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Effect of cover crops on emergence and growth of carrot (*Daucus carota* L.) in no-plow and traditional tillage

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Abstract

The aim of the experiment was to determine the influence of cover crop biomass incorporated into the soil at different times and using different treatments on carrot emergence and growth. 7 species of cover crops were included in the study: *Secale cereale*, *Avena sativa*, *Vicia sativa*, *Sinapis alba*, *Phacelia tanacetifolia*, *Fagopyrum esculentum*, and *Helianthus annuus*.

Number of emerged carrot plants significantly depended on the cover crop used and on the method of pre-winter and spring pre-sowing tillage. Carrot emerged best after a rye or oats cover crop. Regardless of the cover crop species used, the largest number of carrots emerged in cultivation on ridges. In other variants of no-plow tillage, number of seedlings was significantly lower and did not differ from that under traditional plow tillage. The highest leaf rosettes were formed by carrot growing after a rye or oats cover crop. The highest rosettes were produced by carrots in the treatments where tillage was limited to the use of a tillage implement in spring and the lowest ones after pre-winter plowing. The effect of tillage on the emergence and height of carrot leaves largely depended on weather conditions in the successive years of the study. The largest number of leaves was found in carrots grown after a buckwheat cover crop and in cultivation without cover crop, while the smallest one after phacelia and white mustard. Carrots produced the largest number of leaves after a sunflower cover crop and the use of a tillage implement in spring, while the number of leaves was lowest when the mustard biomass was incorporated into the soil in spring. The use of cover crops significantly increased the mass of leaves produced by carrot as compared to the cultivation without cover crop. The largest mass of leaves was produced by carrots grown after the phacelia and mustard cover crops. Conventional plow tillage and pre-winter tillage using a stubble cultivator promoted an increase in the mass of carrot leaves.

Keywords: *Daucus carota*; leaves number, mass; soil tillage; catch crops; mulch

Introduction

Seed germination is a very complex process. Its measurable effect is the emergence of plant seedlings. Plant emergence is determined by many factors. The final result is influenced not only by plant genotype, but also by weather conditions, physical properties of the soil, humidity, temperature, biological activity of soil organisms, infection by pathogens, etc. [1]. In recent years, a major role is attributed to the allelopathic interaction of plants. Decaying plant debris is an important source of allelochemicals [2,3]. The use of green manures, catch crops, or plant mulches affects not only the physical and chemical properties of the soil as a source of organic matter and nutrients for plants, but also due to substances of allelochemical character, it affects the emergence and growth of plants [2,4–6]. The importance of green manures increases together with the popularization of organic farming and cover cropping plays an increasingly significant role, not only in agricultural practice but also in gardening [4,7,8]. Many authors report an increase in soil biological activity during conservation tillage. Organic remains, the more abundant development of soil microflora, are more susceptible to degradation. Soil organisms that participate in the decomposition of organic matter and formation of humus affect the soil structure [9,10]. Grown as undersown crops, stubble or winter catch crops, cover crops bring the biodiversity, modify the physical and chemical properties of the soil, and control weed infestation [11–16]. Glucosinolates are an active factor in species from the Brassicaceae family. When they are decomposed, the released isothiocyanates show high toxicity and may have inhibitory effects towards crops [17,18]. It has been shown that hydroxamic acids from rye and coumarins inhibit cell division and cell elongation in cucumber (*Cucumis sativus*) and onion (*Allium cepa*) [19,20]. Environmental factors have a considerable impact on the proportion of particular

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allelochemicals and allelochemical potential of donor-plants as well as acceptor-plant responses [21]. Considering these aspects, it is extremely important to select the best cover crops for certain crop species, taking into account the specific climate and soil characteristics of the habitat. In the case of slaking soils with an unstable structure, the problem of creating optimal conditions for the emergence and growth of plants is of particular importance [1]. Furthermore, the process of degradation of cover crop biomass depends largely on the manner and time of its incorporation into the soil. Tillage contributes to changes in the soil environment and the rate of organic matter decomposition, causing changes in soil moisture, density and aeration as well as in the availability of nutrients for plants [22–25]. Plant emergence has a determining impact on crop yield. Also foliage and in the case of carrot the leaf rosette size greatly determine root yield [26]. Therefore, the aim of the study was to determine the effect of different cover crop species and varied tillage on the emergence and growth of carrot.

Material and methods

The field experiment was carried out in 2009–2012 at the Felin Experimental Farm belonging to University of Life Sciences in Lublin, on podzolic soil developed from loess deposits covering cretaceous marls with a granulometric composition corresponding to medium dusty loam (BN-78/9180-11). These soils are difficult to cultivate, susceptible to rain thickening, and easily crusting during drought periods. Before sowing the cover crops, the soil contained 1.06–1.15% of humus in the 0–20 cm layer and was characterized by slightly acidic reaction (pH in 1 M KCl 5.76–5.90). The amount of available phosphorus, potassium, and magnesium was as follows: P – 146.8; K – 111.5; Mg – 102.9 mg kg^{-1} soil. The experiment was set up as a completely randomized block design in 4 replicates. The area of a single plot was 33 m^2. The experimental design included following factors: I. Cover crop species: spring rye (*Secale cereale* L.), common oat (*Avena sativa* L.), common vetch (*Vicia sativa* L.), white mustard (*Sinapis alba* L.), lacy phacelia (*Phacelia tanacetifolia* Benth.), buckwheat (*Fagopyrum esculentum* Moench), and fodder sunflower (*Helianthus annuus* L.); II. Tillage: 1. Traditional plow tillage with a set of pre-winter treatments (pre-winter plow to a depth of 25–30 cm using a moldboard plow – Oz) and the use of a tillage implement in spring (cultivator + harrow + string roller; Aw); 2. A set of pre-sowing treatments, sowing the cover crops, a stubble cultivator used before winter, a tillage implement in spring, forming the ridges in spring (Gz + Aw + Rw); 3. A set of pre-sowing treatments, sowing the cover crops, subsoiling tillage, a tillage implement in spring (cultivator + harrow + string roller; GLz + Aw); 4. A set of pre-sowing treatments, sowing the cover crops, a stubble cultivator used before winter, a tillage implement in spring (Gz + Aw); 5. A set of pre-sowing treatments, sowing the cover crops, a stubble cultivator used in spring (NTz + Gw); 6. A set of pre-sowing treatments, sowing the cover crops, a tillage implement in spring (NTz + Aw). Cultivation without cover crops was the control.

