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RESEARCH ARTICLE

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Production efficiency of different crop rotations and tillage systems

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Abstract

Aim of study: The production efficiency of crop rotations was evaluated based on the yield of the main crop (cereal grains and pea seeds) and yield of the by-product (straw) converted per cereal units (CU), and on total protein yield.

Area of study: South-eastern Poland, Europe (2017-2019).

Material and methods: The first order experimental factor included crop rotations: A): peas–durum wheat–spring barley; B): spring wheat–durum wheat–spring barley +oats; and C): spring barley–durum wheat–spring wheat. The second order experimental factor included tillage systems: CT, conventional tillage, RT, reduced tillage, and NT, no-tillage.

Main results: The yield of pea seeds, cereal grains, and straw per CU was higher in crop rotation A than B (127.8 CU vs. 101.1 CU). Higher CU yields were also recorded in crop rotation C than B (by 18.9 CU). The tillage system had no effect on CU yield. The total protein yield was significantly higher in crop rotation A (2110.7 kg ha^{-1}) than in crop rotations B (by 808.8 kg ha^{-1}) and C (by 448.0 kg ha^{-1}). A higher protein yield was also recorded in RT than in the NT system.

Research highlights: The units used for CR assessment, *i.e.* CU and total protein yield, enable to reliably evaluate the production yield of both CRs and tillage systems.

Additional key words: cereal unit; total protein yield; cropping system; soil tillage.

Abbreviations used: CR (crop rotation); CT (conventional tillage); CU (cereal units); NT (no-tillage); RT (reduced tillage); TS (tillage systems)

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Introduction

Crop rotation (CR) is defined as the naturally and economically justifiable sequence of different plant species planned for specific years and farm fields (Montemurro & Maiorana, 2014; Woźniak *et al.*, 2019). Its task is to maintain soil fertility, reduce weed infestation, reduce the occurrence of diseases and pests, and ensure stable yields (Sharma *et al.*, 2009; Kunzová, 2013; Woźniak, 2019a). CR integrates all agrotechnical practices in the field, *i.e.* tillage, fertilization, as well as protection and care of plants (Karlen *et al.*, 1994). Cultivation of plants in CR has a range of beneficial effects such as: it gives stable and high yields (Woźniak, 2019a), reduces the costs of purchasing production means (Wijnands, 1997; Haliniarz *et al.*, 2018; Woźniak *et al.*, 2019), improve the biological and enzymatic activity of the soil, increases biomass and organic carbon content in the soil (Francaviglia *et al.*, 2019; Woźniak, 2019b), ensures plant health and low weed infestation (Struik & Bonciarelli, 1997; Roldán *et al.*, 2005; Chauhan *et al.*, 2012). The assessment of CR also takes into account organizational effects relating to labor-consumption, demand for machinery and tools, and also energy effects related to the energy inputs of the means of production and the energy value of the produced crop. CRs are also evaluated in terms of cereal unit yields per CR area unit, converting the main yield (seed, grain, tuber, root) and by-product yield (straw, leaves, stems) into cereal units (Brankatschk & Finkbeiner, 2014, 2017; Henryson *et al.*, 2019; Journal of Laws of the Republic of Poland, 2019). The cereal unit (CU) is suggested to underlie a new approach to the allocation for agriculture (Brankatschk & Finkbeiner, 2014). It has been used for decades as a common denominator in German agricultural statistics and is mainly based on the nutritional value provided to farm animals. This unit also includes by-products not intended for animal feedstuffs. More than 200 items specified in CU have been provided for plant and animal products and by-products generated during their processing (Brankatschk & Finkbeiner, 2014).

