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The Effects of Agronomic Management in Different Tillage Systems on the Fall Growth of Winter Oilseed Rape

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Abstract: The article presents the results of a three-year study, which analyzed agronomic management in the production of winter oilseed rape (WOSR) in different tillage systems. The effects of weed control and growth regulation in fall on the number of rosette leaves, epicotyl length, root collar diameter, taproot length, rosette weight, root weight, and the overwintering success of WOSR plants in different tillage systems were determined in the study. A field experiment was conducted at the University's Agricultural Experiment Station in Bałcyny in north-eastern Poland in three growing seasons (2016/2017–2018/2019). The experiment had a mixed $2^1 \times 3^2$ factorial design with two replications, where one factor was evaluated at two levels, and two factors were evaluated at three levels. The experimental factors were: A—tillage: (A0) strip-till, (A1) low-till, and (A2) conventional tillage; B—weed control: (B0) pre-emergent, (B1) foliar, and (B2) sequential; C—growth regulation: (C0) none and (C1) in fall. Winter oilseed rape plants developed rosettes with the optimal morphometric parameters in the strip-till system. Sequential and foliar application of herbicides decreased the dry matter (DM) content of leaf rosettes (by approx. 18%). The application of the growth regulator in BBCH stages 14–15 increased taproot length by 3%.

Keywords: *Brassica napus* (L.); tillage; weed control; growth regulators; rosette parameters; overwintering success

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1. Introduction

Oilseed rape is the dominant oilseed crop in cold temperate climates [1]. The share of oilseed rape in total oilseed crops produced in Canada and Northern and Central Europe ranges from 53–68% (Slovakia, Canada) to 86–100% (Sweden, Finland, Norway, Denmark, Ireland, UK, Poland, Czechia, Germany) [2]. The role of oilseed rape in the global production of oilseed crops has been increasing since the 1980s when erucic acid (EA) was practically eliminated and the content of glucosinolates (GLS) in seeds was significantly reduced [3]. Unfortunately, the use of two spring cultivars (Liho and Bronowski) in the process of breeding canola-type winter oilseed rape (WOSR) varieties (with reduced content of EA and GLS) decreased their winter hardiness [3]. Continuous attempts are being made to improve the overwintering performance of WOSR, but this trait is still largely unsatisfactory. In Poland, the probability of freeze damage to WOSR ranges from 5–10% to 20%, which implies that in some Polish regions, entire WOSR plantations are destroyed by low temperatures every five years [4]. In the continental climate (*Dfb* – Köppen climate classification), the overwintering success of WOSR is determined by genetic factors as well as the development of the leaf rosette before winter dormancy, which is assessed based on the root collar diameter, taproot length, and the height of the terminal bud above the soil surface [5,6].

In agricultural practice, the development of WOSR rosettes in fall can be modeled by skillfully managing agronomic factors, including tillage, weed control, and chemical growth regulation.

The growth and development of WOSR plants in fall is very important because it determines seed yields. From a physiological and morphological perspective, the fall–winter season is crucial to the yield potential of WOSR plants. During this period, environmental conditions and agronomic factors determine plant density before harvest and the potential number of side branches and siliques. Therefore, they significantly affect two main yield components (plant density and number of siliques) [7]. Uniform seedling emergence is determined by weather conditions and the properties of soil (mostly topsoil) [8–10]. Adequate seedbed preparation is particularly important in the cultivation of small-seeded crops, including oilseed rape [11,12]. Tillage influences soil aeration and moisture content, and it determines the rate at which plants, in particular the root system, emerge and develop [7,11–14]. Under the agroecological conditions of Poland, simplified tillage exerts varied effects on the growth habit of WOSR plants, and the extent of simplification plays a key role. Muśnicki [15], Muśnicki et al. [16,17], Ojczyk and Jankowski [18], and Jankowski and Budzyński [19] reported that shallow plowing had a minor influence on rosette habit during fall growth. An increasingly popular alternative to conventional tillage is low-till practice where soil is loosened without inverting it [7]. Budzyński et al. [20] demonstrated that the low-till system (disking, soil loosening with a rototiller, and direct sowing) leads to the development of smaller rosettes (with smaller leaves and a smaller root collar diameter) and shorter taproots during the fall growing season compared with the conventional tillage system. Strip-till has gained popularity in European agricultural practice because this technique combines the advantages of conventional tillage, zero-tillage, and direct sowing [21,22]. In comparison with conventional tillage, the benefits of strip-till include effective work organization on the farm, improved soil properties, reduced impact of unpredictable weather, and environmental protection [23–25]. According to Jaskulska et al. [14], strip-till enhances the growth of WOSR plants in fall (a higher number of rosette leaves, higher dry matter (DM) content of leaf rosettes, and thicker root collars) compared with conventional tillage.

The presence of segetal vegetation in WOSR stands may affect the growth and development of plants and, as a consequence, their habit. Weed control promotes the growth and development of WOSR plants in fall. In the absence of weed control, WOSR competes with weeds for resources (light, water, and nutrients) during the fall growing season. Due to evolutionary adaptation, weeds have the ability to use these resources more rapidly and effectively than WOSR. Therefore, segetal vegetation is not eliminated from the stand by WOSR in fall, and weeds may cause plant freezing because they negatively affect the growth habit of rosettes (excessive height of the terminal bud and a small number of leaves) [15,19]. In a study by Jankowski and Budzyński [19], the absence of weed management resulted in the overgrowth of WOSR rosettes and decreased their winter hardiness. Herbicide application is one of the most effective weed control methods in WOSR stands [26]. Around 200 agents (23 active ingredients representing 13 chemical groups) have been registered in Poland for chemical protection of WOSR against weed infestation. Derivatives of aryl-phenoxypropionic acid (quizalafop-P ethyl, propaquizafop, fluazifop-P-butyl, and haloxyfop) account for approximately 20% of them, and chloroacetamides (dimethachlor, dimethenamid-P, metazachlor, and pethoxamid) constitute another 20%. In Central Europe (Czechia, Germany, Poland, and Slovakia) and Lithuania, herbicides containing the following active ingredients, clopyralid + picloram, clomazone + metazachlor, quinmerac + metazachlor, and dimethenamid-P + quinmerac + metazachlor, are most often applied to WOSR [27]. Dicotyledonous weeds can be effectively controlled with pre-emergent herbicides (containing e.g., napropamide, clomazone, metazachlor, or dimethachlor) [28]. According to Gradilă et al. [29], pre-emergent herbicides play an important role in WOSR cultivation because they can limit competition for water, light, and nutrients between crops and weeds already at the beginning of the growing season. In France, pre-emergent herbicides are

