

## THE EFFECT OF COVER CROPS ON SOIL MOISTURE IN PLOUGHLESS AND TRADITIONAL TILLAGE IN THE CULTIVATION OF CARROT

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### ABSTRACT

In a view of the predicted drought that has appeared in recent years and water shortage in the growing season, which is getting worse every year, the problem of water retention in the soil and increasing its humidity becomes of exceptional importance. The field experiment was carried out in 2009–2012 on grey brown podzolic soil developed from loess formations covering the cretaceous marls with a granulometric composition corresponding to medium dusty loam. The aim of the study was to assess the impact of various species of cover crops and the method and date of mixing their biomass with the soil on the soil moisture in ploughless carrot cultivation. The experimental design included seven cover crop species (spring rye, common oat, common vetch, white mustard, lacy phacelia, buckwheat, fodder sunflower) and six kinds of soil tillage. The effect of cover crops and tillage on soil moisture was modified by the course of the weather and varied depending on the year of research, sampling date and soil layer. In spring, the highest layer of soil (0–20 cm) not cultivated before winter (NTz) accumulated the most water, and the least after pre-winter ploughing (Oz). In the 0–40 cm layer, the lowest humidity was in the soil ploughed before winter (Oz), and the highest after no-till (NTz) and after subsoiling before winter (GLz). The ridge cultivation performed in the spring caused the soil to dry out. In the remaining variants of no-ploughing tillage, soil moisture in the 0–40 cm layer was similar to that of conventional cultivation. Cover crops exerted a significant influence on the soil moisture in carrot cultivation at all test dates, increasing its moisture content compared to cultivation without cover crops. The rye cover crop had particularly favourable effect on the soil moisture.

**Key words:** catch crops, *Secale*, *Avena*, *Fagopyrum*, *Helianthus*, *Phacelia*, *Daucus*

### INTRODUCTION

In a view of the predicted drought that has appeared in recent years and water shortage in the growing season, which is getting worse every year, the problem of water retention in the soil and increasing its humidity becomes of exceptional importance. Physical properties of the soil are the resultant of many biotic and abiotic factors, among which organic matter and cultivation procedures play an important role, which in various ways affect the changes taking place in the soil environment. Contemporary tillage

systems are increasingly abandoning the traditional plough tillage favouring cultivation simplification or no-till cultivation [Bartlová et al. 2015, Šimanský and Lukáč 2018]. This is especially true for organic farming. Among the disadvantages of plough cultivation, apart from high costs and energy consumption [Konopiński et al. 2014], there are mentioned: drying up of the topsoil, disturbance of nutrient circulation, reduction of geobiont population, destruction of natural protective layer of the soil, favouring water

and wind erosion [Czyż and Dexter 2008, Melero et al. 2011].

Sustainable agriculture, which is an alternative to the progressive degradation of the natural environment, considers the use of cover crops, which not only provide organic matter and nutrients [Gaskell and Smith 2007, Zaniewicz-Bajkowska et al. 2010, Lithourgidis et al. 2011, Błażewicz-Woźniak and Wach 2012, Bodner et al. 2015], but also protect the soil against erosion, improve water infiltration and retention, reduce water evaporation from the soil, significantly affect the soil fertility, its physical and chemical properties, and stabilise the soil structure [Kęsik et al. 2006, 2007, Villamil et al. 2006, Zhang et al. 2007, Bodner et al. 2008, Mulumba and Lal 2008, Gómez et al. 2009, Kęsik and Błażewicz-Woźniak 2010, Dexter and Czyż 2011, Błażewicz-Woźniak and Konopiński 2013, Błażewicz-Woźniak et al. 2019, Adetunji et al. 2020]. They modify the soil environment also in biological terms [Patkowska et al. 2016, 2018]. Mulching mimics the processes of decomposition of organic matter common in nature, where the dead plant mass covering the soil in the form of litter gradually decomposes on its surface. The effect of cover crops on soil properties varies depending on the way and date they are applied. Impact of the plant mass left on the soil surface in the form of mulch is different, whilst the effect is different when the biomass is mixed with the soil.

The aim of this study, which is part of a wider research, was to assess the impact of various species of cover crops and the method and date of mixing their biomass with the soil on the soil moisture in ploughless carrot cultivation. It was assumed that the biomass of catch crops, mixed with the top layer of soil before winter or in spring, will protect the soil against the destructive effects of external factors, and simultaneously, will have a positive effect on the properties of the catchment soil with unstable structure, including its moisture, while resigning from ploughing for the benefit of tillage applying a grubber, subsoiler or cultivator.

