ACTA Acta Sci. Pol. Hortorum Cultus, 21(2) 2022, 3–17

https://czasopisma.up.lublin.pl/index.php/asphc ISSN 1644-0692 e-ISSN 2545-1405 https://doi.org/10.24326/asphc.2022.2.1

ORIGINAL PAPER

Accepted: 29.07.2021

EFFECTS OF DIFFERENT FARMING SYSTEMS AND CROP PROTECTION STRATEGIES ON THE HEALTH STATUS AND YIELD OF CARROTS *Daucus carota* L. ssp. *sativus*

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ABSTRACT

The aim of this study was to evaluate the effects of farming systems on the health status of carrots cv. Koral and root yield components. The organic farming system promoted the spread of damping-off of seedlings in the first two wet growing seasons and Alternaria leaf blight in the last growing season with normal precipitation levels. At harvest, the severity of root diseases was low. During storage, carrot roots were susceptible to soft rot, Sclerotinia rot and dry rot. In the integrated farming system, the symptoms of mixed rot were more observed at harvest and after storage, and of dry rot after storage. In the organic farming system, the symptoms of dry rot were more noted at harvest, and the symptoms of crater rot were more observed after storage. During storage, the applied crop protection methods significantly suppressed mixed rot in the integrated farming system, and dry rot in the organic system. The isolation of potential pathogens from carrot petioles and roots confirmed their participation in the disease process. Negative correlations were found between the severity of Alternaria leaf blight vs. the marketable yield of carrots and single root weight in both production systems in selected years of the study.

Key words: *Daucus carota* L., integrated farming system, organic farming system, diseases, fungal pathogens, yield

INTRODUCTION

Consumers have a growing interest in healthy crops with high nutritional value. As a result, various efforts are being made by agricultural and horticultural producers to minimize the accumulation of toxic chemical residues in edible plant parts. This goal can be achieved by replacing mineral fertilizers with organic fertilizers, and by minimizing the use of pesticides through the application of biocontrol methods [Jayaraj et al. 2008, Patkowska and Błażewicz-Woźniak 2014, Shin et al. 2017, Jamiołkowska 2020]. The carrot is a root vegetable that can be stored for many months, and fresh carrots are available around the year. Carrots can be processed in a variety of ways, which contributes to their popularity. In Poland, the average per capita consumption of vegetables reaches 47.5 kg per year, and carrot consumption is estimated at 6 kg per year [Statistics Poland 2018]. Organic carrots contained less nitrates and only trace amounts of pesticides [Bender et al. 2009], compared with conventionally grown carrots. They were also more abundant in phenolic compounds than carrots grown in integrated farming systems [Cwalina-Ambroziak et al. 2014].

Infections and diseases decrease the quantity and quality of crop yields and lead to considerable eco-

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nomic losses. Microorganisms, in particular fungi, pose a threat to field-grown carrots and stored roots. The above-ground parts of carrots are infected by *Alternaria dauci* (Kühn) Groves & Skolko, *A. radicina* Meier, Drechsler & Eddy, *Botrytis cinerea* Pers., and *Cercospora carotae* /Pass./ Kazn. and Siemaszko pathogens which are ubiquitous in seeds, soil, weeds and stored roots [Pryor et al. 2002, Farrar et al. 2004, Irzykowska et al. 2007]. Carrots can be effectively protected against dangerous leaf pathogens through the use of adequate agronomic practices and alternative biological protection methods [Töfoli et al. 2019] involving seaweed extracts with antifungal properties [Jayaraj et al. 2008, Khallil et al. 2015], and effective microorganisms (EM) that improve the physicochemical properties and the biological activity of soil [Shin et al. 2017].

Root-rot diseases caused by *Pectobacterium carotovorum* subsp. *carotovorum*, *Streptomyces scabies* (Thaxt.) Lambert & Loria, *Sclerotinia sclerotiorum* (Lib.) De Bary, *Fusarium* spp., *A. radicina*, *Rhizoctonia carotae* Rader, *Rhizoctonia solani* Kühn, *Thielaviopsis basicola* (Berk. & Broome) Ferraris, and *Phoma rostrupii* Sacc. affect stored carrots and pose a significant risk for consumer health [Snowden 1992, Farrar et al. 2004, Mazur and Nawrocki 2007, Lerat et al. 2009]. Antagonistic microorganisms (*Propionibacterium freudenreichii* ssp. *shermanii*, *Bacillus coagulans*, *B. circulans, Pseudomonas* spp., *Pythium oligandrum*, *Gliocladium* spp., *Penicillium* spp., *Trichoderma* spp.) effectively prevent microbiological damage to carrot roots [Patkowska and Błażewicz-Woźniak 2014]. In a study by Pershakova et al. [2018], the application of *Bacillus subtilis* IMP 215 bacterial strain inhibited the growth of *A. radicina* on carrot roots. Asahi SL, Bio-Algeen 90, Kelpak SL and Tytanit biostimulants increased the marketable yield of carrots [Kwiatkowski et al. 2013, Szczepanek et al. 2015].

The aim of this study was to determine the effects of different farming systems on the health status of carrots cv. Koral and selected root yield components.

MATERIALS AND METHODS

Location of the experiment, methodological assumptions. A small-area plot experiment was conducted in 2010–2012, in integrated and organic farming systems, in the Agricultural Experiment Station in Bałcyny near Ostróda, owned by the University of Warmia and Mazury in Olsztyn. The experiment was established on proper lessive soil of good quality [IUSS Working Group WRB 2015]. During the experimental period, a topsoil layer of 0–20 cm was characterized by a slightly acidic to acidic pH_{KCl} of 5.3–5.7, high potassium content (19 mg K 100 g^{-1} on average), a moderate content of phosphorus (9 mg P 100 g^{-1} on average) and magnesium (7.5 mg Mg 100 g^{-1} on average), organic carbon content of approximately 0.9 g 100 g^{-1}, total nitrogen content of approximately 98 mg 100 g^{-1} (mean values for soil samples collected in accordance with the relevant standards in both farming systems; soil anylyzes were carried out annually in Chemical and Agricultural Station in Olsztyn.

Carrots were grown in accordance with the recommendations for integrated and organic farming systems. In both production systems, cereals (winter wheat, winter rye, winter triticale) were the preceding crop. Certified carrot seeds of the late cv. Koral were sown on 26–28 April at a rate of 4000 seeds ha^{-1} (flat cultivation, row spacing of 40 cm). All agronomic practices were consistent with the recommendations of the Institute of Horticulture in Skierniewice. Weeds were controlled mechanically and manually. In the integrated farming system, fertilizer rates were determined based on soil nutrient content and the nutrient requirements of carrots: pre-sowing application of 70 kg N ha^{-1} (ammonium nitrate, 34% N), 35 kg P ha^{-1} (superphosphate, 40% P_2O_5) and 140 kg K ha^{-1} (potassium salt, 60% K_2O); top dressing with 50 kg N ha^{-1} (ammonium nitrate, 34% N). In the organic farming system, carrots were grown in a field site that had been cultivated organically for 3 years, in the third year after manure application. Biological, biotechnological and chemical control agents were applied after the first disease symptoms had been observed, in accordance with the recommendations of the Institute of Plant Protection-National Research Institute in Poznań: EM-1 (lactic acid bacteria, yeasts and phototrophic bacteria); Grevit 200 SL (1.5 dm^{-3} ha^{-1},0.2% application rate, 33% grapefruit extract); Asahi SL (0.5 dm^{-3} ha^{-1}, 0.1% application rate, sodium o-nitrophenol, sodium p-nitrophenol, sodium 5-nitroguaiacol); seed dressing with Zaprawa nasiennaT 75 DS/DW (5g kg^{-1} seeds, 75% thiram); Bravo 500 SC (2,5 dm^{-3} ha^{-1} application dose, 40.65% chlorothalonil); Tiotar 800 SC (2 dm^{-3} ha^{-1} application dose, 80% sulfur). Both farming systems involved four treatments with crop protection agents and one control (unprotected) treatment. Each treatment consisted of four plots (four replicates) with an area of 8 m^2 (harvest area of 7.2 m^2). The experiment had a randomized block design.

