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The Yield and Weed Infestation of Winter Oilseed Rape (*Brassica napus* L. ssp. *oleifera* Metzg) in Two Tillage Systems

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Abstract: Results from a four-year field experiment were used to evaluate the effect of conventional tillage (CT) and no-tillage (NT) systems on the yield, selected yield and crop structure elements, weed infestation, and contents of fat and glucosinolates in the seeds of winter oilseed rape (*Brassica napus* L. ssp. *oleifera* Metzg). The study proved the beneficial effect of the NT system on the winter rape seed yield only during the precipitation shortage in the growing season. In the years with a sufficient sum of precipitation, a higher seed yield was produced in the CT than in the NT system. Considering the average values from the four-year study period, the seed yield and straw yield, plant density after emergence and before harvest, number of branches and main shoot length, and finally the 1000 seed weight were significantly higher in the CT compared with the NT system. In contrast, the NT system proved more beneficial regarding seed weight per silique and fat content of the seeds. The statistical analysis of the study results showed no effect of the tillage systems on the glucosinolate content of the seeds. In turn, a significantly higher number and air-dry weight of weeds as well as an increased density of *Viola arvensis* weeds were demonstrated in the NT plot compared with the CT plot of winter oilseed rape. *Sonchus asper* and *Sonchus arvensis* were identified in the NT plot but not in the CT plot. A significantly higher density of *Chenopodium album* and *Euphorbia helioscopia* weeds was detected in the CT system compared with the NT system. The statistical analysis of study results regarding weed community diversity showed similar values to the Shannon-Weinner diversity index (H') in both tillage systems and a significantly higher value of the Simpson dominance index (SI) in the NT system compared with the CT system.

Keywords: winter oilseed rape; tillage system; yield; weed infestation of crop stand; content of fat and glucosinolates

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1. Introduction

Oilseed rape, and especially its winter form, is currently the most frequently cultivated oil-bearing crop not only in Poland but also in the entire European Union. Moreover, Poland ranks 8th among its global producers [1,2]. Rapeseed oil is widely known for its high content of monounsaturated fatty acids; a moderate content of polyunsaturated fatty acids; and a substantial content of tocopherols, phytosterols, and omega-3 fatty acids. Considering today's nutritional standards, it is probably the only well-balanced oil among all the vegetable oils [3,4]. Due to the great importance of oilseed rape in the food and chemical industries and its role as a source of alternative renewable fuels, research aimed at determining optimal agrotechnical conditions to ensure high yields of this crop with beneficial quality parameters is of key importance.

Soil tillage has a significant impact on the yield and its quality because it directly affects the growth and development of crops by modifying the physical, chemical, and biological properties of the soil [5–11]. Properly conducted tillage should counteract the negative outcomes of the technological progress and mechanization of agriculture, including excessive soil compaction, and at the same time, should create optimal conditions for plant growth and yielding [12–14].

In Poland, the most popular method of soil pre-treatment for crops sowing and planting is still the conventional tillage system; this method, however, may increase production costs, compact the soil and, therefore, cause its insufficient aeration [13,15–17]. Other premises for abandoning the conventional tillage system include the destruction of topsoil structure and the reduction of soil biodiversity [18,19]. Conventional tillage, especially on heavy soils, may trigger a tendency for lump formation and is additionally associated with a high risk of soil drying after ploughing [20]. For the above reasons, the use of plows is often limited in modern agriculture and other tools, such as disc harrows or grubbers, are used instead [21]. The no-tillage (NT) system loosens and mixes the topsoil without the need of turning it over. The studies conducted so far indicate that NT has a positive effect on soil quality by improving its structure, enhancing its biological activity, and its increasing water retention capacity [6,22,23]. An important aspect in favor of harnessing NT is that it can reduce production costs and increase its profitability by reducing energy consumption and labor inputs compared with the conventional system [24,25]. According to Omidi et al. [26], the no-tillage system, with lower capital and labor inputs, can be just as profitable as a conventional system, even with lower rape seed yields. The decision to introduce no-tillage cultivation system may therefore be driven by both economic and environmental concerns [19,22,27]. However, opinions about the influence of tillage systems on crop yield are inexplicit, as the experimental results obtained are largely influenced by the habitat and climatic conditions as well as the species of the cultivated crop [13,22,28–36]. The results of many studies also indicate that simplifications in tillage, including the use of NT, may significantly increase the weed infestation of the crop stand and, consequently, decrease the yield of cultivated crops [37–39]. Such an increase may be due to the accumulation of freshly shed weed seeds in the topsoil layer [40–42]. As a matter of fact, a tillage system does not affect the seed bank size but changes both the composition and distribution of diaspores in the soil profile [34]. The results of studies regarding the effect of tillage systems on the weed infestation of crops are not unequivocal. Santín-Montanyá et al. [43] did not prove that conventional tillage and no-tillage systems have a significant impact on the number of weeds in the winter wheat crop. However, the results of these authors' research, similar to that of Gawędy et al. [44] show that weed community diversity, as expressed by the Shannon index, increased under the NT system. However, the experiences of some authors indicate a positive influence of the NT system on the yield and weed infestation of plants. In the experiment of Romaneckas et al. [11] ploughless soil tillage mostly had a significant positive influence on winter oilseed rape productivity parameters. Winter oilseed rape plants grown under the NT system grew about 67 boughs and up to 4000 pods more per m^2 than those grown under the CT system, which led to a higher (41%) biological yield of seeds. Whereas Kende et al. [30] demonstrated a positive effect of NT cultivation on plant weed infestation. During the six years of the wheat, weed coverage significantly decreased in all treatments, and the number of species also dropped from 18 to five. Weed coverage most often decreased in the order: direct drilling > disking > tine tillage (deep) > tine tillage (shallow) > subsoiling > ploughing. This study shows the possibility of the weed coverage decrease by the well-adopted soil tillage, including ploughless systems.

The study presented was undertaken because tillage systems can strongly affect the size and quality of crop yield and because of the paucity of literature data on winter oilseed rape response to the no-tillage system under soil and climatic conditions of Poland. This study aimed to analyze the effect of tillage systems: conventional tillage (CT) and no-tillage (NT), on the yield, selected elements of seed and crop yield structure, and weed infestation of winter oilseed rape. Additional analyses were carried out to evaluate the effect of tillage systems on the contents of fat and glucosinolates in the seeds of this oil-bearing crop.

2. Materials and Methods

2.1. Location of the Experiment and Soil and Climatic Conditions

A field experiment was conducted over the period of 2013–2017 (growing seasons of rapeseed: 2013/2014, 2014/2015, 2015/2016, 2016/2017) at the Experimental Farm in Uhrusk, owned by the University of Life Sciences in Lublin (51°18′ N, 23°36′ E) on Rendzic Phaeozem [45] with grain-size distribution of sandy loam. The humus content of the soil (0–30 cm layer) the experiment was established on was 1.6%, and the content of fine particles (<0.02 mm) was 20.7%. The soil had an alkaline pH value (KCl = 7.6 in 1 M) and was very rich in phosphorus (228.7 mg P kg^{-1} soil) and potassium (149.2 mg K kg^{-1} soil) and very low in magnesium (15 mg Mg kg^{-1} soil).