## MATERIAL AND METHODS

This study is part of a broader research, therefore the methodology was given according to Błażewicz-Woźniak et al. [2019]. The field experiment was

carried out in 2009–2012 at the Experimental Station Felin (ES Felin) belonging to University of Life Sciences in Lublin (Poland, 22°56'E, 51°23"N), on grey brown podzolic soil (AP) developed from loess formations covering the cretaceous marls with a granulometric composition corresponding to medium dusty loam (BN-178/9180-11). These soils are difficult to cultivation, are susceptible to rain thickening easily, and easy-crusting during drought periods. Before cover crops sowing, the soil contained 1.06–1.15% of humus in 0–20 cm layer and was characterized by slightly acidic reaction (pH in KCl 5.76–5.90). Soil fertility in available phosphorus, potassium, and magnesium was: P – 146.8; K – 111.5; Mg – 102.9 mg kg<sup>-1</sup> soil. The experiment was set up by means of completely randomized blocks in 4 replications. The area of single plot was 33 m<sup>2</sup>. 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 plough cultivation with a set of pre-winter measures (pre-winter ploughing 25–30 cm using mouldboard plough – Oz) and cultivation with aggregate (10–15 cm depth) in spring (cultivator + harrow + string roller) (Aw); 2. Sowing the cover crops, stubble grubber cultivator (25 cm depth) use before winter, cultivation aggregate in spring (10–15 cm depth), forming the ridges in spring (Gz + Aw + Rw); 3. Sowing the cover crops, subsoiling tillage (30 cm depth), cultivation aggregate in spring (cultivator + harrow + string roller) (GLz + Aw); 4. Sowing the cover crops, stubble grubber cultivator (25 cm depth) use before winter, cultivation aggregate (10–15 cm depth) in spring (Gz + Aw); 5. Sowing the cover crops, stubble grubber cultivator (25 cm depth) use in spring (NTz + Gw); 6. Sowing the cover crops, cultivation aggregate (10–15 cm depth) in spring (NTz + Aw). Cultivation without cover crops was the control. Sowing the cover crops was performed after the harvest of pre-crop, i.e. winter wheat. Directly after wheat harvesting, the disking was made, and then ploughing to the depth of about 15 cm with subsequent harrowing. Every year, the cover crops were sown on the same date, i.e. on August 1<sup>st</sup>. The sowing rates for cover crops 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<sup>-1</sup>. Before winter, grown mass of cover crops was mixed with top soil or left on the soil surface as a mulch, according to the experimental scheme. Mineral fertilization was applied in the spring in the following amounts of NPK – 150 : 50 : 160 kg ha<sup>-1</sup>. The experimental plant was carrot (*Daucus carota* L.) ‘Flakkee 2’ cv., that was sown every year on April 26<sup>th</sup> in rows (at 50 cm spacing). The carrot was harvested at the beginning of October.

Analyses of the physical properties of the soil in the 0–20 and 20–40 cm layers were carried out in 3 terms (beginning of April, beginning of June and end of September). The actual soil moisture was determined by the dryer-weight method in 100 cm<sup>3</sup> capacity cylinders. Achieved results were statistically processed using variance analysis (ANOVA). The difference significance was determined by means of Tukey test at  $P = 0.05$ .

## RESULTS AND DISCUSSION

Soil moisture in carrot cultivation varied depending on the year of research and the date of sampling (April, June, September). The observed significant impact of cover crops and tillage was largely modified by the growing season, which resulted from the course of the weather (Tab. 1). Differences in temperature and precipitation distribution not only changed the soil moisture, but also modified the bio-

mass of cover plants [Błażewicz-Woźniak and Wach 2012], which influenced the state of soil aggregation, its porosity [Błażewicz-Woźniak and Konopiński 2013] and moisture content.

In spring, before the pre-sowing tillage, the soil was the least wet in 2011 (17.8% on average) compared to the remaining years of the study (18.4%) – Table 2. In all years, the soil moisture after winter in the 0–20 cm layer was higher than in the 20–40 cm layer. Particularly much water in April was accumulated in the upper layer of the soil not cultivated before winter (NTz) – 18.8% on average, and the least after pre-winter ploughing (Oz) – 18.0%. Similar results were obtained by Konopiński et al. [2001], Kęsik et al. [2006], and Harasim et al. [2016].

