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Zonal Tillage as Innovative Element of the Technology of Growing Winter Wheat: A Field Experiment under Low Rainfall Conditions

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Abstract: Zonal tillage, including strip-till, can have a positive effect on soil properties, seed germination, plant emergence, growth, and yield of crops. The aim of this two-factor field experiment was to compare different technologies of basic soil tillage, fertilisation, and sowing of winter wheat carried out after two post-harvest agrotechnical practises in a region with low rainfall. The three treatments of the first factor were: conventional technology (CT)—plough tillage, pre-sowing fertilisation, seedbed preparation and sowing; reduced technology (RT)—plough tillage replaced with deep loosening and (ST)—one pass strip-till technology using a hybrid machine. Agrotechnical practises carried out after the harvest of the previous crop were the second factor treatments, i.e., crushed straw and shallow tillage (TS), mulch from crushed straw (MS). The measurement of the treatment effects included changes in soil moisture, plant emergence, yield components and their correlation, grain yield, and the dependence of the yield components on soil moisture. Wheat growing in ST technology resulted in a higher soil moisture than in RT and CT. Only immediately after winter was the soil moisture similar. Grain yield in ST was similar as in CT and significantly, up to 10.4%, higher than in RT. The higher ST grain yield resulted from uniform plant emergence, greater ear density, and grain weight per ear. The correlation between yield components was weaker in ST than in CT and RT. The positive dependence of the size of the crop components on soil moisture was also weaker. The agrotechnical practises performed right after the previous crop harvest affected neither the soil moisture during the growing season of winter wheat, nor the grain yield and its components.

Keywords: hybrid machine; innovative technology; one pass strip-tillage; soil moisture; wheat

1. Introduction

The main soil tillage system used in the world, especially in Europe, is conventional plough tillage (CT). The necessity to limit the unfavourable effect of agriculture on the environment and to cut on energy consumption in plant production results in an increasingly frequent application of the principles of conservation agriculture, including reduced tillage (RT) and no-tillage [1,2]. The suitability of soil tillage methods depends on climatic conditions [3]. RT is especially recommended in dry climates. Limited soil loosening and mulch reduce unproductive water loss [4,5]. One of the methods of conservation tillage, especially recommended in low rainfall conditions, is zonal tillage—strip till (ST) [6,7]. The essence of ST is deep loosening of narrow soil strips and no interference in soil between the strips. Loosened soil accounts for a maximum of one third of the field area, and more than 50% of plant residue remains on its surface [8,9]. Crop seeds and mineral fertilisers are placed into loosened soil. Seeds are sown after a few days, or even a few months. However, there are few machineries with construction allowing for a deep tillage of soil strips, fertiliser application, and sowing in one pass [10]. A combination of many agricultural practises in a single process line is beneficial to the environment and the economic effect of plant production. Water and soil organic matter losses, as well as fuel inputs and labour time, are lower, whereas biodiversity, soil resistance to erosion, and degradation increase [11,12].

ST has a special enhancing effect on water in soil [13]. According to Jabro et al. [14], the crop water productivity for sugar beet ST technology was 10% higher than for CT technology. Hasan et al. [15] and Alhajj Ali et al. [16] recommend simplified soil tillage methods also for wheat production, including zero tillage and ST, due to the highest water productivity and least total water used.

The ST is easy to perform for the crops grown in a wide row spacing, e.g., corn [17,18], sunflower [19], sugar beet [20], and other plant species [21]. It is difficult to loosen the narrow strips of soil covered with large amounts of plant residue deep down [22] and to perform sowing precisely with a narrow row spacing, e.g., cereal crops. It is possible due to a special hybrid machine construction which facilitates strip tillage, mineral fertilisers application and two-row sowing with one pass [23]. The machine triggers much interest among farmers. Over the last two years, in Poland and in Central and Eastern Europe on large-acreage farms, more than 100 such machines have been operating, mostly for cereal crop production.

