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Soil properties and crop yields as influenced by the frequency of straw incorporation in a rape-wheat-triticale rotation

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Abstract: Straw, particularly cereal straw, is a valuable by-product of crop production, which can be used for various purposes, e.g. as livestock feed and bedding or for making fuels, however it should primarily be retained on farmland in order to prevent soil organic matter (SOM) losses and thus to maintain or improve soil quality. The aim of this study was to analyze effects of the frequency of crop residues (straw) incorporation into the soil on the content of soil organic matter and on crop yields. There were the following experimental treatments: SR – straw of all crop in the rotation removed, S1 – straw of one crop per rotation incorporated, S2 – straw of two crops in the rotation incorporated, and S3 – straw of three crops incorporated into the soil (loamy sand). After 21 years of crop rotation with straw removal (SR) the SOM level in the soil slightly decreased to 14.4 g·kg^{-1} soil DM, compared to that in 1997 (14.6 g·kg^{-1}). However, when straw of one crop (rape) per rotation was incorporated (S1) the content of SOM increased to 15.0 g·kg^{-1} soil DM, and to 15.6 and 16.0 g·kg^{-1} in S2 and S3 treatments, respectively. Straw retention had also a beneficial effect on the content of labile fractions of SOM (hot water extractable C and N). Grain yields and yield components of wheat and triticale, and seed yields of rape in the SR treatment were not significantly different from those obtained in S1, S2 and S3 treatments.

Keywords: crop rotation, grain yield, soil organic matter, straw application

INTRODUCTION

Soil organic matter (SOM) is a key component of agricultural soils that contributes positively to soil physical, chemical and biological properties, and overall to soil fertility and sustainability [Blanchet *et al.* 2016; Kuś 2015; Reeves 1997]. SOM is a mixture of multiple compounds, from simple to very complex molecules, which differ in their stability. Labile fractions of SOM, such as POM (particulate organic matter), DOC (dissolved organic carbon), hot water extractable C and N, and microbial biomass C, are more sensitive to changes in agricultural practices than the total SOM and have been shown to have a primary role in numerous soil functions related to soil biological activity, productivity and resilience [Bongiorno *et al.* 2019; Doran, Parkins 1994; Ghani *et al.* 2003; Hazarika *et al.* 2009]. It is well known and documented that regular application of organic amendments (animal manures, green manures, composts, organic by-products) is one of the most important measures to maintain or increase organic matter (OM) stocks in arable soils [Diacono, Montemuro 2010; Kuś 2015; Reeves 1997; Wang *et al.* 2021]. Other agricultural practices that are also important in this respect include: (i) reduced tillage intensity, which restricts losses of soil organic C through its mineralisation, (ii) diversified crop rotations, particularly those including grass-legume leys rich in OM, and (iii) balanced mineral fertilisation, which increases both harvestable yields and crop residues, including straw [Blanchet *et al.* 2016; Lemke *et al.* 2010; Martyniuk *et al.* 2019; Nyborg *et al.* 1995; van Groenigen *et al.* 2011]. Straw, particularly cereal straw, is a valuable by-product of crop production, which can be used for various purposes, e.g. as livestock feed and bedding or for making fuels, however it should primarily be incorporated into the soil in order to prevent SOM losses and thus to maintain or improve soil fertility and crop productivity [Hazarika *et al.* 2009; Kuś 2015; Lemke *et al.* 2010; Smagacz 2003;

