Optimization of Chemical Suppression of *Alternaria dauci*, the Causal Agent of Alternaria Leaf Blight in Carrots

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ABSTRACT

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Alternaria leaf blight, caused by *Alternaria dauci*, is a major constraint to carrot production in Israel. Israeli carrot growers apply prophylactic sprays at 3- to 10-day intervals throughout the season until harvest, up to 30 sprays in a growing season. In this study, we attempted to optimize the chemical suppression of the disease, in order to reduce fungicide use. The efficacy of nine fungicides was determined in two field experiments. All fungicides reduced disease severity, but there were significant differences in efficacy among them. The most effective were difenoconazole and chlorothalonil; less effective were copper hydroxide, tebuconazole, trifloxystrobin, and mancozeb; the least effective in our experiments were flutriafol, propineb, and iprodione. The effect of the time of spray initiation on fungicide efficacy was determined in three field experiments. Qualitative (analysis of variance) and quantitative (regression) analyses of the data revealed that initiating sprays after disease onset reduced control efficacy. Thus, an action threshold model could not be developed for *A. dauci* in carrots. The time before harvest at which sprays could be terminated was tested in two field experiments and it was found that terminating sprays 14 days before harvest did not significantly affect the overall control efficacy. The main conclusions derived from these experiments were tested and corroborated in two additional field experiments.

Additional keywords: action threshold, integrated pest management, yield loss

Carrots (*Daucus carota* L. var. *sativa* DC.) are grown in Israel (30°E latitude, 31°N longitude) in three main seasons. The spring crop is sown in January to March and harvested in June to July; the autumn crop is sown in June to August and harvested in October to December; and the winter crop is sown in September to October and harvested in January to April. Alternaria leaf blight, caused by *Alternaria dauci* (Kühn) Groves and Skolko, is a major foliar disease of carrot in Israel (7,18) and other countries (8,16,17); severe epidemics may reduce yields by 40 to 60% (7,18). The disease is most important in Israel toward the end of the spring crop and in the autumn crop; epidemics affecting the winter crop are usually mild. Alternaria leaf blight damages carrot plants by

rapidly blighting or killing the leaves. Such damage usually results in poor growth and causes technical problems at harvest because leaves weakened by blight often break off when gripped and pulled by a mechanical harvester.

To suppress the disease and to prevent the losses it causes, carrot fields are intensively sprayed with fungicides. Fungicides of various chemical groups are currently registered in Israel for use against *A. dauci* in carrot. Among them are protectant fungicides of the carbamate group (e.g., mancozeb and maneb), tin fungicides (e.g., brestan), and copper fungicides (e.g., copper-hydroxide); others include chlorothalonil, propineb, and iprodione. Several systemic fungicides are also registered for use against *A. dauci* in carrot; most belong to the triazole group (e.g., tebuconazole, difenoconazole, and flutriafol). Recently, fungicides of the strobilurin group (e.g., trifloxystrobin) also have been registered. Growers are advised to alternate among fungicides of differing chemical groups and modes of action to reduce the risks of development of resistant pathogen populations; therefore, it is not always possible to determine the efficacy of individual fungicides and to quantify their relative contribution to overall disease suppression. In other Alternaria diseases, such as potato early blight (caused by *A. solani*) and

Alternaria leaf blight in cotton (caused by *A. macrospora*), it has been demonstrated that systemic fungicides were more effective than protectant fungicides in disease suppression (13,15).

Currently, carrot growers are advised to initiate sprays against Alternaria leaf blight before the appearance of the first disease symptoms. Sprays are initiated approximately 30 days after sowing in the autumn season and approximately 70 days after sowing in the spring season. Subsequent sprays are applied periodically, following irrigation. In the spring, the crop is irrigated every 5 to 10 days; in the summer and autumn, every 3 to 5 days. Thus, fungicides are applied 10 to 20 times on the spring crop and 20 to 40 times on the autumn crop. The time of disease onset and the suitability of the environment to the pathogen vary from field to field and from year to year; therefore, it is likely that at least some of the sprays are not needed. Some sprays could be avoided if adequate disease suppression were achieved through reactive sprays (i.e., in response to observing disease symptoms in the field). Accordingly, development of a disease action threshold is a crucial step toward optimization of Alternaria leaf blight management. An action threshold that was developed in Ontario, Canada saved one to three applications per season by delaying the initiation of sprays (3).

Currently, carrot growers in Israel are advised to protect the crop with fungicides until harvest. However, in other pathosystems (e.g., potatoes) it has been demonstrated that terminating sprays against Alternaria up to 14 to 17 days before harvest did not result in a significant increase in disease severity as compared with crops that were protected until harvest (12,14). Thus, early termination of sprays may save two to six sprays without increasing the risks of uncontrolled epidemics.

The goal of the present study was to optimize the use of fungicide application for the suppression of Alternaria leaf blight in carrot. Specific objectives were to (i) determine the efficacy of fungicides belonging to several chemical groups with differing modes of action, (ii) examine the possibility of developing an action threshold model for spray initiation, and (iii) determine the earliest time at which spray termination would not result in an increased risk of uncontrolled epidemics.