Figure 1 presents the distribution of precipitation and air temperatures in individual months of the growing seasons of winter oilseed rape. Compared with the long-term average, a lower sum of precipitation was recorded in the 2014/2015 season, a similar one in the growing season of 2016/2017; however, higher ones were recorded in the 2013/2014 and 2015/2016 seasons. Throughout the experimental period, the highest sum of precipitation was recorded in the third growing season of rape (2015/2016). It was higher by 125.5 mm than the long-term average of the same period and by 234.4 mm than the precipitation recorded in the driest 2014/2015 season. In the most humid growing season of winter rape (2015/2016), the highest sum of precipitation was noted in September and in the seed harvest month (July). The sums of precipitation in the remaining months were evenly distributed. In the driest growing season of 2014/2015, the lowest sum of precipitation was recorded in the period of vegetation cessation (November), wintering (February), and at the onset of seed ripening (June).

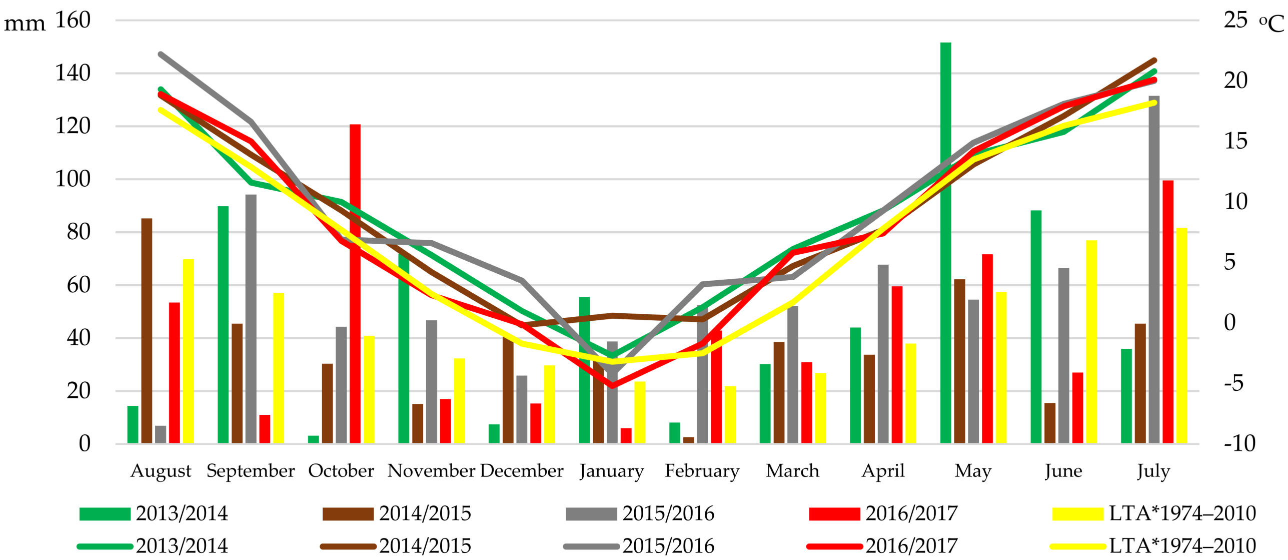

Figure 1. Total precipitations and mean monthly air temperature in the growing season of winter oilseed rape, recorded by the Meteorological Station in Bezek (Poland). * LTA—long term average.

All growing seasons of winter oilseed rape (August–July) were characterized by a higher average air temperature compared with the long-term average (Figure 1). The warmest turned out to be the third growing season of rape (2015/2016). Across the experimental years, the lowest average air temperature was noted in the 2016/2017 season, mainly in the winter months (December–February). In all study years, the temperatures recorded during seed ripening were beneficial for this process (June, July).

2.2. Experimental Design and Agronomic Practices

A four-year field experiment was established in a randomized block design in three replications. A single plot area was 32 m^2. Winter oilseed rape of 'Arsenal F1' cultivar, grown after winter wheat, was analyzed in the study. This rape cultivar is highly resistant to white mold and stem cancer of brassicas and has low susceptibility to lodging.

Winter oilseed rape was grown in a four-field crop rotation: soybean—winter wheat—rapeseed—winter wheat, which was conducted in all the fields simultaneously. The same tillage systems were used for all plants. The straw after the winter wheat harvest was harvested from the field. In the season preceding the described experiment (2012/2013), a crop rotation was established (soybean—winter wheat—winter oilseed rape—winter wheat) so that in the following year, the tested plants would be sown after the appropriate forecrops, e.g., oilseed rape after winter wheat.

The experimental factor analyzed was the tillage system: conventional tillage—CT and no-tillage—NT. The conventional tillage included pre-sowing ploughing to the depth 20 cm, harrowing, seed sowing, and post-sowing harrowing. In the no-tillage system (NT), ploughing and harrowing was replaced by cultivation with a stubble cultivator (grubber (depth 15 cm) + cage roller), while the other tillage operations were analogous to those used in the CT system. The remaining elements of winter oilseed rape agro-engineering measures were the same on all plots. Winter oilseed rape was sown in 2013, 2014, 2015, and 2016, between the 21 and 26 August (depending on the study year), and harvested in 2014, 2015, 2016, and 2017, in the third decade of July when the plants had reached full maturity (BBCH 89). Qualified, dressed sowing material was sown with a precision seed drill in the amount of 50 seeds per 1 m^2 at a row spacing of 20 cm. The phosphorus-potassium fertilization and the first nitrogen dose were applied before sowing, at the following rates: N—35 kg ha^{-1} (ammonium nitrate 34.5%), P—70 kg ha^{-1} (superphosphate 40%), and K—50 kg ha^{-1} (potassium salt 60%). Nitrogen was applied as top dressing in two terms—90 kg ha^{-1} at the 5 side shoots detectable stage (BBCH 25) and 50 kg ha^{-1} at the 4 visibly extended internodes stage (BBCH 34). To control weed infestation, a Butisan Star 416 EC herbicide (metazachlor 333.0 g L^{-1} and quinmerack 83.0 g L^{-1}) was applied immediately after sowing in a dose of 2.5 L ha^{-1}, and a Fusilade Forte 150 EC herbicide (fluazifop-P-butyl 150.0 g L^{-1}) was applied at the fourth leaf stage (BBCH 13) in a dose of 1.5 L ha^{-1}. The intensity of pest invasion was reduced by the use of a Mavrik 240 EW insecticide (tau-fluvalinate 240.0 g L^{-1}) applied in a dose of 0.2 ha^{-1} because of the threat of common pollen beetle and cabbage seed weevil appearance.

2.3. Methods of Plant Analyses

Evaluations and biometric measurements were carried out on each plot. Plant density was determined per plot area of 1 m^2 in two terms: in the autumn before vegetation cessation and before harvest. Before the harvest, 20 plants were used to determine: main shoot length and number of branches, number of siliquae per plant as well as number and weight of seeds per silique. After the harvest, 1000 seed weight was determined as well. Seed yield and straw yield were determined separately from each plot, and the results obtained were converted per hectare. Winter rape seeds were harvested in one stage with a Wintersteiger harvester. The straw from each plot was weighed and removed from the field.

The fat content of the seeds was determined with a modified Soxhlet method (ISO 659: 2009). The content of glucosinolate was determined with the method involving methanolic extraction, purification and enzymatic desulfation, followed by reverse-phase chromatography (ISO 9167-1: 1992). The above data was used to calibrate the OmegAnalizer G produced by Bruins Instruments. The wavelength range was from 730 to 1100 nm transmission with a scan increment of 5 nm. Automatic feed with multiple sub-sample measurements allowed repeatable results for the tested seed parameters to be achieved.

The evaluation of the species composition of the weed community as well as of the weed density and air-dry weight of weeds was performed each year with the botanical-gravimetric method at the seed growth and ripening stage (BBCH 85) [46]. The sampling area was delineated by a quadrat frame with dimensions of 1 m × 0.5 m in two randomly selected points of each plot. Weed species nomenclature followed Mirek et al. [47].