applied in approximately 90% of WOSR stands [30], and they exert protective effects on seed yields [26,31–33]. It should be stressed, however, that the efficacy of pre-emergent herbicides is largely determined by seedbed preparation and soil moisture content [33]. When soil moisture content is low, dicotyledonous weeds can be more effectively controlled with foliar herbicides (containing e.g., metazachlor or dimethachlor) [28,33]. However, according to Jankowski [7], delayed treatment (BBCH 14-16) may be less effective because weeds have already established a strong root system and well-developed WOSR rosettes may inhibit herbicide penetration into the stand. For this reason, recent years have witnessed a growing interest in sequential weed control (a combination of pre-emergent and foliar herbicides). In this approach, the active ingredient of a foliar herbicide can be selected so as to target weed species remaining in the field after the previous herbicide treatment [7].

Growth regulation is an important link in the WOSR production technology [34–38]. Triazoles and mepiquat chloride are most widely applied to modify the growth of WOSR plants [37,39]. Commercial mixtures of metconazole + mepiquat chloride and paclobutrazol + diflufenican have also gained popularity [39]. Triazoles are used as fungicides in many crop species, and in WOSR they also suppress stem elongation by inhibiting gibberellin synthesis [39–43]. Triazoles induce various physiological and morphological processes in plants, and their effects include shorter stems due to the inhibition of cell elongation, inhibition of ethylene synthesis, delay in plant aging, and a higher root-to-shoot ratio [43–46]. Triazole compounds also increase the chlorophyll content of WOSR plants [47–49] and induce tolerance to abiotic stresses (drought and low and high temperatures) by enhancing the activity of antioxidant enzymes [49]. Growth regulating agents affect the morphometric parameters of WOSR rosettes and exert an indirect influence on their overwintering success [37,50–52]. In a study by Miliuviene et al. [51], the autumn application of growth regulators to WORS plants in BBCH stages 14-15 increased root diameter and dry mass by 15% and 16%, respectively. Plants with exposed and excessively high apical meristems are more susceptible to damage by frost, which decreases their overwinter survival [51]. It should be noted that the efficacy of growth regulators applied in fall may vary depending on the development of WOSR rosettes determined by genetic factors [53], environmental and weather conditions [54,55], and seeding date and rate [6,38,56]. Balodis and Gaile [52] demonstrated that growth regulators applied to WORS plants in autumn exerted a stronger effect on a hybrid cultivar than on an open-pollinated cultivar. Metconazole decreased single plant mass by 3% (open-pollinated cultivar) and 24% (hybrid cultivar) and reduced terminal bud height by 12% (open-pollinated cultivar) and 29% (hybrid cultivar). Similar trends were observed by Bankina et al. [53] who found that the autumn application of growth regulators reduced terminal bud height by 17% (open-pollinated cultivar) and 33% (hybrid cultivar) and increased root mass by 7% (open-pollinated cultivar) and 14% (hybrid cultivar). In the work of Zamani-Noor and Knüfer [37], changes in the growth habit of WOSR plants induced by triazoles (tebuconazole, metconazole, and prothioconazole) and mepiquat chloride increased their overwintering success by 9% (open-pollinated cultivars) up to 15–48% (hybrid cultivars), relative to the control treatment (without growth regulation).

Seedling emergence and the initial development of WOSR rosettes are largely affected by weather conditions in the period prior to seeding until the end of the growing season in fall. The effects of agroecological conditions on the fall growth of WOSR can be modeled and modified by agronomic management practices. Seedbed preparation and early elimination of segetal vegetation (weed control) are key to seedling emergence and the development of leaf rosettes and roots. In the later stages of plant development, chemical growth regulators can be are applied to modify rosette habit. The effects of such agricultural operations, treated as single treatments, have been extensively researched and evaluated in classical field experiments with one or two factors and randomized complete block (RCB) and split-plot or strip-plot (split-block) designs. However, the interaction effects of the above factors on WOSR rosette habit, in particular in the strip-till system, have not been described in the literature. In classical field experiments, the number of experimental factors is limited and numerous interaction effects cannot be evaluated although they can significantly affect

the studied parameters in experiments with multifactorial designs. Experiments with the s^{k-p} factorial design can be performed to determine the agronomic requirements of crops in new tillage systems, such as strip-till. Therefore, a three-year small-area field experiment with a mixed $2^1 \times 3^2$ factorial design was conducted to fill this knowledge gap. The aim of this study was to determine the effects of weed control (pre-emergent, foliar, and sequential) and growth regulation (none or application of triazole compounds in BBCH stages 14–15) on the development of WOSR rosettes in fall (number of rosette leaves, epicotyl length, root collar diameter, taproot length, rosette weight, and root weight) and their overwintering success in different tillage systems (conventional tillage, low-till, and strip-till). The research hypothesis postulates that tillage system can modify the effects exerted by herbicides with different modes of action (soil/foliar application) and growth regulators on the parameters of WOSR rosette development in fall. The number of active substances approved for use in plant protection products has been reduced, and the use of chemical crop protection agents in the European Union is to be limited. Thus, field studies should be conducted to find effective strategies for modeling the fall growth of WOSR in regions where the risk of freeze damage is high. Recommendations for future research are included in the Conclusion Section 5.

