



The effect of exogenous organic matter on the thermal properties of tilled soils in Poland and the Czech Republic

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Abstract

Purpose Organic matter improves soil fertility and water and thermal properties, but its content often decreases. This decrease may be mitigated by the addition of exogenous organic matter (EOM). The aim of this study was to assess the effect of EOMs, including compost from manure, slurry, and straw (Ag); industrial organic compost from sewage sludge (Ra); animal meal from animal by-products (Mb); and digestate from a biogas fry factory (Dg) on soil thermal conductivity, heat capacity, thermal diffusivity, water content, and bulk density in the top (0–15-cm) layer of two soils in Poland and the Czech Republic.

Materials and methods Irrespective of EOM type, the total yearly nitrogen application rate being 200 kg N ha⁻¹ (100%) was from a given EOM at the rates 0, 50, 75, and 100% and the remaining parts from the mineral fertilizer. The study was conducted in 2013–2014 in Poland (Braszowice) and the Czech Republic (Pusté Jakartice) on loam silt and clay silt loam, respectively, as part of a cross-border cooperation project. The soil properties were examined using classical descriptive statistics, semivariograms, and kriging-interpolated maps.

Results and discussion Analysis of linear regressions (trends) showed that the EOM application rate influenced (positively or negatively) the soil properties in most measurement occasions. The variability of all soil properties was low and medium (coefficient of variation 7.3–34%). Geostatistical analysis indicated that the spatial dependence ($C_0/(C_0 + C_s)$) of the soil properties on the EOM-amended plots was very strong or moderate. The maps revealed that the heterogeneity and degree of patch fragmentation were greater for thermal conductivity and heat capacity than for thermal diffusivity, water content, and bulk density. In general, all the soil properties were spatially more variable in the Braszowice than Pusté Jakartice soil and in spring than autumn in both sites.

Conclusions The spatial analysis and maps enhance the comprehensive understanding of changes in soil thermal properties in response to EOM application. Suitability of the results from the field experiments in models predicting some thermal properties based on soil bulk density and water content in relation to EOM addition was indicated. Expressing the amount of EOMs added using the organic carbon content basis (% kg OC/kg of soil) instead of the nitrogen content basis allowed identifying areas on the kriging-interpolated maps where the distribution of soil thermal properties resembled that of soil organic carbon content, water content, and bulk density. Thus, the effect of EOMs on soil thermal properties is considered along with changes in soil water content and bulk density.

The results will be helpful in forecasting effects of exogenous organic matter on the soil thermal properties affecting surface-energy partitioning, temperature distribution in soil, and plant growth.

Keywords Czech Republic · Kriging maps · Poland · Recycled organic matter · Semivariograms · Soil thermal properties

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1 Introduction

Organic matter improves soil fertility, increases crop yields, and affects positively many functions of the soil including food production, nutrient and water storage, filtration, biological habitat, and climate regulations or negatively soil

hydrophobicity (Kwiatkowska-Malina 2018; EASAC 2018; Garratt et al. 2018).

However, its content in tilled soils frequently decreases (Olivier et al. 2015; Beck-Broichsitter et al. 2018), is maintained on the same level, or increases depending on the site conditions and management practices (Lal 2017; Ajayi and Horn 2017; GSOC17 2017; Bolinder et al. 2018). It has been assessed that losses of organic C due to tillage and erosion on a global scale vary from 42 to 78 Gt (Lal 2004). The review presented by Post and Kwon (2000) demonstrates that intensive 30–50-year tillage can result in as high as 50% loss of organic carbon from the top 20-cm soil layer. This is mostly attributed to reduced physical protection of organic matter by soil disturbance (West and Post 2002; Six et al. 2004), greenhouse gas emission (Hatano and Lipiec 2004), crop residue removal, and water erosion (Ruysschaert et al. 2006). However, in another long-term (30 years) field experiment of Rutkowska and Pikula (2013) in Poland, soil organic matter in tilled soil increased by approximately 12% when solid manure was regularly applied. Soil organic matter decomposition rates tend to increase with observed soil warming associated with climate change (Intergovernmental Panel Climate Change 2007; Qian et al. 2011; Bolinder et al. 2013).

To increase organic matter accumulation or prevent its losses in agricultural soils, additional inputs of organic materials should be applied (Dębska et al. 2016; Bolinder et al. 2018). Important sources of such materials can derive from by-products of agricultural industry, biochar, compost, digestate, biogas plant, and intensive livestock farming (Voelkner et al. 2015; Ajayi and Horn 2017) as well as lignin (Zhang et al. 2015).

Their effects depend on the quantity applied and the proportion transformed to more resistant soil organic matter (Diacono and Montemurro 2010; Bolinder et al. 2018). Application of the by-products to the soil allows minimizing waste streams and recycling nutrients in the closing cycle. Therefore, the use of recycled organic materials are efficient alternatives to chemical input-dependent and high-price mineral fertilizers in cropping systems (EASAC 2018; Bolinder et al. 2018).

There have been many studies examining the effects of organic materials on soil water retention and stability of soil structure (Minasny et al. 2017; Minasny and McBratney 2017). Some studies have shown that organic matter is able to hold several times more water in reference to its mass (Rawls et al. 2003; Yang et al. 2014) and increase the available water capacity to a greater extent in coarse than fine-textured soils (Minasny and McBratney 2017). Organic matter encourages formation of soil aggregates that stabilize the pore system and allow storing larger quantities of rainwater in the soil for the growth of plants. It also protects the natural “organic carbon” in the aggregates from microbial decomposition (McKenzie et al. 2011; Wiesmeier et al. 2012).

A substantially lower number of studies, however, have been focused on the effect of recycled organic matter on soil thermal properties although they are a significant factor influencing surface energy partitioning, temperature distribution (Chung and Horton 1987; Mady and Shein 2016), water transmission in the soil and nearby ground atmosphere system (Heitman et al. 2007), and seed germination and plant growth (Wardani and Purqon 2016). Besides, thermal properties are used to assess heat migration in the soil in terms of using geothermal energy (Mondal et al. 2015; Di Sipio and Bertermann 2018).

Addition of organic materials can modify the thermal properties of a given soil through changes in the soil structure (Yang et al. 2014; Horn et al. 2014; Zhang et al. 2015) affecting the relative contribution of air, water, and organic matter (Usowicz et al. 2013, 2016; Zhang et al. 2015) with significantly different thermal properties. For example, air displays very low thermal conductivity of $0.025 \text{ W m}^{-1} \text{ K}^{-1}$, which increases to 0.25, 0.57, and up to $8.80 \text{ W m}^{-1} \text{ K}^{-1}$ for organic matter, water, and mineral particles, respectively (de Vries 1963).

The effect of recycled organic matter addition on the thermal properties can be mediated by the application rate and type of the exogenous organic material and the site conditions. Therefore, the aim of this study was to assess the effect of EOMs, including compost from manure, slurry, and straw (Ag); industrial organic compost from sewage sludge (Ra); animal meal from animal by-products (Mb); and digestate from a biogas fry factory (Dg) on soil thermal conductivity, heat capacity, thermal diffusivity, water content, and bulk density in the top (0–15-cm) layer of two soils in Poland and the Czech Republic.

2 Materials and method

2.1 Study area and exogenous organic materials applied

A 2-year (2013–2014) field experiment was conducted with exogenous organic matter on loam silt and clay silt loam located in Poland (Braszowice, $50^{\circ} 34' 03.0'' \text{ N } 16^{\circ} 48' 07.4'' \text{ E}$) and the Czech Republic (Pusté Jakartice, $49^{\circ} 58' 23.5'' \text{ N } 17^{\circ} 57' 19.8'' \text{ E}$), respectively. The soils in both sites were classified as Haplic Cambisols (IUSS 2015). The soils contain 14 and 20% of clay and 1.12 and 1.13% of organic carbon in Braszowice and Pusté Jakartice, respectively (Table 1). Visual observations showed that the combined size class for soil structure type was fine to coarse (1–10 mm) (FAO 2006) in both sites and aggregates of the latter were more fragile.

