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Kinetic parameters of soil organic matter decomposition in soils under forest in Hungary

Dóra Zacháry[a,b*], Tibor Filep[a], Gergely Jakab[a], György Varga[a], Marianna Ringer[a,c], Zoltán Szalai[a,c]

[a]*Geographical Institute, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Budaörsi út 45., H-1112 Budapest, Hungary*

[b]*Institute for Nuclear Research, Hungarian Academy of Sciences, Bem tér 18/c, H-4026, Debrecen, Hungary*

[c]*Department of Environmental and Landscape Geography, Eötvös Loránd University, Pázmány Péter sétány 1/c, H-1117 Budapest, Hungary*

*Corresponding author at: Geographical Institute, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Budaörsi út 45., H-1112 Budapest, Hungary.

E-mail addresses: zachary.dora@csfk.mta.hu (D. Zacháry), filep.tibor@csfk.mta.hu (T. Filep), jakab.gergely@csfk.mta.hu (G. Jakab), gyorgy.varga@csfk.mta.hu (G. Varga), ringer.marianna@csfk.mta.hu (M. Ringer), szalai.zoltan@csfk.mta.hu (Z. Szalai)

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Abstract

To obtain better knowledge on how soil organic matter (SOM) decomposition is regulated by different soil properties, 13 soil samples amended with maize residues were incubated for 163 days. Carbon mineralization kinetics was modelled by fitting five different kinetic models, from which the first-order two pools model was selected for further analysis. The results showed that residue addition increased the rate of C mineralization, particularly in sand samples, where four times as much C was released as CO_2 in amended samples as in control samples. Residue addition also affected the kinetic parameters of the two C pools modelled. The mean residence time (MRT) averaged 31.9 days for the fast C pool and 65.1 days for the slow C pool phase in the amended soils, whereas in the control soils MRT_1 and MRT_2 averaged 52.3 and 94.2 days, respectively. The kinetics of C decomposition was found to be influenced to the greatest extent by soil organic carbon (SOC) content and soil texture. The texture primarily affected the size of the fast carbon pool (C_1): in both the amended and control samples C_1 was increased by the clay content ($r = 0.574$ and $r = 0.554$, respectively) and decreased by the sand content ($r = –0.771$ and $r = –0.583$, respectively). Our results confirm the fact that texture has a significant role in soil organic matter mineralization, however other parameters also play a crucial role in the decomposition due to the complexity of the processes.

Keywords

Soil organic carbon; carbon mineralization; carbon turnover; model fitting; soil texture

1. Introduction

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The significant role of SOM in the global carbon cycle is well known. The global soil carbon pool (2500 Gt) is 3.3 times the size of the atmospheric pool and 4.5 times the size of the biotic pool (Lal, 2004). Promoting the amount of SOM sequestered in terrestrial ecosystems is important as it may help slow the rise in atmospheric CO_2 in coming decades (Janzen, 2006). Therefore, a better understanding of the properties and dynamics of SOM and the identification of the factors that regulate soil respiration in natural and managed ecosystems is critical in predicting ecosystem responses to global change (Ahn et al., 2009).

Soil organic matter consists of a variety of materials, ranging in age from a few hours for root exudates through weeks and months for plant residues to thousands of years for resistant organic compounds (Kuzyakov, 2006; Schmidt et al., 2011; Trumbore, 2000). Models that aim to describe the cycles of these compounds cannot characterize every carbon pool with different turnovers, but differentiate one, two or three pools of SOM. The mathematical description of nutrient release patterns and the fitting of kinetic equations to mineralization curves make it possible to characterize SOM pools and calculate the fraction of potentially mineralizable C and its mineralization rate (Bernal et al., 1998; Saviozzi et al., 1993).

There are many potential approaches for modelling the C and N decomposition kinetics of soils. The original approximation was the first-order logarithmic form used by Stanford & Smith (1972). According to this exponential model, there is only one pool of potentially mineralizable C, decomposing at a rate proportional to its initial concentration. Since then many other models have been postulated. Some authors modified the simple first-order model and used approaches that take into account several organic pools with different decomposition rates. For example, Murayama (1984) described a first-order model with two compartments (two exponential

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equations), one for SOM with fast turnover and the other for SOM which decomposes more slowly. Others (Jones, 1984; Beauchamp et al., 1986) used an additional parameter in the simple first-order model to differentiate the fast initial flush caused by easily decomposable substrates at the beginning of the incubation period. Although first-order approaches are more common, other models with zero-order (Addiscott, 1983; Tabatabai and Al-Khafaji, 1980) and mixed-order (first-order plus zero-order) equations (Bonde and Rosswall, 1987; Seyfried and Rao, 1988) have also been used to study SOM decomposition kinetics.

SOM decomposition depends on many biotic and abiotic factors and may be altered by climate change (IPCC, 2013). Among the abiotic factors, climatic conditions, soil moisture, chemical recalcitrance and the physical accessibility of C compounds are significant (Manzoni et al., 2012). Soil texture is also an important parameter influencing SOM decomposition through factors such as particle surface area and porosity, which affect water-holding capacity, cation exchange capacity and many other factors (Procter et al., 2015). Soils with higher silt and clay content generally sequester more C than sandier soils, because decomposition is slower in the finer textured soils where lower O_2 inhibits aerobic microbial processes and the chemical and physical stabilization of SOM by soil minerals is more effective (Barré et al., 2014; Hassink, 1997; Wattel-Koekkoek et al., 2003). Since the specific surface area of the fine particle-size fractions is several orders of magnitude higher than that of the sand fraction, and since minerals belonging to these groups have reactive surfaces, not just clay minerals but also Fe-oxides play an important role in SOM binding (Eusterhues et al., 2005; Gu et al., 1994; Kaiser and Guggenberger, 2003). In incubation experiments the major influencing factors are soil pH and redox conditions, clay content, the size and quality of soil C pools and microbial activity

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(Ahn et al., 2009; Delaune et al., 1981; Riffaldi, 1996). In addition to soil parameters, the organic materials added to soils also have a great influence on the amount and rate of organic matter decay (Kassam et al., 2017; Singh and Gupta, 1977).

Soil incubation is a direct approach to quantifying the mineralizable soil C (Ahn et al., 2009), so many experiments have used this method to model SOM decomposition by fitting kinetic equations to mineralization curves. However, most incubation experiments test one or two soil samples, so it is not clear how soil type, texture and other soil parameters influence SOM decomposition kinetics. Therefore, it was aimed to provide more complete insights into (1) the description of the dynamics and kinetics of C mineralization in 13 different soil samples with widely differing properties; (2) the effectiveness of some commonly used decay models for describing C mineralization; and (3) the quantification of the relationship between soil properties and mineralization parameters derived from the best model.

2. Materials and methods

2.1 Soil samples

Thirteen topsoil samples were collected from seven sites in Hungary (Fig. 1, Table 1). The samples were mainly forest soils with high clay, silt and organic matter content, but three forest soils developed on sand were also collected (Tables 1 and 2). Soil samples were taken from the upper 0–20 cm horizon with one exception, where the bedrock was near the surface (sample code BAT in Table 1). Undisturbed soil samples were taken in order to determine the water-holding capacity (WHC). The soils were air-dried, homogenized, passed through a 2-mm sieve and stored at room temperature. Soil texture, total and dissolved organic and nitrogen content, iron

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content and the cation exchange capacity were measured before the incubation experiment.