Cover crop sowing was performed after the harvest of the previous crop, i.e. winter wheat. Directly after wheat harvesting, disking was done and then plowing to a depth of about 15 cm with subsequent harrowing. Every year, the cover crops were sown on the same date, i.e. on August 1st. Given the experience of the previous years and very poor emergence of cover crops, higher than recommended seeding rates were used. As a result, the rates for cover crop sowing were as follows: rye – 300 kg, oats – 300 kg, vetch – 200 kg, mustard – 200 kg, phacelia – 50 kg, buckwheat – 200 kg, sunflower – 125 kg ha^{-1}. Before winter, the cover crop biomass was incorporated into the soil or left on the soil surface as a mulch, according to the experimental design. Mineral fertilization was applied in the spring at the following amounts of NPK: 150:50:160 kg ha^{-1}. Phosphorus in the form of triple superphosphate and potassium in the form of potassium salt were applied at the full rate prior to sowing, while nitrogen in the form of ammonium nitrate in 2 equal doses: ½ before sowing and ½ as a top dressing. The experimental plant was carrot (*Daucus carota* L.) cv. Flakkee 2, which was sown every year on April 26th in rows (at 50 cm spacing). The seeding rate was 2.61 kg ha^{-1}. Before sowing, the seeds were dressed with Marshal 250 DS (carbosulfan) at the amount of 70 g kg^{-1} seeds. For growing carrot, the following chemical agents were used: after sowing (in April) – Afalon Dyspersyjny 450 SC (linuron) at a dose of 1.8 l ha^{-1}; in June – Dursban 480 EC (chlorpyriphos) at a dose of 1.5 l ha^{-1}; in August – spraying with the fungicide Amistar 250 SC (azoxystrobin) at a dose of 0.8 l ha^{-1}. Soil samples for soil moisture analysis were collected from the layer of 0–20 and 20–40 cm in April, June, and September. The weather conditions during the carrot growing season in the years 2010–2012 are shown in Tab. 1.

Tab. 1 Mean monthly air temperatures and amount of precipitation at the Felin ES in 2010–2012.

Year	Month						
	IV	V	VI	VII	VIII	IX	X
Temperature (°C)							
2010	9.4	14.5	18.0	21.6	20.2	12.5	5.6
2011	10.2	14.3	18.6	18.4	18.8	15.2	8.0
2012	9.5	15.0	17.3	21.4	19.2	15.0	8.0
Mean for 1951–2000	7.5	13.0	16.5	17.9	17.3	12.9	7.9
Amount of precipitation (mm)							
2010	24.5	156.7	65.6	101.0	132.8	119.0	11.2
2011	29.9	42.2	67.8	189.0	65.3	5.4	28.5
2012	34.0	56.3	62.8	52.3	37.6	35.5	88.8
Mean for 1951–2000	40.6	58.3	65.8	78.0	69.7	52.1	40.3

Carrot emergence was determined at the beginning of June in four replicates in randomly selected sections of rows with a length of 1 m. During the full growth of carrots (end of July), measurements of plant height were made and the average number of leaves on a single plant was calculated. At the time of harvest (first decade of October), the leaf mass per plant was determined. The obtained results were statistically processed using variance analysis (ANOVA). The significance of differences was determined by Tukey's test at $P = 0.05$. The r-Pearson correlation coefficients were also calculated to determine the linear relationship between the selected random variables.

Results

Emergence rate

Every year, carrot emerged at a similar time (Fig. 1). The beginning of emergence in 2010 was on May 10th. In 2011 the first seedlings were observed on May 13th; while on May 26th the plants already formed the second true leaf (Fig. 1b). In 2012 the carrots began sprouting on May 10th, at the same time as in 2010 (Fig. 1a–c). On average, 38.0 carrot seedlings grew on 1 m of the row (Tab. 2) and their number was within the range from 10 to 113.

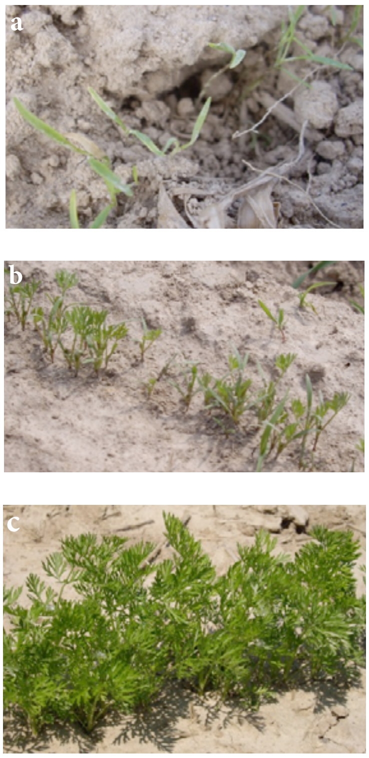

Fig. 1 Emergence and initial growth of carrot (photo by M. Błażewicz-Woźniak). **a** Beginning of carrot emergence (10.05.2012). **b** Carrot seedlings (26.05.2011). **c** Young carrot plants (10.06.2010).