With a more and more frequent use of those machines by farmers, resulting from good effects of crop production, a hypothesis has been formulated that ST technology has a positive effect on soil water conditions and that it facilitates receiving at least similar winter wheat yields as CT and RT technologies. The aim of this research has been to verify the hypothesis in various environment conditions due to a three-year field experiment in a region with low rainfall.

2. Materials and Methods

2.1. Experiment Site

The field experiment was performed in three seasons of winter crops growing, namely in 2013/2014, 2014/2015, and 2015/2016. The experiment was located at Śmielin (53°09′04″N, 17°29′11″E, 92 m above sea level), Kuyavian-Pomeranian voivodeship, Poland (Figure 1). The field experiment in successive years was carried out on a soil classified as Cambisol [24]. The average percentage content of sand, silt and clay fractions in soil texture was: 41.4%, 52.3%, 6.3%, respectively. The soil contained available forms of macronutrients: 105 mg P kg^{-1} of soil and 308 mg K kg^{-1} of soil, according to Egner-Riehm, 103 mg Mg kg^{-1} of soil (Schachtschabel method), pH_{KCl} was 6.1. According to the Köppen climate classification, the region shows a warm-summer humid continental climate [25]. Rainfall shortage and droughts often occur at the experiment site [26,27]. Meteorological conditions during the study years and in the long-term period are presented in Figure 2.

Figure 1. Site of field-scale experiment at Śmielin, Kuyavian-Pomeranian voivodeship, Poland [28,29].

2.2. Experimental Design

The experiment was established in a large arable field using commercial agricultural machinery and tools. Plots were 250 m long and 12 m wide, with an area of 3000 m^2. Two experiment factors were distributed in a split-plot design with four replications. Right after the previous harvest the sub-blocks were determined; three areas for winter wheat growing following the respective technologies of the first factor. Then in each sub-block, post-harvest treatments were performed that were compliant with the second experiment factor. The first factor treatments were three different technologies of growing winter wheat with elements of basic tillage, pre-sowing fertilisation, and sowing:

– conventional (CT): plough—20 cm deep, pre-sowing mineral fertilisation on the whole surface, seedbed preparation, sowing,
– reduced (RT): ploughless tillage—20 cm deep loosening, pre-sowing mineral fertilisation on the whole surface, seedbed preparation, and sowing with the combined aggregate,
– strip-till (ST): strip tillage, fertiliser application into loosened strip and two-row sowing with one pass.

Right after the previous crop harvest, prior to basic tillage, two treatments were made:

– crushed straw, shallow tillage (TS),
– no post-harvest tillage, mulch—crushed previous crop straw (MS).

These were the treatments of the second experimental factor.

