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Alternaria Black Spot (*Alternaria brassicae*) Infection Severity on Cruciferous Oilseed Crops

Eve Runno-Paurson [1,2,*], Peeter Lääniste [1], Helina Nassar [1], Merili Hansen [2], Viacheslav Eremeev [1], Luule Metspalu [2], Liina Edesi [3], Astrid Kännaste [1] and Ülo Niinemets [1,4]

[1] Chair of Crop Science and Plant Biology, Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Kreutzwaldi 1, 51006 Tartu, Estonia; peeter.laaniste@emu.ee (P.L.); helina.nassar@emu.ee (H.N.); vyacheslav.eremeev@emu.ee (V.E.); astrid.kannaste@emu.ee (A.K.); ylo.niinemets@emu.ee (Ü.N.)
[2] Chair of Plant Health, Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Kreutzwaldi 1, 51006 Tartu, Estonia; Merili_H@hotmail.com (M.H.); luule.metspalu@emu.ee (L.M.)
[3] Department of Agrotechnology, Estonian Crop Research Institute, J. Aamisepa 1, 48309 Jõgeva, Estonia; liina.edesi@etki.ee
[4] Estonian Academy of Sciences, Kohtu 6, 10130 Tallinn, Estonia
* Correspondence: eve.runno-paurson@emu.ee; Tel.: +372-5558-1322

Abstract: The increase in the cultivation area of cruciferous oilseed crops and the use of short crop rotation has resulted in the enhanced spread of several major pests in Northern latitudes. There is currently limited information about incidence and severity of Alternaria black spot disease (*Alternaria brassicae*) on the main oilseed crop, spring oilseed rape (*Brassica napus*), in the Northern Baltics. Thus, spring oilseed rape and five alternative cruciferous oilseed crops were selected and their resistance to black spot disease was evaluated in field conditions during two growing seasons. We hypothesized that spring oilseed rape is more susceptible to Alternaria black spot disease than other alternative cruciferous oilseed crops. Both growing seasons were warmer and drier compared to the long-term average, and were thus suitable for *A. brassicae* development and assessments. In both years, incidence of Alternaria black spot infection was recorded on all cruciferous species, yet the disease development differed considerably among the crops. During both growing seasons, black mustard (*B. nigra*) plants were the most infected. Based on our observations during warm growing seasons we conclude that alternative oilseed crops such as *Sinapis alba*, *Eruca sativa* and *Raphanus sativus* are more resistant to the Alternaria black spot infection than the traditional oilseed crops and thus, possess a great potential to grow with limited chemical disease control in Northern Baltic conditions.

Keywords: agriculture in northern latitudes; *Brassica juncea*; *B. napus*; *B. nigra*; disease resistance; emerging diseases; *Eruca sativa*; *Raphanus sativus*; *Sinapis alba*; year-to-year variability

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1. Introduction

The area of cultivation of cruciferous oilseed crops has been increasing and oilseed rape (*Brassica napus* var. *oleifera*) has become one of the most important oilseed crops worldwide [1]. In Estonia, oilseed rape (*B. napus*) and turnip rape (*B. rapa*) have been important cash crops for farmers since the middle of 1990s. In 2010, the cultivation area of cruciferous oilseed crops culminated in 100,000 ha, comprising approximately 26% of the total cultivation area of cereal-dominated crop rotations [2]. However, by now, the area of these two cruciferous crops has stabilized at 75,000 ha [2]. Similar trends have been observed in the two other Baltic countries Latvia and Lithuania in the early 1990s to 2005 [3,4]. In recent years, the reduction in growth area is due to serious pest problems, especially for spring oilseed rape and turnip rape [5,6]. The major cruciferous pests with enhanced dispersal include several insects such as pollen beetle (*Brassicogethes aeneus*) [7], flea beetles (*Phyllotreta* spp.) [8], etc., and difficult-to control soilborne diseases Sclerotinia stem rot (*Sclerotinia sclerotiorum*) [5], Phoma stem canker (*Leptosphaeria* spp.) and clubroot (*Plasmodiophora brassicae*) [9]. Heavy input of various synthetic pesticides for disease and insect control puts considerable economic pressure on farmers as it causes plant disease resistance to pesticides [10] and reduces soil biodiversity [11].

Temperature and humidity are the main environmental factors that favor the spread of plant diseases, while mild and wet winters affect the survival of debris-borne fungi such as Alternaria disease [12]. Alternaria black spot (*Alternaria brassicae*) is a major pathogen that has worldwide distribution on oilseed rape, mustard and other cruciferous crops and can cause significant yield losses [13,14]. In addition to *A. brassicae*, Alternaria black spot can also be caused by other related species, including *A. japonica*, whichhas been found on oilseed rape in Australian field surveys [15,16]. In Australia, *Alternaria* spp. have caused field yield losses of over 58% on oilseed rape [15]. In the Baltic region, Alternaria black spot disease is one of the main destructive oilseed rape diseases after Sclerotinia stem rot and Phoma stem canker [5,17,18]. In the southern Baltics, in Lithuania, Alternaria black spot occurrence and severity have been studied in winter and spring oilseed rape and spring turnip rape [4,19], and the susceptibility of winter oilseed rape cultivars to the disease has been determined [20]. In Lithuania, a considerable loss of seed yield in spring oilseed rape due to Alternaria black spot has been recorded, whereas the yield loss varied between 11–30% among growing seasons [17]. In Latvia, a winter oilseed rape disease monitoring during 2005–2008 showed that the incidence of Alternaria black spot disease increased in time, but its severity remained insignificant [5]. In Estonia, Alternaria black spot infection score was studied in fertilization trials at the Estonian Crop Research Institute in Jõgeva in 2008–2009; the studied winter oilseed rape cultivar 'Silva' had 20–75% damage depending on treatment variant and year [21].