Carrots emerged most abundantly in 2010 (Fig. 1c), while the poorest emergence was recorded in 2012 (Tab. 2). A dry spring in 2012 (Tab. 1) with marginal rainfall in late April (0.1 mm) and early May (10.3 mm) did not favor the emergence. The number of emerging plants depended significantly on the cover crop used and the method of pre-winter and spring pre-sowing tillage (Tab. 2). Carrots emerged best in the treatments where rye or oats were the cover crop. This relationship was particularly evident in 2011. In the treatments where these cereals were used, 59.1 and 56.6 seedlings × m^{-1} were recorded, respectively. When other cover crops were used, carrot emergence was similar to that of the control, i.e. tillage without cover crop.

Regardless of the cover crops used, most of carrots emerged in cultivation on ridges (50.5 plants × m^{-1}), on average during the 3-year study period. In the other no-plow tillage variants, the number of emerging plants was significantly lower and did not differ from that under traditional tillage when deep plowing had been done before winter (Oz + Aw). The effect of tillage system on carrot emergence, however, was heavily modified by the year, which resulted from weather conditions. The beneficial influence of cultivation on ridges (Gz + Aw + Rw) was observed in 2010 and 2011, which were characterized by good or even excessive soil moisture during the carrot emergence period (Tab. 1). Among the tillage techniques used, particularly in 2011, using a stubble cultivator before winter and ridge formation in spring appeared to be the most favorable for carrot emergence. In this combination, carrots emerged most numerously (approximately 72.6 seedlings × m^{-1}) (Fig. 2a). The lowest number of seedlings was recorded after traditional tillage, i.e. after pre-winter plowing (on average 34.6 plants × m^{-1}). The situation was different in 2012. As a result of a dry spring, carrot emergence on ridges was very poor (on average 23.2 plants × m^{-1}; Fig. 2b), and the most numerous seedlings grew after using a stubble cultivator in spring (NTz + Gw) – an average of 31.4 seedlings × m^{-1}. The lowest number of emerged plants was recorded that year also after pre-winter plowing (Oz + Aw) – an average of 21.4 seedlings × m^{-1}.

When considering the effect of the interaction of tillage and cover crops on carrot emergence, no statistically significant differences between the experimental treatments were recorded (Tab. 2). Statistically confirmed differences were observed only in 2011 when the largest number of carrot seedlings was found in the treatments where ridges were formed after the use of an oats or rye cover crop (104.0 and 96.0 seedlings × m^{-1}, respectively), while the smallest one (an average of 21.5 plants × m^{-1}) when the buckwheat biomass was incorporated into the soil before winter using a stubble cultivator and a tillage implement in spring (Gz + Aw).

On the basis of correlation analysis, it was found that carrot emergence only slightly depended on soil moisture in April and June (Tab. 3). A weak positive correlation was observed between carrot emergence and the moisture of the upper soil layers in April and a quite clear, but low positive relationship occurred between emergence and the moisture of the 0–20 cm soil layer in June. The subsoil moisture content (20–40 cm) had no effect on carrot emergence.

Plant growth

The biometric features of carrot leaf rosettes were determined 2 months after the emergence. Carrots produced higher leaves in 2010 and 2011 (48.1 and 45.2 cm, respectively), while the lowest ones in 2012 (on average 31.4 cm) (Tab. 4). This can be attributed to the higher total rainfall in 2010 and 2011 (Tab. 1). The rainfall recorded in July guaranteed intense vegetative growth of carrots. In 2012 little

Tab. 2 Effect of cover crops and tillage on carrot emergence in 2010–2012.

Cover crop	Control				Spring rye				Common oat				Common vetch			
Year	2010	2011	2012	x̄	2010	2011	2012	x̄	2010	2011	2012	x̄	2010	2011	2012	x̄
Tillage	Emergence (in number m^{-1})															
Oz + Aw	49.0	28.0	24.5	33.8	44.0	45.0	23.5	37.5	60.5	43.5	24.0	42.7	47.5	33.0	26.0	35.5
Gz + Aw + Rw	43.0	70.5	39.5	51.0	46.5	96.0	18.0	53.5	61.0	104.0	19.0	61.3	55.0	54.5	16.5	42.0
GLz + Aw	39.0	42.5	27.0	36.2	39.0	57.0	39.0	45.0	31.5	50.0	23.5	35.0	43.5	52.0	27.0	40.8
Gz + Aw	32.0	39.5	31.0	34.2	45.5	45.5	22.0	37.7	55.5	51.5	26.5	44.5	42.0	43.5	27.5	37.7
NTz + Gw	37.5	26.0	35.0	32.8	46.0	56.5	43.0	48.5	56.0	45.5	29.5	43.7	45.0	48.5	24.0	39.2
NTz + Aw	26.0	44.5	29.0	33.2	47.0	54.5	32.5	44.7	37.0	45.0	32.5	38.2	35.0	40.5	23.5	33.0
Mean	37.8	41.8	31.0	36.9	44.7	59.1	29.7	44.5	50.3	56.6	25.8	44.2	44.7	45.3	24.1	38.0
	White mustard				**Lacy phacelia**				**Buckwheat**				**Sunflower**			
Oz + Aw	39.0	36.0	15.0	30.0	47.5	36.5	15.0	33.0	48.5	30.5	24.0	34.3	43.5	24.0	19.0	28.8
Gz + Aw + Rw	44.0	61.5	21.5	42.3	59.5	60.0	20.0	46.5	72.0	67.5	29.5	56.3	64.0	66.5	21.5	50.7
GLz + Aw	37.0	31.0	26.5	31.5	30.5	34.0	28.0	30.8	56.0	27.0	22.0	35.0	47.5	35.5	18.0	33.7
Gz + Aw	48.0	37.5	17.0	34.2	37.0	24.0	13.0	24.7	37.0	21.5	30.0	29.5	42.0	27.5	27.5	32.3
NTz + Gw	33.0	33.5	31.5	32.7	44.5	30.0	27.5	34.0	39.0	29.5	32.0	33.5	51.0	34.0	28.5	37.8
NTz + Aw	43.0	41.5	29.5	38.0	37.5	37.0	25.0	33.2	43.0	35.5	19.0	32.5	27.0	24.5	30.0	27.2
Mean	40.7	40.2	23.5	34.8	42.8	36.9	21.4	33.7	49.3	35.3	26.1	36.9	45.8	35.3	24.1	35.1

