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After-effect of long-term soil management on soil respiration and other qualitative parameters under prolonged dry soil conditions

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Abstract: Climatic conditions of environmental zone Nemoral 2 of Europe are favorable for agricultural development. However, more frequent events of hot air-waves and prolonged droughts occurring as a consequence of climate change lead to soil moisture content reduction down to the plant wilting point. Dry soil conditions may have negative consequences for soil as a habitat. The goal of this study was to evaluate the cumulative after-effect of long-term conventional (CT) and no-tillage (NT) application in combination with or without crop residues on soil physicochemical properties, microbiological activity, and soil respiration (SR) under prolonged dry soil conditions. Long-term CT with residue returning created a soil environment that was more resistant to dry conditions than NT. Long-term CT with residue returning created a qualitative soil environment in which the main direct determinants for SR were fungal (F) and bacterial (B) community and carbon/nitrogen ratio (C/N). Slightly weaker contributors for SR were available phosphorus (PAL), plant wilting point (PWP), plant available water (PAW), and urease activity (UR); however, they acted as indirect factors. Long-term spreading of residues on soil surface under NT determined the decrease in water capacity in mesopores and micropores. Significant reduction in field capacity and PWP was revealed, while PAW remained unchanged compared to NT with residues removed. Main direct determinants for SR were F and PAL. Slightly weaker indirect contributors for SR were B, dehydrogenase, UR, and PAW.

Key words: Basic nutrients, carbon, microbiological activity, no-tillage, straw, water

1. Introduction

Global climate change is one of the most significant current discussions from the agricultural point of view as it affects soil quality, water resource availability, crop growth, and soil management conditions worldwide (Tao et al., 2009). In the face of changing climate, when reduction in water resources and nutrient availability is feasible, predicting the effects of different soil management is important to ensure sustainable crop production (Helgason et al., 2014). However, the strength of the impact differs between regions (Olesen and Bindi, 2002). Climate change-related problems are also of interest to Lithuania. This country belongs to the environmental zone Nemoral 2 (NEM2) and represents one of the biogeographical regions of Europe. Air temperature and precipitation changes occurring in this region are important components in prediction of climate change scenarios (Bukantis et al., 2001) and play a key role in agricultural development (Sakalauskienė et al., 2009; Tripolskaja and Pirogovskaja, 2013).

High air temperature during crop growing period is not a common climatic feature of Lithuania. The climate of environmental zone NEM2 is characterized as being a continental one. The sum of temperatures above 10 °C is 2718 °C and the growing period lasts only 195 days. However, during the last decades, air temperature exceeding 25 °C has been registered 12 and 25 times per year at the Baltic Sea coast and in the continental part, respectively (Bukantis et al., 2000; Bukantis and Valiuškevičienė, 2005). According to the HELCOM assessment, hot days will become more frequent and severe

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in the southeastern part of the Baltic Sea region (Kažys et al., 2011). According to the literature, the number of hot days and nights significantly increased during 1998–2010 (Kažys et al., 2011). Recent studies have documented that climate change has already disrupted the steady situation of hot day recurrence, and there will be even more changes at the end of the 21st century (Kažys et al., 2011; Rimkus et al., 2012).

In general, climatic conditions of Lithuania are favorable for agricultural development. However, droughts, hot air-waves, and other extreme events that are expected to occur as a consequence of climatic change may have negative consequences for soil as a habitat (Ministry of Environment of the Republic of Lithuania, 2014).

Fertile soil is vital soil. Therefore, understanding highly complex interactions that occur in life below ground remains one of the most important challenges for agricultural scientists exploring possible mitigation strategies against global climate change processes (Jeffery et al., 2010).

Evidence suggests that plant residues have an impact on soil fertility and quality (Bastida et al., 2012; Giacometti et al., 2013). They may retain moisture and create favorable conditions for microbial life, especially during a dry season (Martens, 2001).

Soil tillage plays an important role in soil water conservation as well. Reduction of soil disturbance increases soil bulk density and penetration resistance and also causes reduction in soil porosity, but can improve soil hydraulic properties and water retention (De Vita et al., 2007; He et al., 2011) and increase soil C sequestration (Luo et al., 2010; Liaudanskienė et al., 2011; Lopez-Garido, 2012). Nevertheless, the impacts of no-tillage (NT) applications on soil properties and primarily on C sequestration should not be generalized (Yang et al., 2013), because the experimental results obtained under contrasting climatic, meteorological, and soil conditions can cause dissimilar or even contradictory conclusions.

Soil microbial community is an important indicator of sustainable land use because of its sensitivity to changes in the soil chemical properties (Hamer et al., 2005; Kuzyakov, 2010), aeration, and water content (Drenovsky et al., 2004; Williams and Rice, 2007). The changed quantity, composition, and functioning of soil microbial communities have been shown under conservation agriculture (González-Chávez et al., 2010; Lopez-Garrido et al., 2012; Janušauskaite et al., 2013; Laudicina et al., 2014).

Soil respiration (SR) is a key factor for understanding soil vitality. Agricultural practices, primarily tillage, play a significant role in production and consumption of greenhouse gases, specifically CO_2 (Smith et al., 2008). However, every practice may influence soil quality either in a positive or negative manner (Giacometti et al., 2013). To date, there has been no consensus on soil CO_2 exchange patterns as affected by soil management practices. Numerous studies have revealed relatively higher SR and CO_2 fluxes under conventional tillage (CT) compared to reduced tillage (RT) and NT (La Scala et al., 2006; Chatskikh et al., 2007, 2008; Luo et al., 2010; Feiziene et al., 2011). Elder and Lal (2008) documented insignificant differences between CO_2 fluxes in CT and NT. The concept of soil CO_2 fluxes remains unclear because of the complexity of the processes involved (Hanson et al., 2000). Long-term field experiments are the primary source of information to determine the management effects on soil productivity and vitality.

In Lithuania, CT, as the most popular soil management method, is employed on about 68% of arable land. RT accounts for 7% and NT for as little as up to 1% of arable land. Large amounts of straw (6–7 t ha^{-1}) are usually produced in the fields of intensive farming. Up to 20% of straw is left on the land as a direct soil amendment.

Recent evidence suggests that the effective soil water utilization will be one of the most important factors determining crop productivity level, while securing plants with available water content during the crop vegetation period will play a vital role in the NEM2 environmental zone of Europe.

The goal of this study was to evaluate the cumulative after-effect of long-term CT and NT applications in combination with or without crop residues on soil physicochemical properties, microbiological functioning, and soil respiration under prolonged dry soil conditions. We hypothesized that in the NEM2 environmental zone of Europe, the application of CT with residue returning would be more resistant to prolonged dry conditions during the most intensive crop vegetation period than under NT.

2. Materials and methods

2.1. Site and soil description and experimental design

The investigation was carried out in 2011 at the Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry (55°23′50″N, 23°51′40″E), on an Endocalcari-Epihypogleyic Cambisol soil in a long-term field trial established in 1999 on a good tilth field with a loam texture (Table 1). The field experiment had a split-plot design in four replications. Two residue management treatments were the main backgrounds; CT and NT were subplots (Table 2). CT involved stubble cultivation, moldboard plowing 3 weeks after stubble cultivation, and presowing tillage. NT involved application of herbicide glyphosate 3 weeks after crop harvesting. Direct drilling was done by a disk seed-drill on the same day for both CT and NT.

The rates of mineral fertilizers (Table 3) were calculated according to soil chemical and physical properties and

Table 1. Soil site characteristics.

Index	Mean	Index	Mean
Sand (%)	51.76	Electrical conductivity (ms m^{-1})	8.06
Clay (%)	19.28	Total N (g kg^{-1})	2.10
Silt (%)	28.96	Total C (g kg^{-1})	21.24
Saturated hydraulic conductivity (cm h–^{1})	0.87	SOC (g kg^{-1})	19.85
Saturation (m^3 m^{-3})	0.46	Available P_{AL} (mg kg^{-1})	120.23
Field capacity (m^3 m^{-3})	0.24	Available K_{AL} (mg kg^{-1})	181.27
Wilting point (%)	12.00	pH_{KCl}	6.71

Table 2. Field trial design.

Tillage		
	Primary tillage	Presowing tillage
CT – conventional tillage	Stubble cultivation (10–12 cm) + plowing (23–25 cm)	Spring tine cultivation (4–5 cm)
NT – no tillage	Glyphosate (3 L ha^{-1})	Direct drilling
Residues		
1	Residues removed	
2	Residues returned (chopped and spread on soil surface; CT – incorporated, NT – not incorporated)	

Table 3. The amount of mineral NPK fertilizers in 2011 and during 13 experimental years.

