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Effect of Reduced Tillage on Soil Enzyme Activity, Pests Pressure and Productivity of Organically Grown Spring Wheat Species

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Abstract: The possibility of using reduced tillage in organic farming is poorly recognized. The study aimed to assess the impact of the tillage method (shallow tillage and plowing) on soil biochemical activity, pest pressure, and grain yield of *Triticum sphaerococcum*, *T. persicum*, and *T. aestivum* ssp. *vulgare*, grown in organic farming systems. For this purpose, field experiments were conducted at three certified organic farms located in different regions of Poland. Enzyme activity was influenced to a greater extent by local soil and weather conditions compared to wheat species and the tillage method. Insect pests (*Oulema* spp.) slightly damaged the leaves of wheat, and the reduced tillage did not increase the damage. Under site conditions favorable for the development of diseases significantly fewer disease symptoms were observed in shallow tillage compared to plowing (powdery mildew by 9.6–46.1%; stripe rust by 15.5–89%; Septoria head blotch by 0-84.4%; Fusarium head blotch by 0–47.4%, Fusarium foot rot by 0–100%). *T. aestivum* was characterized by the highest yield and the yield stability in various locations and tillage methods. Ancient wheat species (*T. sphaerococcum* and *T. persicum*) had a higher yield in shallow tillage compared to plowing tillage (by 64% and 30%, respectively) only under effective weed control.

Keywords: shallow tillage; plowing; dehydrogenase; nitroreductase; Oulema; occurrence of disease; root weight; yield components; grain yield

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1. Introduction

Wheat is one of the most economically important crops. In terms of cultivation area, it ranks first in the world (219 million hectares in 2020). It is also the most important crop in the EU-27 in terms of cultivated area (22.9 million ha in 2020) and production volume of 126.7 million tons [1]. This species, like most other agricultural crops, is cultivated mainly in the traditional plowing tillage system. Intensive plowing can have negative environmental impacts, like pesticide and nutrient runoff, soil erosion, and loss of organic matter [1]. In order to prevent erosion and degradation and to preserve soil biodiversity, it is important to reduce soil disturbance through reduced or no tillage [2]. As an alternative to conventional tillage, conservation tillage techniques such as no till and reduced tillage imply a lack of deep soil inversion. They are encouraged by international institutions such as the Food and Agriculture Organization of the United Nations and by the Common Agricultural Policy in the European Union [2]. Reduced tillage does not abandon all mechanical operations for seedbed preparation but minimizes tillage operations to the smallest frequency. In

Europe 25% of arable land is managed under reduced tillage and no tillage [3]. Recently, a growing interest has been observed in reduced tillage, stimulated by economic and environmental considerations.

According to many authors [4–6], one of the greatest advantages of conservation tillage (no-till and reduced tillage) is the reduction in energy consumption and costs of production. Zikeli [7] reported that lower labor costs are the main motive for conversion to reduced tillage for many farmers.

Elimination of the plow has some environmental advantages, e.g., it prevents soil erosion and limits water losses compared to plowing [5,8]. Reduced tillage and no-tillage have a high potential to increase soil water content [9], improve water infiltration, and reduce evaporation; hence, these techniques can offer a strategy for increasing the resilience of agriculture and a means of adapting to projected climate change [7].

Many researchers highlight the significant influence of tillage practices on soil properties. In studies by Khorami et al. [10] and Berner et al. [11], lower bulk density and lower soil organic carbon were obtained in plowing systems compared to reduced tillage. According to Niewiadomska et al. [12], the soil tillage system affects the microbiological diversity and biochemical activity of soil. The tillage method also influences the pressure of diseases, pests and weeds. Biomass incorporation into the soil by plowing may reduce some soilborne pests and pathogen loads [13,14]. Jasrotia et al. [15] reported a significant effect of tillage on reducing the population of insect pests in wheat. More aphids feeding on the leaves were shown in conventional tillage compared to reduced tillage. Clement et al. [16] did not show a clear and consistent effect of the soil cultivation system on aphid abundance. However, they pointed out the high variability between years in the abundance of *Sitobion avenae* and *Diuraphis noxia*. According to Hussain et al. [17], weed density and biomass are lower under deep tillage than under shallow tillage. Studies by Armengot et al. [3,18] also indicate an effective reduction of weed infestation by deep tillage.

The analysis of the results of the research conducted so far shows that the response of wheat grain yield to simplifications in tillage depends on the farming system (organic and conventional), type of simplifications in tillage [19], weather conditions [20,21], and genotype [22,23]. In some studies conducted on conventional farming, the plowing tillage resulted in higher grain yield compared to reduced tillage [21,24]. In others, there was no significant difference in wheat grain yield between conventional and reduced soil cultivation [10]. Daruza and Gaile [20] in turn claimed that under reduced tillage circumstances it was possible to obtain a higher yield compared to plowing.

The implementation of reduced tillage practices within organic agriculture is less commonly accepted [25]. Reduced tillage could provide new opportunities in organic farming [8], but there are problems with weed pressure [3,25] and a delay in soil nitrogen mineralization [26] which increase the risk of yield depression and yield instability [7]. However, the widespread use of reduced tillage practices among organic farmers would enhance the ecosystem services delivered by organic agriculture and make it more resilient to the effects of climate change [7]. Reduced tillage in organic farming has the potential to increase total soil organic carbon stocks, but crop management has to be improved to increase productivity [27]. Some problems related to reduced tillage, e.g., weed infestation, are rather well recognized, but the pressure of diseases, pests, or enzymatic properties of soils are rarely studied, especially in organic production. Thus, it is justified to conduct research on the effects of reduced tillage techniques in organic farming in different environments [7,8,11], especially since the area of total agricultural land occupied by organic farming is constantly increasing [1].

The main aim of the study was to assess the suitability of reduced tillage in the form of one-year shallow surface tillage for three spring wheat species: common wheat and two ancient genotypes, Indian dwarf wheat (*Triticum sphaerococcum* Percival) and Persian wheat (*T. persicum* Vavilov) grown according to the organic farming system. The specific goals were to assess the effect of shallow surface tillage on: (i) soil biochemical activity, (ii) pest pressure, (iii) plant biometric features, and grain yield. The research hypothesis assumed that one year of reduced tillage would not significantly affect the pressure of pests, and through a beneficial effect on the biochemical or physicochemical properties of the soil, it could indirectly contribute to the increase in grain yield—not only of common wheat, but also of morphologically different primary wheat species, reintroduced in the organic farming system.

2. Materials and Methods

2.1. Side Description

In order to determine the effect and interactions of habitat conditions, genotype, and tillage method on the activity of soil enzymes, pest pressure, and yield of three spring species, strict field experiments were established in three certified organic farms in the following locations: Grabina Wielka, Greater Poland Voivodeship (52°11′ N; 18°80′ E), Zblewo Pomeranian Voivodeship (53°93′ N; 18°31′ E), and Budziszewo, Kuyavian-Pomeranian Voivodeship (53°37′ N; 19°12′ E) (Figure 1). The soil at experimental sites was characterized as Alfisol (USDA). The soil in Grabina Wielka was slightly acidic (pH KCl 5.9) and contained 64.5 mg·kg^{-1} P, 182.6 mg·kg^{-1} K, 57.0 mg·kg^{-1} Mg, 2.8% soil organic matter, 1.63% C_{org}, and 83.8 kg·ha^{-1} N_{min}. On the other hand, the soils in Budziszewo and Zblewo were neutral (pH KCl 6.8 and 6.7, respectively) and contained: 99.0 and 40.5 mg·kg^{-1} P, 193.4 and 169.3 mg·kg^{-1} K, 110.0 and 51.0 mg·kg^{-1} Mg. Furthermore, the soils in Budziszewo and Zblewo contained 3.3% and 1.7% soil organic matter, 1.92 and 0.97% C_{org} as well as 82.7 and 81.0 kg·ha^{-1} N_{min}, respectively.

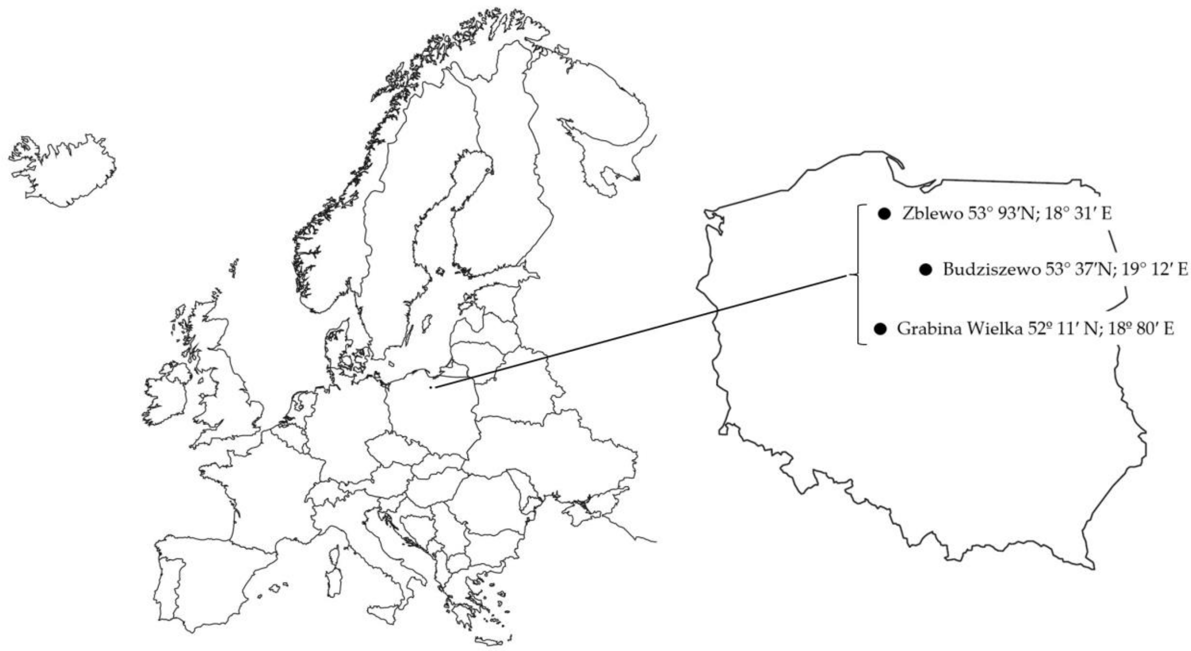

Figure 1. Locality of field experiments (Poland).