	Average independent of cover crop			
	2010	**2011**	**2012**	**Mean**
Oz + Aw	47.4	34.6	21.4	34.5
Gz + Aw + Rw	55.6	72.6	23.2	50.5
GLz + Aw	40.5	41.1	26.4	36.0
Gz + Aw	42.4	36.3	24.3	34.3
NTz + Gw	44.0	37.9	31.4	37.8
NTz + Aw	36.9	40.4	27.6	35.0
Mean	44.5	43.8	25.7	38.0
$LSD_{0.05}$ for:				
cover crop	n.s.	8.15	n.s.	6.46
tillage	12.34	6.61	8.82	5.25
year				3.05
cover crop × tillage	n.s.	23.7	n.s.	n.s.

Oz – pre-winter plow to a 25–30 cm depth; Aw – tillage using a tillage implement (10–15 cm depth) in spring; Gz – pre-winter tillage using a stubble cultivator (25 cm depth); Gw – tillage with using a stubble cultivator (25 cm depth) in spring; GLz – pre-winter cultivation using a subsoiler (30 cm depth); Rw – forming ridges in spring; NTz – no-tillage; n.s. – no significant differences.

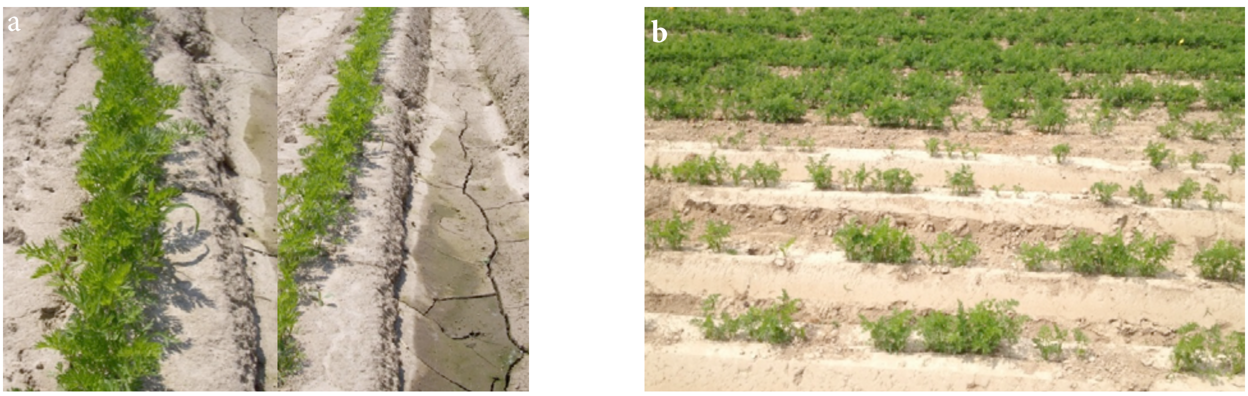

Fig. 2 Carrots grown on ridges during wet and dry periods. **a** Carrots grown on ridges emerged and grew well with abundant rainfall in 2010 and 2011. **b** Few emergences of carrots grown on ridges with rainfall deficiency in 2012.

Tab. 3 Correlation between carrot growth features and soil moisture in 0–20 and 20–40 cm layers.

Soil moisture		Emergence	Height of rosette	Number of leaves	Leaf mass per plant
Date	**Depth (cm)**	**Pearson's correlation coefficient**			
IV	0–20	0.128	0.118	0.223	0.088
	20–40	0.038	0.124	0.194	0.014
	0–40	0.099	0.012	0.241	0.066
VI	0–20	0.211	0.020	0.402	0.211
	20–40	0.018	0.227	0.477	0.435
	0–40	0.113	0.120	0.460	0.330
IX	0–20	-	0.656	0.203	0.703
	20–40	-	0.670	0.156	0.705
	0–40	-	0.667	0.182	0.709
Emergence	-	0.693	−0.184	−0.087	
Height of rosette	0.693	-	−0.182	0.332	
Number of leaves	−0.184	−0.182	-	0.287	

Tab. 4 Effect of cover crops and tillage on height of carrot leaf rosette in 2010–2012.

Cover crop	Control				Spring rye				Common oat				Common vetch			
Year	2010	2011	2012	x̄	2010	2011	2012	x̄	2010	2011	2012	x̄	2010	2011	2012	x̄
Tillage	**Height of carrot leaf rosette (cm)**															
Oz + Aw	48.6	38.8	28.9	38.8	48.9	49.0	37.2	45.0	48.9	44.2	31.5	41.5	49.8	43.1	30.7	41.2
Gz + Aw + Rw	45.6	50.6	24.8	40.3	50.1	50.2	25.1	41.8	48.3	48.2	24.8	40.4	49.8	51.8	25.8	42.5
GLz + Aw	48.9	38.5	35.8	41.1	51.2	47.3	42.1	46.9	51.3	46.7	38.5	45.5	48.6	44.9	27.9	40.4
Gz + Aw	43.6	41.6	35.5	40.2	54.3	49.9	36.2	46.8	51.4	47.6	34.1	44.4	43.5	48.2	30.8	40.8
NTz + Gw	45.6	41.8	27.6	38.3	46.2	50.2	35.7	44.0	46.8	46.4	33.5	42.3	46.5	46.0	30.6	41.0
NTz + Aw	41.3	43.7	35.5	40.2	48.1	50.8	40.5	46.4	50.7	50.0	37.6	46.1	41.8	49.3	36.7	42.6
Mean	45.6	42.5	31.4	39.8	49.8	49.6	36.1	45.2	49.6	47.2	33.3	43.4	46.7	47.2	30.4	41.4
	White mustard				**Lacy phacelia**				**Buckwheat**				**Sunflower**			
Oz + Aw	49.5	45.3	32.0	42.3	49.1	38.8	25.4	37.8	54.2	37.5	33.3	41.7	45.1	39.5	30.0	38.2
Gz + Aw + Rw	49.4	51.3	21.9	40.9	53.1	47.2	22.0	40.8	49.5	48.9	22.3	40.2	49.6	49.3	23.5	40.8
GLz + Aw	50.1	44.5	32.2	42.3	47.8	42.0	30.2	40.0	47.9	39.7	31.9	39.9	47.9	39.9	33.0	40.3
Gz + Aw	52.1	41.0	28.9	40.7	49.9	45.9	30.5	42.1	42.3	44.6	34.2	40.3	42.6	40.8	31.4	38.3
NTz + Gw	46.4	44.7	33.7	41.6	50.4	42.4	30.6	41.1	50.7	41.0	26.2	39.3	47.0	45.9	29.4	40.8
NTz + Aw	52.6	43.4	37.3	44.4	47.7	44.5	31.3	41.2	44.3	46.2	32.1	40.9	38.6	44.4	34.2	39.0
Mean	50.0	45.0	31.0	42.0	49.7	43.5	28.3	40.5	48.1	43.0	30.0	40.4	45.1	43.3	30.3	39.6

