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Effect of penetration resistance, bulk density and moisture content of soil on selected yield components of winter triticale in relation to method of cultivation

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A b s t r a c t. The influence of penetration resistance, bulk density and moisture content of soil on winter triticale crop yield was investigated. The crops were grown on land that had not been cultivated for several years, and two methods of cultivation were used: direct sowing and plough-based cultivation. Winter triticale crop yields did not differ significantly regardless of the method of cultivation. Analysis of the coefficients for multiple regression showed that winter triticale crop yield was most dependent on the mass of a thousand grains and the number of grains per ear in the case of plough-based cultivation. In the case of direct sowing, the mass of a thousand grains and the number of ears per 1 m^2 had a great influence on the crop yield. Negative partial regression coefficients were obtained for penetration resistance and bulk density of the soil, indicating their inverse relationship to the crop yield. Canonical analysis was used, allowing the determination of the range of effect of penetration resistance, bulk density and moisture content (independent variables) on selected components of winter triticale crop yield (dependent variables) relative to the method of cultivation. The presented canonical analysis showed that the analysed components of the yield were 78% dependent on the three fundamental physical parameters of the soil in the case of plough-based cultivation and 58% dependent in the case of direct sowing. In the case of plough-based cultivation, primarily the penetration resistance and then the moisture content of the soil had the greatest influence on the variability of the components of the crop yield. A high penetration resistance and a reduced moisture content caused a reduction in the1000-seed weight. In the case of direct sowing, the moisture content of the soil affected the variability of the number of ears per unit of land surface.

K e y w o r d s: penetration resistance, moisture, soil bulk density, yield components

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INTRODUCTION

As a result of structural and economic transformations, particularly those in agriculture after 1989, cultivation of a considerable part of arable land got relinquished. Estimated data indicate that now about 1.8 million hectares of arable land have been excluded from agricultural use. Due to the high costs of traditional methods of cultivation, it has become increasingly common for alternative methods that do not rely on ploughs to be used (Anken *et al.*, 1999; Brunotte *et al.*, 2001; Cordes, 2001). An extreme method of simplified cultivation is direct sowing. A majority of publications on the subject report on significant reduction in the yield from plants cultivated by direct sowing compared to that from traditionally cultivated plants (Halvorson *et al.*, 2001; Weber, 2004). Other authors relate the yield to the hydrothermal conditions during vegetation (Camara *et al.*, 2003; Pabin *et al.*, 2002). However, in many papers it is stated that in the long-term there is no significant difference between the yield from direct sowing and that from traditional cultivation (Köllker and Linke, 2001; Tebrügge and During, 1999). In the first years of the application of direct sowing, the penetration resistance and bulk density of the top layers of the soil profile increase. In longer-term application of this method of cultivation, a significantly lower penetration resistance and bulk density and an increased water retention are observed due to higher organic substance content in the soil (Dobers *et al*., 2004; Wilkins *et al*., 2002). The results of studies done in Germany show that similar levels for the physical parameters of soil to those for long-term direct sowing can be obtained in the first few years of direct sowing of previously uncultivated land (Köller and Linke, 2001). The yield of winter triticale per unit of land depends mainly on the number of ears per unit of land, the number and mass of grains per ear, and the 1000 seed weight. The relationship between individual components of the crop yield and the penetration resistance, bulk density and moisture content of the soil under conditions of standard plough-based cultivation were described in Weber *et al.* (2004).

The aim of this paper is to determine the answers to the following questions:

- What is the influence of the method of cultivation on the three fundamental physical parameters of soil and the components of winter triticale crop yield in the second and third years of cultivation of previously long-term uncultivated land?
- What is the range of effect of the penetration resistance, bulk density and moisture content of the soil (independent variables) on selected components of winter triticale crop yield (dependent variables) relative to the method of cultivation?
- Which of the sets of independent variables can explain the maximum range of variability of the selected components of the crop?
- Which of the independent variables analysed together explain the largest range of variability in the set of dependent variables?