Crop yields also depend on the use of land management practices. Cruciferous crops like winter oilseed rape (*B. napus*), white mustard (*S. alba*) and oilseed radish (*R. sativus*) grown as green manure and cover crops efficiently suppress soil-born potato pathogens that could otherwise reduce potato tuber quality and yield [22]. A recent study demonstrated that the mustard blend of *S. alba* and *R. sativus* used as green manure and other *Brassica* rotations as an autumn cover crop significantly reduced common scab, silver scurf and black scurf on potato tubers [23]. Some reduction of potato late blight (*Phytophthora infestans*) infestation at early stages of disease development has been achieved using cruciferous winter oilseed crops [24]. Thus, usage of cover crops in agriculture could be a promising alternative disease control strategy for environmentally friendly agriculture. In Estonia, several cruciferous crops have been tested as trap crops that can reduce insect pressure on the main cash crops. Oilseed radish, rucola (*Eruca sativa*), white mustard and mustard green (brown mustard) (*B. juncea*) have been previously shown to be effective trap plants for flea beetles, pollen beetles and cabbage seedpod weevil (*Ceutorhynchus obstrictus*) [6,8,25]. Infected *B. nigra* and *R. sativus* can also serve as a source for insect pest parasitoids; both species supported the parasitoids of cabbage seedpod weevils [6]. Furthermore, oilseed radish has the features of a dead-end trap crop because 35% of the larvae of pollen beetles failed to survive [26].

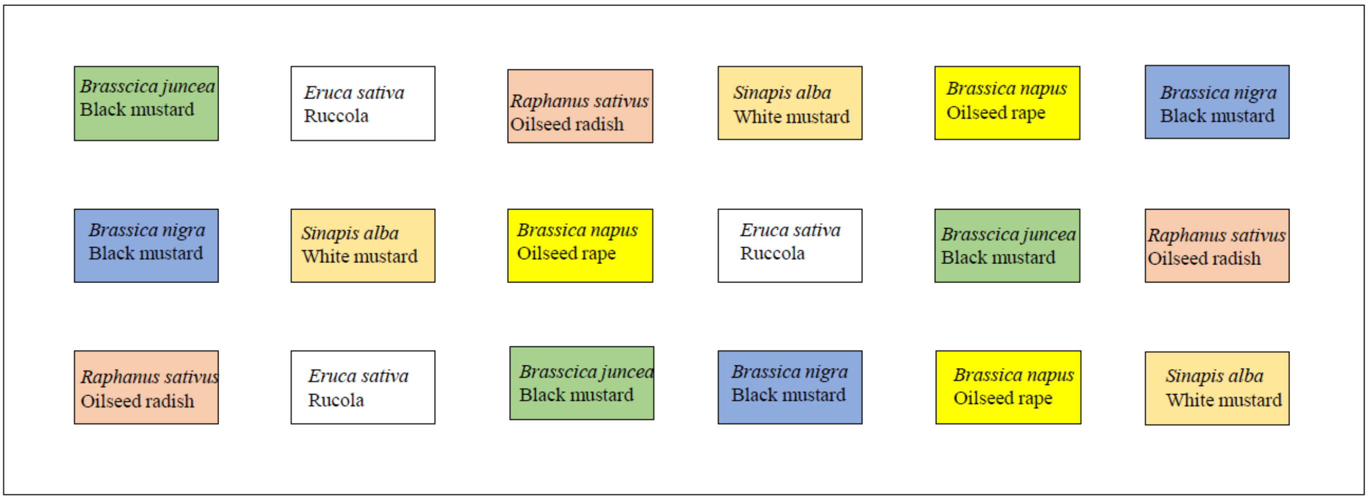
The pathogen *A. brassicae* overwinters inside and outside of the seeds and on the crop residues of cruciferous agricultural crops and weeds [27]. Given the short rotation time of cruciferous crops, it is very important that the plants selected for cover crop, trap cropping, lodging culture, etc., are not susceptible to Alternaria black spot, and therefore, their disease sensitivity should be studied elaborately before harnessing.

In the Baltics, some information about Alternaria black spot occurrence and severity on winter and spring oilseed rape and on spring turnip rape, and the resistance of some winter oilseed rape cultivars to disease, is available [4,5,19,20]. Until now, there is a lack of information about the incidence and severity of Alternaria black spot disease on spring oilseed rape in Estonia. In regard to oilseed radish, rucola, black mustard, white mustard and mustard green, no relevant studies have been conducted in the Baltic countries, but given the climatic modifications due to global change, the Alternaria black spot disease is expected to become more severe in the near future. Thus, it is important to gain insight into interspecific variability in Alternaria black spot disease resistance among cruciferous crops grown as green manure, intercrop, oilseed or trap crop. In this pilot study, we assessed the variation in infection severity of Alternaria black spot disease in spring oilseed rape and five alternative cruciferous crops under organic farming conditions and hypothesized that spring oilseed rape is more susceptible to the plant disease than other alternative cruciferous crops in Northern Baltics.