The soil texture was determined by the pipette method (Gee and Bauder, 1986). The total organic carbon (TOC) content was analyzed using an NDIR-chemiluminescent analyzer (Apollo 9000, Tekmar Dohrmann). The total N content was determined by the Kjeldahl method (Conklin, 2014). The water extractable organic carbon (WEOC) and the total soluble nitrogen (TSN) were measured after extraction with ultrapure water (> 18 MΩ cm) at a 1:10 soil:solution ratio for 2 h and filtration through a 0.45 µm membrane nylon filter (Millipore), in a TOC/TN analyzer (TOC-L, Shimadzu). Iron was determined in acid ammonium oxalate extracts (Schwertmann, 1973) and in dithionite–citrate–bicarbonate extracts (Holmgren, 1967) and measured using an atomic absorption spectrophotometer (210VGP, Buck Scientific). Cation exchange capacity (CEC) was determined according to the method of Gillman (1979). In this method 2 g of air-dried soil was saturated with 20 ml of 0.1 M $BaCl_2$ solution and equilibrated with 20 ml of 0.2 mM $BaCl_2$ solution. Then reacted with 10 ml of 5 mM $MgSO_4$ to replace Ba with Mg. The electrical conductivity of the resultant reactant suspension was adjusted to that of the 1.5 mM $MgSO_4$ ionic strength reference solution. The loss of Mg from the reactant $MgSO_4$ solution was determined by analysis of the equilibrium solution and is equivalent to that adsorbed and hence to CEC. The Mg concentration was measured by an atomic absorption spectrophotometer (210VGP, Buck Scientific). The use of unbuffered solutions throughout ensures that pH approaches the natural soil pH.

2.2 Incubation experiment

Two-hundred grams of sieved and air-dried soil was weighed into 1 litre Duran® glass bottles. The samples were preincubated at 50% WHC at 20°C for two weeks, because

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rewetting and sieving affect the availability of SOM for microorganisms and may cause an increase in the rate of respiration (Franzluebbers, 1999).

The preincubated soils were amended with maize residues. Three replicates of amended soil and one control with no residue addition were used for each soil type. One blank sample without soil or residue was used for the whole incubation experiment. The maize residues were air dried, cut into pieces and sieved through a 2-mm mesh, after which 1 g was thoroughly mixed with 200 g preincubated soil. The samples were kept in an incubator (KBW 400 E5.1**,** Binder) at 20°C for 163 days at 70 % WHC, as this moisture content allowed handling and compaction of the soil without the collapse of small soil aggregates (Frøseth and Bleken, 2015). Soil respiration was trapped in plastic tubes containing 15 ml of 2 M NaOH, placed in the incubation bottles, which were closed air-tight. The NaOH traps were replaced on days 3, 8, 15, 30, 51, 79, 107, 135 and 163. The amount of CO_2 evolved was measured by titrating the NaOH with 1M HCl in the presence of $BaCl_2$ (Anderson, 1982).

2.3 Carbon mineralization kinetic models and statistical analysis

Five different models were used in this experiment to describe the C mineralization kinetics in the studied samples (Table 3). The data of cumulative CO_2 evolution were fitted using non-linear least-squares models in MATLAB version R2016a Curve Fitting Toolbox 3.5.3 (The MathWorks Inc., Natick, USA). The coefficient of determination (R^2) was used to evaluate the different kinetic models. For selection of the appropriate model, Akaike's Information Criterion (AIC) was also used (Akaike, 1973) as R^2 values only indicate the goodness-of-fit, but do not take the simplicity of the model (number of independent parameters, samples sizes) into account (Burnham and Anderson, 2002). AIC integrates model-selection uncertainty by penalizing the

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further addition of independent variables to the model and it is widely applied in the field of kinetic modelling of carbon mineralization of soils (Stewart et al., 2007; Martín et al., 2012).

AIC were calculated for every soils and models from the residual sum of squares (RSS):

$$AIC = n\left[\ln\left(\frac{RSS}{n}\right)\right] + 2k, \quad (1)$$

where n is the sample size, k is the number of fitted parameters. For small sample sizes modified version of AIC is recommended (Hurvich and Tsai, 1989):

$$AIC_c = AIC + \frac{2k(k+1)}{n-k-1}. \quad (2)$$

The lowest AIC and AIC_c values indicate the best approximating model:

$$\Delta_i = AIC_{c_i} - AIC_{c_{min}}, \quad (3)$$

where AIC_{c_i} is the AIC_c of the i^{th} model and $AIC_{c_{min}}$ is the lowest AIC_c value of the compared models.

The relationship between CO_2 concentration and soil variables (organic C, organic N, pH and soil texture parameters) was analyzed by calculating Pearson's correlation coefficient. Principal component analysis (PCA) was applied to reveal relationships between the variables resulting in explanatory variables. The PCA was performed for soil properties on the correlation matrix using varimax with the Kaizer normalization rotation method. The PCA and the correlation analysis were performed with IBM SPSS Statistics version 22 (IBM Corp., New York, USA).

3. Results

3.1 Carbon mineralization

The rate of SOM mineralization (the amount of CO_2 released per day, data not shown) in the treated and control soils (except for SOP3) was observed to reach a maximum

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during the first week of incubation and tended to continuously decline as the incubation time progressed. The total amount of CO_2 released after 163 days of incubation from soils amended with maize residues (Fig 2.a) ranged from 4.94 to 18.90 g CO_2 kg^{-1}, whereas the cumulative amount of CO_2 in the control samples (Fig. 2b) at the end of the incubation ranged from 1.17 to 16.00 g CO_2 kg^{-1}.

Residue addition caused a significant increase in total soil CO_2 efflux compared to the control soil. In general, twice as much C was released in the 13 amended soil samples as in their control pairs. This rate was the most pronounced in the amended CEG and NYIR1 samples, where four and a half times as much C was mineralized as in the control samples. In samples BAT, JOS2, JOS1 and SOP2 a maximum of one and a half times as much CO_2 was released as in the control samples.

3.2 Kinetic parameters of SOM decomposition

A more accurate picture of the process of SOM mineralization and the differentiation of SOM pools and pool sizes was analyzed by fitting the experimental data to the five kinetic models given in Table 3. On the basis of the R^2 values, all the kinetic models offered a very good description of SOM mineralization for all the amended and control samples (Table 4). Even the lowest R^2 value was 0.90. The first-order two pools model was selected for further analysis based on the following facts: 1) there were no statistical differences between the R^2 values of the models for these samples, however the calculated AIC scores indicated the appropriateness (lowest AIC scores) of this model; 2) according to generally accepted theory, SOM can be divided into at least two pools (one with fast turnover and one with slow turnover) (Smith and Falloon, 2000); and 3) the rate of SOM mineralization showed that, in general, mineralization was faster in the first week than in later phases, suggesting at least two SOM pools with different turnovers.

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The kinetic parameters calculated using the first-order two pools model are shown in Table 5 for amended samples and in Table 6 for control samples. The quantity of easily mineralizable carbon (C_1) varied greatly in the soil samples, ranging between 2.20×10^{-7} and 1.71 g kg^{-1} with an average of 0.59±0.61 g kg^{-1} in the amended samples and between 2.35×10^{-12} and 1.21 g kg^{-1} with an average of 0.26±0.39 g kg^{-1} in the control samples. In contrast, the size of the slowly mineralizable pool (C_2) varied over a relatively narrow range (Tables 5 and 6).

Rate constants for the fast C pool (k_1) differed between the soils with values of 0.009 to 0.393 day^{-1} for amended soils and 0.007 to 0.546 day^{-1} for control soils. The rate constants for the slow C pool (k_2) were smaller (0.009 to 0.021 day^{-1} for amended soils and 0.006 to 0.015 day^{-1} for control soils) than for the fast C pool.

The percentage of labile C (C_1%) relative to total mineralizable C ($C_1 + C_2$) showed great variability between soils and treatments (Tables 5 and 6). Overall, C1% was high in both the amended and control samples of JOS1, JOS2 and JOS3.

The mean residence time (MRT), calculated as the reciprocal (k^{-1}) of the decomposition rate constant, ranged between 2.5 and 114.9 days with an average of 31.9 days for the fast C pool (MRT_1) and between 48.4 and 110.5 days with an average of 65.1 days for the slow C pool phase (MRT_2) in the amended soils. Maize addition considerably affected the MRTs of the soils in the fast C pool phase (MRT_1), and samples SOP2, SOP4 and KAR proved to be least sensitive to the treatment.

