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Received: 2017-07-27 ; Accepted: 2017-08-22

PRODUCTIVITY OF CROP ROTATIONS AND SELECTED INDICATORS OF SOIL FERTILITY IN DIFFERENT TYPES OF ECOLOGICAL FARMS

Summary

These studies are based on a field experiment carried out in the years 2011-2016 at RZD IUNG-PIB in Grabów. The experiment consisted of three crop rotations differing with respect to leguminous crops included in these rotation, reflecting three different types of ecological (organic) farms. Crop rotation A, representing a dairy farm, consisted of: maize – cereal-pulse mixture (undersown with grass-red clover) - grass-red clover ley (year I) – grass-red clover ley (year II) – winter wheat. Crop rotation B, representing a pig farm, included: maize – spring barley – cereal-pulse mixture – pea – winter wheat. Crop rotation C, representing a farm without livestock, consisted of: maize – cereal mixture – spring wheat (undersown with red clover) – red clover – winter wheat. The objective of this study was to assess the presented crop rotations with respect to their productivity and effects on yields of particular crops and basic soil fertility indicators. Among the compared rotations the highest productivity in terms of cereal units was obtained in the case of crop rotation A representing the dairy farming system, and the lowest productivity in the case of rotation B representing the livestock (pig) farming system. During the 6-year experimental period no significant differences were found between the compared rotations with respect to phosphorus content in the soil. Potassium contents in the soil of rotations A and C were lower than in rotation B. The compared ecological farming systems had minor effects on soil microbial activity indicators. Dehydrogenase activity and glomalin contents were lowest while hot water extracted C was highest in the soil of rotation B as compared to the soil of rotations A and C.
***Key words**: ecological agriculture, crop rotation, soil fertility, microbial activity*

PRODUKCYJNOŚĆ ZMIANOWAŃ ORAZ WYBRANE WSKAŹNIKI ŻYZNOŚCI GLEB W RÓŻNYCH TYPACH GOSPODARSTW EKOLOGICZNYCH

Streszczenie

Badania polowe prowadzono w latach 2011-2016 w RZD IUNG – PIB w Grabowie. Schemat doświadczenia uwzględniał trzy zmianowania zawierające wybrane gatunki roślin bobowatych. Oceniane zmianowania reprezentowały jednocześnie różne typy gospodarstw ekologicznych. Zmianowanie A – odpowiadające modelowi gospodarstwa mlecznego: kukurydza ++ - mieszanka zbożowo – strączkowa + wsiewka - koniczyna czerwona +trawa I rok - koniczyna czerwona +trawa II rok - pszenica ozima. Zmianowanie B – reprezentujące model gospodarstwa z chowem trzody: kukurydza ++ - jęczmień jary - mieszanka zbożowo-strączkowa – groch - pszenica ozima. Zmianowanie C – reprezentujące model gospodarstwa bezinwentarzowego: kukurydza ++ - mieszanka zbożowa - pszenica jara + wsiewka - koniczyna czerwona - pszenica ozima. Celem badań była ocena zmianowań reprezentujących różne typy gospodarstw ekologicznych obejmująca: plonowanie roślin, produkcyjność zmianowań oraz podstawowe wskaźniki żyzności gleb. Spośród porównywanych zmianowań największą wydajność w jednostkach zbożowych uzyskano w zmianowaniu A reprezentującym model gospodarstwa mlecznego, a najmniejszą w zmianowaniu B odpowiadającym modelowi gospodarstwa z chowem trzody chlewnej. W okresie 6 lat badań we wszystkich ocenianych zmianowaniach nie stwierdzono istotnych zmian zasobności gleb w fosfor. W glebie zmianowania A i C odnotowano największy spadek zawartości potasu. Porównywane sposoby gospodarowania w niewielkim stopniu wpływały na wskaźniki aktywności mikrobiologicznej. W glebie zmianowania B w porównaniu do pozostałych zmianowań stwierdzono najmniejszą aktywność dehydrogenazy, największą ilość C org. w ekstraktach gorącą wodą oraz najmniejszą zawartość glomalin.
***Słowa kluczowe**: rolnictwo ekologiczne, zmianowanie, żyzność gleby, aktywność mikrobiologiczna*

1. Introduction

Soil fertilization is one of the most difficult agrotechnical elements in ecological (organic) agriculture. Since no synthetic mineral fertilizers can be applied, soil fertility and nutrient requirements of crops in this type of farming system can be secured only through: suitable crop rotations, application of organic and natural manures or natural mineral fertilizers. This is particularly important in the case of soil nitrogen pools and sources, which can be solved only by growing and appropriate use of leguminous crops [9, 11, 12, 13].