Cover crops had significant impact on the soil moisture in April (Tab. 2). Regardless of the cultivation method, the most water in the 0–40 cm soil layer was accumulated in spring when rye or buckwheat was the cover crop (18.6% on average), and the least – after using mustard or vetch (17.9%). The upper soil layer after the rye cover crop was particularly abundant in water (on average 19.1%) – Table 3. The positive effect of the use of rye and vetch as cover crops on the water retention capacity of the soil was reported by Villamil et al. [2006]. Many authors note the beneficial effect of rye on the soil structure and water resistance of soil aggregates [Villamil et al. 2006, Kęsik et al. 2010, Steele et al. 2012].

Considering the interaction of the experimental factors for the period of three years, the highest

**Table 1.** Mean monthly air temperatures and amount of precipitation in ES Felin in years 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 1951–2005	7.4	13.0	16.2	17.8	17.1	12.6	7.8	
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 1951–2005	40.2	57.7	65.7	83.5	68.6	51.6	40.1	

**Table 2.** The effect of cover crops and tillage on soil moisture (%) in the cultivation of carrot in years 2010–2012

Factors	Depth (cm)	Soil moisture (%)															
		2010				2011				2012				mean			
		IV*	VI	IX	mean	IV*	VI	IX	mean	IV*	VI	IX	mean	IV*	VI	IX	mean
Control	0–20	17.5	16.4	18.2	17.4	19.1	11.7	8.7	13.2	18.6	15.5	5.2	13.1	18.4	14.6	10.7	14.5
	20–40	18.6	17.7	17.8	18.0	17.5	14.0	9.9	13.8	17.5	15.7	5.6	12.9	17.9	15.8	11.1	14.9
<i>Secale</i>	0–20	18.9	16.6	19.8	18.4	17.9	14.6	9.1	13.9	20.4	16.3	7.3	14.7	19.1	15.8	12.0	15.7
	20–40	17.6	18.4	18.4	18.1	18.1	15.3	9.9	14.4	18.9	17.2	8.5	14.9	18.2	17.0	12.3	15.8
<i>Avena</i>	0–20	17.9	16.6	19.9	18.1	17.5	13.8	9.0	13.4	19.3	15.6	6.8	13.9	18.3	15.3	11.9	15.2
	20–40	18.1	17.9	18.0	18.0	17.7	15.3	9.9	14.3	18.4	16.2	6.9	13.8	18.0	16.5	11.6	15.4
<i>Vicia</i>	0–20	17.7	16.0	18.9	17.5	17.5	13.8	8.6	13.3	19.3	15.7	7.5	14.2	18.2	15.2	11.7	15.0
	20–40	17.6	18.3	18.1	18.0	17.2	15.1	9.6	14.0	18.0	16.8	7.4	14.1	17.6	16.7	11.7	15.3
<i>Sinapis</i>	0–20	18.9	16.6	19.0	18.2	16.0	13.5	9.0	12.8	19.3	15.7	7.0	14.0	18.1	15.3	11.7	15.0
	20–40	18.3	17.8	18.2	18.1	17.1	15.3	10.3	14.2	17.9	16.1	7.6	13.9	17.8	16.4	12.0	15.4
<i>Phacelia</i>	0–20	18.6	16.6	19.0	18.1	17.8	12.4	9.4	13.2	18.3	15.4	6.6	13.4	18.2	14.8	11.6	14.9
	20–40	18.3	18.0	18.2	18.2	17.6	14.8	11.1	14.5	17.7	16.4	7.5	13.9	17.9	16.4	12.2	15.5
<i>Fagopyrum</i>	0–20	19.1	16.4	18.8	18.1	18.0	12.2	10.8	13.7	19.0	14.9	6.2	13.4	18.7	14.5	11.9	15.0
