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ORIGINAL RESEARCH

Field and laboratory evaluation of the long-term effect of various organic fertilizers on sandy soil

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Abstract

Purpose: Recent trends in land use and the effects of climate change resulted in the decline of organic matter content of the soils. Since crop management systems play an important role in soil carbon sequestration, therefore our aim was to determine the long-term effects of different organic fertilizers on soil respiration and its driving factors.

Method: The research work was carried out in two long-term experiments on sandy soil. The field and laboratory measurements of soil respiration were done in fallow, farmyard manure, farmyard manure + fertilizer, green manure and in sewage sludge compost (18 and 27 t ha^{-1}) treatments. In addition, soil physical-chemical parameters were measured for complex evaluation.

Results: The results of laboratory and field soil respiration measurements were usually consistent with each other. The most intensive soil respiration was measured in sewage sludge compost treatments and in farmyard manure with NPK. In these treatments, the organic matter input and the positive changes in the physical and chemical properties of sandy soil stimulated the soil life, which resulted in more intensive soil respiration and enzyme activities. According to the results of correlation analysis the soil respiration was significantly influenced by the organic matter content, pH and moisture content of the soil.

Conclusion: This study indicated the importance of replenishing the soil with organic matter, which can contribute to the maintenance of soil quality. In addition, the application of sewage sludge compost can be well utilized in agriculture for nutrient supply and improving carbon sequestration of sandy soil.

Keywords: Long-term crop rotation, Organic fertilizer, Sewage sludge compost, Soil respiration, Enzyme activity

Introduction

Nowadays, the protection of soil health and maintaining soil fertility is becoming more and more important. Healthy soils are essential for achieving climate neutrality, a clean and circular economy and preventing land degradation (EU Soil Strategy for 2030). Organic matter is one of the most important basic elements of the soils, that is not just responsible for ensuring stable crop production but it is also a source of food for soil fauna and microbes and it mainly determines the soil fertility (Bot and Benites 2005). The intensive land use and the soil degradation processes as a result of climate change led to a 10% decrease in the organic matter content of the soils all over Europe (SoCo 2007). Sandy soils, occurring in Central and Eastern Europe, are even more

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exposed to soil degradation processes because of their low fertility and unfavourable water management properties (Wiesmeier et al. 2016). Since soil management practices play an important role in soil carbon sequestration, it is needed to better understand the mechanisms for carbon sequestration in sandy soils (Huang and Hartemink 2020; Sosulski et al. 2021). Agriculture provides some land use practices for example crop rotation, manure and compost application that can help reduce and protect against soil degradation (Sánchez de Cima et al. 2015; Glab et al. 2020). The problem of decreasing soil organic matter can be met favourably with problems of waste material emplacement through utilization of wastes in agriculture for nutrient supply (Alvarenga et al. 2017; Wu et al. 2017; Tóth et al. 2020). In addition, the circular economy can be achieved by recycling wastewater effluents, minimizing raw materials extraction and improving energy efficiency (Council Directive 2008/98/EC 2008).

The application of sewage sludge compost in agriculture has been considered as an option for conserving/increasing organic matter level of soil, thereby improving soil carbon sequestration (Bai et al. 2017; Hamdi et al. 2019; Wu et al. 2017). Land use of sewage sludge compost can increase soil fertility by promoting microbial activities, improving soil physico-chemical properties, and recycling plant nutrients (Scotti et al. 2016; Guerrini et al. 2017; Dhanker et al. 2021). The effects of compost amendment to soil result in improved soil aeration, increased water- and nutrient-holding capacity and reduced soil compaction level (Aranyos et al. 2016; Alvarenga et al. 2017; Glab et al. 2020).

The microbiological parameters of soil are considered as the most sensitive indicators even to slight modifications in soil and their activity may provide an adequate feedback to changes in soil quality (Macci et al. 2016; Hamdi et al. 2019). The microbiological activity of the soils can be well characterized by measuring the enzyme activity and soil respiration, besides that these dynamic parameters are very sensitive to changes in crop management practices (Dhanker et al. 2021).

Soil enzymes play an important role in organic matter decomposition and nutrient cycling and the enzyme activity in the soil is considered to be a major contributor of overall soil microbial activity (Melo et al. 2018; Aweez and Darwesh 2021; Dong et al. 2021).

Soil respiration is a good indicator to monitor decomposition and it is an important measure of the total biological activity in the soil (Zhang et al. 2014; Lai et al. 2017; Dhanker et al. 2021). However, the results of soil respiration measurements, depending on whether the measurements were carried out in laboratory or in the field, may differ significantly from each other (Aweez and Darwesh 2021). Besides that soil, respiration measurements in relation to farming systems and environmental variables are needed for better understanding of net ecosystem carbon balance and to predict soil's feedback to climate change (Benbi et al. 2020).

Therefore the objectives of this study were to analyze the long-term effects of different organic fertilizers on soil respiration with measurements in field and laboratory and to investigate the relationships between CO_2 efflux and its driving factors. On the other hand, the study of the soil utilization and soil effects of by-products with high organic matter content, such as sewage sludge compost, is very important for sustainable management, preservation of soil health, and the implementation of a circular economy and waste reduction.

Materials and methods

Experimental area

Our research work was carried out in 2020 in the Westsik's crop rotation long-term experiment and in the sewage sludge compost (SSC) long-term experiment at the Research Institute of Nyíregyháza, IAREF, and University of Debrecen in Hungary. The experiments are located at 47º96′N latitude and 21º72′E longitude and they are situated at elevation 108 m a.s.l (Fig. 1).