2. Materials and Methods

2.1. Experimental Site and Design

Alternaria black spot (*Alternaria brassicae*) infection was evaluated in 2010 and 2011 on six different cruciferous plant species in an experimental field of the Estonian University of Life Sciences, Tartu County, Estonia (58°21′ N, 26°39′ E). The plants were grown in a randomized complete block design with three replicates of each of the following species: spring oilseed rape (*Brassica napus* (L.) cv. 'Maskot'), mustard green (brown mustard) (*B. juncea* cv. 'Jadrjonaja'), black mustard (*B. nigra* (L.) W. D. J. Koch), rucola (also called arugula, garden rocket, etc.) (*Eruca sativa* subsp. *sativa* (*E. sativa*) cv. 'Poker'), oilseed radish (*Raphanus sativus* var. *oleiformis* (*R. sativus*) cv. 'Bille') and white mustard (*Sinapis alba* cv. 'Branco') (Scheme 1). In both years, the seeds were obtained from the seed collection of the Estonian University of Life Sciences. The size of each plot (1 m × 5 m) was similar to that used earlier for cruciferous crops in biotic stress studies at the site. To minimize inter-plot interactions, there was a 1 m wide buffer zone of bare soil around each plot. The whole experimental field was surrounded by a hay meadow. Plots were sown on 12 May in 2010 and 9 May in 2011, at 250 seeds per m^2. Seed germination was similar for different species in different years and no differences were noticed in plant density (on average 200 plants per m^2) between the plots. In both years, the same standard crop management practices were used in all trial plots. The fertilizers and pesticides were not used and the trials were undertaken in a system certified for organic agriculture. The plant growth stage (BBCH-scale is used to identify the phenological development stages of plants) was assessed using the decimal code system [28].



Scheme 1. Field experimental layout with six different cruciferous oilseed crops in both study years (2010 and 2011). The individual plot size was 1 m × 5 m and the distance between the trial plots from each other, as well the width of field edges was 1 m.

2.2. Disease Assessment

Alternaria black spot disease (*A. brassicae*) infection on test plants was assessed according to the 0–100% scale, where 0% corresponds to no disease, and in the case of 100%, the leaf area was totally covered with lesions [29]. The disease assessments were made visually under natural infection conditions from 7 July to 2 August in 2010 (five observations) and from 8 July to 5 August in 2011 (five observations), from the growth stage of BBCH 55–63 (inflorescence to flowering) to BBCH 86–89 (ripening) (Tables 1 and 2). The degree of infection was characterized as a percentage of total foliage once a week until the disease peaked. In the case of all species and replications, ten randomly selected plants per plot were assessed for Alternaria black spot disease infection.

Table 1. Growth stages (GS) of studied cruciferous species at each observation date in 2010.

Species	**Date of Disease Evaluation**				
	7 July	**12 July**	**20 July**	**26 July**	**2 August**
Brassica napus Oilseed rape 'Maskot'	65–68 [1]	68–71	72–75	77–79	79–81
Brassica nigra Black mustard	68–70	71–72	75–77	78–80	81–83
Brassica juncea Mustard green 'Jadrjonaja'	69–70	71–72	70–79	80–85	86–88
Eruca sativa Rucola 'Poker'	57–63	63–66	59–66	68–71	71–73
Raphanus sativus Oilseed radish 'Bille'	55–63	58–65	64–69	69–70	70–73
Sinapis alba White mustard 'Branco'	72–74	72–74	75–79	79–81	83–86

[1] Growth stages using the BBCH scale according to Lancashire et al. (1991) [29]: 55–59 (inflorescence emergence), 60–69 (flowering), 70–79 (development of pods), 80–89 (ripening).

Table 2. Growth stages (GS) of studied cruciferous species at each observation date in 2011.

Species	**Date of Disease Evaluation**				
	8 July	**15 July**	**22 July**	**29 July**	**5 August**
Brassica napus Oilseed rape 'Maskot'	68–70 [1]	71–72	72–74	75–77	78–81
Brassica nigra Black mustard	71–72	72–74	75–77	78–81	82–85
Brassica juncea Mustard green 'Jadrjonaja'	71–72	73–74	75–77	78–84	86–89
Eruca sativa Rucola 'Poker'	65–67	68–69	71–72	72–73	73–74
Raphanus sativus Oilseed radish 'Bille'	67–68	71–73	73–75	77–80	80–83
Sinapis alba White mustard 'Branco'	73–74	73–74	75–77	77–82	83–87

[1] Growth stages using the BBCH scale according to Lancashire et al. (1991) [29]: 55–59 (inflorescence emergence), 60–69 (flowering), 70–79 (development of pods), 80–89 (ripening).

The area under the disease progress curve (AUDPC) was calculated from the date of the first occurrence of Alternaria black spot until the last observation of the disease in the trial according to Shaner and Finney (1977) [30] by using the following formula: $\Sigma R = n[(R_{i+1} + R_i)/2)] (t_{i+1} - t_i)$, where R_i is the disease severity (percentage of leaf surface blighted) for the previous assessment (i-th observation), R_{i+1} is the severity for the current observation, t_i and t_{i+1} are the corresponding times of measurements (day of year), and n is the total number of observations.