2. Materials and Methods

2.1. Field Experiment

The presented results were obtained during a small-area field experiment conducted in 2016-2019 in the Agricultural Experiment Station (AES) in Bałcyny, north-eastern Poland (53°35′46.4″ N, 19°51′19.5″ E). The experiment had a mixed $2^1 \times 3^2$ factorial design with two replications, where one factor was evaluated at two levels (0 and 1), and two factors were evaluated at three levels (0, 1, and 2) (Table 1).

Table 1. Experimental factors (2016-2019).

Symbol	Agricultural Operation	Level		
		0	**1**	**2**
A	Tillage [a]	Strip-till	Low-till	Conventional tillage
B	Weed control	Pre-emergent (0–2 days after sowing) 500 g ha^{-1} metazachlor, 500 g ha^{-1} dimethenamid-P, 250 g ha^{-1} quinmera	Foliar (BBCH 12–14 [b]) 72 g ha^{-1} clopyralid, 24 g ha^{-1} picloram, 12 g ha^{-1} aminopyralid, 750 g ha^{-1} metazachlor	Sequential (0–2 days after sowing) 72 g ha^{-1} clomazone (BBCH 12–14) 72 g ha^{-1} clopyralid, 24 g ha^{-1} picloram, 12 g ha^{-1} aminopyralid
C	Growth regulation	None	Fall treatment (BBCH 14–15) 210 g ha^{-1} mepiquat chloride, 30 g ha^{-1} metconazole	-

[a] strip-till with sowing and application of NPK fertilizers to a depth of 10 and 20 cm (50:50%); low-till to a depth of 25–30 cm one day before sowing with a seed drill cultivator; conventional tillage—disking to a depth of 5–8 cm after harvesting the previous crop, pre-sowing plowing to a depth of 18–20 cm 7–10 days before sowing, seedbed preparation, and sowing with a seed drill cultivator. [b] Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie [57].

The harvested plot area was 15 m^2 each (10 m by 1.5 m). Winter wheat was the preceding crop in each year of the study. To prepare the plots for WOSR cultivation, winter wheat was cut to a height of 12–15 cm, and the entire straw was collected. The experiment was established on Haplic Luvisol originating from boulder clay [58]. The chemical properties of the soil are presented in Table 2.

Table 2. Chemical properties of the analyzed soil.

Growing Season	pH [a]	C_{org} (g kg^{-1}) [b]	Available Macronutrients (mg kg^{-1}) [c]			
			P	K	Mg	SO_4^{2-}
2016/2017	5.6	1.28	39.7	120.4	78.0	4.4
2017/2018	5.9	1.04	68.4	124.5	53.7	13.3
2018/2019	6.2	1.15	96.4	161.8	63.0	13.0

[a] digital pH meter with temperature compensation (20 °C) in deionized water and 1 mol dm^{-3} KCl, at a 5:1 ratio. [b] modified Kurmies method (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan). [c] P—vanadium molybdate yellow colorimetric method (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan); K—atomic emission spectrometry (AES) (Flame Photometers, BWB Technologies Ltd., Newbury, UK); Mg—atomic absorption spectrophotometry (AAS) (AAS1N, Carl Zeiss Jena, Oberkochen, Germany); and SO_4^{2-}—nephelometry method (UV-1201V spectrophotometer, Shimadzu Corporation, Kyoto, Japan).

The seeds of hybrid WOSR cv. 'Kuga' were sown between 13 and 23 August at 50 germinating seeds per 1 m^2. Agronomic factors that did not constitute the experimental variables were applied according to good agricultural practice. The following fertilizers were applied before sowing: 40 kg N ha^{-1} (urea), 60 kg P_2O_5 ha^{-1} (enriched superphosphate), and 120 kg K_20 ha^{-1} (potash salt). In the strip-till system (A0), fertilizers were applied together with seeds to a depth of 10 and 20 cm at 50:50%. In low-till (A1) and conventional tillage (A2) systems, fertilizers were distributed on the surface of previous crop residues (stubble). In all treatments, monocotyledonous weeds were controlled with 60 g ha^{-1} propaquizafop (BBCH 12–14).

2.2. Parameters Determined in the Field

The morphological parameters of WOSR plants describing rosette development and DM content were determined before the end of the fall growing season in samples of 10 plants collected from each plot. Dry matter content was estimated by drying a sample at 105 °C in a ventilated oven (FD 53 Binder GmbH, Tuttlingen, Germany) for 48 h until constant weight. Plant density per 1 m^2 was determined before the end of the fall growing season and at the beginning of the spring growing season at five random locations in each plot (1 m section of each of the two middle rows).

2.3. Statistical Analysis

The mixed $2^1 \times 3^2$ factorial ANOVA model was applied. The main effects of fixed factors (A, B, and C) and all two-factor interactions (A×B, A×C, and B×C) were evaluated during an experiment conducted over three consecutive growing seasons (Y) (Y×A, Y×B, Y×C, Y×A×B, Y×A×C, and Y×B×C). The significance of differences between mean values was determined by Tukey's honest significant difference (HSD) test at $p < 0.05$. All analyses were performed in the Statistica 13.3 program [59]. The *F*-values in ANOVA are presented in Table 3.

Table 3. *F*-test statistics in ANOVA of the morphometric parameters of rosettes and the overwintering performance of WOSR plants.