Wang *et al.* 2021]. Recent reviews and meta-analyses of the scientific literature have shown that crop residue retention on farmland exerts in general beneficial changes in SOM and crop yields, although the extent of these changes was site-specific and depended on farming systems, soil types and climatic conditions [Han *et al.* 2018; Hazarika *et al.* 2009; Raffa *at al.* 2015]. Such a meta-analyse made by Raffa *at al.* [2015] indicated that crop residue removal led to average soil organic carbon (SOC) contents that were 12 and 18% lower than in soils amended with crop residues in temperate and tropical climate, respectively. In similar comparisons wheat yields were on average 9% lower when straw residues were removed in tropical climates, but in temperate climates wheat grain yields were almost not affected by crop residues management. In Poland Siuta [1999] reported that already after four years of growing winter wheat in monoculture with yearly incorporation of 3 or 6 $Mg \cdot ha^{-1}$ of straw, the content SOM in the soil of these treatments significantly increased as compared to the control soil with straw removal, however grain yields were similar in all the treatments. As mentioned above, crop residues, especially cereal straw, can be used for various purposes and when used for off-farm production it would be important to establish how much straw can be removed from farmland without causing negative effects on soil quality, particularly on SOM levels. Based on results of a long-term experiment with wheat-fallow cropping systems on Charnozemic clay soil, Lemke *et al.* [2010] have shown that modest amounts of straw (22%) produced each cropping year could be removed without a measurable effect on soil C levels.

The study reported here was based on a long-term rotation of winter crops: oilseed rape-wheat-triticale with the following straw management treatments: straw of all crops removed versus straw of one, two or three crops incorporated into the soil, and the aim of this study was to find out how these treatments affected the status of soil organic matter (SOM) and crop yields.

MATERIALS AND METHODS

The long-term field experiment reported in this research was established in 1997 at the Grabów Experimental Station (lat: 51°21′ N; long: 21°40′ E). It belongs to the Institute of Soil Science and Plant Cultivation in Puławy, Poland. The soil at this site is of loamy sand texture (70% sand, 25% silt, 5% clay) and was classified as an Albic Luvisol [Deckers *et al.* (eds.) 1998]. Basic chemical characteristics of this soil at the beginning of the experiment are given in Table 1. The climate at the site is temperate with an average monthly rainfall and temperature shown in Table 2. In this experiment three winter crops: oilseed rape (*Brassica napus* L. var. *napus*), wheat (*Triticum aestivum* L.) and triticale (*Triticosecale* Wittm. ex A. Camus) were rotated since 1997 and all these crops were grown each year. There were the following experimental treatments: SR – straw of each crop in the rotation was removed after harvest, S1 – straw of one crop (rape) per rotation incorporated into the soil, S2 – straw of two crops (rape and wheat) in the rotation incorporated, and S3 – straw of three crops incorporated. Each treatment was randomly replicated four times in randomised blocks, making 48 plots in total (3 crops × 4 treatments × 4 replications), and the plots were 45 m^2 in size. After harvest, using a conventional plot combine, straw from all plots was collected separately for each plant, than chopped and redistributed evenly on the soil surface in all the plots. Oilseed rape plots received 3 $Mg \cdot ha^{-1}$ straw and cereals plots 5 $Mg \cdot ha^{-1}$ straw. Shortly before straw incorporation by disc harrowing to 8–10 cm depth, usually in the first ten days of August, each plot was treated with 80 $kg \cdot ha^{-1}$ of P_2O_5, as triple superphosphate (45% P_2O_5), and 120 $kg \cdot ha^{-1}$ of K_2O as potassium chloride (60% K_2O). At the same time 30 kg $N \cdot ha^{-1}$ in the form of ammonium nitrate (34% N) was applied in S2 and S3 to reduce soil N immobilisation during straw decomposition. In mid August deep ploughing to 25 cm depth on all plots was performed and shortly before sowing a power harrow with roller was used for seed-bed preparation. Oilseed rape was sown usually at the end of August at the rate of 4.0 kg (0.6 mln) seed per ha. Cereals were seeded at the end of September at the rates of about 4.5 mln $seed \cdot ha^{-1}$. Recently released commercial cultivars of the crops and general recommendations for plant protection in Poland were used throughout the experimental period. The following cultivars of oilseed rape: 'Monolit', 'Monolit', 'Chrobry', wheat: 'Sailor', 'Desamo', 'Memory', and triticale: 'Trismart', 'Meloman', 'Trefl' were grown in 2017, 2018 and 2019, respectively. Oilseed rape was fertilised with 150 kg $N \cdot ha^{-1}$ (100 kg in the spring at the start of vegetation + 50 kg at stem elongation (BBCH[1] 50–52), while wheat and triticale were treated with 90 kg $N \cdot ha^{-1}$ (60 kg in the spring at the start of vegetation + 30 kg at stem elongation (BBCH 32–33). After harvest, cereal grain yields and selected yield components were determined and in the case of oilseed rape seed yields were measured only.