	20–40	19.0	19.1	18.9	19.0	18.1	14.7	12.0	14.9	18.2	16.2	6.9	13.8	18.5	16.7	12.6	15.9
<i>Helianthus</i>	0–20	18.6	16.5	18.4	17.8	19.6	12.0	9.8	13.8	17.4	14.6	5.3	12.4	18.5	14.4	11.2	14.7
	20–40	18.0	17.6	18.0	17.9	18.1	13.9	11.0	14.3	16.4	15.3	5.9	12.5	17.5	15.6	11.7	14.9
<b>Soil tillage</b>																	
Oz + AW	0–20	18.4	16.6	19.5	18.2	17.5	13.5	9.3	13.4	18.3	15.3	5.7	13.1	18.0	15.1	11.5	14.9
	20–40	18.0	18.2	18.4	18.2	17.7	15.6	10.8	14.7	17.0	15.9	6.6	13.2	17.6	16.6	11.9	15.4
Gz + Aw + Rw	0–20	18.5	16.8	18.3	17.9	17.8	9.6	7.5	11.6	18.5	13.9	7.8	13.4	18.3	13.4	11.2	14.3
	20–40	18.3	18.4	18.5	18.4	17.0	13.5	9.4	13.3	17.7	16.1	9.5	14.4	17.7	16.0	12.5	15.4
GLz + Aw	0–20	17.9	17.4	19.4	18.2	18.1	13.9	8.6	13.5	19.9	16.1	6.3	14.1	18.6	15.8	11.4	15.3
	20–40	18.4	19.2	18.2	18.6	17.9	15.4	9.6	14.3	18.5	16.6	6.5	13.9	18.3	17.1	11.4	15.6
Gz + Aw	0–20	18.5	16.5	19.0	18.0	17.8	13.9	9.6	13.8	18.5	15.8	6.0	13.4	18.3	15.4	11.6	15.1
	20–40	18.3	17.8	18.3	18.1	17.0	14.6	10.8	14.1	17.7	16.3	6.6	13.5	17.7	16.3	11.9	15.3
NTz + Gw	0–20	18.9	16.0	19.3	18.1	18.3	13.4	10.1	13.9	19.1	15.8	6.8	13.9	18.8	15.1	12.1	15.3
	20–40	18.1	17.4	18.2	17.9	18.1	14.9	10.9	14.6	18.3	15.9	6.3	13.5	18.1	16.1	11.8	15.3
NTz + Aw	0–20	18.9	15.6	18.5	17.7	18.3	13.7	10.5	14.2	19.1	15.9	6.2	13.7	18.8	15.0	11.8	15.2
	20–40	18.1	17.6	17.7	17.8	18.1	14.9	11.2	14.7	18.3	16.7	6.7	13.9	18.1	16.4	11.9	15.5
Mean	0–20	18.4	16.5	19.0	18.0	17.9	13.0	9.3	13.4	19.0	15.5	6.5	13.6	18.4	15.0	11.6	15.0
	20–40	18.2	18.1	18.2	18.2	17.6	14.8	10.5	14.3	17.9	16.2	7.0	13.7	17.9	16.4	11.9	15.4
	0–40	18.4	17.3	18.6	18.1	17.8	13.9	9.9	13.9	18.4	15.9	6.8	13.7	18.2	15.7	11.7	15.2
NIR <sub>0.05</sub> :	cover crop A	0.56	ns	0.98	0.529	0.83	0.94	0.63	0.529	0.90	0.78	0.87	0.529	0.51	0.50	0.44	0.261
	tillage B	ns	0.71	0.79	0.451	0.67	0.76	0.51	0.451	0.73	0.63	0.71	0.451	0.41	0.40	0.36	0.212
	depth C	0.18	0.27	0.31	0.212	0.26	0.29	0.19	0.212	0.28	0.24	0.27	0.212	0.16	0.16	0.14	0.084
	month D	–	–	–	0.284	–	–	–	0.284	–	–	–	0.284	–	–	–	0.123
	A × B	1.59	2.57	2.85	1.296	2.42	2.75	1.83	1.296	ns	2.28	2.56	1.296	1.49	1.45	1.28	0.748
	A × C	0.89	ns	1.59	0.748	1.34	1.53	ns	0.748	ns	1.27	ns	0.748	ns	0.81	0.72	0.418
	B × C	0.73	ns	1.30	0.648	ns	1.26	0.84	0.648	ns	1.04	1.17	0.648	ns	0.66	0.59	0.345
year	–	–	–	–	–	–	–	–	–	–	–	–	–	0.24	0.23	0.21	0.123

\* after pre-winter tillage, without pre-sowing tillage; ns – not significant

**Table 3.** The effect of cover crops and tillage on soil moisture (%) in the cultivation of carrot on average from years 2010–2012