Source of Variation	Effect	Number of Rosette Leaves	Epicotyl Length (mm)	Root Collar Diameter (mm)	Taproot Length (cm)	Rosette Weight (g Plant^{-1} DM)	Root Weight (g Plant^{-1} DM)	Overwintering Success (%)
Growing season (Y)	Random	518.44 **	261.64**	612.89 **	11.07 **	1028.74 **	736.65 **	31.2 **
Tillage system (A)	Fixed	42.59 **	4.33*	26.96 **	30.65 **	27.08 **	12.80 **	1.95 *ns*
Weed control (B)	Fixed	3.70 *	12.73**	0.07 *ns*	1.49 *ns*	6.02 **	0.01 *ns*	2.06 *ns*

Table 3. *Cont.*

Source of Variation	Effect	Number of Rosette Leaves	Epicotyl Length (mm)	Root Collar Diameter (mm)	Taproot Length (cm)	Rosette Weight (g Plant^{-1} DM)	Root Weight (g Plant^{-1} DM)	Overwintering Success (%)
Growth regulation (C)	Fixed	0.37 *ns*	3.66 *ns*	0.25 *ns*	4.29 **	0.17 *ns*	1.25 *ns*	0.11 *ns*
Y×A	Random	5.32 *	3.16 *	15.87 **	7.18 **	8.74 **	4.03 **	2.11 *ns*
Y×B	Random	0.49 *ns*	21.17 **	0.69 *ns*	1.17 *ns*	4.24 **	0.12 *ns*	1.15 *ns*
A×B	Fixed	0.78 *ns*	0.47 *ns*	0.66 *ns*	1.24 *ns*	0.29 *ns*	0.13 *ns*	0.70 *ns*
Y×C	Random	0.66 *ns*	0.94 *ns*	0.57 *ns*	2.94 *ns*	1.17 *ns*	1.09 *ns*	0.40 *ns*
A×C	Fixed	2.46 *ns*	0.05 *ns*	1.14 *ns*	0.24 *ns*	1.40 *ns*	0.61 *ns*	1.02 *ns*
B×C	Fixed	0.92 *ns*	0.73 *ns*	0.87 *ns*	0.90 *ns*	1.11 *ns*	0.79 *ns*	0.22 *ns*
Y×A×B	Random	0.59 *ns*	0.49 *ns*	0.79 *ns*	0.81 *ns*	0.31 *ns*	0.87 *ns*	1.97 *ns*
Y×A×C	Random	0.12 *ns*	0.17 *ns*	0.65 *ns*	1.37 *ns*	1.72 *ns*	0.63 *ns*	1.46 *ns*
Y×B×C	Random	0.47 *ns*	2.83 *	0.67 *ns*	1.88 *ns*	1.01 *ns*	0.83 *ns*	0.16 *ns*

* significant $p < 0.05$; ** significant $p < 0.01$; *ns*—not significant.

3. Results

3.1. Weather Conditions

The fall growing season of WOSR lasted for 75 to 97 days. In each season, precipitation was sufficient to cover the water needs of WOSR plants determined at 70 mm by Muśnicki [15]. It should be noted that in the second year, total fall precipitation exceeded 400 mm, which significantly inhibited the development of WOSR rosettes. The optimal sum of mean daily temperatures during the fall growing season (850 °C) was not achieved only in the first year (773 °C). Winter dormancy lasted for 121 to 140 days (Table 4). In each season, the mean daily temperature decreased to −10 and −15 °C, but snow cover effectively protected WOSR plants against frost damage. January and February were the coldest months (mean daily temperature of −2.6 to −4.1 °C) (Figure 1).

Table 4. Weather conditions during the fall growing season of WOSR and winter dormancy (data from the meteorological station in Bałcyny).

Growing Season	Fall Growth			Winter Dormancy		
	Number of Days	Total Precipitation (mm)	Sum of Mean Daily Temperatures (°C)	Number of Days	Total Precipitation (mm)	Sum of Mean Daily Temperatures (°C)
2016/2017	75	152	773	140	258	56
2017/2018	97	419	978	121	153	−61
2018/2019	95	91	1073	129	180	168
Long-term average (1981–2015)	76	143	865	152	171	−3
Minimum [15]	–	70	850	–	–	–

Mild temperatures and snow cover during winter dormancy contributed to the overwintering success of WOSR plants (96–99%). The best results were noted in the 2018/2019 season characterized by the highest sum of mean daily temperatures in fall (1073 °C) and winter (168 °C) (Table 5). The overwintering performance of WOSR plants was not significantly affected by the tillage system (intensity of agricultural inputs), weed control, or chemical growth regulation (Table 3).

