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Influence of organic and inorganic fertilization on soil properties and water infiltration

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Abstract. Soil aggregate stability (SAS) belongs to the most important parameters determining the quality of soil and fertilizer influence on soil aggregation. We evaluated the relationship between SAS, hydro–physical soil properties and infiltration rates in three long–term field experiments founded in 1956 on different soils. Soil properties under three fertilization regimes– no fertilization, farmyard manure, farmyard manure and mineral fertilization–were evaluated at silty loam Chernozem, silty loam Phaeozem and sandy loam–loam Cambisol. A significant impact of fertilization on SAS was found, even though the differences in SAS were rather low. The lowest SAS was recorded at plots with manure and mineral fertilization (25.1%) compared with plots without fertilization (28.7%) and plots with manure–only fertilization (28.2%). The highest SAS (36.5%) and the highest semi–capillary porosity (SP; 11%) were observed at sandy loam–loam soil. Hydro–physical soil properties were more favourable at fertilized plots (SP 9.6% and bulk density ρ_b 1.31 g cm^{-3}) compared with unfertilized ones (SP 8.8% and ρ_b 1.35 g cm^{-3}). The lowest SP (8.32%) and the highest ρ_b (1.37 g cm^{-3}) were recorded at Phaeozem, which corresponded with the lowest SAS (19.4%). Chernozem had similar soil texture to Phaeozem, but SAS (24.7%), SP (9%) and ρ_b (1.27 g cm^{-3}) were more favourable. Despite the low level of statistical significance due to the large variation of infiltration measurements, a higher infiltration rate was recorded at fertilized plots (45 mm hour^{-1}) compared to unfertilized ones (35 mm hour^{-1}).

Key words: soil quality, soil aggregate stability, infiltration, porosity, long-term field trial.

INTRODUCTION

At present, frequency and intensity of climate extremes increase due to ongoing climate change and the soil quality and soil resistance become more significant. At soil quality assessment, soil texture, content of soil organic matter (SOM) and quality of soil structure belong to the key factors determining soil physical properties. Soil structure quality may be expressed by water stability of soil aggregates (SAS), i.e. ability of soil aggregates to resist disintegration by water. SAS is easily determined by laboratory measurements and provides reliable information on soil quality. In some cases, SAS responds better to soil management changes compared to the total SOM content (Stehlíková et al., 2016).

Water stability of soil aggregates refers to complex soil characteristics and is directly related to precipitation infiltration, soil crusting, surface runoff and soil erosion (Barthès & Roose, 2002; Soinne et al., 2016). More stable soil structure leads not only to reduction of erosion, but also to better rainfall utilization, which is important especially in areas with more frequent periods of drought. To improve SAS and soil quality, the importance of crop rotation and fertilization is often mentioned (Naveed et al., 2014; Stehlíková et al., 2016; Suwara et al., 2016). The aim of this paper was to find a relationship between soil aggregates stability and hydro–physical soil properties. For this objective, we investigated soil properties at differently fertilized plots of the oldest multi–site field experiment in the Czech Republic.

MATERIALS AND METHODS

The Crop Rotation Experimet (CRE) was established in 1956 at three locations: Čáslav (GPS: N 49°53.45', E 15°23.77'), Ivanovice na Hané (GPS: N 49°18.84', E 17°5.98') and Lukavec (GPS: N 49°33.45', E 14°58.82'; Tables 1, 2). CRE is a four–field experiment with 12 fertilization treatments, 4 plot replicates and the plot size of 9 x 9 m. Experiment design is described in Kunzová & Hejcman (2009). For the present study, the following treatments of one experimental field were chosen: No. 21–control (No. fertilization), No. 11–manure (40 t ha^{-1} every four years before maize and potato) and No.14–full fertilization (manure + mineral fertilization in average doses of 66 kg N ha^{-1}, 40 kg P ha^{-1} and 87 kg K ha^{-1}). The soils were ploughed to the depth of 20–25 cm. Crop residues were removed from plots after the harvest. In the autumn 2014 after the harvest of winter wheat, the manure was applied at the treatments 11 and 14. The crop rotation was as follows: 2011–potato, 2012–spring barley, 2013–clover, 2014–winter wheat, 2015–silage maize, 2016–spring barley, 2017–winter rape, 2018–winter wheat and 2019–potato. Soil samples were collected in four repetitions for each treatment in the following dates: at the end of October 2016 (2 months after winter rape was sown); at the end of October 2017 (1 month after winter wheat was sown); and at the end of April 2018.