	Target yield, Mg ha^{-1}	Rate of fertilizers, kg ha^{-1}		
		N	P_2O_5	K_2O
Fertilization in 2011 (spring oil seed rape)	3.0	90	0	49
Fertilizers during 13 experimental years, Σ		857	0	416

target yield of the grown crop (spring oilseed rape). N fertilizers were applied in the form of ammonium nitrate and K fertilizers were applied as potassium chloride. P fertilizers were not used because of high soil P content. Mineral fertilizers were spread on the soil surface and slightly incorporated by presowing tillage under CT or by a rotary seed-drill under NT. A 5-course crop rotation (winter wheat (*Triticum aestivum* L.) – spring oilseed rape (*Brassica napus* L.) – spring wheat (*Triticum aestivum* L.) – spring barley (*Hordeum vulgare* L.) – peas (*Pisum sativum* L.)) was implemented and persisted from 1999. The rates of residues differed among years and depended on crop species. Winter wheat residues amounted to 5.0–6.4, spring oilseed rape 4.3–5.7, spring wheat 3.9–4.8, spring barley 3.2–3.9, and peas 2.8–3.4 t ha^{-1}. The average amount of returned residues was 4.3 t ha^{-1} $year^{-1}$.

2.2. Weather conditions

Since the field experiment was establishment in 1999 until the present, the meteorological conditions varied widely among years (Figure 1). The amount of rainfall during the most intensive growing period (April, May, June) in 10 out of 13 years was lower by 16%–53% than the long-term average (1924–2011). It is worth noting that the air temperature exhibited a clear tendency to increase, as the mean air temperature during April, May, and June during 12 years out of 13 was 4%–21% higher than the long-term average.

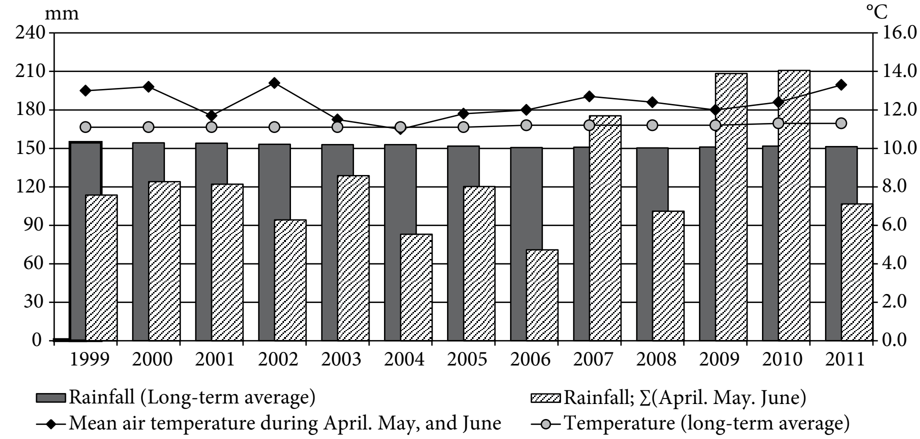

Figure 1. Rainfall and air temperature fluctuations at experimental site during the last 13 years (1999–2011, Dotnuva Meteorological Station).

Warm days and cool nights dominated in April 2011. In the second half of the month, daytime air humidity was 26%–36%. Moderate north winds prevailed. The third 10-day period was warmer than the previous two. Monthly rainfall amounted to 42% of the long-term average; no rainfall occurred during the third 10-day period (Figure 2). In May, the amount of rainfall was 90% of the long-term average. More noticeable rainfall occurred twice during the month. The first 10 days of June were warm and sunny. Rain occurred only twice during the first half of the month. Average daytime air humidity reached 66% (norm: ~75%). Monthly rainfall amounted to up to 71% of the long-term.

2.3. Soil sampling and analysis

Soil samples for physical, chemical, and microbiological analyses were collected at the beginning of the spring oilseed rape stem elongation stage (BBCH 30) on 5 June 2011 at the 0–10 cm soil depth. Disturbed soil samples were prepared in 8 replicates. Soil available phosphorus (P_{AL}) and potassium (K_{AL}) were determined by ammonium lactate extraction (A-L method) (Egner et al., 1960). Total nitrogen (N_{tot}) and total carbon (C_{tot}) were analyzed by the dry combustion method using a Vario EL III CNS autoanalyzer (Elementar Analysensysteme, Germany) (Schmidt et al., 1999). pH_{KCl} was identified with an AS-3010D potentiometer (Labfit Pty. Ltd., Australia). The

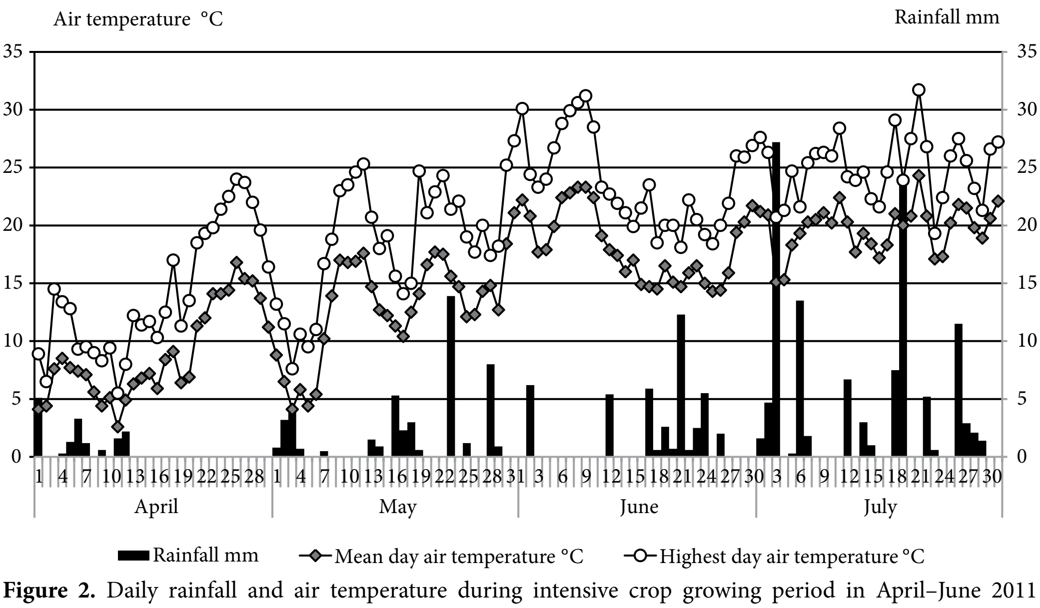

Figure 2. Daily rainfall and air temperature during intensive crop growing period in April–June 2011 (Dotnuva Meteorological Station).

Tyurin titrimetric (classical) method was applied for soil organic carbon (SOC) determination (Vadiunina and Korchagina, 1986). Pipette method was used to determine soil texture according to the FAO.

Undisturbed core samples were collected in 8 replicates using stainless steel rings from 0–5 and 5–10 cm depths to determine soil pore volume distribution, water retention, plant available water content (PAW), bulk density (BD), total porosity (TP), air-filled porosity (AP), field capacity (FC), and permanent wilting point (PWP). The data were averaged for 0–10 cm depth. The sandbox method (sandbox within negative water potential of 0 to −100 hPa; sand/kaolin box within negative water potential of −100 to −490 hPa; membrane apparatus box within negative water potential of −982 to −15,500 hPa) was implemented (Klute, 1986).

Microbiological analysis was performed using standard methods. Conventional dilution spread-plating was performed to assess the culturable bacterial (B) and fungal (F) colony forming units (CFU). For heterotrophic bacteria enumeration soy tryptic agar (TSA/10 agar, Biochemika) and for total fungal counts malt extract agar (Liofilchem Diagnostici) were used. CFU was corrected for soil moisture content before the final counts and expressed as the number of culturable bacteria and fungi cells per 1 g of dry soil. Dehydrogenase activity (DH) was determined using the reduction of 2,3,5-triphenyltetrazolium chloride to triphenyl formazan (TPF) method at 546 nm absorbance (Schinner et al., 1995) and the results were expressed as µg TPF g^{-1} DW 24 h^{-1}. The activity of urease (UR; EC 3.5.1.5) was measured by the colorimetric determination of ammonium formation after enzymatic urea hydrolysis by buffer method (Schinner et al., 1995). The released ammonium was determined spectrophotometrically at 690 nm. The results were expressed as µg NH_4 g^{-1} dry soil. Substrate utilization potential as average well color development (AWCD) and Shannon–Weaver index (H') of the soil microbial community were determined according to the community level physiological profiles method using Biolog EcoPlates (Garland and Mills, 1991).

A closed chamber method was applied to quantify total (autotrophic + heterotrophic) soil surface respiration on the day the soil samples were collected. Measurements of CO_2 fluxes were done between 1100 and 1500 hours using a portable infrared CO_2 analyzer (IRGA) attached to a data logger (LcSRS-1000, ADC BioScientific Ltd., UK). All measurements were automatically compensated for atmospheric pressure and temperature. In each treatment, the collar was inserted into soil at a depth of 7.0 cm; the chamber hood was placed on the collar for 2 min until results were recorded in the data logger. The chamber covered areas in crop rows. Measurements were done in 4 replications. Expression of soil respiration was:

$$SR = u\,(-\Delta c) \qquad (1)$$

where u is molar air flow (mol s^{-1}) and Δc is the difference in CO_2 concentration through the soil hood, dilution corrected (µmol mol^{-1}).

