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The Impact of Cultivation Systems on Weed Suppression and the Canopy Architecture of Spring Barley

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Abstract: Under the pro-environmental principles of agricultural production, soil cultivation and organic fertilization are of particular importance as strategical elements in reducing weed infestation in the context of sustainable agriculture. The aim of this study was to determine the effect of long-term practices that are used in regenerative agriculture (reducing soil tillage, cover crop management, and mineral nitrogen fertilization) on canopy weed infestation and the elements of spring barley architecture. Understanding the impact of the studied factors influences decision-making regarding weed infestation control, and thus may contribute to a reduction in herbicide use. A two-factor field experiment was conducted using the split-plot method. The main factors were four cultivation methods: 1. conventional tillage without a cover crop, 2. conventional tillage + cover crop, 3. reduced tillage + cover crop, and 4. no tillage + cover crop. The subplot factor was differentiated via nitrogen fertilization, at 40, 80, or 120 kg N·ha^{-1}. The research covered canopy weed infestation and the parameters of spring barley canopy architecture. The species composition; the number and weight of weeds; and, for barley, the leaf area index (LAI), density, length, and tillers were determined. The test results were statistically analyzed (ANOVA) in a series of experiments while using Tukey's test for a significance level of $p = 0.05$. Additionally, simple linear regression analysis, principal component analysis (PCA), and data clustering (CA) were utilized. The study showed that simplified tillage contributed to reducing the number of weeds in the barley tillering stage, while also contributing to an increase in weed infestation during grain harvest. Plowing in the cover crop did not reduce the presence of undesirable plants in the canopy, while increasing doses of nitrogen fertilization contributed to a reduction in the number of weeds without affecting their mass. Weed infestation was also affected by meteorological conditions. Increased rainfall in the early stages of barley development benefits the number of weeds, especially in terms of traditional cultivation. Simplified tillage resulted in a reduction in barley density, height, and LAI, as well as an increase in the branching of the tested cereal. A significant negative correlation was also found between the weed infestation of the barley canopy and the characteristics of the canopy architecture. The PCA showed that the highest tillering of barley was provided at the lowest intensity of weed infestation. In turn, the CA indicated that the significantly higher LAI that resulted from a higher density and length of barley was attributed to the simplified cultivation treatments and the practice of direct sowing. It is a comprehensive method that can favor barley growth and development conditions while weakening weed infestation potential.

Keywords: spring barley; cover crop; tillage; nitrogen fertilization; weed infestation; canopy architecture

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1. Introduction

Agriculture plays a particularly important role in implementing the idea of sustainable growth due to its place in the management of natural resources [1,2]. One of the main notions of the European agricultural policy is the implementation of pro-ecological solutions that limit the negative effects of agricultural activity [3]. The protection of soil structure is a key requirement for sustainable soil use. The presence of cover crops and the improvement of soil physical properties through, for example, sowing cover cropping has been proposed as an alternative method of food production called regenerative agriculture [4]. A special factor forming the agricultural environment is tillage, which alters the physical, chemical, and biological properties of the soil [5,6]. Traditional tillage, despite its yield-improving values, has a strong impact on the natural environment [7], and it is also the most energy-intensive—and thus costly—element of crop production [8,9]. Pro-environmental activities are largely based on reducing the intensity of soil cultivation in crop rotations. In sustainable agriculture, technologies of plowless tillage, often referred to as conservative or conservation tillage, are increasingly being promoted [10–13]. An extreme simplification of tillage is reflected in direct sowing, where tillage is limited to the loosening of seed rows [14,15].

The presence of plants that accompany sowing is largely determined by the agricultural technology used. Cultivation plays an important role in this respect [16–19]. Thus far, research on the changes in weed infestation in crop fields in different tillage systems is ambiguous. Discrepancies may result from different environmental conditions, applied agrotechnical methods—mainly in the area of plant protection and fertilization—or in the time for the cultivation system application, as well as many other factors. The literature generally indicates an increase in canopy weed infestation as a result of introducing simplifications in tillage [20–25], including direct sowing [26–29]. In such conditions, increased pressure from perennial, monocotyledonous, and volunteer weeds has been observed [20,30–32]. However, other reports have proven that simplified tillage systems do not increase the occurrence of weeds [33] and may even help to reduce their occurrence [17,34]. Morris et al. [35], Woźniak [36], and Mohler et al. [37] claim that the increase in weed infestation in plowless tillage, when compared to plow tillage, can be explained by the accumulation of freshly shed seeds on the soil surface, which is where they germinate and increase the weed infestation of the canopy. Tørresen and Skuterud [38] are also of a similar opinion. According to Kordas [39], the long-term use of no-tillage cultivation causes an increase in weed infestation only in the initial period. Later, due to a change in the weed species composition (namely due to a significant reduction in the number of annual weeds and the growth of perennial weeds), weed infestation is reduced below that which is found in traditional cultivation. According to Hernández Plaza et al. [40], the tillage system also affects the distribution of weed seed species in the soil. In zero tillage, weeds with fine seeds and high fertility, i.e., those which sprout from the soil surface, are successful. On the other hand, plowing benefits large-seeded weeds, which are able to germinate from deeper layers of soil. These dependencies are important in the development of weed control strategies (depending on the method of soil cultivation) [41].

Cover crops are also a tool to create eco-friendly agriculture [42–45]. Depending on the tillage system used, cover crop biomass can be introduced into the soil at different depths or can be left on the field surface in the form of mulch. The choice of cultivation technology is also important. Cover crops are of particular importance as additional crops in simplified tillage systems, and they are largely replacing deep plowing [46]. Cover crops exhibit an anti-erosion function [47,48]; they counteract the degradation of the physical properties of arable soils [49,50]; they have a positive effect on the soil structure parameters and water storage capacity; they improve the efficiency of the soil layer; and they enable a reduction in the use of mineral fertilizers and chemical protection agents [13,51–54]. Cover crops increase the content of organic carbon, nitrogen, phosphorus, and potassium in the soil [55,56]. In addition, the cultivation of cover crops reduces the movement of labile nutrients, especially nitrates, beyond the reach of the plant root system [57]. As a consequence, environmental value is increased; furthermore, the condition and productivity of successive plants and entire rotations is improved [58]. Moreover, plants grown as cover crops bind an additional amount of carbon dioxide in their phytomass [44,59]. Soil covered with growing plants or mulch slows down the mineralization of organic matter, resulting in reduced CO_2 emissions into the atmosphere [60]. Thanks to their phytosanitary properties, cover crops reduce the occurrence of diseases and the pests of crop plants [61,62]. By competing with weeds for water, nutrients, and (especially) light, they generally contribute to a reduction in weed infestation in the canopy of successive plants [63], as well as a reduction in the seed bank in the soil. Cover crops left on the field as mulch reduce the growth of weeds. This is because they cover the soil surface and/or block access to light [64,65]. Intercrops also exhibit allelopathic effects [64]. The competitiveness of cereals against weeds, especially in simplified tillage systems, can also be increased by applying appropriate nitrogen fertilization [22,56]. The prevailing view is that—as a result of the intensification of nitrogen fertilization—weed infestation is reduced, mainly as a result of increased canopy competitiveness [56]. However, intensive nitrogen fertilization may increase the germination capacity of certain weed species [66]. Additionally, the use of excessively high doses may lead to compensation by nitrophilic species and the lodging of cereals [67]. The condition and level of weed infestation of cereals also depends on the method and the date of fertilizer application [68].