	Average independent of cover crop			
	2010	**2011**	**2012**	**Mean**
Oz + Aw	49.3	42.0	31.1	40.8
Gz + Aw + Rw	49.5	49.7	23.8	41.0
GLz + Aw	49.2	43.0	33.9	42.0
Gz + Aw	47.5	45.0	32.7	41.7
NTz + Gw	47.4	44.8	30.9	41.1
NTz + Aw	45.6	46.5	35.6	42.6
Mean	48.1	45.2	31.4	41.5
$LSD_{0.05}$ for:				
cover crop	3.15	2.30	2.41	1.50
tillage	2.56	1.87	1.46	1.22
year				0.71
cover crop × tillage	9.09	6.64	6.94	4.30

Designations as in Tab. 2.

rain fell during that time. This was proven by a correlation analysis performed (Tab. 3), on the basis of which it was found that the height of carrot leaf rosettes was significantly positively correlated with the soil moisture determined at the beginning of September. Such soil condition was the result of previous rainfall (Tab. 1). A high positive correlation and a significant relationship were observed here. The leaf mass produced by a single plant was even more strongly positively correlated to soil moisture in September. Longer leaves were produced by carrots in the treatments where the emergence was more abundant. A positive though weak correlation was found there (Tab. 3).

Plant height depended significantly both on the cover crop and tillage system (Tab. 4). The highest leaf rosettes were produced by carrot in the treatments where rye (on average 45.2 cm) or oats (43.4 cm) was used as the cover crop. The biomass of white mustard and vetch also favorably influenced the growth of carrot leaves compared to cultivation without cover crop (control). The other cover crops did not significantly increase the height of carrot rosettes as compared with the control, wherein the plants had an average height of 39.8 cm. The no-plow tillage system had a positive impact on the growth of carrot leaf rosettes (Tab. 4). On average for the three-year study period, the highest rosettes were produced by carrots from in the treatments where tillage was limited to the use of a tillage implement in spring (NTz + Aw), while the lowest ones after pre-winter plowing (Oz + Aw). The effect of tillage on the height of carrot leaves depended to a large extent on weather conditions in successive years of the study. Ridged cultivation promoted leaf growth in 2010 and 2011. Carrots grown on ridges produced the highest leaf rosettes in these years. In 2010 plants were shortest when only a tillage implement (NTz + Aw) was used in spring, while in 2011 in the treatments with traditional tillage, i.e. after pre-winter plowing (42.0 cm) or when the subsoiler was used (43.0 cm). In 2012 the situation was different. The highest rosettes were produced by carrots in the treatments where only a tillage implement (NTz + Aw) was used in spring, while the shortest ones when carrots were grown on ridges (Gz + Aw + Rw). The analysis of the interaction of the tested factors revealed that on average for the three-year period significantly higher rosettes, as compared with conventional tillage (Oz + Aw) without cover crop, were produced by carrots in the treatments where the soil was mixed in different proportions and combinations with rye biomass (with the exception of cultivation on ridges) as well as in combinations of oats biomass + Aw, Glz + Aw, + NTz + Gz + Aw, and mustard biomass + NTz + Aw. The response of carrot to tillage combinations was modified by weather in successive years of the research. In 2010 none of the tillage variants significantly increased the length of carrot leaves as compared with conventional tillage. In 2011 no-plow tillage and the use of rye, oats, or vetch biomass (except from Glz + Aw) and when a mustard or phacelia cover crop was used on ridges (Gz + Aw + Rw) proved to be significantly better. In 2012 it proved beneficial to use the rye, oats, vetch, or mustard cover crops when their biomass was incorporated into the soil using a tillage implement (NTz + Aw) in spring, while negative effects were recorded after using a white mustard cover crop in cultivation on ridges.

Number of leaves in carrot rosette determined in the middle of the growing season also significantly depended on the experimental factors (Tab. 5). At that time, the carrots produced from 4 to 13 leaves (7.0 leaves × plant^{-1}, on average). Carrots had more leaves in July 2010 and 2012. The plants had the lowest number of leaves in 2011. The number of leaves per rosette was correlated with soil moisture in June to a moderate extent (Tab. 3). A significant positive correlation was observed between the number of carrot leaves and soil moisture in June in the 20–40 cm soil layer. In most cases, the use of cover crops reduced the foliage of carrots as compared to the cultivation without cover crop. The largest number of leaves was recorded in carrots grown after the buckwheat cover crop as well as in the cultivation without cover crop. Carrots grown after the phacelia or white mustard cover crop had the smallest number of leaves.