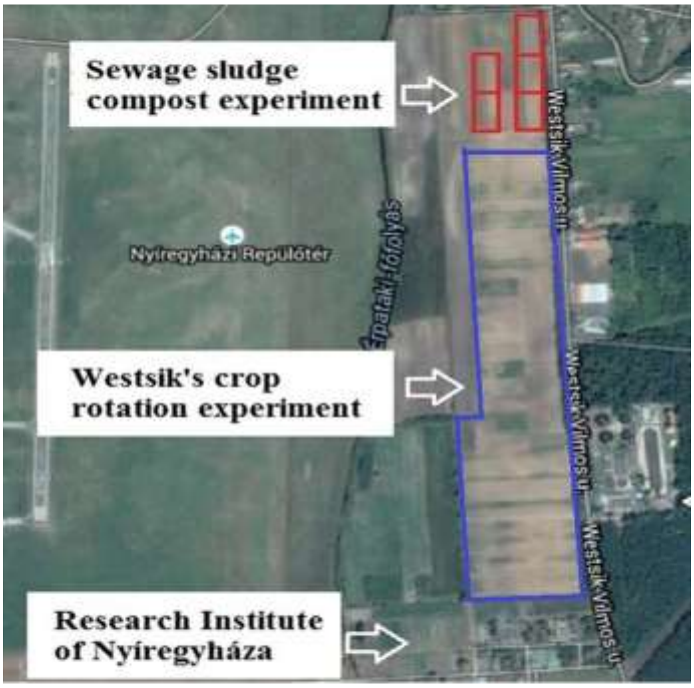

Fig. 1 Locations of the study sites (47º 96′ N latitude and 21º 72′ E longitude) in Nyíregyháza, Hungary (Source: Google Maps 2023)

The characteristic soil type of the experiments was *Dystric Lamellic Arenosol* (87.69% sand, 2.67% silt, 9.64% clay). Table 1 shows the main soil parameters of study site. Soil chemical analysis was carried out for the first time in Westsik's experiment in 1941 (Lazányi 1994).

Table 1 The main soil characteristics of the Westsik's crop rotation experiment in Nyíregyháza, Hungary (Lazányi 1994)

Year	pH (H_2O)	pH (KCl)	SOM (%)	NO_3-N (mg kg^{-1})	AL-P_2O_5 (mg kg^{-1})	AL-K_2O (mg kg^{-1})
1941	6.2	6.1	0.5	9.0	79.6	182.0

SOM: Soil organic matter content, AL: Ammonium lactate soluble

The Westsik's crop rotation experiment started in 1929 represents the classical farming systems of the Eastern Hungarian region on sandy soil with organic matter amendments such as straw, farmyard manure, main and second crop green manure with or without supplementary chemical fertilizers. The total area of the experiment is approximately 12.4 ha. In this study four CRs (I, X, XI, XV) were selected to carry out soil measurements.

The small-plot sewage sludge compost experiment was established in 2003. The applied compost (Table 2) contained sewage sludge (40 m/m% DM: dry matter), straw (25 m/m% DM), bentonite (5 m/m% DM) and rhyolite (30 m/m% DM).

Table 2 The main parameters of applied sewage sludge compost, farmyard manure and green manure

Parameter	SSC	FM	GM
pH (H_2O)	6.9	10.2	N. D.
Organic matter content (m/m %)	48.0	57.8	42.6
Dry matter content (m/m %)	60.7	33.2	N. D.
Total N content (mg kg^{-1}, DM)	31000	17000	28100
Total P_2O_5 content (mg kg^{-1}, DM)	76800	5830	1370
Total K_2O content (mg kg^{-1}, DM)	8900	24100	7800

m/ m %: Mass/mass%, DM: Dry matter, SSC: Sewage sludge compost, FM: Farmyard manure, GM: Green manure, N. D.: Not determined

Test plants rye, maize and rye with hairy vetch were sown in a crop rotation. Each plot is treated every third year with different doses of sewage sludge compost (SSC) from which 18 and 27 t ha^{-1} SSC treated plots were sampled. The last compost application before sampling was done in October 2018.

The design of the investigated crop rotations in Westsik's and SSC experiments is shown in Table 3.

Table 3 Design of the investigated crop rotations in Westsik's and SSC experiments in Nyíregyháza, Hungary

Crop rotation (CR)	Plot	Plants	Sowing	Harvest	Fertilizers: Mineral (kg ha^{-1}) N	P	K	Organic (t ha^{-1} DM) SSC	FM	GM	Treatment year	Tillage method
CR I: F	1	Fallow										Plowing
	2	Potato	April	September								Plowing
	3	Rye*	October	July								Plowing
18 t ha^{-1} SSC	1	Rye*	October	July				18			Every 3rd	Plowing
	2	Maize	April	October				18			Every 3rd	Plowing
	3	Rye+vetch	October	July				18			Every 3rd	Plowing
27 t ha^{-1} SSC	1	Rye*	October	July				27			Every 3rd	Plowing
	2	Maize	April	October				27			Every 3rd	Plowing
	3	Rye+vetch	October	July				27			Every 3rd	Plowing
CR X: FM	1	Oat+vetch	March	July					26.1		Annually	Plowing
	2	Rye*	October	July								Plowing
	3	Potato	April	September								Plowing
CR XI: FM+M	1	Rye*	October	July		31	28				Annually	Plowing
	2	Oat+vetch	March	July		63	56		26.1		Annually	Plowing
	3	Potato	April	September	43						Annually	Plowing
CR XV: GM	1	Rye	October	July								Plowing
	2	Potato	April	September								Plowing
	3	Rye*	October	July						20	Annually	Plowing

* Sampling plot, DM: Dry matter, F: Fallow, SSC: Sewage sludge compost, FM: Farmyard manure, FM+M: Farmyard manure + mineral fertilizer, GM: Green manure

Field soil respiration ($R_{S\text{-}Field}$) measurement and sampling

The first two samplings (1 and 10 July, 2020) were taken as a pre-harvest and another two (30 July and 1 August, 2020) as a post-harvest set in the summer season only in rye plots. For soil physical measurements 100 cm^3 of undisturbed soil samples were collected from the 5-10 cm soil layer in five replicates. The bulk densities of undisturbed soil samples were measured after drying in an oven at 105°C for 24 hours (Buzás 1993). The total porosity was determined by taking the ratio of the volume of water poured and the bulk volume of the soil (Chitra et al. 2022). Soil moisture content was determined by using gravimetric technique (Reynolds 1970).

$R_{S\text{-}Field}$ was measured with open system configuration of soil chamber using a portable tool ADC LCi / LCpro soil pot (ADC Bio Scientific 2007). The soil pot consists of an acrylic pot containing an air stirrer fan and pressure equalisation vent. The attached stainless-steel collar-base was spiked until the sign on it into the soil. Soil respiration was calculated by Net CO_2 Exchange Rate (NCER) and soil temperature (T_{soil}) was recorded simultaneously with the provided probe. The measurements were taken until the NCER reading remained nearly constant.