3.3 Relationship between kinetic parameters and soil properties

Correlations between C mineralization parameters and soil properties are reported in Table 7 for amended soil and in Table 8 for control soil. Table 8 shows that in the control samples C mineralization parameters were mainly affected by soil parameters

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connected with the total and soluble C and N content. In the amended samples the soil texture also seemed to be significant for parameters connected to the fast C pool mineralization phase (C_1, C_1% and C_1k_1 parameters), as these parameters were significantly positively correlated with the silt content ($r=0.728$, 0.638 and 0.747, $p<0.05$, respectively) and negatively correlated with the sand content ($r=-0.771$, -0.653 and -0.787, $p<0.05$, respectively, Table 7). Water extractable organic carbon (WEOC) and total soluble nitrogen (TSN) had a significant positive effect on the size of the easily (C_1) and slowly (C_2) mineralizable pool both in amended and control samples (Tables 7 and 8). The rate constant (k_1) and the mean residence time of the fast C pool phase (MRT_1) in the amended samples were not significantly correlated with the soil properties (except for the negative effect of TSN on MRT_1, Table 7). In the control samples, however, k_1 and particularly the MRT_1 is affected by many soil properties (TOC, TN, WEOC, TSN and sand content, Table 8). The rate constant (k_2) and mean residence time of the slow C pool (MRT_2) were not affected by the soil properties.

Based on the results of principal component analysis, three principal components were selected because their total eigenvalues were greater than 1. These three principal components accounted for 89.1% of the total variability in the dataset. The soil texture characteristics (clay, silt and sand content) and the Fe content constituted the first principal component (PC1), whereas the second principal component (PC2) contained parameters connected to the soil carbon and nitrogen content (TOC, TN, WEOC, TSN and C/N). Soil pH belonged to the third principal component (PC3). Eigenvectors are plotted in the plane of PC1 and PC2 in Figure 3. Analysis showed that texture and the C and N content (both total and dissolved) of the soil jointly affected the C_1 values in the amended and control samples (Fig. 3a, b). Amended soils

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with low C_1 values could be divided into two groups, one is characterized by high clay and low organic matter content, and one containing soils with high sand content (Fig. 3a). This separation could also be seen in the case of the control samples (Fig. 3b). High C_1 values were associated with high TOC, WEOC, TN and TSN values and high clay and silt content in both amended and control samples (Fig. 3, b). In the case of C_2 values the texture had less influence, while the TOC, WEOC, TN and TSN values were more pronounced in both amended and control samples (data not shown). Like the C_1 values, the k_1 values were found to be affected by soil texture parameters and by the soil carbon and nitrogen content in the amended samples (Fig. 3c). In the control samples the k_1 values were more affected by TOC, WEOC, TN and TSN than by textural differences. However, high sand content was associated with small k_1 values (Fig. 3d). The effect of soil parameters on the k_2 values, was less significant, so low and high k_2 groups could not be distinguished (data not shown). Two groups of soils could be detected on the basis of MRT_1 values. High TOC, WEOC, TN and TSN values and high clay and silt content were associated with low MRT_1 values, whereas high MRT_1 values were found in sandy soils and in soils with high clay and low organic matter content (data not shown).

4. Discussion

In this study, significant differences were found in the CO_2 efflux from different soil samples. Soil types with diverse soil parameters considerably influence the decomposition of organic matter. Furthermore, the addition of easily degradable organic compounds to the soil resulted in an increase in CO_2 efflux, indicating a greater organic matter turnover rates.

The 6-month soil incubation resulted in a gradual decrease in the C mineralization rate, which could be attributed to the depletion of the carbon fraction readily available

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to soil microorganisms from the beginning of the incubation (Levi-Minzi et al., 1990). Bernal *et al.* (1998) and Martín *et al.* (2012) reported that the maximum C mineralization rate therefore occurred during the first week of the incubation, as found in the present study.

Generally, SOM is divided into at least two pools. This is supported by incubation experiments. Levi-Minzi *et al.* (1990), for example, identified two SOM pools after 21-day incubation, one decomposing in about a week, and the other less readily decomposable. In the present experiment these two stages could also be distinguished. However, the quality and quantity of the organic matter added to the soils may modify decomposition processes (Aslam et al., 2008; El-Mahrouky et al., 2015). Therefore, in experiments with diverse conditions different kinetic models proved to be the best. For example, Fernández *et al.* (2007) found that the first-order two pools model described carbon turnover most efficiently, whereas in another study the first stage followed a first-order kinetic model, while the second, slow step was characterized by a zero-order kinetic model (Bernal et al., 1998). Despite the fact that all the kinetic models proved to be good, Sleutel *et al.* (2005) pointed out that this does not necessarily mean that the modelled values give a good description of the real biological processes. Our results confirm this statement as despite the fact that the model yielded two C pools with good R^2 values for the selected first-order two pools model, some soils (NYIR1, KAR, SOP1 and SOP3) have almost the same decompostion rate constants for the fast and slow mineralizable carbon pools suggesting rather one C pool than two pools with distinct mineralization kinetics.

4.1 Changes in carbon mineralization as affected by crop residues

There were substantial differences in the CO_2 efflux of the investigated soils when amended samples were compared to control ones. For example, the CO_2 respiration of

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the amended soils was twice as high as that of control samples on average. It is well known that the incorporation of fresh organic matter such as crop residues may cause a significant increase in soil respiration and soil microbial biomass carbon (Martín et al., 2012; Shahbaz et al., 2017; Thiessen et al., 2013). The higher respiration is attributed to the easily degradable organic C from the crop residues, which leads to enhanced microbial activity using this new substrate (Blagodatskaya et al., 2011). This stimulation of SOM mineralization and the increased release of the soil-derived carbon as CO_2 after adding fresh organic matter to soil is known as priming effect (Bingeman et al. 1953). Up to now, negative and positive priming have been distinguished differentiating an increase (positive priming) or decrease (negative priming) in SOM degradation (Kuzyakov et al., 2000).

The addition of fresh OM caused an increment in the C_1 and C_2 pools (compare Table 5 with Table 6). However, in some cases, the size of the easily degradable organic pool (C_1 pool) of the investigated soils decreased due to the higher energy demand of microbes after maize residues were added. This was true for soils having low organic matter content, such as CEG and NYIR1. The C_1k_1 values were also lower in these treated soils (compare Table 5 with Table 6), indicating that they had low initial potential rate of C mineralization (Stanford and Smith, 1972).

Enhanced microbial activity also affects the k and MRT values of soils (Pengthamkeerati et al., 2005; Saviozzi et al., 1993; Turrión et al., 2012). While in the present study the rate of carbon mineralization increased (expressed by k_1 and k_2), the MRT of carbon in the C_1 and C_2 pool decreased in samples treated with maize residues (Table 5) compared to the control (Table 6). The accelerated degradation of the C_1 pool after the addition of maize residues was manifested in the MRT_1 values (the average MRT_1 was 31.9 days and 52.3 days for amended and control soils,

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respectively). Various authors estimated different k and MRT values from different experiments using the first-order two pools model. Sleutel *et al.* (2005) mixed various organic amendments with sandy loam soil and reported k_1 values of 0.0103 to 5.08 day^{-1} and k_2 values of 0.00100 to 0.0296 day^{-1}, which are comparable with the amended k values in the present model (Table 5). Although Turrión *et al.* (2012) reported a narrower range of values (0.15 to 0.36 day^{-1}) for the labile pool phase of Cambisols from Northwest Spain than were found in the present study, the mineralization rate for the slow pool phase (0.009 and 0.020 day^{-1}) was close to that found in this study (Tables 5 and 6). It is difficult to compare the MRT and k values from different studies, since C mineralization kinetics is determined by the diverse soil properties of the different soils. This confirms the significance of studies on the effect of different soil properties on C mineralization.