2.3. Data Analysis

Statistical analysis of collected data was performed with Statistica 13 (Quest Software Inc., Aliso Viejo, CA, USA). Differences in the severity of Alternaria black spot infection in dependence on year, cruciferous crop species and their interaction were tested by ANOVA. Both factors 'year' and 'species' were treated as fixed categorical variables. Tukey HSD post-hoc tests ($p = 0.05$) were applied to separate the differences among the means between years and cruciferous crop species. The level of statistical significance for all effects was $p = 0.05$ except when noted.

3. Results

3.1. Weather Conditions

Weather data were collected from Rõhu weather station situated 0.5 km from the trial site. In May and June 2010, the air temperature was similar to the long-term (48-year) average, but in July, the temperature was 4.7 °C higher than the long-term average (Table 3). In June of the same year, the precipitation was similar to the long-term average, while in July (36.0 mm) and in the beginning of August (13.4 mm for the first two weeks of August), the rainfall was significantly lower than the long-term average (48-year averages of 70.6 mm for July and 33.3 mm for the first ten-day period of August). In May 2011, the temperature was similar to the long-term average, but June was hotter by 1.9 °C and July by 2.4 °C (Table 3). In May, the rainfall was similar to the long-term average, but it was much lower in June, July and the beginning of August (Table 3). In the third ten-day period of July, the warm and humid climate (temperatures over 30 °C for more than 10 days, relative air humidity >72%) was the most favorable period for black spot disease infection and spread.

Table 3. Average monthly temperature (°C), precipitation (mm) and relative humidity (%) in Eerika experimental field during the vegetation period and the corresponding long-term averages (1964–2011).

Month	Ten-Day Period	Temperature (°C)			Rainfall (mm)			Relative Humidity (%)		
		2010	2011	1964–2011	2010	2011	1964–2011	2010	2011	1964–2011
May	I [1]	7.8	8.0	9.7	36.2	0.2	12.9	76.0	56.1	65.5
	II	17.3	11.8	11.4	10.4	46.6	20.9	70.5	73.3	66.3
	III	12.8	13.0	12.8	14.8	11.6	22.8	71.1	67.8	66.9
June	I	13.6	19.7	14.9	25.8	0.0	20.9	72.2	54.4	67.5
	II	14.0	15.9	15.1	8.6	24.8	26.9	71.5	69.7	70.9
	III	16.1	16.2	16.2	38.2	10.4	28.0	71.9	70.1	72.9
July	I	20.2	20.0	17.3	10.6	9.2	19.3	69.5	72.6	72.9
	II	23.3	18.6	17.4	8.0	30.4	24.8	65.7	70.2	74.7
	III	23.0	21.0	17.8	17.4	8.6	26.5	69.5	72.4	75.8
August	I	21.4	16.1	17.6	13.4	16.2	33.3	75.4	66.2	76.3
May–August	I–III	16.9	16.0	14.6	183.4	158.0	236.3	71.3	67.3	71.0

[1] Period of 10 days.

3.2. Development of Alternaria Black Spot Disease

The weather conditions were very favorable for Alternaria black spot development and assessments on both observation years. In 2010, the first occurrence of Alternaria black spot infection was found on 7 July on *B. juncea* and *B. napus* plants, but the infection level was very low (Figure 1a). Five days later, on 12 July, the degree of infection was 7.6 ± 0.3% (average ± SE) on *B. napus* and 10.9 ± 4.5% on *B. juncea*, whereas the degree of infection was already 33.0 ± 2.3% on *B. nigra* plants (Figure 1a). *S. alba* plants were also infected (4.9 ± 4.2%). After 26 July, Alternaria black spot development progressed on *B. nigra*, *B. juncea*, *S. alba* and *B. napus*, being the most severe on plants of *B. nigra* (49.2 ± 3.8%) and *B. juncea* (27.2 ± 5.4%) plots ($F_{5,12} = 16.38$, $p < 0.001$ for comparison between species). On 26 July, the infection was also observed on *E. sativa* plants with 0.5 ± 0.3% and on *R. sativus* with 8.2 ± 1.5% (Figure 1a). By the end of the observation period, 83.2 ± 2.9% of foliage of *B. nigra* plants (BBCH 81–83) and 60.2 ± 6.8% of foliage of *S. alba* plants (BBCH 83–86) were infected. These percentages are significantly higher compared to other cruciferous species ($F_{5,12} = 23.84$, $p < 0.001$) (Figure 1a). At the end of the observation period, the lowest Alternaria black spot infection severities were observed on *E. sativa* plants with 17.2 ± 8.7% and on *R. sativus* plants with 20.8 ± 4.1% (Figure 1a).