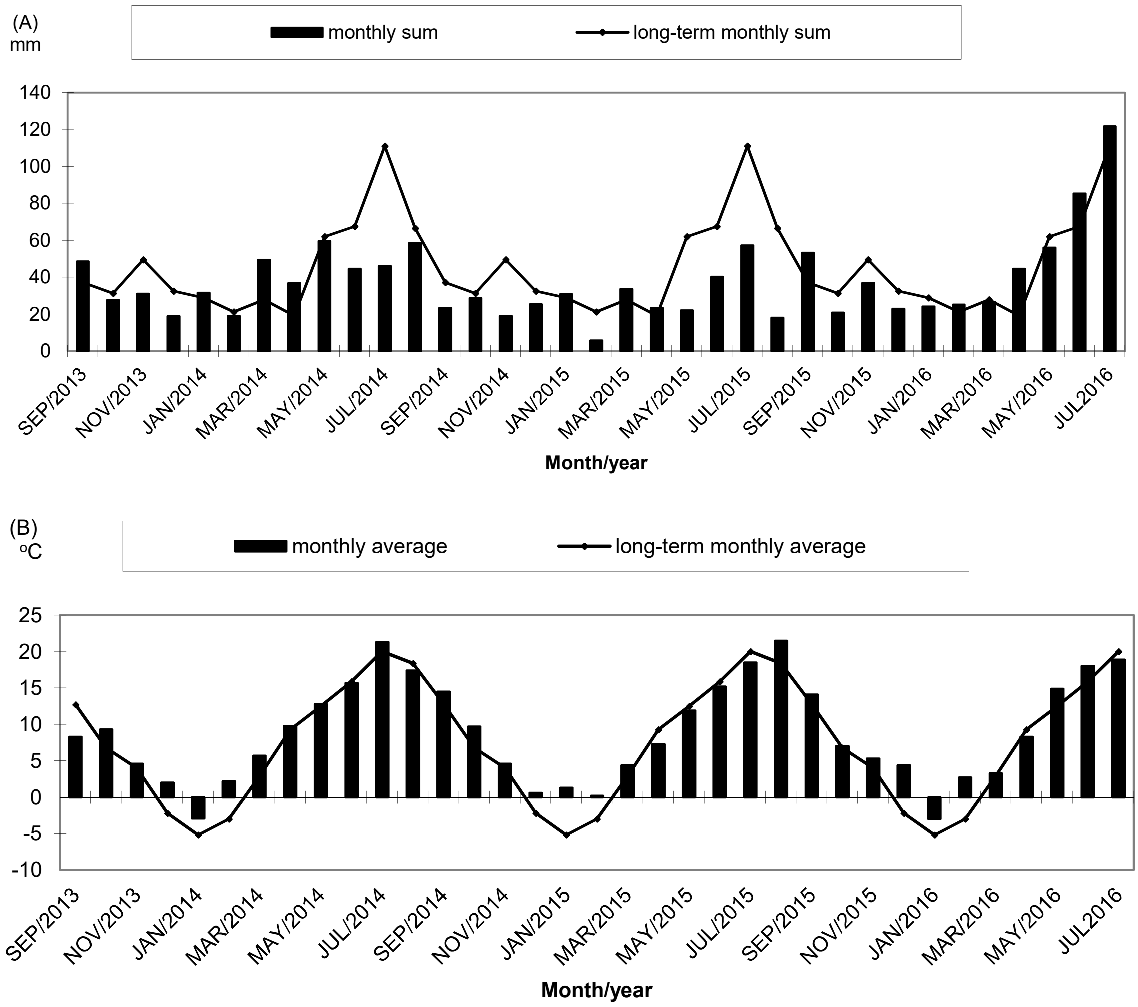

Figure 2. Precipitation (**A**) and air temperature (**B**) at the site of the field experiment.

2.3. Elements of Agrotechnical Practices

Winter wheat cv. Opal was sown depending on the research year, respectively, 15 September in 2014, 12 September in 2015, and 16 September in 2013 at the density of 250 grains per m^2. The row spacing for CT and RT treatments was 14.3 cm, and in ST technology it was 12.0 cm between rows in sowing strip and 36.4 cm between the neighbouring strips. The machines used in CT and RT technology included plough, tillage combined aggregate, fertiliser spreader, seedbed preparation-seed drill combined aggregate: Maschio Gaspardo s4, Horsch Tiger 6 AS, Amazone ZG-TS 8200, Horsch Pronto 4DC, respectively. Tillage, pre-sowing fertilisation, and wheat sowing following technology ST were performed with Mzuri Pro-Til 4T machine. Pre-sowing fertilisation was the same for all the treatments and amounted to 150 kg ha^{-1} of fertiliser with composition NPKS 8:20:30:5. Topdressing N fertiliser was applied in spring at three rates: BBCH 25–28 (70 kg N ha^{-1}), BBCH 32–33 (60 kg N ha^{-1}) and BBCH 53–55 (40 kg N ha^{-1}). During the vegetation period, the plants were protected applying the recommended active ingredients (herbicides: diflufenican, isoproturon, metribuzin, flufenacet, fenoxaprop-P-ethyl; fungicides: protioconazol, bixafen, spiroxamine, tebuconazole; insecticides: deltamethrin, dimethoate; growth regulators: mepiquat chloride, calcium prohexadione, chlormequat chloride). Winter wheat was harvested at full maturity of the plants on 26 July in 2014, 22 July in 2015, and 8 August in 2016.