2.2. Agrotechnical Practice

Considering the possible undesirable impact of heterogeneous previous crops, in all locations, fields where triticale was the previous crop were selected for setting up the experiments. During the previous crop harvest, the straw was removed from the field, but 10–15 cm of stubble was left. Immediately after harvest, shallow tillage (5–7 cm) was made using a tine cultivator, after which a catch crop consisting of mustard, phacelia and legumes (peas, lupin) was sown. Before winter (end of November), the part of the field intended for plowing was plowed, while the other part of the field with shallow surface tillage was cultivated. In mid-March, 12 N, 10 P_2O_5, 26 K_2O, 4 MgO, and 20 SO_3 kg ha^{-1}, were applied in the form of a natural fertilizer, Bioilsa, approved for use in organic crops.

Then, spring seasoning of the soil was carried out with a cultivation unit consisting of a cultivator and a string roller, to a depth of 7–8 cm. Wheat sowing was carried out in the last days of March, in narrowly spaced rows (10.5–11.5 cm). The sowing density for all wheat species was 600 pcs m^{-2}. At the beginning of wheat tillering, weed control harrowing was performed. This treatment was highly effective in reducing weed infestation in Grabina Wielka, where only a few annual weeds appeared on the experimental plots from the wheat shooting stage. In this location, many years of good agricultural practices used by the farmer effectively eliminated couch grass and other persistent weeds from the fields. In the remaining two localities, Zblewo and Budziszewo, despite the weed control harrowing, all plots with wheat, regardless of the experimental factors, were very heavily infested with weeds, especially perennial weeds.

The development rates of Indian dwarf wheat and common wheat were similar, while Persian wheat reached successive development stages 7–10 days earlier. Grain was harvested at full grain maturity with a Wintersteiger plot harvester.In the study area, the growing season of spring cereals begins at the end of March and lasts until the end of July/beginning of August. In the localities of the field experiments: Grabina Wielka, Zblewo, and Budziszewo, the multi-year average (1981–2010) of precipitation from March to July is similar and amounts to 252 mm, 254 mm, and 254 mm, respectively (Table 1). The Zblewo region is the coldest; the average air temperature in the analyzed period is 10.9 °C. For the region of Grabina Wielka and Budziszewo, the temperature is 12.2 and 12.0 °C, respectively. Weather conditions in the research year 2019 varied in individual locations. The total precipitation at the beginning of growth in March and April was the lowest in Budziszewo, while in Grabina Wielka and Zblewo the total rainfall was higher. In the period May-July, the highest rainfall was recorded in Zblewo, slightly lower in Budziszewo, and the lowest in Grabina Wielka. Average monthly air temperatures during the growing season of the studied wheat species (March to July) were the lowest in Zblewo. In Grabina Wielka and Budziszewo, these months were warmer.

Table 1. Mean air temperature and precipitation at experimental sites.

Site	March	April	May	Jue	July	Mean/Sum
			Temperature °C			
Grabina Wielka	6.1	10.1	12.5	22.1	19.2	14.0
Zblewo	5.8	8.6	11.9	20.0	18.0	12.9
Budziszewo	6.3	10.3	12.7	22.3	18.8	14.1
			Precipitation mm			
Grabina Wielka	35.4	14.6	44.7	23.7	50.7	169.1
Zblewo	44.0	2.0	65.0	63.0	59.0	233.0
Budziszewo	31.2	0.9	85.2	39.2	45.7	202.2

2.3. Experimental Treatments

The experiment was established in a split-plot design, in four replications. The size of plots, depending on the type of agricultural equipment available in particular locations, ranged from 12 m^2 to 16 m^2. The whole-plots covered tillage methods: plowing or shallow tillage, and subplots covered three spring wheat species: common wheat (*Triticum aestivum* ssp. *vulgare*), Indian dwarf wheat (*Triticum sphaerococcum* Percival), or Persian wheat (*Triticum persicum* Vavilov). Diversification of tillage methods concerned autumn treatments. In plowing tillage, pre-winter plowing was performed to a depth of 22–24 cm, using moldboard plow, while in shallow surface cultivation, only shallow (10–12 cm) cultivation was performed using tine cultivator. In plowing tillage, the topsoil was inverted, and in surface tillage only mixed with post-harvest residues of previous crops (stubble of the previous crop cereal and biomass of the catch crop).

The cultivars used in the study included common wheat (*T. aestivum* ssp. *vulgare*) cv. Torridon, Indian dwarf wheat (*T. sphaerococcum* Percival) cv. Trispa, and Persian wheat (*T. persicum* Vavilov) cv. Persa. The cultivar Torridon of common wheat belongs to the group of quality wheats. It is characterized by good fertility, an average weight of a thousand seeds, and a fairly high bulk density of grain. The cultivar Trispa of Indian dwarf wheat develops long, stiff stems. The aboveground part of the plant is covered with wax. It has short awns on the ear. The grain of Indian dwarf wheat is naked, rounded, and red. The cultivar Persa of Persian wheat has delicate, long stems, very susceptible to lodging. The medium long ear is brownish, loose, awned. The spikelets are two- or three-flowered, one- or two-grained. Persian wheat is naked, elongated, and red in color [28–30].

2.4. Measurements of the Soil Enzymes Activity

Dehydrogenases activity was analyzed by reduction of 2, 3, 5-triphenyltetrazolium chloride by 24 h of incubation in 37 °C. The reaction product of triphenyl formazan released was extracted with acetone and assayed at 546 nm in UV-VIS spectrophotometer [31]. Nitroreductase activity was measured according to Kandeler [32] using KNO_3 as the substrate. After incubating the soil samples at 25 °C for 24 h, the released nitrates were extracted using a 4 M KCl solution. The activity of nitroreductase was determined colorimetrically at 520 nm. The activity of fluorescein diacetate hydrolysis (FDAH) used like a global soil hydrolysis activity was evaluated by measuring as described by Adam and Duncan [33]. After 1 h of incubation the enzymatic reaction was stopped by putting in the mixture of methyl alcohol and chloroform (1:2). After the soil suspension, the colored end product fluorescein was measured at 490 nm. Soil urease activity was determined according to Kandeler and Gerber [34] by monitoring the release of ammonium from the soil treated with urea as a substrate and incubated with a borate buffer at pH 10.0. The soil β-glucosidase (EC 3.2.1.21) activity was determined using p-nitrophenyl-β-D-glucopyranoside (0.05 M), according to Eivazi and Tabatabai [35]. The concentration of p-nitrophenol was determined at 400 nm after the addition of a Tris/NaOH buffer (pH 10.0) and $CaCl_2$.

2.5. Analysis of the Occurrence of Diseases

During the growing season, the assessment of plant health was carried out twice and concerned the intensity of occurrence of all the most dangerous diseases of roots, stem base, leaves, and ears of wheat. The first assessment was made at the stem elongation stage (BBCH 35-37) and the second at the development of fruit stage (BBCH 75-77). The occurrence of diseases on the leaves was assessed at both development stages, and the intensity of powdery mildew (*Blumeria graminis)*, tan spot (*Pyrenophora tritici-repentis*), brown rust (*Puccinia recondite*), and stripe rust (*Puccinia striiformis*) was determined. In the first period, the health of the lower leaves (L3 and L4) was assessed, and in the second period, the health of the flag leaf (L1) was assessed, which was expressed as a percentage share of leaf area with symptoms of individual diseases. Each time, the health status of 25 plants randomly selected from each plot was analyzed. The assessment of the occurrence of diseases on ears, stem base, and roots was carried out only at the development of fruit (BBCH 75-77). On 50 randomly selected ears from each plot, the percentage of ear area with disease symptoms of Fusarium head blight (*Fusarium* spp.) and Septoria glume blotch (*Septoria glumarum*) was determined. The assessment of the severity of disease symptoms on leaves and ears was made directly on the experimental plots, while the severity of foot rot and root rot diseases was determined in the laboratory. Twenty-five plants from each plot were subjected to health assessment. In laboratory conditions, after separating shoots and removing leaf sheaths from generative tillers, the degree of the stem base infection by *Fusarium* spp. (Fusarium foot rot), *Oculimacula acuformis*, and *Oculimacula yallundae* (eyespot) was assessed. The roots of the plants were thoroughly rinsed from the soil before the assessment. Infestation was assessed on a scale of 0–4 (where 0 meant no symptoms of a given disease and 4 meant severe infestation) [36]. Infestation degrees were converted to the disease index (DI) based on the formula of Townsend and Heuberger [37].