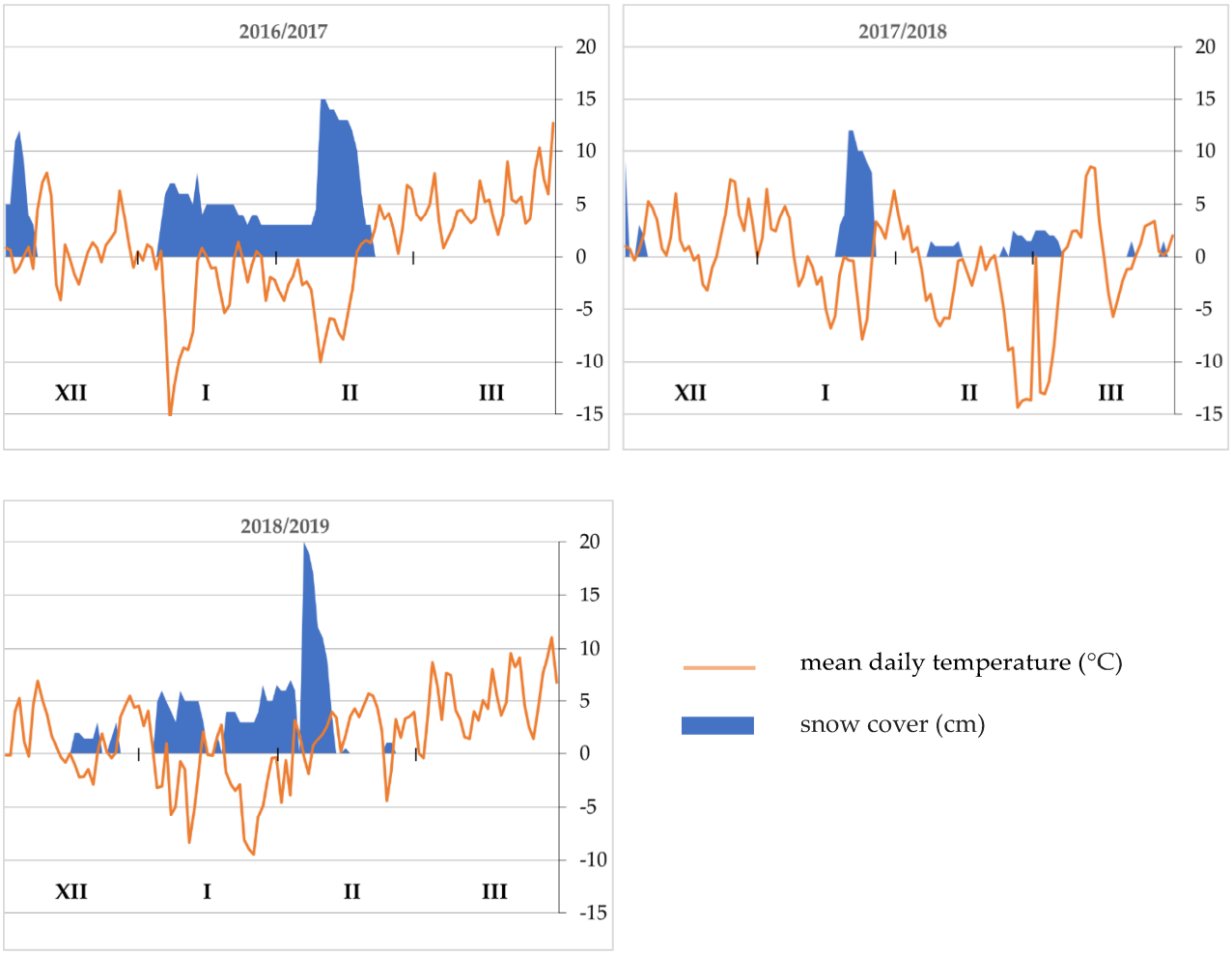


Figure 1. Mean daily temperature (°C) and snow cover (cm) between December and March across years.

Table 5. Morphometric parameters and weight of WOSR leaf rosettes before the end of the fall growing season (main factors).

Agronomic Factor	Level	Number of Rosette Leaves	Epicotyl Length (mm)	Root Collar Diameter (mm)	Taproot Length (cm)	Rosette Weight (g Plant^{-1} DM)	Root Weight (g Plant^{-1} DM)	Overwintering Success (%)
Growing season	2016/2017	7.9 ^{b}	21.5 ^{b}	6.9 ^{b}	16.7 ^{a}	4.3 ^{b}	1.0 ^{b}	96.2 ^{b}
	2017/2018	8.1 ^{b}	10.8 ^{c}	5.5 ^{c}	15.8 ^{b}	1.5 ^{c}	0.5 ^{c}	95.8 ^{b}
	2018/2019	11.8 ^{a}	24.0 ^{a}	11.7 ^{a}	15.5 ^{b}	17.6 ^{a}	3.8 ^{a}	99.2 ^{a}
Tillage	Strip-till	9.9 ^{a}	19.8 ^{a}	8.8 ^{a}	17.2 ^{a}	9.4 ^{a}	2.0 ^{a}	97.6
	Low-till	9.1 ^{b}	18.1 ^{b}	7.6 ^{b}	15.3 ^{b}	6.9 ^{b}	1.6 ^{b}	96.9
	Conventional tillage	8.7 ^{c}	18.4 ^{b}	7.8 ^{b}	15.5 ^{b}	7.0 ^{b}	1.7 ^{b}	96.7
Weed control	Pre-emergent	9.0	20.6 ^{a}	8.1	15.7	8.5 ^{a}	1.8	97.1
	Foliar	9.3	17.8 ^{b}	8.0	16.0	7.7 ^{b}	1.8	97.5
	Sequential	9.4	18.0 ^{b}	8.1	16.2	7.2 ^{b}	1.8	96.6
Growth regulation	None	9.3	19.3	8.0	15.7 ^{b}	7.7	1.7	97.1
	BBCH 14–15	9.2	18.3	8.1	16.2 ^{a}	7.9	1.8	97.0

Means sharing a common letter are not significantly different at $p \leq 0.05$ in Tukey's test.

3.2. Tillage

In fall, the growth rate of WOSR plants was highest in the strip-till system (Table 5). In this system, WOSR plants were characterized by a higher number of rosette leaves (by 9–14%), thicker root collars (by 11%), longer epicotyls (by 8%), longer taproots (by 12%),

and a higher DM content of leaf rosettes (by 35%) and roots (by 21%) than the plants grown in conventional tillage and low-till systems (Table 5).