2.4. Samples and Measurements

Four places along each plot with measurement units 1 m^2 in size were determined. For each unit the plant density was recorded 14 days after sowing at BBCH 11–12 and finally 2 weeks later. The ear density was evaluated at BBCH 89. In measurement units, there were collected ears in which the number of grains, grain weight per ear, and thousand grain weight were determined. Those places were also provided with soil moisture measurement using PR2/4 Profile Probe-Delta-T Devices. The measurements were taken twice a month throughout the winter wheat growing season, except for winter. Winter wheat yield was collected separately from the entire surface of each plot using a combine harvester.

2.5. Data Analysis

The results were statistically analysed. A factorial ANOVA was performed. There, the significance of the effect of the experiment factors were evaluated (first, technologies of growing winter wheat, second, post-harvest agrotechnical practises), and their interaction on soil moisture and the winter wheat features. To evaluate the significance of differences between average values, the Tukey test was used at $p = 0.05$. There has been also evaluated the main effects and the interactions of the effect of the research year (the third factor). The interaction between the factors was insignificant. Despite a varied soil moisture across the research years, in each of them the dependence of soil moisture on individual wheat growing technologies was similar. The paper provides only the significant effect of the treatments on a given trait. For the treatments of the first factor, Pearson's correlation coefficients between the yield components were determined and between the soil moisture during growing season of winter wheat and its yield components.

The plant density distribution was estimated for each treatment with standard error (SE), standard deviation–doubled (2s), and the value of deviating and extreme results. The results of the analysis are given in box plot.

For data verification, Statistica.PL 12 software package was used [30].

3. Results

In the first research year, most favourable for winter wheat emergence, the value of standard deviation of the plant density 14 days after sowing was similar in all the experiment treatments. Only the standard deviation of winter wheat density in ST/TS was smaller than in RT/TS and CT/TS by about 2.5 and 5.0 plants m^{-2}, respectively (Figure 3A). A spatial variation in the plant density in the second year was much greater than in the first one, which is seen from a higher value of standard deviation as well as minimum values of plant density of only 40–70 plants m^{-2} in CT and RT. A more evenly-distributed plant density was found in the treatments with ST, irrespective of post-harvest treatments. In those treatments the standard deviation of that trait was about 3-fold lower than in treatments CT and RT, and the lowest plant density was about 160 plants m^{-2} (Figure 3B). In the third year, the winter wheat plant density in CT and RT also differed a lot, and the minimum density was about 80 plants m^{-2} – CT and 60 plants m^{-2} – RT. More evenly-distributed plants of winter wheat were found in ST. The standard deviation for that trait in that case was a few-fold lower, and the lowest identified plant density in that treatment was not lower than 160 plants m^{-2} (Figure 3C).

In each research year, the basic tillage, pre-sowing fertilisation, and sowing showed a significant effect, although, in a varied way, on the plant density after emergence. In two out of three research years, the treatments differentiated the ear density and grain yield. The grain weight per ear depended on the method of the basic tillage, fertilisation and sowing only in the 2015/2016 season. The first factor treatments, however, did not affect the number of grains per ear and one thousand grain weight. Post-harvest treatments also did not significantly differentiate any of the six features of winter wheat. The effect of post-harvest treatments and the interaction of both factors on yield components and winter wheat grain yield in the research years was non-significant (Table 1).

Table 1. Significance of the effect of basic tillage, pre-sowing fertilisation and winter wheat sowing (I), post-harvest treatments (II), and the interaction of the factors (I × II) on yield components and winter wheat grain yield in the research years, F test (* – significant at $p < 0.05$; ns – non-significant).

Feature	Research Year								
	2013/2014			2014/2015			2015/2016		
	I	II	I × II	I	II	I × II	I	II	I × II
Plant density	*	ns	ns	*	ns	ns	*	ns	ns
Ear density	ns	ns	ns	*	ns	ns	*	ns	ns
No of grains per ear	ns	ns	ns	ns	ns	ns	ns	ns	ns
Grain weight per ear	ns	ns	ns	ns	ns	ns	*	ns	ns
Thousand grain weight	ns	ns	ns	ns	ns	ns	ns	ns	ns
Grain yield	ns	ns	ns	*	ns	ns	*	ns	ns