The Shannon-Wienner diversity index (H′) and Simpson dominance index (SI), were computed using the following formulas [48,49]:

$$H' = -\Sigma \text{ Pi ln Pi} \quad (1)$$

$$SI = \Sigma \text{ Pi}^2 \quad (2)$$

where:

Pi—probability of species occurrence in a sample,
Pi = n/N,
n—number of individuals in species,
N—total number of individuals in the sampling area,
ln—natural logarithm.

The higher the value of the Shannon-Wiener index, the greater the diversity of a community. The range of Simpson index values is from 0 to 1 with values close to 1 indicating a clear dominance of one or several species.

2.4. Statistical Analysis

The study results collected over the period 2014–2017 were analyzed using the analysis of variance (ANOVA), and the significance of differences between mean values was estimated using the Tukey test at a significance level of $p < 0.05$. Correlations were established for the effect of tillage systems and study years, and their interactions, on seed yield and straw yield, contents of fat and glucosinolates in the seeds, as well as weed infestation of winter oilseed rape. A total of 24 results (2 tillage systems × 4 years × 3 replicates) were used for statistical calculations. In addition, Pearson's linear correlation coefficient and determination coefficient (R^2) were computed, and linear regression analysis was conducted to find correlations between selected traits (yield and its components, yield and weed density, yield and air-dry weight of weeds). All computations were made with Statistica 14.0.0 software (TIBCO Software Inc., Tulsa, OK, USA).

3. Results

3.1. Yield and Yield Components of Winter Oilseed Rape

Grain yield and straw yield of winter oilseed rape were significantly higher in the conventional tillage system (CT) compared with the no-tillage system (NT), i.e., by 8.8% and 13.7%, respectively (Table 1). Plant density after emergence and before harvest was also higher in the CT than in the NT system. In 2017, seed yield was significantly lower than in 2016, as well as straw yield—compared to 2015 and 2016.

Table 1. Yield of seeds and straw as well as winter oilseed rape plant density depending on the tillage system (mean for 2014–2017) and research years.

Specification	Seeds Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Plant Density after Emergence (Plants m^{-2})	Plant Density before Harvest (Plants m^{-2})
		Tillage system		
CT	5.08 a	7.54 a	59.7 a	42.2 a
NT	4.67 b	6.63 b	56.3 b	39.2 b
p-Value	0.0000 ***	0.0000 ***	0.0054 **	0.0057 **
		Years		
2014	4.93 ab	7.06 ab	59.8 a	40.7 a
2015	4.85 ab	7.16 a	57.2 a	41.4 a
2016	4.96 a	7.16 a	56.0 a	40.5 a
2017	4.77 b	6.96 b	59.0 a	40.2 a

Table 1. *Cont.*

Specification	Seeds Yield ($t\ ha^{-1}$)	Straw Yield ($t\ ha^{-1}$)	Plant Density after Emergence (Plants m^{-2})	Plant Density before Harvest (Plants m^{-2})
p-Value	0.0435 *	0.0075 **	0.0916	0.7493

CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values. * Significance level at $p \leq 0.05$, ** significance level at $p \leq 0.01$, *** significance level at $p \leq 0.001$.

Data presented in Table 2 indicate that rape seed yield was significantly higher in the conventional compared with the no-tillage system in the first year (2014) and in the fourth year (2017) of the experiment. In the second year of the experiment (2015), characterized by the lowest sum of precipitation, the seed yield was 10.2% higher in the NT than in the CT system. In contrast, the CT system produced a significantly higher straw yield than the NT system in 2014 and 2016. A smaller plant density after emergence and before harvest was recorded in 2017 in the NT system compared to the CT system. The highest seed yield and plant density after emergence and before harvest were determined in 2017 under CT conditions, and the highest straw yield was in 2016 and was also in the CT system.

Table 2. Interactive dependencies of tillage systems and years of research in determining winter oilseed rape yield of seeds, straw, and plant density (mean for 2014–2017).

Years	Tillage System	Seeds Yield ($t\ ha^{-1}$)	Straw Yield ($t\ ha^{-1}$)	Plant Density after Emergence (No. Per m^2)	Plant Density before Harvest (No. Per m^2)
2014	CT	5.23 ab	7.90 b	63.3 ab	43.0 a
	NT	4.63 c	6.22 e	56.3 bc	38.3 ab
2015	CT	4.61 c	7.05 cd	54.3 c	41.0 ab
	NT	5.08 b	7.27 c	60.0 abc	41.7 ab
2016	CT	5.00 b	8.20 a	57.3 ac	40.7 ab
	NT	4.91 b	6.12 e	54.7 c	40.3 ab
2017	CT	5.47 a	7.00 cd	64.0 a	44.0 a
	NT	4.06 d	6.91 d	54.0 c	36.3 b
p-Value		0.0000 ***	0.0000 ***	0.0006 ***	0.0147 *

CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values. * Significance level at $p \leq 0.05$, *** significance level at $p \leq 0.001$.

The statistical analysis proved the effect of tillage systems on seed weight per siliqua, branch number in the main shoot, main shoot length, and 1000 seed weight (Table 3). Compared with the NT system, the crop produced in the CT system was characterized by a higher number of branches in the main shoot, main shoot length, and 1000 seed weight, i.e., by 5.2, 5.5, and 5.8%, respectively. In contrast, the seed weight per siliqua was 3.6% higher in the NT than in the CT system.

Data presented in Table 4 indicate that the interaction of tillage systems and the study year significantly affected the branch number and length of the main shoot, and 1000 seed weight. Likewise, the seed yield, the number of branches, and the length of the main shoot were significantly higher in the CT than they were in the NT system in 2014 and 2017, i.e., by 13.5% and 8.3% as well as by 19.4% and 14.2%, respectively. In 2017, the 1000 seed weight was lower by 15.3% in the NT system compared to the CT system. The highest branch number and length of the main shoot, and 1000 seed weight were obtained in 2017 in the CT system, whereas the lowest values of these yield structure elements were determined in the same year in the NT system.

Table 3. Winter oilseed rape yield and crop components depending on the tillage system (mean for 2014–2017) and the research years.

Specification	Siliqua Number Per Plant (pcs.)	Seed Number Per Siliqua (pcs.)	Seed Weight Per Siliqua (mg)	Branch Number in the Main Shoot (pcs.)	Main Shoot Length (cm)	1000-Seed Weight (g)
			Tillage system			
CT	120.1 a	23.4 a	118.0 b	8.1a	140.8 a	4.75 a
NT	117.9 a	24.5 a	122.2 a	7.7 b	133.8 b	4.49 b
p-Value	0.0956	0.2918	0.0009 ***	0.0052 **	0.0000 ***	0.0002 ***
			Years			
2014	119.8 a	24.0 a	121.0 a	7.9 a	138.3 a	4.63 a
2015	118.7 a	23.5 a	120.3 a	7.9 a	137.5 a	4.64 a
2016	118.4 a	24.7 a	119.9 a	7.8 a	136.1 a	4.58 a
2017	119.1 a	23.6 a	119.2 a	7.9 a	137.2 a	4.64 a
p-Value	0.8436	0.8368	0.6571	0.9790	0.6068	0.8622

CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values. ** Significance level at $p \leq 0.01$, *** significance level at $p \leq 0.001$.

Table 4. Interactive dependencies of tillage systems and years of research in determining winter oilseed rape yield and crop components.