The following EOMs were used: digestate from a biogas fry factory (Dg) in Braszowice, compost from manure, slurry, and straw produced by thermophilic aerobic fermentation

Table 1 General information about the properties of the studied soils

Profile (cm)	Sand (%)	Silt (%)	Clay (%)	SOC (%)	BD (Mg m ⁻³)	SHC (m/day)
Braszowice						
0–15	37	49	14	1.12	1.360	1.79
15–30	36	48	16	0.86	1.491	
30–60	36	46	18	0.42	1.600	
Pusté Jakartice						
0–15	27	53	20	1.13	1.391	0.71
15–30	28	53	19	1.11	1.510	
30–60	28	51	21	0.74	1.605	

SOC soil organic carbon, BD bulk density, SHC saturated hydraulic conductivity

during around 6 months (Ag) in Pusté Jakartice, and industrial organic compost from sewage sludge (Ra) and animal meal from animal by-products (Mb) in both sites (Table 2) (Niedźwiecki et al. 2015). The plot size was 4.5 × 6 m in Braszowice and 3 × 8 m in Pusté Jakartice. The EOMs were

spread at spring of each year on the soil surface and then carefully incorporated into a 15-cm depth using a cultivator before sowing maize (*Zea mays* L.) in both sites. Each EOM was applied at the following 3 rates based on the nitrogen content (100% = 200 kg N ha⁻¹): 50 (50% N from EOM and

Table 2 Types and application rates of exogenous organic matter (EOM) in Braszowice and Pusté Jakartice

EOM	Moist EOM weight ^{a,***} kg m ⁻²	Dry EOM weight kg m ⁻²	Organic carbon weight kg m ⁻²	Dry EOM weight/ dry soil weight [#] kg kg ⁻¹	Dry EOM weight/dry soil weight × 100 %, kg kg ⁻¹	Organic carbon weight/dry soil weight [#] kg kg ⁻¹	Organic carbon weight/dry soil weight × 100 %, kg kg ⁻¹
Braszowice							
50-Mb [*]	0.155	0.145	0.058	0.00071	0.0713	0.00029	0.0286
75-Mb [*]	0.230	0.216	0.087	0.00106	0.1058	0.00042	0.0424
100-Mb [*]	0.305	0.286	0.115	0.00140	0.1403	0.00056	0.0563
50-Ra	0.975	0.625	0.112	0.00307	0.3066	0.00055	0.0549
75-Ra	1.465	0.940	0.168	0.00461	0.4606	0.00082	0.0825
100-Ra	1.950	1.251	0.224	0.00613	0.6131	0.00110	0.1098
50-Dg	1.165	0.139	0.057	0.00068	0.0682	0.00028	0.0277
75-Dg	1.745	0.208	0.085	0.00102	0.1021	0.00042	0.0416
100-Dg	2.330	0.278	0.113	0.00136	0.1364	0.00055	0.0555
Pusté Jakartice							
50-Mb	0.124	0.116	0.047	0.00056	0.0558	0.00022	0.0224
75-Mb	0.184	0.173	0.069	0.00083	0.0828	0.00033	0.0332
100-Mb	0.244	0.229	0.092	0.00110	0.1098	0.00044	0.0440
50-Ra	0.732	0.470	0.084	0.00225	0.2250	0.00040	0.0403
75-Ra	1.464	0.939	0.168	0.00450	0.4501	0.00081	0.0806
100-Ra	1.948	1.250	0.224	0.00599	0.5989	0.00107	0.1072
50-Ag	0.472	0.351	0.085	0.00168	0.1684	0.00041	0.0406
75-Ag	0.940	0.700	0.169	0.00335	0.3353	0.00081	0.0808
100-Ag	1.256	0.935	0.225	0.00448	0.4481	0.00108	0.1080

Ag = compost from manure, slurry, and straw; Ra = industrial organic compost from sewage sludge; Mb = animal meal from animal by-products; Dg = digestate from a biogas fry factory; 50 = 50% N from a given EOM and 50% mineral N; 75 = 75% N from a given EOM and 25% mineral N; and 100 = 100% N from EOM

^a Water content (WC) of the EOMs is given in Table 3

^{*} Applied once (2013) in Braszowice, Poland

^{**} Data from (Niedźwiecki et al. 2015)

[#] dry soil weight from 1 m² of top 0–15 cm (= 204 kg in Braszowice and 209 kg in Pusté Jakartice)

50% mineral N), 75 (75% N from EOM and 25% mineral N), and 100 (100% N from EOM). Control plots received 100% mineral N. Depending on the nitrogen content (N_{tot}) in the EOMs varying from 2.3 to 8.4% (Table 3), the application rates of the organic amendments varied from 0.124 to 2.33 kg m⁻². In Braszowice, in the second year of the experiment, no Mb was added due to the high content of phosphorus and the risk of eutrophication. Instead of Mb, relevant rates of mineral N were applied. The randomized complete block design experiment had 4 blocks (A, B, C, D). Each block included 10 plots (3 EOMs × 3 rates and the control) (Fig. 1). There were 40 plots in each site. The EOMs were spread each year on the soil surface and then carefully incorporated at spring into a 15-cm depth using a cultivator before sowing maize (*Zea mays* L.) in both sites.

To improve the analysis of the effect of organic matter on the soil properties, we calculated the amount of EOMs added on the organic carbon content (OC) basis and expressed in % kg OC/kg of soil. The calculation was based on soil bulk density, organic carbon content, water content, and bulk density of each EOM (Tables 2 and 3). The soil bulk densities, organic carbon content, and soil weight for the 0–15-cm layer per m² in Braszowice and Pusté Jakartice were 1.36 and 1.39 Mg m⁻³, 1.12 and 1.13%, and 204 and 209 kg m⁻², respectively.

2.2 Laboratory and field measurements

Before the field experiments started, measurements of thermal conductivity (K), heat capacity (C), and thermal diffusivity (D) of pure exogenous organic materials were

done at the current soil water content and dry state in the laboratory. The field measurements of soil K, C, and D in each study field were carried out in 120 points (4 blocks × 10 treatments × 3 replicates taken randomly) using a KD2 Pro meter (Decagon Devices), with accuracy 10% for K from 0.2 to 2 W m⁻¹ K⁻¹ and 10% at K above 0.1 W m⁻¹ K⁻¹ for both C and D. The KD2 Pro meter was used in both laboratory and field. The water content using the time-domain reflectometry (TDR) (Easy Test, Lublin, Poland) method with accuracy 2% and bulk density was measured in 80 points (4 blocks × 10 treatments × 2 replicates taken randomly). Soil samples for determination of bulk density and water content were collected in 100-cm³ Kopecky cylinders and dried. The weight values before and after drying were used to calculate bulk density. Soil water content was measured using a TDR meter close to the sampling place with the cylinders. All measurements were performed before sowing of maize in spring and after harvest in autumn at a 0–15-cm depth in both study years.

2.3 Weather conditions

The average annual long-term air temperatures were 8.2 °C and 8 °C in Braszowice (Poland) and Pusté Jakartice (Czech Republic), respectively, and the corresponding sums of precipitations were 568.9 mm and 640 mm (average of 40 years). The data were collected at the meteorological stations Kłodzko, Braszowice, and Ostrava/Mosnov, Pusté Jakartice. In 2013 and 2014, the average annual temperatures were higher than the long-

Table 3 Some properties of exogenous organic matter used in the field experiments—thermal conductivity (K), heat capacity (C), thermal diffusivity (D), water content (WC), bulk density (BD), and organic carbon content (OC) and total nitrogen (N_{tot}) in EOMs at water contents during field application and dry state

EOM	K W m ⁻¹ K ⁻¹	C MJ m ⁻³ K ⁻¹	D mm s ⁻¹	WC m ³ m ⁻³	BD Mg m ⁻³	OC* %	N_{tot} * %
Mb							
Field	0.167	2.020	0.083	0.046	0.702		8.4
Dry	0.153	1.940	0.079			40.1	
Ra							
Field	0.248	1.570	0.158	0.258	0.461		2.3
Dry	0.098	0.861	0.113			17.9	
Ag							
Field [#]	–	–	–	0.225	0.655		2.6
Dry	–	–	–			24.1	
Dg							
Field	0.546	3.883	0.136	0.865	0.117		6.9
Dry	0.061	0.656	0.093			40.7	

Ag = compost from manure, slurry, and straw; Ra = industrial organic compost from sewage sludge; Mb = animal meal from animal by-products; Dg = digestate from a biogas fry factory; dry = after drying at temperature 60 °C to the constant weight

[#] Data from (Khater 2015)

* Data from (Niedźwiecki et al. 2015)

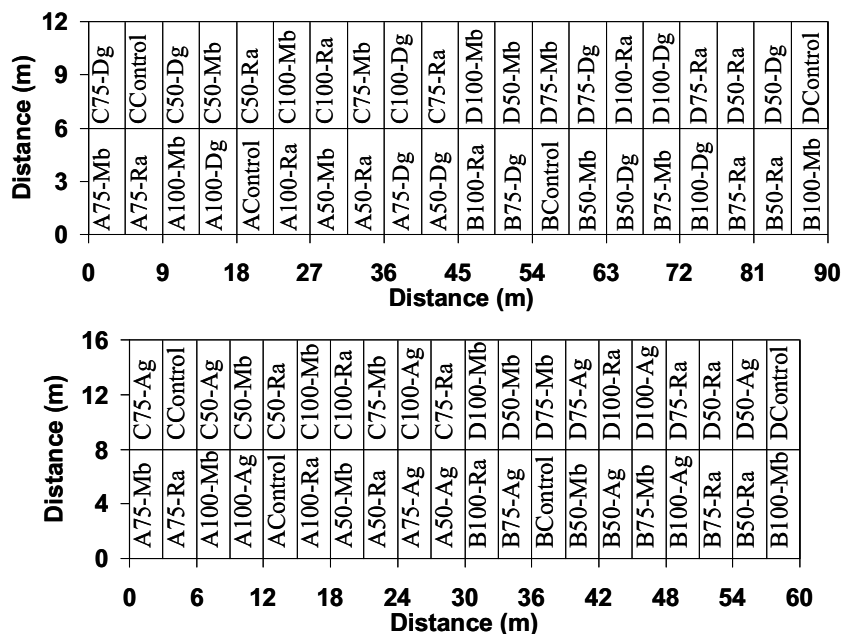
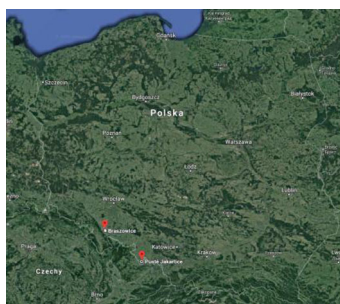