Soil tillage	Depth (cm)	Soil moisture (%)																							
		cover crop																							
		control			<i>Secale</i>			<i>Avena</i>			<i>Vicia</i>			<i>Sinapis</i>			<i>Phacelia</i>			<i>Fagopyrum</i>			<i>Helianthus</i>		
IV*	VI	IX	IV	VI	IX	IV	VI	IX	IV	VI	IX	IV	VI	IX	IV	VI	IX	IV	VI	IX	IV	VI	IX		
Oz + Aw	0–20	19.1	14.9	10.7	17.5	16.0	11.5	17.6	15.3	12.1	16.8	15.7	10.8	17.3	15.5	11.5	17.7	14.7	11.2	19.5	14.5	12.3	18.8	14.6	12.0
	20–40	18.1	16.2	11.3	17.3	16.8	13.5	17.7	16.9	11.8	17.0	16.6	10.8	17.1	16.6	11.6	17.3	16.0	11.5	18.7	17.4	12.5	17.6	16.0	12.2
	0–40	18.6	15.5	11.0	17.4	16.4	12.5	17.7	16.1	11.9	16.9	16.2	10.8	17.2	16.0	11.6	17.5	15.4	11.3	19.1	15.9	12.4	18.2	15.3	12.1
Gz + Aw + Rw	0–20	17.4	12.1	10.2	19.4	15.0	11.7	18.0	14.6	11.4	18.6	14.4	11.3	18.3	14.2	11.4	18.5	12.6	11.7	18.2	12.7	11.4	18.0	11.8	10.6
	20–40	17.0	14.9	11.3	18.4	17.4	13.8	17.2	16.3	12.3	17.8	16.3	12.3	17.7	16.5	12.3	18.3	16.0	13.0	18.0	16.1	13.2	16.8	14.5	11.6
	0–40	17.2	13.5	10.7	18.9	16.2	12.7	17.6	15.4	11.9	18.2	15.4	11.8	18.0	15.4	11.9	18.4	14.3	12.3	18.1	14.4	12.3	17.4	13.1	11.1
GLz + Aw	0–20	19.1	16.1	11.1	19.9	16.6	12.1	18.5	16.0	12.6	18.7	15.6	11.1	18.1	15.7	11.1	18.1	15.9	11.0	18.4	15.0	11.5	18.4	15.3	10.8
	20–40	18.2	16.2	11.5	19.1	18.0	11.6	18.8	16.4	11.5	17.8	18.0	11.4	17.7	16.7	11.1	17.8	17.2	11.1	18.9	17.4	11.5	17.7	16.6	11.6
	0–40	18.7	16.2	11.3	19.5	17.3	11.8	18.6	16.2	12.1	18.3	16.8	11.2	17.9	16.2	11.1	17.9	16.6	11.0	18.7	16.2	11.5	18.1	15.9	11.2
Gz + Aw	0–20	17.4	15.0	10.5	19.4	15.9	12.7	18.0	15.3	11.8	18.6	14.7	11.2	18.3	15.5	11.5	18.5	16.0	12.1	18.2	15.2	12.2	18.0	15.6	10.8
	20–40	17.0	15.4	11.3	18.4	16.9	11.5	17.2	16.0	11.6	17.8	15.9	11.2	17.7	16.4	12.1	18.3	17.0	12.6	18.0	16.7	13.2	16.8	15.7	11.8
	0–40	17.2	15.2	10.9	18.9	16.4	12.1	17.6	15.7	11.7	18.2	15.3	11.2	18.0	15.9	11.8	18.4	16.5	12.4	18.1	16.0	12.7	17.4	15.6	11.3
NTz + Gw	0–20	18.1	14.5	10.8	19.3	16.0	13.0	18.9	15.3	11.7	18.6	15.3	12.7	18.6	15.6	12.6	18.7	14.6	12.8	18.7	14.7	12.0	19.0	14.5	11.0
	20–40	18.1	16.1	10.4	18.1	16.7	12.1	18.5	16.3	11.0	17.7	16.4	12.2	18.6	15.8	12.7	18.2	15.7	12.6	18.2	16.0	12.4	17.8	15.5	11.0
	0–40	18.1	15.3	10.6	18.7	16.3	12.6	18.7	15.8	11.4	18.2	15.8	12.5	18.6	15.7	12.7	18.4	15.1	12.7	18.4	15.4	12.2	18.4	15.0	11.0
NTz + Aw	0–20	18.1	14.7	11.0	19.3	15.7	11.3	18.9	15.5	11.9	18.6	15.2	13.0	18.6	15.2	12.0	18.7	14.8	11.1	18.7	14.9	12.1	19.0	14.4	11.6
	20–40	18.1	16.1	10.9	18.1	16.2	11.3	18.5	16.9	11.2	17.7	17.0	12.2	18.6	16.4	12.3	18.2	16.7	12.6	18.2	16.5	12.8	17.8	15.3	11.8
	0–40	18.1	15.4	10.9	18.7	15.9	11.3	18.7	16.2	11.6	18.2	16.1	12.6	18.6	15.8	12.2	18.4	15.7	11.9	18.4	15.7	12.4	18.4	14.8	11.7
Mean	0–20	18.4	14.6	10.7	19.1	15.8	12.0	18.3	15.3	11.9	18.2	15.2	11.7	18.1	15.3	11.7	18.2	14.8	11.6	18.7	14.5	11.9	18.5	14.4	11.2
	20–40	17.9	15.8	11.1	18.2	17.0	12.3	18.0	16.5	11.6	17.6	16.7	11.7	17.8	16.4	12.0	17.9	16.4	12.2	18.5	16.7	12.6	17.5	15.6	11.7
	0–40	18.2	15.2	10.9	18.6	16.4	12.2	18.1	15.9	11.7	17.9	15.9	11.7	17.9	15.8	11.9	18.1	15.6	11.9	18.6	15.6	12.3	18.0	15.0	11.4
NIR <sub>0.05</sub> :	A×B	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.49	1.45	1.28
	A×B×C	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2.10	2.05	1.82
	A×B×C×D	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	ns	ns	ns