The compared tillage systems exerted varied effects on WOSR growth in response to different weather conditions (Y × A) (Table 3). In the first year of the study (with the shortest fall growing season), fall growth was most intensive in the strip-till system. Plants grown in low-till and conventional tillage systems were characterized by fewer rosette leaves (by 10% and 18%, respectively), thinner root collars (by 23% and 34%, respectively), shorter taproots (by 16% and 15%, respectively) (Figure 2), and a lower DM content of leaf rosettes (by 37% and 59%, respectively) and roots (by 31% and 38%, respectively) (Figure 3). In year 2, the development of WOSR rosettes was not influenced by the tillage system because high fall precipitation disrupted soil moisture and aeration dynamics (Table 4) and inhibited plant growth (Figures 2 and 3). In the third year of the study, weather conditions contributed to intensive plant growth in fall. Rosettes were largest and had the highest DM content in the strip-till system. Plants grown in low-till and conventional tillage systems were characterized by a smaller number of rosette leaves (by 11% and 13%, respectively), shorter epicotyls (by 9% and 8%, respectively), thinner root collars (by 14% and 2%, respectively), shorter taproots (by 15% and 16%, respectively) (Figure 2), and a lower DM content of leaf rosettes (by 24% and 16%, respectively) and roots (by 21% and 14%, respectively) (Figure 3).

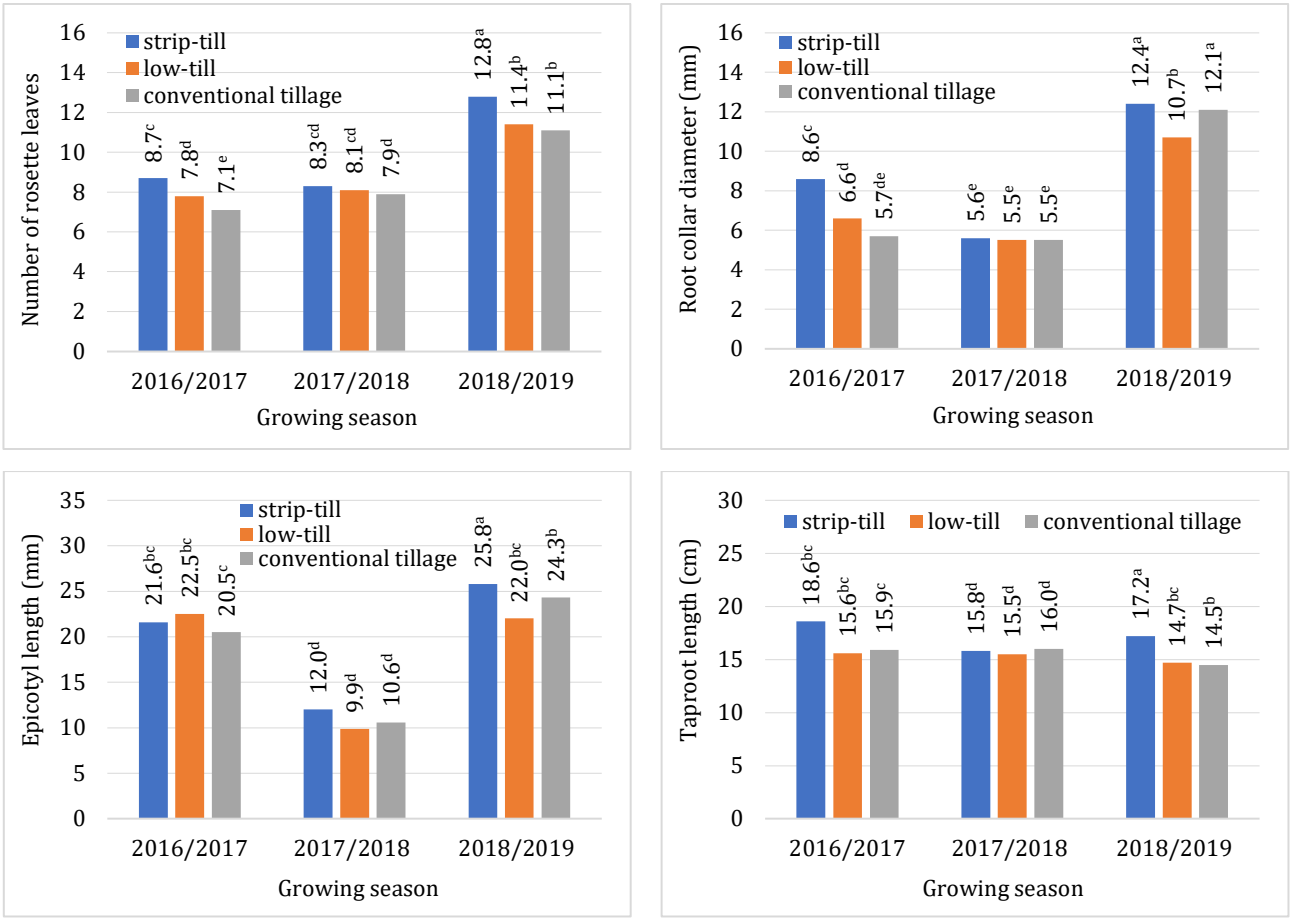


Figure 2. The effect of tillage system on the morphometric parameters of WOSR rosettes before the end of the fall growing season across years (Y × A). Means sharing common letter are not significantly different with $p \leq 0.05$ in Tukey's test.