2.4. Statistical analysis

ANOVA for split-plot design was used to determine tillage and residue effects on soil key drivers. The data were analyzed using software STATISTICA Base, version 6. The data were compared using Fisher's least significant difference test at probability levels P < 0.05 and P < 0.01. Furthermore, the path coefficient analysis was performed as described by Williams et al. (1990) for deeper evaluation of causal relationships (Figure 3). Path analysis differentiates between correlation and causation by partitioning simple correlation coefficients between the independent variables (soil properties investigated) and dependent variable (SR) into direct and indirect effects (Zhang et al., 2005). The sum of the entire path shows the strength of different variables on dependent indices (Y). Path analysis (partitioning of causal pathway) results were determined according to the example of the following equations (Williams et al., 1990):

$$\frac{\begin{array}{c} rx_1y = Px_1y + r_{12}Px_2y + r_{13}Px_3y + r_{14}Px_4y + r_{15}Px_5y; \\ rx_2y = Px_2y + r_{12}Px_1y + r_{23}Px_3y + r_{24}Px_4y + r_{25}Px_5y; \\ rx_3y = Px_3y + r_{23}Px_2y + r_{34}Px_4y + r_{35}Px_5y + r_{13}Px_1y; \end{array}}{\begin{array}{c} rx_ay = Px_ay + r_{a2}Px_2y + r_{a3}Px_3y + \\ r_{a4}Px_4y + r_{a5}Px_5y + \ldots + r_{an}Px_ny, \end{array}} \qquad (2)$$

where rx_ay is the simple correlation coefficient between an independent variable x_a and a dependent variable Y, Px_ay is the path coefficient between x_a and Y and presents the direct effect of x_a on Y, and $r_{an}Px_ny$ is the simple correlation coefficient between x_a and x_n.

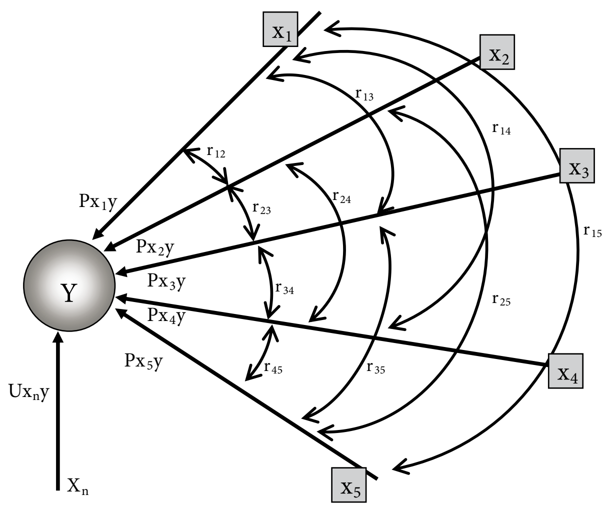

Figure 3. Example of path diagram illustrating relationship between dependent variable (Y) and independent variables (x). Px_ay denotes the direct path and r_{an} is the correlation coefficient.

The residual effect (Ux_ny) was very low in all treatments. It is an unmeasured variable x_n in the model that represents the unexplained part of an observed variable:

$$Ux_ny = \sqrt{(1 - R^2)}, \quad (3)$$

where R^2 is the coefficient of determination.

3. Results

3.1. Soil agrochemical and physical properties as result of long-term management practices

Significantly higher contents of P_{AL} and C_{tot} (averaged across tillage treatments) were in the plots with residues (Table 4). Contents of SOC and K_{AL} were similar on both residue backgrounds. Returned residues reduced N_{tot}, and consequently the C:N ratio become higher than in plots without residues. NT resulted in significantly higher N_{tot}, P_{AL}, K_{AL}, C_{tot}, SOC contents, and C:N ratio than CT (data averaged across residue treatments). CT interaction with residue returning significantly increased SOC, C_{tot}, P_{AL}, and C:N ratio. However, the positive effect of NT with residue returning was seen only for C_{tot} and P_{AL}.

Residue returning (data averaged across tillage treatments) caused a significant ($P \leq 0.01$) decrease in AP compared to residue removal, but it did not reveal any influence on soil BD and TP (Table 5). In NT plots, BD (data averaged across residue treatments) was significantly ($P \leq 0.05$) higher and TP and AP were significantly lower than in CT. The CT combination with residue returning caused significant increase in BD and decrease in TP and AP. Meanwhile, NT with residues returned significantly decreased BD.

Long-term management practices resulted in significant differences in pore structure (Table 6). Returned residues (data averaged across tillage) significantly increased macroporosity, while mesoporosity and microporosity became significantly lower than in the plots without residues. Long-term NT (data averaged across residue management) decreased soil macroporosity and increased mesoporosity, while microporosity remained similar in both CT and NT. However, the NT combination with residue returning resulted in microporosity reduction. CT with residues returned caused significant decrease in mesoporosity and microporosity.

Soil water capacity undoubtedly responded to changes in soil pore structure (Table 7). Residue returning (data averaged across tillage) significantly reduced water capacity in large drainage soil pores with diameter of >750 µm. Significant reduction of water capacity in pores of ≤ 30 µm revealed that FC and PWP under long-term residue

Table 4. After-effect of long-term different soil managements on soil total nitrogen (N_{tot}), total carbon (C_{tot}), C/N ratio, organic carbon (SOC), available phosphorus (P_{AL}), and available potassium (K_{AL}).

Residues (factor A)	Tillage (factor B)	Treatments	Indices†					
			N_{tot} (g kg^{-1})	C_{tot} (g kg^{-1})	C:N	SOC (g kg^{-1})	P_{AL} (mg kg^{-1})	K_{AL} (mg kg^{-1})
Removed			2.12b	20.22b	9.89c	19.65b	82.0c	179.9b
Returned			2.07c	22.27a	10.80a	20.05b	125.4a	183.5b
	CT		1.91d	19.29c	10,14b	18.42c	97.2c	167.3c
	NT		2.29a	23.20a	10,54a	21.28a	110.2b	196.0a
		CT-1	1.91c	18.00d	9,54b	17.46d	82.8c	163.5b
		NT-1	2.33a	22.44b	10,24a	21.84a	81.2c	196.2a
		CT-2	1.90c	20.58c	10,75a	19.38c	111.6b	171.0b
		NT-2	2.24b	23.95a	10,85a	20.72b	139.2a	195.9a
Actions and interactions:								
A			*	**	**	ns	**	ns
B			**	**	*	**	*	**
A × B			ns	ns	*	**	*	ns

†Data followed by the same letters are not significantly different at $P < 0.05$; * and **: the least significant difference at $P < 0.05$ and $P < 0.01$, respectively; ns: not significant. CT-1: conventional tillage, residue removed; CT-2: conventional tillage, residue returned; NT-1: no-tillage, residue removed; NT-2: no-tillage, residue returned.

Table 5. Soil bulk density (BD), total porosity (TP), and air-filled porosity (AP) under prolonged dry conditions after long-term different soil management.

Residues (factor A)	Tillage (factor B)	Treatments	Indices†		
			BD (Mg m^{-3})	TP (m^{3} m^{-3})	AP (m^{3} m^{-3})
Removed			1.60b	0.40b	0.24a
Returned			1.61b	0.39b	0.22c
	CT		1.57c	0.41a	0.24a
	NT		1.64a	0.38c	0.21c
		CT-1	1.54c	0.42a	0.26a
		NT-1	1.66a	0.38c	0.22b
		CT-2	1.60b	0.40b	0.23b
		NT-2	1.62b	0.39c	0.21b
Actions and interactions:					
A			ns	ns	**
B			**	**	**
A × B			**	**	*

†Data followed by the same letters are not significantly different at P < 0.05; * and **: the least significant difference at P < 0.05 and P < 0.01, respectively; ns: not significant. CT-1: conventional tillage, residue removed; CT-2: conventional tillage, residue returned; NT-1: no-tillage, residue removed; NT-2: no-tillage, residue returned.

Table 6. Variance analysis of soil macro-, mezo-, and micropore distributions as a result of long-term different soil managements.

Residues (factor A)	Tillage (factor B)	Treatments	Soil pores †		
			Macropores >30 µm	Mesopores 0.2–30 µm	Micropores <0.2 µm
Removed			0.118b	0.171a	0.108a
Returned			0.128a	0.165b	0.100c
	CT		0.148a	0.157c	0.103b
	NT		0.098c	0.179a	0.104b
		CT-1	0.151a	0.164b	0.105a
		NT-1	0.085c	0.179a	0.111a
		CT-2	0.145a	0.150c	0.102b
		NT-2	0.110b	0.179a	0.098b
Actions and interactions:					
A			*	*	**
B			**	**	ns
A × B			*	*	*

†Data followed by the same letters are not significantly different at P < 0.05; * and **: the least significant difference at P < 0.05 and P < 0.01, respectively; ns: not significant. CT-1: conventional tillage, residue removed; CT-2: conventional tillage, residue returned; NT-1: no-tillage, residue removed; NT-2: no-tillage, residue returned.