Opinions on the influence of cover crops—especially the methods of their application into the soil and the impact of organic–mineral nitrogen fertilization on the phytosanitary condition of the canopy and the condition of the washed plants—are ambiguous. Therefore, it seems advisable to broaden the knowledge on this issue. The aim of this study was to determine the effect of the long-term practices that are used in regenerative agriculture (reducing tillage, the presence and management of cover crops (white mustard), and nitrogen fertilization) on canopy weed infestation and architecture elements of spring barley. An attempt was also made to explain the multidimensional differentiation of the parameters of barley canopy architecture and weed infestation (principal component analysis—PCA), as well as their division into groups that significantly differ in the abovementioned properties (data clustering—CA). Understanding the impact of the studied factors on weed infestation and elements of canopy architecture will enable decisions regarding weed infestation control, and thus may contribute to a reduction in herbicide use. It is a comprehensive method that can favor barley growth and development conditions while weakening weed infestation potential.

2. Materials and Methods

The field experiment was set up at the Research and Training Station in Swojczyce (50°07′ N, 17°08′ E), which belongs to the Wrocław University of Environmental and Life Sciences (southwest Poland). The research was carried out in the third rotation of the crop rotation in the years 2010–2012. The research was based on a strict two-factor experiment that was established with a randomized split plot method in three replications. The area of the plots was 27.5 m^2 (5 m length, 5.5 m width). The forecrop for the spring barley in each year of the study was spring wheat, while sugar beet had been cultivated there earlier. The experiment was located on proper black soil, made of light clay on medium clay, and lined with light clay that was of the following particle size distribution (%): sand 52, silt 20, and clay 28. The chemical properties of the topsoil were as follows: pH_{KCl} 5.8–6.0; total nitrogen 0.87–1.01 $g \cdot kg\ soil^{-1}$; available phosphorus 111–161 $mg \cdot kg\ soil^{-1}$; and available potassium 174–275 $mg \cdot kg\ soil^{-1}$. The soil density was 1.56–1.81 $Mg \cdot cm^{-3}$, with an overall soil porosity of 31.6–39.9 $cm^{-3} \cdot 100\ cm^{-3}$, and a compactness between 3.70 and 8.68 MPa.

The main factor was the method of tillage, including pre-winter tillage and pre-sowing spring tillage (Figure 1). Four of its variants were analyzed in the experiment. On the CT site (conventional tillage without cover crop), after harvesting spring wheat with a plow, stubble cultivation was performed, and pre-winter plowing was carried out in autumn to a depth of 20 cm. On the CTc site (conventional tillage + cover crop), after stubble cultivation, white mustard was sown and was plowed with pre-winter plowing to a depth of 15 cm. In the RTc variant (reduced tillage + cover crop), stubble cultivation was performed with a stubble cultivator. The sown cover crop was left for the autumn–winter period on the field surface in the form of mulch, which was covered in the spring with a rigid-tine cultivator. On the CT, CTc, and RTc sites, sowing was carried out with a traditional seeder (Konskilde, Albertslund, Denmark). In NT site (no tillage + cover crop), the cover crop was sown with a seed drill for direct sowing (Vredo, Dodewaard, Netherlands) and left as mulch for autumn and winter. In spring, a non-selective herbicide (Roundup Energy 450 SL (glyphosate) at a dose of 2.5 L per 200 L $H_2O{\cdot}ha^{-1}$) was applied and spring barley was sown with a direct seed drill.

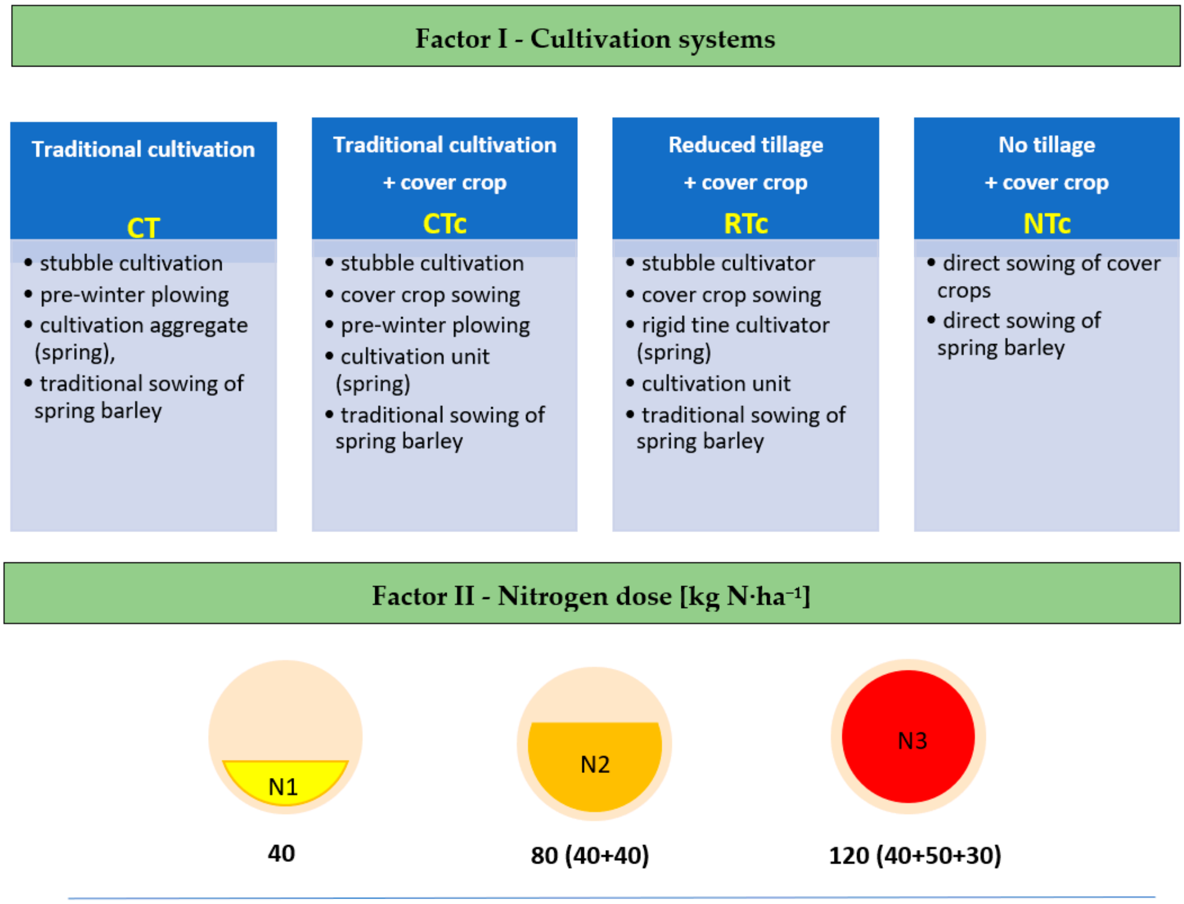

Figure 1. Experiment design.

The subplot factor of the experiment was differentiated via nitrogen fertilization, which was applied in three varying doses of 40 (N1), 80 (N2), or 120 kg $N{\cdot}ha^{-1}$ (N3). Nitrogen, depending on the dose, was applied on one (40 kg $N{\cdot}ha^{-1}$), two (40 + 40 kg $N{\cdot}ha^{-1}$), or three dates (40 + 50 + 30 kg $N{\cdot}ha^{-1}$): I—before sowing barley; II—in the stage of stem elongation (BBCH 30-32); and III—during the heading of plants (BBCH 51-55). The spring barley of the Mercada variety was sown in an amount that ensured a plant density of 350 $pcs{\cdot}m^{-2}$. Protection against weeds was carried out in all years of the study by using the same herbicides each year: Chwastox Trio 540 SL (dicamba, MCPA, mecoprop) at a dose of 1.5 L per 200 L $H_2O{\cdot}ha^{-1}$; Lontrel 300 SL (clopyralid) at a dose of 0.3 L per 200 L $H_2O{\cdot}ha^{-1}$; and Puma Uniwersal 069 EW (fenoxaprop-P-ethyl) at a dose of 1.0 L per 200 L $H_2O{\cdot}ha^{-1}$. The experiment was located on proper black soil, which is made of light clay on medium clay with a light clay bedding.