Treatments in the integrated farming system (Int):

I Int – no plant protection

II Int – EM-1/soil application before sowing; Grevit 200 SL/seed dressing; Grevit 200 SL/3 × spray, every 7–10 days in August

III Int – seed dressing T; Grevit 200 SL/3 × spray, every 7–10 days in August

IV Int – seed dressing T; Asahi SL/spray, the third ten days of July; alternately Bravo 500 SC/2 × spray and Tiotar 800 SC/spray, every 10–14 days from the first ten days of August to the end of the first ten days of September

V Int – EM-1/seed dressing; Asahi SL/spray, the third ten days of July; alternately Grevit 200 SL/2 × spray and Bravo 500 SC/spray, every 10–14 days from the first ten days of August to the end of the first ten days of September

Treatments in the organic farming system (Org):

I Org – no plant protection

II Org – EM-1/soil application before sowing; Grevit 200 SL/seed dressing; Grevit 200 SL/3 × spray, every 7–10 days in August

III Org – Grevit 200 SL/seed dressing; Grevit 200 SL/3 × spray, every 7–10 days in August

IV Org – Grevit 200 SL/seed dressing; Asahi SL/spray, the third ten days of July; alternately Grevit 200 SL/2 × spray and Tiotar 800 SC/spray, every 7–10 days in August

V Org – EM-1/seed dressing; Asahi SL/spray; alternately Grevit 200 SL/2 × spray and Tiotar 800 SC/spray, every 7–10 days in August.

The experiment was conducted under natural infection conditions, and weather data were recorded. Roots were harvested on 28–30 September.

Severity of selected carrot diseases and root yield components. The severity of damping-off was estimated on 25 seedlings, diagonally through the plot, using a three-point scale: 0° – absence of disease symptoms, 1° – weak disease symptoms, 2° – moderate disease symptoms, 3° – severe disease symptoms. In the middle of the growing season, the severity of Alternaria leaf blight (*Alternaria dauci* /Kühn/ Groves & Skolko, *A. radicina* Meier, Drechsler & Eddy) and Cercospora leaf spot (*Cercospora carotae* /Pass./ Kazn. & Siemaszko) was evaluated twice on 25 carrot plants in each of the four plots per treatment (the severity of both diseases was estimated at the same time because their symptoms are difficult to differentiate under field conditions) with the use of a 9-point scale [Pawelec et al. 2006] where 0° – no disease symptoms, 9° – severe defoliation. The results were expressed as the infestation index (%), according to the formula:

$$\text{Infestation index Ii} = \frac{\Sigma(a \cdot b)}{N \cdot I} \cdot 100\%$$

where: (a · b) – sum of the products of the number of the analyzed plants (a) and their severity scores (b), N – total number of the analyzed plants, I – the highest severity score.

The roots harvested from each plot were weighed to determine single root weight (g), total root yield per plot (kg), marketable yield (weight of healthy roots with no signs of damage, decay or skin cracks; root size has not been determined – UN/ECE Standard FFV-10, kg) and the percentage of marketable yield in total yield. The results were expressed as mean values for four plots per treatment; the yield was converted to t ha^{-1}.

Severity of carrot root diseases. The severity of carrot root diseases was estimated at harvest and after five months of storage. The severity of soft rot (*Pectobacterium carotovorum* subsp. *carotovorum* Hauben) and Sclerotinia rot (*Sclerotinia sclerotiorum* (Lib.) de Bary) (combined analysis), and dry rot (*Fusarium* spp.) was evaluated as a percentage of infected roots on 5 kg root samples collected randomly in each of the four plots per treatment. The severity of common scab (*Streptomyces scabies* (Thaxter) Waksman et Henrici), crater rot (*Rhizoctonia carotae* Rader, *Rhizoctonia solani* Kühn) and black rot (*Alternaria radicina* Meier, Drechsler & Eddy, *A. dauci* /Kühn/ Groves & Skolko) was evaluated on samples of 50 roots collected randomly, as described above (Phot. 3–8). The severity of common scab was estimated on a nine-point scale (1° – absence of disease symptoms, 9° – more than 50% of infected root area). The severity of crater rot was also estimated on a nine-point scale (1° – absence of disease symptoms, 9° – more than 25% of infected root area). The severity of black rot was evaluated on a four-point scale (1° –black lesions without root narrowing, 4° – black lesions with root narrowing >50% at discolored sites). The results were expressed as the infestation index (%).

Isolation of fungi from carrot petioles and roots. During the growing season, after the last evaluation of the health status of carrots, petioles were collected randomly (a pooled sample of 30 petioles per treatment), and were cut into 1 cm segments. At harvest and after five months of storage, 30 roots were collected randomly (a pooled sample per treatment) and rinsed with water. Cubes of carrot core with skin, measuring 0.5 × 0.5 × 0.5 cm, were cut out from roots. The cubes were disinfected with 50% ethanol and 0.1% sodium hypochlorite for 30 sec, they were rinsed three times with sterile water, dried on filter paper, and cultured on the potato-dextrose-agar (PDA) medium.

Weather conditions (monitored by the Weather Station in Bałcyny) during the experiment are presented in Table 1. The mean temperature in May – September was around 16°C, i.e. higher than the long-term average (except for September in all years of the study). July and August were particularly warm. The growing seasons of 2010–2012 were characterized by abundant rainfall, and total precipitation levels exceed the long-term average by 36%, 30% and 9%, respectively. The following months were particularly wet: May of 2010, June of 2012, July of 2011 and 2012. During the summer season, below-average precipitation was noted only in June of 2011 and August of 2012.

Statistical analysis. The results were processed statistically by analysis of variance (ANOVA), using the STATISTICA 13.1® software package. Differences between mean values were determined by Tukey's test at a significance level of $P < 0.05$. The relationships between the severity of Alternaria leaf blight (infestation index, %), marketable yield and root weight were determined by linear regression analysis. Coefficients of linear correlation (Pearson's r) were calculated.