Table 7. Soil water capacity after long-term different soil management.

Residues (factor A)	Tillage (factor B)	Treatments	Water capacity (m^3 m^{-3}) †						PAW
			>750 µm	300 µm	100 µm	30 µm	10 µm	<0.2 µm	
			Suction hPa						
			−4	−10	−30	−100	−300	−15,500	
Removed			0.369a	0.347b	0.319b	0.279a	0.236a	0.108a	0.171a
Returned			0.358b	0.345b	0.315b	0.264c	0.224c	0.100c	0.165b
	CT		0.379a	0.355a	0.312c	0.260c	0.220c	0.103b	0.157c
	NT		0.348c	0.337c	0.321a	0.283a	0.240a	0.104b	0.179a
		CT-1	0.395a	0.363a	0.318a	0.269b	0.226b	0.105a	0.164b
		NT-1	0.342d	0.332d	0.319a	0.290a	0.247b	0.111a	0.179a
		CT-2	0.362c	0.348b	0.306b	0.252c	0.214b	0.102b	0.150c
		NT-2	0.354c	0.342c	0.323a	0.277b	0.234b	0.098c	0.179a
Actions and interactions:									
A			*	ns	ns	**	**	**	*
B			**	**	**	**	**	ns	**
A × B			**	**	*	*	ns	*	*

†Data followed by the same letters are not significantly different at P < 0.05; * and **: the least significant difference at P < 0.05 and P < 0.01, respectively; ns: not significant. CT-1: conventional tillage, residue removed; CT-2: conventional tillage, residue returned; NT-1: no-tillage, residue removed; NT-2: no-tillage, residue returned.

returning became lower compared to FC and PWP in the field without residue application. NT (data averaged across residue management) decreased water retention in soil pores with a diameter of ≥300 µm, while water retention in pores of 10–100 µm was significantly higher than under CT. Interaction of tillage × residues was significant for water retention in all soil pores with the exception of pores of 10 µm in diameter. Accordingly, in CT plots with residues returned, FC and PWP were lower by 6% and 3% compared to the plots without residues. In NT plots, FC and PWP reduction under long-term residue returning was lower by 4% and 12% than in the plots without residues.

Traits of pore size distribution and water retention under long-term NT caused significantly higher mean PAW content than CT. However, in the NT plots, returning of residues did not change PAW. Residue returning in CT plots decreased PAW by 9%.

3.2. Soil microbiological properties and respiration

Consistently higher values of enzymes and F were found in NT, while B was similar in both CT and NT. CT led to a significantly higher AWCD and H' (Table 8). The returning of residues favored only UR activity. Significantly (P < 0.01) higher UR values were obtained in the soil under NT than CT (data averaged across residue management). Residue returning significantly (P < 0.01) increased UR activity (data averaged across tillage systems). Tillage interaction with residue handling was also significant (P < 0.05) for UR. UR activity in NT was 63.6% and 54.2% higher (NT-1 and NT-2, respectively) than in CT. DH activity was 15% higher on the background without residues (data averaged between tillage systems). NT (data averaged between residue treatments) caused 24% higher DH activity than CT. DH activity under NT-1 was 52.6% higher compared to CT-1. DH differences under CT-2 and NT-2 treatments were insignificant.

Data averaged across tillage systems revealed that F was significantly (P > 0.01) higher in the treatments without residues. Data averaged across residue handling demonstrated significantly (P > 0.01) higher F content under NT than CT. The contrasts among experimental treatments were more pronounced. In the NT-1 system, F was 82% higher than in CT-1, while in the NT-2 system F was only 9% higher than in CT-2. B was equal under CT and NT. The influence of residue handling was insignificant.

Table 8. Soil microbiological properties under prolonged dry conditions after long-term different soil managements.

Residues (factor A)	Tillage (factor B)	Treatments	Indices†					
			Urease µg NH_4 g^{-1} dry soil	Dehydrogenase µg TPF g^{-1} DW 24 h^{-1}	Bacteria 10^6 CFU g^{-1} dry soil	Fungi 10^4 CFU g^{-1} dry soil	AWCD	H’
Removed			60.93c	173.19a	5.70a	42.93a	0.885a	3.14b
Returned			65.27a	151.04c	5.42a	36.97c	0.691c	3.13b
	CT		48.79c	144.64c	5.53a	32.90c	1.002a	3.22a
	NT		77.41a	179.58a	5.59a	47.00a	0.574c	3.05c
		CT-1	46.23d	137.10d	5.46a	30.43d	1.187a	3.21a
		NT-1	75.63b	209.27a	5.94a	55.43a	0.582c	3.07c
		CT-2	51.36c	152.19c	5.61a	35.37c	0.818b	3.23b
		NT-2	79.18a	149.89c	5.23a	38.57c	0.565c	3.03d
Actions and interactions:								
A			**	**	ns	**	**	ns
B			**	**	ns	**	**	**
A × B			**	**	ns	**	**	**

†Data followed by the same letters are not significantly different at P < 0.05; **: the least significant difference at P < 0.01; ns: not significant. CT-1: conventional tillage, residue removed; CT-2: conventional tillage, residue returned; NT-1: no-tillage, residue removed; NT-2: no-tillage, residue returned.

The soil under CT revealed significantly (P < 0.01) higher AWCD and H’ than under NT. Residue handling did not influence H’, while AWCD was significantly (P < 0.01) higher in the soil without residues. Interaction tillage × residue handling was significant for both H’ (P < 0.05) and AWCD (P > 0.01) and revealed obvious contrasts among soil management practices.

Evolution of CO_2 was 6% higher in the soil with returned residues. SR averaged across residue handling was 22% higher in CT than in NT (Figure 4). In CT plots residue returning supported 29% higher SR; meanwhile, in NT plots SR was 17% lower, compared to residue removal.

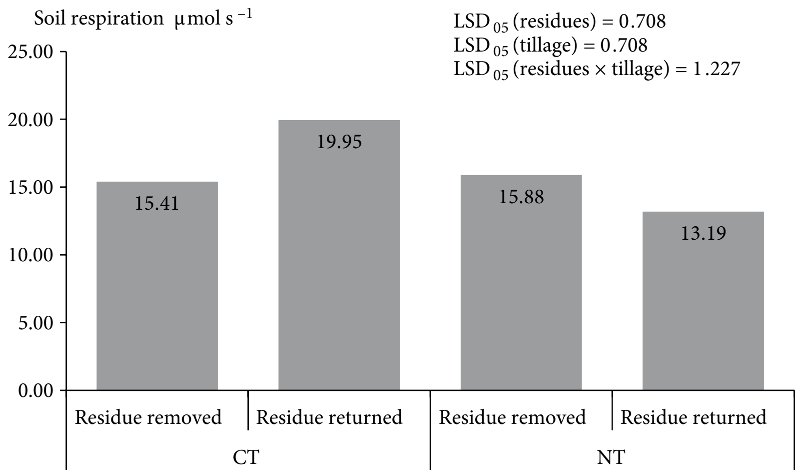

Figure 4. Soil respiration under prolonged dry soil conditions. CT: conventional tillage. NT: no-tillage.

3.3. Paths of soil respiration causality

Under prolonged dry conditions CT, NT, and residue handling affected soil PAW and microbiological functioning differently, with consequences for SOC, basic nutrients, and CO_2 dynamics. Tables 9 and 10 present the relevant correlation matrix and causal pathways for CT applications while Tables 11 and 12 present the same for NT applications.

High K_{AL} content significantly decreased UR (treatments CT-1, CT-2, and NT-1) and DH (CT-2 and NT-1). Soil P_{AL} suppressed DH in both CT-1 and NT-1. Both P_{AL} and K_{AL} were inversely correlated with AWCD and H' under CT-1 and NT-2 (Tables 9 and 11). Inverse correlation between SOC and K_{AL} could demonstrate the increase in soil K_{AL} utilization potential under conventional management.

The relationship between UR and SOC was positive in all treatments. DH positively correlated with SOC only in CT-2 and NT-1. This could indicate that the soil ecosystems under dry conditions had low content of organic substrates to metabolize and those microorganisms were in a reduced state of activity (Gonzalez et al., 2007). It is known that intracellular enzyme activity may increase or decrease without any change in microbial biomass. In soils with straw, decrease of DH activity could respond to the depletion of easily decomposed substrates during the fast primary decomposition. DH activity level subsequently becomes even lower than in soil without straw (Bastida et al., 2012). DH increase may relate to the long-term accumulation of organic matter on the soil surface. Some results that reveal the decrease in DH could relate to the long time since the initial stimulatory effect (Martens et

Table 9. Correlation matrix of investigated indices for long-term conventional tillage either without (CT-1) or with (CT-2) crop residue application.