Table 1. Characteristics of the researched localities

Locality	Altitude (m a. s. l.)	Annual mean temperature (°C)	Annual precipitation (mm)	Soil type (WRB)	pH (H_2O)	Soil texture (USDA)	Parent material
Čáslav	263	8.9	555	Phaeozem	7.05	Silt loam	Loess
Lukavec	610	7.3	683	Cambisol	6.4	Sandy loam–loam	Gneiss
Ivanovice	225	9.2	548	Haplic Chernozem	7.1	Silt loam	Loess

Table 2. Texture (USDA), TOC (total organic carbon) and soil particle density of topsoils

Locality	Clay % < 0.002 mm	Silt % 0.002–0.05 mm	Sand % > 0.05 mm	Soil particle density–ρ_d (g cm^{-3})	TOC (%)
Čáslav	17.2	68.8	14	2.56	1.323
Ivanovice	18.7	72.3	9	2.53	1.936
Lukavec	9.8	36.3	53.9	2.59	1.378

To assess the soil aggregate stability (SAS), disturbed soil samples to the depth of 7 cm were collected. Samples were gently sieved to obtain the fraction of 1–2 mm. Soil aggregate stability, measured as the proportion of water stable aggregates was assessed by the wet–sieving method of Kandeler (1996), using a laboratory equipment HERZOG (Adolf Herzog GmbH, Vienna, AT) with sieving time of 5 minutes and 3 repetitions per sample.

To determine hydro–physical soil properties, undisturbed soil samples were collected using the steel cylinders with the volume of 100 cm^3 to the depth of 7 cm. Three samples were collected for each trial plot, i. e. 12 samples for each treatment were taken. In 2018, the undisturbed samples were collected in July instead of April, after the harvest of winter wheat, as it was necessary to avoid damaging the canopy.

Bulk density (ρ_b), capillary porosity (CP), non–capillary porosity (NP), semi-capillary porosity (SP) and the maximum content of non–gravitational soil water (soil moisture reduced from full saturation after 30 minutes of free drainage–θ_{30}; this parameter reflects the amount of water held in capillary and semi–capillary pores) were determined according to the methods described in Zbíral et al. (2011) and Pospíšilová et al. (2016). According to the authors, capillary pores have the diameter of < 0.2 µm and retain water for plants. Semi–capillary pores are those of the 0.2–10 µm diameter and are comprised both gravitation pores supporting water infiltration and capillary pores retaining water for plants. Non–capillary pores are characterized by the diameter > 10 µm and they enable the water flow into deeper layers of soil profile.

In summer 2018, measurements of water infiltration were carried out after the harvest. Saturated hydraulic conductivity (K_{fs}) was determined using the method of ponded infiltration (Bagarello et al., 2006) using the cylinders with the diameter 150 mm. In 8 repetitions, the fully fertilized treatment and the unfertilized treatments were evaluated. Cylinders were sunk into the soil to the depth of 10 cm and the soil moisture was recorded using the ML3 Theta Probe sensor in the surrounding soil. Then, the cylinder was in 20 seconds gently filled with 1,000 mL of water using the perforated bowl. The water volume corresponded to precipitation of 56 mm. The time needed to soak the water was recorded. When the water infiltrated completely, soil moisture inside the cylinder was measured. To assess soil texture the parameter α was set to 12. Data were evaluated using the ANOVA and Scheffe’s multiple comparison test at $\alpha = 0.05$ determined homogenous groups. Analysis was conducted in STATISTICA 13.3 software (TIBCO Software Inc.).

RESULTS AND DISCUSSION

Soil aggregate stability

Soil aggregate stability (SAS) was predominantly influenced by site characteristics (Fig. 1). In the finer soils of Čáslav and Ivanovice, SAS was significantly lower as compared to the lighter soil of Lukavec. SAS usually increases with the content of fine particles (Le Bissonnais, 1996), but lower SAS values in finer soils were also reported (Stehlíková et al., 2014). Between the experimental sites with finer soils, SAS was slightly higher at Chernozem with higher total organic carbon content (Table 1, 2). Higher SAS at cultivated soils with higher carbon content were reported also by Soinne et al. (2016).

