro-aggregates, SOC in WSAma 0.5–3 – soil organic carbon in water-stable macro-aggregates in size fractions 0.5–3 mm
Means and standard deviations for the treatments are presented. In Skierniewice site, different letters within rows indicate significant differences between treatments – based on Tukey's test at 0.05 significance level. In Dražovce site, without statistical evaluation

against microbial attack. Elliott (1986) reported that macroaggregates have elevated C concentrations because of the conversion of organic-matter-binding microaggregates into macroaggregates and that this organic matter is 'qualitatively more labile and less highly processed' than the organics-stabilizing microaggregates. The results of this study in the case of the Skierniewice site do not confirm this finding (Table 4). In the Skierniewice, a higher SOC content was determined in WSAmi than in WSAma in all treatments. The reason may be soil texture – high sand content (loamy sand – sandy loam textural classes). Sand has little ability to form stable soil aggregates (Bronick & Lal, 2005). In addition, intensive soil management practices, including fertilization, promotes the breakdown of larger macroaggregates and results in the incorporation of SOC into WSAmi. Since the SOC content was the lowest in the overall bulk soil (Table 2) when compared to its content in different aggregate fractions (Table 4), it is assumed that SOC physically stabilizes mainly in WSAmi and decreased in the following order: WSAmi > WSAma > WSAma 0.5–3 mm > bulk soil. Both rates of NPK decreased SOC in WSAmi – more in NPK2 than NPK1. In comparison to NF, SOC in WSAma increased by 19% in NPK1 but decreased by 10% in NPK2. In Dražovce site, higher SOC content was observed in WSAma than in WSAmi (Table 4). Overall, the highest SOC was observed in bulk soil (Table 2). The application of NPK1 had a more positive effect on SOC in WSAma but also WSAma 0.5–3 mm compared to NF or NPK2. In NPK2, SOC in WSAmi was higher than in NF. The application of NPK1 had a negative effect on SOC in WSAmi compared to NF.

4 Conclusions

All in all, from soil structure point of view SOC is very important in coarse-textural soils. Carbon sequestration mechanisms were different in both soils. Except higher SOC, sequestration mechanisms depend on carbonates content in soils with loamy sand – sandy loam textural classes. The results of this study confirmed that mineral fertilization is a significant factor affecting carbon sequestration. In general, lower rates of NPK fertilization had more pronounced positive effect on soil structure and soil organic carbon compared to higher NPK level. Even through a properly selected dose of NPK fertilization, a farmers/winegrowers are able to manage carbon sequestration in the soil and thus eliminate the negative effects of climate change.

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