Despite these facts many ecological farms face problems with soil nutrients shortage and balance [2, 16, 17]. This concerns mainly livestock-less farms or farms with a low stocking density. Problems with nutrients deficiencies can have also highly productive farms due to nutrients export with crop yields [2, 5, 9].

Taking into account the above mentioned considerations, studies were undertaken to assess crop rotations representing different types of ecological farming with respect to: productivity of these rotations, their effects on yields of particular crops, soil nutrient contents and microbial activity.

2. Materials and methods

These studies are based on a field experiment carried out in the years 2011-2016 at RZD IUNG-PIB in Grabów. The experiment, in a split-block design with 4 replicated plots, consisted of three crop rotations differing with respect to leguminous crops included in these rotations, reflecting three different types of ecological (organic) farms.

Crop rotation A, representing a dairy farm, with the following crops:

1. Maize (for silage)
2. Oats, barley, wheat, pea - mixture (for green forage, undersown with red clover-grass)
3. Red clover-grass ley (year I)
4. Red clover-grass ley (year II)
5. Winter wheat.

Crop rotation B, representing a pig farm, included:

1. Maize (for grain)
2. Spring barley
3. Oats, barley, wheat, pea – mixture (for grain)
4. Pea
5. Winter wheat.

Crop rotation C, representing a farm without livestock, consisted of:

1. Maize (for grain)\
2. Oats, barley, wheat – mixture (for grain)
3. Spring wheat (undersown with red clover)
4. Red clover (biomass for composting)
5. Winter wheat.

The experimental fields were located on the soil classified as Albic Luvisol with loamy sand texture (complex: rye-very good). Other soil characteristics: soil organic matter content 1.3%, pH – slightly acidic, contents of: P – medium, K – low, Mg – very low. Plots area for harvesting was 60 m^2. Soil samples for chemical and microbiological analyses were collected in the autumn (after wheat harvest) and in the spring before vegetation onset from winter wheat fields. Contents of mineral nitrogen ($N\text{-}NO_3$ and $N\text{-}NH_4$ forms) were determined in 0-30, 30-60 and 60-90 cm soil layers using 1% K_2SO_4 solution and a flow colorimetric method. Microbial analyses included determination of C org. and N total in cold and hot water extracts and microbial biomass. To prepare hot water (80°C) extracts from field moist soils duplicate samples, equivalent to 5 g soil dry matter (d.m.), were weighed into 50 ml centrifuge tubes, mixed with 25 ml of distilled water and further treated as described by Ghani et al. [4]. Microbial biomass C was determined by the chloroform-fumigation-extraction method and calculated according to the following formula: $C_{mic.} = E_C/k_{EC}$, where E_C = soluble C in fumigated samples – soluble C in control (un-fumigated) samples and $k_{EC} = 0.45$ [9]. An Automated N/C Analyzer (Multi N/C 2100, Analytik Jena, Germany) was used to measure C and N contents in cold and hot water soil extracts and in microbial biomass. Dehydrogenase activity was estimated using TTC (2,3,5-triphenyltetrazolium chloride) as the substrate [1] and glomalin (glyco-proteins produced by endo-mycorrhizal fungi) content [18].

The data were subject to the analysis of variance (ANOVA) with significance of differences assessed at $p < 0.05$.

3. Results and discussion

Productivity of rotations and crop yields. The highest mean productivity of the compared crop rotations expressed in cereal units – 55.9 c.u.·ha^{-1} was obtained in the case of rotation A, representing a dairy farming system. The productivity of the crop rotations C (without livestock) and B (pig farming)was by 13% and 26%, respectively, lower than that of the crop rotation A (tab. 1). A higher productivity of the crop rotation A was connected with yields of fodder crops, which had a 80% share in this rotation. Among the crops grown in the rotation A, the highest biomass yields were obtained in the case of grass-red clover mixture. In the first growing season yields of fresh mass of grass-red clover mixture ranged from 37 to 74 t·ha^{-1}, and in the second year from 33 to 91 t·ha^{-1}. The mean (for 6 years) yields of fresh biomass of maize and cereal-pulse mixture were lower than those of grass-red clover mixture and amounted to 33.1 t·ha^{-1} and 18.9 t·ha^{-1}, respectively. The variability of fresh biomass yields of maize and cereal-pulse mixture was lower than that of grass-red clover yields and this was the main reason for the stability of the total productivity of this rotation, and these results are in accordance with those obtained by other authors [2, 10, 15].