When considering the interaction of experimental factors, the largest number of leaves (7.9 leaves × plant^{-1}, on average) was produced by carrots in the treatments where fodder sunflower biomass was incorporated into the soil in the spring using a tillage implement, while the smallest one (an average of 4.9 leaves × plant^{-1}) when mustard biomass was incorporated into the soil in spring.

The mass of leaves produced by a single plant ranged from 9.4 to 50.7 g during the harvest; it was the highest in 2010 (mean of 34.9 g), while the lowest in 2012 (19.0 g) (Tab. 6). The use of cover crops (except for rye) significantly increased the mass of leaves produced by carrot as compared with cultivation without cover crop (on average 21.0 g × plant^{-1}). The highest leaf mass was produced by carrots grown after the phacelia (28.1 g × plant^{-1}) and mustard cover crop (27.2 g × plant^{-1}). Traditional plow tillage (Oz + Aw) and pre-winter tillage using a stubble cultivator (Gz + Aw) favored an increase in carrot leaf mass, while the lowest mass of leaves was produced by carrots grown in the treatments where only a tillage implement was used in spring (NTz + Aw) – an average of 23.2 g × plant^{-1}. It was also positively correlated with soil moisture in September (Tab. 3).

Discussion

Cover crop plants used in the experiment belong to several botanical families and in the majority have high allelopathic potential. They differ not only in their biology but also in their chemical composition, phytosanitary impact, and content of active substances [3,6,13,25]. Carrots emerged best in the treatments where rye or oats were the cover crop. Kęsik et al. [27] found that rye mulch affected more positively onion emergence than vetch biomass. Carrots emerged in greatest numbers after oats and white mustard mulching [28]. According to Gniazdowska et al. [29], glucosinolates from mustard, once hydrolyzed to the volatile mustard oils, inhibited the germination and growth of wheat seedlings. In the studies by Konopiński and Błażewicz [30], scorzonera and salsify emerged best in the plots mulched with phacelia, while root chicory in cultivation without plant mulch. Allelochemicals contained in cover crop plants interact in different ways with the crops, and the nature and degree of this impact depends on the species specificity as well as on various external factors.

Tab. 5 Effect of cover crops and tillage on number of leaves per rosette in 2010–2012.

Cover crop	Control				Spring rye				Common oat				Common vetch			
Year	2010	2011	2012	x̄	2010	2011	2012	x̄	2010	2011	2012	x̄	2010	2011	2012	x̄
Tillage	**Number of leaves per rosette (number per plant)**															
Oz + Aw	8.5	5.9	7.0	7.1	6.5	6.3	7.3	6.7	6.8	5.1	7.4	6.5	6.4	5.4	8.1	6.6
Gz + Aw + Rw	6.1	6.6	7.8	6.8	6.7	6.3	7.7	6.9	7.0	5.8	7.8	6.9	6.6	6.4	6.9	6.6
GLz + Aw	7.8	5.8	8.5	7.3	7.8	5.7	6.6	6.7	7.2	5.5	7.6	6.8	7.7	5.8	7.8	7.1
Gz + Aw	6.1	6.6	8.1	6.9	6.0	5.9	7.3	6.4	6.7	5.9	7.4	6.7	6.7	5.9	6.7	6.5
NTz + Gw	8.0	6.1	6.9	7.0	6.1	6.0	6.5	6.2	6.8	5.3	6.4	6.2	6.9	5.4	6.1	6.1
NTz + Aw	8.4	6.0	7.3	7.2	6.1	6.0	7.4	6.5	6.7	5.9	7.8	6.8	7.9	5.8	7.2	7.0
Mean	7.5	6.2	7.6	7.1	6.5	6.0	7.1	6.6	6.9	5.6	7.4	6.6	7.0	5.8	7.1	6.7
	White mustard				**Lacy phacelia**				**Buckwheat**				**Sunflower**			
Oz + Aw	7.4	5.6	7.4	6.8	7.1	5.4	6.7	6.4	9.4	5.6	7.3	7.5	7.7	5.5	6.8	6.7
Gz + Aw + Rw	5.9	6.1	7.4	6.5	5.8	6.6	6.8	6.4	6.8	6.4	6.5	6.6	6.7	6.5	7.6	6.9
GLz + Aw	8.0	5.4	7.0	6.8	8.3	5.1	7.3	6.9	10.3	5.3	7.0	7.5	7.1	5.4	6.6	6.4
Gz + Aw	8.2	4.9	7.7	6.9	6.1	6.3	7.8	6.7	8.2	6.7	7.5	7.4	8.2	6.3	6.8	7.1
NTz + Gw	5.9	5.5	6.6	6.0	6.1	5.3	6.3	5.9	8.1	5.4	6.6	6.7	7.2	6.3	7.0	6.8
NTz + Aw	5.8	5.0	7.0	5.9	6.5	6.1	6.4	6.3	8.0	6.5	6.7	7.0	9.9	6.8	6.9	7.9
Mean	6.9	5.4	7.2	6.5	6.7	5.8	6.9	6.4	8.5	6.0	6.9	7.1	7.8	6.2	7.0	7.0

	Average independent of cover crop			
	2010	**2011**	**2012**	**Mean**
Oz + Aw	7.5	5.6	7.2	6.8
Gz + Aw + Rw	6.5	6.4	7.3	6.7
GLz + Aw	8.0	5.5	7.3	6.9
Gz + Aw	7.0	6.1	7.4	6.8
NTz + Gw	6.9	5.7	6.6	6.4
NTz + Aw	7.4	6.0	7.1	6.8
Mean	7.2	5.9	7.1	6.7
$LSD_{0.05}$ for:				
cover crop	0.97	0.36	0.51	0.38
tillage	0.79	0.30	0.41	0.31
year				0.18
cover crop × tillage	2.81	1.06	1.47	1.09

Designations as in Tab. 2.