Years	Tillage System	Siliqua Number Per Plant (pcs.)	Seed Number Per Siliqua (pcs.)	Seed Weight Per Siliqua (mg)	Branch Number in the Main Shoot (pcs.)	Main Shoot Length (cm)	1000-Seed Weight (g)
2014	CT	120.2 a	23.3 a	119.3 a	8.4 ab	143.8 abc	4.80 ab
	NT	119.4 a	24.6 a	122.7 a	7.4 cd	132.8 de	4.45 bc
2015	CT	118.4 a	23.0 a	116.8 a	7.6 bcd	134.9 cde	4.58 bc
	NT	119.0 a	23.9 a	123.8 a	8.2 abc	140.0 abd	4.70 ab
2016	CT	119.4 a	24.4 a	118.2 a	7.8 abcd	138.0 bd	4.60 bc
	NT	117.3 a	25.0 a	121.6 a	7.8 abcd	134.1 de	4.56 bc
2017	CT	122.2 a	22.8 a	117.7 a	8.6 a	146.3 a	5.02 a
	NT	116.0 a	24.4 a	120.7 a	7.2 d	128.1 e	4.25 c
p-Value		0.2467	0.9891	0.5019	0.0003 ***	0.0000 ***	0.0002 ***

CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values. *** Significance level at $p \leq 0.001$.

In the conventional system, significant positive values of the Pearson correlation coefficient (r_{emp}) were found for the relationship between the seed yield of winter oilseed rape and plant density (both after emergence and before harvest), the branch number, main shoot length, and the 1000 seed weight as shown in Table 5. The regression analysis model indicates that the 1 g increase in the 1000 seed weight caused the seed yield to increase by as much as 1.09 t ha^{-1} on average. However, the value of the determination coefficient (R^2) shows that the presented model explained only 50% of the yield variability. The increase in the values of the other yield structure elements by one unit contributed to a yield increase of 0.05 t ha^{-1} to 0.57 t ha^{-1}.

In the no-tillage system, winter oilseed rape yielding was significantly affected by similar yield structure elements as in the case of the conventional tillage system in Table 5. The seed yield remained unaffected only by plant density after emergence. The strongest correlation was confirmed between seed yield and 1000 seed weight because 1000 seed weight increase by 1 g caused the seed yield to increase by as much as 1.72 t ha^{-1} on average; however, the presented regression model explained 67% of the yield variability.

The increase in the values of the other yield structure elements by one unit contributed to a yield increase by 0.06 t ha^{-1} to 0.52 t ha^{-1}.

Table 5. Straight correlation coefficients and simple regressions for the relationship between yield and elements of the yield structure of winter oilseed rape in different tillage systems.

Quality Parameter	r_{emp}	Significance	R^2	Regression Equation
		Conventional tillage		
Plant density after emergence	+0.91	***	0.84	y = 1.0337 + 0.0677 * x
Plant density before harvest	+0.59	*	0.35	y = 1.3769 + 0.0878 * x
Branch number in the main shoot	+0.83	***	0.68	y = 0.4706 + 0.5691 * x
Main shoot length	+0.83	***	0.69	y = −2.5561 + 0.0542 * x
1000-seed weight	+0.71	**	0.50	y = −0.1 + 1.0905 * x
		No-tillage		
Plant density before harvest	+0.74	***	0.54	y = 0.2254 + 0.1128 * x
Branch number in the main shoot	+0.66	*	0.44	y = 0.6603 + 0.5243 * x
Main shoot length	+0.80	**	0.64	y = −4.0053 + 0.0649 * x
1000-seed weight	+0.82	**	0.67	y = −3.0724 + 1.7239 * x

r_{emp}—Pearson correlation coefficient, *—significance level 0.05, **—0.01, ***—0.001, R^2—coefficient of determination.

3.2. Contents of Fat and Glucosinolates in Winter Oilseed Rape

Across site-year, the type of tillage significantly affected the fat content of winter rape seeds. The study year also had a significant effect on the rape seed fat content (Figure 2). A 1.3% higher fat content was determined in the seeds produced in the NT compared with the CT system. The highest fat content of seeds was recorded in the most humid growing season, i.e., in 2016, and it differed significantly from the values determined in the other study years. In contrast, the lowest percentage of fat content was determined in the seeds harvested in 2015, i.e., in the year characterized by the smallest sum of precipitation.

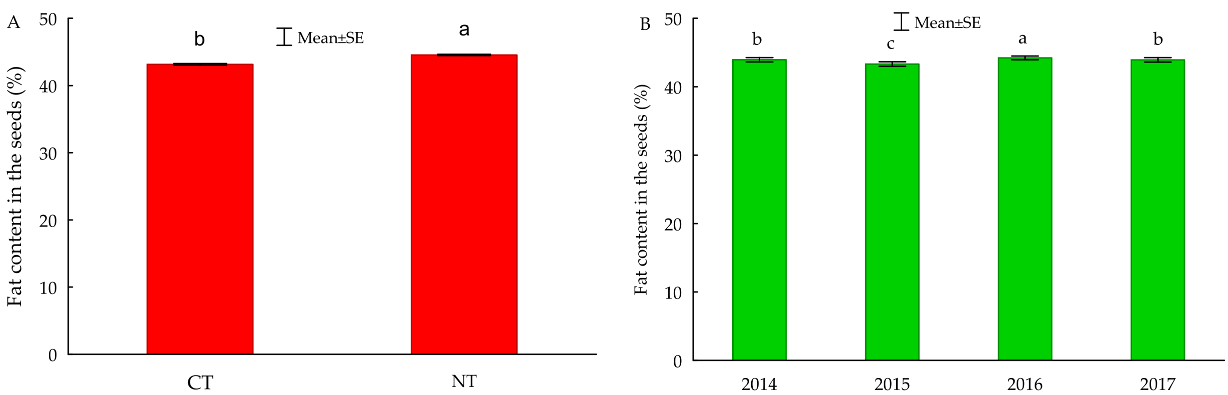

Figure 2. Fat content in winter oilseed rape seeds depending on the tillage system (**A**) (mean for 2014–2017) and years of research (**B**). CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values.

The statistical analysis of study results showed no significant effect of tillage systems and study years on the fat content of winter rape seeds (Figure 3).

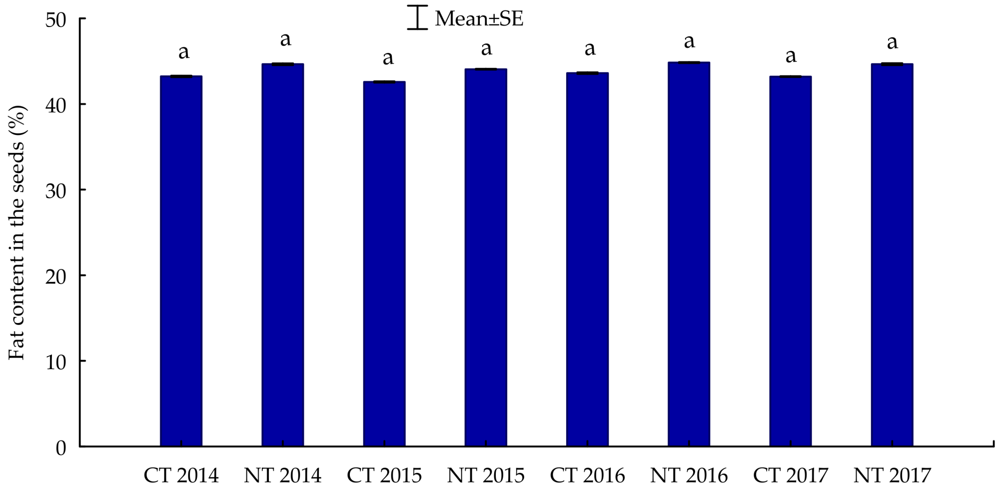

Figure 3. Interactive dependencies of tillage systems and years of research in determining fat content winter oilseed rape seeds. CT—Conventional tillage; NT—No-tillage. The same letter means not significantly different values ($p \leq 0.05$).