Soil Respiration (Net Molar Flow of CO_2 in/out of the Soil), C_e (p mol s^{-1})

$C_e = u\,(-\Delta c)$

Where

u molar air flow in mol s^{-1};

Δc difference in CO_2 concentration through soil pot, dilution corrected, µmol mol^{-1}.

Net CO_2 Exchange Rate (C_e per unit area), NCER (µmol s^{-1} m^{-2})

$NCER = u_s\,(-\Delta c)$

Where

u_s molar flow of air per square meter of soil, mol m^{-2} s^{-1};

Δc difference in CO_2 concentration through soil pot, dilution corrected, µmol mol^{-1}.

Weather parameters

Precipitation and mean air temperature data were recorded by the meteorological station of UD IAREF Research Institute of Nyíregyháza (Table 4).

Table 4 Precipitation and mean air temperature data in 2020 in Nyíregyháza, Hungary (own data)

	January	February	March	April	May	June	July	August
Precipitation (mm)	23	44	27	4	38	175	70	63
Mean temperature (°C)	-0.9	4.6	6.6	11.5	14.3	20.0	21.0	22.3

Laboratory measurements

Composite soil samples of 5 subsamples for laboratory tests and soil respiration ($R_{S\text{-}Lab}$) measurement were collected in 3 replicates from the soil surface of 0 – 25 cm depth at every point of measured field soil respiration. The soil samples were stored in the freezer prior to the laboratory analysis. The soil samples were put into controlled temperature of 15 °C overnight before they were sieved through a 2-mm sieve. Each soil sample was separated into two parts. One part was oven dried at 105 °C before getting measured for its soil dry mass fraction. The other part was prepared for laboratory soil respiration analysis. The procedure of analysing soil respiration was referring to the International Organization for Standardization for soil quality (ISO 16072) (2002). The carbon dioxide released from the soil was determined by titration in a static system, incubating the samples for 24 hours in a temperature-controlled room at 22°C.

Dehydrogenase activity (DHA) was measured according to Casida et al. 1964. Shortly, soil samples

were incubated with 2, 3,5-triphenyl tetrazolium chloride (TTC) for 24 hours. After the incubation period, the quantity of produced triphenyl formazan (TPF) was measured photo metrically at 485 nm.
Air dried soil samples were used for catalase activity (CAT) measurement based on the utilization of H_2O_2 as an artificial substrate. The remaining H_2O_2 quantity was titrated with $KMnO_4$. Results were given as mg O_2 g^{-1} soil h^{-1} used for H_2O_2 oxidation in the samples (Roberge 1978). The soil chemical tests were carried out according to the Hungarian guideline. Soil pH_{KCl} was measured using the electrometric method in 1M potassium chloride (KCl) suspension (Buzás 1988). SOM was determined by the Tyurin method with spectrophotometric measurement (Buzás 1988). The KCl-soluble nitrogen forms of soil were quantified by FIA spectrophotometry (Buzás 1988). For extracting the available P and K content of soils, ammonium-lactate solution (so-called AL extractant) was used, and then the amount of phosphorus was quantified colorimetrically with the phospho molybdovanadate method. Potassium content was quantified by flame atomic emission spectrophotometry (Egner et al. 1960; Buzás 1988).

Statistical analysis

The analyses of the variance (ANOVA) of the data from different treatments were evaluated using SPSS 13.0 program. For comparison of means, Tukey's test was used at the significance level $p<0.05$. To describe and evaluate the relationship between the soil parameters correlation analysis was performed.

Results and discussion

Soil chemical parameters

As expected, the soil chemical properties were highly responsive to organic matter treatments (Table 5). The soil pH_{KCl} was the lowest in F and in GM, which remained close to pH 4. The soils of FM and FM+M showed almost the same pH values at the range of 4.57-4.76. The soil pH was significantly increased to a value of 6 by both compost treatments, that means more than 50% increase compared to pH value of the F. There was no treatment effect on soil organic matter content (SOM) in GM. However, the application of SSC, FM and FM+M contributed to a significant increase in SOM content.

Table 5 The changes in chemical parameters of sandy soil in different treatments

Treatment	pH (KCl)	SOM (%)	NO_3-NO_2-N (mg kg^{-1})	AL-P_2O_5 (mg kg^{-1})	AL-K_2O (mg kg^{-1})
F	4.06 ± 0.16 cd	0.35 ± 0.02 *c*	3.04 ± 1.40 **ab**	73.5 ± 11.3 ***c***	72.1 ± 6.1 c
18 t ha^{-1} SSC	6.00 ± 0.19 a	0.68 ± 0.09 *a*	2.86 ± 0.39 **b**	504.9 ± 248.9 ***a***	137.9 ± 30.3 bc
27 t ha^{-1} SSC	6.09 ± 0.28 a	0.55 ± 0.06 *ab*	5.87 ± 1.11 **a**	426.9 ± 79.6 ***ab***	125.5 ± 14.4 bc
FM	4.76 ± 0.24 b	0.59 ± 0.03 *a*	1.79 ± 0.93 **b**	188.3 ± 7.6 ***bc***	226.7 ± 21.0 a
FM + M	4.57 ± 0.36 bc	0.67 ± 0.07 *a*	4.05 ± 1.38 **ab**	243.7 ± 61.3 ***abc***	208.7 ± 64.9 ab
GM	3.88 ± 0.03 d	0.41 ± 0.01 *bc*	4.54 ± 0.58 **ab**	57.7 ± 2.9 ***c***	93.4 ± 3.0 c

SOM: Soil organic matter content, AL: Ammonium lactate soluble, F: Fallow, SSC: Sewage sludge compost, FM: Farmyard manure, FM+M: Farmyard manure + mineral fertilizer, GM: Green manure

a-d indexes mean different groups of means according to the Tukey's test at the significance level of $p<0.05$, mean ± Standard Deviation (SD)

The total amount of N, P, K added to the investigated crop rotations between 2018-2020 are shown in Table 6. The most amounts of the nitrogen and phosphorus was added to the soil with 27 t ha^{-1} SSC. The largest amount of potassium was applied into the soil by FM+M.