MATERIALS AND METHODS

The study was carried out in 2003-2005 in Jelcz-Laskowice on land that had been uncultivated (set aside) for 12 years and was overgrown by annuals and perennials. This was a lessive soil composed of strongly loamy sand with an organic carbon content of 0.95% and pH 4.6 (properties of the top soil). In the study, the following methods of cultivation were used:

- Plough-based cultivation:
  - post-harvest ploughing with the cultivator set to a depth of 15 cm and a cage roller used,
  - basic ploughing to a depth of 25 cm and a harrow used,
  - pre-sowing using a cultivation aggregate (cultivator and cage roller); herbicides were used as required,
- Direct sowing, using herbicides as required.

The experiment was constructed using the method of random-selected blocks. Each of the treatments had four replications. Each replication of 150 m^2 area was divided into ten plots. The surface area of each plot was 15 m^2. In each plot the yield and its components as well as physical properties of the soil were estimated separately. Winter triticale was sown using each of the aforementioned cultivation methods after oats in 2003-2005. The temperature and rainfall during the growth of the plants in the years of the study are shown in Table 1. Despite the differentiated rainfalls and temperatures, the yields of grain in the three test years did not differ significantly. The physical properties of the soil were analysed during propagation, shooting, flowering and maturity by doing ten assays for each separate treatment. Measurement of the soil volumetric moisture content was done using a CPN Hydroprobe-type neutron probe, with the measurement taken twice a month during the growth of the plants. The moisture content was measured at depths from 0 to 20 cm. The bulk density of the soil was measured in such a way as to preserve its structure undisturbed, taking soil samples into 100 cm^3 cylinders from three depths: 0-5, 5-10 and 10-20 cm. The penetration resistance of the soil was measured at the same three depths with a penetrometer –

T a b l e 1. Average temperature and rainfall during the growth of winter triticale

Year	Month						Total
	March	April	May	June	July	August	
			Temperature (°C)				
2003	3.0	7.5	15.7	19.7	19.7	19.8	85.1
2004	3.9	9.4	12.9	17.0	18.6	19.6	81.4
2005	1.3	9.3	14.2	17.0	19.9	19.7	81.4
Long-term mean	3.3	8.2	13.4	16.6	18.1	17.6	77.2
			Rainfall (mm)				
2003	16.2	19.6	57.7	27.6	77.7	59.4	258.2
2004	63.6	24.3	37.3	43.7	55.3	47.9	272.1
2005	12.3	20.3	86.2	22.4	93.7	67.8	302,7
Long-term mean	31.6	36.9	63.8	71.6	75.4	70.6	349.8

an impact probe with a 2.17 kg weight and a conical sensor with a diameter of 24 mm and an apical angle of 30º. Penetration resistance, *Z*, was calculated according the formula:

$$Z = (M\, g\, H\, n) / (h\, s),$$

where: M – weight of the plummet (kg), g – acceleration of gravity (m s^{-1}), H – plummet drop height = 24.5 cm, n – number of impacts, h – penetration of the probe (cm), s – base of the cone surface (cm^2).

The results obtained (N cm^{-2}) were converted to MPa. The average moisture content, penetration resistance and bulk density of the soil for the measurement set from the growth period of the plants were compared to selected components of the crop yield for each sample. The selected components were the number of ears per 1 m^2, the number of grains per ear, the mass of grains per ear, the 1000 seed weight and the ear length. Selected yield components usually show high correlations with the yield of grain. A mineral fertilizer was used and necessary procedures were carried out as per the universally accepted standards. In order to give a complex assessment of the relationship between the three physical parameters of the soil and the selected components of the yield, a canonical analysis was performed as described in the literature (Johnson and Wichern, 1988; Krzyśko and Ratajczak, 1978).

RESULTS AND DISCUSSION

Table 2 shows the average values of the three fundamental physical parameters of the soil and the components of winter triticale crop yield for each of the methods of cultivation. The winter triticale crop yield from direct sowing did not differ significantly from that from plough-based cultivation. A few studies carried out in Poland did indicate that there was a significant reduction in winter triticale crop yield when conventional cultivation was replaced with ploughless cultivation (Dzienia and Piskier, 1998; Małecka *et al.*, 2004). In order to determine the influence of the selected parameters of the crop and the physical parameters of the soil on the yield of winter triticale crop, first of all, an analysis of multiple regression was carried out initially. It indicated the following equations:

- for plough-based cultivation:

$$Y1 = 0.8\ NEU - 2.03\ LE + 0.84\ NGE + 0.14\ MGE + 3.26\ MTG - 0.73\ PR - 0.33\ BD + 0.11\ MC,$$

$$R^2 = 0.97,$$

- for direct sowing:

$$Y2 = 0.71\ NEU - 0.1\ LE - 0.15\ NGE + 0.49\ MGE + 0.13\ MTG - 0.17\ PR - 0.16\ BD - 0.04\ MC,$$

$$R^2 = 0.89.$$

where: Y1, Y2 – crop yield measured (kg plot^{-1}), NEU – number of ears per unit of land (1 m^2), LE – length of ears (cm), NGE – number of grains per ear, MGE – mass of grain per ear (g), MTG – 1000 seed weight (g), PR – penetration resistance of soil (MPa), BD – bulk density of soil (g cm^{-3}), MC – moisture content of soil (% vol.)

The standardized regression coefficients indicate that plough-based cultivation of winter triticale is most dependent on the mass of a thousand grains and the number of grains per ear. In the case of direct sowing, the mass of grains per ear and the number of ears per 1 m^2 had a large influence on winter triticale crop yield. The negative partial regression coefficients for the penetration resistance and bulk density of the soil are noteworthy, as they indicate that these parameters have an inverse relationship to winter triticale crop yield. The values of the determination coefficients for multiple regression for the methods of cultivation indicate that the variability in the crop yield was significantly determined by the group of studied characteristics. In order to determine the relationships between the physical parameters of the soil and the components of the yield, the canonical analysis formed new 'hidden' canonical variables that are weighted sums for the two analysed sets. The high canonical correlation (R = 0.85 for direct sowing, R = 0.98 for plough-based cultivation) between the sum of the analysed variables indicates a high correlation between the physical parameters of the soil and the selected components of the yield (Table 3).

However, the total redundancy of the set of physical parameters of the soil indicates that they account for 78% of the variability of the components of winter triticale crop

Table 2. Average values of penetration resistance, bulk density and moisture content of the soil and the components of winter triticale crop yield from 2003-2005

Method of cultivation	Grain yield (kg plot^{-1})	NEU	LE	NGE	MGE	MTG	PR	BD	MC
Plough-based	85.0	520.0	8.41	45.09	2.04	46.50	2.27	1.58	8.07
Direct sowing	72.4	480.5	8.20	44.74	2.05	47.20	2.65	1.58	8.77
	ns	*	ns	ns	ns	*	ns	ns	*

ns – non-significant difference at p> 0.05; * – significant difference at p<0.05.

T a b l e 3. Results of canonical analysis

Method of cultivation	Number of variables	Separated variance (%)	Total redundancy (%)
Plough-based	Soil physical parameters : 3	100	78.1
	Yield components : 5	92.8	73.2
	Canonical R = 0.98; Chi^2 = 43.14; p = 0.0001		
Direct sowing	Soil physical parameters: 3	100	57.5
	Yield components : 5	81.32	38.26
	Canonical R = 0.85; Chi^2 = 31.11; p = 0.008		

T a b l e 4. Chi tests – estimate of squares of the canonical variables

Root removed	Canonical R	Canonical R^2	Chi^2	p-level	Primary lambda
Plough-based cultivation					
0	0.98	0.96	43.14	0.0001	0.00006
1	0.96	0.92	13.24	0.01	0.05
2	0.46	0.21	1.09	0.77	0.78
Direct sowing					
0	0.85	0.72	31.11	0.008	0.011
1	0.66	0.43	12.10	0.014	0.04
2	0.47	0.22	3.76	0.28	0.77