Plant density of winter wheat after emergence in ST was significantly lower than in RT only in the first research year. In the successive two years, the plant density in ST technology was higher than in RT, and in the 2014/2015 season it was also higher than CT (Table 2). ST, as compared with RT, enhanced the ear density in two out of three research years, especially after the cold winter of 2015/2016 and on average for the entire period. The ears of winter wheat grown in ST in the 2015/2016 season and on average in 2013–2016 showed the grain weight higher than in RT and not lower than in CT. The grain yield in ST technology was higher than in RT, except 2013/2014 season, and in a single research year was also higher than the grain yield in CT. In the 2015/2016 season, winter wheat yield in ST was even 10.4% higher than in RT technology.

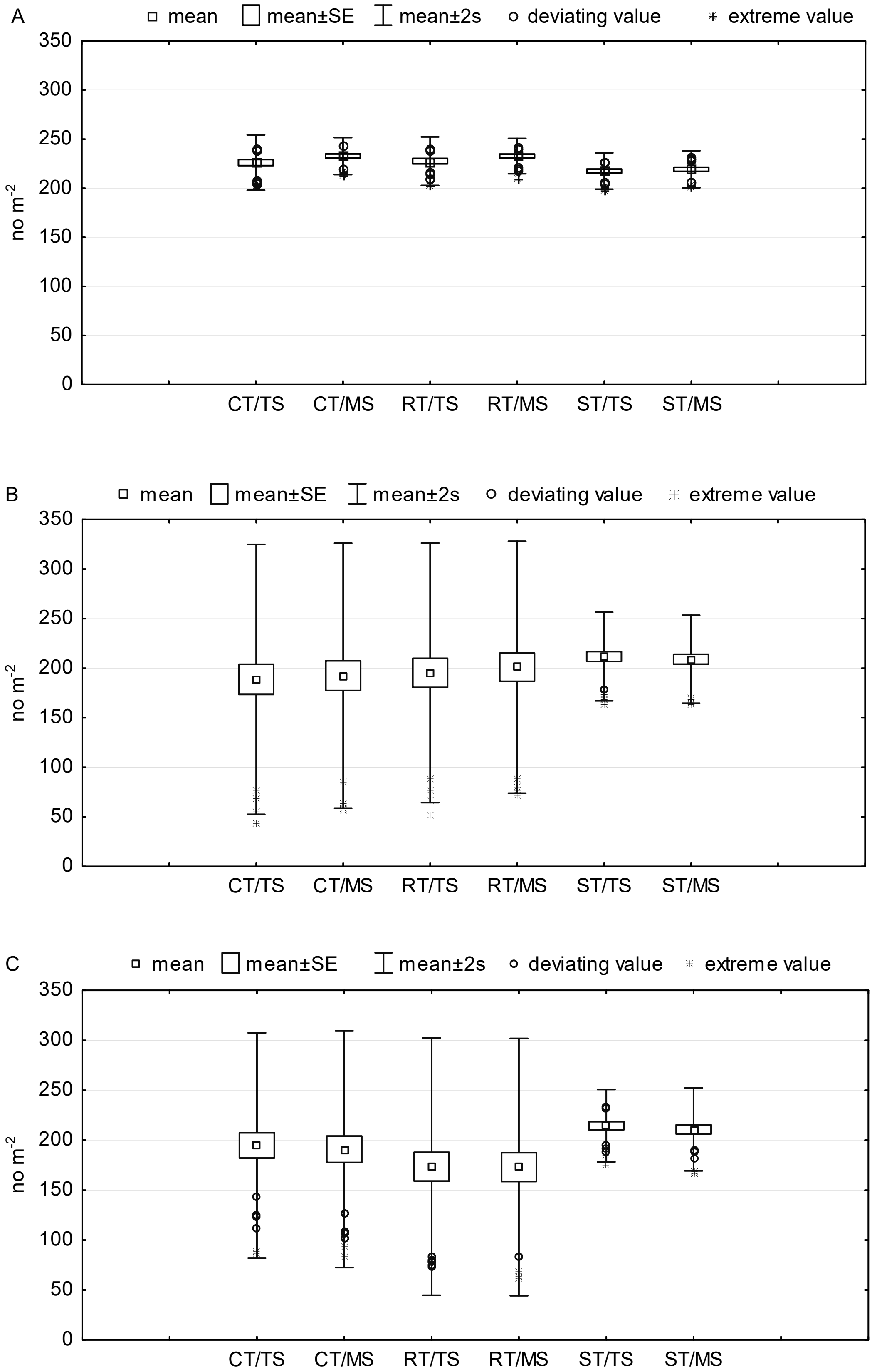

Figure 3. Variation in plant density in the first (**A**), second (**B**), and third (**C**) research year depending on winter wheat growing technology (CT—conventional, RT—reduced, ST—strip-till) and post-harvest treatments (TS—shallow tillage, MS—mulch).

Table 2. Effect of technology basic tillage, pre-sowing fertilisation, and winter wheat sowing on the yield components and winter wheat grain yield.

Technology	Research Year		
	2013/2014	**2014/2015**	**2015/2016**
Plant density after emergence (no m^{-2})			
Conventional (CT)	229 ab	191 c	193 ab
Reduced (RT)	230 a	198 b	173 b
Strip-till (ST)	218 b	210 a	213 a
Ear density (no m^{-2})			
Conventional (CT)	685 a	641 ab	472 a
Reduced (RT)	684 a	630 b	451 b
Strip-till (ST)	676 a	663 a	481 a
Grain weight per ear (g)			
Conventional (CT)	1.61 a	1.49 a	1.65 a
Reduced (RT)	1.57 a	1.49 a	1.58 b
Strip-till (ST)	1.60 a	1.52 a	1.65 a