Fig. 1 Randomized field arrangement in Braszowice (50° 34' 03.0" N 16° 48' 07.4" E) (Poland) (upper part) and in Pusté Jakartice (49° 58' 23.5" N 17° 57' 19.8" E) (Czech Republic) (lower part). Initial capital letters A, B, C, and D refer to blocks (replicates) of the experiment. 50 = 50% N from a given EOM and 50% mineral N, 75 = 75% N from a given

EOM and 25% mineral N, and 100 = 100% N from EOM, control = 100% mineral N. Ag = compost from manure, slurry, and straw, Ra = industrial organic compost from sewage sludge, Mb = animal meal from animal by-products, Dg = digestate from a biogas fry factory

term temperature by 0.4 °C and 1.1 °C in Braszowice and 0.92 °C and 2.29 °C in Pusté Jakartice, respectively. The precipitations in Braszowice were higher than the long-term average by 56 and 20 mm in 2013 and 2014, respectively, whereas these values in Pusté Jakartice were lower by 58 mm in 2013 and higher by 94 mm in 2014. The precipitation sums during the growing season (April–September) amounted to 460 mm both in 2013 and in 2014 in Braszowice, whereas the sums in Pusté Jakartice were 444 in 2013 and 568 mm in 2014.

2.4 Data analysis

Basic statistics, including the mean, minimum, maximum, standard deviation, and coefficient of variation (CV), were calculated. Spatial dependence and distribution of each soil property were evaluated using geostatistical methods.

Experimental semivariograms $\gamma(h)$ were calculated using standard formulae (Zawadzki et al. 2005; Gamma Design Software 2008):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2$$

where $N(h)$ is the number of pairs of points with values of $z(x_i)$, $z(x_i + h)$, distant by h . In these analyses, mathematical functions were fitted to the experimental semivariograms. The nugget values, sills, and ranges of spatial autocorrelation were determined:

$$\gamma(h) = C_0 + C[1 - \exp(-h/A_0)]$$

where $\gamma(h)$ is the semivariance for internal distance class h , h is the lag interval, C_0 is the nugget variance ≥ 0 , C is the structural variance $\geq C_0$, and A_0 is the range parameter. In the exponential model, the effective range for the major axis is equal to $3A_0$, which is the distance at which the sill $(C_0 + C)$ is within 5% of the asymptote.

Proportion $C_0/(C_0 + C)$ is a measure of the proportion of sample variance ($C_0 + C$) that is explained by spatially structured variance C . According to Cambardella et al. (1994), the spatial dependences ($C_0/(C_0 + C) < 25\%$, $25\text{--}75\%$, and $> 75\%$) are strong, moderate, and weak, respectively.

Estimation of values in places, where no samples have been taken, was conducted with the help of mapping using the ordinary kriging method (Gamma Design Software, GS+9, 2008):

$$z^*(x_o) = \sum_{i=1}^N \lambda_i z(x_i)$$

where N is the number of measurements, $z(x_i)$ is the value measured at point x_i , $z^*(x_o)$ is the estimated value at the point of estimation x_o , and λ_i are weights.

3 Results

3.1 Exogenous organic materials added

As described in “Materials and methods,” we expressed the EOMs added on an organic carbon content basis (% kg OC/kg of soil) (Table 2). Application of EOMs containing 18–41% of organic carbon twice resulted in a wide range of the organic carbon weight values ranging from $0.045\% \text{ kg kg}^{-1}$ (0.0224×2 years) for Mb in Pusté Jakartice up to almost $0.22\% \text{ kg kg}^{-1}$ (0.109×2 years) for 100-Ra in Braszowice as well as 100-Ra and 100-Ag in Pusté Jakartice. It is worth noting that the lower organic carbon input with Mb in Braszowice was in part due to application thereof only in the first year of the study.

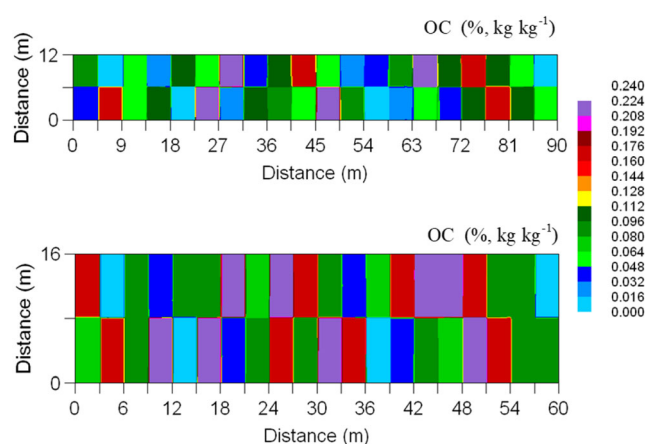


Fig. 2 Spatial distribution of soil organic carbon content (% kg OC/kg of soil) at 0–15 cm depth in Braszowice (upper part) and Pusté Jakartice (lower part) after addition of EOMs to the soil in the 2nd of the experiment (2014). The plot size was 4.5×6 m in Braszowice and 3×8 m in Pusté Jakartice

The results in Fig. 2, as calculated in Table 2, indicate that in Pusté Jakartice vs. Braszowice, there were more grouped (neighbouring) plots with the same soil organic carbon content (OC). This refers especially to areas with OC of $0.096\text{--}0.112\% \text{ kg kg}^{-1}$ (marked in green) and $0.160\text{--}0.176\% \text{ kg kg}^{-1}$ (marked in red). Moreover, the Pusté Jakartice vs. Braszowice site had more sub-areas with maximum OC ($0.208\text{--}0.224\% \text{ kg kg}^{-1}$).

3.2 Characteristics of exogenous materials and soils

As can be seen in Table 3, the values of the thermal conductivity and heat capacity of the EOMs at the water contents during application into the soils were the highest in the Dg treatment ($0.546 \text{ W m}^{-1} \text{ K}^{-1}$ and $3.883 \text{ MJ m}^{-3} \text{ K}^{-1}$, respectively) and considerably lower and similar in the Mb and Ra variants ($0.167\text{--}0.248 \text{ W m}^{-1} \text{ K}^{-1}$ and $1.570\text{--}2.020 \text{ MJ m}^{-3} \text{ K}^{-1}$, respectively). However, the values of thermal diffusivity were the highest and similar in the case of Ra and Dg ($0.136\text{--}0.158 \text{ mm s}^{-1}$) and the lowest in the Mb treatment (0.083 mm s^{-1}). In the dry state, the values of thermal conductivity and heat capacity were the highest in the Mb variant ($0.153 \text{ W m}^{-1} \text{ K}^{-1}$ and $1.940 \text{ MJ m}^{-3} \text{ K}^{-1}$, respectively) and the lowest in the Dg treatment ($0.061 \text{ W m}^{-1} \text{ K}^{-1}$ and $0.656 \text{ MJ m}^{-3} \text{ K}^{-1}$, respectively). However, the thermal diffusivity value was the highest in the Ra variant (0.113 mm s^{-1}) but lower and similar in the Mb and Dg treatment ($0.079\text{--}0.093 \text{ mm s}^{-1}$). The relative reductions in the thermal properties from the water content in the field application to the dry state were the largest for Dg (by 32–89%) and the lowest for Mb (by 4–8.4%). This was due to the highest water content at the time of application in the Dg variant ($0.865 \text{ m}^3 \text{ m}^{-3}$) and substantially lower in the other amendments ($0.046\text{--}0.258 \text{ m}^3 \text{ m}^{-3}$). The inverse was true for the bulk density values (0.117 Mg m^{-3} vs. $0.461\text{--}0.702$). Although the thermal properties were not measured in the Ag treatment, their values can be assumed to be similar to those of Ra, having similar contents of organic carbon, water content, and bulk density, which are regarded as main factors influencing the thermal properties of EOMs.

As can be seen in Table 4, the overall mean values ($n = 320\text{--}480$) of soil bulk density, water content, thermal conductivity, heat capacity, and thermal diffusivity in Braszowice were 1.360 Mg m^{-3} , $0.222 \text{ m}^3 \text{ m}^{-3}$, $1.024 \text{ W m}^{-1} \text{ K}^{-1}$, $2.435 \text{ MJ m}^{-3} \text{ K}^{-1}$, and 0.428 mm s^{-1} , respectively. The corresponding means in Pusté Jakartice were 1.391 Mg m^{-3} , $0.265 \text{ m}^3 \text{ m}^{-3}$, $1.156 \text{ W m}^{-1} \text{ K}^{-1}$, $2.641 \text{ MJ m}^{-3} \text{ K}^{-1}$, and 0.434 mm s^{-1} . The values of all properties in both sites and study years except the water content in 2013 in Braszowice were greater in autumn than spring. As suggested by Dahiya et al. (1984), the variability of the bulk density was low ($\text{CV} =$

Table 4 Summary statistics of the soil variables at the 0–15-cm depth

Parameters	Bulk density Mg m ⁻³	Water content m ³ m ⁻³	Thermal conductivity W m ⁻¹ K ⁻¹	Heat capacity MJ m ⁻³ K ⁻¹	Thermal diffusivity mm s ⁻¹
Braszowice					
<i>n</i> —sample number	320	320	480	480	480
Mean	1.360	0.222	1.024	2.435	0.428
CV (%)	10.9	21.0	28.0	26.3	22.7
Minimum	1.035	0.079	0.438	1.117	0.231
Maximum	1.674	0.382	1.780	3.992	0.937
Pusté Jakartice					
<i>n</i> —sample number	320	320	480	480	480
Mean	1.391	0.265	1.156	2.641	0.434
CV (%)	7.3	21.9	30.4	27.3	22.1
Minimum	1.152	0.126	0.361	1.090	0.237
Maximum	1.558	0.417	1.767	3.993	0.790

CV coefficient of variation

7.3–10.9%) and medium for the other properties (CV = 21.0–30.4%).