Except for two sand samples, the higher C_2k_2 and shorter MRT_2 values of amended samples compared to control ones underlined the significance of easily degradable compounds that enhance microbial activity in the slow phase, as also found in soils amended with compost (Fernández et al., 2007). Kuzyakov *et al.* (2000) and von Lützow & Kögel-Knabner (2009) also reported that the input of fresh organic matter stimulates the decomposition of the recalcitrant SOM pool. Overall, fresh organic matter addition caused more pronounced changes in the labile organic matter pool (demonstrated by C_1, k_1 and MRT_1), whereas the kinetic parameters of the stable pool (C_2, k_2 and MRT_2) were more resistant to the treatment, confirming that this pool is more recalcitrant.

4.2 Soil properties controlling carbon turnover

Besides the effect of adding organic matter to the soil, the soil properties themselves may have a significant effect on carbon mineralization. Carbon mineralization,

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determined as the evolution of CO_2 from different carbon fractions, depends greatly on the size and quality of these pools (Ahn et al., 2009; Riffaldi et al., 1996). In the present study, the kinetic parameters of carbon mineralization (C_1, C_2, k_1, k_2) in the control samples were affected more by the TOC and TN content of the soil than by the SOM quality, represented by the C/N ratio (Table 8). The significant positive correlation between TOC and TN on the one hand and the carbon pool size and turnover rate on the other was confirmed by other authors (Ahn et al., 2009; McLauchlan and Hobbie, 2004), who reported the strong influence of the total organic C and N content on microbial processes. Although the C/N ratio is also considered to be an important factor in determining the rate of mineralization, immobilization and nitrification (Bengtsson et al., 2003), in the present experiment there were no significant correlations between kinetic parameters and the C/N ratio of the soils, probably because the C/N ratio measured in the total soil is a less good indicator for the recalcitrant C pools. In the treated samples neither the quantity nor the quality of soil organic carbon affected the kinetic parameters (Table 7), so presumably the large amount of organic matter added to the soil altered the original state of the soil. This observation is consistent with the findings of Levi-Minzi *et al.* (1990), who reported that the C/N ratio was not found to be correlated with the decomposition rate. In spite of the fact that adding maize to the soil shifts the native soil conditions, there was a significant correlation between the total nitrogen content of the soil and the C_nk_n product (Table 7), indicating that the initial potential rate of C mineralization (C_nk_n) could be a more useful index for quantifying effects influencing the quality of SOM than C_n and k_n separately (Stanford & Smith, 1972; Saviozzi et al., 1993).

In the present study the fraction readily available for microbial degradation was represented by the two dissolved organic fractions, WEOC and TSN. The strong

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correlation between these labile pool parameters and C_2 (Tables 7 and 8) is probably due to the fact that the WEOC and TSN concentrations are determined not only by the labile pool, but also by the size of the stable organic matter pool (Tegen and Dörr, 1996).

Texture is considered to be one of the most significant parameters affecting the breakdown of SOM. In general, the C in finer textured soils is less bioavailable due to binding with organic matter and the formation of soil aggregates (Procter et al., 2015; Six et al., 1999). The effect of maize addition, expressed as the difference between the CO_2 efflux from control and amended samples, was more pronounced in the sand samples (e.g. samples CEG and NYIR1), since the microbial oxidation of SOM was more intense in these soils due to the favorable aerobic conditions (Demeter et al., 2013; Pengthamkeerati et al., 2005).

The mathematically estimated pools (especially the C_1 pool) were significantly correlated with soil texture; sand content decreased the size of the C_1 pools, whereas clay content increased it. However, no strong connection was found between the texture and C decomposition. Other authors, however, reported less C mineralization in clay soils (Frøseth and Bleken, 2015; Hassink, 1995; Saviozzi et al., 2014), suggesting that clay minerals give protection against SOM degradation. Nevertheless, besides the TOC, TN, WEOC and TSN content, soil texture was found in the PCA evaluation to be a decisive factor separating low and high values of kinetic parameters (Fig. 3). The PCA results revealed that soil parameters have a complex influence the carbon mineralization. Although the individual effects of the parameters could be clearly demonstrated, the real relationships were described by their combined effects. For instance, MRT_1 values could be clearly distinguished on the basis of both TOC

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content and soil texture, indicating a strong connection between TOC and sand/clay content.

5. Conclusions

It was hypothesized that the carbon mineralization of soils, measured as CO_2 efflux, was considerably affected by soil conditions. The 13 soil samples studied, which had diverse soil parameters, responded differently to the 163-day incubation. On the one hand, crop residue addition affected the kinetic parameters of the two modelled C pools, the labile carbon pool generally exhibiting greater changes after amendment. On the other hand, soil parameters also had different effects on the SOM decomposition from which the organic matter content and soil texture were found to be key factors controlling the turnover of the mathematically estimated labile carbon pool (C_1, k_1, MRT_1). The kinetic parameters of the stable pool (k_2 and MRT_2) were independent of the soil parameters, confirming that this pool was more recalcitrant. Although the persistence of carbon against microbiological degradation is generally associated with high clay content, this was not fully supported by this study, indicating that in real systems, such as soils, much more complex effects prevail, which means that SOM dynamics cannot be described by one soil parameter. The kinetic parameters of the carbon turnover of the various SOM pools could be important input parameters for environmental models, confirming the importance of research on the effect of soil parameters on the kinetics of SOM decomposition.

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FIGURE CAPTIONS

Figure 1 Location of the sampling sites. Numbers indicate the numbers of the samples. See Tables 1 and 2 for details.

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Figure 2 Cumulative carbon respiration during the 163-day incubation period for 13 soil samples. (a) Carbon respiration from soils amended with maize residues. Mean values with standard errors (n = 3). Very small errors are not depicted since error bars remained within the symbol. (b) Carbon respiration from control soils.

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Figure 3 PC1 and PC2 biplots of soil properties of 13 soil samples. (a) C_1 of amended samples. (b) C_1 of control samples. (c) k_1 of amended samples. (d) k_1 of control samples. Eigenvectors are doubled for better visualization.

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TABLES

Table 1 Site characteristics of the soil samples

Code	Soil order	Soil type	Location N	Location E	Forest type (tree species)	Texture class
BAT	Leptosol	Skeletic Dystric Leptosol Humic Loamic	46°12'47.6"	18°36'00.8"	oak (*Quercus paetrea, Quercus cerris*)	Silt loam
JOS1	Phaeozem	Leptic Phaeozem Loamic	48°28'04.0"	20°32'18.5"	oak (*Quercus cerris*)	Silty clay loam
SOP3	Umbrisol	Leptic Umbrisol Loamic	47°39'49.1"	16°33'42.2"	pine, chestnut, birch, beech (*Pinus sylvestris, Catanea sativa, Betula pendula, Fagus sylvatica*)	Sandy loam
SOP1	Luvisol	Stagnic Luvisol Clayic Humic	47°39'34.1"	16°33'18.0"	beech, pine (*Fagus sylvatica, Pinus sylvestris*)	Silt loam
SOP2		Albic Luvisol Humic Loamic	47°39'44.9"	16°33'55.4"	pine, chestnut, birch (*Pinus sylvestris, Catanea sativa, Betula pendula*)	Loam
SOP4		Haplic Luvisol Loamic	47°40'14.6"	16°33'53.6"	beech (*Fagus sylvatica*)	Silt loam
KIS		Haplic Luvisol Loamic	48°00'55.7"	19°40'29.2"	oak, hornbeam (*Quercus paetrea, Carpinus betulus*)	Silt loam