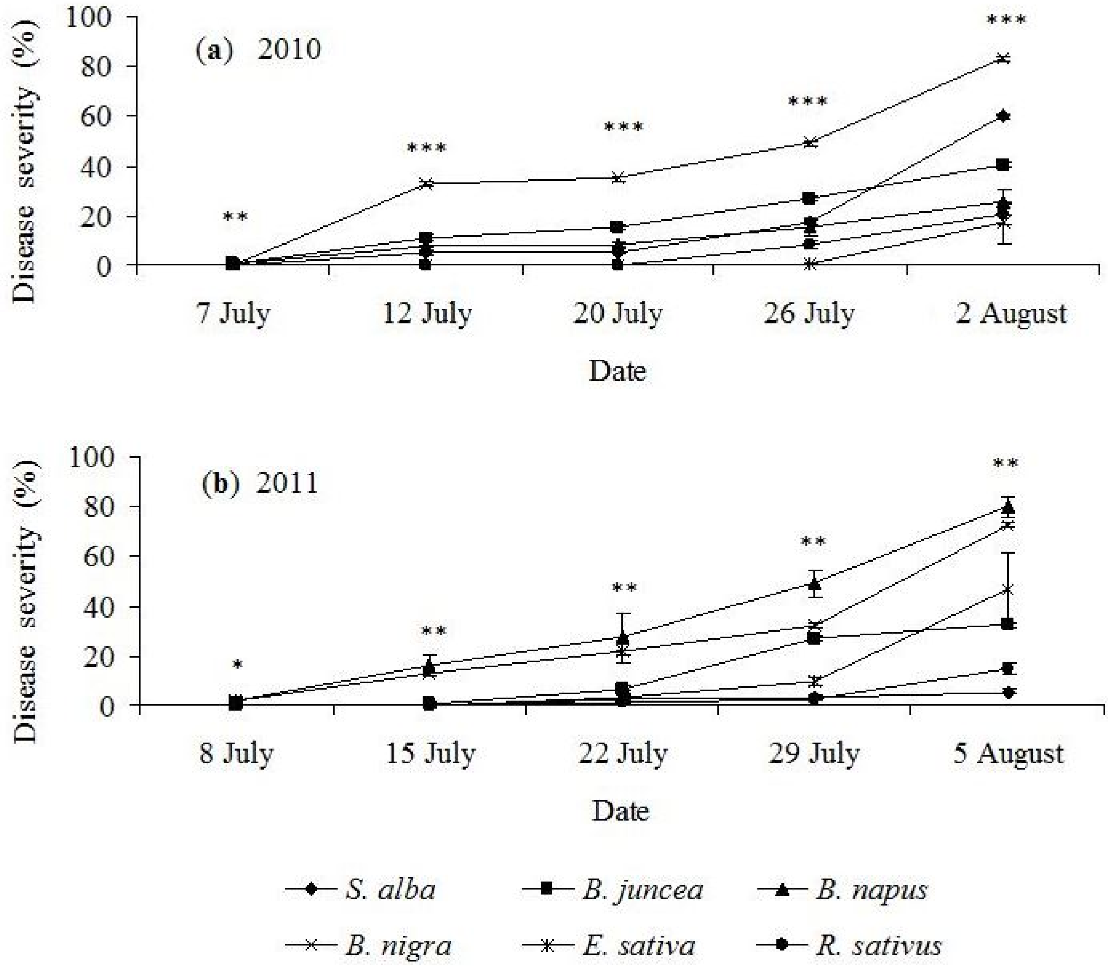


Figure 1. Development and Alternaria black spot (*A. brassicae*) severity (mean ± SE, %) on six different cruciferous oilseed crops in 2010 (**a**) and 2011 (**b**). The growing season of 2010 during the disease observations was hotter (22.2 °C for the period 1 July–10 August) than the growing season of 2011 (18.9 °C for the period 1 July–10 August). The asterisks demonstrate the significance of the species effect at $p < 0.05$ (*); $p < 0.01$ (**); and $p < 0.001$ (***).

In 2011, the first Alternaria black spot symptoms were recorded on 8 July on *B. napus* and *B. nigra* plants (Figure 1b). A week later, on 15 July, low-level infection was observed on *E. sativa* and *B. juncea* plants (Figure 1b). At that date, the disease infection on *B. napus* had increased to 15.7 ± 4.5% and on *B. nigra* plants to 12.7 ± 4.4% (Figure 1b). From 29 July, the disease infection rapidly progressed on *B. napus*, *B. nigra* and *E. sativa* and culminated on *B. napus* (BBCH 78–81) with 79.8 ± 4.1%, on *B. nigra* (BBCH 82–85) with 72.5 ± 4.0% and on *E. sativa* (BBCH 74–74) with 46.5 ± 14.9% ($F_{5,12} = 6.91$, $p < 0.01$). At the end of the observation period, low infection severity was recorded only on *S. alba* plants with 5.2 ± 1.9% and on *R. sativus* plants with 14.7 ± 2.4% (Figure 1b).

In both study years, Alternaria black spot infection and development differed considerably in all six cruciferous crops. In both growing seasons, a severe infection was recorded on *B. nigra* and by the end of the observation period, the disease was so advanced that infection exceeded 70% (Figure 1a). In 2011, too, by the end of the growing season, the disease severity on *B. napus* reached up to 79%, which was the highest value among the tested species. However, in 2010, the development rate of Alternaria black spot on *B. napus* remained moderate compared to *B. nigra* and *S. alba* (Figure 1). The lowest degree of infection was recorded in both growing seasons on *R. sativus*, and very low Alternaria black spot infection rate was also found on *E. sativa* in 2010 and on *S. alba* in 2011 (Figure 1).