Indices (x) †	Mean values	Correlation matrix										
		SR	SOC	K_{AL}	P_{AL}	C/N	DH	UR	H'	F	B	PAW
CT-1 – conventional tillage, residue removed												
SR	15.41	1.00										
SOC	17.46	0.93**	1.00									
K_{AL}	0.16	−0.99**	−0.86**	1.00								
P_{AL}	0.08	−0.14	−0.50*	0.00	1.00							
C/N	9.54	0.55*	0.41*	−0.59*	0.19	1.00						
AWCD	1.19	1.00	0.91**	−1.00**	−0.09	0.57*						
DH	137.1	−0.72*	−0.40*	0.81**	−0.59*	−0.59*	1.00					
UR	46.23	0.99**	0.97**	−0.96**	−0.26	0.52*	−0.62*	1.00				
H'	3.21	1.00**	0.92**	−0.99**	−0.13	0.56*	−0.73*	0.99**	1.00			
F	30.43	0.39*	0.01	−0.51*	0.86**	0.47*	−0.92**	0.27	0.40*	1.00		
B	5.46	0.77**	0.48*	−0.85**	0.52*	0.60*	−1.00**	0.69*	0.78**	0.88**	1.00	
PAW	0.164	0.91**	0.75**	−0.93**	0.11	0.29	−0.81**	0.87**	0.91**	0.57*	0.85**	1.00
PWP	0.105	−0.30	0.08	0.43*	−0.90**	−0.43*	0.88**	−0.18	−0.31	−1.00**	−0.84**	−0.50*
CT-2 – conventional tillage, residue returned												
SR	19.95	1.00										
SOC	19.38	−1.00**	1.00									
K_{AL}	0.17	0.68*	−0.62*	1.00								
P_{AL}	0.11	−0.57*	0.50*	−0.99**	1.00							
C/N	10.75	−0.17	0.08	−0.83**	0.90**	1.00						
AWCD	0.82	0.12	−0.03	0.81**	−0.88**	−0.99**						
DH	152.19	−0.62*	0.59*	−0.62*	0.57*	0.29	1.00					
UR	51.36	−0.89**	0.85**	−0.94**	0.88**	0.59*	0.67*	1.00				
H'	3.23	0.04	0.05	0.76**	−0.84**	−0.99**	−0.29	−0.49*	1.00			
F	35.37	−0.63*	0.70*	0.14	−0.28	−0.66*	0.18	0.21	0.75**	1.00		
B	5.61	0.76**	−0.70*	0.99**	−0.97**	−0.77**	−0.64*	−0.97**	0.68*	0.03	1.00	
PAW	0.150	0.09	−0.15	−0.49*	0.56*	0.79**	−0.34	0.26	−0.74**	−0.64*	−0.42*	1.00
PWP	0.102	−0.93**	0.90**	−0.90**	0.83**	0.51*	0.67*	0.99**	−0.40*	0.30	−0.94**	0.19

†SR: soil respiration (µmol s^{-1}), SOC: soil organic carbon (g kg^{-1}), K_{AL}: available K (g kg^{-1}), P_{AL}: available P (g kg^{-1}), C/N: ratio of total carbon/total nitrogen, AWCD: substrate utilization potential as average well color development, DH: dehydrogenase, UR: urease, H': Shannon–Weaver index of the soil microbial community, F: fungi community, B: bacteria community, PAW: plant available water, PWP: permanent wilting point; * and **: least significant difference at $P < 0.05$ and $P < 0.01$, respectively.

Table 10. Causal pathways among dependent variable (SR(rY) and independent variables (x) for long-term conventional tillage either without (CT-1) or with (CT-2) crop residue application.

Indices (x) †	Path coefficient ††												SR (rY)
	SOC	K_{AL}	P_{AL}	C/N	AWCD	DH	UR	H’	F	B	PAW	PWP	
CT-1 – conventional tillage, residue removed													
SOC	**−0.126**	0.070	−0.581	0.031	−0.042	0.139	1.281	0.065	−0.011	−0.028	0.127	0.001	0.93**
K_{AL}	0.109	**−0.081**	−0.001	−0.045	0.046	−0.280	−1.279	−0.070	0.713	0.050	−0.158	0.006	−0.99**
P_{AL}	0.063	0.000	**1.157**	0.015	0.004	0.205	−0.347	−0.009	−1.202	−0.030	0.018	−0.012	−0.14
C/N	−0.052	0.047	0.224	**0.076**	−0.026	0.204	0.684	0.039	−0.651	−0.035	0.049	−0.006	0.55*
AWCD	−0.114	0.080	−0.106	0.043	**−0.046**	0.260	1.306	0.070	−0.598	−0.047	0.155	−0.005	1.00**
DH	0.051	−0.065	−0.683	−0.045	0.034	**−0.347**	−0.828	−0.051	1.284	0.058	−0.138	0.012	−0.72*
UR	−0.122	0.078	−0.303	0.039	−0.045	0.217	**1.326**	0.070	−0.372	−0.040	0.147	−0.002	0.99**
H’	−0.116	0.080	−0.145	0.042	−0.046	0.252	1.313	**0.070**	−0.555	−0.046	0.154	−0.004	1.00**
F	−0.001	0.041	0.995	0.035	−0.020	0.319	0.353	0.028	**−1.397**	−0.052	0.096	−0.013	0.39*
B	−0.060	0.069	0.604	0.046	−0.037	0.346	0.910	0.055	−1.235	**−0.058**	0.144	−0.011	0.77**
PAW	−0.094	0.075	0.126	0.022	−0.042	0.283	1.152	0.064	−0.792	−0.050	**0.170**	−0.007	0.91**
PWP	−0.010	−0.035	−1.044	−0.032	0.016	−0.305	−0.237	−0.022	1.391	0.049	−0.085	**0.013**	−0.30*
CT-2 – conventional tillage, residue returned													
SOC	**0.906**	−0.249	1.415	0.287	0.026	0.132	−0.982	0.010	2.039	−2.600	0.053	−2.032	−1.00**
K_{AL}	−0.558	**0.404**	−2.822	−3.064	−0.710	−0.138	1.092	0.153	0.401	3.715	0.167	2.045	0.68*
P_{AL}	0.449	−0.400	**2.852**	3.325	0.778	0.128	−1.024	−0.170	−0.815	−3.619	−0.194	−1.883	−0.57*
C/N	0.070	−0.335	2.565	**3.697**	0.875	0.064	−0.689	−0.199	−1.927	−2.861	−0.271	−1.157	−0.17
AWCD	−0.027	0.326	−2.517	−3.672	**−0.881**	−0.076	0.646	0.201	2.042	2.758	0.252	1.067	0.12
DH	0.533	−0.250	1.633	1.064	0.300	**0.224**	−0.778	−0.059	0.520	−2.398	0.117	−1.522	−0.62*
UR	0.767	−0.380	2.516	2.195	0.491	0.150	**−1.160**	−0.099	0.606	−3.629	−0.090	−2.257	−0.89**
H’	0.045	0.306	−2.403	−3.646	−0.878	−0.066	0.568	**0.202**	2.203	2.549	0.256	0.905	0.04
F	0.630	0.055	−0.793	−2.432	−0.614	0.040	−0.240	0.152	**2.929**	0.116	0.219	−0.691	−0.63*
B	−0.630	0.402	−2.763	−2.832	−0.651	−0.144	1.127	0.138	0.091	**3.736**	0.145	2.138	0.76**
PAW	−0.139	−0.197	1.609	2.917	0.646	−0.076	−0.305	−0.150	−1.864	−1.580	**−0.344**	−0.431	0.09
PWP	0.812	−0.365	2.368	1.886	0.415	0.150	−1.154	−0.080	0.892	−3.521	−0.065	**−2.268**	−0.93**

†SR: soil respiration (μmol s^{-1}), SOC: soil organic carbon (g kg^{-1}), K_{AL}: available K (g kg^{-1}). P_{AL}: available P (g kg^{-1}), C/N: ratio of total carbon/total nitrogen, AWCD: substrate utilization potential as average well color development, DH: dehydrogenase, UR: urease, H’: Shannon–Weaver index of the soil microbial community, F: fungi community, B: bacteria community, PAW: plant available water, PWP: permanent wilting point. ††Numbers in bold: direct effect, underlined numbers: dominant effect; * and **: least significant difference at $P < 0.05$ and $P < 0.01$, respectively.

al., 1992). Feedback mechanisms inhibited later enzyme activity due to inadequate supply of energy, as microbes reduced the available materials in residues and their secreted enzymes. On the other hand, some authors noted that residues did not increase enzyme activities (Esther et al., 2013).

The correlation coefficient is one of the most commonly used statistical tools for analyzing associations among different traits. However, practice shows that far too often it is misinterpreted or misunderstood (Kozak et al., 2012). Path analysis partitions each individual rY value into a basic direct effect and 11 indirect effects. The dominant

Table 11. Correlation matrix of investigated indices for the long-term no-tillage either without (NT-1) or with (NT-2) crop residue application.