Fully fertilized treatment showed significantly lower SAS compared to unfertilized ones (Fig. 1). SAS did not significantly differ between plots fertilized with manure and the unfertilized plots. However, the application of manure slightly decreased SAS when compared to unfertilized treatment in Ivanovice and Čáslav, while in Lukavec this effect was not observed. Organic fertilization is usually reported to increase organic carbon (Šimon & Czakó, 2014) content and the ratio of macroaggregates (Zhao et al., 2018) and to also have a positive effect on SAS (Kroulík et al., 2010; Badalíková et al., 2015). Šimon et al. (2018) point out the influence of excessive mineral fertilization on mineralization of soil organic carbon. A negative effect of mineral fertilization on SAS is reported e.g. by Stehlíková et al. (2014) and Stehlíková et al. (2016). Brtnický et al. (2017) described a negative influence of increasing mineral fertilization on SAS as well as a reduction in the effect of organic fertilizers on the SAS decrease. On the contrary, Suwara et al. (2016) reported a positive effect of mineral fertilization on higher SAS values at sandy loam Phaeozem.

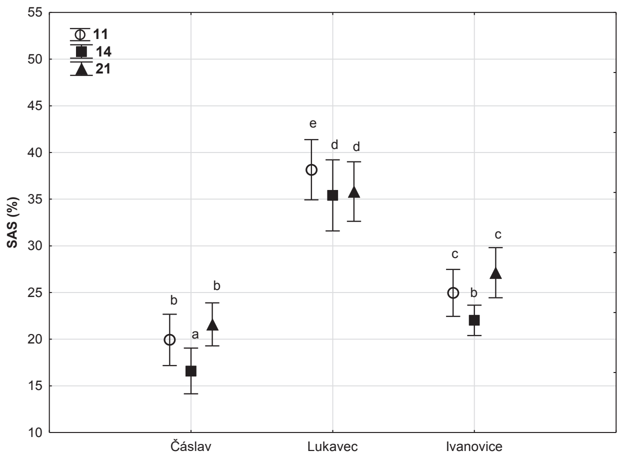

Figure 1. Influence of the treatments on the soil aggregate stability (SAS) at experimental sites (**11** – farmyard manure; **14** – mineral + farmyard manure; **21** – no fertilization). Different letters indicate significant differences at $\alpha = 0.05$ by Scheffe's test. Vertical columns show 0.95 confidence interval.

A significant year–to–year differences in SAS were observed, with the possible effect of seasonal dynamics (Fig. 2). Large year–to–year SAS variability is often reported (Badalíková et al. 2015). Fig. 2 shows significantly higher SAS in 2018 (39.4%), when the samples were collected from wheat plots in spring during the vegetation growth. Significantly lower SAS were then recorded in autumn, when the vegetation is inhibited. The lowest SAS was recorded in autumn 2017, when the samples were collected from winter wheat plots one month after sowing. On the contrary, SAS was higher in autumn 2016, when the samples were collected 2 months after winter rape was sown. The higher SAS in 2016 might be due to a higher rooting intensity of winter rape.

Nevertheless in the event of excessive precipitation or snow melting, soil infiltration and water holding capacity can be exceeded. Finer soils with lower SAS, especially in combination with mineral fertilization, might then be more susceptible to erosion or degradation. It is for these reasons that bulk density, porosity and rate of infiltration of soil are important.

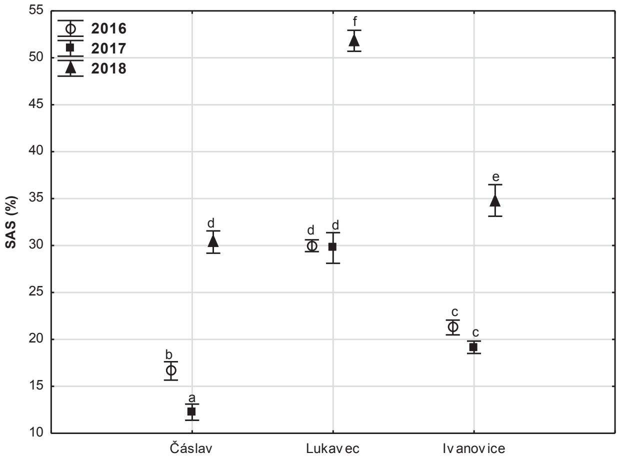

Figure 2. Year to year variability on the soil aggregate stability (SAS) at experimental sites. Different letters indicate significant differences at α = 0.05 by Scheffe's test. Vertical columns show 0.95 confidence interval.