3.3. Evaluation of AUDPC

Based on AUDPC values, Alternaria black spot disease pressure did not differ significantly between the two observation years. Across the species, it averaged 424.1 ± 51.3 in 2010 and 403.5 ± 92.1 in 2011 (Figure 2), but AUDPC values differed significantly between the six species studied (Table 4) in both years ($F_{5.12} = 23.48$, $p < 0.001$ for 2010 and $F_{5.12} = 9.08$, $p < 0.001$ for 2011; Figure 2). In 2010, the highest mean ± SE AUDPC value of 953.5 ± 11.5 was observed on *B. nigra* followed by *B. juncea* with a value of 561.8 ± 64.9 and *B. napus* with a value of 516.1 ± 70.2. The lowest AUDPC values were observed on *E. sativa* with 54.4 ± 27.9 and *R. sativus* with 111.9 ± 19.8 (Figure 2). In 2011, the highest AUDPC values were 943.0 ± 52.3 on *B. napus* and 734.0 ± 187.9 on *B. nigra* (Figure 2), showing high susceptibility to Alternaria black spot. *Brassica juncea* plants with the AUDPC value of 354.2 ± 208.0 and *E. sativa* plants with AUDPC value 253.1 ± 59.6 were classified as moderately susceptible to *A. brassicae*. The lowest AUDPC values were found on *S. alba* with 60.1 ± 27.7 and on *R. sativus* with 76.4 ± 16.7 (Figure 2).

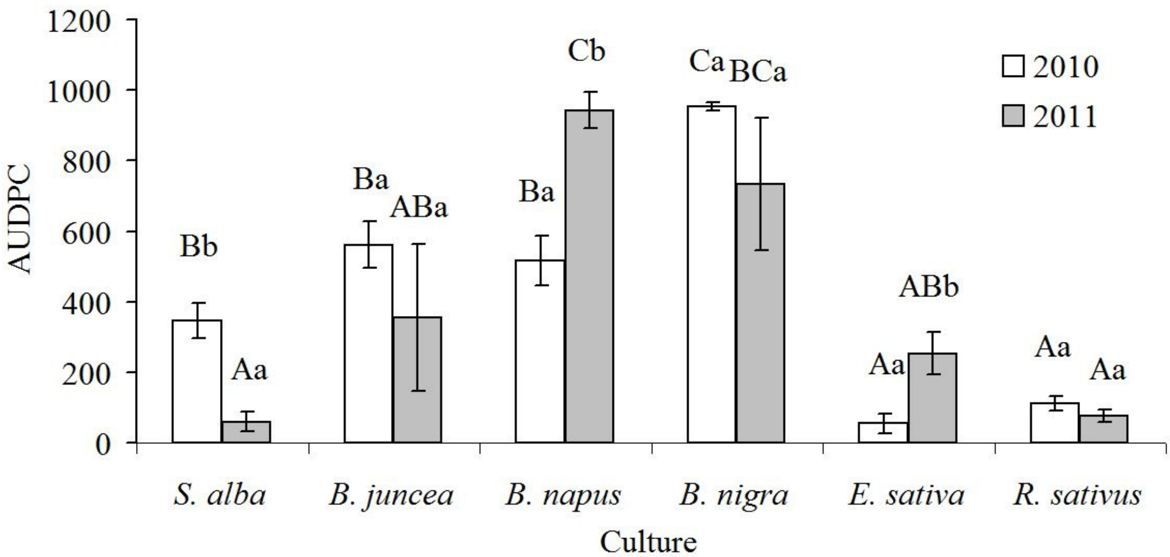


Figure 2. Mean area under the disease progress curve (AUDPC) values of Alternaria black spot (*A. brassicae*) infection in different cruciferous oilseed crops in the two study years. Error bars denote the standard error of the means. Means followed by different capital letters above each bar indicate a significant influence ($p < 0.05$) of cruciferous oilseed crop species in different years (Tukey HSD test). Means followed by different lowercase letters above each bar indicate a significant influence ($p < 0.05$) of year (Tukey HSD test).

Table 4. Impact of study year and species and their interaction on Alternaria black spot (*A. brassicae*) AUDPC values according to a two-way ANOVA.

Factor	Black Spot Disease
Year (Y)	$F_{1,24} = 0.16$; $p = 0.70$
Crop species (C)	$F_{5,24} = 24.29$; $p < 0.001$ *
Y × C	$F_{5,24} = 4.77$; $p < 0.01$ *

*—$p < 0.05$.

Combining the two-year AUDPC values, the most susceptible crops to Alternaria black spot were *B. nigra* (843.7 ± 97.5) and *B. napus* (729.7 ± 103.1), and both were considerably different from other tested crops ($F_{5,30}$ = 15.18, $p < 0.001$). Significantly lower AUDPC values were observed on *E. sativa* (154.0 ± 53.2) and *S. alba* (203.1 ± 69.0). Based on two years data, the most resistant cruciferous species was *R. sativus* with a very low average AUDPC value of 94.2 ± 14.1 (Figure 3).