Indices (x)[†]	Mean values	Correlation matrix											
		SR	SOC	K_{AL}	P_{AL}	C/N	AWCD	DH	UR	H’	F	B	PAW
NT-1 – no-tillage, residues removed													
SR	15.88	1.00											
SOC	21.84	0.87**	1.00										
K_{AL}	0.20	0.35*	–0.15	1.00									
P_{AL}	0.08	0.69*	0.24	0.92**	1.00								
C/N	10.24	–0.13	–0.11	–0.07	–0.11	1.00							
AWCD	0.58	0.86**	0.50*	0.78**	0.96**	–0.12	1.00						
DH	209.3	0.08	0.56*	–0.90**	–0.67*	0.01	–0.44*	1.00					
UR	75.63	0.41*	0.80**	–0.71*	–0.38*	–0.04	–0.12	0.94**	1.00				
H’	3.07	0.33*	–0.17	1.00**	0.91**	–0.06	0.77**	–0.91**	–0.73*	1.00			
F	55.43	–0.81**	–0.42*	–0.83**	–0.98**	0.12	–1.00**	0.52*	0.20	–0.82**	1.00		
B	5.94	–0.99**	–0.93**	–0.23	–0.59*	0.13	–0.79**	–0.20	–0.52*	–0.21	0.73*	1.00	
PAW	0.179	–0.73*	–0.34*	–0.83**	–0.95**	0.41*	–0.94**	0.55*	0.26	–0.82**	0.95**	0.65*	1.00
PWP	0.111	–0.90**	–1.00**	0.09	–0.30	0.11	–0.55*	–0.51*	–0.77**	0.11	0.48*	0.95**	0.40*
NT-2 – no-tillage, residues returned													
SR	13.19	1.00											
SOC	20.72	0.94**	1.00										
K_{AL}	0.20	–0.70*	–0.41*	1.00									
P_{AL}	0.14	–0.15	0.21	0.81**	1.00								
C/N	10.85	0.78**	0.75*	–0.52*	–0.07	1.00							
AWCD	0.56	0.21	–0.15	–0.84**	–1.00**	0.12	1.00						
DH	149.9	–0.48*	–0.14	0.96**	0.94**	–0.33*	–0.96**	1.00					
UR	79.18	0.17	0.50*	0.59*	0.95**	0.17	–0.93**	0.79**	1.00				
H’	3.03	0.28	–0.08	–0.88**	–0.99**	0.17	1.00**	–0.98**	–0.90**	1.00			
F	38.57	0.76**	0.48*	–1.00**	–0.76*	0.56*	0.80**	–0.94**	–0.52*	0.84**	1.00		
B	5.23	–0.81**	–0.56*	0.99**	0.69*	–0.61*	–0.74*	0.90**	0.44*	–0.78**	–1.00**	1.00	
PAW	0.179	0.90**	0.99**	–0.32	0.29	0.77**	–0.23	–0.05	0.57*	–0.16	0.40*	–0.48*	1.00
PWP	0.098	–0.63*	–0.86**	–0.11	–0.68*	–0.53*	0.63*	–0.38*	–0.87**	0.57*	0.03	0.06	–0.90**

[†]SR: soil respiration (µmol s^{-1}), SOC: soil organic carbon (g kg^{-1}), K_{AL}: available K (g kg^{-1}), P_{AL}: available P (g kg^{-1}), C/N: ratio of total carbon/total nitrogen, AWCD: substrate utilization potential as average well color development, DH: dehydrogenase, UR: urease, H’: Shannon–Weaver index of the soil microbial community, F: fungi community, B: bacteria community, PAW: plant available water, PWP: permanent wilting point; * and **: least significant difference at P < 0.05 and P < 0.01, respectively.

effect represents the strongest influence in the sum of the entire path connecting each individual soil property with SR.

In CT plots without residues (Tables 9 and 10), partitioning by path analysis demonstrated dominant direct effects of F (Pxy = –1.397) and UR (Pxy = 1.326) on SR. Furthermore, UR, acting as the dominant indirect factor, determined strength and direction of SR correlation with SOC ($r_{an}Px_ny$ = 1.281; r(Y) = 0.93), K_{AL} ($r_{an}Px_ny$ = –1.279; r(Y) = –0.99), C/N ($r_{an}Px_ny$ = 0.684; r(Y) = 0.55), AWCD

Table 12. Causal pathways among dependent variable (SR(rY) and independent variables (x) for the long-term no-tillage either without (NT-1) or with (NT-2) crop residue application.

Indices (x)†	Path coefficient ††												SR (rY)
	SOC	K_{AL}	P_{AL}	C/N	AWCD	DH	UR	H’	F	B	PAW	PWP	
NT-1 – no-tillage, residue removed													
SOC	**–0.023**	–0.009	0.537	0.002	–0.190	–0.051	0.159	0.002	–0.875	1.513	–0.021	–0.173	0.87**
K_{AL}	0.004	**0.059**	2.038	0.001	–0.300	0.082	–0.141	–0.013	–1.725	0.382	–0.052	0.016	0.35*
P_{AL}	–0.006	0.055	**2.212**	0.002	–0.369	0.060	–0.075	–0.012	–2.037	0.970	–0.060	–0.052	0.69*
C/N	0.002	–0.004	–0.235	**–0.019**	0.048	–0.001	–0.007	0.001	0.249	–0.213	0.026	0.019	–0.13
AWCD	–0.012	0.046	2.129	0.002	**–0.383**	0.040	–0.023	–0.010	–2.067	1.290	–0.059	–0.095	0.86**
DH	–0.013	–0.054	–1.477	0.000	0.169	**–0.090**	0.186	0.012	1.069	0.333	0.034	–0.088	0.08
UR	–0.019	–0.042	–0.844	0.001	0.045	–0.085	**0.198**	0.009	0.416	0.847	0.016	–0.133	0.41*
H’	0.004	0.059	2.019	0.001	–0.295	0.083	–0.144	**–0.013**	–1.700	0.348	–0.051	0.020	0.33*
F	0.010	–0.049	–2.172	–0.002	0.382	–0.047	0.040	0.010	**2.075**	–1.201	0.060	0.083	–0.81**
B	0.022	–0.014	–1.311	–0.002	0.302	0.018	–0.102	0.003	1.523	**–1.636**	0.041	0.164	–0.99**
PAW	0.008	–0.049	–2.093	–0.008	0.361	–0.049	0.051	0.010	1.973	–1.069	**0.063**	0.069	–0.73*
PWP	0.023	0.005	–0.669	–0.002	0.210	0.046	–0.151	–0.001	0.989	–1.549	0.025	**0.173**	–0.90**
NT-2 – no-tillage, residue returned													
SOC	**0.095**	0.020	0.175	0.011	0.005	0.028	0.123	0.000	0.487	0.148	–0.114	–0.042	0.94**
K_{AL}	–0.039	**–0.049**	0.667	–0.008	0.026	–0.193	0.144	0.000	–1.019	–0.262	0.037	–0.005	–0.70*
P_{AL}	0.020	–0.040	**0.826**	–0.001	0.031	–0.189	0.234	0.000	–0.775	–0.185	–0.034	–0.033	–0.15
C/N	0.071	0.025	–0.057	**0.015**	–0.004	0.067	0.043	0.000	0.574	0.162	–0.089	–0.026	0.78**
AWCD	–0.014	0.041	–0.824	0.002	**–0.031**	0.193	–0.228	0.000	0.815	0.196	0.027	0.031	0.21
DH	–0.013	–0.047	0.776	–0.005	0.030	**–0.201**	0.193	0.000	–0.957	–0.240	0.006	–0.019	–0.48*
UR	0.048	–0.029	0.786	0.003	0.029	–0.158	**0.246**	0.000	–0.533	–0.117	–0.066	–0.042	0.17
H’	–0.008	0.043	–0.819	0.003	–0.031	0.196	–0.221	**0.000**	0.857	0.209	0.019	0.028	0.28
F	0.045	0.049	–0.627	0.009	–0.025	0.188	–0.128	0.000	**1.022**	0.265	–0.046	0.002	0.76**
B	–0.053	–0.048	0.574	–0.009	0.023	–0.181	0.108	0.000	–1.018	**–0.266**	0.055	0.003	–0.81**
PAW	0.095	0.016	0.243	0.012	0.007	0.010	0.141	0.000	0.406	0.128	**–0.115**	–0.044	0.90**
PWP	–0.082	0.005	–0.559	–0.008	–0.020	0.077	–0.214	0.000	0.034	–0.016	0.103	**0.049**	–0.63*

†SR: soil respiration (μmol s^{-1}), SOC: soil organic carbon (g kg^{-1}), K_{AL}: available K (g kg^{-1}). P_{AL}: available P (g kg^{-1}), C/N: ratio of total carbon/total nitrogen, AWCD: substrate utilization potential as average well color development, DH: dehydrogenase, UR: urease, H’: Shannon–Weaver index of the soil microbial community, F: fungi community, B: bacteria community, PAW: plant available water, PWP: permanent wilting point. ††Numbers in bold: direct effect, underlined numbers: dominant effect; * and **: least significant difference at $P < 0.05$ and $P < 0.01$, respectively.