Bulk density

Bulk density (ρ_b) was significantly influenced by fertilization. Mean lower ρ_b was recorded at fertilized plots (1.31 g cm^{-3}) compared to 1.35 g cm^{-3} at unfertilized plots (Fig. 3). Lower ρ_b values at fertilized treatments were reported also by Suwara et al. (2016) in sandy loam Phaeozems, by Kroulík et al. (2010) in clay loamy soil and by Šařec & Novák (2017) in silty loam soil. Bulk density varied largely among sampling terms; in 2016 it was significantly lower compared to other samplings terms (Fig. 4).

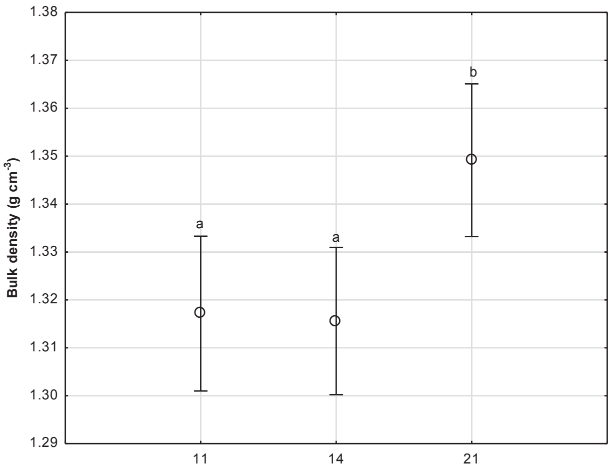

Figure 3. Influence of the treatments (**11** – farmyard manure; **14** – mineral + farmyard manure; **21** – no fertilization) on the bulk density of soil. Different letters indicate significant differences at α = 0.05 by Scheffe's test. Vertical columns show 0.95 confidence interval.

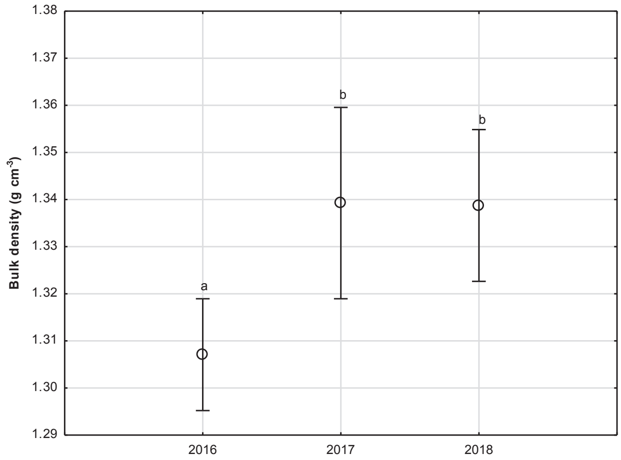

Figure 4. Soil bulk density at three sampling terms. Different letters indicate significant differences at α = 0.05 by Scheffe's test. Vertical columns show 0.95 confidence interval.

Higher rooting intensity of winter rape can be possible explanation. No difference in ρ_b was observed between 2017 and 2018. Differences in ρ_b among treatments and years reached 0.05 g cm^{-3}, but difference among sites were two–times higher (Fig. 5). The lowest ρ_b was recorded at Chernozem (Table 1, 2). Samples with similar content of soil carbon and different soil texture showed slightly higher ρ_b in Čáslav when compared to Lukavec. However, the differences were not significant.

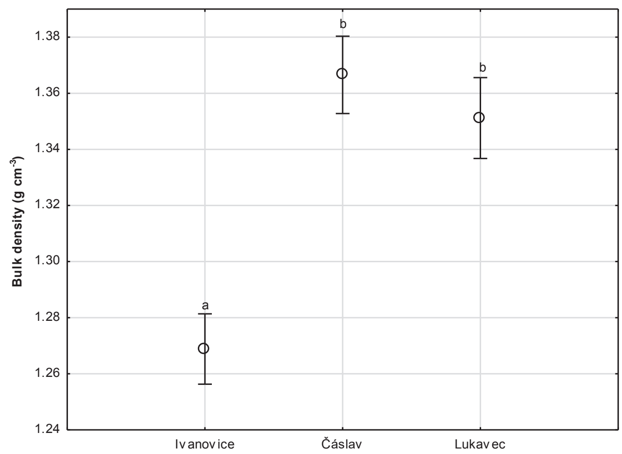

Figure 5. Soil bulk density at experimental sites. Different letters indicate significant differences at α = 0.05 by Scheffe's test. Vertical columns show 0.95 confidence interval.