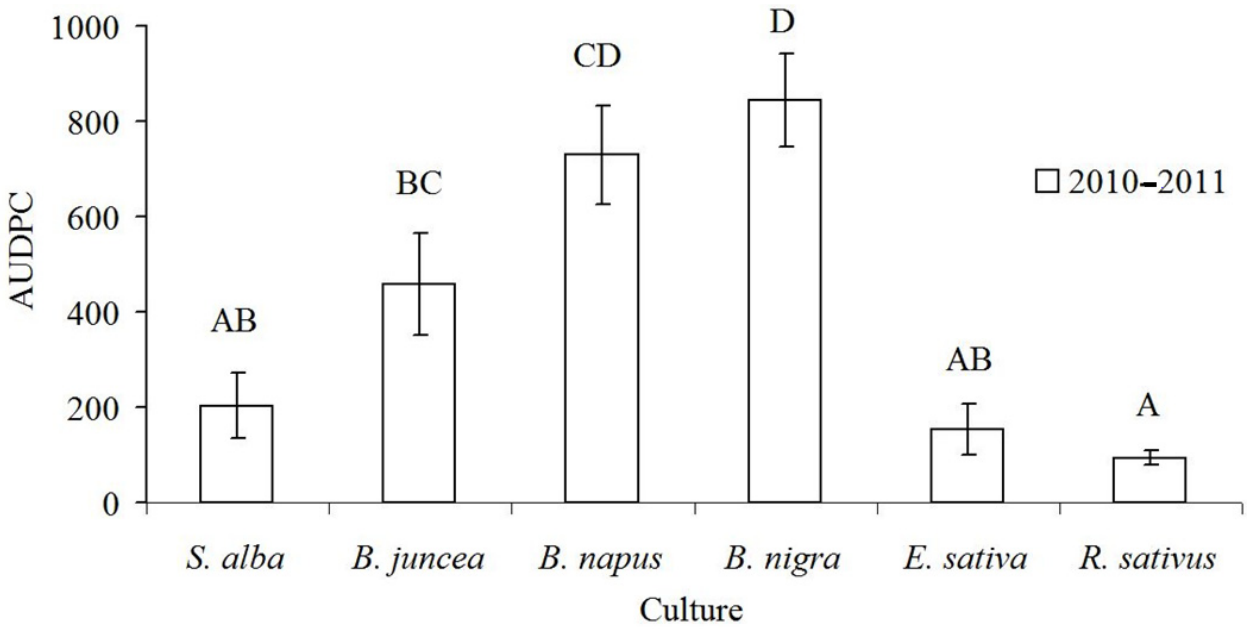


Figure 3. Mean area under the disease progress curve (AUDPC) of Alternaria black spot (*A. brassicae*) infection in different cruciferous oilseed crops (averages for the two study years). Error bars denote the standard error of the means. Means followed by different capital letters (A–D) above each bar indicate a significant influence ($p < 0.05$) of cruciferous oilseed crop species (Tukey HSD test).

4. Discussion

Weather conditions strongly influence the Alternaria black spot development [31], and previous studies have demonstrated that under suitable weather conditions mass spread of this pathogen can occur [14,16]. In this research, development of Alternaria black spot disease was assessed on spring oilseed rape and on five alternative cruciferous oilseed crop species. Both growing seasons, 2010 and 2011, were hotter and dryer compared to long-term (48 years) average and thus, were suitable for pathogen *A. brassicae* development and disease assessments.

Our research findings clearly showed that *Alternaria* spp. is an important pathogen on spring oilseed rape and on some alternative oilseed crops (*B. nigra*, *B. juncea*) in Northern Baltic conditions. The optimum temperature for sporulation of *A. brassicae* is 18–24 °C [32]. In our results, the main triggers for higher disease damage on some cruciferous species were warm weather conditions. Similarly, Al-lami et al. (2020) have found in lab experiments that the infection of *B. napus* and *B. juncea* by *A. brassicae* was less, 42%, under low temperatures of 14/10 °C (day/night) compared with higher temperatures of 22/17 °C (day/night), where 88.2% leaf area was infected [33]. Wet periods during the growing season are another factor promoting Alternaria black spot pathogen sporulation and disease development [32]. According to Brazauskiene et al. (2011), Alternaria black spot disease incidence and severity on winter and spring oilseed rape are greater in years with a wet growing season than in years with dry or very dry growing seasons [4]. In our research, the combination of two-year weather data showed a negative relationship between temperature and relative humidity, with lower temperatures and higher humidity in both years in May and drier and warmer weather in August. Thus, the high degree of infection of *B. napus* and *B. juncea* by *A. brassicae* in our study in 2010 and 2011 is consistent with the main role of growing season weather conditions as highlighted by Brazauskiene et al. (2011) [4].