Table 1. Soil organic matter (SOM) levels, pH and macronutrients contents in the soil at the start of the experiment (1997) and in 2018 as influenced by straw management in a long-term rotation: rape-wheat-triticale

Straw management	SOM ($g \cdot kg^{-1}$ soil DM)	pH (KCl)	P_2O_5	K_2O	Mg	N_{min}
			($mg \cdot kg^{-1}$ soil DM)			
1997						
Initial values	14.6	6.2	160	124	49	nd
2018						
SR	14.4	5.0	120	148	24	7.35
S1	15.0	5.0	119	163	24	7.38
S2	15.7	5.1	118	160	27	9.06
S3	16.2	5.0	117	158	24	8.27
LSD $p \geq 0.05$	1.64	0.09	ns	ns	2.5	ns

Explanations: SR = straw removed, S1 = straw of one crop incorporated, S2 = straw of two crops incorporated, S3 = straw of three crops incorporated, *LSD* = least significant difference for the data in 2018, *p* = probability, ns = not significant, nd = not determined.
Source: own study.

[1] BBCH is derived from the Biologische Bundesanstalt, Bundessortenamt and CHemical industry and is the system used for uniform coding of phenologically similar growth stages of all mono- and dicotyledonous plant species.

Table 2. Monthly mean air temperature and sum of precipitation in the research period and multiyear values 1976–2019 reported by the Grabów Meteorological Station

Month	Temperature (°C)				Precipitation (mm)			
	2016/2017	2017/2018	2018/2019	1976/2019	2016/2017	2017/2018	2018/2019	1976/2019
IX	15.7	14.0	15.4	13.3	20.7	102.7	50.6	61.5
X	7.5	9.6	9.9	8.4	86.7	85.5	50.1	44.6
XI	2.8	4.2	3.8	3.3	31.8	47.4	6.7	38.6
XII	0.6	2.0	0.7	–0.5	65.1	40.6	56.7	37.7
I	–4.9	0.3	–2.4	–2.5	3.2	16.9	33.2	31.7
II	–0.8	–4.0	2.5	–1.5	38.4	11.9	19.7	27.6
III	5.7	–0.2	5.4	2.3	34.8	20.3	22.2	37.7
IV	7.4	13.3	9.8	8.4	69.1	19.4	37.5	43.3
V	13.9	16.8	13.0	13.8	34.5	97.3	51.5	66.2
VI	18.1	18.7	21.9	17.0	32.5	44.6	51.2	76.8
VII	18.5	20.3	18.6	18.7	86.4	109.4	20.2	87.0
VIII	19.7	20.3	20.1	18.2	55.3	71.3	69.8	75.1

Source: own study.

In 2018 after harvesting of the crops, the soil was sampled to determine changes in SOM and other soil properties. Soil samples (ten per plot) were taken between stubble rows from the plough layer (0–25 cm) using a soil corer (30 mm internal diameter). Field moist soil samples were passed through a sieve with 2 mm openings, air dried and stored at room temperature. Determinations of: C org. (PN-ISO 14235), N min. (CFP – PN-EN ISO 11732), exchangeable P, K and Mg (extracted with 1.0 M ammonium acetate and measured by AAS) and soil pH (potentiometerically in 1:2.5 suspension of soil in 1 M KCl [ISO 10390:2005]) were performed by the certified chemical laboratory of the Institute of Soil Science and Plant Cultivation in Puławy, Poland. The contents of SOM were calculated as follows: C org.·1.724 [Ostrowska *at al.* 1991].