Porosity

Bulk density, SAS and water regime depend on the distribution of soil pores. Fig. 6 compares capillary porosity (CP), semi–capillary porosity (SP) and non–capillary (NP) porosity in three sampling years. Higher rooting intensity in winter rape likely impacted higher NP in 2016. On the contrary, CP was the highest in 2017 in winter wheat. In 2018, CP was lower compared to previous years whereas SP increased. The highest NP was recorded in Ivanovice and the highest SP was recorded in Lukavec (11%; Fig. 7), which corresponded with the highest SAS. The effect of increased SAS on the amount of micropores refers Regelink et al. (2015). Conversely, the lowest SP values were observed in Čáslav (8.3%), where the lowest SAS as well as the highest differences in SP among treatments were recorded. Significantly higher SP was demonstrated at fertilized treatments (9.6% on average) when compared to unfertilized treatments (8.8%).

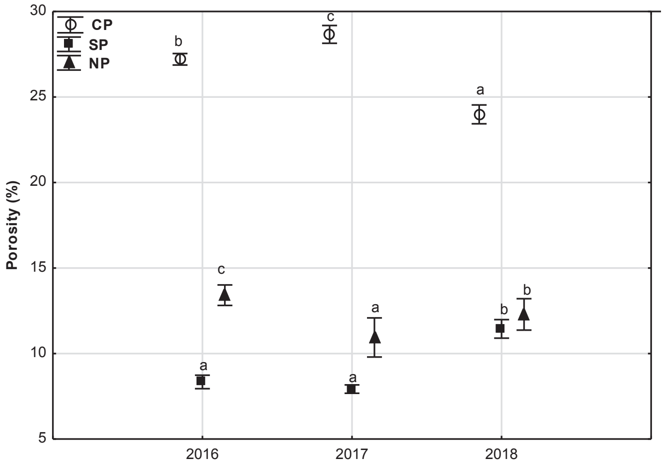

Figure 6. Distribution of porosity between three types of pores (**CP** – capillary porosity; **SP** – semi capillary porosity; **NP** – non–capillary porosity). Different letters indicate significant differences at α = 0.05 by Scheffe's test. Vertical columns show 0.95 confidence interval.

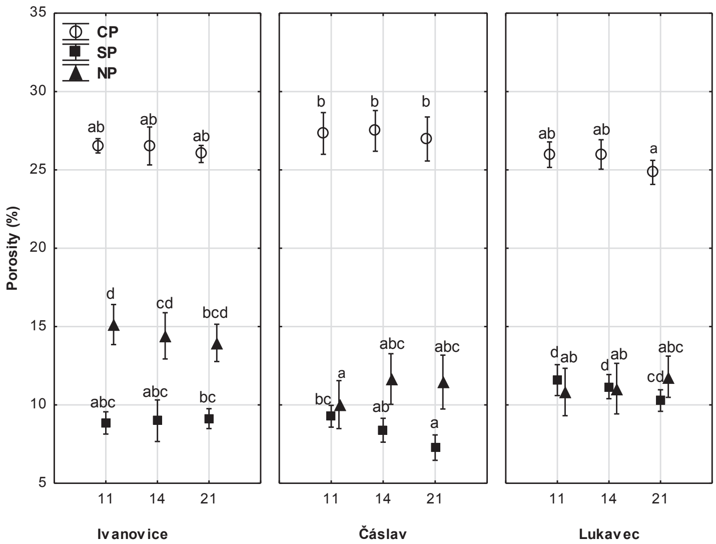

Figure 7. Influence of the treatments (**11** – farmyard manure; **14** – mineral + farmyard manure; **21** – no fertilization) at experimental sites on the distribution of porosity between three types of pores (**CP** – capillary porosity; **SP** – semi capillary porosity; **NP** – non – capillary porosity). Different letters indicate significant differences at α = 0.05 by Scheffe's test between sites and treatments within CP, SP, and NP. Vertical columns show 0.95 confidence interval.

Fertilized treatments retained significantly more non-gravitational water compared to unfertilized treatments (Table 3). Significantly more water was held in Lukavec compared to Ivanovice and Čáslav. Higher water retention is related to higher CP and SP ratio at sites and fertilized treatments (Fig. 7). Lower soil moisture at the unfertilized treatment are confirmed by Suwara et al. (2016) in sandy loam Phaeozem and by Badalíková et al. (2015) in clay loamy soil.