RESULTS AND DISCUSSION

In both integrated and organic farming systems, the symptoms of damping-off of carrot seedlings were observed more frequently in the first two years of the study, compared with the last year. The highest value of the infestation index (approx. 20%) was noted in treatment II Org (soil application of EM and seed dressing with Grevit 200 SL) and in unprotected plots in the integrated farming system in 2011 (significant differences relative to the remaining treatments) (Fig. 1). In the analyzed period, infection rates were lowest on carrot seedlings in treatments III Int and IV Int (chlorothalonil), and in treatments III Org and IV Org (seed dressing with Grevit 200 SL). Carrot seedlings were the healthiest in the last year of the study. *Alternaria radicina* is the main fungal pathogen responsible for root-rot of carrot seedlings [Pryor and Strandberg 2002]. *Alternaria* spp. pose a serious threat in organic farms where chemical seed dressing is not allowed [Köhl et al. 2004]. Dorna et al. [2018] demonstrated that grapefruit extract used as an alternative method of seed disinfection effectively suppressed infections caused by *A. alternata* and *A. radicina*. In an *in vitro* study by Singh and Singh [2006], chlorothalonil, copper oxychloride, azoxystrobin, propineb, copper hydroxide and mancozeb significantly reduced the radial growth of *A. alternata*.

The most severe symptoms of Alternaria leaf blight (infestation index of approx. 50%) were observed in the warm growing season of 2012, with normal precipitation levels, in treatments II Org (soil application of EM, seed dressing and three sprays with Grevit 200 SL) and III Org (seed dressing and three sprays with Grevit 200 SL) (Tab. 2). The lowest infestation index of 17% was noted in 2011 in the integrated farming system, in treatments with fungicides (seed dressing T, sprays with Bravo 500 SC and Tiotar 800 SC) and the Asahi SL biostimulant – III Int, IV Int and V Int. Throughout the experiment, lower infection rates were observed in the integrated framing system than in the organic system, with significant differences between means. Disease severity decreased in response to the applied protective measures in the first two years of the study, but the differences between treatments were not significant. *Alternaria* spp. predominated in the fungal community isolated from carrot petioles (Tab. 3, Fig. 2), and they were most frequently encountered in unprotected treatments in both production systems (55.3–63.2% of all isolates). However, a significantly smaller infestation of carrot petioles

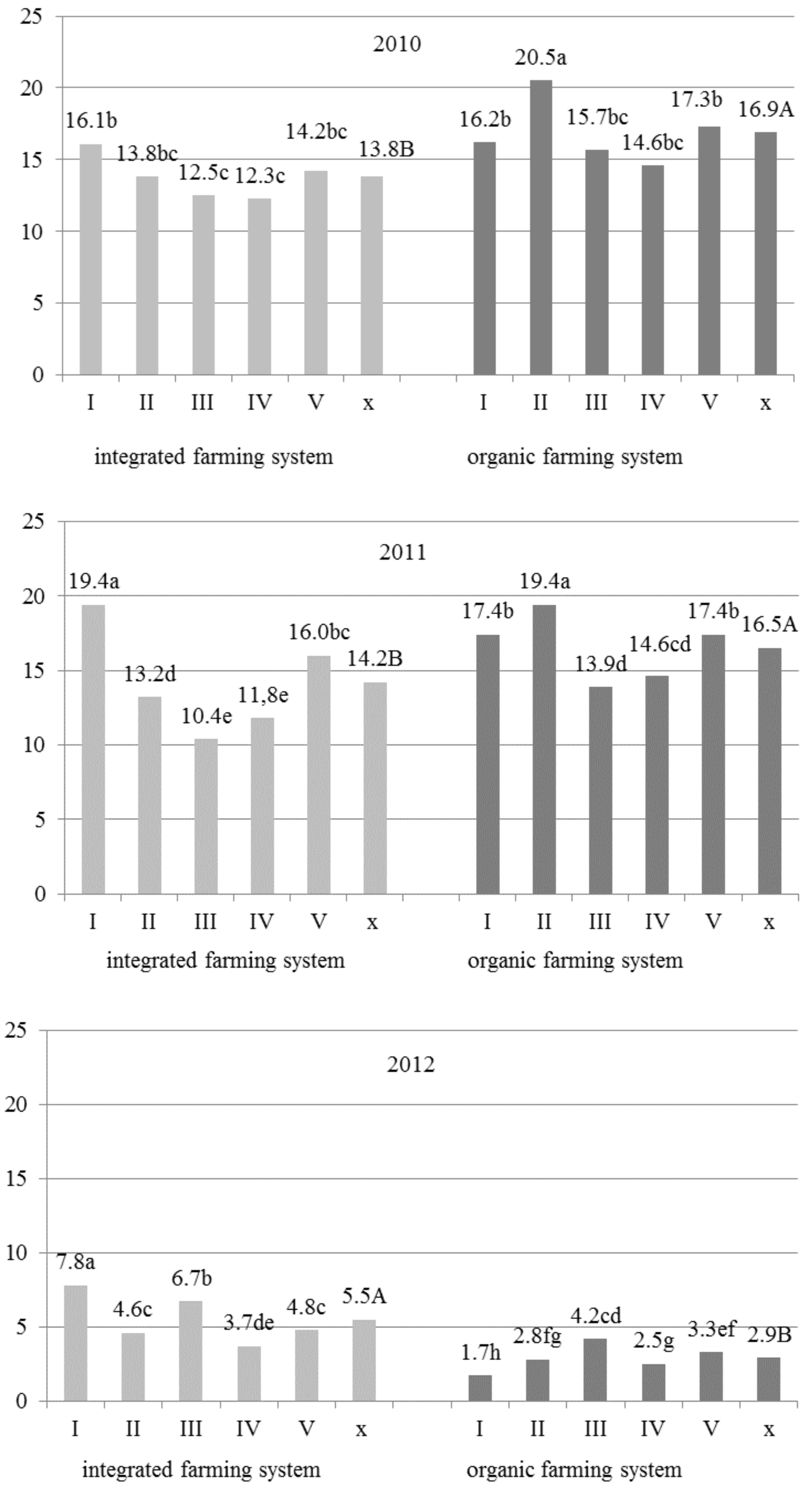


Fig. 1. Damping-off of carrot seedlings, infestation index Ii (%). Means followed by the same letters do not differ significantly at $p < 0.05$, statistics within year

Table 1. Weather conditions monitored by the Weather Station in Bałcyny

Month	Temperature (°C)				Rainfall (mm)			
	2010	2011	2012	1961–1995	2010	2011	2012	1961–1995
May	12.0	13.6	13.9	12.4	105.5	41.5	42.5	56.7
June	15.7	17.5	15.2	15.7	73.7	56.2	107.2	68.3
July	20.8	18.0	19.0	15.3	87.8	171.9	112.2	81.3
August	19.3	18.1	17.9	17.9	99.3	83.6	25.7	78.1
September	12.2	14.6	14.0	17.9	45.0	38.9	41.0	17.9
Mean/Total	16.0	16.4	16.0	15.8	411.3	392.1	328.6	302.3

Table 2. Health status of carrot leaves (*Alternaria* spp., *Cercospora carotae*, infestation index Ii, %)