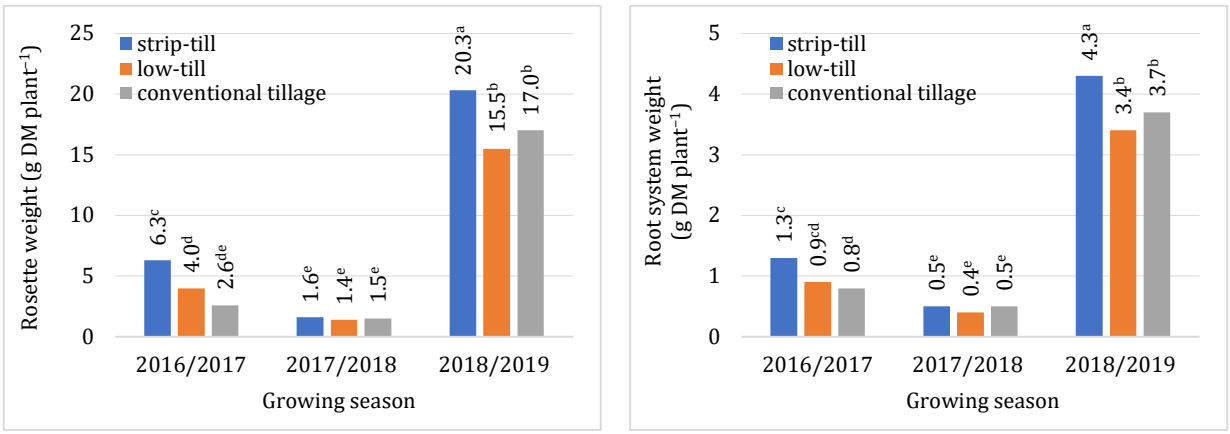


Figure 3. The effect of tillage system on the weight of WOSR rosettes and roots before the end of the fall growing season across years (Y × A). Means sharing common letter are not significantly different with $p \leq 0.05$ in Tukey's test.

3.3. Weed Control

Pre-emergent herbicides applied to the soil promoted the growth of aerial rosettes. Foliar and sequential herbicides (pre-emergent and foliar) decreased the DM content of leaf rosettes (by 12% on average) and decreased epicotyl length (by 13% on average) (Table 5). In year 3, when weather conditions in fall promoted rapid WOSR growth, these herbicides led to an additional decrease in the DM content of leaf rosettes (15% on average) and a decrease in epicotyl length (31% on average) (Figure 4). In the first and second year of the study, Y × B interactions did not affect the morphometric parameters of WOSR rosettes (Table 4).

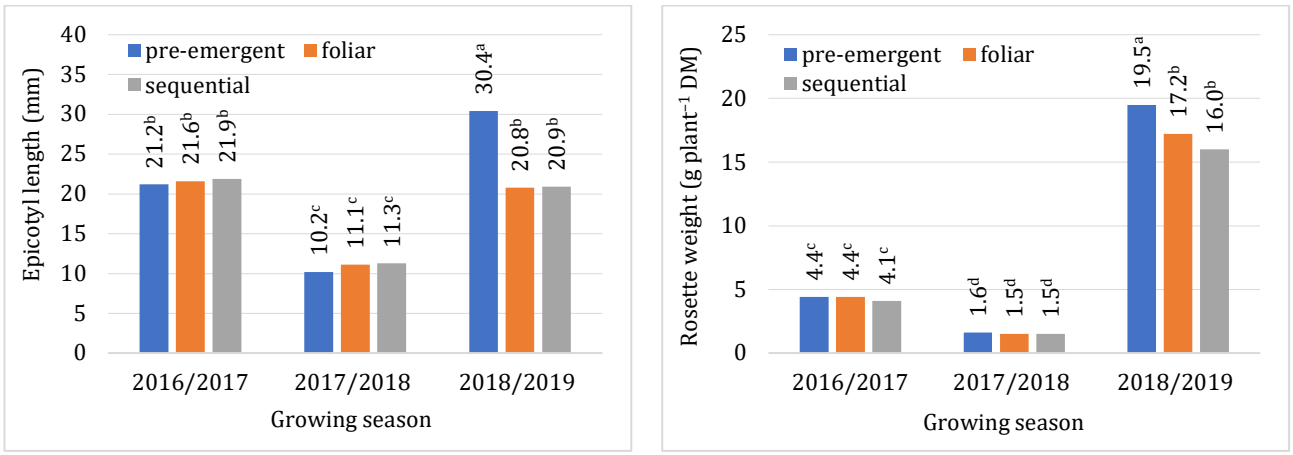


Figure 4. The effect of weed control on epicotyl length and rosette weight in WOSR plants before the end of the fall growing season across years (Y × B). Means sharing common letter are not significantly different with $p \leq 0.05$ in Tukey's test.

3.4. Growth Regulation

In fall, growth regulators had a beneficial impact on root growth only. The application of 210 g ha^{-1} mepiquat chloride and 30 g ha^{-1} metconazole in BBCH stages 14–15 increased taproot length by 0.5 cm (Table 5). No relationships were found between the use of growth regulators and the number of rosette leaves, epicotyl length, root collar diameter, or the weight of leaf rosettes and roots. Growth regulators did not influence the above parameters even during rapid WOSR growth in the fall of year 3 (Table 3).