yield in the case of plough-based cultivation and for 57.5% in the case of direct sowing. The canonical variables indicate a defined part of the variability in the analysed data sets. Further canonical variables are calculated such that each successive variable describes an additional part of the variability. The canonical variables are not correlated with each other, and they represent a percentage of the total variance of the whole set. Table 4 presents the assessment of significance of the analysed canonical variables for the physical parameters of the soil and the components of winter triticale crop yield. Based on the significant values from the Chi^2 test, we can state that in the analysis (for both the plough-based cultivation and direct sowing) it is necessary to take into account only the first two canonical variables. Furthermore, the low value of lambda for these canonical variables confirms this conclusion. Therefore, the dependence between the sets of variables can be described with the aid of two pairs of canonical variables. Based on the canonical analysis, we can also define what percentage of variability of the analysed characteristics in the set is described by a given canonical variable (Table 5). The first canonical variable for the physical parameters of the soil (independent variables) in the case of plough-based cultivation defines 38% of the variability of the studied set. In the case of direct sowing, the first canonical variable describes 58% of the variability of the physical characteristics of the soil. The first canonical variable of the winter triticale crop yield elements defines only 26% of the variability in the case of the plough-based cultivation, while the second canonical variable defines 46% of the variability. The redundancy of the first canonical variable for the physical parameters of the soil in the case of plough-based cultivation is 0.262. This variable thus defines 26% of the variability of the components of the crop yield. The redundancy of the second canonical variable describes 42% of the variability of the winter triticale crop yield components. The significantly lower redundancy of the canonical variables for the case of direct sowing indicates a lower degree of dependence between the physical parameters of the soil and the selected components of the crop yield. The initial simple analysis of the correlation of the physical parameters of the soil and the components of winter triticale crop in conditions of plough-based cultivation (Table 6) indicated an inverse relationship between the penetration resistance and the number of ears per 1 m^2, the mass of grain per ear and the mass of a thousand grains. In the case of direct sowing, a lower dependence was found between the penetration resistance and the number of ears per 1 m^2, the mass of grain per ear and the 1000 seed weight. The moisture content of the soil also showed a lower correlation with the number of ears per 1 m^2.

T a b l e 5. Contributions of separated variance and redundancy of physical parameters of the soil and winter triticale crop yield components

Variable	Separated variance for the set		Redundancy of the set of dependent variables
	of independent variables	of dependent variables	
Plough-based cultivation			
Root 1	0.380	0.262	0.262
Root 2	0.372	0.455	0.424
Root 3	0.246	0.209	0.045
Direct sowing			
Root 1	0.577	0.173	0.126
Root 2	0.269	0.526	0.230
Root 3	0.152	0.113	0.026

T a b l e 6. Correlation of physical parameters of the soil with the components of winter triticale crop yield

Parameters	NEU	LE	NGE	MGE	MTG
Plough-based cultivation					
PR	-0.80	-0.60	0.19	-0.83	-0.85
BD	-0.15	-0.54	-0.34	-0.36	-0.36
MC	0.82	0.87	-0.17	0.94	0.96
Direct sowing					
PR	-0.37	-0.41	0.31	-0.61	-0.54
BD	-0.51	0.30	-0.21	0.05	0.17
MC	0.76	-0.05	0.21	0.09	-0.02

Explanations as in Table 2.

More detailed information can be obtained by elucidating the structure of the first two canonical variables which are weighted sums. The partial coefficients of the weighted sums for the dependent and independent variables ($a_1X_1 + a_2X_2 + a_3X_3$ and $b_1Y_1 + b_2Y_2 + ... + b_5Y_5$) are referred to as canonical weights. They are given for the standardized variables in the set X (the physical parameters of the soil) and the set Y (the components of winter triticale crop). The greater the absolute value of this weight, the greater the part played by a given dependent or independent variable in the analysis of the canonical variables. The greatest part in the formation of the first canonical variable for the plough-based cultivation is played by the penetration resistance of the soil in the first data set and by the 1000 seed weight in the second (Table 7). Therefore, the correlation between the 1000 seed weight and the penetration resistance of the soil was the fundamental factor in the canonical correlation between the analysed data sets for plough-based cultivation. The penetration resistance and moisture content of the soil in the first data set and the length of the ears, 1000 seed weight and number of ears per 1 m^2 in the second had the largest role in forming the second canonical variable. In the case of plough-based cultivation, the significant effect of the moisture content and penetration resistance of the soil on the number of ears per 1 m^2 and the 1000 seed weight is confirmed by the simple correlation between these variables and the correlation (canonical factor loadings) between the canonical variables and the analysed factors in each set.