2.6. Assessment of Plant Damages by Pest Insects

Three genotypes of spring wheat (*Triticum sphaerococcum*, *T. persicum*, and *T. aestivum*) were analyzed at the flag leaf stage (BBCH 39) and the flowering stage (BBCH 65) [38]. The area of damage caused by feeding of pests (*Oulema melanopus* and *O. gallaeciana*) was assessed. Twenty-five wheat stalks were randomly selected, and the effects of pest feeding organoleptically were assessed according to EPPO [39] and Walczak [40]. The assessment was carried out in each locality (Grabina Wielka, Zblewo and Budziszewo), in 4 repetitions of each treatment.

2.7. Measurements of Plant Features and Grain Yield

At the end of flowering stage, the number of generative tillers per plant-2 was determined on subsequent plants collected from 1 linear meter from each plot. At the same development stage, measurements of roots and length of generative tillers were taken. In order to determine the length and weight of the roots, thirty consecutive plants in a row (the aboveground part and roots from a depth of 20 cm) were collected. Then, the above-ground part was cut off, and the soil was rinsed from the roots, after which their length was measured; then they were dried, and the dry matter was weighed. The length of the tillers (from the base to the tip of the ear, without awns) was determined based on 50 measurements of randomly selected generative tillers from each plot, made with a measuring bar. At full maturity, the density of generative tillers was determined on test plots of 1 m^2 on each experimental plot. At the same development stage, 50 ears were randomly collected from each plot, on which the number of fertile and sterile spikelets and of grains per ear were measured. To determine the yield, grain was collected from the entire area of the field of each plot. Then yields were converted into a constant humidity of 15%. The 1000-grain weight was determined based on samples taken after achieving a constant grain moisture content of 12%, based on 500 pcs, in four replications of each treatment.

2.8. Statistical Analyses

Analysis of the results was performed using statistical inference methods [41,42]. The basic statistical descriptors included mean values $\overline{x}$ and standard deviation ($\pm$SD). The normality of the distribution was tested with the Kolmogorov–Smirnov test, while equality of variance in different samples was tested with a Levene test. Fixed factors were locality, soil tillage and species. For the soil enzymes activity, the occurrence of disease and plant damage by pest insects, the features studied such as root length and weight, the generative tillers' length and number per plant, the number of fertile and sterile spikelets per ear, the grain yield, and the yield components multifactorial analysis of variance were used to find significant differences; in addition, the interaction of habitat conditions, genotype, and soil tillage was determined. Tukey's post hoc test was used to identify significant differences between means. The level of significance for all statistical tests was accepted as $\alpha = 0.05$. The statistical calculations mentioned above were carried out with MS Excel 2019 software (Microsoft, Redmond, WA, USA, 2019) and Statistica 13.3 (Dell, Round Rock, TX, USA, 2021) software.

3. Results

3.1. Soil Enzymes Activity

The activities of dehydrogenases, nitroreductase, fluorescein diacetate hydrolysis (FADH), urease, and glukosidase were affected by interactions of location x farming method and wheat species ($p \leq 0.001$, $p = 0.059$, $p = 0.035$, $p = 0.041$, and $p < 0.001$, respectively) (Table 2).

Table 2. The soil enzymes activities as dependent on growing wheat species (*Triticum sphaerococcum* (*TS*), *T. persicum* (*TP*) and *T. aestivum* (*TA*) at different tillage methods, in three field experimental localities.

Locality	Soil Tillage	Species	Dehydrogenases mg TPF kg^{-1} 24 h^{-1}	Nitroreductase mg NO_2 kg^{-1} 24 h^{-1}	FDAH mg F kg^{-1} h^{-1}	Urease mg NH_4 kg^{-1} h^{-1}	Glucosidases mg pNP kg^{-1} h^{-1}
Grabina Wielka	Plowing	*TS*	36.49 ± 1.44 b [1]	1.30 ± 0.12 bc	15.30 ± 2.62 f	1.37 ± 1.20 bc	0.36 ± 0.04 d–g
		TP	41.28 ± 2.00 b	1.83 ± 0.15 bc	19.08 ± 0.70 d–f	1.54 ± 1.55 bc	0.44 ± 0.01 c–f
		TA	44.16 ± 0.73 b	2.37 ± 0.14 bc	24.41 ± 0.63 b–d	3.21 ± 3.34 a–c	0.84 ± 0.07 b
	Shallow tillage	*TS*	51.66 ± 6.13 b	7.95 ± 3.44 a	27.06 ± 4.12 a–c	2.60 ± 0.52 a–c	1.47 ± 0.04 a
		TP	51.83 ± 1.53 b	5.61 ± 0.36 a–c	29.11 ± 1.78 ab	2.56 ± 3.15 a–c	1.47 ± 0.08 a
		TA	46.35 ± 5.32 b	4.74 ± 0.58 a–c	30.33 ± 3.74 a	3.08 ± 0.53 a–c	0.96 ± 0.20 b
Zblewo	Plowing	*TS*	56.47 ± 3.03 b	4.53 ± 0.53 a–c	26.18 ± 1.28 a–c	1.86 ± 0.82 a–c	0.20 ± 0.06 g
		TP	54.39 ± 0.87 b	3.28 ± 1.88 a–c	25.28 ± 1.46 a–c	3.08 ± 0.16 a–c	0.19 ± 0.07 g
		TA	55.65 ± 2.51 b	4.71 ± 1.06 a–c	25.48 ± 3.41 a–c	2.84 ± 0.16 a–c	0.22 ± 0.02 g
	Shallow tillage	*TS*	66.17 ± 4.74 b	3.05 ± 1.14 bc	22.78 ± 0.65 c–e	4.58 ± 0.56 ab	0.41 ± 0.11 c–f
		TP	63.38 ± 4.36 b	3.83 ± 0.86 a–c	21.62 ± 3.59 c–e	4.05 ± 0.57 a–c	0.34 ± 0.01 fg
		TA	61.85 ± 1.91 b	4.47 ± 0.23 a–c	23.32 ± 2.37 c–e	2.25 ± 0.47 a–c	0.36 ± 0.01 e–g
Budziszewo	Plowing	*TS*	209.35 ± 19.03 a	5.81 ± 1.60 ab	18.14 ± 1.78 ef	5.51 ± 2.20 a	0.53 ± 0.04 c–e
		TP	176.22 ± 8.56 a	5.74 ± 1.82 ab	15.20 ± 1.96 f	3.07 ± 0.51 a–c	0.48 ± 0.04 c–f
		TA	222.35 ± 23.83 a	4.63 ± 1.55 a–c	15.27 ± 0.88 f	4.06 ± 0.70 a–c	0.54 ± 0.07 cd
	Shallow tillage	*TS*	85.27 ± 8.59 b	0.95 ± 0.17 c	14.94 ± 1.02 f	1.96 ± 0.98 a–c	0.46 ± 0.02 c–f
		TP	171.54 ± 83.38 a	4.92 ± 5.68 a–c	15.74 ± 0.45 f	0.81 ± 0.62 c	0.55 ± 0.03 c
		TA	227.01 ± 43.06 a	1.45 ± 0.32 bc	15.59 ± 0.99 f	1.38 ± 1.40 bc	0.54 ± 0.07 c

[1] Mean values ± standard deviation (SD) in columns followed by different letters indicate significant differences between treatments at $p \leq 0.05$; FADH–fluorescein diacetate hydrolysis.

In Grabina Wielka, the activity of FADH and glucosidase in the soil from the cultivation of primary wheats (*Triticum sphaerococcum* and *T. persicum*) in shallow tillage was significantly higher than in the soil from the cultivation of the same species under plowing tillage. Similarly, the soil from the cultivation of common wheat (*T. aestivum*) in shallow tillage was characterized by higher FADH activity than the soil from plowing tillage of this species. The nitroreductase activity in the soil taken from shallow tillage was higher than in the soil from plowing tillage, but the differences were statistically significant only in the treatment with *T. sphaerococcum.*

In Zblewo, as in Grabina Wielka, the activity of enzymes such as dehydrogenases, urease, and glucosidase was higher in shallow tillage than in plowing. Statistically, greater activity of glucosidase was found in the soil from the shallow tillage of *T. sphaerococcum* compared to plowing tillage of all studied wheat species.

Dehydrogenase activity depended mainly on the experimental locality; in the soil taken from Budziszewo, it was on average 3.5 times higher than in the soil from Grabina Wielka and Zblewo. In Budziszewo, the lowest activity of this enzyme was recorded in samples from shallow tillage of *T. sphaerococcum*.