2.1. Cover Crop Yielding

The condition for a high yield of white mustard when it is grown as a cover crop is a sufficient supply of water in the soil at the time of plant emergence and optimal precipitation and air temperature during growing season. The weather during the experiment was varied (Table 1), and this affected the emergence and yield of the mustard (Figure 2). In the first year of the study, white mustard was sown in the first tenth of September in dry conditions. Low rainfall contributed to extended cover crop emergence. Water shortages were compensated for only in October and November, which enabled a full emergence and proper growth of the plants. The next year of the experiment (2010) was the most unfavorable in terms of hydrothermal conditions during the mustard growing season. At the time of sowing the cover crop (the third tenth of August) and during its initial growth, heavy rainfall was recorded; this caused partial flooding, especially on the plots where the cover crop was sown with a direct sowing seeder, which resulted in a reduction in plant density and, as a result, a low yield. The last year of the study (2011) was also characterized by unfavorable weather conditions. Due to the low rainfall and high temperatures in September and due to the complete lack of rainfall and low temperatures in November, the vegetation period of the cover crop was significantly shortened. The highest mustard dry matter yield was obtained in the first year of the study, and it was significantly higher than in 2010 and 2011, by 37.5 and 32.6%, respectively. The cover crop yield also varied under the influence of tillage (Figure 3). Regardless of the years of research, the driest matter was produced by mustard cultivated in the traditional cultivation system.

Table 1. Mean temperatures and the sum of precipitation.

Year	Month								
	III	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**
	Temperature (°C)								
2009	4.6	12.0	14.2	15.8	19.5	19.3	14.8	7.9	6.6
2010	4.2	9.3	12.7	17.9	21.4	18.9	12.6	7.0	6.5
2011	4.3	11.9	14.7	19.1	18.3	19.3	15.5	9.4	3.8
2012	6.1	9.8	15.8	17.2	20.0	19.3	14.6	8.6	5.9
Means 1968–2012	3.5	8.6	13.9	16.9	18.7	18.2	13.7	9.0	4.2
	Precipitation (mm)								
2009	49.5	30.9	67.5	162.0	134.2	53.5	12.0	76.0	32.5
2010	44.9	45.4	140.7	32.9	78.6	109.1	134.1	5.7	66.4
2011	45.2	27.0	49.4	95.7	170.9	64.8	30.3	42.6	0.0
2012	13.7	27.6	63.7	94.7	108.0	73.2	52.6	35.4	31.8
Means 1968–2012	32.2	37.1	55.4	71.8	87.4	72.3	47.2	39.0	41.3

In the experiment, the weed infestation of the canopy and the parameters of the spring barley canopy architecture were examined. The weed infestation of the spring barley canopy was defined in two terms:

- In spring, before herbicide treatment, at the stage of tillering of barley (BBCH 23). Quantitative and qualitative methods were used. This was achieved by using a closed frame on sample plots of 0.2 m^2, with two repetitions per plot;
- Before harvesting the crop (BBCH 92). This was achieved by the quantitative weight method, with two repetitions per plot, and by using an open frame with an area of 0.5 m^2.

The leaf area index (LAI) was determined at the flowering stage of barley (BBCH 61–65) using a LAI-2000 (LI-COR) device, with five repetitions per plot. At the stage of full maturity (BBCH 92), the number of plants per 1 m^2 in four adjacent rows was used to determine the number of plants per 1 m^2. The plant height and productive tillering were determined using 25 representative plants from each plot.

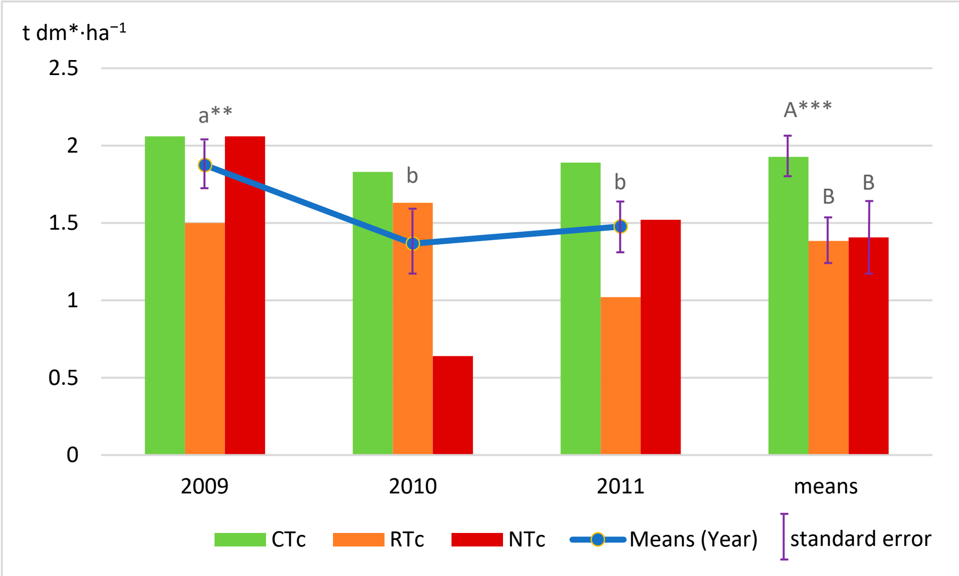

Figure 2. Dry mass of the cover crops. CTc—conventional tillage, RTc—reduced tillage, and NTc—no-tillage, * dm—dry mass. Different letters indicate the significant differences ($p < 0.05$) in the study years (**) or between cultivation systems (***).

Figure 3. Field prepared for sowing spring barley. CT—conventional tillage, CTc—conventional tillage + cover crop, RTc—reduced tillage + cover crop, and NTc—no-tillage + cover crop.

2.2. Statistical Methods

The results of the study were statistically analyzed using analysis of variance (ANOVA) for a series of experiments (split–split plot) based on the main two factors. Years were selected as the random factor in the mixed model of the total variance. Post hoc analyses were performed using Tukey's HSD test ($p = 0.05$). A simple linear regression analysis and Pearson's correlation coefficient were utilized to find the relationship between the number of weeds in the canopy and the parameters of barley canopy architecture. The exploration technique of principal component analysis was used to explain the multidimensional diversity of seven characteristics (in terms of the first two components): barley density, barley length, number of barley tillers, the LAI, weed density in spring, weed density in summer, and weed biomass. The division of the barley treatment into groups that differed significantly in terms of the aforementioned characteristics was achieved via cluster analysis with the k-means method. The confirmation of significance between groups was performed via ANOVA with the grouping variable. The calculations were performed in STATISTICA 13.0 software (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

The methods of tillage clearly influenced the degree of barley weed infestation at the time of barley tillering (Table 2). The smallest number of weeds (38.7 pcs.$\cdot$m^{-2}) was found after giving up tillage (NTc). There were significantly fewer weeds—by as much as 45.3%—than the numbers found under conditions of traditional cultivation (CTc). Additionally, simplified cultivation (RTc) contributed to a significant reduction, by 26.1%, in the number of weeds. The tillage system affected species diversity, determined in the spring before herbicide spraying (Figure 4). *Viola arvensis* dominated in traditional cultivation; its number was significantly higher than in other cultivation systems. *Amaranthus retroflexus* also had a significant share in CT and CTc. On the other hand, *Galium aparine*, *Viola arvensis*, and *Amaranthus retroflexus* dominated under the conditions of simplified tillage. If tillage was abandoned (NTc), *Anthemis arvensis* was by far the most abundant weed, and it was more numerous than in CT, CTc, or RTc. The spring infestation of barley was influenced by meteorological conditions. Significantly more weeds were found in the first year of the study than in the following years, which could have resulted from the heavy rainfall in March and April or could be due to the poor emergence of the barley (Table 1). Under such conditions, the weed count was significantly higher under CT and CTc conditions than under RTc and NTc conditions.