Plant production efficiency is also influenced by the adopted tillage system (Zikeli *et al.*, 2013; Montemurro & Maiorana, 2015; Woźniak & Soroka, 2018). Generally, it can be stated that in warm and arid regions the best production results are obtained in the no-tillage cultivation system, while in moderately moist regions better results are obtained in the conventional ploughing system (De Vita *et al.*, 2007; Lahmar, 2010; Gruber *et al.*, 2012). Soil cultivation affects its physical, chemical, and biological properties (Triplett & Dick, 2008; Woźniak, 2019b). Cultivation without using a plow increases the content of organic carbon, total nitrogen and nutrients in the soil compared to the conventional ploughing system (Baker *et al.*, 2007; Ernst & Emmerling, 2009; Cheng *et al.*, 2013; Zhang *et al.*, 2014; Dua *et al.*, 2017; Woźniak, 2019b). The NT system protects the soil against erosion and water loss as well as stabilizes its structure (Jordan *et al.*, 2000; Madari *et al.*, 2005; Celik *et al.*, 2012). It also increases the number of earthworms and soil biological activity (Tabaglio *et al.*, 2008; Laossi *et al.*, 2010; Woźniak & Soroka, 2018). The ploughless cultivation systems, especially the NT system, are inseparably associated with the use of non-selective herbicides with a total spectrum of activity, which may adversely affect the agro-ecosystem and increase production costs (Boyette *et al.*, 2008; Kalia & Gosal, 2011; Haliniarz *et al.*, 2018; Woźniak & Rachoń, 2019).

Based on the presented literature and previous research, it can be hypothesized that the best production effects expressed in CU and protein yield in the regions with moderate rainfalls can be obtained using CR with the participation of legumes and conventional tillage (CT) system. The aim of this study was to assess the production efficiency of different CRs and tillage systems expressed in cereal units and protein yield.

Material and methods

Location and scheme of the experiment

A strict field experimental design was carried out in the years 2017-2019 at the Uhrusk Experimental Farm (south-eastern Poland, 51°18'N, 23°36'E) belonging to the University of Life Sciences in Lublin. A split-plot experimental design (25 m × 6 m) with three replications was adopted. The first order experimental factor included CR, and the second order experimental factor included tillage systems (TS). CRs were based on the succession of the following crops: A): peas–durum wheat–spring barley; B): spring wheat–durum wheat–spring barley +oats; and C): spring barley–durum wheat–spring wheat. The following tillage systems were used in each crop rotation: CT, conventional, RT, reduced, and NT, no-tillage. In the CT system, shallow ploughing (at a depth of 10-12 cm) with harrowing were used under each plant after previous crop harvest, and pre-winter ploughing (25 cm) at the end of October. In the RT system, a cultivator set was used after previous crop harvest, whereas in the NT system glyphosate (4 L ha^{-1}, 360 g L^{-1}) was applied on the stubble field. In the springtime, a cultivation set comprising a cultivator, a string roller, and a harrow was used on all plots.