\* after pre-winter tillage, without pre-sowing tillage; A – cover crop; B – soil tillage; C – depth; D – month; ns – not significant

soil moisture in spring was determined when the rye biomass was introduced into the soil with the use of a subsoiler (GLz) – on average 19.5%, and the lowest when the vetch biomass was mixed with the pre-winter ploughing soil (Oz) – 16.9% – Table 3. Deep soil penetration with a subsoiler in combination with large rye biomass [Błażewicz-Woźniak and Wach 2012] created good conditions for accumulation water in winter. However, in individual years of the study, there were discrepancies resulting not only from the course of the weather, but also from differences in the biomass of cover crops. In 2010, the use of cover crops significantly increased the soil moisture in the 0–20 cm layer compared to the cultivation without cover crops, where only 17.5% moisture was determined – Table 2. The highest humidity of this soil layer was recorded when the cover crops were buckwheat, rye or mustard (from 18.9 to 19.1%). In the 20–40 cm layer, the effect of cover crops was not so significant. On average, for the entire layer of 0–40 cm, the highest soil moisture in April was determined when the cover crop was buckwheat (average 19.0%), as well as mustard or phacelia, and the lowest when vetch was used (17.7%) as well as in cultivation without cover crops (18.1%). After using mustard and phacelia cover crops, Błażewicz-Woźniak and Konopiński [2013] noted a significant increase in total soil porosity compared to the cultivation without the cover crop. The lack of mulching effect with vetch in 2010 can be explained by the small amount of produced biomass [Błażewicz-Woźniak and Wach 2012]. The data of Kálmar et al. [2013] on different degrees of coverage clearly indicate that evaporation reduction requires minimum coverage of >50%. In spring 2010, the highest humidity was recorded in objects not cultivated before winter (NTz) – 18.9%.

In the spring of 2011, the topsoil contained more water than 20–40 cm layer, the difference being the greatest after pre-winter cultivation with grubber (Gz), while after pre-winter ploughing (Oz), in the 0–20 cm layer, slightly less water was determined than in the layer of 20–40 cm – Table 2. The highest actual soil moisture in April 2011 was determined when the cover crop was sunflower (18.8% on average, and 19.6% in the 0–20 cm layer). In the 20–40 cm layer, the effect of cover crops on soil moisture was not so visible. The soil was characterised by the lowest humidity when the cover crop was white mustard (average

16.5%). That year, the soil contained the most water when the cultivation before winter was not performed (NTz). The top (0–20 cm) layer of uncultivated soil collected an average of 18.3% of water during this time. The lowest humidity was determined in the soil cultivated before winter with grubber (Gz) – on average 17.4%.