Relatively good productivity of the crop rotation C, allowing farming without livestock, resulted from high yields (91,7 c.u.·ha^{-1}) of red clover grown for composting and grain maize (50 c.u.·ha^{-1}). The productivity of the crop rotation B, the lowest among the compared rotations, was connected mainly with grain yields produced as a fodder crop for pigs. Yields of grain crops grown in this rotation were relatively high and amounted to 4.3 t·ha^{-1} for winter wheat and 5.1 t·ha^{-1} in the case of maize (tab. 1).

In particular growing seasons yields of all crops grown in this experiments varied substantially. Grain yields of winter wheat were relatively stable, 4.2-4.3 t·ha^{-1}, in all rotations and irrespective on fore-crops. Spring cereals - wheat and barley - grown in pure stands and in mixtures gave yields lower by 1-1.6 t·ha^{-1} in comparison to those of winter wheat, but their yields were stable in different years. These results are similar to those obtained in other studies [2, 10, 15] and indicate that under ecological production system grain yields of spring cereals are less variable. This effect seems to be a result of lower pressure of fungal pathogen and weeds in growing spring cereals than in winter cereals.

The greatest variability of yields was found in the case of maize grown for grain in rotations B and C, with V (coefficient of variation) = 40-46% and in the case of pea with V = 38%. These variations might be caused by drought in 2015 and a high weed infestation in 2012.

Chemical soil characteristics. At the beginning of the experiment (2011) the soil in all rotations was characterized by medium content of phosphorus, low content of potassium, very low content of magnesium and slightly acid reaction (tab. 2). At the end of the experimental period P content in the soil increased to a high level and it was caused by application of P fertilizer in 2015. The greatest differences between the rotations were found for potassium (K) contents in the soil. In the rotation A with high share of fodder crops K levels in soil drop to very low levels (tab. 2). Similar results were obtained for the rotation C.

Table 1. Crop yields (t·ha^{-1}) and productivity of crop rotation (in cereal units) in different models of plant production
Tab. 1. Plonowanie roślin (t·ha^{-1}) i wydajność zmianowań (j.zb.) w zależności od modelu produkcji roślinnej

Crop rotation	Average of years 2011-2016 [t·ha^{-1}]	Min-max [t·ha ^{1}]	Coefficient of variation V [%]	Productivity crop rotation (2011-2016) [cereal units]
Crop rotation A				
Fodder maize	33,1	17,8-38,0	23	39,7
Oats, barley, wheat, pea – mixture for green forage	18,9	14,1-21,6	13	22,7
Red clover with grass I year	57,6	36,7-73,5	24	86,4
Red clover with grass II year	59,2	33,0-91,0	37	88,9
Winter wheat	4,2	2,0-5,5	33	42,1
Average				***55,9 a****
Crop rotation B				
Grain maize	5,1	1,7-7,4	44	51,3
Spring barley	3,3	2,7-4,2	16	33,1
Oats, barley, wheat, pea – grain mixture	4,1	3,1-5,0	17	44,7
Pea	3,0	1,9-4,9	38	35,9
Winter wheat	4,3	2,4-5,4	28	42,6
Average				***41,5 b***
Crop rotation C				
Grain maize	5,0	1,4-7,1	46	50,0
Oats, barley, wheat – grain mixture	3,4	3,0-4,0	11	34,3
Spring wheat (undersown with red clover)	2,7	1,3-3,3	29	26,6
Red clover compost	61,2	31,9-80,2	31	91,7
Winter wheat	4,2	2,2-5,3	31	42,1
Average				***48,9 c***

*/ - the letters show statistically significant difference (P = 0.95)

Source: own work / Źródło: opracowanie własne

Table 2. Chemical properties of soil in different models of plant production
Tab. 2. Chemiczne właściwości gleby w różnych modelach produkcji roślinnej