Table 6 The total amount of N, P, and K added to the investigated crop rotations during 2018-2020 in Nyíregyháza, Hungary

Treatment	Plot	Plants	N	P	K
				kg ha^{-1}	
F	1	Fallow			
	2	Potato			
	3	Rye			
18 t ha^{-1} SSC	1	Rye	558	1382	160
	2	Maize	558	1382	160
	3	Rye+vetch	558	1382	160
27 t ha^{-1} SSC	1	Rye	837	2074	240
	2	Maize	837	2074	240
	3	Rye+vetch	837	2074	240
FM	1	Oat+vetch	444	152	629
	2	Rye	444	152	629
	3	Potato	444	152	629
FM+M	1	Rye	487	277	741
	2	Oat+vetch	487	277	741
	3	Potato	487	277	741
GM	1	Rye	562	27	156
	2	Potato	562	27	156
	3	Rye	562	27	156

F: Fallow, SSC: Sewage sludge compost, FM: Farmyard manure, FM+M: Farmyard manure + mineral fertilizer, GM: Green manure

Soil organic matter and soil pH are important indicators of soil quality and thereby soil health. The organic matter of soil provides essential nutrients for plants and soil microorganisms, but also it affects the chemical and physical properties of the soil. Soil pH influences mobility, adsorption, solubility, and availability of plant nutrients in the soil and it also has a great impact on the composition of the soil microbial community (Hamdi et al. 2019; Dhanker et al. 2021). In this study the F and GM treatments had no effect on SOM content and on soil pH that can be explained by the quality of organic matters and the rapid mineralization processes in acidic sandy soil (Weber et al. 2014). Masto et al. (2006) explained the reduction in soil organic carbon after fallow with the higher air temperature in summer that led to the loss of soil organic matter content due to rapid decomposition. Our results are consistent with this statement, because during the test the highest soil temperature was usually measured in fallow and green manure treatments. However, our experiences contradict the finding that the extensive tillage and the incorporation of green manure biomass to the soil usually improve the

SOM content of sandy soil (Sharma et al. 2017; Li et al. 2019a; Ansari et al. 2022).

The organic matters applied into the soil by farmyard manure and sewage sludge compost are more stable and more resistant to mineralization processes, than by green manure, therefore organic substances could increase the SOM and the pH of acidic soil through their acid/base buffering effect (Alvarenga et al. 2017; Jiang et al. 2018). Sewage sludge compost is a good source of organic substances because it has high organic matter content. In addition, during the composting process bentonite has an important role in humification (Wang et al. 2016; Awasthi et al. 2017). Alvarenga et al. (2017) also suggest that it is advisable to use more stable and mature organic wastes, which have longer lasting positive effects on soil characteristics. The enhancement of soil organic matter content and soil pH was reported previously as a result of the addition of sewage sludge compost to acidic sandy soil (Uzinger et al. 2020; Dhanker et al. 2021; Elsalam et al. 2021).

Our results showed the highest increase of SOM content in 18 t ha^{-1} SSC and FM+M. Several research findings also indicated positive effects of farmyard manure especially on soil organic carbon contents and soil pH in many field experiments (Marinari et al. 2006; Heinze et al. 2010; Ozlu and Kumar 2018). Guerrini et al. (2017) found the combined application of composted sewage sludge and cattle manure lead to an increased soil organic carbon and pH. Our results confirmed the statement that the long-term application of manure and mineral fertilizers increased the SOC of sandy soil. That can be explained that a higher nutrient content through increased biomass production can enrich the soil with organic carbon and maintain the soil fertility (Šimanský et al. 2019). Although several authors (Rothé et al. 2019; Ai et al. 2020; Dong et al. 2021) reported the application of green manure increases the available nitrogen for the next crop, but in our study there were no significant differences in NO_3-NO_2-N content of soil among the treatments compared to control. In our opinion, this is because it indicates the rapid decomposition of green manure in sandy soil.

The applied fertilization methods remarkably affected the macro element content, such as K and P of sandy soil. The lowest P_2O_5 content of soil was measured in GM and in F. The application of farmyard manure and compost resulted in significant increase of phosphorus content of soil, but statistically verified P_2O_5 content increase was detected only in the two SSC treatments. The utilisation of sewage sludge compost in agriculture as fertiliser and soil conditioner had a beneficial effect on available P of soil due to its high phosphorus content (Ai et al. 2020; Elsalam et al. 2021; Dhanker et al. 2021). The increase in soil pH as a result of SSC application also had a certain effect on P availability (Uzinger et al. 2020). Furthermore, the increased P content and availability could be related to the solubilised organically bound P from the SSC by enhanced microbial activity (Ziadi et al. 2013). Guerrini et al. (2017) suggest the combined application of composted sewage sludge and cattle manure to increase soil P content.

The K_2O content of soil was also the lowest in F and GM. The SSC treatments had no significant effect on the potassium content of soil. However, the addition of FM and FM+M to soil caused a significant increase in K_2O content of sandy soil. This beneficial effect can be explained by the fact that the application of organic manure increased the nutrient supply capacity and the microbial activity of soil due to its high potassium content (Han et al. 2016).

Soil physical parameters

The application of all organic fertilizers had a significant beneficial effect on soil compaction level in the 5-10 cm soil layer. The bulk density was significantly lower (at the range of 1.40-1.43 g cm^{-3}) in FM, FM+M and GM compared to control.

Addition of compost to soil significantly reduced the soil bulk density to 1.35 g cm^{-3} in SSC treatments from 1.49 g cm^{-3} measured in fallow plots. The total porosity of soil in different treatments was consistent with the values of bulk density. The total porosity was the lowest in F and in GM and compared to these values it was statistically higher in both SSC treatments, in FM and FM+M (Table 7).

Bulk density and total porosity depend on soil structure and these parameters are the indicators of soil compaction level. Several studies reviewed the positive effects of compost addition on the soil physical properties and structure of sandy soil (Wu et al. 2017; Glab et al. 2020; Siedt et al. 2021). Organic matter and bentonite in compost played an important role in the formation of soil aggregates, which resulted in reduced bulk density and increased total porosity (Aranyos et al. 2016).

Soil temperature and soil moisture

Soil temperature in the field showed significant differences between fertilization treatments in all sampling time (Fig. 2). Over time, the mean soil temperature increased tendentially in each plot treatment. The highest soil temperature was usually measured in F and GM treatments and the lowest was generally detected in SSC treatments that were statistically verified.