Treatment	2010	2011	2012	Mean
I Int	30.7 abc	23.9 abc	36.6 abc	30.4 a
II Int	23.2 abc	20.1 bc	38.3 abc	27.2 a
III Int	22.2 abc	17.8 c	32.1 abc	24.0 a
IV Int	19.8 bc	16.4 c	30.4 abc	22.2 a
V Int	20.4 bc	16.9 c	31.4 abc	22.9 a
Mean	23.2 bc	19.0 c	33.7 ab	25.3 A
I Org	39.3 abc	26.5 abc	41.2 abc	35.7 a
II Org	32.6 abc	23.1 abc	46.6 ab	34.1 a
III Org	26.0 abc	20.2 bc	49.7 a	32.0 a
IV Org	29.3 abc	22.7 abc	36.6 abc	29.5 a
V Org	31.7 abc	23.3 abc	38.4 abc	31.1 a
Mean	31.8 ab	23.1 bc	42.4 a	32.5 B

Statistics for 2010–2012; values followed by the same letters do not differ significantly at $P \leq 0.05$
Int – integrated farming system; Org – organic farming system

Table 3. Pathogens isolated from carrot petioles (2010–2012, % of all isolates)

Species	Integrated farming system					Organic farming system				
	I	II	III	IV	V	I	II	III	IV	V
Alternaria alternata (Fr.) Keissler	42.7	36.7	19.8	18.3	19.6	36.2	31.5	30.8	14.2	18.4
A. dauci (J.G. Kühn) Groves & Skolko	20.5	9.2	19.8	8.7	19.6	19.1	15.3	9.2	16.5	10.6
A. radicina Meier, Drechsler & E.D. Eddy		4.1	3.0	2.9	11.6			5.0	1.6	4.3
Fusarium spp.	15.4	14.3	13.9	10.6	9.8	13.8	35.1	21.7	25.2	35.5
Rhizoctonia spp.		2.0	1.0				1.8		3.9	2.1
Total (No.)	117	98	101	104	112	94	111	120	127	141

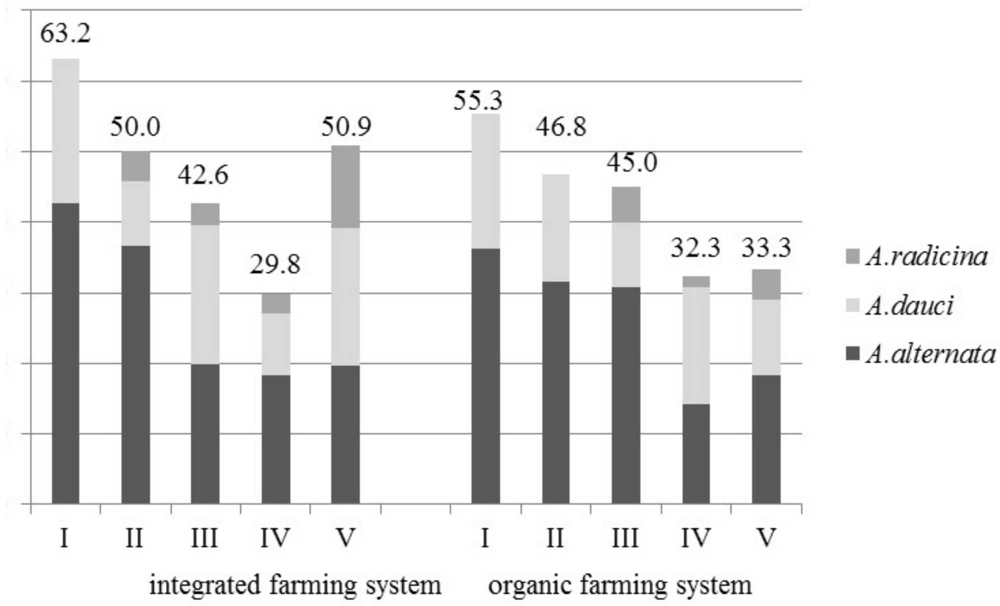
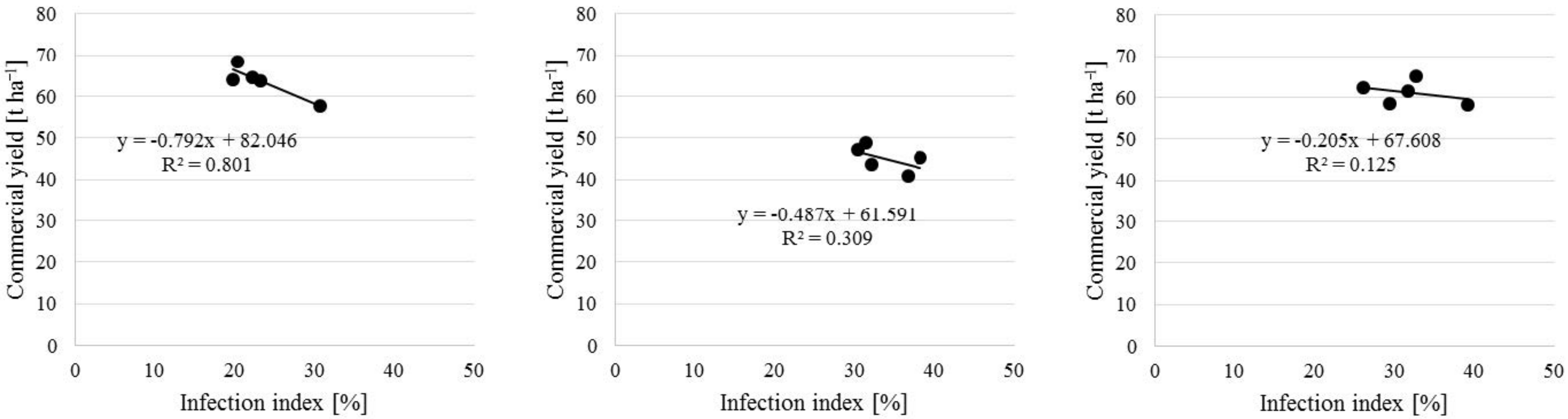


Fig. 2. Species of the genus *Alternaria* isolated from carrot petioles (2010–2012, % of all isolates)