Irrespective of the wheat species, nitroreductase activity in the soil from plowing tillage was higher than from shallow tillage, especially from Budziszewo (2.2 times), but also in Zblewo and Grabina Wielka (by 10.6% and 9.9%, respectively). In contrast, glucosidase activity was higher for shallow tillage than for plowing (by 85% in Zblewo and 15.1% in Grabina Wielka).

3.2. Occurrence of Disease

During the first assessment, carried out at the stem elongation stage (BBCH 35-37), the occurrence of powdery mildew symptoms was noted on the wheat leaves, most of them in Budziszewo, much less in Grabina Wielka and Zblewo (Table 3). Only in Budziszewo did the severity of this disease depend on the type of cultivation. On Indian dwarf wheat and Persian wheat plants, significantly fewer symptoms of this disease were found in the treatment with shallow tillage than after plowing. However, there was no difference in the severity of the disease depending on the species of wheat.

Table 3. Occurrence of disease symptoms on *Triticum sphaerococcum* (*TS*), *T. persicum* (*TP*) and *T. aestivum* (*TA*) at different tillage methods, in three field experimental localities.

Locality	Soil Tillage	Species	Powdery Mildew	Tan Spot	Brown Rust	Stripe Rust	Septoria Head Blotch	Fusarium Head Blotch	Root Rot	Fusarium Foot Rot	Eyespot
			Leaf or Ear Area with Disease Symptoms (%)						Disease Index (%) for Foot and Root Rot Diseases		
			Stem Elongation (BBCH 35-37)	Development of Fruit (BBCH 75-77)					Development of Fruit (BBCH 75-77)		
Grabina Wielka	Plowing	*TS*	3.13 ± 1.50 d [1]	2.20 ± 0.40 e–g	0.00 ± 0.00 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	5.50 ± 2.08 d–f	1.25 ± 1.26 cd	15.00 ± 4.55 cd
		TP	7.67 ± 2.72 d	4.00 ± 2.59 e–g	0.00 ± 0.00 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	8.00 ± 1.83 c–f	2.25 ± 0.50 cd	4.00 ± 1.83 e
		TA	0.24 ± 0.07 d	0.45 ± 0.52 g	0.00 ± 0.00 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	12.25 ± 3.77 b–e	0.75 ± 0.50 cd	10.00 ± 3.74 c–e
	Shallow tillage	*TS*	3.08 ± 1.77 d	0.42 ± 0.25 g	0.00 ± 0.00 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	10.25 ± 3.86 b–f	3.25 ± 3.20 b–d	18.75 ± 8.02 bc
		TP	4.33 ± 2.94 d	5.00 ± 4.95 e–g	0.00 ± 0.00 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	11.50 ± 2.08 b–e	1.25 ± 1.50 cd	6.75 ± 3.30 de
		TA	0.00 ± 0.00 d	0.05 ± 0.06 g	0.00 ± 0.00 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	11.00 ± 3.92 b–e	1.25 ± 0.96 cd	8.00 ± 1.63 de
Zblewo	Plowing	*TS*	2.58 ± 1.13 d	9.33 ± 2.34 d–f	3.75 ± 1.10 c	7.67 ± 0.98 a	5.83 ± 2.20 b	0.00 ± 0.00 c	23.50 ± 8.70 a	15.25 ± 2.99 a	35.25 ± 7.32 a
		TP	0.68 ± 0.27 d	5.67 ± 1.98 e–g	0.92 ± 0.20 c	1.00 ± 0.24 c	0.00 ± 0.00 d	0.00 ± 0.00 c	17.75 ± 4.72 a–c	7.00 ± 3.83 b	18.50 ± 5.69 bc
		TA	3.75 ± 2.81 d	1.08 ± 2.17 fg	0.02 ± 0.02 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	0.00 ± 0.00 f	0.00 ± 0. 00 d	0.00 ± 0.00 e
	Shallow tillage	*TS*	3.92 ± 0.74 d	9.83 ± 2.38 c–e	4.42 ± 0.42 c	6.33 ± 1.28 b	8.17 ± 1.64 b	0.00 ± 0.00 c	18.50 ± 8.06 ab	4.75 ± 2.36 bc	28.75 ± 8.06 ab
		TP	0.68 ± 0.27 d	6.92 ± 1.45 e–g	0.20 ± 0.12 c	0.11 ± 0.06 cd	0.00 ± 0.00 d	0.00 ± 0.00 c	14.00 ± 2.94 a–d	2.50 ± 1.29 cd	8.75 ± 3.86 c–e
		TA	10.50 ± 1.23 d	0.00 ± 0.00 g	0.01 ± 0.01 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	0.00 ± 0.00 f	0.00 ± 0.00 d	0.00 ± 0.00 e
Budziszewo	Plowing	*TS*	47.92 ± 5.51 ab	24.50 ± 5.67 ab	20.42 ± 7.62 a	0.00 ± 0.00 d	17.16 ± 2.99 a	9.65 ± 1.80 a	9.00 ± 5.35 b–f	0.05 ± 0.10 d	2.60 ± 0.94 e
		TP	52.08 ± 8.32 a	22.25 ± 3.14 ab	3.25 ± 0.74 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	4.25 ± 1.71 d–f	0.00 ± 0.00 d	1.90 ± 0.96 e
		TA	43.33 ± 6.09 ab	17.50 ± 3.43 b–d	1.83 ± 1.04 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	9.25 ± 4.79 b–f	0.25 ± 0.19 d	1.50 ± 0.53 e
	Shallow tillage	*TS*	25.83 ± 17.24 c	24.58 ± 6.85 ab	13.50 ± 2.44 b	0.00 ± 0.00 d	2.68 ± 0.90 c	5.08 ± 0.67 b	6.50 ± 2.89 d–f	0.00 ± 0.00 d	2.45 ± 0.60 e
		TP	36.67 ± 7.07 bc	27.50 ± 5.69 a	3.42 ± 1.00 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	3.25 ± 0.96 ef	0.10 ± 0.20 d	2.40 ± 0.99 e
		TA	39.17 ± 3.19 a–c	17.92 ± 3.20 bc	1.96 ± 0.52 c	0.00 ± 0.00 d	0.00 ± 0.00 d	0.00 ± 0.00 c	4.00 ± 1.83 d–f	1.05 ± 0.41 cd	0.60 ± 0.16 e

[1] Mean values ± standard deviation (SD) in columns followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

At the development of fruit (BBCH 75-77), on the leaves of the analyzed wheat, mainly tan spot disease symptoms were observed, which were found in all localities on all species, and the most on Indian dwarf wheat and Persian wheat (Table 3). No unequivocal effect of the cultivation type on the occurrence of this disease was observed. The signs of brown rust were observed mainly in Budziszewo and significantly less in Zblewo. Only in Budziszewo and only in Indian dwarf wheat, the type of cultivation affected the severity of the disease, the symptoms of which were much more severe in plowing tillage than in shallow tillage. Symptoms of stripe rust were noted only in Zblewo and most of them were found on Indian dwarf wheat, where more symptoms of the disease were found after plowing. The symptoms of Septoria head blotch and Fusarium head blotch were observed on the ears of Indian dwarf wheat, but the first of these diseases was found only in Zblewo and Budziszewo, and the other only in Budziszewo. In Budziszewo, many more signs of these diseases were recorded when plowing was performed.

Among take-all diseases, eyespot and root rot symptoms were observed most often; Fusarium foot rot symptoms were less frequent (Table 3). On the Indian dwarf wheat plants, the most symptoms of foot and root rot diseases were found in Zblewo. However, no symptoms of the above diseases have been found on common wheat at this location. Among the foot and root rot diseases, tillage significantly affected only the intensity of Fusarium foot rot, which was observed only in Zblewo. In both Indian dwarf wheat and Persian wheat, significantly more signs of the disease were noted after plowing. In the case of the other foot and root rot diseases and locations, the effect of the tillage method on the intensity of disease signs was ambiguous.

3.3. Plant Damage by Pests Insects

The average surface damage caused by feeding of cereal leaf beetles was small and did not exceed a dozen or so percent. In Grabina Wielka, a greater degree of damage caused by the feeding of both the pest adults and larvae was found, compared to Zblewo and Budziszewo (Table 4).

Table 4. The damaged plant surface of *Triticum sphaerococcum* (*TS*), *T. persicum* (*TP*) and *T. aestivum* (*TA*) by pests at different tillage methods, in three field experimental localities (%).