In spring 2012, the effect of cover crops on soil moisture was different than in 2011 (Tab. 2). The highest humidity was determined when the cover crop was rye (19.7%) and the lowest when sunflower was growing there (16.9%). The highest amount of water was contained in the soil cultivated before winter with subsoiler (GLz) – on average 19.2%, and the least – ploughed before winter (Oz) – on average 17.7%. The 20–40 cm soil layer after pre-winter ploughing accumulated only 17.0% of water on average. In the studies by Kęsik et al. [2007] in spring, before the commencement of field tillage, soil layer moisture 0–20 cm was higher in plots with no tillage before winter under spring rye or vetch mulch than after traditional tillage with pre-winter ploughing. Bodner et al. [2008] found that cover crops stabilised effective pore properties over winter on a silt loam soil in semi-arid Eastern Austria.

The soil moisture in carrot cultivation in June decreased compared to the spring condition – Table 2. The highest humidity was recorded in 2010 (17.3% on average), and the lowest in 2011 (13.9%). Contrary to the spring period, the topsoil layer (0–20 cm) was drier than 20–40 cm one. On average, for the period of three years, the greatest amount of water was accumulated by the soil when the cover crop was rye (16.4% on average), and the least when the sunflower was used (15.0%) and in the cultivation without cover crop (control) (15.2%) – Table 3. In tropical conditions, Ramakrishna et al. [2006] found even 22% more moisture in the soil covered with plant litter, and Zaongo et al. [1997] reported a 28% reduction in evaporation. Similar results were obtained by Balwinder-Singh et al. [2011]. In the studies by Konopiński et al. [2001], the positive effect of cover crops on soil moisture and soil water supply was maintained during the vegetable vegetation period and disappeared only during the harvest.

Cultivation on ridges, commonly used in the cultivation of carrot (Gz + Aw + Rw), which was performed in spring, caused the soil to dry out (Tab. 2).



In June, the soil layer of 0–20 cm contained particularly little water in the ridges (average 13.4%). The highest soil moisture in the 0–40 cm layer was determined in the GLz + Aw combination (average 16.4%), which resulted from the higher moisture content of the 20–40 cm layer (17.1%). In the remaining variants of no-ploughing tillage, soil moisture in the 0–40 cm layer was similar to that of conventional tillage (Oz + Aw). The use of cover crops (except sunflower) increased the soil moisture even in cultivation on ridges (Tab. 3). Lampurlanés and Cantero-Martínez [2006] showed in Mediterranean climate that higher water content in soil with no-till compared to conventional tillage resulted from a higher residue cover. Mrabet et al. [2003] reported a 10% higher water accumulation during the summer period when the soil was covered with a layer of mulch compared to the cultivation without a cover.

In June 2010, the influence of cover crops on its moisture content was not so visible as in April (Tab. 2). The soil mixed with buckwheat or rye biomass was still more moist, but these differences were not statistically significant. Significantly the highest humidity in June 2010 was characteristic for the soil after cultivation before winter with a subsoiler (GLz + Aw) (18.3% on average) and the lowest when the soil was cultivated only in spring with a cultivator (Aw) (16.6%) or a grubber (Gw) (16.7%), where the top layer of soil was the driest. After the pre-winter cultivation with the subsoiler, both soil layers accumulated more water (17.4% and 19.2%, respectively) than after other treatments.

In June 2011, the soil moisture was much lower than in the early spring period and averaged to 13.9% (Tab. 2). The highest soil moisture in this period was provided by the rye cover crop, while the lowest was determined in the soil from the control plots (without the cover crop) and after the sunflower cover crop. The implementation of spring tillage changed the impact of sunflower cover crops on the soil moisture in comparison to the previous period and reduced its moisture content. The soil in the ridges formed in spring was the driest (11.6% on average), and the remaining methods of no-ploughing cultivation ensured the soil moisture similar to that after pre-winter ploughing (Oz + Aw). The upper soil layer in the ridges was particularly dry, where the humidity in cultivation without cover crops

was only 7.2%. Also, Verhulst et al. [2011], comparing no-till cultivation with traditional cultivation, noted a higher water content in soil under residue covered treatments, especially in the dry season.