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KAR		Haplic Luvisol Loamic	48°09'11.5"	19°46'20.6"	oak, hornbeam (*Quercus paetrea, Carpinus betulus*)	Loam
CEG	Arenosol	Eutric Arenosol Humic	47°11'14.8"	19°40'55.2"	oak (*Quercus robur*)	Loamy sand
NYIR1		Dystric Arenosol Ochric	47°31'40.0"	21°43'46.1"	pine (*Pinus sylvestris*)	Loamy sand
NYIR2		Eutric Arenosol Humic	47°31'39.9"	21°43'54.0"	oak, poplar (*Quercus robur, Populus alba*)	Loamy sand
JOS2	Regosol	Dystric Regosol Clayic	48°28'16.1"	20°32'11.3"	oak, hornbeam, beech (*Quercus paetrea, Carpinus betulus, Fagus sylvatica*)	Clay
JOS3		Eutric Regosol Loamic	48°28'01.1"	20°32'21.0"	oak, hornbeam (*Quercus paetrea, Carpinus betulus*)	Silt loam

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Table 2 Main chemical properties (± standard error) of the soils

Code	pH (dw)	pH (KCl)	$CaCO_3$ content (%, m m^{-1})	TOC content (%, m m^{-1})	TN content (%, m m^{-1})	C/N ratio	WEOC (mg l^{-1})	TSN (mg l^{-1})	Fe ontent (mg kg^{-1})	CEC (mol_c kg^{-1})	C stock* (kg m^{-2})	N stock* (kg m^{-2})
BAT	4.63	3.68	-	7.24±0.09	0.39	18.61	153.60±1.26	8.42±0.04	8778±272	9.9	16.1	0.87
JOS1	5.66	4.84	-	9.73±0.07	0.68	14.39	135.50±1.01	9.83±0.15	27274±43	29.4	18.2	1.65
SOP3	4.48	3.44	-	2.55±0.04	0.15	17.10	58.01±0.39	3.24±0.04	19290±667	6.0	4.65	0.27
SOP1	4.47	3.33	-	2.65±0.03	0.15	18.31	58.21±0.74	2.99±0.11	14688±561	6.2	6.65	0.38
SOP2	3.69	2.85	-	10.96±0.10	0.24	46.25	127.50±0.42	4.18±0.03	4535±181	6.8	15.6	0.34
SOP4	4.31	3.27	-	2.97±0.00	0.15	20.46	80.74±0.49	4.50±0.02	12106±563	7.7	5.92	0.30
KIS	5.14	3.96	-	3.60±0.05	0.25	14.34	77.61±0.57	4.42±0.01	7780±159	16.9	6.89	0.48
KAR	4.54	3.22	-	1.41±0.04	0.07	19.85	37.08±0.40	1.47±0.10	11689±292	8.1	4.42	0.22
CEG	6.21	5.56	1.28	1.85±0.10	0.15	12.40	42.11±0.52	4.42±0.02	2441±85	7.8	5.48	0.44
NYIR1	4.93	3.71	-	0.56±0.02	0.05	10.50	23.03±0.23	1.79±0.05	3374±16	4.3	1.66	0.15
NYIR2	6.23	5.66	-	2.24±0.06	0.17	13.18	58.64±0.20	5.29±0.13	2456±51	11.8	6.63	0.50
JOS2	5.17	4.30	-	11.72±0.07	0.41	28.81	145.50±1.37	7.97±0.04	29089±1918	19.1	22.4	0.78

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JOS3	5.92	5.53	-	3.95±0.03	0.29	13.45	88.12±0.76	7.29±0.13	18062±90	16.9	8.99	0.66

TOC: total organic carbon; TN: total nitogen, WEOC: water extractable organic carbon; TSN: total soluble nitrogen; CEC: cation exchange capacity.

*C ans N stocks calculated from the bulk density of undisturbed samples for the upper 20 cm layer of the soils.

Soils are separated by each other with dashed lines according to their soil order as follows: BAT – Leptosol; JOS1 – Phaeozem; SOP3 – Umbrisol; SOP1, SOP2, SOP4, KIS and KAR – Luvisol; CEG, NYIR1 and NYIR2 – Arenosol; JOS2 and JOS3 – Regosol.

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Table 3 The five kinetic models applied

Model	Cumulative model	Reference
Power function	$C = kt^m$	Pal & Broadbent (1975)
First-order exponential	$C = C_0(1 - e^{-kt})$	Stanford & Smith (1972)
First-order E	$C = C_0(1 - e^{-kt}) + C_1$	Jones (1984)
First-order two pools	$C = C_1(1 - e^{-k_1 t}) + C_2(1 - e^{-k_2 t})$	Molina et al. (1980)
First-order + zero order	$C = C_0(1 - e^{-k_1 t}) + k_2 t$	Bonde & Rosswall (1987)

C: cumulative carbon mineralized over t time; C_0: potentially mineralizable carbon; C_1: easily mineralizable carbon pool; C_2: slowly mineralizable carbon pool; t: time from start of the incubation; k: decomposition rate constant; m: rate constant characterizing the shape of the curve.

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Table 4 Coefficients of determination (R^2) and Akaike's Information Criterion (AIC) used to compare the 5 different kinetic models

	Model	R^2 (mean)	R^2 (std. dev.)	AIC	AIC_c	Δ_i
Amended samples	Power function	0.983	0.009	-15.92	-18.21	38.09
	First-order exponential	0.996	0.003	-40.59	-38.30	18.00
	First-order E	0.997	0.003	-43.59	-41.59	14.71
	First-order two pools	0.997	0.002	**-56.30**	**-56.30**	**0.00**
	First-order + zero order	0.999	0.001	-53.65	-51.65	4.66
Control samples	Power function	0.988	0.007	-43.85	-41.56	23.26
	First-order exponential	0.988	0.027	-53.72	-51.43	13.39
	First-order E	0.995	0.005	-56.38	-54.38	10.43
	First-order two pools	0.991	0.021	**-64.36**	**-64.36**	**0.46**
	First-order + zero order	0.996	0.005	-62.41	-60.41	4.40

Std. dev.: standard deviation; AIC_c: Akaike Information Criterion corrected for small sample size; $\Delta_i = AIC_{c_i} - AIC_{c_{min}}$.

bold highlighting indicate the lowest values [best model] of AIC approach.

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Table 5 Estimated kinetic parameters of the first-order two pools model (Molina et al., 1980) for the amended soil samples

Soil	C_1 (g kg^{-1})	C_2 (g kg^{-1})	k_1 (day^{-1})	k_2 (day^{-1})	C_1%	C_1k_1 (g kg^{-1} day^{-1})	C_2k_2 (g kg^{-1} day^{-1})	MRT_1 (day)	MRT_2 (day)
BAT	1.488	19.280	0.096	0.013	7.165	0.143	0.257	10.4	75.0
JOS1	1.048	9.183	0.170	0.020	10.243	0.178	0.183	5.9	50.2
SOP3	0.054	8.284	0.017	0.016	0.653	0.001	0.135	60.4	61.4
SOP1	0.346	6.185	0.393	0.019	5.299	0.136	0.117	2.6	53.1
SOP2	0.012	9.173	0.018	0.012	0.134	2.18×10^{-4}	0.114	56.5	80.7
SOP4	1.711	5.987	0.033	0.017	22.227	0.056	0.101	30.5	59.4
KIS	0.855	7.859	0.080	0.017	9.809	0.069	0.135	12.5	58.2
KAR	0.228	6.070	0.009	0.009	3.614	0.002	0.055	114.9	110.5
CEG	2.20×10^{-7}	9.682	0.024	0.021	2.27×10^{-6}	5.34×10^{-9}	0.200	41.2	48.4
NYIR1	1.52×10^{-5}	6.076	0.018	0.012	2.51×10^{-4}	2.79×10^{-7}	0.072	54.7	83.9
NYIR2	0.077	7.617	0.148	0.018	1.006	0.011	0.140	6.8	54.6
JOS2	1.063	10.210	0.088	0.017	9.430	0.093	0.171	11.4	59.7
JOS3	0.833	7.143	0.149	0.019	10.443	0.124	0.138	6.7	51.7

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C_1: size of the easily mineralizable carbon pool; C_2: size of the slowly mineralizable carbon pool; k_1: decomposition rate constant of the easily mineralizable carbon pool; $k_{2:}$ decomposition rate constant of the slowly mineralizable carbon pool; C_1%: percentage of easily mineralizable carbon relative to the total mineralizable carbon ($C_1 + C_2$); C_1k_1: initial potential rate of carbon mineralization of the easily mineralizable carbon pool; C_2k_2: initial potential rate of carbon mineralization of the slowly mineralizable carbon pool; MRT_1: mean residence time of the easily mineralizable carbon pool; MRT_2: mean residence time of the slowly mineralizable carbon pool.