Table 4. Carrot root yield at harvest

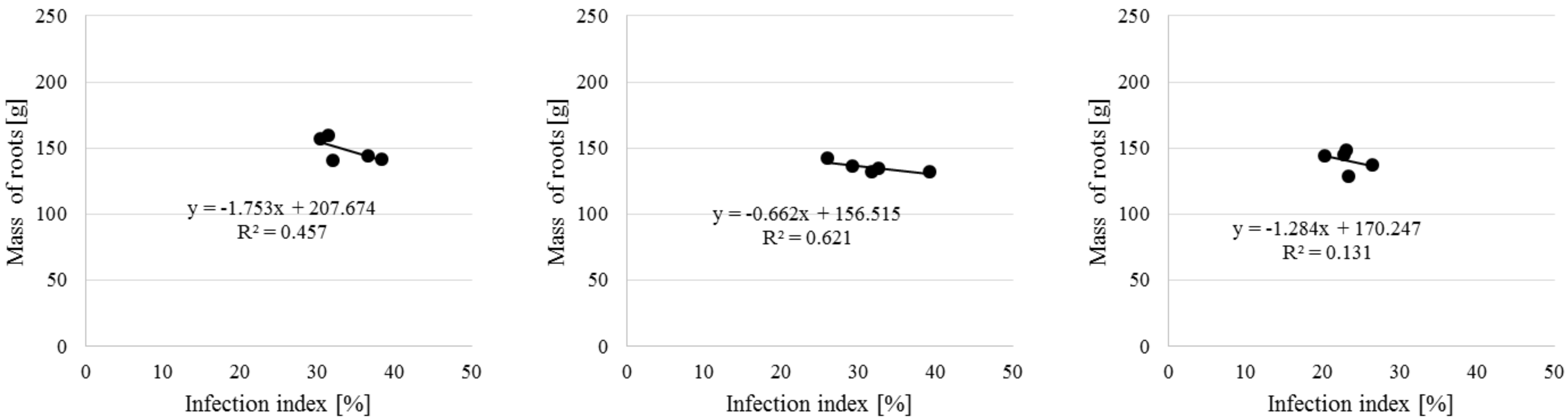
Treatment	2010				2011				2012			
	root weight (g)	total yield (t ha^{-1})	marketable yield (ha^{-1})	marketable yield (%)	root weight (g)	total yield (t ha^{-1})	marketable yield (ha^{-1})	marketable yield (%)	root weight (g)	total yield (t ha^{-1})	marketable yield (ha^{-1})	marketable yield (%)
I Int	168.6 a	85.1 a	57.6 b	67.7 c	199.1 a	94.17 b	73.3 a	66.4 b	143.9 b	53.8 a	41.0 a	76.2 b
II Int	161.8 b	86.4 a	63.6 a	73.6 b	170.1 b	96.0 a	71.1 a	74.1 a	141.7 b	55.3 a	45.3 a	81.9 a
III Int	154.7 bc	86.0 a	64.5 a	75.0 b	165.2 b	96.9 a	71.8 a	74.1 a	140.4 b	56.4 a	43.5 a	77.0 b
IV Int	161.8 b	87.2 a	64.0 a	73.4 b	168.8 b	96.8 a	70.8 a	73.1 a	156.9 a	58.2 a	47.1 a	80.9 a
V Int	168.5 a	85.7 a	68.4 a	79.8 a	207.9 a	99.3 a	62.5 b	73.8 a	159.5 a	59.0 a	48.8 a	82.5 a
Mean	163.1 a	86.1 a	63.6 a	73.9 b	182.2 a	96.6 a	69.9 a	69.2 a	148.5 a	56.7 a	45.1 a	79.7 a
I Org	132.3 d	73.3 b	58.1 b	79.2 a	136.9 cd	74.7 c	51.0 c	68.2 b	135.3 c	51.1 a	41.0 a	80.1 a
II Org	135.0 cd	78.4 ab	65.0 a	82.9 a	148.3 c	70.4 c	49.4 c	70.2 ab	152.5 a	56.9 a	47.2 a	82.9 a
III Org	142.1 bc	76.5 ab	62.3 ab	81.4 a	143.7 c	68.3 c	49.3 c	72.2 ab	143.4 b	53.8 a	44.0 a	81.9 a
IV Org	136.2 cd	73.8 b	58.5 b	79.3 a	145.3 c	69.0 c	45.0 c	65.2 b	155.9 a	53.1 a	43.8 a	82.4 a
V Org	131.8 d	78.1 ab	61.5 ab	78.7 a	128.4 d	67.4 c	49.6 c	73.6 a	146.4 ab	58.2 a	48.2 a	83.0 a
Mean	135.5 b	76.0 b	61.1 a	80.3 a	140.5 b	70.0 b	48.9 b	69.9 a	146.7 a	54.6 a	44.8 a	82.1 a

Means followed by the same letters in columns do not differ significantly at $p < 0.05$ Int – integrated farming system; Org – organic farming system



a) integrated farming system 2010
b) integrated farming system 2012
c) organic farming system 2010

Fig. 3. Effect of carrot infections on the marketable yield



a) integrated farming system 2012
b) organic farming system 2010
c) organic farming system 2011

Fig. 4. Effect of carrot infections on root weight

was observed on protected treatments IV Int and IV Org (29.8–32.3%) as well as V Org (33.3%). The potentially pathogenic *A. alternata* was the dominant species. *Alternaria dauci,* which is the main causative agent of Alternaria leaf blight in most agricultural regions, was isolated more frequently than *A. radicina* in all treatments. Under conditions of high humidity and

During the first two growing seasons, single root weight, marketable yield and total yield were significantly higher in the integrated farming system than in the organic system (except for the marketable yield in 2010). Root weight was highest in 2011 in treatment V Int (approx. 208 g), and the noted value was 62% higher than the lowest root weight recorded in

Table 5. Carrot root infections caused by *P. carotovorum* subsp. *carotovorum* and *Sclerotinia sclerotiorum* (% of infected root weight)

Treatment	2010		2011		2012		Mean	
	harvest	storage	harvest	storage	harvest	storage	harvest	storage
I Int	3.2 r-u	32.4 c	0 w	35.2 b	15.2 lmn	21.5 hi	6.1 i	29.7 a
II Int	0 w	13.8 no	0 w	29.8 cde	2.0 s-w	30.5cd	0.7 l	24.7 d
III Int	3.9 r-u	11.0 op	5.0 rs	18.2 kl	1.5 tuw	22.8 ghi	3.5 k	17.3 f
IV Int	4.6 rst	17.2 klm	2.0 s-w	40.8 a	6.1qr	25.0 fg	4.2 jk	27.7 b
V Int	8.6 pq	28.6 de	0 w	29.5 cde	20.0 ijk	21.3 hij	9.5 h	26.5 bc
Mean	4.1 f	20.6 c	1.4 hi	30.7 a	9.0 e	24.2 b	4.8 c	25.2 a
I Org	0 w	15.3 f-n	0 w	31.0 cd	1.4 tuw	27.2 ef	0.5 l	24.5 d
II Org	3.6 r-u	23.6 gh	13.3 no	22.1 ghi	0 w	18.1 kl	5.6 ij	21.3 e
III Org	0 w	18.7 jk	0 w	22.3 ghi	2.9 r-w	13.8 no	1.0 l	18.3 f
IV Org	4.2 r-u	25.2 fg	1.0 uw	27.2 ef	0 w	22.3 ghi	1.7 l	24.9 cd
V Org	4.4 rst	14.4 mn	0 w	13.6 no	0 w	15.1 lm	1.5 l	14.4 g
Mean	2.4 gh	19.4 cd	2.9 fg	23.2 b	0.9 i	19.3 cd	2.1 d	20.7 b
Mean	6.0 f	18.4 d	0 h	28.8 a	2.2 g	14.3 e	2.7 c	20.5 b

Explanation as in Table 2

Table 6. Carrot root infections caused by *Fusarium* spp. (% of infected root weight)