4. Discussion

4.1. Tillage

The objective of tillage is to improve agricultural productivity by increasing soil aeration, promoting the development of granular soil structure, and creating favorable conditions for the growth and development of plants [10,60–63]. Jankowski [31] demonstrated that simplified tillage can decrease taproot length in WOSR plants. Shallow tillage (10–12 cm) in the low-till system with direct sowing was most detrimental to proper root development and induced the greatest decrease in the DM content of roots. In simplified tillage systems (tillage depth reduced to 10–12 cm, shallow non-inversion tillage, and direct sowing), most root biomass was distributed in the shallow subsurface horizon (0–10 cm) rather than in the 10–20 cm depth layer. In the direct sowing system, the subsurface layer contained 90% of total root biomass. The DM content of WOSR roots was around 36% lower in the low-till system than in the conventional tillage system. In the present study, the strip-till system created the optimal conditions for root development. Conventional tillage and low-tillage reduced taproot length (by 11%) and decreased the DM content of roots (by 20–23%). Simplified tillage exerted varied effects on aerial rosettes in WOSR plants. In the work of Jankowski and Budzyński [19], shallow tillage had only a minor influence on the main morphometric parameters of WOSR rosettes (number of rosette leaves, root collar diameter, and height of the terminal bud above the soil surface) before the end of the fall growing season. According to Jankowski [31], WOSR plants grown in the conventional tillage system were characterized by the highest number of rosette leaves, thickest root collars, and the highest DM content. Shallow conventional tillage and shallow non-inversion tillage exerted positive effects only on the height of the terminal bud (by shortening the epicotyl), mainly by inhibiting the development of the leaf rosette. Overwintering success was highest in the conventional tillage system (medium-deep and shallow tillage). Shallow non-inversion tillage and direct sowing decreased overwintering success by 8–9%. In a study by Jaskulska et al. [14], the replacement of conventional tillage with strip-till had a beneficial influence on the development of WOSR plants during the fall growing season. In strip-till treatments, WOSR plants were characterized by a higher number of rosette leaves (by 6%), thicker root collars (by 11%), and a higher DM content (by 10%). Similar observations were made in the present study where WOSR plants cultivated in the strip-till system produced more rosette leaves (by 9–14%), thicker root collars (by 11%), and longer epicotyls (by 8%) than the plants grown in conventional tillage and low-till systems. The overwintering success of WOSR plants was not affected by the tillage system.

4.2. Weed Control

Winter oilseed rape is sensitive to weeds because this crop species is sown early (in segetal vegetation, seed germination, and plant emergence are fully induced by temperature) in wide rows and has high fertilizer requirements. These factors enable segetal vegetation to effectively compete with crops [64,65]. In commercial practice, WOSR is often grown after self-sown cereals, which also suppress the growth of the main crop [66]. In fall, the presence of weeds in WOSR stands adversely affects the height of the terminal bud and the number and weight of rosette leaves [19,67]. In the work of Jankowski [31], weed control exerted a significant effect only on the number of rosette leaves in WOSR plants. Overwintering success was highest in treatments with full weed control in fall, and it was significantly lower (by 4–5%) in treatments where monocotyledonous and dicotyledonous weeds were not managed [31]. In the present study, pre-emergent herbicides also promoted the development of WOSR rosettes in fall. The application of foliar herbicides in BBCH stages 14–15 significantly decreased the DM content of rosettes (by 12%) and epicotyl length (by 13%) in comparison with pre-emergent herbicides. The applied weed control methods strongly affected the growth habit of rosettes but did not differentiate the overwintering success of WOSR plants.

4.3. Growth Regulation

The application of chemical growth retardants in fall influences the morphological parameters, growth habit, and overwintering success of WOSR plants. Numerous studies have demonstrated that growth regulators promote the development of the root system [51–53]. Miliuviene et al. [51] found that the application of growth regulators in BBCH stages 14–15 increased the diameter and DM content of WOSR roots by 15% and 16%, respectively. In the work of Bankina et al. [53], growth regulators also induced a 7–14% increase in the DM content of the root system. When applied in fall, growth regulators also inhibit the growth of aerial rosettes [52,53]. According to Balodis and Gaile [52], the application of metconazole in fall decreased rosette weight and terminal bud height by 24% and 29%, respectively. Similar results were reported by Bankina et al. [53] who found that chemical growth regulators applied in fall decreased epicotyl length in WOSR plants by 18–33%. Chemical retardants modify the growth habit of plants, increase tolerance to low temperatures, and contribute to overwintering success. In the work of Zamani-Noor and Knüfer [37], triazoles (tebuconazole, metconazole, and prothioconazole) and mepiquat chloride increased the overwintering success of WOSR plants by 9–15% or even 48%. In the current study, the application of mepiquat chloride and metconazole in BBCH stages 14–15 increased taproot length by 3%, but it did not influence other growth habit characteristics of WOSR plants in fall or their overwintering success.

5. Conclusions

This study evaluated the relationship between weed control (pre-emergent, foliar, and sequential) and growth regulation (none or in fall) *vs.* WOSR rosette development and overwintering success in conventional tillage, low-till, and strip-till systems. To achieve this goal, a three-year (2016–2019) small-area field experiment with a mixed $2^1 \times 3^2$ factorial design was performed in NE Poland.

Winter oilseed rape plants grown in the strip-till system were characterized by a higher number of rosette leaves (by 9–14%), thicker root collars (by 11%), longer epicotyls (by 8%), longer taproots (by 12%), and a higher DM content of leaf rosettes (by 35%) and roots (by 21%) in comparison with the plants produced in conventional tillage and low-till systems. Pre-emergent herbicides applied to the soil increased the height of the terminal bud (15%) and the DM content of leaf rosettes (14%). Growth regulators applied in fall increased taproot length (by 3%). The effects of weed control and growth regulation on the growth habit and weight of WOSR rosettes were not influenced by the tillage system. The overwintering performance of WOSR plants was not affected by the tillage system, weed control, or growth regulation.

Agroecological conditions exerted a strong influence on the relationship between chemical weed control and growth regulation *vs.* the fall development of WOSR in different tillage systems. Unfortunately, mild temperatures during winter dormancy prevented a comprehensive analysis of the correlation between WOSR rosette development (affected by agronomic management practices) and overwintering success. Therefore, future studies should be conducted under various environmental conditions with particular emphasis on Eastern and Northern Europe. The number of active substances approved for use in plant protection products has been reduced, and the use of chemical crop protection agents in the European Union is to be limited. Thus, field experiments should be performed to find effective strategies for modeling the fall growth of WOSR in regions where the risk of freeze damage is high.

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