3.3 Linear regressions (trends) between EOM application rates and soil properties

The data collected allowed obtaining relationships between the amounts of EOMs applied and the physical and thermal soil properties using linear regression at different occasions.

Figure 3 indicates that the ascending trend lines of soil water content with increasing EOM application rate added occurred at all occasions except in spring 2014 in Braszowice and in spring 2013 and 2014 in Pusté Jakartice. The trend lines for bulk density differed between the study sites. The bulk density values decreased or remained the same with the increasing EOM application rate in Braszowice, but increased in all cases in Pusté Jakartice. This was probably related to the different within-site variability of bulk density and the more aggregated structure in the Pusté Jakartice soil. Overall, the changes in bulk density were relatively smaller in Pusté Jakartice than Braszowice.

As to thermal conductivity, there was no clear trend with the increasing application rate of the EOMs except the decreasing and increasing trend lines in autumn 2013 in Braszowice and in autumn 2014 in Pusté Jakartice, respectively (Fig. 4). In most cases, the variability indicated by standard deviation was greater in Braszowice than Pusté Jakartice. *There was an ascending trend line for soil heat capacity with the increasing EOM application rate in Pusté Jakartice in autumn 2013 and 2014. In turn, in spring 2014, the trend for the heat capacity with the EOM rate was increasing in Braszowice and decreasing in Pusté Jakartice. In the other cases, the trends remained*

unchanged. At all occasions, in contrast to spring 2014, the heat capacity values were greater in Pusté Jakartice than Braszowice. Irrespective of the occasion, EOM type, and application rate, the variability of the heat capacity shown by the standard deviation values was lower in Pusté Jakartice than Braszowice. Thermal diffusivity was not substantially influenced by the increasing EOM application rates (Fig. 4). Similar to heat capacity, the variability of this property was in most cases lower in Pusté Jakartice than in Braszowice. Overall, comparison of the arrangement of the trend lines for all soil properties (Figs. 3 and 4) indicated that the differences in the response of thermal diffusivity to the increasing EOM application rate were much lower than those for the other soil properties studied.

3.4 Geostatistical analysis

3.4.1 Semivariograms

The skewness that describes the degree of distribution asymmetry around the mean (normal distribution = zero) that is 80 or 120 data depending on the property varied from –0.5 to 0.5 in most cases and was similar to the normal distribution and thereafter met the condition of a stationary or quasi-stationary process. The semivariogram exponential model was adjusted to the empirical semivariogram for most variables with a satisfactory accuracy in both sites ($R^2 > 0.7$). Alongside, the residual sums of squares for the semivariogram model were low (from 2.83E–09 to 1.87E–03) indicating good fit of the model to the experimental semivariogram data. The relatively low nugget effect (C_0) ranging from 0.00046 to 0.251 (Table 5) indicates regular and continuous distribution of all soil variables in both sites and that the accepted lag sampling was

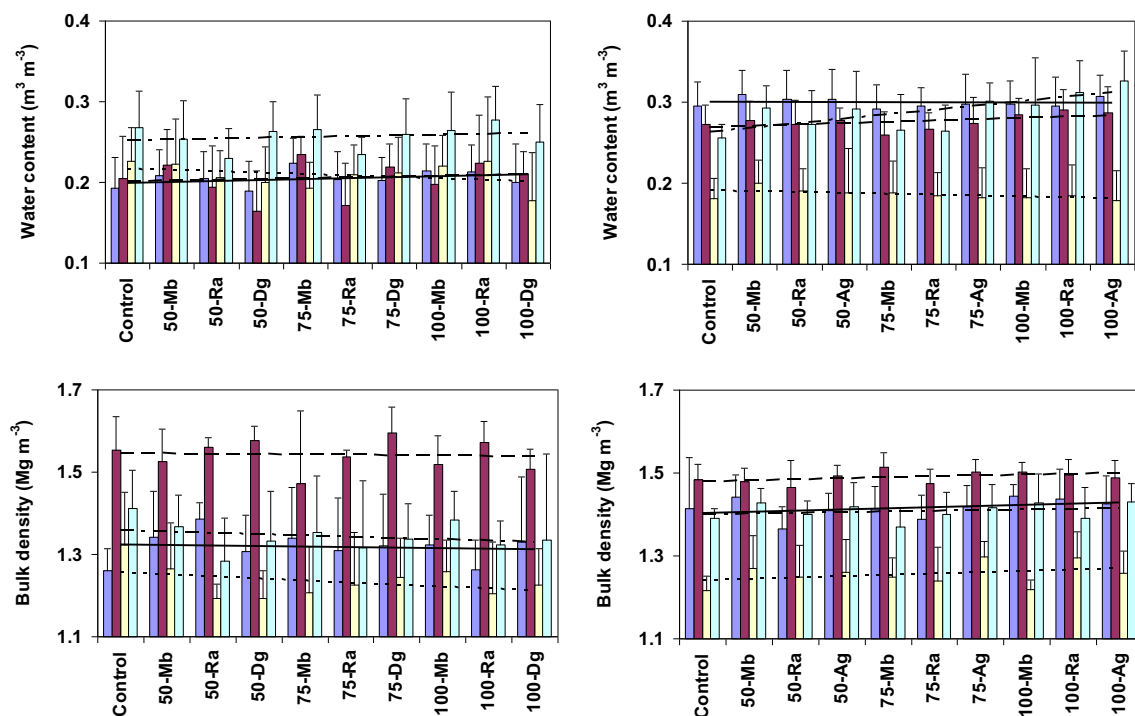


Fig. 3 Mean values with standard deviations ($n=8$) and linear regressions between EOM application rates and soil water content and bulk density for spring and autumn 2013 and for spring and autumn 2014 (successively from the left). 50 = 50% N from a given EOM and 50% mineral N, 75 = 75% N from a given EOM and 25% mineral N, and 100 = 100% N from EOM, control = 100% mineral N. Ag = compost

from manure, slurry, and straw, Ra = industrial organic compost from sewage sludge, Mb = animal meal from animal by-products, Dg = digestate from a biogas fry factory. Linear regressions between EOM application rates and soil water content and bulk density correspond to: spring (—) and autumn (—) 2013 and for spring (- - -) and autumn (- - -) 2014

sufficient to recognize the variance. The sills ($C_0 + C_s$) (C_s —structural variance) had the highest values for the heat capacity (0.074–0.315) in both sites and considerably lower values for the other soil variables (0.0002–0.006). The respective spatial dependences were strong and moderate for all soil variables, measurement occasions, and sites. The effective ranges of spatial dependencies (A) varied from 2.8 m for heat capacity in Pusté Jakartice in autumn 2013 to 48 m for thermal conductivity in Braszowice in autumn 2014.

3.4.2 Kriging-interpolated maps

The maps of the soil variables were first drawn by means of ordinary kriging and co-kriging methods. The results from both methods were alike, and hence, we used ordinary kriging built on theoretical semivariogram models (Table 5). Visual comparison of Figs. 2, 5, and 6 indicates interrelations (resemblance) between soil organic carbon content, water content, bulk density, and thermal properties. For example, the greater amount of soil organic carbon content (0.08–0.096% kg kg^{-1}) at approximately 51–57 m in the upper part and 54–60 m in the lower part of the field in Pusté Jakartice soil (Fig. 2) corresponds with greater soil water content, thermal conductivity, and heat capacity in spring 2013 (Figs. 5 and 6). This relation can in part be supported by the descending

distribution trend of organic carbon content from 0.224 to 0.08% kg kg^{-1} (Fig. 2) and thermal conductivity within the area approximately from 42 to 60 m in spring and autumn 2013 (Fig. 6). Such a trend was also observed for heat capacity (Fig. 6).

Moreover, the relatively high soil water content and bulk density in a large area of the field in Pusté Jakartice at harvest in 2013 and 2014 correspond with the relatively high thermal conductivity and heat capacity (Figs. 5 and 6). Therefore, the low soil water content and bulk density predominating in both experimental fields in spring 2014 match with low thermal conductivity and heat capacity that correspond with low soil water content and bulk density. However, the similar pattern of thermal conductivity and heat capacity in spring 2013 and 2014 in Braszowice corresponds with the relatively low soil water content and bulk density.