Grain yield (t ha^{-1})			
Conventional (CT)	10.35 a	9.22 b	7.56 a
Reduced (RT)	10.29 a	9.01 b	6.70 b
Strip-till (ST)	10.12 a	9.56 a	7.40 a

a, b – letters in columns indicate significantly different trait average values for technologies at $p < 0.05$.

In ST technology, the correlation between yield components was lower than in CT and RT, e.g., the ear density and the number of grains in the ear, as well as the ear density and grain weight per ear (Table 3). The relationship between the number of grains and the weight of grain in the ear and the weight of a thousand grain was non-significant.

Table 3. Pearson's correlation coefficients between the yield components depending on the basic tillage, pre-sowing fertilisation, and winter wheat sowing technology (N = 32).

Yield Component	Yield Component			
	(1)	**(2)**	**(3)**	**(4)**
Conventional (CT)				
Ear density (1)	–	−0.723	−0.719	ns
No of grains per ear (2)		-	0.630	−0.487
Grain weight per ear (3)			–	ns
Thousand grain weight (4)				–
Reduced (RT)				
Ear density (1)	–	−0.769	−0.805	ns
No of grains per ear (2)			0.684	−0.516
Grain weight per ear (3)		-	–	−0.386
Thousand grain weight (4)				–
Strip-till (ST)				
Ear density (1)	–	−0.512	−0.489	ns
No of grains per ear (2)			0.713	ns
Grain weight per ear (3)		–	–	ns
Thousand grain weight (4)				–

ns – non-significant.

The basic soil tillage, fertilisation, and sowing technology affected the soil moisture throughout the winter wheat growing season (Figure 4). On average, in the research years the soil moisture in the 0–10 cm and 10–20 cm layers in the field of winter wheat grown following the ST was higher than CT and RT. Right after winter, the water content in soil was the highest and only in that period it did not depend on the soil tillage and sowing technology.