Treatment	2010		2011		2012		Mean	
	harvest	storage	harvest	storage	harvest	storage	harvest	storage
I Int	4.0 opq	28.5 cde	0 s	35.5 a	1.4 qrs	15.0 j	1.8 i	26.3 bc
II Int	4.2 opq	21.8 h	0 s	23.0 gh	0 s	23.2 gh	1.4 ij	22.7 d
III Int	0 s	26.6 def	0 s	28.0 c-f	0 s	20.8 hi	0 j	25.1 c
IV Int	3.5 o-r	27.0 def	2.0 o-s	11.5 kl	0 s	21.7 h	1.8 i	20.1 ef
V Int	0 s	18.8 i	0.4 s	30.0 c	2.2 o-s	32.7 b	0.7 ij	27.2 ab
Mean	2.3 g	24.5 b	0 h	25.6 b	0.7 h	22.7 c	1.2 d	24.3 a
I Org	8.0 n	26.1 ef	0 s	36.3 a	4.6 o	21.9 h	4.2 h	28.1 a
II Org	0 s	21.3 hi	0 s	27.8 c-f	1.0 s	8.5 mn	0.3 ij	19.2 f
III Org	14.0 jk	20.5 hi	0 s	29.3 cd	2.7 o-s	15.5 j	5.6 h	21.8 d
IV Org	3.6 o-r	10.9 lm	0 s	27.5 c-f	1.6 p-s	25.5 fg	1.7 i	21.3 de
V Org	4.4 op	13.0 jkl	0 s	23.3 gh	1.3 qrs	0 s	1.9 i	12.1 g
Mean	6.0 f	18.4 d	0 h	28.8 a	2.2 g	14.3 e	2.7 c	20.5 b

Explanation as in Table 2

blight and marketable yield was noted in the integrated farming system in 2010 and 2012, and in the organic system in 2010. Single root weight decreased with increasing disease severity in the integrated farming system in 2012, and in the organic system in 2010 and 2011. The observed correlations were confirmed by a regression analysis (Figs 3 and 4). In contrast to the present findings, Sink et al. [2017] noted higher carrot yields in the organic farming system (42–44 t ha^{-1}) than in the integrated system (37–40 t ha^{-1}). Asahi SL, similarly to other plant growth regulators (Bio-Algeen S 90 Kelpak SL and Tytanit), increased the yield of medium-sized and large carrot roots with no visible symptoms of infection or deformities [Kwiatkowski et al. 2013, Szczepanek et al. 2015].

At harvest, the severity of mixed rot (soft rot *P. carotovorum* subsp. *carotovorum* and Sclerotinia rot *S. sclerotiorum*) was low (approx. 5% of infected roots) excluding treatments II Org, I Int and V Int (Tab. 5), and the severity of dry rot (*Fusarium* spp.) was low excluding treatment III Org (Tab. 6). The above storage fungal pathogens exacerbated disease symptoms during five months of storage. The number of carrot roots affected by mixed rot was lower in the organic farming system, and the differences noted in the last two years were significant (Tab. 5). The applied crop protection agents significantly reduced the severity of this devastating disease in the integrated farming system in 2010, in both production systems in 2011 (except for IV Int storage), and in the organic system in 2012. In both production systems, carrot roots in unprotected treatments were most severely infected by *Fusarium* spp. in 2011 (36% of infected roots) (Tab. 6). The applied protective measures significantly reduced the symptoms of dry rot also in the growing season of 2010, but carrot roots were significantly more infected in the integrated farming system. A combination of biocontrol agents such as for instance Contans®WG (*Coniothyrium minitans*, CON/M/91-08 strain) [McQuilken and Chalton 2009] and chemical agents [Derbyshire and Denton-Giles 2016] was highly effective in suppressing *S. sclerotiorum*. In France, *F. tricinctum* and *F. avenaceum* were isolated from diseased plants that dried prematurely and showed symptoms of rot [Le Moullec-Rieu et al. 2020]. In an *in vitro* study, the Asahi SL biostimulant inhibited the mycelial growth of selected *F. oxysporum* isolates, depending on the applied dose [Ogórek et al. 2011]. Asahi SL reduced also the severity of dry rot symptoms on stored potato tubers [Cwalina-Ambroziak et al. 2015].

Both at harvest and after storage, the symptoms of common scab and black rot (similarly to the symptoms of Alternaria leaf blight) on carrot roots were most severe in the growing season of 2012, with the lowest total precipitation levels, whereas the symptoms of

Table 7. Carrot root infections caused by *Streptomyces scabies* (infestation index Ii, %)

Treatment	2010		2011		2012		Mean	
	harvest	storage	harvest	storage	harvest	storage	harvest	storage
I Int	0.4 w-z	2.0 p-t	1.3 s-x	5.0 fg	2.0 p-t	3.8 h-m	1.2 g	3.6 d
II Int	0.4 w-z	4.7 fgh	0 z	0 z	0 z	8.7 c	0.1 i	4.5 c
III Int	1.8 q-u	3.5 j-n	0.7 v-z	3.7 h-m	3.1 k-o	10.6 b	1.9 ef	5.9 a
IV Int	1.1 s-y	4.6 f-i	1.3 s-x	1.3 s-x	2.4 o-r	9.4 c	1.6 fg	5.1 b
V Int	0.4 w-z	4.0 g-l	2.6 n-q	1.5 r-v	2.9 m-p	4.3 fi	2.0 ef	3.3 d
Mean	0.8 e	3.8 c	1.2 e	2.3 d	2.1 d	7.4 a	1.4 b	4.5 a
I Org	0.7 v-z	3.2 k-o	0.7 v-z	7.6 d	1.8 q-u	5.3 f	1.1 gh	5.4 b
II Org	0 z	3.8 h-m	0 z	2.8 m-q	1.8 q-u	4.7 fgh	0.6 hi	3.8 d
III Org	0.7 v-z	3.6 i-n	0 z	3.1 k-o	0.7 v-z	3.4 j-o	0.3 i	3.4 d
IV Org	0.4 w-z	4.1 g-k	1.3 s-x	1.3 s-x	2.9 m-p	13.2 a	1.5 fg	6.2 a
V Org	0 z	3.0 l-p	2.0 p-t	2.0 p-t	4.9 fg	6.0 e	2.3 e	3.7 d
Mean	0.3 f	3.5 c	0.8 e	3.6 a	2.4 d	6.5 b	1.2 b	4.5 a

Explanation as in Table 2

Table 8. Carrot root infections caused by *Rhizoctonia carotae*, *Rhizoctonia solani* (infestation index Ii, %)