Crop management

The sowing density of peas (*Pisum sativum* L.) cv. 'Tarchalska' was 100 seeds m^{-2}. Fertilization before sowing included: 20 kg N ha^{-1}, 32 kg P ha^{-1}, and 65 kg K ha^{-1}. The sowing density of durum wheat (*Triticum durum* Desf.) cv. 'Duromax' was 500 seeds m^{-2}. Phosphorus-based (34 kg P ha^{-1}) and potassium-based (90 kg K ha^{-1}) fertilizers were used in the springtime before sowing, whereas nitrogen-based fertilizers (120 kg N ha^{-1} in total) were applied in the following terms: 50 kg N ha^{-1} before sowing, 30 kg N ha^{-1} at the tillering stage (23-24 in the BBCH scale), 20 kg N ha^{-1} at the shooting stage (34-35 BBCH), and 20 kg N ha^{-1} at the ear formation stage (52-53 BBCH) (BBCH Working Group, 2001). The sowing density of spring wheat (*Triticum aestivum* L.) cv. 'Sonett' was 450 seeds m^{-2}. Phosphorus-based (34 kg P ha^{-1}) and potassium-based (90 kg K ha^{-1}) fertilizers were used in the springtime before sowing, whereas nitrogen-based fertilizers (140 kg N ha^{-1} in total) were applied in the following terms: 50 kg N ha^{-1} before sowing, 40 kg N ha^{-1} at the tillering stage (23-24 in the BBCH scale), 30 kg N ha^{-1} at the shooting stage (34-35 BBCH), and 20 kg N ha^{-1} at the ear formation stage (52-53 BBCH). Spring barley (*Hordeum vulgare* L.) cv. 'Tocada' was sown at the density of 320 seeds m^{-2}. Nitrogen-based (90 kg N ha^{-1}) fertilizers were used at the following doses and terms: 60 kg N ha^{-1} before sowing and 30 kg N ha^{-1} at the tillering stage (23-24 BBCH). Phosphorus-based (30 kg P ha^{-1}) and potassium-based (80 kg K ha^{-1}) fertilizers were used before barley had been sown. Fertilization applied under a mix of spring barley (170 seeds m^{-2}) and oats (*Avena sativa* L.) cv. 'Furman' (200 seeds m^{-2}) included: 50 kg N ha^{-1} before sowing and 30 kg N ha^{-1} at the shooting stage (34-35 BBCH), as well as phosphorus-based (34 kg P ha^{-1}) and potassium-based (90 kg K ha^{-1}) fertilizers before sowing. In each study year, peas and cereals were sown in the first week of April.

Soil and weather conditions

The experiment was established on the sandy-clay soil classified as Rendzic Phaeozem. This soil type is rich in available phosphorus, potassium, and magnesium. The mineral fraction distribution and contents of nutrients in the soil are provided in Table 1.

The growing season at the study area starts in the second half of March and lasts 210-215 days on average. The course of weather conditions in the study years is presented in Fig. 1. The annual sums of precipitation ranged from 413 mm to 661 mm. The highest monthly sums were recorded in May (71 mm on average), June (70 mm), and July (82 mm), whereas the lowest ones in December (25 mm), January (31 mm), and February (29 mm). The average annual air temperatures ranged from 8.9°C to 9.6°C. The highest average daily air temperatures were recorded in June (19.5°C), July (19.8°C), and August (20.3°C), whereas the lowest ones in December (0.3°C), January (-3.0°C), and February (-1.3 °C).

Production traits and statistical analysis

The production efficiency of CR was evaluated based on the main yield (yield of cereal grains and pea seeds) and by-product yield (yield of straw) converted into CUs (Brankatschk & Finkbeiner, 2014), and on total protein yield (kg ha^{-1}) (Woźniak, 2016). The coefficients of yield conversion into CU were adopted after the Journal of Laws of the Republic of Poland (2019) assuming that: 100 kg pea seeds = 1.46 CU, 100 kg wheat grain = 1.00 CU, 100 kg barley grain = 0.90 CU, 100 kg cereal mix grain = 0.84 CU, 100 kg cereal straw = 0.10 CU, and 100 kg pea straw = 0.25 CU. The content of nitrogen in cereal grains and pea seeds was determined with the Kjeldahl's method using a conversion factor of N × 6.25.

Results were subjected to analysis of variance (ANOVA) method, whereas the significance of differences between mean values obtained for CRs and tillage systems were evaluated with the HSD Tukey's test at a significance level of p<0.05.

Table 1. Physicochemical properties of soil (in the 0-25 cm layer).