Crop rotation */ Models of crop production	Years	Organic matter	pH in KCl	Contents [mg/100g soil]		
				P_2O_5	K_2O	Mg
A *Dairy*	2011	1,39	5,9	15,0	10,1	1,5
	2012	1,23	5,6	13,6	5,5	1,5
	2013	1,15	5,6	14,5	5,4	1,1
	2014	1,18	5,7	13,8	6,4	1,5
	2015	1,36	5,5	14,6	7,0	1,1
	2016	1,35	5,6	17,4	9,0	1,9
B *Pigs fatting*	2011	1,25	5,7	14,4	11,2	1,4
	2012	1,20	5,6	13,4	7,3	1,4
	2013	1,04	5,5	14,7	8,7	1,2
	2014	1,14	5,4	13,3	8,0	1,6
	2015	1,37	5,3	14,3	7,3	1,5
	2016	1,23	5,4	19,2	11,1	1,8
C *Without livestock*	2011	1,28	5,5	13,6	9,6	1,3
	2012	1,22	5,4	13,0	5,4	1,0
	2013	1,05	5,3	13,2	5,9	1,0
	2014	1,18	5,4	13,4	6,2	1,1
	2015	1,41	5,4	13,6	6,8	1,5
	2016	1,38	5,2	15,7	10,1	1,7

*/- explanation as in tab. 1.

Source: own work / Źródło: opracowanie własne

In general, soil organic C contents at the beginning and at the end of the experimental period did not differ markedly for the crop rotations A and B, but in the case of the rotation C the content of organic C in the soil increased by 0.1% at the end of the experiment (tab. 2). These results suggest that the ecological farming system is sustainable with respect to management of soil organic matter, even on farms without livestock production [2, 13].

Nmin levels in soil. Transformation and mineralization of organic materials and transport of mineral N forms in the soil prolife of this experiment depend on many factors, such as soil variability, weather conditions, composition of plat residues and share of particular crops, particularly leguminous plants, in crop rotation [6, 9, 11]. In the 0-90 cm soil profile in crop rotation A after 2 years ley of growing grass-red clover mixture Nmin contents ranged from 49 to 150 kg·ha^{-1} (tab. 3). Concentrations of Nmin in the profile were correlated with yields of grass-red clover mixture and the share of the leguminous component [6, 12]. The obtained results indicate that in most of the experimental years contents of Nmin in the whole soil profile were higher in the spring than in the autumn. This observation would indicate on intensive mineralization and immobilization of N in soil of the rotation A, and in consequence on low N losses due to leaching [6].

In the crop rotation B after pea harvest Nmin content in soil samples collected in the autumn was highest and ranged from 72 to 160 $kg \cdot ha^{-1}$, depending on the year. In the spring Nmin content decreased and moved down the soil profile, which might indicate on a potential N losses by leaching [3, 6]. In this rotation the average content of Nmin in spring was by 12 $kg \cdot ha^{-1}$ lower than in autumn sampling (tab. 3).

In the case of the crop rotation C the all year average concentration of Nmin amounted to 90 $kg \cdot ha^{-1}$. In particular years Nmin contents in the soil profile during autumn period ranged from 62 to 178 $kg \cdot ha^{-1}$. Small differences between spring and autumn Nmin contents indicate that in this rotation N losses from soil due to leaching are insignificant.

In general, the compared crop rotations did not affect significantly the studied in this work microbial and chemical properties of the soil. Only dehydrogenase activity in the soil of the rotation B was significantly lower than that of the rotations A and C (tab. 4). This soil contained also the lowest amounts of glomalin, but the highest content of C org. in hot water extract. The soil in the rotation C contained more microbial biomass C and showed higher activity of the enzyme dehydrogenase than the soils in the rotations A and B, but the differences were statistically insignificant, although they would suggest a higher biological activity of soil in the rotation C. Dehydrogenase activity is often related with general activity of soil microorganisms [1, 14]. The lowest activity of this enzyme in the soil of the rotation B would indicate that this soil had lower microbial activity than the soils of rotations A and C and this result could be related with substantially lower amounts of spring Nmin in the soil B than in the soil A and C (tab. 3). Glomalin, a glyco-protein, is produced by endo-mycorrhizal fungi and this substance is often called as "soil glue" due to its great resistance to degradation and ability to increase water stability of soil aggregates [14, 18]. The highest amounts of glomalin found in the soil of the rotation A would indicate that this soil had greater physical stability than the soil in rotations B and C.