It is worth noting that the areas with the relatively high and maximum thermal diffusivity at 45–52 m and 65–67 m (lower side) in Braszowice in autumn 2013 correspond with the increased bulk density (Figs. 5 and 6). However, the lowest thermal diffusivity in both sites, recorded in autumn 2014, corresponds with the relatively high water content and bulk density. These effects were more pronounced in Pusté Jakartice than Braszowice. However, the predominantly low thermal diffusivity in spring 2013 in Pusté Jakartice soil corresponds with

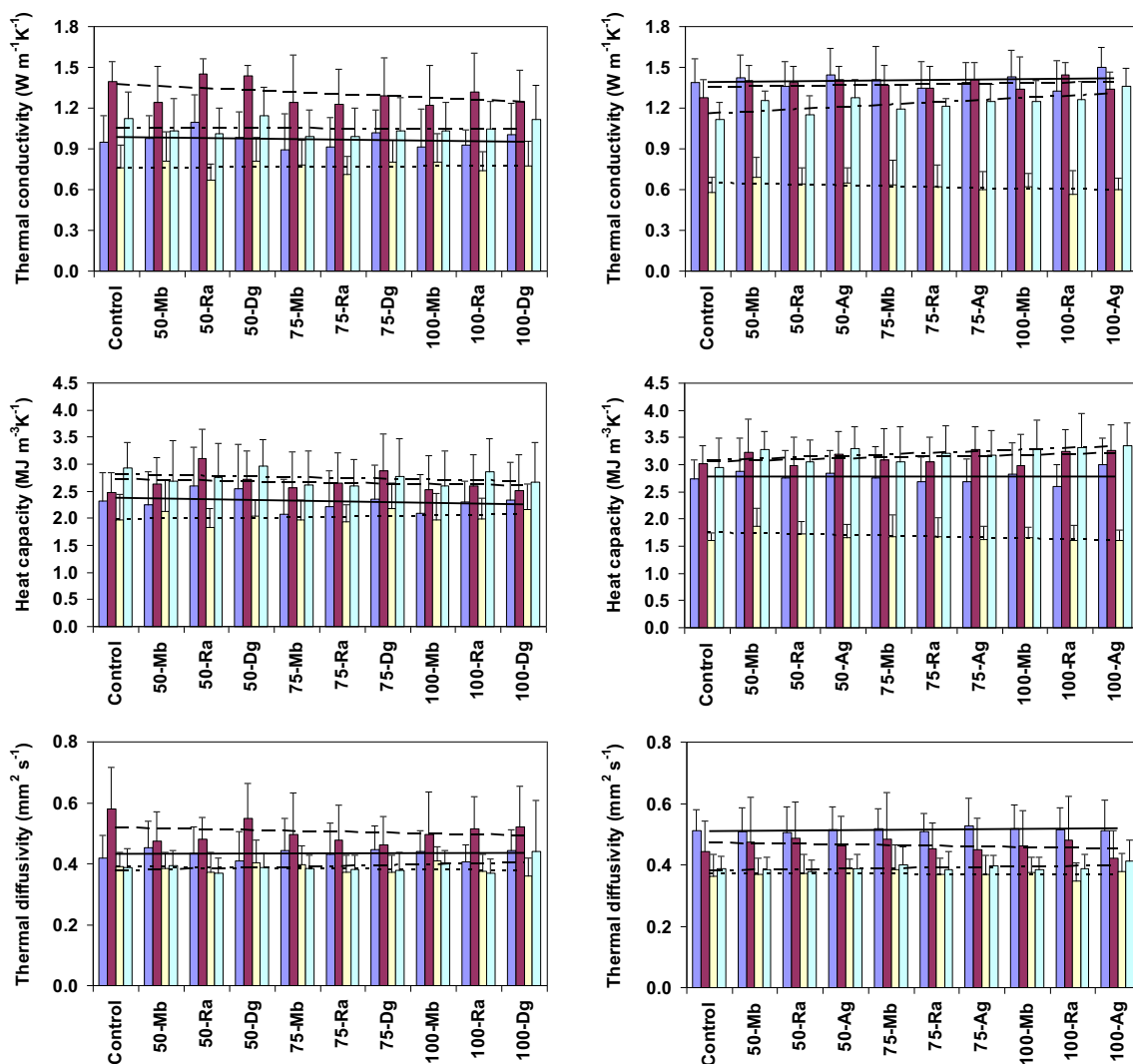


Fig. 4 Mean values with standard deviations ($n = 12$) and linear regressions between EOM application rates and soil thermal properties for spring and autumn 2013 and for spring and autumn 2014 (successively from the left). 50 = 50% N from a given EOM and 50% mineral N, 75 = 75% N from a given EOM and 25% mineral N, and 100 = 100% N from EOM, control = 100% mineral N. Ag = compost

both the low soil water content and bulk density. The effect of both factors is also clearly visible by comparison of the lower values of all thermal properties and bulk density and soil water content in spring in 2014 than in 2013, especially in Pusté Jakartice. Overall, the kriging-interpolated maps revealed that the heterogeneity and degree of patch fragmentation were higher for thermal conductivity and heat capacity than for thermal diffusivity, water content, and bulk density.

4 Discussion

According to the experiment schedule, the amount of each exogenous organic matter (EOM) added corresponded to 50, 75, or 100% of nitrogen (200 kg ha^{-1}) for maize growth. This

from manure, slurry, and straw, Ra = industrial organic compost from sewage sludge, Mb = animal meal from animal by-products, Dg = digestate from a biogas fry factory. Linear regressions between EOM application rates and soil thermal conductivity, heat capacity and thermal diffusivity correspond to: spring (—) and autumn (—) 2013 and spring (- - -) and autumn (- - -) 2014

was based on the fact that nitrogen supply plays a dominant role in accumulation of dry matter and final crop yield (e.g. Wilczewski et al. 2006). Taking into consideration that organic matter significantly affects soil physical and thermal properties, in this study, we expressed the added EOM as a percentage of organic carbon in soil ($\% \text{ kg OC/kg of soil}$). Thus, we obtained various and arbitrarily distributed amounts of organic carbon (Fig. 2) added due to the different application rates, organic carbon content in EOMs, and randomization of the experimental plots. Analysis of the spatial kriging-interpolated maps facilitated identification of areas where changes in the studied thermal properties are related to those of organic carbon from the EOMs. This supports the usefulness of the approach quantifying the application of EOMs in terms of carbon provided for studying the spatial effect of

Table 5 Semivariogram parameters for bulk density, water content, thermal conductivity, heat capacity, and thermal diffusivity in the 0–15-cm layer

Parameters	Model	C_0	$C_0 + C_s$	A (m)	$C_0 / (C_0 + C_s)$	Model	C_0	$C_0 + C_s$	A (m)	$C_0 / (C_0 + C_s)$	
Brasowice—2013 spring						Pusté Jakartice—2013 spring					
Bulk density	Exp.	0.00115	0.01020	7.4	0.113	Exp.	0.00059	0.00418	6.4	0.141	
Water content	Exp.	0.00007	0.00049	6.9	0.141	Exp.	0.00006	0.00046	6.6	0.134	
Thermal conductivity	Exp.	0.00411	0.03272	9.7	0.126	Exp.	0.00287	0.03294	5.2	0.087	
Heat capacity	Exp.	0.02500	0.25000	9.6	0.100	Exp.	0.02670	0.25140	6.6	0.106	
Thermal diffusivity	Exp.	0.00043	0.00395	6.6	0.109	Exp.	0.00017	0.00137	5.5	0.122	
Brasowice—2013 autumn						Pusté Jakartice—2013 autumn					
Bulk density	Exp.	0.00325	0.00722	45.6	0.450	Exp.	0.00026	0.00245	4.6	0.105	
Water content	Exp.	0.00035	0.00289	12.4	0.121	Exp.	0.00018	0.00048	18.5	0.381	
Thermal conductivity	Exp.	0.00330	0.06120	7.9	0.054	Exp.	0.00286	0.03062	8.1	0.093	
Heat capacity	Exp.	0.02410	0.31520	5.6	0.076	Exp.	0.01050	0.11700	2.8	0.090	
Thermal diffusivity	Exp.	0.00703	0.01034	9.4	0.680	Exp.	0.00057	0.00491	4.5	0.116	
Brasowice—2014 spring						Pusté Jakartice—2014 spring					
Bulk density	Exp.	0.00088	0.00986	7.8	0.089	Exp.	0.00043	0.00391	6.7	0.110	
Water content	Exp.	0.00008	0.00055	8.5	0.144	Exp.	0.00021	0.00036	30.0	0.589	
Thermal conductivity	Exp.	0.01220	0.02406	7.3	0.507	Exp.	0.00116	0.01252	5.4	0.093	
Heat capacity	Exp.	0.06374	0.10415	11.3	0.612	Exp.	0.00910	0.07420	6.5	0.123	
Thermal diffusivity	Exp.	0.00052	0.00370	8.2	0.141	Exp.	0.00027	0.00204	4.8	0.132	
Brasowice—2014 autumn						Pusté Jakartice—2014 autumn					
Bulk density	Exp.	0.00097	0.01214	7.6	0.080	Exp.	0.00169	0.00271	21.1	0.622	
Water content	Exp.	0.00022	0.00143	4.3	0.156	Exp.	0.00059	0.00116	20.8	0.507	
Thermal conductivity	Exp.	0.01930	0.05780	48.1	0.334	Exp.	0.00380	0.02260	7.9	0.168	
Heat capacity	Exp.	0.01360	0.21720	8.1	0.063	Exp.	0.01690	0.12080	4.7	0.140	
Thermal diffusivity	Exp.	0.00032	0.00175	9.9	0.184	Exp.	0.00046	0.00092	18.1	0.499	