In June 2012, as in the previous years, the highest water content was found in the soil after the rye cover crop (16.8% on average) and the least after sunflower (15.0%) – Table 2. The soil in the ridges was the driest (15.0% on average), while the cultivation with a subsoiler (GLz + Aw) and the limitation of cultivation to the application of a tilling set in spring (Aw) significantly increased the soil moisture not only in comparison with cultivation in ridges, but also with traditional tillage (Oz + Aw). The pre-winter use of stubble cultivator provided the largest amount of mesopores, when compared with other non-ploughing methods of cultivation [Błażewicz-Woźniak and Konopiński 2013]. The smallest amount of mesopores was found in ridged soil. The least amount of water was recorded in the soil in the ridges without the use of cover crops (14.2% on average), and in the 0–20 cm layer – only 12.8%.

In September, the highest soil moisture was determined in 2010 (18.6% on average) and the lowest in 2012 (6.8%). The soil layer of 0–20 cm was drier than 20–40 cm (Tab. 2). This relationship was recorded in 2011 and 2012, while in 2010 the situation was reversed. Cover crops had a significant effect on the soil moisture in carrot cultivation in September, increasing its moisture content compared to cultivation without cover crops. On average, for the period of three years, the most water was accumulated in autumn when the cover crop was buckwheat (12.3% on average) and rye (12.2%), and the least in the cultivation without cover crop (control; 10.9%) – Tab. 3. After the application of these cover crops, more water was determined in both the upper (11.9–12.0%) and lower layers of the soil (12.3–12.6%). The driest soil layer in September was 0–20 cm in cultivation without cover crop (10.7% on average). These relationships also occurred in 2010 and 2012, while in 2011 the highest soil moisture in autumn was provided by the cover crops of buckwheat (average 11.4%), sunflower and phacelia, and the lowest when the cover crop consisted of vetch (9.1%) and when no cover crops were used (9.3%). Kálmar et al. [2013] measured 8–11% higher soil water content in 0–65 cm soil depth for undisturbed mulch covered soil

with 55–65% coverage compared to a conventionally tilled soil without mulch cover. Similar results were obtained by Kęsik et al. [2007] in the cultivation of onion.

The method of tillage significantly modified the soil moisture in September (Tab. 2). On average, for the period of three years, the most water in autumn was found in soil cultivated with grubber in spring (NTz + Gw), and the least after pre-winter cultivation with subsoiler (GLz + Aw). The soil layer of 0–20 cm was the driest in the cultivation in the ridges (Gz + Aw + Rw), but more water was accumulated in the 20–40 cm soil layer. Cultivation treatments affect the soil moisture by modifying, among others, geometry and size of pores in the soil profile. Numerous works confirmed general trend of decreasing the macropore and increasing storage pore volume in conservation tillage systems and the use of cover crops [Błażewicz-Woźniak et al. 2001, Bodner et al. 2015]. The course of the weather, the size and composition of biomass of cover plants, activity of soil microflora, etc. affect the stability of soil aggregates and soil structure [Czyż and Dexter 2008, Kęsik et al. 2010, Błażewicz-Woźniak and Konopiński 2013, Patkowska et al. 2016]. Hence, the influence of cultivation on the soil moisture was different in particular years of the study and changed during the growing season (Tab. 2). In September 2010, the most water in the 0–40 cm layer of soil was determined after pre-winter ploughing (Oz + Aw), and the least after spring cultivation with soil aggregate without pre-winter cultivation (NTz + Aw). In 2011, in this combination of cultivation (NTz + Aw), the highest soil moisture was determined, and soil in the ridges was the driest (Gz + Aw + Rw), especially in their upper layer (7.5%), while in September 2012, the ridges contained the most water (especially in the 20–40 cm layer), and the least water was found after pre-winter ploughing.

## CONCLUSIONS

1. The effect of cover crops and tillage on soil moisture in carrot cultivation was modified by the course of the weather and varied depending on the year of research, sampling date and soil layer.

2. In spring, the highest layer of soil (0–20 cm) not cultivated before winter (NTz) accumulated the most water, and the least after pre-winter ploughing (Oz).

In the 0–40 cm layer, the lowest humidity was in the soil ploughed before winter (Oz), and the highest after no-till (NTz) and after subsoiling before winter (GLz).

3. The ridge cultivation performed in the spring caused the soil to dry out. In the remaining variants of no-ploughing tillage, soil moisture in the 0–40 cm layer was similar to that of conventional cultivation (Oz + Aw).

4. Cover crops exerted a significant influence on the soil moisture in carrot cultivation at all test dates, increasing its moisture content compared to cultivation without cover crops. The rye cover crop had particularly favourable effect on the soil moisture.

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