Specification	Value
Sand: 2.0-0.05 mm (%)	51
Silt: 0.05-0.002 mm (%)	25
Clay: <0.002 mm (%)	24
P (mg kg^{-1})	146
K (mg kg^{-1})	270
Mg (mg kg^{-1})	64
Total N (g kg^{-1})	0.91
Organic C (g kg^{-1})	8.19
pH_{KCl}	6.1

Results

Cereal unit yield

The yield of CUs was significantly higher in crop rotations A (127.8 CU) and C (120.0 CU) than in crop rotation B, *i.e.*, by 26.7 CU and 18.9 CU, respectively (Table 2). It was also differentiated by the tillage systems, with a higher number of CUs produced by crops in the RT than in the NT system. Significant differences in CU yield were also due to the CR × TS interaction. In crop rotation A, a higher number of CUs was produced by the crops grown in the RT than in CT and NT systems; in crop rotation B, by these grown in NT and RT systems than by these cultivated in the CT system; whereas in crop rotation C, by crops grown in CT and RT systems compared to these from NT system. In crop rotation A, more CUs were produced by peas than by durum wheat and spring wheat. Besides, a higher pea yield was demonstrated in RT than

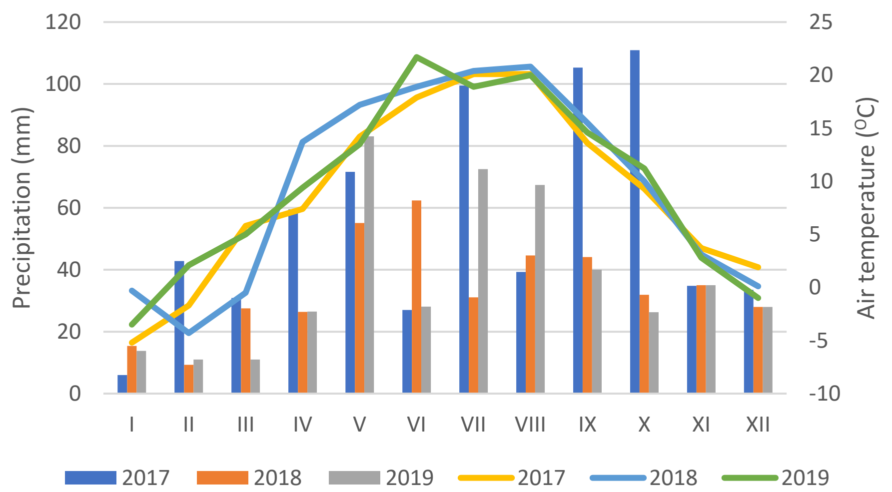


Figure 1. Monthly sums of precipitation and average air temperatures at the Uhrusk Experimental Station.

Table 2. Combined effects of crop rotation (CR) and tillage system (TS) on main yield and by-product yield in cereal units per hectare (average of 2017-2019), and analysis of variance.

Crop rotation [1]	Tillage systems [2]			Mean
	CT	RT	NT	
A: p-dw-sb	126.7[a]	132.0[b]	124.8[a]	127.8[A]
B: sw-dw-sb+o	95.3[a]	103.3[b]	104.7[b]	101.1[B]
C: sb-dw-sw	125.7[a]	123.2[a]	111.1[b]	120.0[A]
Mean	115.9[ab]	119.5[a]	113.5[b]	-
Value	**CR**	**TS**	**CR × TS**	
F	4818.1	30.3	312.6	
p	<0.01	<0.05	<0.01	

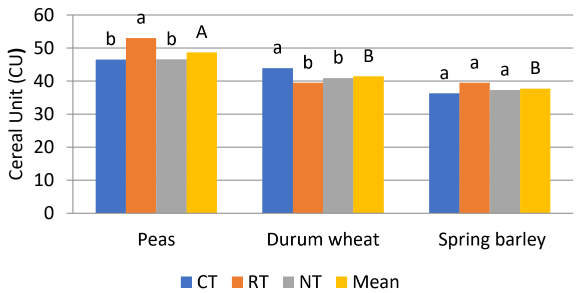
[1]p: peas. dw: durum wheat. sb: spring barley. sw: spring wheat. o: oats. [2]CT: conventional tillage; RT: reduced tillage; NT: no-tillage. Mean values in rows with the same lower case letters do not differ significantly, $p<0.05$. Mean values in columns with the same upper case letters do not differ significantly, $p<0.05$.