Treatment	2010		2011		2012		Mean	
	harvest	storage	harvest	storage	harvest	storage	harvest	storage
I Int	3.3 k-o	11.6 bc	0 u	6.4 gh	2.7 m-r	1.0 stu	2.0 hi	6.3 c
II Int	3.0 l-q	12.0 b	1.3 r-u	10.5 cd	2.7 m-r	0 u	2.3 h	7.5b
III Int	1.4 r-u	6.0 hi	0 u	7.5 fg	0 u	1.7 q-t	0.5 k	5.1 de
IV Int	1.1 stu	6.2 ghi	0 u	3.5 k-n	0.7 stu	1.5 rst	0.6 jk	3.7 fg
V Int	2.6 n-r	8.5 ef	0.7 stu	7.4 fg	1.8 p-t	9.3 de	1.7 hi	8.4 a
Mean	2.3 fg	8.9 b	0.4 i	7.1 c	1.6 h	2.7 ef	1.4 c	5.1 b
I Org	3.2 k-p	9.7 de	0 u	0.7 stu	0.7 stu	0.4 tu	1.3 ij	3.6 g
II Org	3.8 j-n	10.5 cd	0.7 stu	2.6 n-r	0.7 stu	0 u	1.7 hi	4.4 ef
III Org	3.6 k-n	16.0 a	0 u	2.0 o-s	1.3 r-u	4.2 jkl	1.6 hi	7.4 b
IV Org	4.1 jkl	10.6 cd	0 u	5.0 ij	0 u	1.3 r-u	1.4 ij	5.6 cd
V Org	3.0 l-q	6.0 hi	0 u	4.5 jk	0.7 stu	3.0 l-q	1.2 ij	4.5 e
Mean	3.5 d	10.6 a	0.1 i	3.0 e	0.7 i	1.8 gh	1.5 c	6.2 a

Explanation as in Table 2

Table 9. Carrot root infections caused by *Alternaria* spp. (infestation index Ii, %)

Treatment	2010		2011		2012		Mean	
	harvest	storage	harvest	storage	harvest	storage	harvest	storage
I Int	3.5 k-q	6.0 i-l	0 r	7.3 h-k	4.5 i-p	21.5 a	2.7e	11.6 a
II Int	4.0 k-q	14.1 bc	0.5 qr	5.5 i-n	5.2 i-n	9.7 efg	3.2 e	9.8 bc
III Int	2.5 m-r	4.7 i-o	0 r	15.5 b	3.6 k-q	12.0 cde	2.0 e	10.7 ab
IV Int	2.0 n-r	2.9 l-r	0 r	5.0 i-o	3.0 k-r	15.0 b	1.7 e	7.6 d
V Int	3.5 k-q	10.6 def	0 r	10.5 def	4.8 i-o	7.5 hij	2.8 e	9.5 bc
Mean	3.1 f	7.7 d	0.1 h	8.8 cd	4.2 e	13.1 a	2.5 b	9.6 a
I Org	1.5 o-r	14.2 bc	0 r	9.5 fgh	4.5 i-p	10.5 def	2.0 e	11.4 a
II Org	3.5 k-q	13.3 bcd	0 r	11.3 de	6.0 i-l	7.3 h-k	3.2 e	10.6 ab
III Org	0.5 qr	5.6 i-m	1.0 pqr	11.0 de	4.4 j-p	6.0 i-l	2.0 e	7.5 d
IV Org	0.5 qr	5.9 i-m	0.5 qr	11.0 de	4.0 k-q	10.0 efg	1.7 e	9.0 cd
V Org	1.5 o-r	7.9 ghi	0 r	9.5 fgh	3.8 k-q	14.5 bc	1.8 e	10.6 ab
Mean	1.5 g	9.4 bc	0.3 h	10.5 b	4.5 e	9.7 bc	2.1 b	9.8 a

Explanation as in Table 2

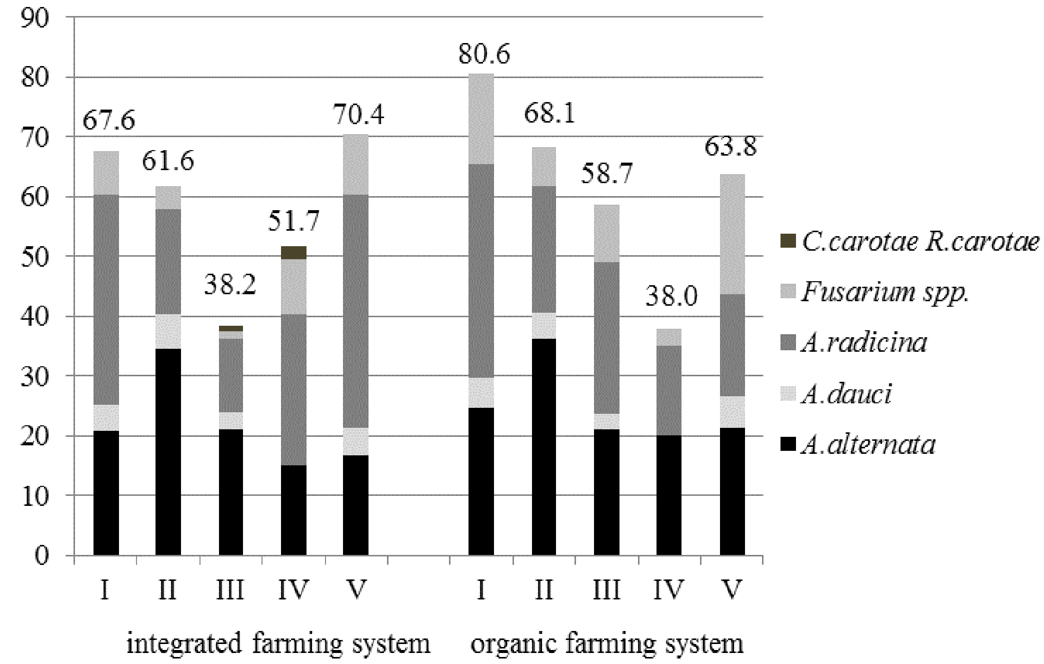
crater rot were most severe in the wettest growing season of 2010 (Tab. 7–9). The analyzed farming systems exerted varied effects on infection rates across the years of the study. Throughout the experiment, root infections caused by *S. scabies* and *R. carotae* in both production systems at harvest and after storage in most cases did not exceed 5% (in some cases, disease symptoms were not observed), excluding stored carrot roots in the last year (with the highest value of the infestation index of 13.2% in treatment IV Org) and in the first year of the study (16% in treatment III Org). At harvest, the symptoms of black rot were observed sporadically, and the infestation index of 6% was noted only in 2012 (the severity of Alternaria leaf blight was highest in this growing season). After storage, root infection was more severe in the organic farming system in successive years of the study. The applied crop protection agents significantly suppressed

Table 10. Pathogenic fungi isolated from carrot roots (2010–2012, % of all isolates)