Table 2. Weed infestation of spring barley.

Factors	Weed Density in Spring [pcs.·m^{-2}]	Weed Density in Summer [pcs.·m^{-2}]	Weed Biomass [g]
CT #	70.2 a	10.1 b	7.0 b
CTc	70.7 a	15.3 b	9.7 b
RTc	51.9 b	18.3 ab	21.7 ab
NTc	38.7 c	25.6 a	36.3 a
40 N	–	20.3 a	18.7
80 N	–	16.7 ab	19.1
120 N	–	14.8 b	18.3
2010	69.2 a	17.7	24.4
2011	54.9 b	16.1	12.3
2012	49.4 b	18.2	19.4
2010			
CT	94.7 a	8.0 c	4.8 c
CTc	98.6 a	13.3 bc	8.5 c
RTc	66.9 b	10.7 c	11.8 bc
NTc	16.7 d	36.7 a	72.5 a
2011			
CT	53.6 bc	12.4 bc	10.1 c
CTc	58.1 bc	13.8 bc	10.1 c
RTc	34.7 cd	13.7 bc	8.4 c
NTc	73.3 ab	24.4 abc	20.5 bc
2012			
CT	62.2 b	9.8 c	6.2 c
CTc	55.6 bc	18.7 bc	10.6 bc
RTc	53.9 bc	30.6 ab	44.9 ab
NTc	26.1 d	13.6 bc	15.8 bc
Tillage	***	***	***
Fertilization	–	**	NS
Year	***	NS	NS
Tillage × fertilization	–	NS	NS
Tillage × year	***	***	***
Fertilization × year	–	NS	NS

CT—conventional tillage, CTc—conventional tillage + cover crop, RTc—reduced tillage + cover crop, and NTc—no-tillage + cover crop. The means in a column followed by different letters show the significant differences ($p < 0.05$) as per the Tukey test. Significance set at as follows: *** $p < 0.001$; ** $p < 0.01$; and NS not significant.

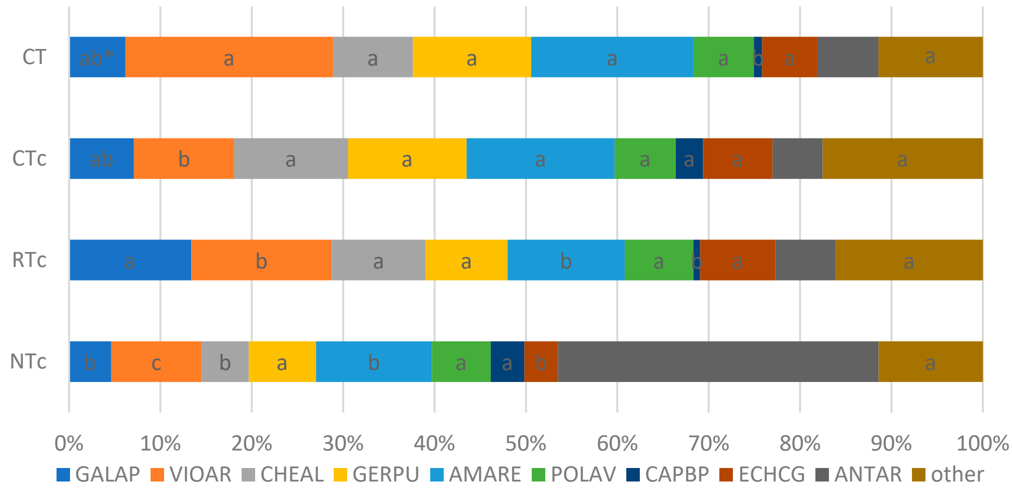

Figure 4. The percentage of dominant weed species at the tillering date of the spring barley (means 2010–2012). CT—conventional tillage, CTc—conventional tillage + cover crop, RTc—reduced tillage + cover crop, and NTc—no-tillage + cover crop, GALAP—*Galium aparine*, VIOAR—*Viola arvensis*, CHEAL—*Chenopodium album*, GERPU—*Geranium pusillum*, AMARE—*Amaranthus retroflexus*, POLAV—*Polygonum aviculare*, CAPBP—*Capsella bursa-pastoris*, ECHCG—*Echinochloa crus-galli*, and ANTAR—*Anthemis arvensis*. * Different letters indicate the significant differences ($p < 0.05$) in the weed species between cultivation systems.

At the time of the spring barley harvest, the tillage systems also significantly influenced the difference between the number of weeds (Table 2). However, the relationships were different than those found in the early development stages of the tested plant. The highest weed infestation was observed after NTc. Compared to the CT system, no tillage resulted in a significant—more than 2.5-fold—increase in the number of weeds. After cover crop management with a cultivator, an 81.2% increase in weed infestation was also observed compared to that recorded on conventionally cultivated plots. Thus, the common opinion about the negative impact of simplified farming on weed infestation was confirmed. However, in the early and later stages of barley development, no effect of the plowing of cover crops on weed infestation was found. The intensification of nitrogen fertilization was conducive to a systematic reduction in the degree of weed infestation. However, it was statistically confirmed that only a threefold increase in the dose (up to 120 kg N·ha^{-1}) reduced the number of undesirable plants in the barley canopy, i.e., by 27.5%. The analysis of variance also showed that the summer weed infestation of barley was dependent on the interaction between cultivation years and cultivation systems. Changeable weather conditions did not affect the number of weeds in classical tillage conditions. However, no-tillage cultivation conditions with particularly high precipitation in May and a lower air temperature compared to the multi-year period (first year of the study) resulted in a significantly higher number of weeds than in 2011 and 2012, when May was moderately humid and heavy rainfall occurred only in July.

The dry weight of weeds that was determined at the time of the spring barley harvest was strongly dependent on the method of tillage. Compared to TC, the use of RTc contributed to an increase in weed weight by more than three times, while for NTc it was more than five times. Statistical analysis did not show any significant variation in weed dry matter due to the influence of increasing nitrogen fertilization or due to the year of the study. It was shown, however, that a cold and wet May, as well as a dry and warm June and July (the first year of the study), benefited the accumulation of weed mass in barley in the no-tillage system. Increased weed infestation was influenced in a simplified tillage system in the third year of the study, which was the closest to the optimum in terms of rainfall (2012). There was no significant interaction between the cropping system and N fertilization or between testing years and N fertilization on spring barley weed infestation (Tables S1 and S3).

Modern measurement techniques make it possible to determine the condition of crops and to forecast their productivity. A quick and non-invasive assessment of the growth dynamics and biomass accumulation can be obtained by measuring the leaf area index (LAI). The analysis of variance showed a significant dependence of the LAI index on the studied factors (Table 3). In the conditions of direct sowing in white mustard mulch (NTc), the LAI index decreased significantly (by 27.1%) when compared to the value recorded in CT conditions. Moreover, the field management of the cover crop and the introduction of cultivation simplification contributed to a reduction in the assimilation area of the leaves. However, this trend has not been statistically proven. The intensification of nitrogen fertilization significantly influenced the leaf area index diversity. It was observed that the use of higher doses of nitrogen contributed to an increase in leaf area, and if the dose of N was increased from 40 to 80 or to 120 kg N·ha^{-1}, then the LAI index increased by 21.6 and 27.9%, respectively. It was also noted that, in the first year of the study, when the least favorable conditions for the growth and development of barley occurred, the LAI of the barley cultivated in the TC system was significantly lower than in the second year of barley cultivation (which was characterized by a warm and humid March, a dry April and May, optimal precipitation in June, and a particularly wet July).