Soils are separated by each other with dashed lines according to their soil order as follows: BAT – Leptosol; JOS1 – Phaeozem; SOP3 – Umbrisol; SOP1, SOP2, SOP4, KIS and KAR – Luvisol; CEG, NYIR1 and NYIR2 – Arenosol; JOS2 and JOS3 – Regosol.

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Table 6 Estimated kinetic parameters of the first-order two pools model (Molina et al., 1980) for the control soil samples

Soil	C_1 (g kg^{-1})	C_2 (g kg^{-1})	k_1 (day^{-1})	k_2 (day^{-1})	C_1%	C_1k_1 (g kg^{-1} day^{-1})	C_2k_2 (g kg^{-1} day^{-1})	MRT_1 (day)	MRT_2 (day)
BAT	1.211	17.130	0.068	0.012	6.603	0.082	0.202	14.8	84.8
JOS1	0.437	7.362	0.189	0.012	5.601	0.083	0.091	5.3	81.3
SOP3	1.03×10^{-6}	6.322	0.007	0.006	1.63×10^{-5}	7.106×10^{-9}	0.039	145.2	160.1
SOP1	3.91×10^{-7}	2.853	0.013	0.012	1.37×10^{-5}	4.899×10^{-9}	0.033	79.8	85.8
SOP2	0.524	5.143	0.546	0.012	9.248	0.286	0.060	1.8	85.7
SOP4	0.028	4.042	0.235	0.015	0.686	0.007	0.060	4.3	67.3
KIS	7.18×10^{-5}	4.801	0.024	0.011	0.001	1.700×10^{-6}	0.055	42.3	87.4
KAR	2.35×10^{-12}	2.316	0.010	0.010	1.01×10^{-10}	2.390×10^{-14}	0.023	98.2	100.0
CEG	0.001	2.559	0.010	0.009	0.028	6.715×10^{-6}	0.024	105.0	106.5
NYIR1	0.006	1.369	0.013	0.013	0.400	7.373×10^{-5}	0.018	74.6	75.1
NYIR2	3.18×10^{-6}	3.798	0.016	0.009	1.00×10^{-4}	6.044×10^{-8}	0.036	63.1	106.3
JOS2	0.735	8.740	0.077	0.013	7.759	0.057	0.116	13.0	75.2
JOS3	0.434	4.975	0.031	0.009	8.020	0.013	0.045	32.5	109.9

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C_1: size of the easily mineralizable carbon pool; C_2: size of the slowly mineralizable carbon pool; k_1: decomposition rate constant of the easily mineralizable carbon pool; k_2: decomposition rate constant of the slowly mineralizable carbon pool; C_1%: percentage of easily mineralizable carbon relative to the total mineralizable carbon (C_1 + C_2); $C_1k_{1:}$ initial potential rate of carbon mineralization of the easily mineralizable carbon pool; C_2k_2: initial potential rate of carbon mineralization of the slowly mineralizable carbon pool; MRT_1: mean residence time of the easily mineralizable carbon pool; MRT_2: mean residence time of the slowly mineralizable carbon pool.

Soils are separated by each other with dashed lines according to their soil order as follows: BAT – Leptosol; JOS1 – Phaeozem; SOP3 – Umbrisol; SOP1, SOP2, SOP4, KIS and KAR – Luvisol; CEG, NYIR1 and NYIR2 – Arenosol; JOS2 and JOS3 – Regosol.

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Table 7 Pearson's correlation coefficients between kinetic parameters derived from the first-order two pools model (Molina et al., 1980) and the chemical and physical soil properties of the amended samples

	pH (dw)	pH (KCl)	TOC	TN	C/N	WEOC	TSN	Fe	CEC	Clay	Silt	Sand
C_1	–0.076	–0.058	0.363	0.532	–0.025	**0.620***	**0.627***	0.433	0.450	**0.574***	**0.728****	**–0.771****
C_2	–0.025	0.026	0.466	0.476	0.132	**0.668***	**0.583***	0.011	0.126	0.235	0.297	–0.315
k_1	0.146	0.150	0.034	0.236	–0.180	0.097	0.218	0.269	0.228	0.147	0.303	–0.282
k_2	**0.643***	**0.682***	0.029	0.363	–0.373	0.081	0.463	0.271	0.456	–0.020	–0.007	0.013
C_1 %	–0.078	–0.066	0.173	0.331	–0.051	0.360	0.399	0.423	0.392	0.448	**0.638***	**–0.653***
C_1k_1	0.132	0.152	0.436	**0.758****	–0.145	**0.618***	**0.741****	**0.600***	**0.653***	**0.578***	**0.747****	**–0.787****
C_2k_2	0.356	0.413	0.440	**0.631***	–0.089	**0.624***	**0.764****	0.164	0.381	0.210	0.206	–0.238
MRT_1	–0.415	–0.466	–0.309	–0.547	0.202	–0.466	**–0.681***	–0.248	–0.507	–0.313	–0.303	0.351
MRT_2	–0.544	**–0.597***	–0.102	–0.376	0.297	–0.174	–0.494	–0.259	–0.413	–0.030	–0.019	0.026

TOC: total organic carbon; TN: total nitrogen; WEOC: water extractable organic carbon; TSN: total soluble nitrogen; CEC: cation exchange capacity.

**: significant at P <0.01 and *: significant at P <0.05 are in bold.

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Table 8 Pearson's correlation coefficients between kinetic parameters derived from the first-order two pools model (Molina et al., 1980) and the chemical and physical soil properties of the control samples

	pH (dw)	pH (KCl)	TOC	TN	C/N	WEOC	TSN	Fe	CEC	Clay	Silt	Sand
C_1	–0.121	–0.024	**0.747****	**0.646***	0.376	**0.879****	**0.730****	0.303	0.328	**0.554***	0.483	**–0.583***
C_2	–0.119	–0.060	**0.572***	**0.610***	0.163	**0.802****	**0.697****	0.294	0.288	0.449	0.522	**–0.568***
k_1	–0.520	–0.388	**0.622***	0.236	0.283	0.498	0.140	–0.047	0.023	0.056	0.062	–0.068
k_2	–0.273	–0.299	0.330	0.210	0.221	0.330	0.174	0.066	0.147	0.487	0.194	–0.343
C_1%	–0.105	0.045	**0.846****	**0.639***	0.349	**0.831****	**0.673***	0.384	0.427	0.532	0.405	–0.516
C_1k_1	–0.461	–0.325	**0.752****	0.344	0.340	**0.621***	0.243	–0.036	0.062	0.145	0.067	–0.109
C_2k_2	–0.140	–0.090	**0.638***	**0.645***	0.213	**0.851****	**0.723****	0.298	0.334	**0.554***	0.530	**–0.617***
MRT_1	0.109	0.021	**–0.705****	**–0.615***	–0.422	**–0.772****	**–0.647***	–0.210	–0.504	–0.541	–0.468	**0.566***
MRT_2	0.149	0.175	–0.331	–0.235	–0.205	–0.327	–0.206	0.032	–0.202	–0.449	–0.195	0.328

dw: distilled water; TOC: total organic carbon; TN: total nitrogen; WEOC: water extractable organic carbon; TSN: total soluble nitrogen; CEC: cation exchange capacity.