4. Conclusions

1. The highest productivity expressed in cereal units - 56 $t \cdot ha^{-1}$ - was obtained in the crop rotation A, representing a model of dairy farm. The productivity of the rotations C (without livestock) and B (pig fatting) were lower and amounted to 49 c.u. $t \cdot ha^{-1}$ and 42 c.u. $t \cdot ha^{-1}$, respectively. The high productivity of the rotation A was related with high yields of red clover – grass mixture (86 c.u. $t \cdot ha^{1}$ in the first year and 89 c.u. $t \cdot ha^{-1}$ in the second year).

Table 3. The content of mineral nitrogen (kg $N_{min} \cdot ha^{-1}$) in different models of plant production - 0-90 cm soil profile (years 2011-2016)

Tab. 3. Zawartość azotu mineralnego ($N_{min} \cdot ha^{-1}$) w zależności od modelu produkcji roślinnej - profil glebowy 0-90 cm (lata 2011-2016)

Crop Rotation *	Soil profile	*Years* 2011/2012		2012/2013		2013/2014		2014/2015		2015/2016		*Average for crop rotation*	
		autumn	*spring*	*autumn*	*spring*	*autumn*	*spring*	*autumn*	*spring*	*autumn*	*spring*	*autumn*	*spring*
A	**0-30**	51	42	40	31	34	31	36	66	68	**55**	**46**	**45**
	30-60	21	37	27	27	12	22	14	64	52	**61**	**25**	**42**
	60 -90	10	19	12	181	3	13	5	32	30	**50**	**12**	**59**
	0-90	82	97	79	76	49	67	54	162	150	166	**83**	**114**
Difference s/a		**15**		**-3**		**18**		**108**		**16**		**31**	
B	**0-30**	**67**	**28**	**46**	**32**	**40**	**20**	**51**	**50**	**58**	**52**	**52**	**36**
	30-60	39	40	51	24	25	20	40	55	59	**49**	**43**	**38**
	60 -90	19	20	21	26	7	15	11	47	43	**40**	**20**	**30**
	0-90	125	89	118	81	72	55	103	152	160	**142**	**116**	**104**
Difference s/a		**-36**		**-37**		**-17**		**49**		**-18**		**-12**	
C	**0-30**	50	36	33	27	41	27	47	68	86	**53**	**51**	**42**
	30-60	26	41	28	24	18	19	17	66	58	**58**	**29**	**42**
	60 -90	10	15	11	16	3	14	5	53	34	**53**	**13**	**30**
	0-90	**86**	**92**	**72**	**66**	**62**	**61**	**69**	**187**	**178**	**164**	**93**	**114**
Difference s/a		**6**		**-6**		**-1**		**118**		**-14**		**21**	

*/- explanation as in tab. 1

Source: own work / Źródło: opracowanie własne

Table 4. Microbiological and chemical properties of soil under winter wheat cultivated in different models (crop rotations) of plant production

Tab. 4. Mikrobiologiczne i chemiczne właściwości gleby pod pszenicą ozimą uprawianą w różnych modelach (zmianowaniach) produkcji roślinnej

Crop rotation	Microbial biomass C [µg C* g⁻¹]	Dehydrogeneze [µg formazan g⁻¹]	C-HW* [µg C* g⁻¹]	N-HW* [µg N* g⁻¹]	C-CW* [µg C* g⁻¹]	Glomalin [µg C* g⁻¹]
A	198 a	111 a	431 a	24,0 a	160 a	84 a
B	202 a	83 b	443 a	21,0 a	161 a	72 a
C	219 a	135 a	383 a	25,0 a	153 a	77 a

*C org. or N tot. extracted with hot(HW) or cold water(CW)

Source: own work / Źródło: opracowanie własne

2. Winter wheat grain yields were similar in all rotations (4.2-4.3 $t \cdot ha^{-1}$) and they did not depend on a fore-crop.
3. During 6 years of studies in all rotations no significant changes were found for soil phosphorus and soil organic matter contents. In the rotation A and C soil potassium contents drop to very low levels. In the rotation B, with 60% share of cereals, a decrease of soil K was lower.
4. The lowest activity of dehydrogense in the soil of the rotation B would indicate that this soil had lower microbial activity than the soils of rotations A and C and this result could be related with substantially lower amounts of spring Nmin and total N in hot water extract from the soil B than from the soil A and C.
5. Losses or leaching of Nmin from soil seem to be insignificant for all rotations. However, analyses of Nmin in the soil profile during autumn indicate, that in soil after pea and red clover harvest N surpluses 72-178 kg $N \cdot ha^{-1}$ can cause N losses environmental contaminations.

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