Table 3. Selected properties of spring barley canopy architecture.

Factors	LAI	Barley Tillers	Barley Density [no·m^{-2}]	Barley Length [cm]
CT [#]	1.44 a	2.64 b	297 a	54.0 a
CTc	1.37 a	2.59 b	291 a	52.4 ab
RTc	1.30 ab	2.92 a	234 b	50.5 b
NTc	1.05 b	2.65 b	229 b	39.3 c
40 N	1.11 b	2.54 b	243 b	47.6 b
80 N	1.35 a	2.74 a	264 ab	49.2 ab
120 N	1.42 a	2.82 a	281 a	50.4 a
2010	1.00 b	2.91 a	216 b	46.2 b
2011	1.53 a	2.23 b	281 a	41.4 b
2012	1.34 a	2.95 a	292 a	59.5 a
2010				
CT	0.89 cd	3.00 abc	261 bcd	50.7 bc
CTc	1.16 bcd	2.95 abc	232 cde	48.6 cd
RTc	1.24 bcd	3.15 ab	198 de	54.7 b
NTc	0.71 d	2.55 cd	172 e	30.8 f
2011				
CT	1.95 a	2.21 d	279 abcd	42.5 e
CTc	1.43 abc	2.18 d	307 abc	41.8 e
RTc	1.41 abc	2.36 d	267 bcd	43.5 de
NTc	1.31 bcd	2.18 d	272 abcd	37.9 e
2012				
CT	1.49 abc	2.70 bcd	351 a	68.6 a
CTc	1.53 ab	2.64 bcd	335 ab	67.0 a
RTc	1.25 bcd	3.24 a	239 cde	53.3 bc
NTc	1.11 bcd	3.24 a	243 cde	49.1 bcd
Tillage	**	**	***	***
Fertilization	***	***	***	**
Year	**	***	***	***
Tillage × fertilization	NS	NS	NS	NS
Tillage × year	*	**	*	***
Fertilization × year	**	*	NS	NS

[#] CT—conventional tillage, CTc—conventional tillage + cover crop, RTc—reduced tillage + cover crop, and NTc—no-tillage + cover crop. The means in a column followed by different letters show the significant differences ($p < 0.05$) as per the Tukey test. Significance set at as follows: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; and NS not significant.

Furthermore, the productive tillering of spring barley was significantly determined by the methods of tillage and nitrogen fertilization. The barley that proliferated most was observed after the application of the cover crop to the soil with a cultivator. The tillering of plants was significantly greater (by 10.6%) than that found in the traditional cultivation system. This dependence was probably a consequence of the smaller number of plants occurring in no-tillage crops than those that occurred after plowing. The intensification of nitrogen fertilization was conducive to the formation of an increased number of stalks by barley. After the application of 80 and 120 kg $N \cdot ha^{-1}$, productive tillering increased significantly, by 6.6% and 10.2%, respectively, in relation to the fertilization rate of 40 kg $N \cdot ha^{-1}$. Additionally, the analysis of variance showed that the rainfall deficit in April and May, as well as the high temperatures at that time (2011), which exceeded the average of 1968–2012, contributed to the inhibition of plant tillering in each of the tested cultivation systems. In turn, the wet March, April, and (especially) May in 2010 benefited the barley that was cultivated in CT and CTc conditions, while the dry March and April, as well as the optimal May, in 2012 benefited the barley that was cultivated in RTc and NTc conditions.

The number of spring barley plants per 1 m^2 was significantly altered by the method of tillage and nitrogen fertilization. Using tillers instead of plowing showed a significant decrease in plant density (by 21.2%). Additionally, the use of direct sowing of mustard mulch contributed to a significant reduction in the number of plants (by 22.9%) when compared to those found in the conditions of conventional cultivation. The analysis of variance showed that tripling the dose of nitrogen fertilization from 40 to 120 kg $N \cdot ha^{-1}$ contributed to a significant increase in the number of plants per 1 m^2 (by 15.6%). The highest plant density in CT and CTc conditions was recorded in the third year of the study, while for RTc and NTc it was in the second year.

Both the cultivation systems and the mineral nitrogen fertilization systems significantly altered the height of the spring barley. The shortest plants (39.3 cm) were observed after NTc. Compared to CT, NTc contributed to a significant reduction in plant height—on average by 14.7 cm (27.2%). A significantly lower plant height, i.e., an average of 3.5 cm (6.5%) compared to those found under CT, was also observed after RTc. The intensification of nitrogen fertilization was conducive to a significant increase in the height of the spring barley. On plots where nitrogen was applied at a dose of 120 kg $N \cdot ha^{-1}$, the plants were significantly higher than those found after the application of 40 kg $N \cdot ha^{-1}$—by 2.8 cm (5.9%). The plant height in traditional cultivation and in simplified cultivation systems benefited from the increased rainfall in the third year of research, which was higher than the rainfall in previous years. There was no significant interaction between cropping system and N fertilization or between the testing years and N fertilization on the properties of spring barley canopy architecture (Tables S2 and S3).

The analysis of straight correlation showed a significant relationship between the number of weeds and the selected characteristics of spring barley canopy architecture (Figure 5). A strong, negative relationship between the number of weeds and plant height was proved ($r = -0.7033$). Increasing the height of plants by 1 cm contributed to reducing the number of weeds by 0.9 $pcs. \cdot m^{-2}$. The number of undesirable plants in the canopy was also significantly correlated with plant density ($r = -0.5992$) and the LAI ($r = -0.6357$). A similar direction of correlation was observed for the weed mass (Figure 6). The closest relation was found for plant height ($r = -0.9026$). If the length of the blades increased by 1 cm, the dry weight of weeds decreased by 2.3 g. The weed weight also depended on the number of plants per area unit ($r = -0.6966$) and the LAI ($r = -0.5924$).

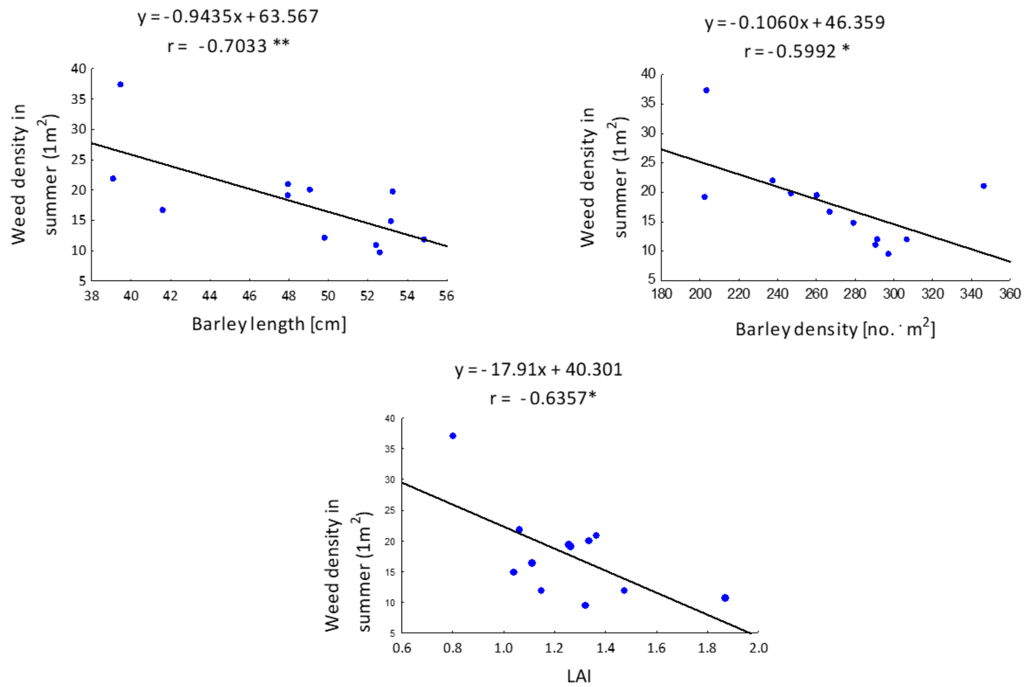

Figure 5. The linear relationship between the number of weeds (determined in the summer) and the selected elements of the spring barley canopy architecture. The linear regression equation and the Pearson correlation coefficient (r) are shown when the r is significant (*, **—at 0.05 and 0.01 probability level, respectively (*n* = 12)). The points represent the means over 2010–2012.