**: significant at P <0.01 and *: significant at P <0.05 are in bold.

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Highlights

- SOM decomposition kinetics was studied in 13 soils with and without maize addition
- SOC content and texture are factors controlling the rapid pool mineralization
- Stable pool decomposition was independent from the studied soil parameters
- SOM dynamics insufficiently described by one soil parameter

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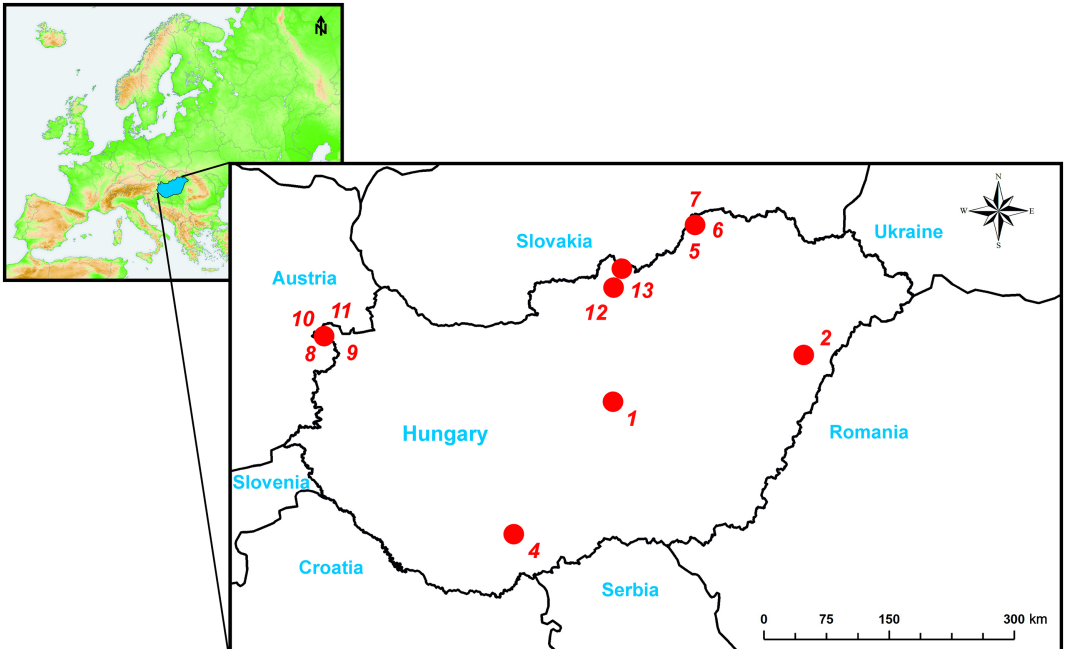
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Ukraine
Austria
Hungary
Romania
Slovenia
Croatia
Serbia
1
2
4
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13
N
W
E
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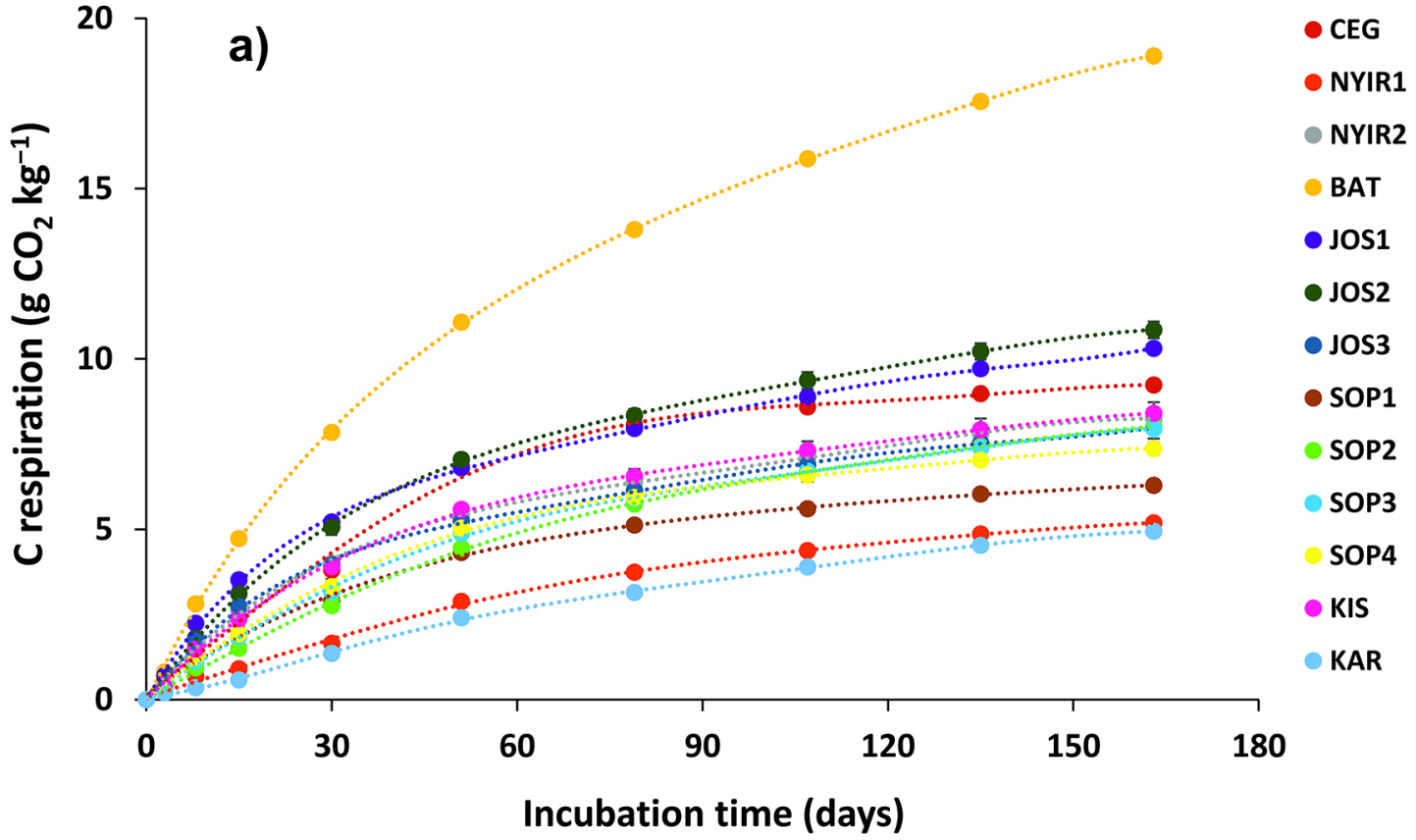
0
75
150
300 km

Figure 1


a)
C respiration (g CO2 kg−1)
Incubation time (days)
0
5
10
15
20
0
30
60
90
120
150
180
CEG
NYIR1
NYIR2
BAT
JOS1
JOS2
JOS3
SOP1
SOP2
SOP3
SOP4
KIS
KAR