Table 7 The changes in physical parameters of sandy soil

Treatment	Bulk density (g cm^{-3})	Total porosity (V/V %)
F	1.49 ± 0.02 a	43.2 ± 2.1 *b*
18 t ha^{-1} SSC	1.35 ± 0.03 c	49.4 ± 0.7 *a*
27 t ha^{-1} SSC	1.35 ± 0.02 c	49.1 ± 1.2 *a*
FM	1.40 ± 0.03 b	48.1 ± 0.9 *a*
FM + M	1.40 ± 0.02 b	47.1 ± 0.7 *a*
GM	1.43 ± 0.01 b	44.2 ± 1.7 *b*

V/V%: Volume/volume %, F: Fallow, SSC: Sewage sludge compost, FM: Farmyard manure, FM+M: Farmyard manure + mineral fertilizer, GM: Green manure

a-c indexes mean different groups of means according to the Tukey's test at the significance level of $p<0.05$, mean ± Standard Deviation (SD)

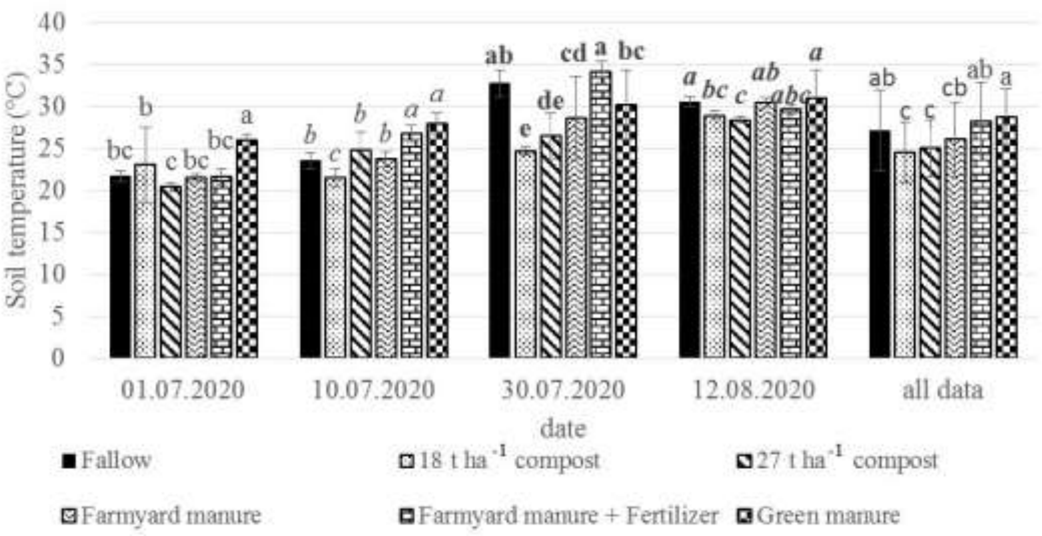

Fig. 2 Changes in soil temperature in different fertilization treatments in 2020 (Nyíregyháza, Hungary)

a-e indexes mean different groups of means according to the Tukey's test at the significance level of $p<0.05$, mean ± Standard Deviation (SD)

During the vegetation period, there were significant differences in the soil moisture (M_{soil}) content of different treatments. As clearly shown in Fig. 3, the soil moisture content was significantly higher in both SSC treatments compared to the other treatments in all sampling time. At the end of the growing season, when the soil moisture content in each treatment was the lowest compared to the previous period, the soil of fallow treatment retained significantly less moisture content.

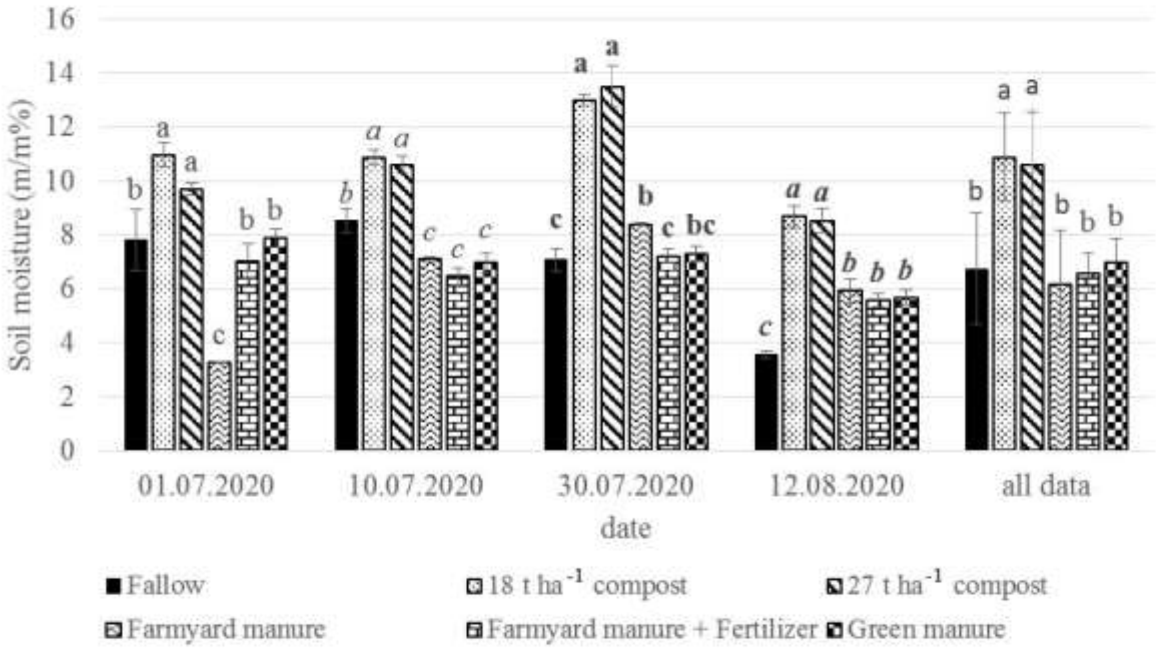

Fig. 3 Changes in soil moisture in different fertilization treatments in 2020 (Nyíregyháza, Hungary)
a-c indexes mean different groups of means according to the Tukey's test at the significance level of $p<0.05$, mean ± Standard Deviation (SD)

Soil moisture as well as soil temperature are key factors influencing the rate of organic matter decomposition and the rate of soil respiration (Han et al. 2017; Fang et al. 2018; Duan et al. 2021). The highest soil temperature was usually measured in F and GM treatments and the lowest was generally detected in SSC treatments that were statistically verified. It can be explained by different plant densities and soil moisture content in plots. Despite the rapid mineralization processes, the water retention of sandy soil was significantly improved by both compost doses compared to other treatments. The added organic matter and bentonite composition with compost application promoted soil structure and improved the water retention of soil by absorbing water molecules (Aranyos et al. 2016; Ramos 2017; Glab et al. 2020). In accordance with the increase in soil moisture content, in all sampling times the soil temperature was significantly lower in both compost treatments than in other fertilization methods.