in CT and NT systems. In turn, durum wheat produced more CUs when grown in the CT system, whereas spring wheat produced similar numbers of CUs in all tillage systems (Fig. 2A). In crop rotation B, similar CU yields were produced by spring wheat, durum wheat, and spring barley + oats mix (Fig. 2B). In this crop rotation, more CUs were produced by spring wheat in CT and RT than in NT system, by durum wheat in RT than in NT system, and by spring barley + oats in NT than in CT and RT systems. In crop rotation C, a significantly higher number of cereal units was produced by spring barley than by durum wheat and spring wheat (Fig. 2C). In this CR, the yields of spring barley and spring wheat were similar in all tillage systems, whereas durum wheat produced a significantly higher number of CUs in CT and RT than in NT system.

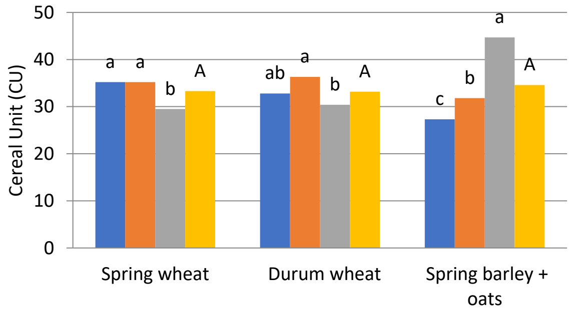
The variance analysis components indicate that the CU yield was mainly determined by the CR and to a lesser extent by its interaction with tillage systems (Table 2).

Total protein yield

The total protein yield was higher in crop rotation A (2110.7 kg ha^{-1}) than in crop rotations C and B by 448 kg ha^{-1} and 808.8 kg ha^{-1}, respectively (Table 3). Significant differences were also found between crop rotations C and B. The total protein yield was also differentiated by tillage systems, with its higher value determined in RT than in NT system. The evaluation of variance analysis components indicates that this production trait was affected to a greater extent by CR than by tillage system (Table 3). In crop rotation A, a significantly higher protein yield was produced by peas than by durum wheat and spring barley (Fig. 3A). In this CR, more protein was produced in RT than in CT and NT systems. Protein yield produced by



A)



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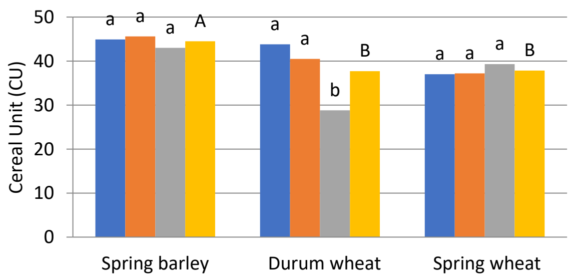

C)

Figure 2. Main yield and by-product yield in cereal units per hectare in crop rotations A, B and C. Different letters above the histogram bars indicate significant differences between mean values ($p<0.05$).

Table 3. Combined effects of crop rotation (CR) and tillage system (TS) on total protein yield in kg per hectare, and analysis of variance.

Crop rotation [1]	Tillage systems [2]			Mean
	CT	RT	NT	
A: p-dw-sb	2071.4^{a}	2210.6^{b}	2050.1^{a}	2110.7^{A}
B: sw-dw-sb+o	1235.4^{a}	$1330.^{1b}$	1340.0^{b}	1301.9^{B}
C: sb-dw-sw	1740.1^{a}	1701.9^{a}	1545.9^{b}	1662.7^{C}
Mean	1682.3^{ab}	1747.5^{a}	1645.3^{b}	-
Value	**CR[1]**	**TS**	**CR × TS**	
F	16046.1	261.6	219.7	
p	<0.01	<0.01	<0.01	

[1] p: peas. dw: durum wheat. sb: spring barley. sw: spring wheat. o: oats. [2] CT: conventional tillage; RT: reduced tillage; NT: no-tillage. Mean values in rows denoted with the same lower case letters do not differ significantly, $p<0.05$. Mean values in column denoted with the same upper case letters do not differ significantly, $p<0.05$.