Locality	Soil Tillage	Species	*Oulema* spp. Adults	*Oulema* spp. Larvae	*Oulema* spp. Adults	*Oulema* spp. Larvae
			Flag Leaf Stage (BBCH 39)		Flowering (BBCH 65)	
Grabina Wielka	Plowing	*TS*	8.25 ± 2.99 a [1]	9.25 ± 1.50 bc	8.25 ± 2.36 b	6.00 ± 1.15 b
		TP	0.25 ± 0.50 c	1.50 ± 1.00 ef	0.00 ± 0.00 c	0.50 ± 0.58 fg
		TA	1.25 ± 0.50 c	10.75 ± 2.99 ab	11.25 ± 2.50 ab	5.50 ± 0.58 bc
	Shallow tillage	*TS*	4.50 ± 1.91 b	12.50 ± 0.58 a	13.75 ± 2.50 a	6.75 ± 1.26 ab
		TP	2.25 ± 0.50 bc	0.25 ± 0.50 f	1.50 ± 0.58 c	0.25 ± 0.50 fg
		TA	2.25 ± 1.26 bc	6.75 ± 2.87 cd	12.50 ± 2.89 a	8.00 ± 1.41 a
Zblewo	Plowing	*TS*	0.00 ± 0.00 c	10.75 ± 0.96 ab	2.75 ± 0.96 c	1.50 ± 0.58 e–g
		TP	0.00 ± 0.00 c	1.50 ± 0.58 ef	1.50 ± 0.58 c	0.50 ± 0.58 fg
		TA	0.00 ± 0.00 c	3.75 ± 0.96 de	1.00 ± 0.82 c	0.50 ± 0.58 fg
	Shallow tillage	*TS*	1.50 ± 0.58 c	2.25 ± 0.50 ef	0.25 ± 0.50 c	1.25 ± 0.50 e–g
		TP	0.75 ± 0.50 c	2.00 ± 0.00 ef	0.75 ± 0.96 c	1.25 ± 0.50 e–g
		TA	1.75 ± 0.50 c	2.75 ± 0.50 ef	0.00 ± 0.00 c	0.50 ± 0.58 fg
Budziszewo	Plowing	*TS*	0.00 ± 0.00 c	1.75 ± 0.50 ef	0.25 ± 0.50 c	3.75 ± 0.96 cd
		TP	0.00 ± 0.00 c	0.75 ± 0.50 ef	0.00 ± 0.00 c	0.00 ± 0.00 g
		TA	0.00 ± 0.00 c	1.25 ± 0.50 ef	1.75 ± 0.50 c	2.75 ± 0.50 de
	Shallow tillage	*TS*	0.25 ± 0.50 c	1.25 ± 0.50 ef	0.75 ± 0.50 c	2.00 ± 0.82 d–f
		TP	0.50 ± 0.58 c	2.25 ± 0.50 ef	0.00 ± 0.00 c	0.00 ± 0.00 g
		TA	0.50 ± 0.58 c	1.75 ± 0.96 ef	2.25 ± 0.50 c	0.75 ± 0.50 fg

[1] Mean values ± standard deviation (SD) in column followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

Statistical analysis showed the interaction of factors (locality x soil tillage x species) on the damaged plant surface by *Oulema* spp. adults and *Oulema* spp. larvae, both at the flag leaf stage ($p < 0.001$, $p < 0.001$, respectively) and the flowering ($p = 0.015$, $p < 0.001$, respectively). In Grabina Wielka, at the flag leaf stage of wheats, the most damage to the assimilation surface of leaves caused by feeding of *Oulema* spp. adults was observed in plowing tillage of *T. sphaerococcum*. Both in plowing and shallow surface tillage, the least damage to leaves caused by *Oulema* spp. larvae was observed on *T. persicum*. Similarly, at the flowering stage, Persian wheat was the least damaged by *Oulema* spp. adults and larvae of this pest. At this development stage, Indian dwarf wheat had more damage from feeding by *Oulema* spp. adults in shallow tillage compared to plowing. The effect of tillage on the size of leaf area damaged by *Oulema* spp. larvae on common wheat was similar. In Zblewo, a significant effect of tillage methods and wheat species on the amount of damage to leaves caused by *Oulema* spp. was noted only at the flag leaf stage (BBCH 39). Damage caused by the larvae of this pest was the highest on wheat *T. sphaerococcum* with plowing tillage. In Budziszewo, the amount of damage to the leaves caused by cereal leaf beetles was the smallest. Only at the flowering stage, the method of tillage and the type of wheat affected the amount of leaf damage caused by this pest. On common wheat, *Oulema* spp. larvae caused more damage in the plowing tillage variant compared to shallow tillage.

3.4. Plant Features and Grain Yield

The root length of the studied wheat species as well as their mass were shaped by the interactions of location x cultivation methods and species ($p = 0.008$, and $p = 0.039$, respectively). However, no directional reactions of the root length of individual wheat species to the tillage methods were found in Grabina Wielka or Zblewo. In Budziszewo, in turn, the roots of common wheat were significantly longer, both in plowing and shallow surface tillage (Table 5). On average, for species and methods of tillage, wheat developed a longer root system in Grabina Wielka than in Zblewo and Budziszewo (by 31% and 37%, respectively). In Grabina Wielka as well as in Budziszewo, the weight of common wheat roots was usually greater than that of primary Indian dwarf and Persian wheats. Only in Zblewo, the weight of roots of Indian dwarf wheat with plowing tillage was more than twice as high as that of other wheat species in simplified tillage and after plowing.

Tillers of Indian dwarf wheat and Persian wheat were, on average for localities and tillage methods, longer than those of common wheat (by 2.9 cm and 3.8 cm, respectively) (Table 5). The analysis of factor interactions (locality x soil tillage x species, $p < 0.001$) showed that in Grabina Wielka and Zblewo primary wheats in shallow tillage had usually longer generative tillers than common wheat, while there were no species differences in plowing tillage. In Budziszewo, the effect of the species and tillage method on the length of tillers was insignificant.

The number of generative tillers per common wheat plant was 1.35 and was higher than that of Indian dwarf wheat (1.17) and Persian wheat (1.08), but this trait was significantly affected by the interaction of locality x soil tillage x species ($p = 0.004$). Significant interspecific differences in this trait were proven only in Budziszewo, where the number of generative tillers per common wheat plant with plowing tillage was significantly higher in Persian wheat for both methods of tillage and in Indian dwarf wheat for plowing tillage (Table 5).

Table 5. Root length and weight, generative tillers length and number per plant, and the number of fertile and sterile spikelets per ear of *Triticum sphaerococcum* (*TS*), *T. persicum* (*TP*) and *T. aestivum* (*TA*) at different tillage methods, in three field experimental localities.

Locality	Soil Tillage	Species	Root Length (cm)	Root Weight (DM, g/30 Plants)	Generative Tillers Length (cm)	Generative Tillers (no plant^{-1})	Fertile Spikelets (no ear^{-1})	Sterile Spikelets (no ear^{-1})
Grabina	Plowing	*TS*	9.29 ± 0.76 b–d [1]	5.34 ± 2.56 c–e	69.88 ± 8.89 c–e	0.99 ± 0.04 d	12.44 ± 0.17 a–d	4.78 ± 0.54 b–e
		TP	10.43 ± 1.91 a–c	5.07 ± 1.40 c–e	70.48 ± 4.54 b–e	0.98 ± 0.07 d	10.63 ± 0.50 d–f	3.10 ± 0.26 gh
		TA	9.35 ± 2.13 b–d	9.44 ± 1.63 bc	68.05 ± 2.98 de	1.09 ± 0.07 d	12.64 ± 1.26 a–e	4.69 ± 0.71 b–f
	Shallow tillage	*TS*	11.86 ± 1.18 ab	7.27 ± 1.41 c–e	78.69 ± 5.53 a–c	0.98 ± 0.03 d	13.07 ± 0.48 a–d	5.48 ± 0.26 bc
		TP	12.79 ± 1.29 a	6.82 ± 0.97 c–e	77.89 ± 1.03 a–c	1.01 ± 0.06 d	11.23 ± 0.94 c–f	3.38 ± 0.51 d–h
		TA	10.32 ± 2.95 a–c	13.42 ± 4.02 ab	63.97 ± 3.91 e	1.28 ± 0.15 b–d	12.86 ± 0.86 a–e	3.88 ± 0.74 d–g
Zblewo	Plowing	*TS*	6.50 ± 1.04 d–f	15.28 ± 2.90 a	79.69 ± 2.29 ab	1.14 ± 0.11 cd	12.22 ± 0.55 b–f	7.44 ± 0.63 a
		TP	5.66 ± 0.34 ef	6.64 ± 1.89 c–e	78.08 ± 1.67 a–c	1.00 ± 0.00 d	10.26 ± 1.66 ef	3.36 ± 0.53 e–h
		TA	6.56 ± 0.72 d–f	5.95 ± 0.99 c–e	78.43 ± 1.67 a–c	1.04 ± 0.06 d	15.01 ± 0.61 a	1.83 ± 0.25 h
	Shallow tillage	*TS*	6.37 ± 1.20 d–f	6.30 ± 1.22 c–e	77.77 ± 4.17 a–c	1.03 ± 0.03 d	11.94 ± 0.63 b–f	5.51 ± 0.06 b
		TP	6.82 ± 0.42 d–f	6.71 ± 1.83 c–e	83.02 ± 2.23 a	1.14 ± 0.13 cd	10.33 ± 2.19 ef	3.00 ± 0.50 gh
		TA	8.06 ± 1.33 c–e	6.57 ± 1.82 c–e	71.26 ± 1.66 b–e	1.14 ± 0.15 cd	13.55 ± 0.13 a–c	2.05 ± 0.38 h
Budziszewo	Plowing	*TS*	5.22 ± 0.57 ef	4.79 ± 2.63 c–e	75.81 ± 1.95 a–d	1.70 ± 0.66 ab	12.34 ± 1.00 b–f	5.83 ± 1.11 b
		TP	5.47 ± 0.28 ef	2.89 ± 2.71 de	76.69 ± 2.89 a–d	1.13 ± 0.27 cd	10.25 ± 0.79 ef	3.16 ± 0.41 f–h
		TA	11.98 ± 1.23 ab	9.72 ± 4.62 a–c	73.54 ± 3.06 a–d	1.88 ± 0.04 a	12.72 ± 1.03 a–e	4.96 ± 0.89 b–d
	Shallow tillage	*TS*	5.30 ± 0.54 ef	3.51 ± 1.00 de	67.42 ± 4.22 de	1.21 ± 0.20 b–d	10.62 ± 0.70 d–f	5.75 ± 1.01 b
		TP	4.58 ± 0.69 f	1.92 ± 0.56 e	68.21 ± 2.70 de	1.21 ± 0.14 b–d	9.73 ± 1.46 f	2.87 ± 0.51 gh
		TA	11.58 ± 1.07 ab	8.01 ± 0.29 b–d	76.39 ± 1.88 a–d	1.65 ± 0.30 a–c	14.18 ± 0.93 ab	3.92 ± 0.59 c–g