Field and laboratory measurements of soil respiration

$R_{S\text{-}Field}$ demonstrated significant differences between soil treatments at each sampling time as shown in Fig. 4. Generally, the intensity of soil respiration was the highest in both SSC and FM+M treatments and it was the lowest in F and GM treatments. However, there was no statistical difference in the rate of soil respiration between the two different doses of compost treatment at any field measurement date. In the field the highest soil respiration was recorded in FM+M with close to 5 µmol CO_2 s^{-1} m^{-2} in August throughout the whole investigation period.

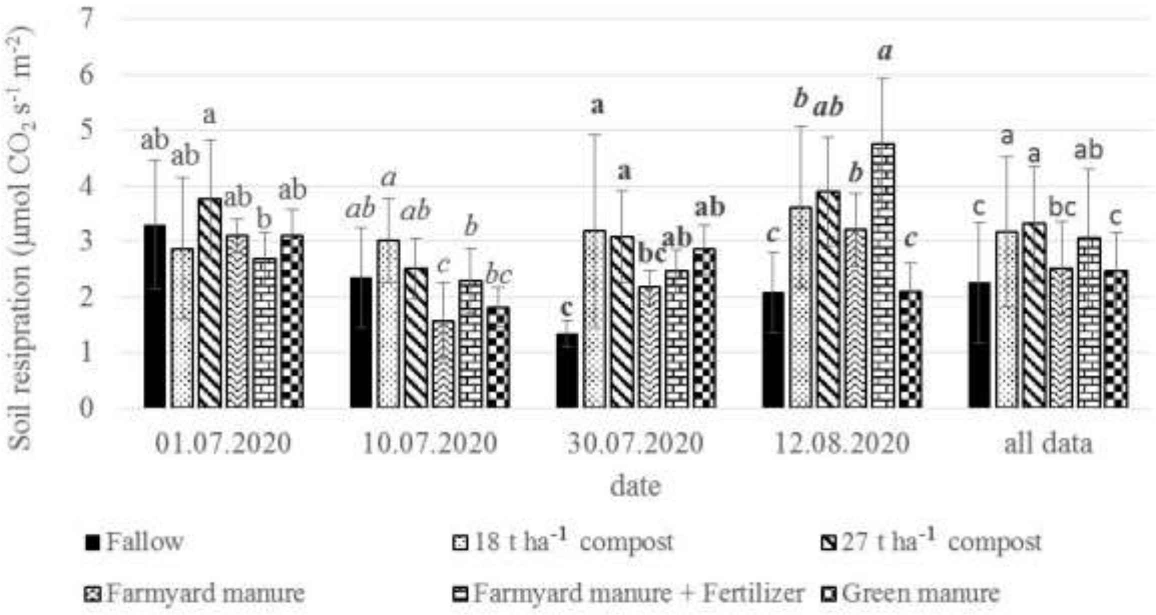

Fig. 4 Results of soil respiration measurements in the field in 2020 (Nyíregyháza, Hungary)

a-c indexes mean different groups of means according to the Tukey's test at the significance level of $p<0.05$, mean ± Standard Deviation (SD)

The rate of $R_{S\text{-}Lab}$ in each treatment changed similarly to the results of field soil respiration measurements in all sampling time. Commonly, the lowest carbon dioxide emission of soil was measured in F or in GM, and the highest rate was measured in the two SSC treatments and in FM+M (Fig. 5).

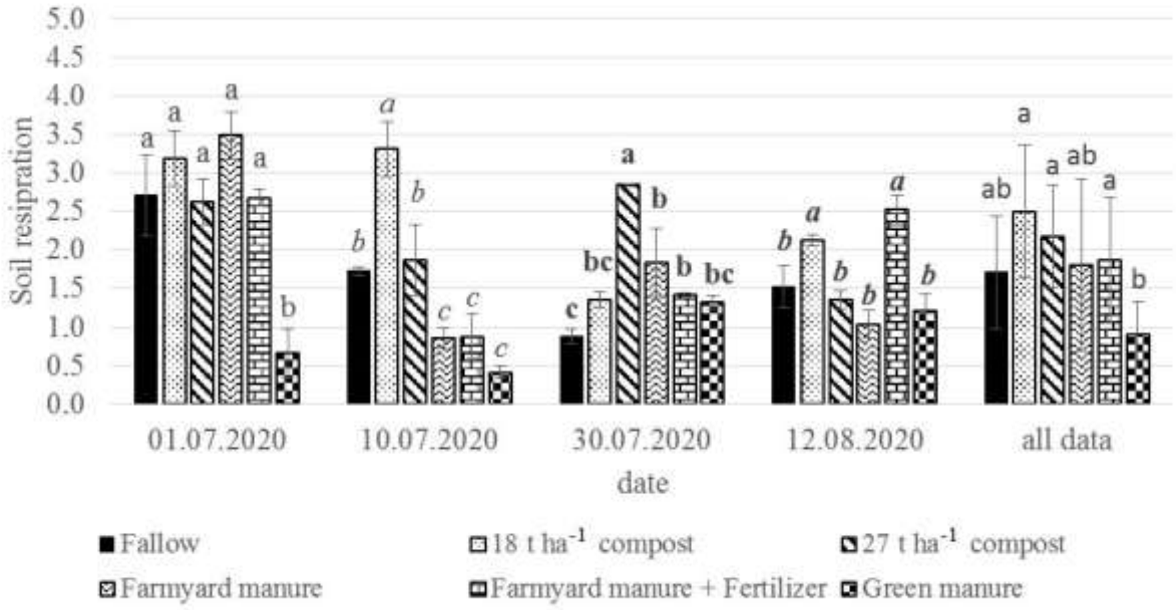

Fig. 5 Results of soil respiration measurements in laboratory in 2020 (Nyíregyháza, Hungary)

a-c indexes mean different groups of means according to the Tukey's test at the significance level of $p<0.05$, mean ± Standard Deviation (SD)