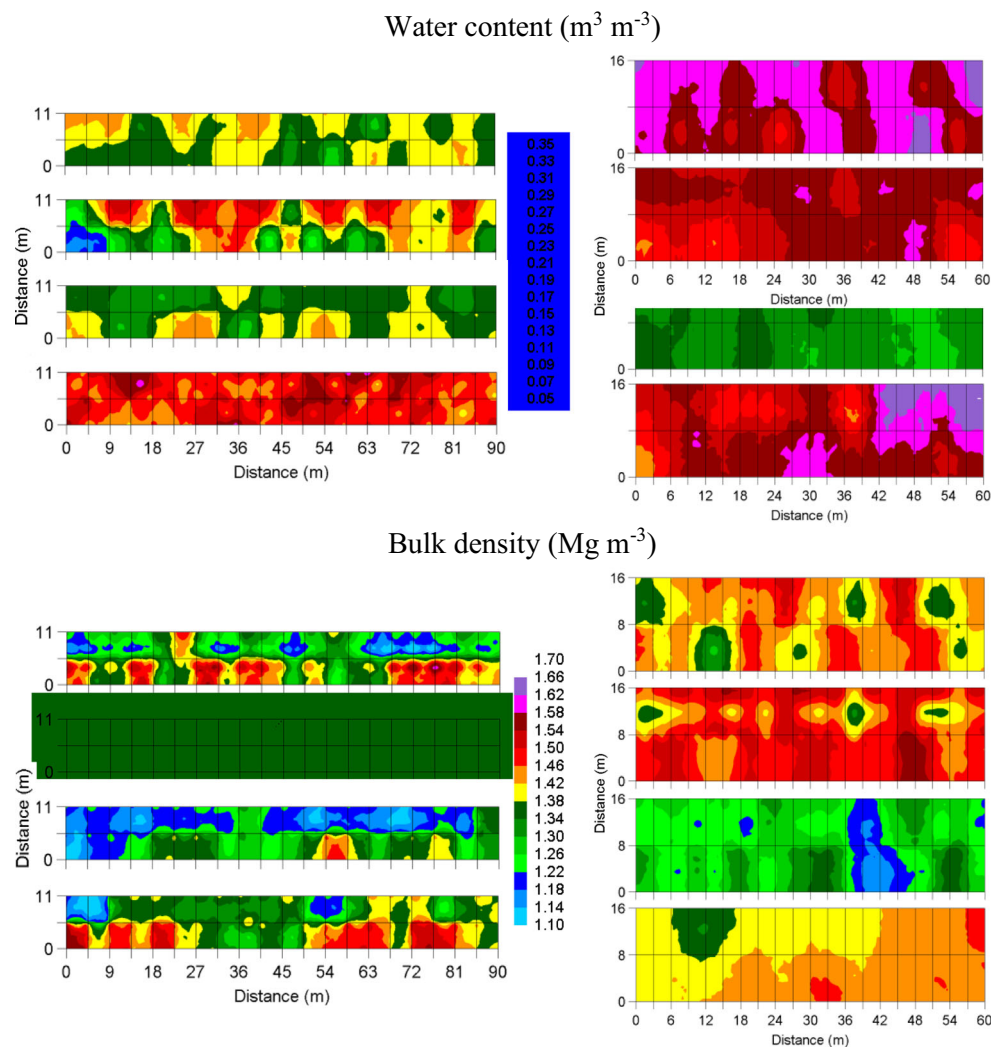
Exp. exponential, C_0 nugget, A (m) range, $C_0 + C_s$ sill

exogenous organic materials (EOMs) on soil thermal properties. The occurrence of spatial similarity (resemblance) of the organic carbon added and soil water content, bulk density, thermal conductivity, and heat capacity is worth noting. This implies that the effect of added organic carbon from the EOMs on the thermal properties could be manifested by changes in soil water holding capacity and density. This is in line with earlier studies showing that organic matter can significantly improve soil water retention (Minasny et al. 2017; Pachepsky et al. 2006) and modify soil structure and density (Usowicz et al. 2013). Irrespective of the soil organic matter effect, the thermal properties are principally influenced by soil mineralogy and soil texture (Cai et al. 2017; Zhang et al. 2017). Taking into consideration the relatively small area of both experimental fields (12×90 and 16×60 m), one can assume that the quartz content does not change significantly. This supports our results of the geostatistical analysis indicating that variations of the thermal properties were largely influenced by the randomly added organic matter and associated soil water content and bulk density. The use of the geostatistical analysis was justified by normal distribution of the studied properties required in such analysis.

The results have shown that the spatial variation of thermal diffusivity at most occasions in both sites was less heterogeneous than that of the thermal conductivity and heat capacity (Fig. 6). This can be related to the non-linear response of diffusivity to the increasing water content (a rapid increase to the inflection point and a slower rise afterwards) (Mady and Shein 2016; Usowicz et al. 2016).

Our results imply similarity in the spatial distribution of a particular thermal property between the occasions or of different thermal properties at the same occasions in the scale of whole fields. An example can be the similar distribution of thermal conductivity occurring in spring and autumn 2013 and the similar distribution of thermal conductivity and heat capacity in spring 2014 in Pusté Jakartice. Another example can be the predominantly low thermal diffusivity over the whole field in autumn 2014 both in Brasowice and Pusté Jakartice coinciding with the relatively high water content. These spatial similarities observed visually on the maps, however, were not reflected by the basic statistics such as the coefficient of variation and linear regressions (trends) describing the whole size of the results. Thus, the spatial analysis and maps enhance the comprehensive understanding of changes in

Fig. 5 Spatial distribution for bulk density and water content at the 0–15-cm layer in the experimental fields, successively from the top: spring, autumn 2013, spring, autumn 2014



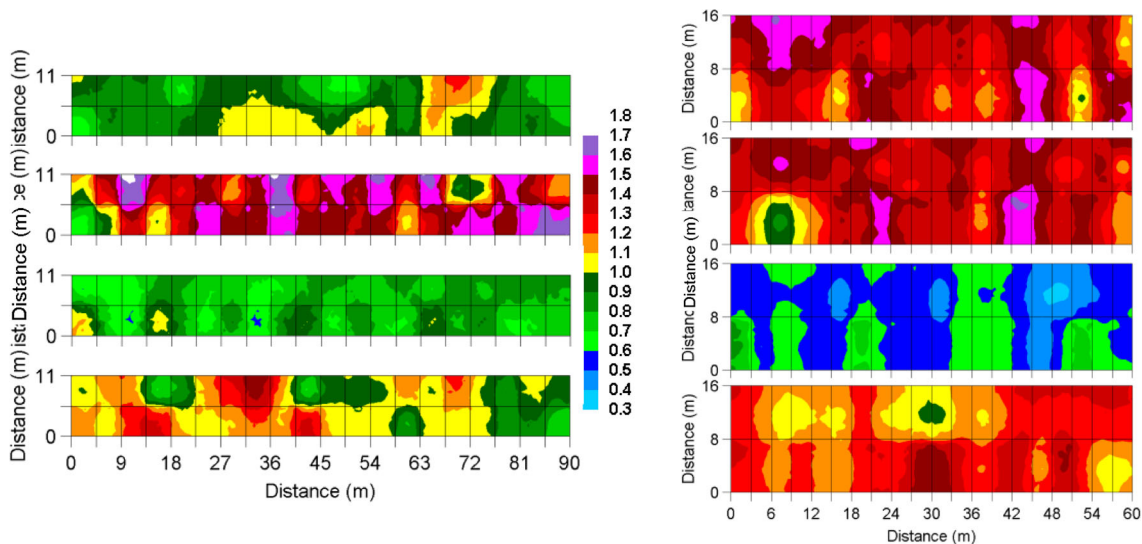
soil thermal properties in response to EOM application. Interestingly, the similarities mentioned above were observed in field conditions, where they are largely diminished by weather conditions and inherent variability of soil. Hence, these results provide some links for better deployment of the information on soil thermal properties in response to application of organic amendments that has been collected from experiments conducted in better-controlled laboratory conditions.