To prepare hot water extracts (80°C), soil samples equivalent to 5 g soil dry matter (DM), were weighed in triplicate into 50 cm^3 centrifuge tubes, mixed with 25 cm^3 of distilled water and further treated as described by Ghani *et al.* [2003]. An automated N/C Analyzer (Multi N/C 2100, Analytik Jena, Germany) was used to measure C and N contents in hot water extracts (hwe-C, hwe-N).

The data were subjected to the analysis of variance (ANOVA) using the FR-ANALWAR software based on Microsoft Excel, with significance of differences assessed by Tukey test at $p \leq 0.05$.

RESULTS AND DISCUSSION

In 1997 the soil in the experimental field contained 14.6 $g \cdot kg^{-1}$ of organic matter (OM) and after 21 years of growing winter crops (oilseed rape-wheat-triticale) with straw removal (SR) the SOM level in this soil slightly decreased to 14.4 $g \cdot kg^{-1}$ soil DM (Tab. 1). However, when straw of one crop (rape) per rotation was incorporated into the soil (S1) the content of SOM increased to 15.0 $g \cdot kg^{-1}$ soil DM. Markedly higher amounts of SOM accumulated in the soil when the straw of wheat and triticale was also incorporated by ploughing, 15.7 and 16.2 $g \cdot kg^{-1}$ soil DM in S2 and S3 treatments respectively, but only in the case of S3 was the increase statistically significant compared to the SR treatment (Tab. 1). These results are consistent with those of earlier studies, showing that straw retained on the soil surface or incorporated into the soil increased SOM accumulation [Diacono, Montemuro 2010; Han *et al.* 2018; Laird, Chang 2013; Siuta 1999; van Groenigen *et al.* 2011]. However, there are also reports showing that SOM contents in conventionally tilled soils under corn or cereal monocultures were not affected by crop residues management (removal vs retention) [Lemke *et al.* 2010; Wang, Dalal 2006].

In Poland, the EU countries and in many regions of the world with intensive arable farming systems, crops are mainly grown in short rotations focusing principally on market crops, especially cereals [EU (DGENV) 2010; Leff *et al.* 2004], and also in this study the crops were grown for more than 20 years in such a short 3-years rotation. The results obtained under the conditions of this experiment have shown that the retention and incorporation of the straw of one crop per rotation prevented SOM losses, or even allowed for a modest SOM accumulation in the soil (Tab. 1). This finding is also important for practical agriculture as it indicates that straw of cereals grown in such a rotation could be collected and used by farmers for other purposes, e.g. as energy sources or animal bedding, without a risk of the deterioration of soil quality, particularly with respect to the SOM content.

Figure 1 shows that the amounts of hot water extractable C and N (hwe-C and hwe-N) in the soil of S1, S2 and S3 treatments were significantly higher, with the exception of hwe-N in S1 and S2, than those in the soil of the control treatment (SR, straw removed), proving that straw incorporation, irrespective of its frequency, beneficially affects not only the total SOM (Tab. 1), but also labile fractions of SOM, such as those assessed in this study (hwe-C and hwe-N). These fractions have been shown to be highly informative about changes in SOM, transformation of nutrients and activity of microorganisms in soils, and are often