In the analyzed experiment, regardless of the cover crop used, most of carrots emerged in cultivation on ridges on average for the 3-year study period. The effect of tillage system on carrot emergence, however, was heavily modified by the year, which resulted from weather conditions. With good water supply, ridges guaranteed an adequate structure and porosity of the soil [16,30]. Due to a dry spring in 2012, carrot emergence on ridges was very poor. Soil crusting and water deficiency are able to completely prevent the emergence of plants from the Apiaceae family [1]. A considerable acceleration in the emergence of dill as a result of irrigation was reported by Biesiada and Kędra [31]. As regards the effect of the interaction of tillage and cover crops on carrot emergence, in 2011 the largest number of carrot seedlings was found in the treatments where ridges were formed after the use of an oats or rye cover crop. The study by Konopiński et al. [32] revealed that onion emerged in largest numbers when the biomass of spring rye was incorporated into the soil before winter disking, whereas the poorest emergence was observed after no-tillage and spring vetch mulch. Borowy [33] found that no-tillage using white mustard as a cover crop did not affect the emergence of root parsley 'Alba', while the further growth of plants grown using this method was slower.

Plant emergence and growth are dependent on many factors, among which an important role is played by soil conditions, in particular soil moisture which is determined to a large extent by weather conditions, but also by agronomic practices [22–34]. On the basis of the correlation analysis, it was found that carrot emergence only slightly depended on soil moisture determined in April and June. This can be explained by the fact that, in addition to soil moisture, carrot emergence was also influenced by other factors such as temperature, soil porosity, allelochemicals released by the cover crops, etc.

Tab. 6 Effect of cover crops and tillage on leaf mass per carrot plant in 2010–2012.

	Leaf mass per carrot plant (g)								
	Cover crop								
Tillage	**Control**	**Rye**	**Oat**	**Vetch**	**Mustard**	**Phacelia**	**Buckwheat**	**Sunflower**	**Mean**
2010									
Oz + Aw	29.4	29.1	32.1	37.6	37.5	40.1	32.1	37.4	34.4
Gz + Aw + Rw	19.7	32.4	34.8	24.6	27.5	26.3	20.2	22.1	26.0
GLz + Aw	25.5	41.6	37.7	43.3	36.4	41.9	39.0	28.4	36.7
Gz + Aw	29.0	38.6	31.1	34.3	37.1	34.0	36.5	35.6	34.5
NTz + Gw	31.4	39.6	40.2	43.8	44.6	37.2	33.7	36.6	38.4
NTz + Aw	50.7	33.1	35.9	49.3	41.4	31.8	26.8	47.5	39.6
Mean	31.0	35.7	35.3	38.8	37.5	35.2	31.4	34.6	34.9
$LSD_{0.05}$ for:									
cover crop A									5.24
tillage B									4.26
A × B									15.10
2011									
Oz + Aw	14.0	21.9	22.6	29.0	26.5	24.4	28.0	27.8	24.3
Gz + Aw + Rw	18.9	26.0	21.9	26.3	23.7	23.6	30.4	24.0	24.4
GLz + Aw	14.0	17.1	18.9	19.1	22.6	32.4	23.9	21.8	21.2
Gz + Aw	10.7	15.8	19.6	18.2	20.8	29.3	29.8	29.6	21.7
NTz + Gw	19.4	12.8	13.6	20.8	22.3	40.9	38.1	25.5	24.2
NTz + Aw	9.4	11.0	10.2	14.2	18.0	20.7	17.5	10.6	13.9
Mean	14.4	17.4	17.8	21.3	22.3	28.6	27.9	23.2	21.6
$LSD_{0.05}$ for:									
cover crop A									3.18
tillage B									2.59
A × B									9.17
2012									
Oz + Aw	31.3	17.7	25.9	27.3	17.4	18.8	14.3	22.9	22.0
Gz + Aw + Rw	15.2	27.7	29.0	23.8	38.0	25.7	22.6	22.8	25.6
GLz + Aw	15.9	6.0	21.3	25.4	12.1	15.0	12.0	16.8	15.6
Gz + Aw	15.3	15.7	17.7	18.1	37.5	34.7	24.4	19.2	22.8
NTz + Gw	12.0	10.6	14.7	11.4	10.4	11.8	11.9	10.9	11.7
NTz + Aw	16.1	10.0	14.5	16.9	16.1	17.0	26.1	11.8	16.1
Mean	17.6	14.6	20.5	20.5	21.9	20.5	18.5	17.4	19.0
$LSD_{0.05}$ for:									
cover crop A									4.05
tillage B									3.30
A × B									11.69
Average for 2010–2012									
Oz + Aw	24.9	22.9	26.9	31.3	27.1	27.8	24.8	29.4	26.9
Gz + Aw + Rw	17.9	28.7	28.6	24.9	29.8	25.2	24.4	23.0	25.3
GLz + Aw	18.4	21.6	26.0	29.3	23.7	29.8	25.0	22.3	24.5
Gz + Aw	18.3	23.4	22.8	23.6	31.8	32.7	30.2	28.1	26.4
NTz + Gw	20.9	21.0	22.8	25.3	25.8	30.0	27.9	24.3	24.8
NTz + Aw	25.4	18.0	20.2	26.8	25.2	23.1	23.4	23.3	23.2
Mean	21.0	22.6	24.5	26.9	27.2	28.1	26.0	25.1	25.2
$LSD_{0.05}$ for:									
cover crop A									2.41
tillage B									1.96
A × B									6.89
year									1.13

Designations as in Tab. 2.

The highest leaf rosettes were produced by carrot in the treatments where rye or oats was used as the cover crops. Also the biomass of white mustard and vetch favorably influenced the growth of carrot leaves compared to cultivation without cover crop (control). Similar results were obtained by Kęsik et al. [28] after using phacelia and white mustard mulch. In contrast, onion formed the longest leaves after a rye cover crop, but the largest number of leaves was produced after a vetch cover crop [35]. The better growth of carrot leaf rosettes after using cover crops can be explained by their beneficial effects on soil moisture and structure [12,16,23,24,27]. In contrast, Olfati et al. [36] found no significant differences in carrot growth due to the mulch applied as compared to conventional tillage.