Table 3. Non-gravitational soil moisture (θ_{30}) at experimental sites and treatments. The averages marked by the same letter in individual columns did not significantly differ at $\alpha = 0.05$ (Scheffe's test)

Locality	Average (θ_{30}) in %	Standard error
Ivanovice	35.35^{a}	0.17
Čáslav	35.58^{a}	0.30
Lukavec	36.61^{b}	0.23
Treatment		
Not fertilized	34.82^{a}	0.23
Farmyard manure	36.44^{b}	0.23
Farmyard manure + mineral fertilization	36.11^{b}	0.24

Water infiltration

Organic fertilization influences infiltration of water into the soil. Season 2018 was extremely dry from April to September. Drought was probably the main cause of an insignificant effect of fertilization and site on water infiltration rate, measured after harvest of winter wheat in summer 2018. Nevertheless, Fig. 8 shows a lower infiltration rates at the unfertilized treatment (35 mm $hour^{-1}$) compared to higher rates of fully fertilized treatment (45 mm $hour^{-1}$). Influence of organic fertilization on higher infiltration rate in sandy loam Cambisol during the years following application were reported by Badalíková & Bartlová (2014) and at clay loamy soils by Kroulík et al. (2010).

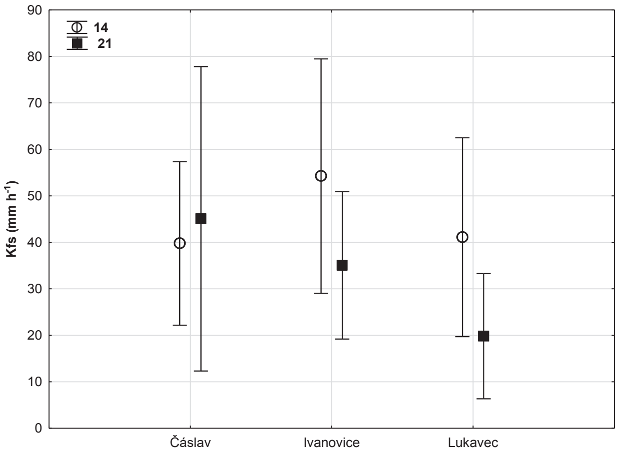

Figure 8. Influence of the treatments (**14** – mineral + farmyard manure; **21** – no fertilization) on the saturated hydraulic conductivity (K_{fs}) at three experimental sites. There are not significant differences between treatments ($p > 0.05$). Vertical columns show 0.95 confidence interval, $p > 0.05$.

Despite the expected highest infiltration rate on sandy loam–loam soil in Lukavec, a higher infiltration rate was recorded on silty loam soil in Ivanovice, which was related to the highest non–capillary porosity (14.5%). The significant impact of macropores on higher infiltration rate in clay soils are referenced by Kodešová et al. (2006). The lowest infiltration rate, based on the distribution of pores, was presumed on silty loam soil in Čáslav. Nevertheless, likely due to drought and very low soil moisture at the time of infiltration measurements (8%), the highest infiltration rate was recorded at the unfertilized plots in Čáslav, but rates varied largely. On average, the infiltration rate at the fully fertilized treatment in Čáslav was comparable to the unfertilized treatment.

CONCLUSIONS

Higher SAS and higher semi–capillary porosity leads to higher water retention; this can be concluded for the trial in sandy loam–loam Cambisol, but not for two trials in silty loam soils. Significantly lower SAS were recorded at fully fertilized plots of fine texture soils. However the differences were small. Despite slightly lower SAS, fertilized plots showed significantly higher semi–capillary porosity and content of non–gravitational water. The lowest SAS and semi–capillary porosity and the highest soil bulk density were observed at Phaeozem. Semi–capillary and capillary pores determine maximum content of non–gravitational soil water. On the other hand, semi–capillary and non–capillary pores are related to bulk density and infiltration rate. We found that fertilization promotes higher infiltration rates. The results show that even small differences in SAS, porosity and soil bulk density were reflected by increased infiltration rates at fertilized treatments. Organic fertilization had a positive impact on SAS, semi–capillary porosity and soil bulk density. Significant year–to–year differences in soil properties were also shown, therefore the influence of seasonal climate can not be excluded. However, the differences in infiltration rates not always corresponded with the change of SAS. Within finer soils especially, higher infiltration rates were probably impacted by macropores and soil cracks caused by period of drought prior the measurements.

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