In the case of direct sowing, the greatest part in the formation of the first canonical variable was played by the moisture content of the soil in the first set and by the number of ears per 1 m^2 in the second; the number of ears per unit of land shows the greatest correlation (canonical factor loading) with this canonical variable. In the formation of the second canonical variable, the penetration resistance of the soil played the greatest role among the physical parameters of the soil. From the second data set, the mass of grains per ear was the most important. The significant effect of the penetration resistance of the soil on the mass of grains per ear and that of the moisture content of the soil on the number of ears per 1 m^2 confirm the significant correlation between the studied parameters. The bulk density of the soil has a lesser influence on the variability of the studied components of the crop yield in both systems of cultivation. The presented canonical analysis indicated that the analysed components of winter triticale crop were 78% dependent on the three fundamental physical parameters of the soil in plough-based cultivation and 58% dependent in direct sowing. The remaining unexplained percentage of variability in the analysed characteristics of the structure of the crop yield could be due to differences in the time of sowing in particular years, atmospheric conditions, fungal infections, quality of the material sown and timing of nitrate fertilization. In the case of direct sowing, a large role in the variability of the components of the crop yield was played by changes in the structure and texture of the upper layers of the soil. In the second year of direct sowing of previously uncultivated soil, the penetration resistance of the soil was not found to be significantly lower compared to that in plough-based cultivation. The increased penetration resistance of the soil in the third year of cultivation without a plough was caused by the use of heavy harvesting machinery and by the low organic content in the soil (Dauda and Samari, 2002; Marks and Buczyński, 2002).

The penetration resistance of the soil was a limiting factor in the crop yield in 2003 and 2004. Other publications also report on the significant effect of this physical parameter of the soil on crop yield (Baumhardt and Jones, 2002; Munkholm *et al*., 2003). Despite the increased penetration resi- stance of the soil in 2004, soil that had not undergone

T a b l e 7. Canonical weights of the studied physical parameters of the soil (U) and the components of winter triticale crop yield (V)

Parameters	Plough-based cultivation			Direct sowing		
	Canonical variables of the physical parameters of the soil					
	U1	U2	U3	U1	U2	U3
Penetration resistance	1.42	0.90	0.57	-0.17	1.07	-1.17
Bulk density	-0.12	-0.08	-1.11	-041	-0.03	-0.08
Moisture content	0.57	1.54	-0.93	0.64	0.50	-1.04
	Canonical variables for the components of the crop yield					
	V1	V2	V3	V1	V2	V3
Number of ears per 1m^2	-0.77	-1.08	-004	0.81	0.37	-0.48
Length of ears	2.65	1.94	-0.56	-0.90	0.58	-1.60
Number of grains per ear	-1.20	-1.01	1.30	0.25	-0.22	-1.03
Mass of grains per ear	0.61	0.75	-1.25	0.82	-1.34	-2.87
1000 seed weight	-3.11	-0.90	1.99	0.07	-0.39	-2.38

cultivatory procedures gathered more moisture than ploughed soil. This result was verified in other reports (Viegas and Choudhary, 2002). The greatest effect on the variability of the elements of the structure of the crop yield in the case of plough-based cultivation was first that of the penetration resistance and then that of the moisture content of the soil. A high penetration resistance and a reduced moisture content caused a reduction in the 1000 seed weight. In conditions of direct sowing, the moisture content influenced the variability of the number of ears per unit of land. The results of the study show that this aspect is the fundamental yield- forming factor (Naylor, 1989; Rozbicki and Mądry, 1999). An increased penetration resistance in the case of ploughless cultivation limited the 1000 seed weight and the mass of grains per ear. The significantly different crop yields from 2003-2005 indicate a low degree of stability in the yield of this type of winter triticale.

CONCLUSIONS

1. The presented canonical analysis indicates that the analysed components of winter triticale crop yield are 78% dependent on the three fundamental physical parameters of the soil in the case of plough-based cultivation and 58% dependent in the case of direct sowing.

2. The greatest part in the variability of the components of the crop yield was played primarily by the penetration resistance and then by the moisture content of the soil. In conditions of direct sowing this order was reversed, with moisture content being more important, followed by penetration resistance.

3. The penetration resistance and the moisture content of the soil in the case of plough-based cultivation affected the variability of the mass of a thousand grains. In ploughless cultivation, the penetration resistance of the soil limited the mass of grains per ear. In the case of direct sowing, the moisture content of the soil also influenced the variability in the number of ears per unit of land surface area.

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