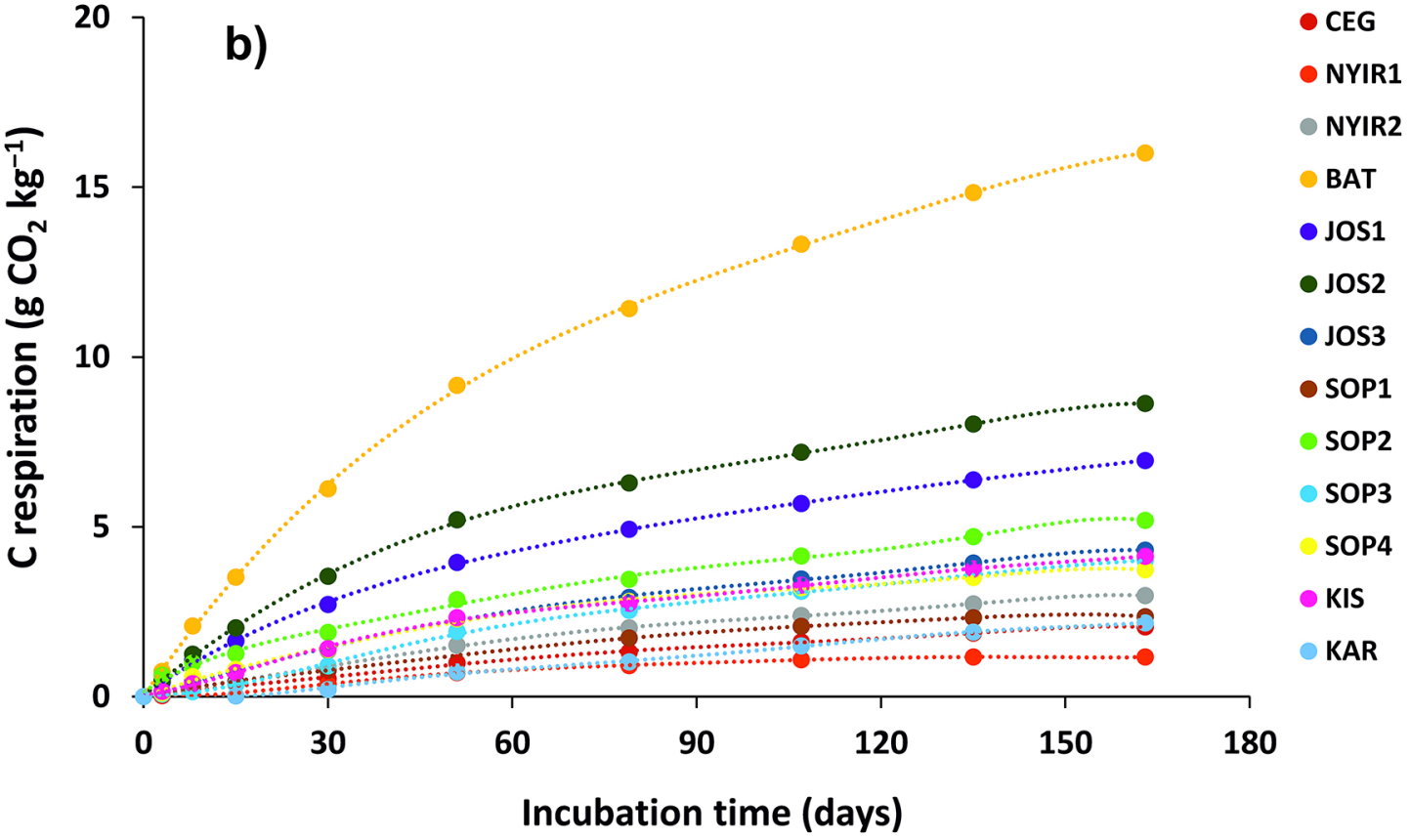

b)
C respiration (g CO2 kg−1)
Incubation time (days)
0
5
10
15
20
0
30
60
90
120
150
180
CEG
NYIR1
NYIR2
BAT
JOS1
JOS2
JOS3
SOP1
SOP2
SOP3
SOP4
KIS
KAR

Figure 2

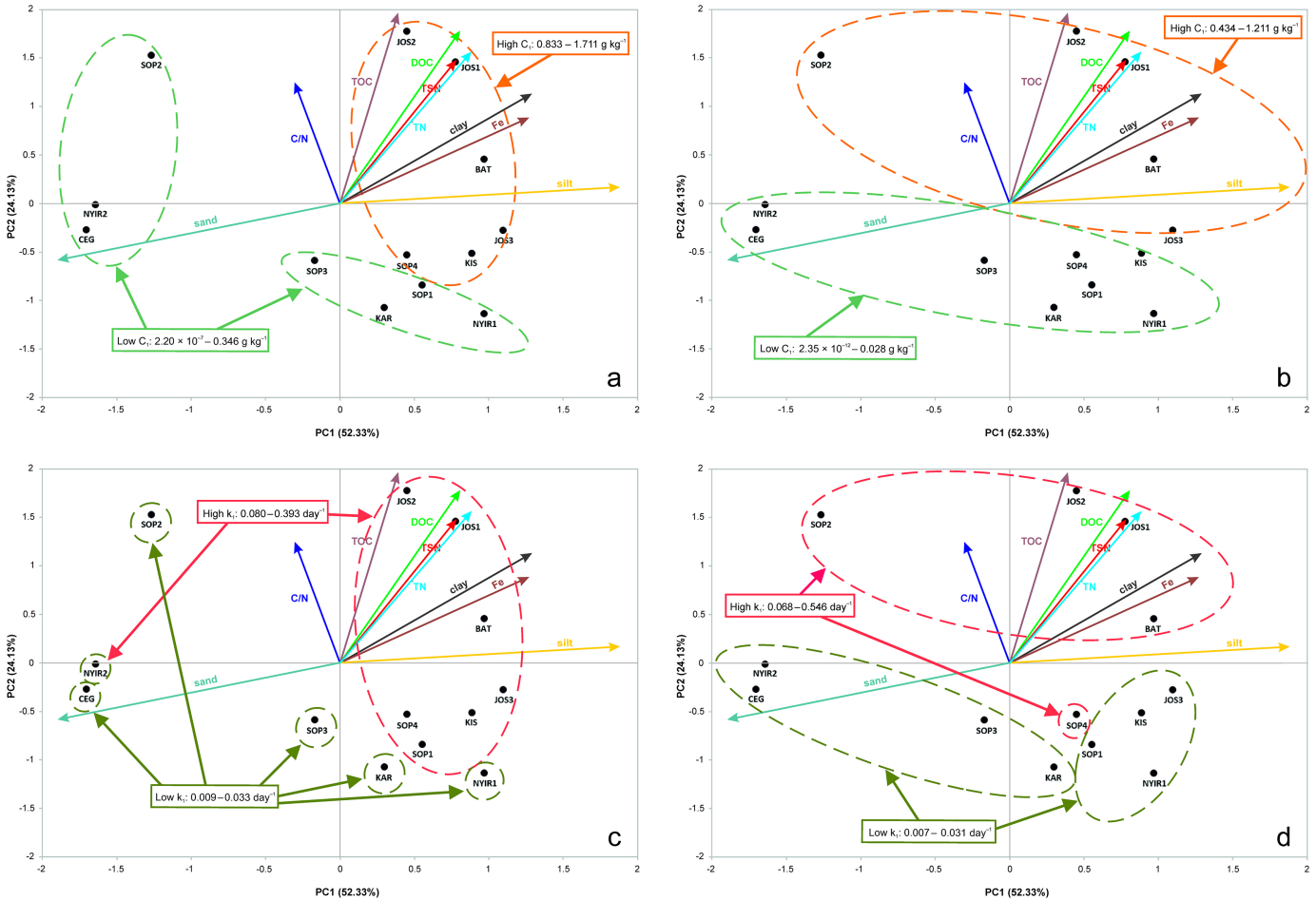

a
High C_i: 0.833 – 1.711 g kg^{-1}
Low C_i: 2.20 × 10^{-7} – 0.346 g kg^{-1}
b
High C_i: 0.434 – 1.211 g kg^{-1}
Low C_i: 2.35 × 10^{-12} – 0.028 g kg^{-1}
c
High k_i: 0.080 – 0.393 day^{-1}
Low k_i: 0.009 – 0.033 day^{-1}
d
High k_i: 0.068 – 0.546 day^{-1}
Low k_i: 0.007 – 0.031 day^{-1}
PC1 (52.33%)
PC2 (24.13%)
JOS2
JOS1
JOS3
KIS
BAT
SOP1
SOP2
SOP3
SOP4
KAR
NYIR1
NYIR2
CEG
TOC
DOC
TSN
TN
C/N
clay
Fe
silt
sand

Figure 3