In turn, the content of glucosinolates in rape seeds was similar in both tillage systems but differed significantly across the growing seasons (Figure 4). The highest glucosinolate content of the seeds was determined in 2017 (14.0 μmol g^{-1}) and a similar one in 2016 (13.7 μmol g^{-1}). In contrast, their lowest content (13.1 μmol g^{-1}) was assayed in the seeds harvested in 2016. These seeds also featured the highest fat content, which was significantly different from the values obtained in the remaining growing seasons.

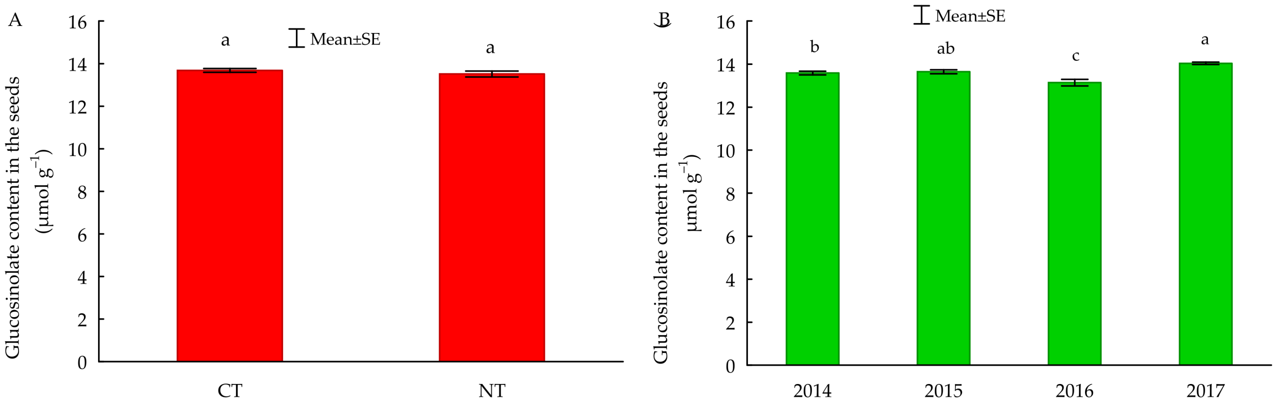

Figure 4. Glucosinolate content in winter oilseed rape seeds depending on the tillage system (**A**) (mean for 2014–2017) and years of research (**B**). CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values.

The glucosinolate content of the winter rape seeds remained unaffected by the interaction of tillage systems and study years (Figure 5).

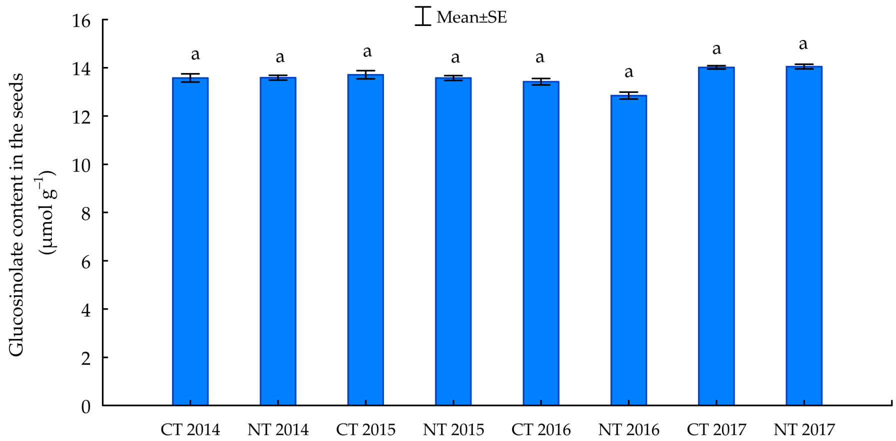

Figure 5. Interactive dependencies of tillage system and years of research in determining glucosinolate content winter oilseed rape seeds. CT—Conventional tillage; NT—No-tillage. The same letter means not significantly different values ($p \leq 0.05$).

3.3. Weed Infestation of Winter Oilseed Rape

The statistical analysis demonstrated that the number and air-dry weight of weeds were significantly lower in the CT system compared with the NT system, i.e., by 30.3 and 31.2%, respectively (Table 6). The values of the mentioned indicators of weed infestation also differed significantly between individual study years, with their highest values determined in 2016 and the lowest ones in 2015. In the growing season of 2016, characterized by the highest sum of precipitation, the weed density was 73.9% higher and the weed air-dry weight was 76.0% higher than in 2015.

Table 6. Number and air-dry weight of weeds in winter oilseed rape crop depending on tillage system (mean for 2014–2017) and years of research.

Specification	Number of Weeds (pcs m^{-2})	Air-Dry Weight of Weeds (g m^{-2})
	Tillage system	
CT	17.7 b	29.3 b
NT	25.4 a	42.6 a
p-Value	0.0000 ***	0.0000 ***
	Years	
2014	23.5 ab	35.4 b
2015	15.7 c	27.1 c
2016	27.3 a	47.7 a
2017	19.8 bc	33.6 b
p-Value	0.0000 ***	0.0000 ***

CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values. *** significance level at $p \leq 0.001$.

The interaction of tillage systems and study years both significantly affected the number and the air-dry weight of weeds (Table 7). Significantly higher values of both weed infestation indicators were found in the NT system compared with the CT system in 2015 and 2016, i.e., by 61.1 and 56.3% higher weed density and by 41.3 and 80.3% higher air-dry weight of weeds. The highest number and air-dry weight of weeds was determined on the NT plot in 2016, whereas the lowest ones were found on the CT plot in 2015.

Table 7. Interactive dependencies of tillage systems and years of research in determining the number and weight of weeds in winter oilseed rape crop.

Years	Tillage System	Number of Weeds (pcs m^{-2})	Air-Dry Weight of Weeds (g m^{-2})
2014	CT	18.0 c	29.3 cd
	NT	29.0 ab	41.4 b
2015	CT	14.3 c	23.8 d
	NT	17.0 c	30.4 cd
2016	CT	21.3 bc	34.0 bc
	NT	33.3 a	61.3 a
2017	CT	17.3 c	30.1 cd
	NT	22.3 bc	37.1 bc
p-Value		0.0381 *	0.0001 ***

CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values. * Significance level at $p \leq 0.05$, *** significance level at $p \leq 0.001$.

The agrophytocenosis of winter oilseed rape grown in the CT system was composed of 11 weed species, 9 of which (81.8%) were the short-lived taxa (Table 8). In the NT system, plots were infested by 3 species of perennial weeds and 10 species of short-lived weeds, accounting for 76.9% of the total number of identified taxa. A significantly lower weed density was found in the NT than in the CT system in the case of: *Chenopodium album* (by 57.1%) and *Euphorbia helioscopia* (by 81.8%). The *Viola arvensis* species was over 3-fold more abundant in the NT system compared with the CT system. In turn, *Sonchus asper* and *Sonchus arvensis* were detected only in NT plots.

Table 8. Species composition of weeds per 1m^2 in winter oilseed rape crop depending on the tillage system (mean for 2014–2017).