[1] Mean values ± standard deviation (SD) in column followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

The studied wheat species were characterized by a varied number of fertile spikelets per ear (Table 5). On average, for localities and tillage methods, it was the highest in common wheat (13.5), lower in Indian dwarf wheat (12.1) and the lowest in Persian wheat (10.4). The interaction of factors (locality x soil tillage x species, $p = 0.007$) on the number of fertile spikelets was demonstrated. In Grabina Wielka, the wheat species and the method of tillage did not have a significant effect on the number of fertile spikelets per ear, with the number of such spikelets slightly higher in Indian dwarf wheat in shallow surface tillage. On the other hand, in Zblewo and Budziszewo, common wheat had more fertile spikelets than primary Indian dwarf and Persian wheats. Indian dwarf wheat was characterized by the largest number of unfertile spikelets. The proportion of fertile spikes in the total number of spikelets was similar in common and Persian wheats (79% and 77%, respectively), while in Indian dwarf wheat it was relatively lower (68%).

The interaction of factors (locality x soil tillage x species, $p = 0.006$) had a significant influence on the number of generative tillers per 1 m^2 (Figure 2). Indian dwarf wheat in shallow surface tillage in Grabina Wielka was characterized by a significantly higher density of generative tillers than in Budziszewo. Similarly, the number of generative tillers of Persian wheat was more dependent on the location than on the tillage method, which was particularly visible in Grabina Wielka and Budziszewo. Plowing in Grabina Wielka and Budziszewo was conducive to the density of generative tillers of common wheat.

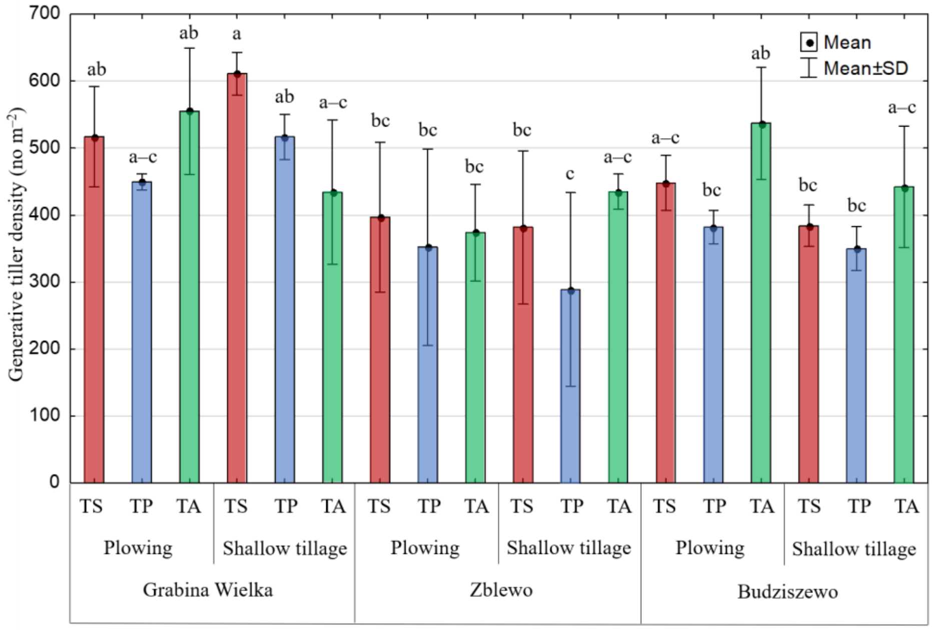

Figure 2. Generative tiller density of *Triticum sphaerococcum* (TS), *T. persicum* (TP) *and T. aestivum* (TA) at different tillage methods, in three field experimental localities (no m^{-2}). Mean values followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

A significant ($p = 0.013$) interaction of locality, soil tillage, and wheat species on number of grains per ear was demonstrated (Figure 3). In Zblewo, the number of grains per ear of common wheat in plowing and shallow surface tillage was higher than in both primary wheats. In Budziszewo, a similar difference was noted only in shallow surface tillage. In Grabina Wielka, in turn, simplified tillage was conducive to the formation of more numerous grains per ear of Indian dwarf wheat compared to Persian wheat.

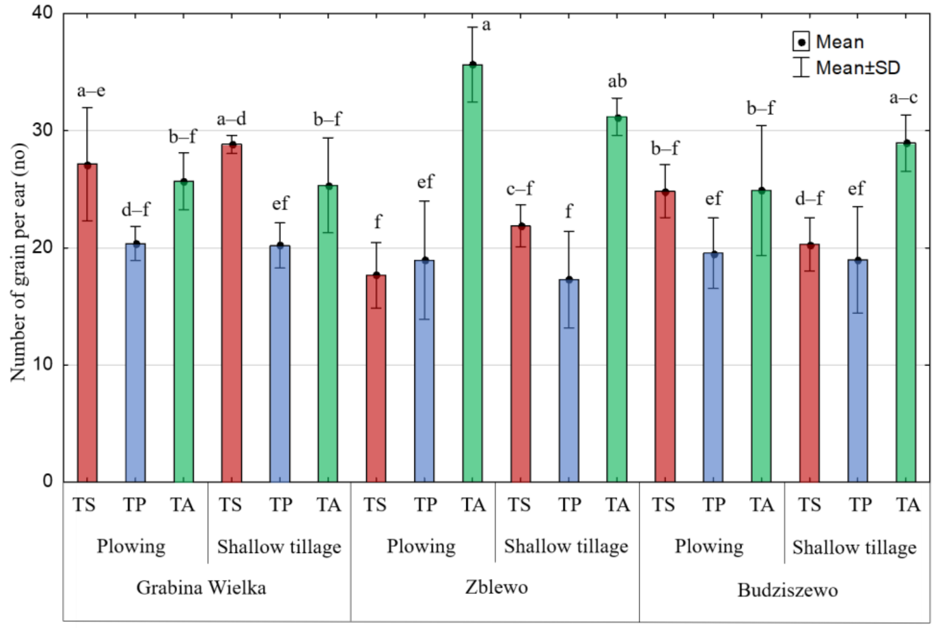

Figure 3. Number of grains per ear of *Triticum sphaerococcum* (TS), *T. persicum* (TP) *and T. aestivum* (TA) at different tillage methods, in three field experimental localities (no). Mean values followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

As in other yield components, the interaction of locality x soil tillage x species significantly affected the 1000 grain weight, $p = 0.041$. In Zblewo, common wheat had a greater 1000 grain weight than primary wheats in both tillage methods. In Grabina Wielka, such a relation was recorded only between common wheat and Persian wheat (Figure 4).

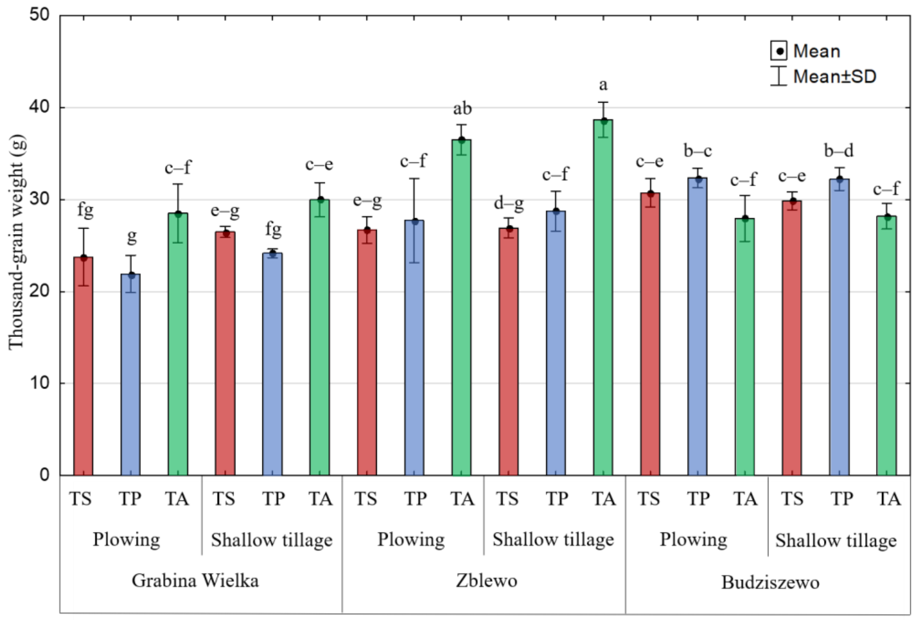

Figure 4. Thousand-grain weight of *Triticum sphaerococcum* (TS), *T. persicum* (TP) *and T. aestivum* (TA) at different tillage methods, in three field experimental localities (g). Mean values followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

Locality x soil tillage x species interaction was demonstrated, with $p < 0.001$ per grain yield. Irrespective of the method of tillage, both in Zblewo and in Budziszewo, the yield of common wheat was higher than that of both types of primary Indian dwarf wheat and

Persian wheat, which did not differ significantly in terms of yield (Figure 5). In Grabina Wielka, the same relationship between common wheats and primary wheats was observed only in plowing tillage. In shallow surface tillage, however, Indian dwarf wheat gave high yields, and its grain yield was even slightly higher than that of common wheat and significantly higher than that of Persian wheat. On average for the location, the grain yield of Indian dwarf wheat was 15.6% higher with shallow surface tillage compared to plowing tillage.