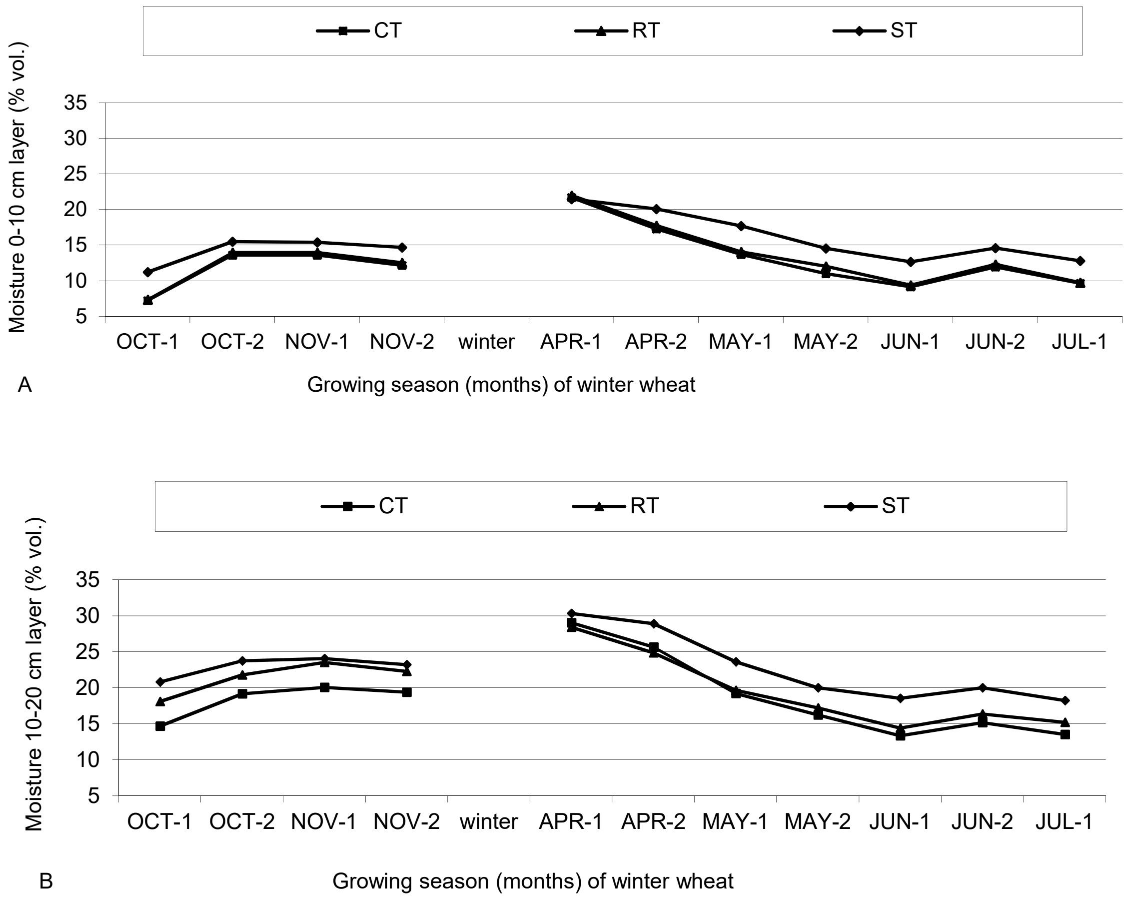

Figure 4. Soil moisture in the 0–10 cm (**A**) and 10–20 cm (**B**) layers during the growing season of winter wheat depending on the basic tillage, pre-sowing fertilisation, and sowing technology (average in the three research years).

As for growing winter wheat in ST, a weaker dependence between its yield components and soil moisture than in CT and RT was found (Table 4). Apart from that, there were identified no significant dependencies between the soil moisture and the density of ears and the number of grains per ear, thousand grain weight, grain weight per ear, in the 2013/2014, 2014/2015, 2015/2016 seasons, respectively. Although, the correlation between soil moisture and these features of winter wheat was positive and significant.

Table 4. Pearson's correlation coefficients between the soil moisture during the growing season of winter wheat and its yield components depending on the basic tillage, pre-sowing fertilisation, and sowing technology (*N* = 32).