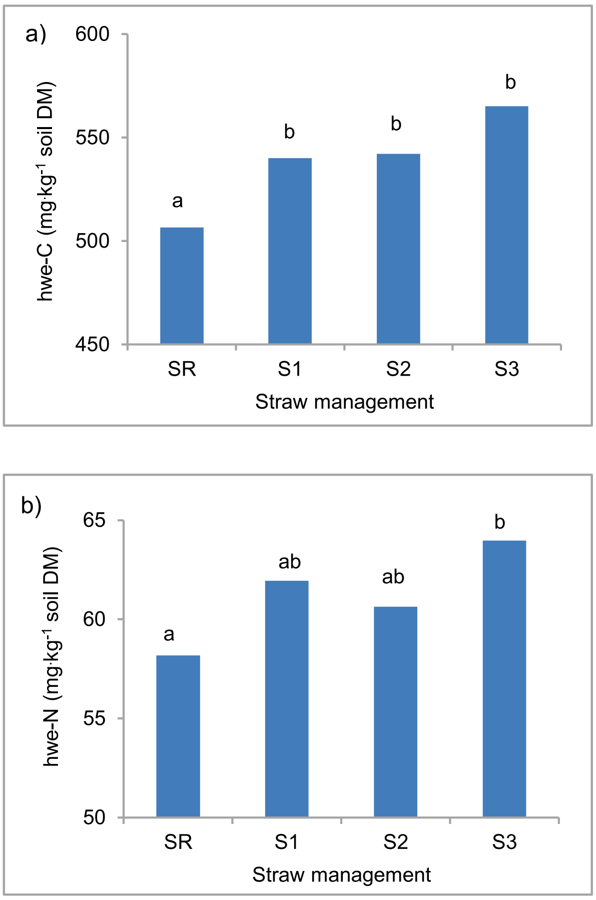

Fig. 1. Contents of carbon (A) and nitrogen (B) in hot water extracts (hwe) from soil as influenced by straw management in a long-term rotation: rape-wheat-triticale; SR = straw removed, S1 = straw of one crop incorporated, S2 = straw of two crops incorporated, S3 = straw of three crops incorporated; a, b = values with the same letters are not significantly different ($p \geq 0.05$); source: own study

used as indicators of various soil functions, such as C sequestration, nutrient cycling and soil fertility [Bongiorno *et al.* 2019; Ghani *et al.* 2003; Hazarika *et al.* 2009].

The experimental factors used in our field trial did not change significantly the content of basic plant nutrients in the soil, with the exception of Mg^{2+}, the amount of which was significantly greater in the S2 treatment then in all other treatments (Tab. 1). In comparison with the contents of these nutrients in the soil at the beginning of the experiment (1997), the amounts of phosphorus (P_2O_5) and magnesium (Mg^{2+}) measured in 2018 were lower, but those of potassium (K_2O) were greater. Such a comparison made for soil pH clearly indicates that the values of this parameter determined in 2018 for all the treatments were markedly lower than the pH of the soil in 1997 (Tab. 1). The main cause for this decrease was probably connected with fertilisation of the crops with relatively high doses of mineral N fertilisers. In this experiment no soil liming was applied to show soil buffering properties of crop residues, as the results of previous laboratory and pot experiments indicated that soil amendments with various plant materials increased soil pH [Yan, Shubert 2000]. However, under field conditions in Australia no such a liming effect of wheat residues retention was found in a long-term crop rotation, and in this study a strong soil acidification due to N fertilisation was also shown [Xu *et al.* 2002]. These findings are therefore in line with those reported here.

The largest grain yields of wheat were obtained in 2017 and the lowest in 2019 (Tab. 3). We attribute this variation to different yield potentials of wheat cultivars grown in particular years, rather than to differences in weather conditions, which were in general favourable for the crops during the experimental period 2017–2019 (Tab. 2). Grain yields and yield components of wheat and triticale, and seed yields of rape grown on the plots with straw removal (SR) were not significantly different from those obtained on the plots with various frequencies of straw incorporation: S1 – once per rotation, S2 – twice in rotation and 3 – three times in rotation (Fig. 2, Tab. 3). Only in the case of oilseed rape (Fig. 2)

Table 3. Grain yields and yield components of winter wheat and triticale as influenced by straw management in a long-term rotation: rape-wheat-triticale