Comparison of the results between both sites indicates that the Pusté Jakartice soil compared to the Braszowice soil exhibited on average greater soil water content (0.265 vs. $0.222 \text{ m}^3 \text{m}^{-3}$) and thermal conductivity (1.156 vs. $1.024 \text{ W m}^{-1} \text{K}^{-1}$). This implies higher thermal propagation rates in the former although more energy has to be used for *warming up the soil* due to the greater heat capacity (2.641 vs. $2.435 \text{ MJ m}^{-3} \text{K}^{-1}$). The energy partitioning in both study sites is important in spring to gain sufficient soil temperature for planting crops. The thermal propagation in the Pusté Jakartice soil can be further modified by the presence of a greater

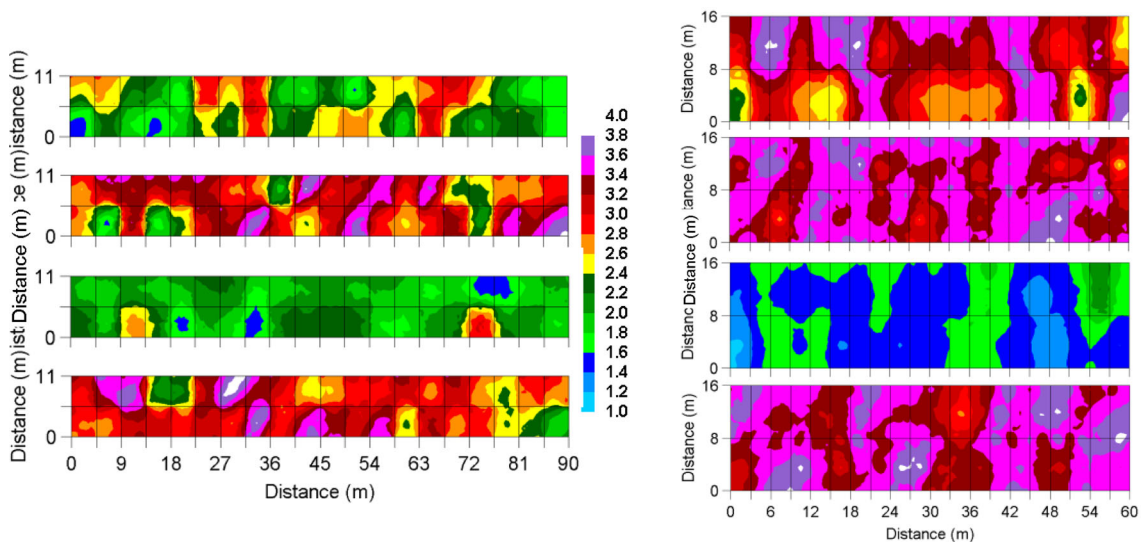
number of earthworms that we observed during the field measurements. Large pores between relatively stable cast aggregates and burrows made by earthworms can serve as transport pathways of preferential water movement allowing a rapid flow of heat with water migrating down the soil profile (Heitman et al. 2007; Votrubova et al. 2012). However, at relatively low soil water contents and high temperatures, the earthworm channels can create pathways for convective transport of heat (Kimball et al. 1976). According to the intensity-capacity concept proposed by Horn and Kutilek (2009), arrangement of both soil particles and/or aggregates and earthworm casts in a given volume can also contribute to heat flux processes.

The interrelations of soil thermal properties and water content and bulk density observed in this field study confirm the effect of organic matter amendment, bulk density, and soil water status on the thermal properties, as observed earlier in controlled conditions (Usovicz et al. 2013, 2016; Cai et al. 2017). They are useful in mathematical modelling of soil thermal properties (Tarnawski

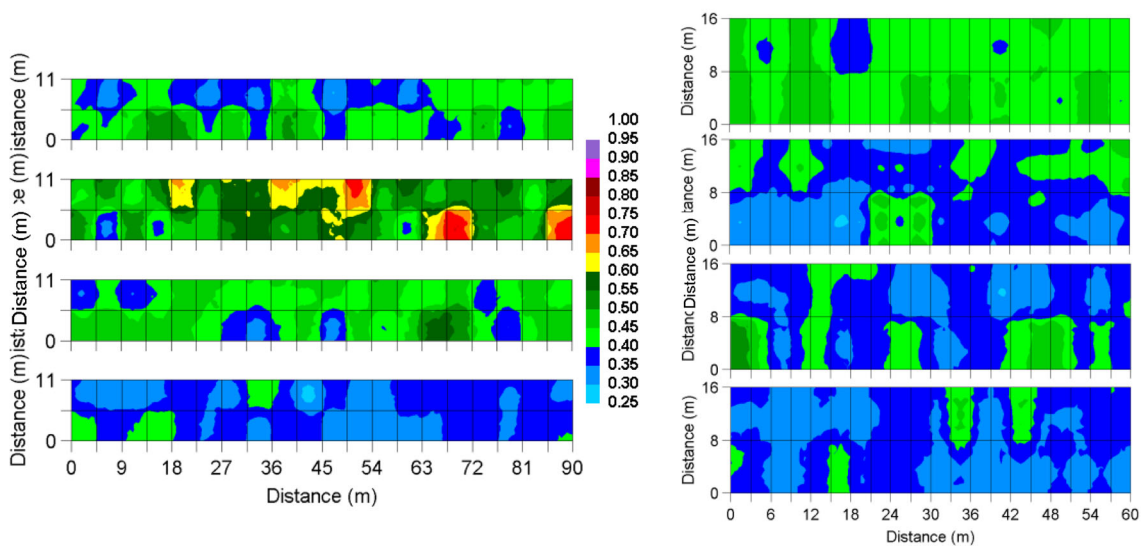
Thermal conductivity ($W\ m^{-1}K^{-1}$)



Heat capacity ($MJ\ m^{-3}\ K^{-1}$)



Thermal diffusivity ($mm^2\ s^{-1}$)



◀ **Fig. 6** Spatial distribution for thermal conductivity, heat capacity, and thermal diffusivity at the 0–15-cm layer in the experimental fields, successively from the top: spring, autumn 2013, spring, autumn 2014

et al. 2009; Bi et al. 2018). As shown in recent studies (Mady and Shein 2016; Arkhangelskaya et al. 2016; Zhang et al. 2017), incorporation of soil bulk density and water content into input data improved the prediction capacity of the model of thermal diffusivity in different soil types. In the study conducted by Mady and Shein (2016), the effect of soil bulk density and water content on thermal diffusivity was shown to be greater than that of clay content. In biochar-amended soil, the increase in thermal conductivity and thermal diffusivity with increasing soil water content was more pronounced in soil with greater rather than lower bulk density (Usowicz et al. 2016). Moreover, the results on soil thermal properties from this study provide additional opportunities for prediction of other soil physical properties. An example can be the approach developed recently for characterization in situ of bulk density (Lu et al. 2016) and quartz content (Tarnawski et al. 2009) based on thermal conductivity measurements.

5 Summary and conclusions

The spatial variation of thermal conductivity, heat capacity, thermal diffusivity, water content, and bulk density in the topsoil (0 to 15 cm depth) in response to application of exogenous (recycled) organic materials (EOMs) on maize fields in Poland and the Czech Republic was explored and evaluated by means classical descriptive statistics, semivariograms, and spatial kriging-interpolated maps. The variability of all soil properties was low and medium, and their spatial dependence was very strong and moderate. The mean values of the thermal soil properties, water content, and bulk density and their spatial distribution were greater in the Polish than the Czech study field and greater in spring than in autumn in both fields. Irrespective of in measurement occasion and study field, the heterogeneity and degree of patch fragmentation were higher for thermal conductivity and heat capacity than for thermal diffusivity, water content, and bulk density. Expressing amount of the EOMs added to the soil on the organic carbon content basis instead of the nitrogen content basis allowed indicating areas on the kriging-interpolated maps where spatial distribution of soil thermal properties was similar to that of soil organic carbon content, soil water content, and bulk density. Thus, the effect of EOMs on soil thermal properties (intensity parameters) is considered along with changes in soil water content and bulk density (capacity parameters). The

results of this field study provide valuable input data for models predicting thermal properties based on soil bulk density and water content or bulk density and texture based on soil thermal properties.

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Compliance with ethical standards

Conflict of interest The authors declared that there is no conflict of interest.

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References

- Ajayi AE, Horn R (2017) Biochar-induced changes in soil resilience: effects of soil texture and biochar dosage. *Pedosphere* 27:236–247
- Arkhangelskaya TA, Velichenko MV, Tikhonravova PI (2016) Thermal properties of typical chernozems in Kursk Oblast. *Eurasian Soil Sci* 49:1109–1116
- Beck-Broichsitter S, Fleige H, Horn R (2018) Compost quality and its function as a soil conditioner of recultivation layers – a critical review. *Int Agrophys* 32:11–18
- Bi J, Zhang M, Wu CW, Lu J, Lai Y (2018) A new model to determine the thermal conductivity of fine-grained soils. *Int J Heat Mass Transfer* 123:407–417
- Bolinder MA, Fortin JG, Anctil F, Andren O, Kätterer T, de Jong R, Parent LE (2013) Spatial and temporal variability of soil biological activity in the Province of Québec, Canada (45–58 °N, 1960–2009) - calculations based on climate records. *Clim. Change* 117(4):739–755
- Bolinder MA, Crotty F, Elsen A, Fraç M, Kismányoky T, Lipiec J, Tits M, Tóth Z, Kätterer T (2018) The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: a synthesis of reviews. *Mitig Adapt Strat Gl. Change* (submitted in July 2018)
- Cai G, Liu S, Puppala AJ (2017) Investigation on thermal characteristics and prediction models of soils. *Int J Heat Mass Transfer* 106:1074–1086
- Cambardella CA, Moorman TB, Novak JM, Parkin TB, Karlen DL, Turco RF, Konopka AE (1994) Field-scale variability of soil properties in Central Iowa soils. *Soil Sci Soc Am J* 58(5):1501–1511
- Chung SO, Horton R (1987) Soil heat and water flow with a partial surface mulch. *Water Resour Res* 23:2175–2186
- Dahiya IS, Ritcher J, Mark PS (1984) Soil spatial variability: review. *Int J Trop Agric* 11:1–102