Species	Tillage System		*p*-Value
	CT	NT	
I. Short-lived			
Amaranthus retroflexus L.	0.7 a	0.5 a	0.3046
Anagallis arvensis L.	2.9 a	3.8 a	0.1243
Chenopodium album L.	0.7 a	0.3 b	0.0346 *
Euphorbia helioscopia L.	1.1 a	0.2 b	0.0004 ***
Melandrium album (Mill.) Garcke	1.6 a	1.9 a	0.4292
Papaver rhoeas L.	2.1 a	1.0 a	0.0790
Polygonum aviculare L.	1.8 a	2.6 a	0.1423
Sonchus asper (L.) Hill	-	0.8 a	0.0000 ***
Veronica arvensis L.	0.9 a	1.1 a	0.3844
Viola arvensis Murr.	1.9 b	6.0 a	0.0000 ***
II. Perennial			
Cirsium arvense (L.) Scop.	1.3 a	1.0 a	0.3791
Convolvulus arvensis L.	2.7 a	2.3 a	0.4516
Sonchus arvensis L.	-	3.9 a	0.0000 ***
Number of weed species	11	13	-

CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values. * Significance level at $p \leq 0.05$, *** significance level at $p \leq 0.001$.

The weed species composition in the winter oilseed rape stand differed significantly between the particular study years (Table 9). In 2014 and 2015, the numbers of *Amaranthus retroflexus* plants were significantly lower than in 2016, by 75.0% and 83.3%, respectively. The *Chenopodium album* species infested winter rape stands significantly more intensively in 2015 and 2016 than in 2017, whereas it was not detected in 2014. In the case of the *Veronica arvensis* species, its density was the highest in 2016. In 2014, it was proved similar, whereas in 2015 and 2017 it was significantly lower compared with 2016. The *Viola arvensis* species was found more abundant in 2016 and 2014 than in 2015 and 2017. In 2014 and 2017, the density of a perennial taxon *Cirsium arvense* was significantly lower in 2014 and 2017 than in 2016 by 61.1% and 72.2%, respectively. Data presented in Table 10 indicate that the high sum of precipitation promoted the development of the discussed weed species because these taxa infested winter rape stands most intensively in the most humid growing season of 2015/2016 (harvest year—2016).

Table 9. Species composition of weeds per 1 m^2 in winter oilseed rape crop depending on years of research.

Species	**Years**				***p*-Value**
	2014	**2015**	**2016**	**2017**	
I. Short-lived					
Amaranthus retroflexus L.	0.3 b	0.2 b	1.2 a	0.8 ab	0.0315 *
Anagallis arvensis L.	3.8 a	2.3 a	3.8 a	3.3 a	0.1712
Chenopodium album L.	-	0.8 a	0.8 a	0.3 b	0.0018 **
Euphorbia helioscopia L.	0.5 a	0.5 a	0.7 a	0.9 a	0.6175
Melandrium album (Mill.) Garcke	1.8 a	1.2 a	2.3 a	1.7 a	0.4451
Papaver rhoeas L.	2.2 a	0.7 a	1.3 a	2.0 a	0.2765
Polygonum aviculare L.	3.0 a	1.2 a	2.3 a	2.3 a	0.1001
Sonchus asper (L.) Hill	0.5 a	0.2 a	0.7 a	0.3 a	0.1251
Veronica arvensis L.	1.0 ab	0.8 b	1.5 a	0.7 b	0.0330 *
Viola arvensis Murr.	5.0 a	2.0 b	6.0 a	2.8 b	0.0000 ***
II. Perennial					
Cirsium arvense (L.) Scop.	0.7 b	1.5 ab	1.8 a	0.5 b	0.0091 **
Convolvulus arvensis L.	2.0 a	2.3 a	3.3 a	2.5 a	0.3767
Sonchus arvensis L.	2.7 a	2.0 a	1.5 a	1.7 a	0.1213
Number of weed species	12	13	13	13	

Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values. * Significance level at $p \leq 0.05$, ** significance level at $p \leq 0.01$, *** significance level at $p \leq 0.001$.

Table 10. Interactive dependencies of tillage systems and years of research in determining weeds composition per 1m^2 in winter oilseed rape crop.

Species	Years								p-Value
	2014		2015		2016		2017		
	CT	NT	CT	NT	CT	NT	CT	NT	
I. Short-lived									
Amaranthus retroflexus L.	0.3 a	0.3 a	0.3 a	-	1.3 a	1.0 a	1.0 a	0.7 a	0.9439
Anagallis arvensis L.	2.7 a	5.0 a	3.0 a	1.7 a	3.7 a	4.0 a	2.3 a	4.3 a	0.0803
Chenopodium album L.	-	-	1.0 a	0.7 a	1.0 a	0.7 a	0.7 a	-	0.4680
Euphorbia helioscopia L.	1.0 a	-	1.0 a	-	1.0 a	0.3 a	1.3 a	0.3 a	0.9173
Melandrium album (Mill.) Garcke	1.7 a	2.0 a	1.0 a	1.3 a	2.0 a	2.7 a	1.7 a	1.7 a	0.9940
Papaver rhoeas L.	3.3 a	1.0 a	0.7 a	0.7 a	1.7 a	1.0 a	2.7 a	1.3 a	0.5419
Polygonum aviculare L.	3.0 a	3.0 a	1.0 a	1.3 a	1.3 a	3.3 a	2.0 a	2.7 a	0.1001
Sonchus asper (L.) Hill	-	1.0 a	-	0.3 a	-	1.3 a	-	0.7 a	0.1251
Veronica arvensis L.	1.0 ab	1.0 ab	0.7 b	1.0 ab	1.0 ab	2.0 a	1.0 a	0.3 b	0.0412 *
Viola arvensis Murr.	2.0 bc	8.0 a	1.3 c	2.7 c	3.0 bc	9.0 a	1.3 c	4.3 b	0.0028 **
II. Perennial									
Cirsium arvense (L.) Scop.	0.7 a	0.7 a	2.0 a	1.0 a	2.0 a	1.7 a	0.3 a	0.7 a	0.3933
Convolvulus arvensis L.	2.3 a	1.7 a	2.3 a	2.3 a	3.3 a	3.3 a	3.0 a	2.0 a	0.8850
Sonchus arvensis L.	-	5.3 a	-	4.0 a	-	3.0 a	-	3.3 a	0.1213
Number of weed species	10	11	11	11	11	13	11	12	

CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values. * Significance level at $p \leq 0.05$, ** significance level at $p \leq 0.01$.

The interaction of tillage systems and study years caused significant differences in the population numbers of two taxa in the winter oilseed rape stand, i.e., *Veronica arvensis* and *Viola arvensis* (Table 10). In 2017, density of the *Veronica arvensis* species was significantly lower in the NT than in the CT system (by 70.0%). In three experimental years, a lower number of *Viola arvensis* weeds was determined in the CT system compared with the NT system, i.e., by 75.0% in 2014, by 66.7% in 2016, and by 69.8% in 2017.

The evaluation of segetal flora biodiversity demonstrated a similar value of the Shannon-Weinner diversity index (H′) in both tillage systems and a significantly higher value of the Simpson dominance index (SI) in the NT system compared with the CT system (Figures 6 and 7). In 2014, the winter oilseed rape stand was characterized by the least diversity of the weed community and by the highest value of the Simpson dominance index (SI). The diversity of the weed community (H′) assessed in 2016 was significantly higher compared to 2014.