Soil respiration is considered to reflect the availability of carbon for microbial maintenance (Masto et al. 2006). Researchers have generally reported increased soil respiration rate under lupine cultivated in crop rotation (Sosulski et al. 2021), because the green manure is one of the easily available sources of organic matter that can improve soil fertility due to a high rhizosphere activity (Zotarelli et al. 2012). However, in our study the soil moisture content decreased below a critical limit (field capacity) in F and GM, therefore most of the metabolic activities were reduced significantly that resulted in a low soil respiration (Gill et al. 2016). In addition, the increased soil temperature also had an inhibitory effect on soil respiration (Buragiené et al. 2019). Reduced soil respiration rate was also reported under legumes (Alluvione et al. 2009) and in the fallow periods (Masto et al. 2006) that were explained by the variable amounts of labile organic carbon accumulated with different fertilizer treatments.

The organic matter input and the positive changes in soil parameters, such as soil humidity and pH stimulated the soil respiration processes in both SSC and FM+M (Masto et al. 2006; Lai et al. 2017; Ai et al. 2020). The pH influenced most of the biochemical reactions in the soil, including the bacterial enzymes synthesis, which affected soil respiration (Kemmitt et al. 2006). The soil moisture content was usually near the field capacity that represents the quantity of water to which soil respiration functions in optimum conditions (Han et al. 2019). The higher soil moisture was accompanied by a lower soil temperature, which also had a favourable effect on the processes affecting soil respiration. Soil humidity directly influenced the physiological processes of the plant roots and bacterial cell, and indirectly modified the capacities of gas and substances diffusion, thereby influencing soil respiration as well (Bao et al. 2016; Bogužas et al. 2018; Brangarí et al. 2020).

Enzyme activity

The dehydrogenase activity (DHA) of the soil changed in line with the results of soil respiration measurements. The DHA usually was the lowest in F and GM. The activity was at the same level, slightly above 10 µg formazan g^{-1} soil day^{-1} in the 27 t ha^{-1} SSC and in FM+M. The highest DHA activity was measured in FM and in the 18 t ha^{-1} SSC treatment, but only the 18 t ha^{-1} SSC enhanced significantly the DHA in the upper soil layer compared to the F. (Fig. 6).

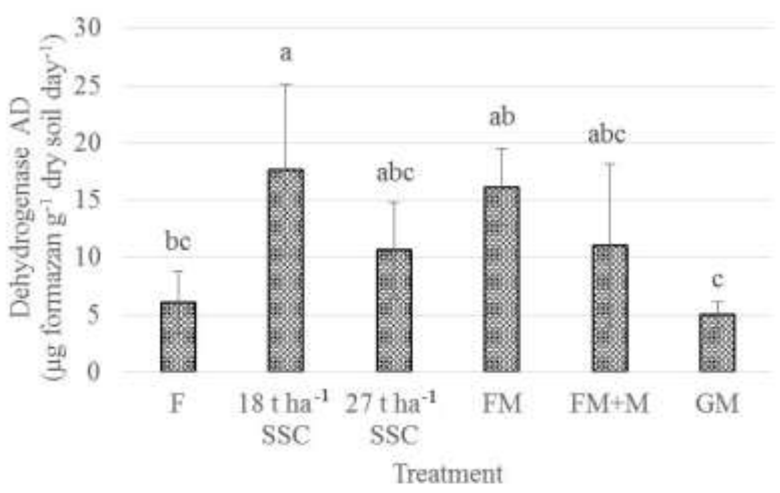

Fig. 6 Changes in dehydrogenase activity in different fertilization treatments in 2020 (Nyíregyháza, Hungary)

a-c indexes mean different groups of means according to the Tukey's test at the significance level of $p<0.05$, mean ± Standard Deviation (SD); F: Fallow, SSC: Sewage sludge compost, FM: Farmyard manure, FM+M: Farmyard manure + mineral fertilizer, GM: Green manure

There was a relatively low catalase activity (CAT) measured in FM+M and in GM. Compared to these values, a slight increase in CAT can be observed in F and in FM. The SSC applications also had a beneficial effect on CAT that was statistically higher as compared to other fertilization treatments (Fig. 7).

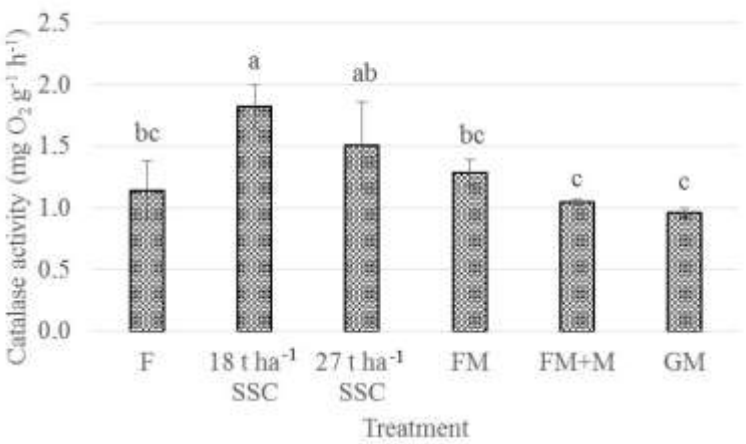

Fig. 7 Changes in catalase activity in different fertilization treatments in 2020 (Nyíregyháza, Hungary)
a-c indexes mean different groups of means according to the Tukey's test at the significance level of $p<0.05$, mean ± Standard Deviation (SD)
F: Fallow, SSC: Sewage sludge compost, FM: Farmyard manure, FM+M: Farmyard manure + mineral fertilizer, GM: Green manure

Activities of dehydrogenase (DH) and catalase (CAT) enzymes are considered ecotoxicological indicators of soil quality and soil health (Farsang et al. 2020). Their activity is an indicator of the biological activity of soil that depends on the metabolic state of soil microorganisms (Hamdi et al. 2019; Dhanker et al. 2021). The organic matter content of applied sewage sludge compost was good nutrient sources for soil microbes, which is also reflected in the high enzyme activity (Ai et al. 2020). The bentonite with high montmorillonite content also provided a living space for soil microorganisms due to its large specific surface area, especially in sandy soil (Zhang et al. 2020). In addition, the mineral particles with complement of organic substances formed organo-mineral complexes, which resulted in a better soil structure and improved air and water management, thereby promoting microbial activities (Glab et al. 2020; Zhang et al. 2020; Dhanker et al. 2021). Several authors reported that sewage sludge/compost application increased the dehydrogenase activity and soil respiration rate on sandy soil (Hamdi et al. 2019; Dhanker et al. 2021; Aweez and Darwesh 2021). Wang et al. (2012) published an increased catalase activity after adding varying doses of the sewage sludge compost to the soil that can be explained by the increased soil porosity and thus improved aeration of soil (Tejada and Gonzalez 2006).