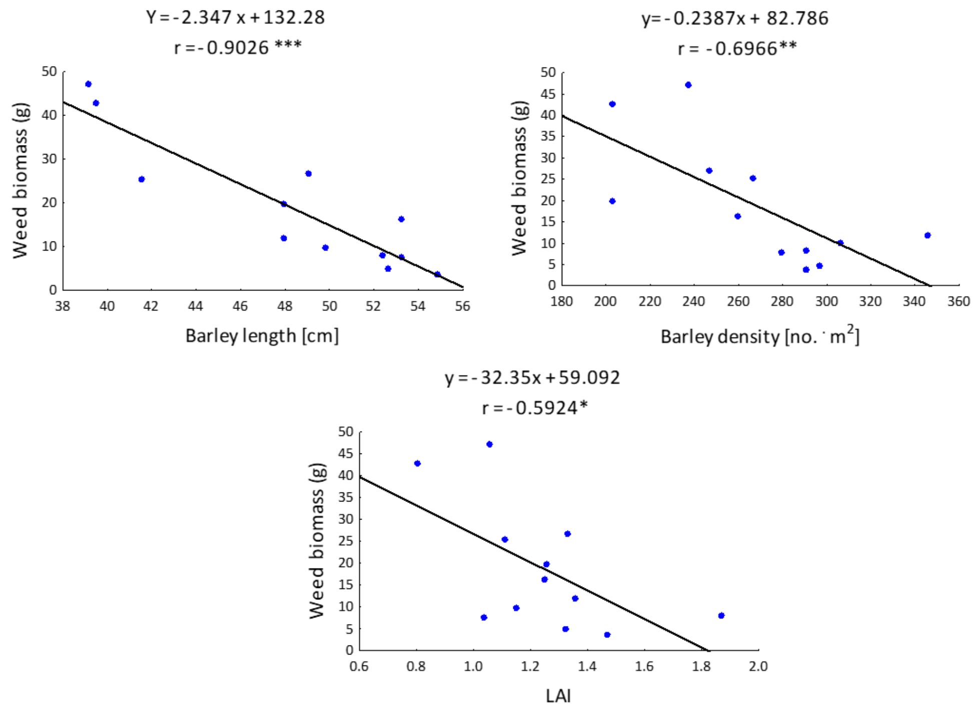

Figure 6. The linear relationship between the dry weight of weeds [g] and the selected elements of the spring barley canopy architecture. The linear regression equation and the Pearson correlation coefficient (r) are shown when the r is significant (*, **, ***—at 0.05; 0.01 and 0.001 probability level, respectively (*n* = 12)). The points represent means over 2010–2012.

The first component (Y1) explained 72.85% of the total variance (Figure 7). It was significant for the complex of the three characteristics, i.e., the leaf area index (LAI) of the barley (−0.85), the length of the barley (−0.93), and the density of the barley (−0.87), in the same direction, while the effect of weed density (+0.95) and the weed biomass (+0.94) in the summer was significant in the opposite direction. Weed density in the spring also participated in the first component, in parallel with the barley canopy characteristics. The second principal component (Y2) explained 18.36% of the total variance, and it was significant (+0.96) only for the numbers of the barley tillers. This indicates the lowest intensity of weed infestation, whereby the highest tillering of barley was provided. Consequently, the summer density of weeds was reduced by 42% overall and the weed biomass was reduced 2.4-fold.

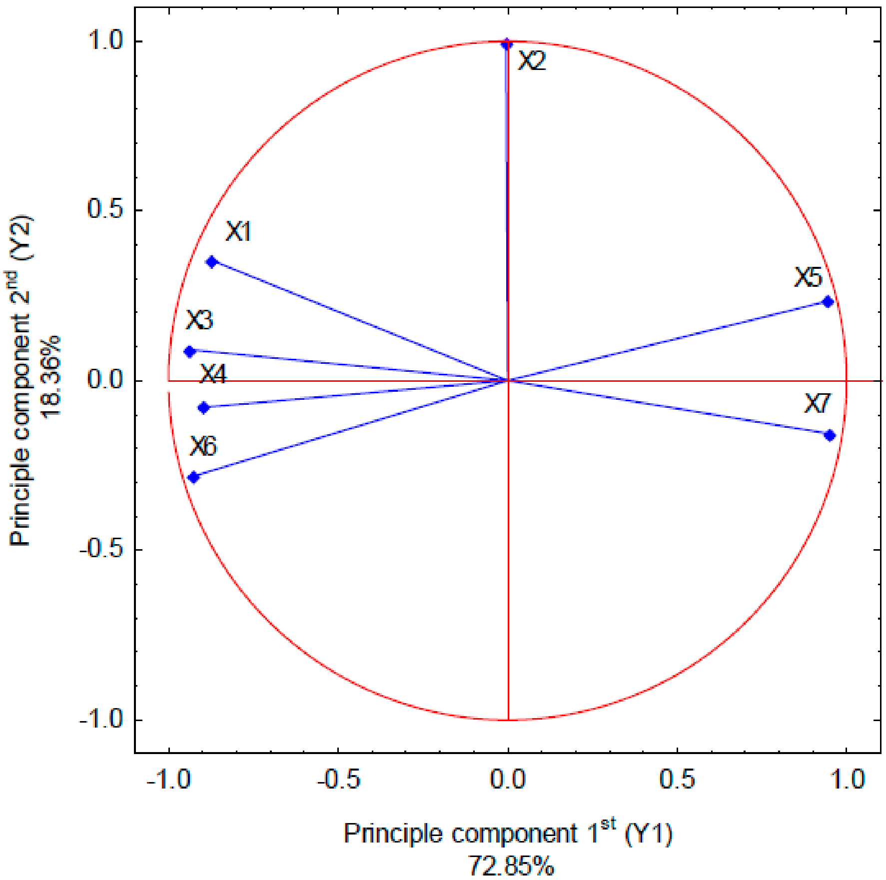

Figure 7. Projection of the barley's characteristics and weed infestation in the various types of cultivation. X1—LAI; X2—Tillers; X3—Length; X4—Density; X5—Weed biomass; X6—Weed density in spring; X7—Weed density in summer; Y1 = −0.85 × 1 − 0.004 × 2 − 0.93 × 3 − 0.87 × 4 + 0.94 × 5 − 0.93 × 6 + 0.95 × 7. Y2 = 0.33 × 1 + 0.96 × 2 + 0.09 × 3 − 0.06 × 4 + 0.22 × 5 − 0.27 × 6 − 0.16 × 7.

Based on the k-means (CA) analysis, two of the clusters were significantly different in terms of the six characteristics (except for the number of barley tillers (Table 4, Figure 8)). A significantly higher LAI resulted from a higher density and length of barley, which was attributed to the simplified cultivation treatments and zero tillage treatments. The same tendency applied to the spring weeding. It was not found that differentiated nitrogen fertilization alleviated or strengthened the pressure of weeds in barley crops.

Table 4. Clusters of the barley treatments in terms of the various characteristics that determined the weed infestation.