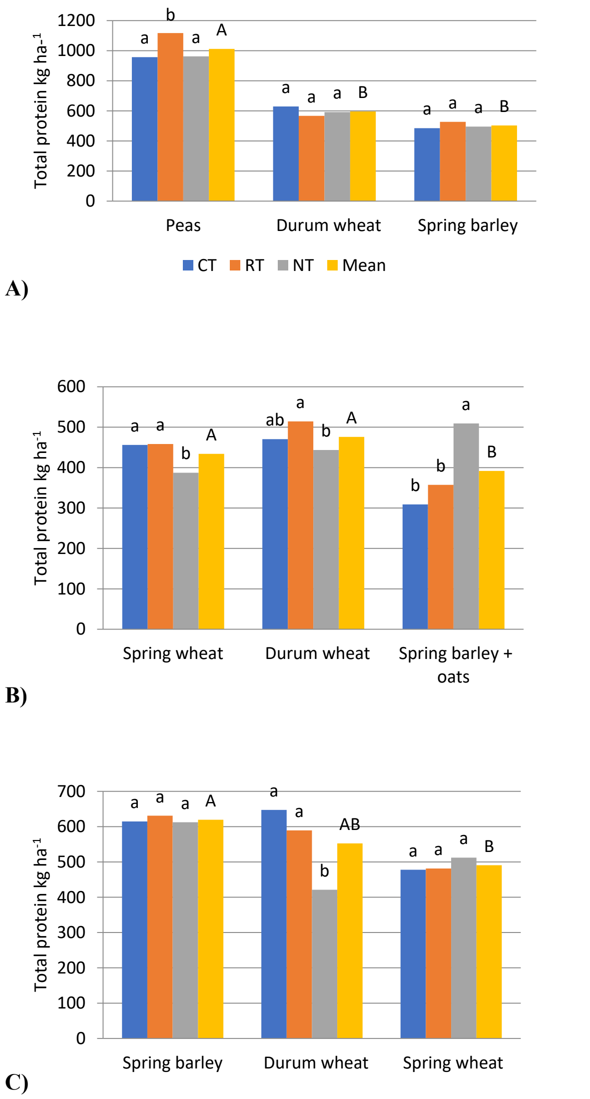

Figure 3. Total protein yield in kg ha^{-1} in crop rotations A, B and C. Different letters above the histogram bars indicate significant differences between mean values ($p<0.05$).

durum wheat and spring barley was not differentiated by tillage system. In crop rotation B, a higher protein yield was produced by durum wheat and spring wheat than by the spring barley + oats mix (Fig. 3B). A higher protein yield was produced in RT respect to NT system (durum wheat), in CT and RT respect to NT (spring wheat) and in NT respect to CT and RT (cereal mix). In crop rotation C, a higher protein yield was produced by spring barley than by spring wheat (Fig. 3C). In this CR, durum wheat produced more protein in CT and RT than in NT system.

Protein yield depended on protein content of the seeds and grains, and on seed yield produced (Table 4). In pea seeds, protein content was at 33% and was higher than in cereal grains. In cereals, a higher protein content was found in durum wheat grain than in grains of spring wheat and spring barley. The lowest protein content was demonstrated for spring barley + oats mix. By contrast, the tillage system had little effect on this production trait. A higher protein content was found in pea seeds from RT than from CT and NT system (crop rotation A), in durum wheat grain from NT than RT system (crop rotation B), and also in spring barley grain from NT than from CT and RT systems (crop rotation C).