Masto et al. (2006) also observed increased soil respiration and dehydrogenase activity after FM and FM+NPK application, but the dehydrogenase activity is very sensitive to the inhibitory effects associated with large amounts of nitrogenous fertilizer additions. Numerous scientific papers have shown the benefits of green manure on enzyme activities, soil microbial biomass, and microbial community structure (Ai et al. 2020; Dong et al. 2021). However, in our study the enzyme activity was low in green manure treatment, which can be explained by the fast decomposition of organic matter in soils because low carbon to nitrogen ratio is often associated with high proportion of easily decomposable carbon (Tian et al. 2015). Liang et al. (2014) also found no change in the microbial biomass after using green manures. Ai et al. (2020) suggest the combined application of compost and green manure to enrich the microbial community diversity of soil.

Correlation analysis

According to the results of correlation analysis (Table 8) it was a weak correlation between the data of field

($R_{S\text{-}Field}$) and laboratory ($R_{S\text{-}Lab}$) soil respiration measurements. The $R_{S\text{-}Field}$ was strongly related to SOM, pH_{KCl} and DHA. There was a negative correlation between $R_{S\text{-}Field}$ and T_{soil}, but it was not significant. $R_{S\text{-}Lab}$ had a strong relationship with all variables.

There was a negative relationship between T_{soil} and M_{soil}. Positive correlation was observed between SOM and pH_{KCl}. In addition, the soil pH correlated with all variables. The DHA was in strong correlation with $R_{S\text{-}Field}$, $R_{S\text{-}Lab}$, SOM and pH_{KCl}. The CAT had a strong correlation with $R_{S\text{-}Lab}$, T_{soil}, M_{soil} and pH_{KCl}.

Table 8 The results of Pearson Correlation analysis

	$R_{S\text{-}Field}$	$R_{S\text{-}Lab}$	T_{soil}	M_{soil}	SOM	pH_{KCl}	DHA	CAT
$R_{S\text{-}Field}$	1	.337	-.457	.403	.584*	.687**	.472*	.387
$R_{S\text{-}Lab}$	.337	1		.617**	.606**	.489*	.626**	.535*
T_{soil}	-.457		1	-.504*	-.388	-.732**		
M_{soil}	.403	.617**	-.504*	1	.404	.632**	.148	.654**
SOM	.584*	.606**	-.388	.404	1	.570*	.757**	.344
pH_{KCl}	.687**	.489*	-.732**	.632**	.570*	1	.501*	.825**
DHA	.472*	.626**		.148	.757**	.501*	1	.419
CAT	.387	.535*		.654**	.344	.825**	.419	1

Strong correlation is marked with * ($p < 0.05$) and ** ($p < 0.01$).

$R_{S\text{-}Field}$: Field soil respiration, $R_{S\text{-}Lab}$: Laboratory soil respiration, T_{soil}: Soil temperature, M_{soil}: Soil moisture, SOM: Soil organic matter content, DHA: Dehydrogenase activity, CAT: Catalase activity

General statement is that soil respiration is significantly influenced by soil temperature and soil moisture content (Meyer et al. 2018; Buragiené et al. 2019). According to some opinions, soil temperature has a greater role in regulating soil respiration than soil moisture (Wei et al. 2020). However, Fang et al. (2018) showed that soil moisture content has greater influence than temperature on CO_2 flux exchange. The latter statement is supported by our experience that there is a strong positive correlation between $R_{S\text{-}Lab}$ and M_{soil}.

The soil pH and SOM were closely related to $R_{S\text{-}Field}$ and $R_{S\text{-}Lab}$ as well. Similar findings were also published by Kemmitt et al. 2006; Lai et al. 2017; Li et al. 2019b. Based on the results the rate of soil respiration measured in the laboratory and in the field was usually consistent with each other, which is also confirmed by previous research works (Sima et al. 2012; Haney et al. 2008).

The activity of soil enzymes are also affected by different abiotic factors such as temperature, moisture, soil pH, compaction and nutrient content of soil (Aweez and Darwesh 2021). This is also confirmed by our results.

Conclusion

Field and laboratory measurements were conducted in long-term experiments to study the effects of different organic fertilizers (sewage sludge compost, fallow, farmyard manure, farmyard manure + NPK fertilizers, second crop green manure) on soil respiration and also to find the main driving factors of soil microbial properties.

The quality of the applied organic matter had a significant effect on the treatment efficiency. The sewage sludge compost treatments and the farmyard manure applications significantly increased the SOM content of sandy soil, but the green manure application did not affect it.

The results of laboratory and field measurements of soil respiration were usually consistent with each other. Among the investigated organic fertilizer treatments, the most intensive soil respiration was usually measured in both sewage sludge compost treatments and in farmyard manure with NPK.

According to the results of correlation analysis the main driving factors of soil respiration were the organic matter content and the pH of the soil, and in addition the laboratory soil respiration was influenced by soil moisture content as well.

Land use of sewage sludge compost could increase soil fertility by promoting microbial activities. The organic matter input and the positive changes in the physical and chemical properties of the soil stimulated the soil life, which resulted in more intensive soil respiration and enzyme activities. This statement is also confirmed by the results of the correlation analysis. The experiment indicated that the application of sewage sludge compost in agriculture can be well utilized for increasing organic matter content of sandy soil, thereby improving soil carbon sequestration and contributing sustainable management.

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Compliance with ethical standards

Conflict of interest; The authors declare that there are no conflicts of interest associated with this study.

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