Characteristic	Cluster 1 (RTcN1, RTcN2, RTcN3, NTcN1, NTcN2, NTcN3)		Cluster 2 (CTN1, CTN2, CTN3, CTcN1, CTcN2, CTcN3,)		*p*
	Mean	s_e	Mean	s_e	
Barley density	294.1	7.19	231.7	8.81	<0.001
Barley length	53.2	1.63	44.9	2.55	0.02
LAI	1.41	0.08	1.17	0.08	0.05
Weed density in spring	70.5	2.62	45.3	3.18	<0.001
Barley tillers	2.61	0.03	2.79	0.09	0.10
Weed density in summer	12.7	1.34	21.9	2.27	0.006
Weed biomass	8.38	0.74	28.99	3.68	<0.001

CT—conventional tillage; CTc—conventional tillage + cover crop; RTc—reduced tillage + cover crop; NTc—no-tillage + cover crop; N1—40 kg N·ha^{-1}; N2—80 kg N·ha^{-1}; N3—120 kg N·ha^{-1}.

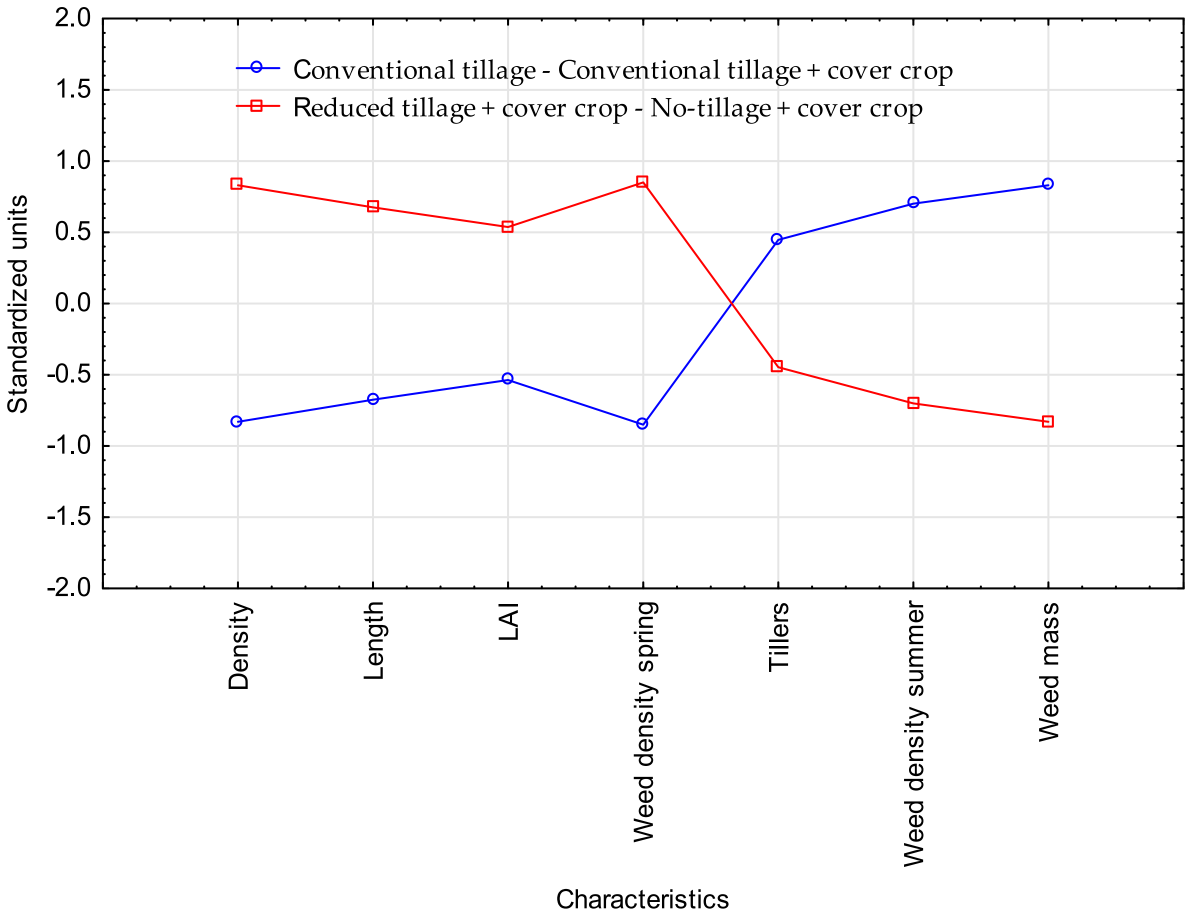

Figure 8. Two clusters of barley treatment separated on the basis of the *k*-means cluster analysis. Means ± standard errors from the years 2010–2012.

4. Discussion

In the three-year field experiment, the effect of a white mustard cover crop on canopy weed infestation and spring barley architecture parameters was studied. The white mustard cover crop was implemented into the soil through three methods of tillage and with varying levels of nitrogen fertilization. Under the principles of integrated production, including plant protection, tillage, and other non-chemical treatments, the elements of the weed control strategy become of particular importance [69–71]. Tillage has a significant impact on the weed infestation of a canopy [17,18,25,32]. Its method determines the abundance and distribution of seeds in the soil [38,40]. Under conventional tillage, weed diaspores are placed at a considerable depth, which temporarily limits their germination, but leads to an increase in the soil seed bank. In subsequent years, the weed seeds are plowed up and stimulated to germinate, which can increase the weed infestation of the crop canopy [16,20]. Under reduced tillage, especially in zero tillage, weed seeds remain in the shallower soil layer and on the soil surface, germinate faster, and are easier to control, which, combined with proper rotations, can lead to a reduction in weed infestation [24]. A characteristic of reduced and zero tillage is that plant residues are left on the soil surface in the form of mulch, which effectively hinders the germination and emergence of weeds [23,31,64]. In addition, weed diasporas lodged in the top layer are degraded more quickly than those lodged deep down, which can also help reduce weed infestation [20,39]. As agricultural practice shows, an absence or reduction in mechanical tillage that stimulates weed seeds to germinate or destroys them, which is used in the traditional cropping model, generally forces the use of more intensive chemical protection of the canopy [35,72]. In the conducted experiment, simplifications in tillage contributed to an increase in weed infestation, which was determined at the end of the barley vegetation period. This is consistent with the results of many studies, which indicate that the modification of plowing, and primarily its simplification, may cause an increase in the weed infestation of fields and, consequently, a decrease in the yield of the crops [72–74]. Stankiewicz-Kosyl et al. [19] found that the resistant populations of weeds are most frequently collected from fields where moldboard ploughing dominates. While examining the impact of simplifications in tillage on the weed infestation of durum wheat, Woźniak and Soroka [75] found that the use of cultivation instead of plowing contributed to an increase in the number and mass of weeds by 81 and 36%, respectively. Wacławowicz [22], in turn, observed an over four times greater air-dry mass of weeds by replacing deep plowing with disk plowing. Kordas [39] proved that the replacement of plow tillage, both in post-harvest and pre-sowing cultivation, with no-tillage (cultivator or disc) resulted in an increase in the weed infestation of the canopy by 50%. The modification of the classic plow tillage in favor of simplified techniques, especially direct sowing, also contributed to an increase in the weed infestation of small grains in other experiments [17,20,41,72]. However, in the studies of Majchrzak and Piechota [26], as well as Faltyn and Kordas [34], a greater weed infestation occurred under plowing rather than under simplified or zero tillage. The reason for this relationship may have been the ploughing up of weeds from deeper soil layers that had been placed there in earlier years. The field experiment showed that, in the spring barley tillering phase, the fewest undesirable plants were observed on plots where no-tillage or zero tillage was applied. This is often associated with the plant cover left in the field as a mulch, which, in addition to limiting the development of weeds as a result of covering the soil surface, is also attributed to an allelopathic effect [64,65]. In addition, lower soil temperature in no-till crops may have contributed to less weed infestation of barley in RTc and NTc than in CTc, which led to delayed germination and weed growth. This was especially the case in the first year of research. The weed infestation of cultivated plants depends on meteorological conditions. During our experiment, heavy rainfall in March and April contributed to an increase in the spring weed infestation of barley, which was especially applicable in CT and CTc conditions. In turn, a cold and wet May, as well as a dry and warm June and July contributed to the summer occurrence of an increased number and weight of weeds in the canopy of spring barley that was cultivated in the NTc system. Kraska and Pałys [76] proved, however, that a dry May and wet June and July resulted in a greater weed infestation of spring barley that was cultivated in the simplified system than in the traditional one. A reverse relationship was observed by the authors if May was wet and June and July were dry. Velykis and Satkus [77] noted, however, that, in dry years—which are less favorable for the germination, growth, and development of barley—simplified tillage systems contribute to an increased weed infestation of the canopy.