- de Vries DA (1963) Thermal properties of soil. In: van Wijk WR (ed) *Physics of plant environment*. North-Holland, Amsterdam, pp. 210–235.
- Dębska B, Długosz J, Piotrowska-Długosz A, Banach-Szott M (2016) The impact of a bio-fertilizer on the soil organic matter status and carbon sequestration—results from a field-scale study. *J Soils Sediments* 16:2335–2343
- Di Sipio E, Bertermann D (2018) Thermal properties variations in unconsolidated material for very shallow geothermal application (ITER project). *Int Agrophys* 32:149–164
- Diacono M, Montemurro F (2010) Long-term effects of organic amendments on soil fertility: a review. *Agron Sustain Dev* 30(2):401–422
- EASAC (European Academies' Science Advisory Council) (2018) Opportunities for soil sustainability in Europe. Policy report 36.
- FAO (2006) Guidelines for soil description, 4th edn, Rome
- Gamma Design Software, GS (2008) Geostatistics for the environmental sciences.
- Garratt MPD, Bommarco R, Kleijn D, Martin E, Mortimer SR, Redlich S, Senapathi D, Steffan-Dewenter I, Świttek S, Takacs V, van Gils S, van der Putten WH, Potts SG (2018) Enhancing soil organic matter as a route to the ecological intensification of European arable systems. *Ecosystems* 21:1404–1415
- GSOC17 (2017) Proceedings of the Global Symposium on Soil Organic Carbon (2017). FAO, Rome, Italy, 534 p. ISBN: 978–92–5–109, 838-7
- Hatano R, Lipiec J (2004) Effects of land use and cultural practices on greenhouse gases fluxes in soil. *Acta Agroph* 109(6):1–51
- Heitman JL, Horton R, Ren T, Ochsner TE (2007) An improved approach for measurement of coupled heat and water transfer in soil cells. *Soil Sci Soc Am J* 71(3):872–880
- Horn R, Kutilek M (2009) The intensity-capacity concept – how far is it possible to predict intensity values with capacity parameters. *Soil Till Res* 103:1–3
- Horn R, Peng X, Fleige H, Dörner J (2014) Pore rigidity in structured soils—only a theoretical boundary condition for hydraulic properties? *Soil Sci Plant Nutr* 60(1):3–14
- Intergovernmental Panel Climate Change (IPCC) (2007) *Climate Change 2007: Impacts, adaptation and vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, U.K. and New York, NY
- IUSS Working Group WRB (2015) World Reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. In: *World Soil Resources Reports No. 106*. FAO, Rome
- Khater E-SG (2015) Some physical and chemical properties of compost. *Int J Waste Res* 5:172
- Kimball BA, Jackson RD, Reginato RJ, Nakayama FS, Idso SB (1976) Comparison of field-measured and calculated soil-heat fluxes. *Soil Sci Soc Am J* 40:18–25
- Kwiatkowska-Malina J (2018) Qualitative and quantitative soil organic matter estimation for sustainable soil management. *J Soils Sediments* 18:2801–2812
- Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. *Science* 304(5677):1623–1627
- Lal R (2017) Soil organic carbon sequestration: importance and state of science. In: *Proceedings of the global symposium on soil organic carbon*. Global symposium on soil organic carbon, 21–23 March 2017. FAO - Rome, Italy, pp 6–11
- Lu Y, Liu X, Heitman J, Horton R, Ren T (2016) Determining soil bulk density with thermo-time domain reflectometry: a thermal conductivity-based approach. *Soil Sci Soc Am J* 80:48–54
- Mady AY, Shein EV (2016) Modeling soil thermal diffusivity as a function of soil moisture. *Bull. Orenburg State Univ* 12(200):56–60
- McKenzie BM, Tisdall JM, Vance WM (2011) Soil physical quality. In: Gliński J, Horabik J, Lipiec J (eds) *Encyclopedia of agrophysics*. Springer, Dordrecht, Heidelberg, London, New York, pp 770–777
- Minasny B, McBratney AB (2017) Limited effect of organic matter on soil available water capacity. *Eur J Soil Sci* 69(1):1–9
- Minasny B, Malone BP, McCartney AB, Angers DA, Arrouays D, Chambers A et al (2017) Soil carbon 4 per mille. *Geoderma* 292: 59–86
- Mondal S, Padmakumar GP, Sharma V, Singh DN, Baghini MS (2015) A methodology to determine thermal conductivity of soils from flux measurement. *Geomechanics and Geoenvironment* 11:73–85
- Niedźwiecki J, Smatanova M, Gałązka R, Cyganek K, Siebielec G (2015) Research methodology and characteristics of investigated organic materials. In: Maly S, Siebielec G (eds) Report of project “Risks and benefits of introducing exogenous organic matter into the soil” (CZ.3.22/1.2.00/12.03445, 2013–2015)
- Olivier JGJ, Janssens-Maenhout G, Muntean M, Peters JAHW (2015) Trends in global CO₂ emissions: 2015 Report. PBL Netherlands Environmental Assessment Agency, The Hague, PBL publication number: 1803, JRC Technical Note number: JRC98184 80 pp.
- Pachepsky YA, Rawls WJ, Lin HS (2006) Hydropedology and pedotransfer functions. *Geoderma* 131(3):308–316
- Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. *Glob Change Biol* 6:317–327
- Qian B, Gregorich EG, Gameda S, Hopkins DW, Wang XL (2011) Observed soil temperature trends associated with climate change in Canada. *J Geophys Res* 116:D02106. <https://doi.org/10.1029/2010JD015012>
- Rawls WJ, Pachepsky YA, Ritchie JC, Sobecki TM, Bloodworth H (2003) Effect of soil organic carbon on soil water retention. *Geoderma* 116:61–76
- Rutkowska A, Pikula D (2013) Effect of crop rotation and nitrogen fertilization on the quality and quantity of soil organic matter. *InTech Open*. <https://doi.org/10.5772/53229>
- Ruysschaert G, Poesen J, Verstraeten G, Govers G (2006) Soil losses due to crop harvesting in Europe. In: Boardman J, Poesen J (eds) *Soil erosion in Europe*. John Wiley & Sons Ltd, Hoboken
- Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res* 79:7–31
- Tarnawski VR, Momose T, Leong WH (2009) Assessing the impact of quartz content on the prediction of soil thermal conductivity. *Géotechnique* 59:331–338
- Usovich B, Lipiec J, Usovich JB, Marczewski W (2013) Effects of aggregate size on soil thermal conductivity: comparison of measured and model-predicted data. *Int J Heat Mass Tran* 57: 536–541
- Usovich B, Lipiec J, Lukowski M, Marczewski W, Usovich JB (2016) The effect of biochar application on thermal properties and albedo of loess soil under grassland and fallow. *Soil Tillage Res* 164:45–51
- Voelkner A, Holthausen D, Horn R (2015) Influence of homogenized residues of anaerobic digestate on the physicochemical properties of differently textured soils. *J Plant Nutr Soil Sci* 178:261–269
- Votrubova J, Dohnal M, Vogel T, Tesář M (2012) On parameterization of heat conduction in coupled soil water and heat flow modelling. *Soil Water Res* 7:125–137
- Wardani AK, Purqon A (2016) Thermal conductivity prediction of soil in complex plant soil system using artificial neural networks. *J Phys Conf Ser* 739:012,007. <https://doi.org/10.1088/1742-6596/739/1/012007>
- West TO, Post M (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Sci Soc Am J* 66: 1930–1946

- Wiesmeier M, Steffens M, Mueller CW et al (2012) Aggregate stability and physical protection of soil organic carbon in semiarid steppe soils. *Eur J Soil Sci* 63:22–31
- Wilczewski E, Lemańczyk G, Skinder Z, Sadowski C (2006) Effect of nitrogen fertilization on the yielding and health status of selected nonpalonaceous plant species grown in stubble intercrop. *Electron J Polish Agric Univ EJPAU* 9(2), #04. Available Online: <http://www.ejpau.media.pl/volume9/issue2/art-04.html>
- Yang F, Zhang GL, Yang JL, Li DC, Zhao YG, Liu F et al (2014) Organic matter controls of soil water retention in an alpine grassland and its significance for hydrological processes. *J Hydrol* 519(Part D):3086–3093
- Zawadzki J, Cieszewski CJ, Zasada M, Lowe RC (2005) Applying geostatistics for investigations of forest ecosystems using remote sensing imagery. *Silva Fennica* 39(4):599–617
- Zhang T, Liu S, Cai G, Puppala AJ (2015) Experimental investigation of thermal and mechanical properties of lignin treated silt. *Eng Geol* 196:1–11
- Zhang N, Yu X, Pradhan A, Puppala AJ (2017) A new generalized soil thermal conductivity model for sand–kaolin clay mixtures using thermo-time domain reflectometry probe test. *Acta Geotechnica* 12:739–752

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