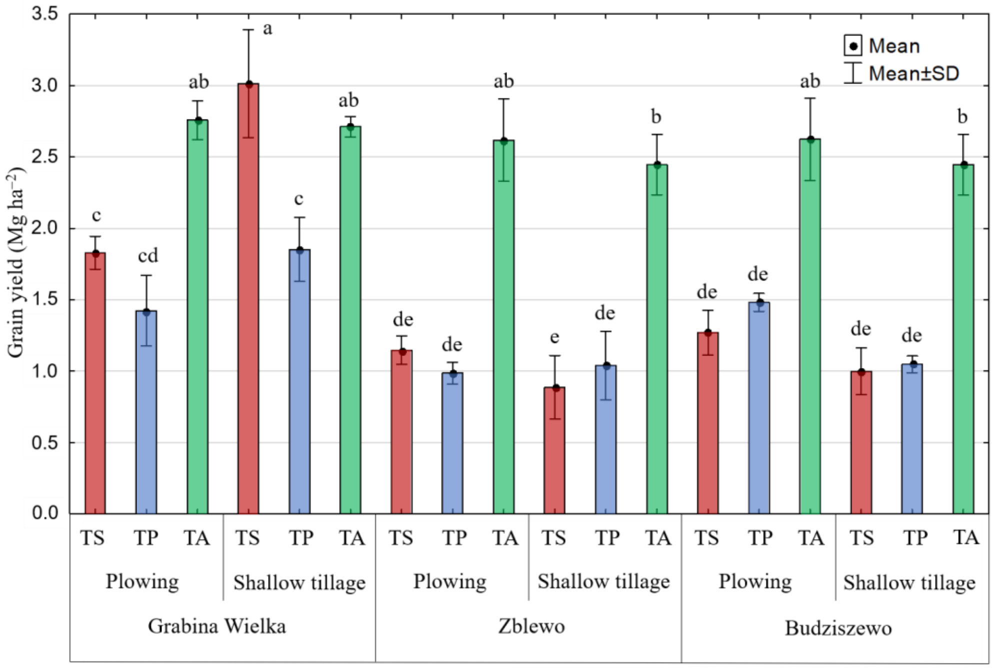

Figure 5. Grain yield of *Triticum sphaerococcum* (TS), *T. persicum* (TP) *and T. aestivum* (TA) at different tillage methods, in three field experimental localities (Mg ha^{-1}). Mean values followed by different letters indicate significant differences between treatments at $p \leq 0.05$.

4. Discussion

The activity of enzymes are recognized as an indirect indicator of the amount and activity of soil microorganisms. Our results indicate that dehydrogenases activity depend mainly on local soil and weather conditions at the experimental site. Increased dehydrogenases activity in soils from Budziszewo were observed in all soil tillage methods and wheat species compared to the soil from Grabina Wielka and Zblewo. Weather and soil conditions in Budziszewo may have influenced the ease of water accumulation and adsorption of some nutrients in the soil by intensifying oxidoreduction reactions in viable cells present in this soil. According to Morris et al. [43], the soil moisture level affects the activity of dehydrogenases. However, the lowest FADH activity in all soil samples from Budziszewo can indicate a different cause or effect of such intense dehydrogenases activity.

The hydrolytic enzyme FDAH participates in catalyzing the nutrient-rich "unstable" soil organic matter, which is related to meeting the demand of soil microorganisms and plants for C, N, and P [44]. The results of our research, therefore, suggest the introduction of "stable" organic matter into the soil, and not just plant debris, contributing to greater activity of microorganisms and oxidative enzymes, and thus to a decrease in the activity of hydrolytic enzymes (FDAH).

Melero et al. [45] reported higher dehydrogenases activity in the soil where reduced tillage was applied. Similarly, in our study, in Grabina Wielka and Zblewo higher dehydrogenases activity were observed in shallow tillage as compared to plowing (by 23% and 15%, respectively). Soil cultivation practices change the physical and chemical properties of the soil, transforming the number of microbes in the soil, and thus the biochemical reactions which have the impact of transforming energy and organic matter. Shallow tillage is widely used to improve soil texture and nutrient status in arid regions [46]. The consequence of shallow tillage practices which affect the microbiological and enzyme activity of soil was observed in the Grabina Wielka experiment. The activity of NR, FADH, UR and GL was significantly higher in soil samples from shallow tillage compared with plowing.

According to Niewiadomska et al. [12], low-water content inhibits the growth of some groups of microorganisms. It reduces their populations and the populations of so-called inductive enzymes which are secreted into the soil by microorganisms. The different activities of enzymes in different localities, with different tillage methods and in different wheat species in our study confirmed that their activity depends on soil conditions, which are labile and dependent on many factors. One of the most important is the content of organic matter that is both synthesized and degraded in the soil by the activity of microbial enzymes.

During the growing season, the assessment of plant health was carried out twice and concerned the intensity of occurrence of all the most dangerous diseases of roots, stem base, leaves, and ears of wheat. The analyzed Indian dwarf wheat and Persian wheat plants showed signs of diseases similar to those observed in common wheat, both in organic [47] and conventional crops [34]. However, disease severity in common wheat plants was usually lower than in ancient wheat species. This is in line with research conducted by Kuś et al. [48], who found that in organic cultivation, "old" wheat cultivars were more heavily affected by pathogens causing diseases on the leaves and stem base than in the currently cultivated cultivars. Cereal diseases are one of the main causes of crop losses, and disease resistance is highly important [49]. The different severity of diseases observed both between the analyzed locations of experiments and cereal species may also result from different canopy architecture, as indicated by Baccar et al. [50] Typically, tall plants are less affected by leaf and ear pathogens. In the case of leaf diseases, the closer the leaves are to each other, the easier it is for pathogen spores to be transported up the plant, thanks to their dissemination by raindrops splashing from the lower infected leaves to the upper leaves [29,51].

In Indian dwarf wheat and Persian wheat plants, a similar severity of disease symptoms was noted as in previous studies on these wheat species grown both in the organic system [28] and in the experiment using integrated pest management [29]. In our study, regardless of the cultivation system of these cereals, the leaves of the analyzed plants also had the highest number of powdery mildew disease signs. The occurrence of this disease depends to a considerable extent on weather conditions, and it is particularly favored by high humidity prevailing in cereal stands [52]. Also, the severity of other diseases of leaves and ears depended on weather conditions. In Grabina Wielka, where the total rainfall was the lowest, signs of the least or no disease were noted on the leaves (tan spot, brown rust, stripe rust) and ears (Fusarium head blight, Septoria head blotch).

The lower amount of precipitation recorded in Grabina Wielka contributed to the premature withering of wheat plants, thus preventing the development of pathogens, especially since most of the observed diseases on leaves were caused by obligate pathogens that need living tissues of host plants for development. Therefore, no symptoms caused by *B. graminis*, *P. recondite*, and *P. striiformis* were observed in the organic experiment during the second observation period. A small amount of rainfall was also not conducive to infection of ears by *Fusarium* spp. and *S. glumarum*, which is also indicated by Suproniene et al. [53] and Leplat et al. [54].

Among foot and root rot diseases, on Indian dwarf wheat and Persian wheat, most signs of eyespot and root rot and fewer signs of Fusarium foot rot were observed. This confirms previous observations carried out on these cereals in organic farming, using different sowing densities [28]. On the other hand, in conventional cultivation, with the use of integrated pest management on primary wheat species, the most signs of root rot were observed; there were fewer signs of Fusarium foot rot, and eyespot signs were observed sporadically [29], which could be the result of the use of fungicides.