Our research found no significant effect after plowing of cover crops on the number and weight of weeds in the spring barley canopy, although a certain tendency toward an increase in weed infestation was observed. Woźniak [78] and Shrestha et al. [31] also noticed no significant increase in weed infestation when under cover crop influence. On the other hand, a reduction in both the number and weight of weeds in the canopy of spring barley with which a cover crop was used has been indicated by other researchers [79–81]. What is more, Gawęda et al. [82] obtained an almost two-fold reduction in weed mass after plowing in white mustard when compared to a control site without cover crop cultivation. They did not, however, find a significant effect of the plowing of cover crops on the number of weeds in the spring barley canopy. In turn, Hruszka and Brzozowska [83] claim that cover crops do not sufficiently protect the succeeding plants against weeds, and they may even increase weed infestation. Majchrzak and Piechota [26] indicated that the presence of a cover crop of white mustard in a zero-till plot reduced the number of weeds in the spring wheat canopy by 68%. However, Kuc [84] observed a significant decrease in the number of weeds after applying conservation tillage when compared to traditional tillage. According to Kordas [39], the long-term use of simplified tillage and direct sowing results in an increase in weed infestation only in the initial period, and this is followed by a decrease in weed infestation below the level of that which occurs in traditional cultivation.

An important element regulating weed infestation is proper mineral fertilization, especially nitrogen fertilization. Typically, higher rates of nitrogen reduce weed infestation, mainly as a result of the increased competitiveness of better-nourished crops [56,81,82]. However, intensification of nitrogen fertilization can increase the germination capacity of some weed species and lead to compensation by nitrophilous species [67]. In our research, the intensification of nitrogen fertilization resulted in a significant systematic reduction in the number of weeds in the spring barley canopy. A similar result was also observed by Suwara et al. [85] and Harasim and Wesołowski [86]. This may be related to the better nutrition of barley, which increases the density of the canopy and the competitiveness of the crop against weeds. In a study by Giemza-Mikoda et al. [27] and Brzozowska and Brzozowski [87], the level of mineral fertilization did not cause significant changes in the tested weed infestation parameters. In turn, Wacławowicz [22] observed an increase in the number of weeds, while Kakabouki et al. [88] observed an increase in their weight due to the intensification of nitrogen fertilization. The varied effect of nitrogen fertilization on weed infestation may result from, among other causes, weed species composition [89], the method of nitrogen fertilizer application [90], and the sowing date. An increased dose of nitrogen reduces weed infestation if winter wheat is sown at an early or optimal date, and this contributes to the growth of weed mass if the sowing date is delayed [91].

Reducing tillage, introducing cover crops, and using nitrogen fertilization cause some changes. The three-year field experiment investigated the effect of a white mustard cover crop, which was introduced into the soil by three methods of tillage, and a different level of nitrogen fertilization on canopy infestation and spring barley architecture parameters. The use of cover crops reduced the barley LAI, especially when traditional tillage was abandoned in favor of direct sowing. It was also shown that the number and biomass of weeds in the barley field decreased along with the increase in the LAI. The competitiveness of crop plants with a higher leaf index was better and, as a result, they shaded weeds better, causing their limited growth and development. Szafrański and Kulig [92] found that both the autumn plowing of the cover crop and its spring mixing with the soil caused an increase in the assimilation surface of the leaves. Kulig et al. [93], as well as Agenbag and Maree [94]—who compared plowing systems with shallow loosening and with zero tillage—showed that the simplification of tillage contributes to a reduction in the assimilation area of cereals. The LAI was increased in this experiment due to intensification of N fertilizer, which is supported by other findings [22,95,96]. The increase in LAI results from the greater vegetative mass of barley fertilized with higher doses of nitrogen. The presence of a cover crop increased barley sprouting, but only after simplified tillage. According to Wojciechowski [56], productive tillering also depends on the plant species cultivated in the cover crop. Leaving the white mustard mulch for the autumn and winter period contributed to a reduction in plant density and a reduction in plant height. However, these parameters increased under the influence of an increased nitrogen dose. In our study it was also proved that the number of plants and their height were negatively correlated with the number and weight of weeds in the canopy of the studied cereal. Kwiatkowski [62], by examining the effect of three different cover crops on the parameters of canopy architecture, concluded that white mustard is the most beneficial in this respect. In other studies [23], the beneficial effect of simplifications in tillage has been proven in terms of barley stocking.

5. Conclusions

Cultivation systems influence changes in the weed infestation of the spring barley canopy. In the cereal tillering phase, a significant reduction in the number of weeds was demonstrated if CTc was replaced by RTc or NTc; additionally, in each system, a cover crop was used. Weed infestation is also affected by meteorological conditions. Increased rainfall in the early stages of barley development benefits the number of weeds, especially in traditional cultivation conditions.

In the full maturity phase, RTc generally contributed to an increase in the number and mass of weeds, which was observed in every year of the study. The use of reduced or no tillage may contribute to an increase in weed infestation, especially if there is heavy rainfall in May and the air temperature is below the long-term average. This translates into an increase in the number and weight of weeds that coincides with the period of intensive cereal growth. The intensification of nitrogen fertilization resulted in a systematic reduction in the number of weeds in the canopy. The abandonment of tillage and the direct sowing of barley in mustard mulch (NTc) resulted in a decrease in the barley leaf area expressed by the LAI. Simplifications in cultivation (RTc and NTc) also caused a reduction in plant density and height. In turn, the branching of plants was the highest when RTc was used. Increasing the doses of nitrogen fertilization improved the examined parameters of the canopy architecture. A significant negative correlation was also found between the barley weed infestation and the leaf area index (LAI), plant height, and number of barley plants per area unit. This proves the desirability of managing agrotechnical treatments, which, by improving the condition of crops, contribute to reducing weed infestation and, consequently, reduce the use of herbicides. The utilization of PC analysis enabled determination of the net multicharacteristic contribution between barley and weeds. Principal component analysis showed that the highest tillering of barley caused the lowest intensity of weed infestation. Consequently, the summer density of weeds was reduced by 42% overall and the weed biomass decreased 2.4-fold. In turn, the cluster analysis indicated that a significantly higher LAI resulted from a higher density and length of barley, and this was attributed to the simplified cultivation treatments and zero tillage treatments. In the future, sustainable agriculture should pay particular attention to implementing regenerative practices. Reducing tillage and the use of stubble cover crops improves soil fertility, which has a positive effect on the environment; however, in certain weather conditions it may increase the weed infestation of cultivated plants.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13091747/s1, Table S1. Weed infestation of spring barley. Interaction between tillage and N fertilization and year and N fertilization. Table S2. Selected properties of spring barley canopy architecture. Interaction between tillage and N fertilization and year and N fertilization. Table S3. Effect size for Analysis of Variance (ANOVA).

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