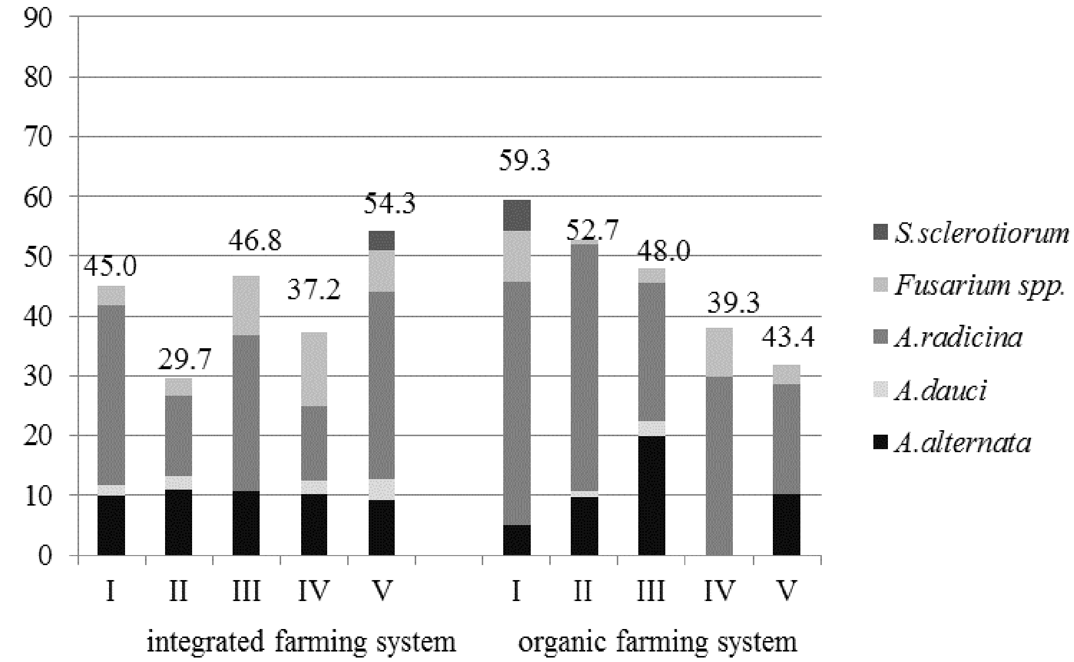
Species	Integrated farming system					Organic farming system				
	I	II	III	IV	V	I	II	III	IV	V
at harvest										
Alternaria alternata (Fr.) Keissler	20.7	34.6	21.0	14.9	16.7	24.6	36.2	21.1	20.0	21.3
Alternaria dauci (J.G. Kühn) Groves & Skolko	4.5	5.6	2.9		4.6	5.1	4.3	2.6		5.3
Alternaria radicina Meier, Drechsler & E.D. Eddy	35.1	17.8	12.4	25.3	38.9	35.6	21.3	25.4	15.0	17.0
Total	60.4	57.9	36.2	40.2	60.2	65.3	61.7	49.1	35.0	43.6
Fusarium spp.	7.2	3.7	1.0	9.2	10.2	15.3	6.4	9.6	3.0	20.2
Cercospora carotae (Pass.) Kazn.			1.0							
Rhizoctonia spp.				2.3						
Total (No.)	111	107	105	87	108	118	94	114	100	94
after 5 months of storage										
Alternaria alternata (Fr.) Keissler	10.0	10.9	10.8	10.1	9.3	5.0	9.8	20.0	0	10.1
Alternaria dauci (J.G. Kühn) Groves & Skolko	1.7	2.3	0	2.3	3.4	0	0.8	2.4	0	0
Alternaria radicina Meier, Drechsler & E.D. Eddy	30.0	13.3	26.1	12.4	31.4	40.7	41.4	23.2	29.8	18.6
Total	41.7	26.6	36.9	24.8	44.1	45.7	51.9	45.6	29.8	28.7
Fusarium spp.	3.3	3.1	9.9	12.4	6.8	8.6	0.8	2.4	8.3	3.1
Sclerotinia sclerotiorum (Lib.) de Bary					3.4	5.0			1.2	11.6
Total (No.)	120	128	111	129	118	140	133	125	84	129

disease development. An analysis of the mean values for the entire experiment revealed that the production systems did not affect disease severity – except for a higher rate of infection caused by *R. carotae* on stored carrot roots in the organic farming system. Chemical control involving seed dressing (Zaprawa Nasienna T) and foliar spray (Bravo 500 SC) in treatment IV Int and biological control involving seed dressing and foliar spray with Grevit 200 SL in treatments III Org and IV Org reduced the severity of black rot on stored carrot roots. EM-X (EM1/ species of photosynthetic bacteria – *Rhodopseudomonas palustris* and *Rhodobacter sphaeroides*; lactobacillus – *Lactobacillus plantarum*, *L. casei* and *Streptococcus lactis*; yeasts – *Saccharomyces* spp.; Actinomycetes – *Streptomyces* spp./ + *Bacillus subtilis* + arbuscular mycorrhiza + *Azotobacter chrococcum*) were more effective in reducing *Rhizoctonia solani* and *Sclerotinia rolfisii* in sunflowers [El-Hadidy 2018]. *Alternaria radicina* is the main causative agent of black rot in carrots, but the disease can also be caused by *A. dauci* [Pryor et al. 2002, Farrar et al. 2004, Mazur and Nawrocki 2007]. Mancozeb and prochloraz proved to be more effective in controlling *Alternaria* rot caused by *A. alternata* [Mohsan et al. 2011].

The highest number of pathogenic fungi were isolated from carrot roots at harvest and after storage in the unprotected treatment in the organic farming system (Tab. 10). Species of the genus *Alternaria* were identified most frequently, and their number was higher at harvest (60% of isolates in treatments I Int, V Int, and above 60% in I Org and II Org) than after storage (50% of isolates in treatment II Org) (Fig. 5). In all treatments, *A. radicina* was isolated most frequently from carrot roots – approximately 40% at harvest (treatment V Int) and after storage (treatments I Org and II Org). *Alternaria dauci* was isolated less frequently – 5.6% (or the species was absent). At harvest, the smallest population of fungi responsible for black rot was isolated from treatments III Int and IV Org (plants in these treatments were also characterized by the weakest symptoms of Alternaria leaf blight). Fungi



a) at harvest



b) after 5 months of storage

Fig. 5. Pathogens isolated from carrot roots (2010–2012, % of all isolates)

of the genus *Fusarium* were isolated from carrot roots in all treatments, both at harvest (15% in treatment I Org) and after storage (12.4% in treatment IV Int). Single isolates of *C. carotae*, *R. carotae* and *S. sclerotiorum* were also identified.

CONCLUSIONS

Disease severity on the above-ground plant parts and storage roots was determined by weather conditions rather than farming system or crop protection. The first two wet growing seasons promoted the spread of damping-off of seedlings and the last growing season with normal precipitation levels was conducive to the development of Alternaria leaf blight. The symptoms of the above diseases were encountered more frequently in the organic farming system than in the integrated system. At harvest, the severity of root diseases was low. During storage, carrot roots were susceptible to mixed rot and dry rot (*Fusarium* spp.). In the integrated system, the symptoms of dry rot were less severe at harvest and the symptoms of crater rot were less severe after storage. In the organic system, the symptoms of soft rot and Sclerotinia rot were less severe at harvest and after storage, and the symptoms of dry rot were less severe after storage. During storage, the applied crop protection methods significantly suppressed mixed rot in the integrated farming system, and dry rot in the organic system. The frequency of isolation of potential pathogens from carrot petioles and roots was partially consistent with the severity of Alternaria leaf blight during the growing season and root diseases. An increased rate of infection caused by *Alternaria* spp. on above-ground plant parts led to a decrease in the marketable yield of carrots (in the integrated farming system in 2010 and 2012, and in the organic farming system in 2010) and single root weight (in the integrated farming system in 2012, and in the organic farming system in 2010 and 2011).

SOURCE OF FUNDING

Project financially supported by Minister of Education and Science in the range of the program entitled "Regional Initiative of Excellence" for the years 2019–2022, Project No.010/RID/2018/19, amount of funding 12 000 000 PLN.

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