Discussion

The production yield of CRs was expressed in the yield of cereal units and protein yield. The cereal units are a universal measure that allows bringing pea seed yield, cereal grain yield, and yield of their straw to the common denominator. According to Brankatschk & Finkbeiner (2014, 2017) and Henryson *et al.* (2019), the CU can be widely used in agricultural, environmental, and statistical research, as well as in estimating damage caused by

Table 4. Total protein content (%) of pea seeds and cereal grains.

Crops	Tillage systems			Mean
	CT	RT	NT	
Crop rotation A				
Peas	33.0^{a}	33.8^{b}	33.1^{a}	33.3^{A}
Durum wheat	15.5^{a}	15.5^{a}	15.6^{a}	15.5^{B}
Spring barley	13.0^{A}	13.0^{a}	12.9^{a}	13.0^{C}
Crop rotation B				
Spring wheat	14.2^{a}	14.1^{a}	14.2^{a}	14.2^{A}
Durum wheat	15.4^{ab}	15.2^{a}	15.7^{b}	15.4^{B}
Spring barley+oats	10.5^{a}	10.4^{a}	10.6^{a}	10.5^{C}
Crop rotation C				
Spring barley	13.4^{a}	13.5^{a}	13.9^{b}	13.6^{A}
Durum wheat	15.7^{a}	15.5^{a}	15.6^{a}	15.6^{B}
Spring wheat	14.1^{a}	14.1^{a}	14.2^{a}	14.1^{A}

Mean values in rows denoted with the same lower case letters do not differ significantly, $p<0.05$. Mean values in column denoted with the same upper case letters do not differ significantly, $p<0.05$.

animals to agricultural crops (Journal of Laws of the Republic of Poland, 2019).

Productivity of CRs is the result of an interaction of habitat factors (soil quality, precipitation distribution, air temperature, length of the growing season), plant species, and the order of their cultivation as well as agrotechnical measures applied (fertilization, plant protection, soil cultivation) (Rachoń & Woźniak, 2020; Woźniak, 2020). In many regions of Poland, plant productivity is determined by such factors as rainfall deficiencies during the vegetation period and not very diverse cereal CRs. Plant productivity in cereal CRs is much lower than in CRs with legumes (Kunzová, 2013). Also in our research, the yield of cereal units in the CR with peas was higher than in the cereal CRs. According to Tajnšek *et al.* (2001), this is due to the additional nitrogen supplied by legumes to the soil. In the multi-species CR, the competitiveness of weeds against crops is much lower than in the monoculture, which has a positive effect on plant productivity (Woźniak & Soroka, 2018). Plant yields also depend on soil tillage systems. In our experiment, the CU yield depended on the interaction between CR and tillage system. In the CR with peas (crop rotation A), the highest CU yield was obtained in RT system, while in the cereal CRs (crop rotations B and C) better results were obtained in CT and RT systems. Plant sequence in the CR and soil tillage system affected also the total protein yield. In the CR with peas, the protein yield was higher than in the cereal CRs, especially in the RT system. This was due to a high protein content of pea seeds (over 33% total protein content) and a high seed yield of this crop. In turn, in the cereal CRs, the soil tillage system differentiated this production trait only to a little extent. Lower seed yields of spring wheat and durum wheat were obtained only in the NT system; however, their values were affected to a greater extent by CR than by tillage system. Also in a previous work (Woźniak, 2016), the tillage system had a little effect on the total protein content of spring triticale. According to De Vita *et al.* (2007), this production trait was determined rather by nitrogen fertilization than by soil tillage system.

In conclusion, the yield of cereal units (CU) and the total protein yield were determined to a greater extent by plant sequence in the crop rotation (CR) than by soil tillage systems. A higher productivity was offered by crop rotation A with peas than by cereal crop rotations B and C. The tillage systems had little effect on CU yield and total protein yield. The units used for CR assessment, *i.e.* CU and total protein yield, enable to reliably evaluate the production yield of both CRs and tillage systems.

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