Alternaria brassicae is a well-known seed-borne pathogen, causing also pod infection and thereby early maturation by pod splitting and seed fall-off. In Estonia, *A. brassicae* has been found on several species belonging to the Brassicaceae family: *Brassica oleracea* var. *botrytis* L., *B. napus* subsp. *napus*, *B. rapa* subsp. *oleifera*, indicating that the pathogen is able to infect a wide spectrum of cruciferous crops and weeds from the *Brassicaceae* family and other families [27]. Plant pathogen resistance is considered the most promising control method in sustainable agriculture. Common cultivated *Brassica* crops have very low genetic variability and are therefore highly susceptible to several diseases that can cause major yield losses [34]. In our field trial, AUDPC values were the lowest in *R. sativus*, *E. sativa* and *S. alba* compared to the other species. In both seasons, the infection severity was very low before the last observation week in all these three species. *Sinapis alba* is a wild member of the Brassicaceae family and is considered to possess high resistance against Alternaria black spot [35]. On the other hand, the information on *E. sativa* vulnerability to Alternaria black spot has been limited. According to a recent report by da Silva et al. (2020) [36] from Brazil, *A. brassicae* infects older plants of *E. sativa*, and it is likely that the association between *A. brassicae* and *E. sativa* is widespread there, though the degree of disease damage in cultivated plants is unknown. A higher tolerance of 35-day old cruciferous plants to *A. brassicola* compared to the 45- or 55-day-old plants is another possible reason why *R. sativus* and *E. sativa*, both in an earlier growth phase, were more resistant to the *Alternaria* black spot disease than *B. napus*, *B. nigra* and *B. juncea*, which were in a more advanced growth phase (Figure 1, Tables 1 and 2) [37]. In 2020, Macioszek et al. [38] showed that due to lower foliar contents of protective and antifungal polyphenolic compounds and glucosinolates, the older *B. juncea* leaves had a considerably greater *A. brassicola* damage than the younger leaves. A similar result was obtained by Mathpal et al. (2011) [39], who compared different plant genotypes with varying susceptibility against *Alternaria* black spot disease and found that, compared to *B. juncea* as the most susceptible species, the resistance of *B. alba* was related to higher content of phenolic compounds in the leaves. Nevertheless, there is evidence that during the infection, the contents of antifungal phenolic compounds increase [38], but the capacity for accumulation of protective compounds might decrease with increasing leaf age and onset of leaf senescence.

As discussed above, higher temperatures promote the Alternaria black spot disease development. Thus, climate warming could directly enhance the risk for Alternaria black spot pressure on cruciferous species, including oilseed crops [33], and might increase the yield gap. Similarly, in the Northern Baltics, recent unusually warm summers have increased the spread of *Alternaria* spp. on potato fields and led to severe infections [24,40]. In addition, the predicted increase in the frequency of warmer and drier summers with temporary heat waves [41] could increase problems due to *Alternaria* spp. pathogen spread, damage and Alternaria black spot disease control in Northern regions. Recent research has shown that in the Baltic Sea region, the climate has warmed particularly fast compared to the global average [42]. In the current study, Alternaria black spot disease infection was high on half of the tested cruciferous species, and we consider that this pathogen constitutes a direct threat to oilseed crops. Altered climatic conditions for plant growth due to global change and the growing population of the world reinforce the development of strategies for a sustainable agriculture and food system that ensure the efficient land use and high nutritional value of plants [43]. Thus, the knowledge of Alternaria black spot spread and plant vulnerability allows selection of more resistant species and cultivars, and this information is highly relevant for oilseed, intercrop, cover crop and green manure production, especially in sustainable farming systems. Currently, there is a limited assortment of alternative cruciferous and non-cruciferous oilseed crops for cultivation in upper latitudes, and there is a strong demand for new oilseed crops by local producers [44]. Alternative cruciferous species should be recommended for cultivations as green manure, intercrop, oilseed or for trap crop only if their susceptibility to Alternaria black spot is examined/known in a certain region. In the case of use of susceptible cultivars, one should carefully assess whether the losses do not exceed profits.

Until this work, information about the Alternaria black spot disease climatic sensitivity and cruciferous crop resistance was not available for Northern Baltic region conditions. Based on our observations in two extremely warm growing seasons in the Northern Baltics, we suggest that under favorable conditions for Alternaria black spot infection, alternative oilseed crops such as *S. alba*, *E. sativa* and *R. sativus* possess a great potential to grow with limited chemical inputs even in the case of conventional farming. The results of this work can be harnessed by local organic and sustainable farmers, who have already started to cultivate alternative cruciferous crops such as *B. juncea*, *S. alba* and *R. sativus* as intercrop and green manure. Furthermore, in the Northern Baltics, white mustard has growing importance in organic farming as an alternative lodging culture due to increasing the lodging resistance of field peas [45]. Based on our findings, in cultivating *B. juncea* plants, farmers should consider some need of chemical input for Alternaria black spot control; however, the pesticide requirements depend strongly on the weather conditions in the particular growing season.

5. Conclusions

This is the first report about infection rate of black spot disease (*A. brassicae*) on alternative cruciferous oilseed crop plants (*Brassica juncea*, *Brassica nigra*, *Sinapis alba*, *Raphanus sativus*, *Eruca sativa*) and evaluation of host species resistance in organic field conditions in the Northern Baltics. All tested cruciferous oilseed crops were infected by Alternaria black spot disease, but the infection severity varied strongly between the species and growing seasons. Two species, *B. napus* and *B. nigra*, were the most heavily infected by Alternaria black spot and thus, cannot be recommended for cultivations without chemical input for conventional growers. Based on our observations under extremely warm growing seasons that were favorable for Alternaria black spot infection, alternative oilseed crops *S. alba*, *E. sativa* and *R. sativus* are promising cultures for cultivation in organic farming or in the case of conventional farming with limited chemical input in Northern Baltic conditions.

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