($r_{an}Px_ny$ = 1.306; r(Y) = 1.00), H’ ($r_{an}Px_ny$ = 1.313; r(Y) = 1.00), and PAW ($r_{an}Px_ny$ = 1.152; r(Y) = 0.91). F acting as the dominant indirect factor determined correlation strength of SR with P_{AL} ($r_{an}Px_ny$ = –1.202; r(Y) = –0.14), DH ($r_{an}Px_ny$ = 1.284; r(Y) = –0.72), B ($r_{an}Px_ny$ = –1.235; r(Y) = 0.77), and PWP ($r_{an}Px_ny$ = 1.391; r(Y) = –0.30). On the other hand, UR activity and F amount were significantly weakened by K_{AL} (r = –0.96 and r = –0.51, respectively; Table 9). Such integrated causal pathways in CT plots without residues under dry conditions determined SR with value 15.41 μmol s^{-1}. Based on the strength of direct effects, the main determinants of SR under dry conditions in CT without residues were UR (Pxy = –1.397) and F (Pxy = 1.326). Slightly weaker contributors to SR were P_{AL} (Pxy = 1.157), DH (Pxy = –0.347), and PAW (Pxy = 0.170).

In CT plots, residue returning significantly changed soil environment. There were registered distinct relationships among soil properties compared to CT without residues (Tables 9 and 10). Partitioning by path analysis demonstrated dominant direct effects of C/N ratio (Pxy = 3.697), F (Pxy = 2.929), and B (Pxy = 3.736) on SR. The C/N ratio, acting as a dominant indirect factor, negatively correlated with AWCD (r(Y) = –0.99) and weakened the AWCD contribution to SR ($r_{an}Px_ny$ = –3.672). C/N also negatively correlated with H' (r(Y) = –0.99) and reduced the H' influence on SR ($r_{an}Px_ny$ = –3.646). The relationship of C/N with F and B was also negative (r(Y) = –0.66 and r(Y) = –0.77, respectively). Correlation between C/N ratio and PAW was positive (r(Y) = 0.79), and the C/N contribution to the PAW effect on SR was also positive ($r_{an}Px_ny$ = 2.917). However, the entire path connecting PAW and SR was weak (r(Y) = 0.09). B, acting as a dominant indirect factor, determined strength and direction of SR correlation with SOC ($r_{an}Px_ny$ = –2.600; r(Y) = –1.00), K_{AL} ($r_{an}Px_ny$ = 3.715; r(Y) = 0.68), P_{AL} ($r_{an}Px_ny$ = –3.619; r(Y) = –0.57), DH ($r_{an}Px_ny$ = –2.398; r(Y) = –0.62), UR ($r_{an}Px_ny$ = –3.629; r(Y) = –0.89), and PWP ($r_{an}Px_ny$ = –3.521; r(Y) = –0.93). P_{AL} correlation with AWCD, H', and B was negative (r(Y) = –0.88, r(Y) = –0.84, and r(Y) = –0.97, respectively). The implication is that higher P_{AL} accumulation in the soil acted as a significant distorter for the effect of AWCD ($r_{an}Px_ny$ = –2.517), H' ($r_{an}Px_ny$ = –2.403), and B ($r_{an}Px_ny$ = –2.763) on SR. On the other hand, P_{AL} accumulation in the soil acted as a positive contributor to strengthening the UR and DH effects on SR ($r_{an}Px_ny$ = 2.516 and $r_{an}Px_ny$ = 1.633, respectively). Nevertheless, the sum of positive and negative effects determined the character of integrated causal pathways. This gave a summarized answer about the influence of CT with residue returning on SR under insufficient soil moisture. SR in this treatment under dry conditions was 29% higher than in CT treatment without residues. The main direct determinants of SR under dry conditions in CT with residues were B (Pxy = 3.736), C/N ratio (Pxy = 3.697), and F (Pxy = 2.929). Slightly weaker contributors to SR were P_{AL} (Pxy = 2.852), PWP (Pxy = –2.268), and UR (Pxy = –1.160).

In the NT plots without residues (Tables 11 and 12), partitioning by path analysis demonstrated dominant direct effects of P_{AL} (Pxy = 2.212) and B (Pxy = –1.636) on SR. P_{AL}, acting as a dominant indirect factor, determined strength and direction of SR correlation with K_{AL} ($r_{an}Px_ny$ = 2.038; r(Y) = 0.35), AWCD ($r_{an}Px_ny$ = 2.129; r(Y) = 0.86), DH ($r_{an}Px_ny$ = –1.477; r(Y) = 0.08), H' ($r_{an}Px_ny$ = 2.019; r(Y) = 0.33), F ($r_{an}Px_ny$ = –2.172; r(Y) = –0.81), and PAW ($r_{an}Px_ny$ = –2.093; r(Y) = –0.73). F acting as a dominant indirect factor determined correlation strength of SR with C/N ($r_{an}Px_ny$ = 0.249; r(Y) = –0.13). B acting as a dominant indirect force determined the strength and direction of SR correlation with SOC ($r_{an}Px_ny$ = 1.513; r(Y) = 0.87), UR ($r_{an}Px_ny$ = 0.847; r(Y) = 0.41), and PWP ($r_{an}Px_ny$ = –1.549; r(Y) = –0.90). Contrary to expectations, soil environment under dry conditions in NT without residues for SR was not superior to CT treatment without residues (Figure 4). AWCD and H', which represent soil microbial functional diversity, were significantly lower in NT than in CT. It is likely that the significant decrease in the catabolic capability of soil microbial communities after 13 years of NT practices was determined by the creation of new conditions for the development of antagonists and predators. It originated as a new active ecological medium. However, the relationship between AWCD and SR was strengthened by P_{AL} ($r_{an}Px_ny$ = 2.129), K_{AL} ($r_{an}Px_ny$ = 0.046), DH ($r_{an}Px_ny$ = 0.040), and B ($r_{an}Px_ny$ = 1.290). Therefore, the sum of the entire path connecting AWCD with SR was very high (r(Y) = 0.86). Functioning of UR, DH, and F were significantly higher in NT than in CT (Table 8); however, their contribution to SR was lower than in CT. We suppose that P_{AL} was the main cause of the contribution of UR and DH to SR being weak ($r_{an}Px_ny$ = –0.844; r(Y) = 0.41 and $r_{an}Px_ny$ = –1.477; r(Y) = 0.08, respectively) and contribution of F to SR being negative ($r_{an}Px_ny$ = –2.172; r(Y) = –0.81). Direct effect of SOC on SR was weak (Px_ny = –0.023), but integrated interactions among different soil properties determined a high SOC contribution to SR (r(Y) = 0.87). The main direct determinants to SR under dry conditions in NT without residues were P_{AL} (Pxy = 2.212) and B (Pxy = –1.636). F (Pxy = 2.075), UR (Pxy = 0.198), and PWP (Pxy = 0.173) acted slightly more weakly. All integrated causal pathways under dry conditions in NT without residues determined SR with the value of 15.88 µmol s^{-1}.

In NT plots, residue returning significantly changed the soil environment (Tables 11 and 12). Partitioning by path analysis demonstrated the dominant direct effects of P_{AL} (Pxy = 0.826) and F (Pxy = 1.022) on SR. P_{AL}, acting as a dominant indirect factor, weakened the correlation strength of SR with AWCD ($r_{an}Px_ny$ = –0.824; r(Y) = 0.21) and PWP ($r_{an}Px_ny$ = –0.559; r(Y) = –0.63) and influenced the effect of UR on SR ($r_{an}Px_ny$ = 0.786; r(Y) = 0.17). F, acting as a dominant indirect factor, determined the strength and direction of SR correlation with SOC ($r_{an}Px_ny$ = 0.487; r(Y) =094), K_{AL} ($r_{an}Px_ny$ = –1.019; r(Y) = –0.70), C/N ratio ($r_{an}Px_ny$ = 0.574; r(Y) = 0.78), DH ($r_{an}Px_ny$ = –0.957; r(Y) = –0.48), H' ($r_{an}Px_ny$ = 0.857; r(Y) = 0.28), B ($r_{an}Px_ny$ = –1.018; r(Y) = –0.81), and PAW ($r_{an}Px_ny$ = 0.406; r(Y) = 0.90). Under dry soil conditions residue returning did not act as a water saving factor. PAW remained the same as under NT with residues removed. The C/N ratio also remained unchanged. High P_{AL} accumulation in the soil acted as a significant distorter of microbial functional diversity. P_{AL} negatively correlated with AWCD and H' (r(Y) = –1.00 and r(Y) = –0.99, respectively) and weakened their influence on SR ($r_{an}Px_ny$ = –0.824 and $r_{an}Px_ny$ = –0.819, respectively). However, P_{AL} accumulation in the soil significantly enhanced UR (r(Y) = 0.95) and DH (r(Y) = –0.57) activity. UR and DH contribution to SR was also high and positive ($r_{an}Px_ny$ = 2.516 and $r_{an}Px_ny$ = 1.633, respectively). However, the entire path connecting DH and UR with SR revealed a negative effect of DH and insignificant effect of UR on SR. The leading direct determinants of SR under dry conditions in NT with residues were F (Pxy = 1.022) and P_{AL} (Pxy = 0.826). B (Pxy = –0.266), UR (Pxy = 0.246), DH (Pxy = –0.201), and PAW (Pxy = –0.115) demonstrated a weaker influence on SR. Eventually the integrated causal pathways determined a low total SR. In NT plots with residues returned, under dry conditions, SR was 17% lower than in NT treatment with residues removed.