In the analyzed experiment, the effect of tillage on height of carrot leaves depended to a large extent on weather conditions in successive years of the study. In dry years, flat cultivation provided better water infiltration than cultivation on ridges, which contributed to the growth of leaves. This view is also shared by Adamicki et al. [37] and Babik et al. [38]. During the cultivation of radish 'Agata', the combination of flat cultivation with soil mulching appeared to be optimal for the growth, while the shortest leaf rosettes were produced by radish grown on ridges without any mulch [39].

In most cases, the use of cover crops (except buckwheat) reduced the foliage of carrots as compared to the cultivation without cover crop. In contrast, Golisz et al. [40] reported an inhibitory effect of buckwheat on lettuce growth and concluded that rutin, among other compounds tested, was the main determinant of this effect. As far as the interaction of experimental factors is concerned, the largest number of leaves was produced by carrots in the treatments where fodder sunflower biomass was incorporated into the soil in spring using a tillage implement. The beneficial effects of sunflower mulch can be attributed to the fact that, among the cover crop plants studied, sunflower produced the greatest biomass as well as it was an abundant source of K, Ca, and Mg [25]. Many authors indicate the allelopathic potential of sunflower towards weeds [20,41,42].

The use of cover crops significantly increased the mass of leaves produced by carrot as compared with cultivation without cover crop. Traditional plow tillage and pre-winter tillage using a stubble cultivator favored an increase in carrot leaf mass. It was also positively correlated with soil moisture. Carrot leaves, although not directly used by humans, are valuable feed for livestock, both in fresh and dried form [26]. Abundant foliage of plants, useful for photosynthesis, promotes an increase in carrot root yields. On the other hand, however, soil conditions that are unfavorable for root system development adversely affect the size and mass of the leaf rosette. This fact can explain the observed effect of the experimental factors on the leaf mass per plant.

Conclusions

Carrot emerged best after a rye or oats cover crop. Carrot emergence after the other cover crops was similar to that in the cultivation without any cover crop. Regardless of the cover crop species used, the largest number of carrots emerged in cultivation on ridges. In other variants of no-plow tillage, the number of seedlings was significantly lower and did not differ from that in traditional plow cultivation when deep plowing was done before winter.

The highest leaf rosettes were produced by carrots grown after the rye or oats cover crop as compared to the cultivation without cover crop. No-plow tillage had a positive impact on the growth of carrot leaf rosettes. The highest rosettes were produced by carrots in the treatments where tillage was limited to the use of a tillage implement in spring and the lowest ones after pre-winter plowing.

Among the tillage methods, only the use of a stubble cultivator in spring decreased the carrot foliage as compared with conventional tillage. Other methods of no-plow tillage did not negatively affect the number of leaves per rosette. Carrots produced the largest number of leaves after the sunflower cover crop and tillage using a tillage implement in spring, while the smallest one when the mustard biomass was incorporated into the soil in spring.

The use of cover crops (except rye) significantly increased the mass of leaves produced by carrot as compared to the cultivation without cover crop. The largest mass of leaves was produced by carrots grown after the phacelia and mustard cover crop. Conventional plow tillage and pre-winter tillage using a stubble cultivator favored an increase in the mass of carrot leaves, while the lowest mass of leaves was produced by carrots grown in the treatments where only a tillage implement was used in spring.

The effect of tillage on carrot emergence and height of carrot leaves depended largely on weather conditions in successive years of the study.

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Authors' contributions

The following declarations about authors' contributions to the research have been made: design of the experiments: MBW; performance of the experiments: MBW, DW, MK, MB, EP; analysis of the experimental data: MBW; writing the paper: MBW.

Competing interests

No competing interests have been declared.

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Wpływ roślin międzyplonowych na wschody i wzrost marchwi (*Daucus carota* L.) w uprawie bezorkowej i tradycyjnej

Streszczenie
Celem doświadczenia było określenie wpływu biomasy roślin międzyplonowych wprowadzonej do gleby w różnych terminach i przy zastosowaniu zróżnicowanych uprawek na wschody i wzrost marchwi. W badaniach

uwzględniono 7 gatunków miedzyplonów: *Secale cereale*, *Avena sativa*, *Vicia sativa*, *Sinapis alba*, *Phacelia tanacetifolia*, Fagopyrum esculentum, *Helianthus annuus*.

Marchew wschodziła najlepiej po międzyplonie z żyta lub owsa. Wschody marchwi po pozostałych międzyplonach były zbliżone do tych z uprawy bez międzyplonu. Niezależnie od rośliny międzyplonowej najwięcej marchwi wschodziło w uprawie na redlinach. W pozostałych wariantach uprawy bezorkowej liczba siewek była istotnie mniejsza i nie różniła się od tej z tradycyjnej uprawy płużnej. Najwyższe liście miała marchew po międzyplonie z żyta lub owsa. Najwyższe rozety formowała marchew, gdy uprawa roli ograniczyła się do zastosowania wiosną agregatu uprawowego, a najniższe – po orce przedzimowej. Wpływ uprawy roli na wschody i wysokość liści zależał w dużym stopniu od przebiegu pogody w kolejnych latach badań. Zastosowanie międzyplonów w większości przypadków zmniejszyło ulistnienie marchwi. Najwięcej liści oznaczono u marchwi rosnącej po gryce oraz w uprawie bez międzyplonu, a najmniej – po facelii i gorczycy białej. Najwięcej liści wytworzyła marchew po międzyplonie ze słonecznika i uprawie wiosennej agregatem zaś najmniej, gdy biomasę gorczycy wymieszano z glebą wiosną. Największą masę liści wytworzyła marchew uprawiana po facelii i gorczycy. Tradycyjna uprawa płużna oraz przedzimowa uprawa gruberem sprzyjały zwiększeniu masy liści marchwi natomiast najmniejszą masę liści uzyskano w obiektach uprawianych tylko wiosną agregatem.