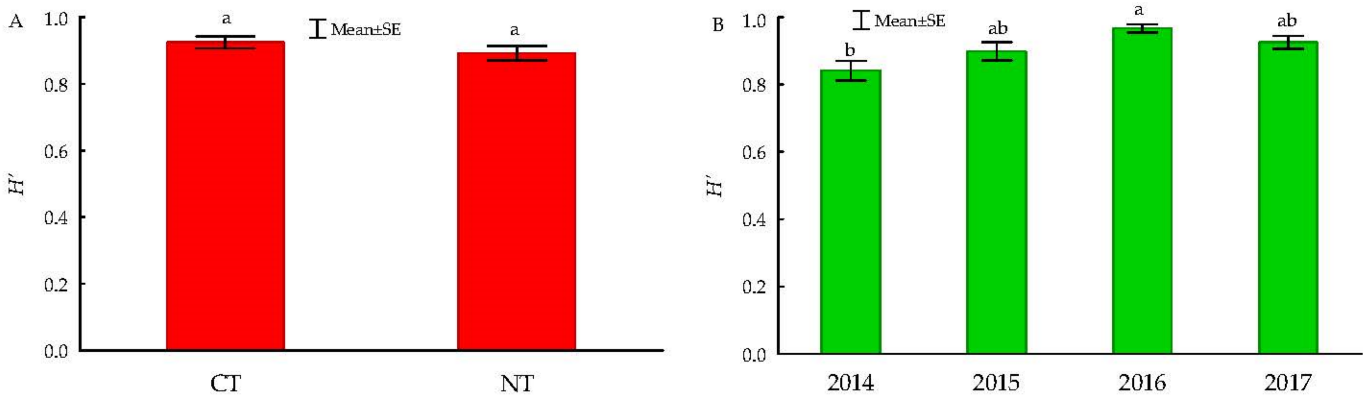

Figure 6. Shannon-Wiener's diversity index (H') of weed community in winter oilseed rape crop depending on the tillage system (**A**) (mean for 2014–2017)) and years of research (**B**). CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values.

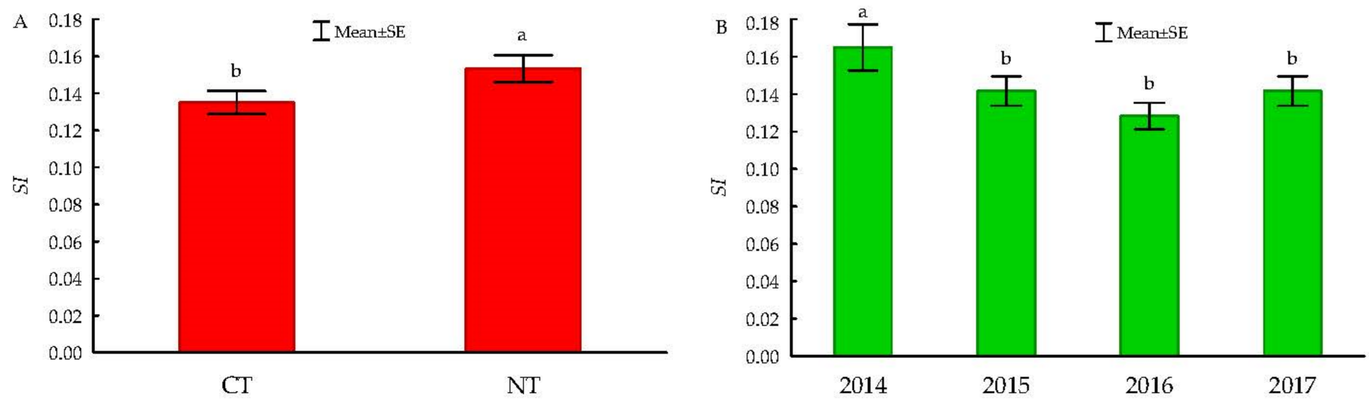

Figure 7. Simpson's dominance index (*SI*) of weed community in winter oilseed rape crop depending on tillage system (**A**) (mean for 2014–2017) and years of research (**B**). CT—Conventional tillage; NT—No-tillage. Different letters denote significant differences ($p \leq 0.05$). The same letter means not significantly different values.

The interaction of tillage systems and study years did not affect the values of both biodiversity indices (Figures 8 and 9).

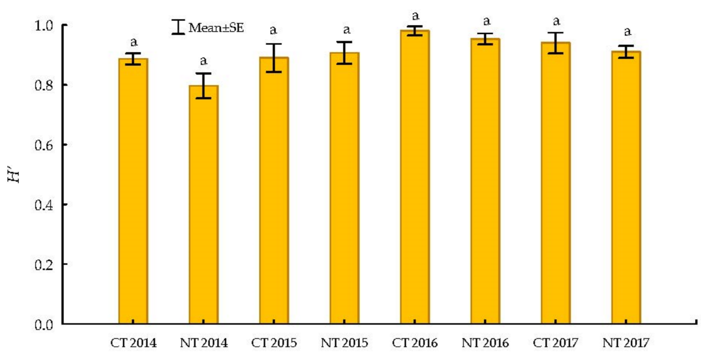

Figure 8. Interactive dependencies of tillage system and years of research in shaping of Shannon-Wiener's diversity index (H') of weed community in winter oilseed rape crop. CT—Conventional tillage; NT—No-tillage. The same letter means not significantly different values ($p \leq 0.05$).

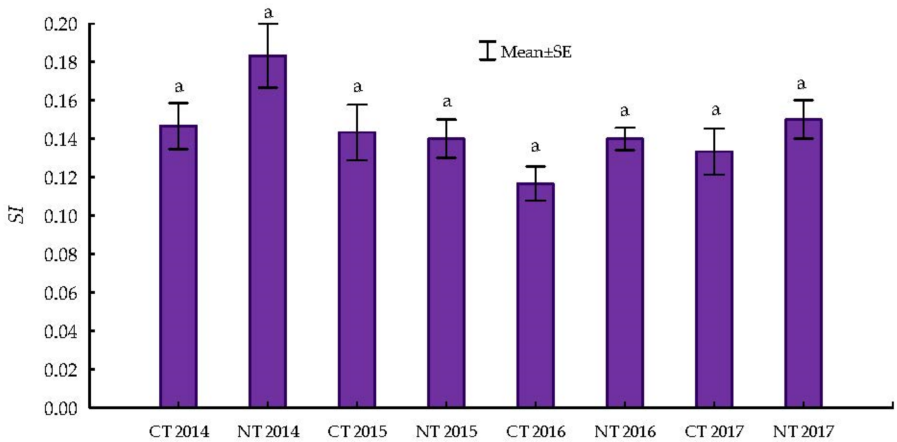

Figure 9. Interactive dependencies of tillage systems and years of research in shaping of Simpson's dominance index (SI) of weed community in winter oilseed rape crop. CT—Conventional tillage; NT—No-tillage. The same letter means not significantly different values ($p \leq 0.05$).