Yield Component	Year		
	2013/2014	2014/2015	2015/2016
Conventional (CT)			
Ear density	0.586	0.811	0.740
No of grains per ear	0.567	0.733	0.632
Grain weight per ear	0.612	0.713	0.567
Thousand grain weight	0.608	0.663	ns
Reduced (RT)			
Ear density	0.629	0.798	0.675
No of grains per ear	0.517	0.748	0.655
Grain weight per ear	0.571	0.730	0.533
Thousand grain weight	0.619	0.665	ns
Strip-till (ST)			
Ear density	ns	0.577	0.491
No of grains per ear	ns	0.630	0.526
Grain weight per ear	0.495	0.524	ns
Thousand grain weight	0.547	ns	ns

ns – non-significant.

4. Discussion

Soil tillage plays an important role in crop production [31]. Rieger et al. [32] point to tillage and fertilisation as the agrotechnical elements strongly differentiating growth, yield components and grain yield. According to the authors, a decrease in the grain yield due to simplified tillage was a result of a lower ear density and thousand grain weight. In the present research, the interactive effect of the elements of winter wheat technology and years of study on yield components and the grain yield could have resulted from the different effect of the tillage on soil properties depending on the weather pattern. According to Zibilske and Bradford [33] and Williams et al. [34], zone tillage, e.g., strip-till or ridge tillage, enhances the retention and accumulation of water in topsoil. This is due to the improvement of many physical and chemical properties of soil, e.g., the accumulation of organic matter, the formation of permanent soil structure aggregates [35,36]. In the present research, a higher water content in soil, both in autumn and spring–summer winter wheat vegetation, was found for ST technology. Similarly, as reported by Hossain et al. [37], the difference in soil moisture, showing an advantage of ST technology, as compared with RT and CT tillage, was increasing in no-precipitation periods.

The even distribution of winter wheat emergence and its plant density seems to be related to the weather pattern in the study years and perhaps the interactive effect of the tillage methods and environmental conditions on the seedbed soil properties. In the year with favourable rainfall conditions in the sowing period, the emergence was uniform. In the year with low rainfall, emergence was uniform only for ST technology. Diacono et al. [38] indicated that the weather conditions throughout the growing season affect the spatial variability of wheat plants as well as the plants' reaction to the tillage method. Licht and Al-Kaisi [39] indicated that ST affects the moisture and temperature of the topsoil and shapes favourable conditions to seed germination and plant emergence. According to Evans et al. [40], it can be concluded that strip-till improves the surface layer conditions only in some years. In the present research rainfall in September and the first half of October 2014 was very low, and single rainfall events did not exceed 7.0 mm. In 2015 after dry August, from 2 September to 10 October rainfall was only 26 mm. It is in those two years that the application of ST technology resulted in the winter wheat good plant density after emergence and its even distribution in large experiment area was better than in CT and RT. In the autumn of 2013, a rainfall and its favourable distribution during sowing resulted in a higher plant density in CT and RT technology.

Scientific literature showed few results of the research which would compare the effect of ST with other tillage methods on wheat yielding. Choudhary and Singh [41] show that the yields of that crop in ST and no-till were similar and about 4% higher than after traditional plough tillage. In our own studies, the increase in winter wheat yield growing in ST technology compared to RT was 4.2%, however, in one year it was even over 10%. In the 2014/2015 season, the yield in ST technology was also higher than in CT by 3.7%. The research reported by other authors indicated that the wheat yield in ST technology can be not only a few percent higher but also by 0.5 t ha^{-1} (i.e., over 10%) higher, as compared with CT [42,43].

Deep tillage of only the soil strips increases the effectiveness of the water use by plants and its productivity as compared with conventional tillage [44]. It is of special importance for a low amount of precipitation and water in soil [45,46]. ST also weakens the response of the plants to varied soil conditions, including the water conditions at the scale of the field [47]. This was probably the reason for the weaker correlation between soil moisture and winter barley yield components, as compared with CT and RT tillage. In the present research, the dependence between respective yield components was also weaker in ST technology.

5. Conclusions

To conclude, one can state that ST technology facilitated producing the same grain yield as CT, and significantly higher than RT, especially in the years with an unfavourable weather pattern. The grain yield in ST resulted from uniform plant emergence, greater ear density and grain weight per ear. This technology of winter wheat growing weakens the dependence of the yield components on soil moisture and their mutual correlations.

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