4. Discussion

Climate change significantly influenced the character of crop growing season in Lithuania. In our environmental zone, NEM2, prolonged dry conditions in spring and early summer have become a new frequent intrusive phenomenon. Therefore, the data of our experiments show that the newly emerged soil environmental conditions under different soil management practices can not always be explained by universally accepted theories.

Long-term tillage and residue handling apparently affected the topsoil chemical properties and influenced the soil microbiological behavior. The positive impact of residue returning on soil C_{tot}, C/N ratio, and P_{AL} presented in the current study, agrees with the findings of Van Den Bossche et al. (2009). On the other hand, our results (averaged across tillage systems) on straw management's insignificant influence on SOC were in contrast to those of Malhi and Lemke (2007) and Lafond et al. (2009). However, we found that the character of SOC changes depending on combined effect of tillage and residues. SOC content in NT with residue returning was significantly lower, while in CT it was significantly higher compared to the plots with residues removed. In contrast to some theories (De-Shui et al., 2007), the influence of long-term residue returning was insignificant for K_{AL} in both CT and NT.

The influence of tillage and residues on soil vitality was not positive in all management systems. SR and microbiological functioning were associated with SOC and soil agrochemical properties. However, effects of SOC and agrochemical properties on SR in many cases were indirect and nondominant. Only the effect of P_{AL} was determined as direct and dominant on SR in NT. P_{AL} acted also indirectly. Indirect effect of P_{AL} was frequently asserted as a suppressive factor for microbial functional diversity and enzyme activity. These traits influenced the strength and direction of soil microbiological properties' contribution to SR, especially in treatments with returned residues. Thirukkumaran and Parkinson (2000) found that whenever a suppressive effect of P was detected, it was associated with higher P concentration. This supports the argument that the suppression in microbial indices could occur due to osmotic effects. In our field experiment the soil had a high P_{AL} content, especially in NT, because of the pronounced stratification (Feiza et al., 2011).

Traditionally, the prevailing opinion is that residues increase available water capacity, total porosity, and soil water retention (Mulumba and Lal, 2008). Our experimental results are different. We documented that the after-effect of CT with residue returning under prolonged dry conditions emerged as a factor that significantly deteriorated soil BD, TP, AP, FC, and PAW. In contrast to CT, residue returning in NT significantly reduced soil BD and FC, but TP, AP, and PAW remained unchanged. However, FC under NT with residue returning remained higher than in the other treatments. This means that the larger difference between FC and reduced PWP values still remains high and leaves the PAW unchanged. Such results could have occurred as a consequence of different distribution of soil macro-, mezzo-, and micropores. Various authors reported a reduction of primarily larger pores due to compaction (Schäffer et al., 2007; Dörner et al., 2010). This preferential loss of larger pores can potentially change some important soil ecological functions, such as the transmission and storage of water or microbial functioning (Ball et al., 1988). Direct drilling is often reported to increase the density and strength of the upper soil layers and affect their pore continuity and tortuosity (Schjønning and Rasmussen, 2000; Feiza et al., 2014).

In our experiment PAW was an observable contributor to soil vital processes, while PAW effect on SR under dry soil conditions was indirect and had no highly expressed causal effect. However, PAW, acting as a component in the entire path connecting PAW and SR, revealed a significant positive correlation with SR in CT-1 (r(Y) = 0.91; Table 10) and NT-2 (r(Y) = 0.90; Table 12), while correlation of these indices in NT-1 was negative (r(Y) = –0.73; Table 12) and in CT-2 was insignificant (r(Y) = 0.09; Table 10). Microbial functional diversity and enzyme activity responded even to slight changes in soil PAW. Significant correlations between soil microbiological properties and PAW demonstrated this response. These findings corresponded to the results of Singh and Malhi (2006).

It is known that only active microorganisms drive biogeochemical processes (Blagodatskaya and Kuzyakov, 2013). The relationships among different soil microbiological factors can contrast under different soil managements. Numerous authors noted the positive effects of conservation tillage on soil enzyme activities

(Melero et al., 2008; Jin et al., 2009; Gajda and Przewłoka, 2012), improvement of soil microbiological properties, and an increase in microbial activities (Madejon et al., 2007; Mohammadi, 2011). Residues also affect the organic matter content and soil microbial activity (Mungai et al., 2005). We determined that under dry soil conditions in the 0–10 cm soil layer, F in NT was higher than in CT. This result corresponds to the findings of Sipilä et al. (2012). CT-2 significantly increased H' compared to CT-1. This could be related to the uniform distribution of straw during soil disturbance and an increase in contact area between soil and residues. An increase in microbial population could also be triggered by an abundance of feeding substrate. On the other hand, less numerous F and B populations in NT-2 could reflect their reduced activity due to a higher nutrient availability. As Fontaine et al. (2011) suggest, fungi, as the predominant actors of cellulose decomposition, induce a priming effect (PE) and adjust their degradation activity to nutrient availability: PE is low when nutrient availability is high, and, in contrast, microbes release nutrients from SOM when nutrient availability is low. Additionally, we cannot ignore the negative influence of herbicides on microbial functioning. Nevertheless, AWCD in NT was 43% lower than in CT, and residue returning reduced AWCD by 22% compared to residue removal. Govaerts et al. (2007) also suggested that CT practice can produce higher AWCD. Traditionally, higher values of AWCD and H' occur both under NT practice compared to CT and for residue returning compared to residue removal (Helgason et al., 2010). As a result, soil disturbance was more influential on microbial properties than straw management. Theoretically, CT should promote the growth of B populations; however, we did not register significant differences in B. The higher AWCD under CT indicated that tillage created soil conditions with accessible compounds and feeding substrate. The lower AWCD and H' under NT can be related to the traditional concept of community development towards a more stable state (Griffiths et al., 2001). SR was closely related to AWCD only in the plots without residues (CT-1 and NT-1). NT influence on AWCD decrease and the increase of other biological parameters could be explained by the relation of microbial community metabolic profiles with microorganisms' potential to respond to substrates, while soil enzyme activities reflect the status of microbial metabolism in situ (Bending et al., 2004). Marschner et al. (2003) reported that long-term addition of organic amendments influenced the B community structure and correlated with enzyme activities. According to these authors, the functional redundancy of soil microorganisms as well as the long-term survival of adsorbed enzymes to soil particles is coupled with the use of assays that measure potential activity instead of actual activity. That suggests that changes in the microbial community structure do not necessarily lead to immediate changes in enzyme activities.

It could be summarized that in the Cambisol of the European NEM2 zone under dry soil conditions, the after-effects of different long-term tillage techniques with residue handling created different soil qualitative environments.

Long-term incorporation of residues into soil under CT significantly increased C_{tot}, SOC, P_{AL}, enzyme activity, and F content. However, soil physical quality significantly deteriorated. FC, PAW, and PWP significantly decreased as a result of water capacity reduction, primarily in meso- and micropores due to their possible clogging. Based on the strength of direct effects, the main direct determinants of SR under dry conditions were F, B, and C/N. Slightly weaker contributors to SR were P_{AL}, PWP, PAW, and UR; however, they acted as indirect factors sustaining the effects of each independent variable on SR. Nevertheless, integrated interactions among all investigated soil properties determined the highest SR compared to CT without residue and NT with and without residue returning.

Long-term spreading of residues on the soil surface under NT significantly increased C_{tot}, P_{AL}, and UR activity. However, values of the rest of the chemical, physical, and microbiological indices significantly decreased. Decrease in water capacity in mesopores (30 µm) and micropores (0.2 µm) demonstrated significant reduction in FC and PWP, while PAW remained unchanged compared to NT with residues removed. Main direct determinants of SR were primarily F and P_{AL}. Slightly weaker contributors to SR were B, DH, UR, and PAW, but they acted as indirect factors. Nevertheless, integrated interactions among all soil properties determined the lowest SR compared to the other treatments.

Our results suggest that long-term CT with residue returning created a soil environment that is more resistant to prolonged dry conditions than NT.

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