In our study, the type of crop used significantly affected the severity of disease signs of powdery mildew, brown rust, stripe rust, Septoria head blotch, Fusarium head blotch and Fusarium foot rot on the primary wheat species, which was particularly visible on Indian dwarf wheat. Under conditions favorable for the development of the above diseases, significantly fewer signs were found in shallow tillage compared to plowing. In the literature there are usually different views on this subject. However, Suproniene et al. [53] report that the applied tillage systems had no significant effect on the severity of disease caused by these fungi, but they had an indirect effect, increasing the content of mycotoxins in wheat grain. According to Dordas et al. [55], minimum tillage concentrates residues on the soil surface, and therefore concentrates the pathogen propagule number on the soil surface; this might or might not affect disease incidence. Minimum and zero tillage do not disrupt the plant residues in the soil as much as the conventional tillage system, thereby leaving more stubble on the soil surface. According to Dordas et al. [55], minimal tillage concentrates residues on the soil surface and thus concentrates the number of pathogen propagules on the soil surface. This may or may not have an effect on disease occurrence. Minimal and no tillage does not destroy plant debris in the soil as much as conventional tillage, thus leaving more stubble on the soil surface. Stagnant residues or residues lying on the soil surface are colonized by soil organisms much more slowly, and pathogen survival and growth in intact residues are favored in these systems.

In our study, the type of cultivation did not cause the intensity of occurrence of tan spot and root rot to differ. However, according to Ivchenko et al. [56], traditional plowing significantly reduces root rot of spring wheat compared to the absence of any soil tillage. Bankina et al. [14] add that simplified tillage increases the level of plant infection by *P. tritici-repentis*. In addition, Jørgensen and Olsen [49] confirmed that tillage without inversion was the main factor increasing the severity of tan spot compared to conventional plowing.

Our research also included an analysis of wheat damage by pest insects. The leaves of *T. sphaerococcum*, *T. persicum*, and *T. aestivum* were slightly damaged by cereal leaf beetles. This corresponds to the results of previous studies on the effect of sowing density on the occurrence of pest insects such as *Oulema* spp. and Aphididae on primary wheats [28]. The amount of damage caused by *Oulema* spp. adults and larvae assessed in our study resulted from the interaction of locality, soil cultivation method, and wheat species. The results regarding the impact of farming methods on the number of insects available in the literature are ambiguous. Jasrotia et al. [15] studied the effect of tillage intensity on the abundance of important wheat pests: the aphids *Rhopalosiphum maidis* and *R. rufiabdominalis* and the butterfly *Sesamia inferens*. Aphid numbers were generally higher under conventional tillage, lower under reduced tillage, and lowest under zero tillage. In contrast, in the case of the butterfly *S. inferens*, wheat was the least damaged for conventional tillage, and the most for zero tillage, while for reduced tillage it showed intermediate values. In our study, it can be seen that the amount of damage caused by *Oulema* spp. adults and larvae was generally lowest in *T. persicum*, for both shallow tillage and plowing. The influence of wheat species on the number of insects was also shown by Clement et al. [16]. In their study, the aphid *Diuraphis noxia* was most numerous on continuous no-till hard red spring wheat, while *Sitobion avenae* were most numerous on no-till soft white spring wheat.

The grain yield of the studied wheat species was determined to a great extent by weather conditions. The highest yields were obtained in Grabina Wielka, where the distribution of rainfall in spring was more favorable for the growth and development of wheat, and only a few annual weeds were present on the plots. In other locations, with high weed infestation, both in plowing and shallow surface tillage, grain yield was greatly reduced. This concerned mainly primary wheats and, to a lesser extent, common wheat. The better competitiveness of common wheat against weeds could result from the increased density of generative tillers compared to primary wheats, especially in Budziszewo. Literature data indicate that plowing is traditionally considered a key preventive weed control method for arable crops, especially in organic farming, while reduced tillage increases weed infestation [17]. This is confirmed by a study by Armengot [3], in which weed abundance was

2.3 times higher under reduced tillage compared to plowing. According to Husain [17], the increase in weed infestation in reduced tillage may be the reason for the reduction of wheat yield, although in our study, due to weed infestation, the yield was reduced in both plowing and shallow tillage.

In our study, on average for localities and species, grain yields under shallow surface tillage were similar to those obtained under plowing tillage. It is known that the soil tillage system influences the physiological state of spring wheat (net photosynthesis rate, stomatal conductance, transpiration rate) [12], but the final yield response is equivocal. Some literature reports indicate that reduced tillage is the viable cropping system for organic farming. Armengot [3] showed that despite the weed increase, yields of wheat and spelt were similar for reduced tillage and conventional tillage. Similarly, in the Khorami et al. [10] study, there was no significant difference in grain yield or the number of generative tillers from 1 m^2 of wheat in conventional and reduced soil cultivation. However, many research results indicate the advantage of plowing tillage. According to Hussain [17], the deep tillage treatments resulted in the highest number of ears per m^2, 1000-grain weight, and grain yield, while shallow tillage showed the lowest values. Similarly, in a study by Kayan et al. [24], conventional tillage methods resulted in higher grain yield and yield components compared to reduced tillage. Yildirim at al. [22], based on a study of bread wheat, state that the tillage systems significantly affected the number of fertile ears per m^2, number of fertile spikelets per ear, number of grains per ear, and grain yield. Over the two study years, values of all traits in conventional tillage were higher than those of reduced tillage. However, the response of yield components and wheat grain yield to simplifications in tillage is fundamentally dependent on weather conditions in the year of a study [3,11,21].

In our study, Indian dwarf wheat, in site conditions favorable for growth and development, under shallow surface tillage in Grabina Wielka yielded three times more than the average in other locations. It is also worth noting that the wheat in this location had 37.7% more roots under shallow tillage than under plowing conditions. This could indirectly contribute to an increase in grain yield. Earlier studies by Ujj at al. [57] also indicate an increase in root weight of wheat under shallow tillage conditions compared to plowing. Fradgley et al. [58], in turn, emphasize significant genotype-by-tillage interactions for many wheat root traits. Certainly, the yield of Indian dwarf wheat in Grabina Wielka was positively affected by the highest rainfall in this location in April, which was conducive to uniform emergence and ultimately to a high density of generative tillers per area unit before harvesting. Indian dwarf wheat in this location, under shallow surface tillage conditions, developed numerous grains per ear. Kayan et al. [24] report that wheat grain yield is significantly affected by tillage methods, but this response varies by year (e.g., hydro-thermal conditions during the growing season). In that study, only in one year out of four years of research, thanks to the increase in the number of grains per ear, were greater yields of wheat grain obtained with simplified tillage. According to Figueroa-Bustos et al. [59], insufficient water supply to plants at the initial stages of development (at the stage of leaf formation) has a strong, negative impact on the physiological state of cereals (it reduces the conductivity of stomata, transpiration rate, rate of leaf photosynthesis, and shoot biomass).

Armengot et al. [3] and Berner et al. [11] agree that the response of wheat yield to simplifications in tillage depends not only on weather conditions during the years of a study, but also on genetically determined species characteristics. The cultivar is also important. Andruszczak [23] reports that *Triticum spelta* L. cultivars responded differently to a reduced tillage system. Similarly, in a study by Hansdorf et al. [60], it was confirmed that the combined effect of both genotype and tillage was significant for yield in bread wheat. In our study, common wheat was characterized by the highest yield stability. In changing soil and climatic conditions in individual locations and with various methods of tillage, grain yield was even and ranged from 2.44 to 2.76 Mg ha^{-1}. Higher yield of common wheat in relation to primary Indian dwarf and Persian wheats resulted from the difference in the number of fertile spikes, grains per spike, and the thousand grain weight, traits that are strongly genetically determined. Better yields could also result from the generally higher weight of common wheat roots compared to other species, which resulted in better uptake of water and nutrients from the soil during growth. In all locations and in both methods of sowing, Persian wheat yielded at a relatively low level. This species was characterized by the lowest number of grains per ear (19.2), where it was higher by 49% and 22%, respectively, in common wheat and Indian dwarf wheat.

5. Conclusions

The studies on the activity of dehydrogenases, nitroreductase, FDAH, urease, and glucosidases confirm that they are sensitive indicators of changes in the soil, and their activity is much more affected by local soil and weather conditions compared to the influence of wheat species and tillage methods.

The analysis of damage caused by insect pests shows that both the larvae and adults of *Oulema* spp. slightly damaged the leaves of spring wheats, and the reduced method of soil tillage in the form of shallow surface tillage did not increase the damage caused by these pests compared to plowing. The amount of leaf damage caused by cereal leaf beetles was generally lower in Persian wheat compared to Indian dwarf wheat and common wheat (by 76% on average).

The method of tillage had a significant effect on the severity of the symptoms of powdery mildew, brown rust, stripe rust, Septoria head blotch, Fusarium head blotch, and Fusarium foot rot, which was particularly visible on Indian dwarf wheat. Under site conditions favorable for the development of diseases, significantly fewer disease symptoms were found after shallow tillage than after plowing (powdery mildew by 9.6–46.1%; stripe rust by 15.5–89%; Septoria head blotch by 0–84.4%; Fusarium head blotch by 0–47.4%, Fusarium foot rot by 0–100%).

The effect of tillage methods on the yield of spring wheat species was relatively small. The grain yield was determined to a greater extent by genetic factors (the number of grains per ear and the thousand grains weight) and habitat factors (rainfall in April and the weed infestation). Common wheat was characterized by the highest grain yield and the highest yield stability. Higher yields of the ancient wheat species Indian dwarf wheat and Persian wheat can be obtained in shallow surface tillage as compared to plowing (by 64% and 30%, respectively) only with effective weed control.

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