4. Discussion

The four-year field experiment has shown that the CT system had a more favorable effect on the yield of winter rape seeds than the NT system. Similar results were obtained by Jaskulska et al. [50] and Chiriac et al. [51], who claimed that the replacement of the conventional plow tillage of winter oilseed rape with the no-tillage system was unjustified due to the lower seed yield. The results of the present study and findings reported by Jaskulska et al. [50] indicate a beneficial effect of the CT system on plant density, main shoot length, number of branches in the main shoot as well as on the 1000 seed weight of winter oilseed rape. In the case of the carefully and well-performed sowing of winter oilseed rape, the reduction of the seed yield in the NT system may, however, be small or none, which is confirmed by the results of other studies [11]. The ultimate effects of harnessing the NT system are largely dependent on the length of its application and habitat conditions. As Castellini et al. [52] claimed, the NT system had a positive effect on the yield of plants only after its long-term application. According to these authors, the physical and chemical properties of the soil may deteriorate immediately after the shift from conventional to no-tillage system. Chandrasekhar et al. [53] believe that deterioration of soil properties, including a decrease in its porosity, may occur after this shift for up to 4–5 years. With the long-term use of the NT system, the physical and chemical properties of the soil successively improve and the activity of soil microflora and microflora increases [54,55]. Roldán et al. [56] showed that the no-tillage system increased the accumulation of crop residues on the soil surface. In their study, the content of organic matter in the soil layer from 0 to 5 cm increased with the reducing intensity of tillage, and the no-tillage system most effectively improved the physical and biochemical properties of the soil. Furthermore, the experiment conducted by Romaneckas et al. [11] has indicated lower compaction and higher humidity of soil in no-tillage plots compared to the conventionally cultivated plots, due to the accumulation of crop residues in the topsoil. According to Kováč et al. [20], a large amount of crop residues remaining after harvesting the forecrop may sometimes negatively affect seed germination and, consequently, the seed yield of winter rape. In their experiment conducted by these authors, higher average seed yields were obtained in those variants of tillage in which the negative impact of straw residues left after the harvest on the sprouting and development of winter rape was eliminated. For this reason, conventional tillage allowed a significantly higher seed yield to be produced compared with the no-tillage system, after which rape seeds were not applied to the appropriate depth and were not evenly distributed in the soil.

The present study results indicate that the influence of tillage systems on the seed yield of winter oilseed rape largely depended on the course of weather conditions. In the years with the highest sum of precipitation, higher seed yields were obtained in the CT system compared with the NT system. In the second year of the study, characterized by a lower sum of precipitation compared to the remaining years of the experiment and the long-term average, higher rape yielding was promoted by the no-tillage system (NT). According to Pittelkow et al. [22], in regions with low precipitation, it is important to properly prepare the soil so that it can retain as much rainwater as possible. Such possibilities are provided by agrotechnical treatments involving the replacement of the plow with non-reversing tools. Thus, in dry climates, the no-tillage system makes it possible to produce crop yields similar to or higher than those produced under the conditions of conventional tillage. Romaneckas et al. [57] indicate that reducing the intensity of cultivation causes an increase in the moisture content of the topsoil (0–10 cm). Therefore, resignation from the conventional plow tillage elicits a better effect on crop yields in the years with an insufficient sum of precipitation [8].

The essential criteria used to assess the quality of rapeseed intended for oil production include, inter alia, the contents of fat and glucosinolates, which are differently affected by agrotechnical and climatic factors and crop variety [4,58]. The glucosinolate content of oilseeds is usually inversely proportional to the oil content [59–61]. According to Pan et al. [60], this correlation is due to the competition between fatty acid and amino acid biosynthetic pathways for carbon skeletons. The present study results showed that cultivation in the NT system increased fat accumulation in winter rape seeds, while the glucosinolate content was similar in both tillage systems. The availability of nutrients in soil is largely dependent on its structure [62,63]. Hence, tillage systems that affect soil structure and thus nutrient uptake, can also influence rape growth and oil production. Plant residues increase nitrogen availability to plants by immobilizing N and then successively mineralizing it [64]. The modified nutrient availability to plants observed in the NT system, which leaves a lot of post-harvest residues in the topsoil, may therefore affect not only the seed yield, but also the oil content of the seeds [65].

The results of the research conducted so far have shown that the content of fat in seeds of Brassica species was influenced by temperature and soil moisture [66]. According to Morrison and Stewart [67], high temperatures and low soil moisture in the flowering and siliqua-filling phases reduce the concentration of oil from rapeseeds. Also, the results of the experiment by Pritchard et al. [68] have demonstrated that the oil content was, on average, the lowest in oilseed rape grown in dry years or in warmer regions. This was confirmed in our experiment, because the lowest fat content was determined in rape seeds from 2015 characterized by low precipitation and high temperature, especially during the period of pod filling (June).

In the present experiment, a significantly greater number and air-dry weight of weeds were recorded in the NT system than in the CT system. The increase in weed infestation of crops under the NT system conditions was also found in the studies of other authors [37–39,44,69]. By contrast, Santín-Montanyá et al. [43] showed that the number of weeds in the winter wheat stand was not influenced by the conventional or the no-tillage system. On the other hand, Sebayang and Rifai [70] found a similar air-dry weight of weeds in the soybean stand in the conventional tillage, minimal tillage, and no-tillage systems [66]. In a study conducted by Romaneckas et al. [71], the reduced intensity of tillage resulted in a slight increase in the density and biomass of weeds in horse bean plots, especially in disc and no-tillage plots. The tillage system modifies the number and distribution of weed seeds in the soil profile. Therefore, it influences both the species composition of weeds and the intensity of weed infestation in crop stands [34]. Higher weed infestation in the NT system may result from the accumulation of freshly sprinkled weed seeds and vegetative reproductive organs in the topsoil, from where they germinate and appear abundantly in the crop stand [40–42,72]. In the experiment conducted by Cardin et al. [73], the highest number of weed seeds was accumulated in the soil layer from 0 to 5 cm in the NT system, while in the other tillage systems, diasporas were evenly distributed throughout the arable layer. In turn, Romaneckas et al. [71] found a greater weed seed bank in disked (+43.0%) and unplowed (+21.6%) soils compared to the plowed ones.

Investigations conducted so far have indicated that tillage systems modify the species composition of weeds in the stands of arable crops to a different extent. Their results, however, are not unequivocal and largely depend on the crop species. Based on the Shannon index values, Santín-Montanyá et al. [43] proved that the application of the NT system increased the diversity of the weed community in the soybean stand. In the experiment conducted by Gawęda et al. [44], the stand of soybean cultivated in the NT system was characterized by a slightly greater diversity of the weed community than that grown in the CT system, which was indicated by a higher value of the Shannon diversity index and a slightly lower value of Simpson dominance determined in the NT. However, the research presented in this paper indicates that the value of the Shannon-Weinner diversity index was slightly higher, and the value of the Simpson dominance index was significantly lower in the CT than in the NT system. By modifying the physical, chemical, and biological properties of soil, the tillage systems affect the growth and development of crops, which may result in changes in the species composition of weeds colonizing their stands [32,74]. The results of the present study and findings reported by Almoussawi et al. [75] showed that the use of reduced tillage increased the population number of the *Viola arvensis* taxon. The studies of other authors indicate, inter alia, that compared with the CT system, the NT system increases the abundance of *Galium aparine* and *Chenopodium album* [39] and intensifies the prevalence of perennial weed species that are particularly difficult to control [44,76,77]. Also, the present study demonstrated that the winter oilseed rape NT plots are populated by a perennial species *Sonchus arvensis*, which was not observed on the CT plots.

5. Conclusions

The four-year field experiment has demonstrated that cultivation in the CT system produced higher yields of winter oilseed rape than the NT system. This was mainly indicated by higher plant density and the 1000 seed weight.

The no-tillage system (NT) significantly increased the number and air-dry weight of weeds compared to those found on the plot with conventional tillage (CT). The winter oilseed rape canopy cultivated in the CT system was also characterized by a greater diversity of the weed community than in the NT system.

The seed yield of winter oilseed rape was largely influenced by the weather conditions. The experiment showed a beneficial effect of the no-tillage system on the seed yield in the growing season characterized by the lowest sum of precipitation. Therefore, the cultivation of winter oilseed rape in the no-tillage system can be recommended in a climate characterized by a shortage of rainfall.

Drought is a global problem in agriculture, that reduces plant productivity, therefore further research on the yield of winter oilseed rape, mainly in no-tillage systems, should be conducted.

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