Straw management	Winter wheat			Winter triticale		
	2017	2018	2019	2017	2018	2019
Grain yield ($Mg \cdot ha^{-1}$)						
SR	10.4 [a]	9.4 [a]	8.0 [a]	8.0 [a]	7.6 [a]	8.0 [a]
S1	10.0 [a]	9.8 [a]	8.3 [a]	7.8 [a]	8.2 [a]	8.3 [a]
S2	10.1 [a]	9.0 [a]	8.8 [a]	8.1 [a]	8.1 [a]	8.0 [a]
S3	10.5 [a]	8.7 [a]	8.0 [a]	8.2 [a]	8.7 [a]	8.2 [a]
Ear number ($pcs. \cdot m^{-2}$)						
SR	576 [a]	418 [a]	698 [a]	432 [a]	416 [a]	460 [a]
S1	574 [a]	420 [a]	574 [a]	446 [a]	372 [a]	482 [a]
S2	534 [a]	403 [a]	674 [a]	415 [a]	422 [a]	455 [a]
S3	577 [a]	422 [a]	632 [a]	470 [a]	391 [a]	483 [a]
Thousand grain yield (g)						
SR	43.2 [a]	44.2 [a]	34.8 [a]	46.2 [a]	52.2 [a]	40.2 [a]
S1	43.0 [a]	43.5 [a]	33.3 [a]	43.8 [a]	52.1 [a]	39.0 [a]
S2	43.6 [a]	44.1 [a]	33.6 [a]	45.7 [a]	51.6 [a]	40.0 [a]
S3	43.9 [a]	44.0 [a]	33.3 [a]	45.6 [a]	53.6 [a]	40.5 [a]

Explanations: SR = straw removed, S1 = straw of one crop incorporated, S2 = straw of two crops incorporated, S3 = straw of three crops incorporated, a = numbers within the columns with the same letter do not differ significantly.
Source: own study.

Fig. 2. Mean (2017–2019) seed yields of winter oilseed rape as influenced by straw management in a long-term rotation: rape-wheat-triticale; SR, S1, S2, S3 as in Fig. 1; a = numbers with the same letter do not differ significantly; source: own study

and triticale in 2018 (Tab. 3) the yields of these crops tend to increase with an improvement of SOM levels due to the increasing frequency of straw incorporation into the soil. In this experiment the crops in all treatments received the same adequate NPK fertilisation which allowed for a proper plant performance in all the treatments, irrespective of the straw management. No significant effects of crop residue incorporation into the soil on crop yields under various climatic conditions were also found in other studies [Blanchet *et al.* 2016; Raffa *at al.* 2015; Siuta 1999], although in general reported effects are inconsistent and range from yield decreases [Graham *et al.* 1986; Nyborg *et al.* 1995] to substantial yield improvements [Han *et al.* 2018; Raffa *at al.* 2015] due to repeated straw incorporation in cereal-dominated cropping systems.

CONCLUSIONS

After 21 years of growing winter crop in a rotation (oilseed rape-wheat-triticale) with straw removal, the content SOM in the soil slightly decreased to 14.4 g·kg^{-1} soil DM, compared to that in 1997 (14.6 g·kg^{-1}). However, when straw of one crop (rape) per rotation was incorporated into the soil, the content of SOM increased to 15.0 g·kg^{-1} soil DM. Markedly higher amounts of SOM accumulated in the soil when the straw of wheat and triticale was also incorporated by ploughing. The results obtained in this experiment indicated that the retention and incorporation of the straw of one crop per rotation prevented SOM losses, or even allowed for a modest SOM accumulation in the soil under a 3-year crop rotation. This finding seems to be important for practical agriculture, as it indicates that straw of cereals grown in such a rotation could be collected and used by farmers for other purposes, e.g. as energy sources or animal bedding, without a risk of the deterioration of soil quality, particularly with respect to the SOM content. The experimental treatments had no significant effect on crop yields.

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