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MATERIALS AND METHODS

Cultural practices and experimental design. Nine field experiments were conducted from 1996 to 1999 for optimization of chemical suppression of *Alternaria* leaf blight in carrots. The experiments were conducted in the northern Negev region in Israel, in experimental plots or in commercial fields. Natural epidemics developed in all experiments. The efficacy of various fungicides was evaluated in two experiments; the time of spray initiation was determined in three experiments and the time of spray termination in two experiments. Conclusions derived from these sets of experiments were validated in two additional field experiments.

Carrot seed was sown in rows, approximately 80 seeds per meter of row. There were three or four rows per bed and the distance between beds was 1.8 or 2 m, respectively. Details concerning the cultivars, time of planting and harvesting, and the time of disease onset are presented in Table 1. Cv. Presto is highly susceptible and cvs. Predor and Valor are moderately susceptible to *A. dauci*. The crops were subjected to weed and insect controls as recommended to commercial carrot growers in that region. Irrigation was applied at night via overhead sprinklers once (spring season) or twice (autumn season) per week. Fungicides for *Alternaria* leaf blight management were applied as indicated below.

Experiments were laid out in a complete or split-block design, with four or five replicates per treatment. Each experimental plot was one bed in width and 8 m in length. Sprays were applied at 7- to 14-day intervals, 1 day after irrigation. Details of the fungicides used in this study are given in Table 2. Fungicides (in 250 to 300 liters of water/ha) were applied with a motorized backpack-sprayer, through cone-jet X8 nozzles (Spraying Systems, Wheaton, IL) at a pressure of 275 kPa. The sprays did not contain any additional spreader, sticker, or adjuvant.

The crop was inspected every 3 to 6 days starting 2 weeks after emergence in the autumn experiments and 2 months after

emergence in the spring experiments. After the first disease symptoms on true leaves were observed, disease severity (expressed as the percentage of the aerial plant tissue affected, including leaf blade and petiole lesions) was visually assessed according to the Horsfall-Barratt grading system (5). Assessments were performed every 6 to 10 days until harvest. Two individuals (the same ones throughout each experiment) made assessments on a whole-plot basis and the scores were averaged. For data analyses, the Horsfall-Barratt values were converted to disease percentage ratings. For some analyses, the area under the disease progress curve (AUDPC) was calculated on the basis of the season-long disease assessments. The period used for calculating AUDPC values extended from the date of the first appearance of disease to the last disease assessment. For comparing AUDPC values from different experiments, the relative area under the disease progress curve (RAUDPC) was calculated by dividing the AUDPC value by the duration of the epidemic and multiplying the outcome by 100. RAUDPC units are percentages. Disease severity or RAUDPC values recorded in treated plots (D_t) and in untreated plots (D_u) were used to calculate the fungicide efficacy (CE_t) achieved by the treatments (CE_t (%) = $100 - D_t/D_u \times 100$).

Carrots in the experimental plots were harvested just before harvest took place in the adjacent commercial plot. An area of 2

m² was manually harvested from the center of each experimental plot. Roots were removed, washed, and weighed and the yield per hectare was calculated. Data were analyzed by analysis of variance (ANOVA) or regression analyses, as appropriate. When the *F* test was significant at $P \leq 0.05$, the least significant difference (LSD) was calculated according to Fisher's protected LSD test. In some cases, multiple regression with dummy variables was employed. Details of the dependent and independent variables in each analysis are given below.

Fungicide efficacy. The efficacy of various fungicides in the suppression of *Alternaria* leaf blight was determined in two field experiments conducted in autumn 1997 and autumn 1998. Each experiment consisted of an untreated control and seven fungicide treatments. Five fungicides were applied in both experiments and an additional four fungicides in were applied in one of the experiments (Table 2). Sprays were initiated according to the common management practice and continued, at weekly intervals, until 1 week before harvest. In all, 8 sprays were applied in the 1997 experiment and 11 sprays in the 1998 experiment.

Time of spray initiation and termination. The effect of the time of spray initiation on fungicide efficacy was determined in three field experiments and that of the time of spray termination, in relation to the time of harvesting, in two field experi-

Table 2. Fungicides used in field experiments conducted for studying various aspects of the chemical suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) in carrot

Product name	Generic name	a.i. (%)	Rate (kg a.i./ha)	Fungicide type	Producer
Antracol	Propineb	70.0	1.75	Protectant	Bayer AG
Bravo	Chlorothalonil	50.0	1.25	Protectant	Diamond Shemork
Flint	Trifloxystrobin	50.0	0.15	Mesostemic	Bayer AG
Folicur	Tebuconazole	25.0	0.19	Systemic	Bayer AG
Impact	Flutriol	12.5	0.09	Systemic	Zeneca
Kocide DF	Copper hydroxide	61.4	1.54	Protectant	Kocide
Manzidan	Mancozeb	80.0	2.00	Protectant	Rohm & Haas
Rovral	Iprodione	50.0	0.50	Translaminar	Rhone Poulenc
Score	Difenoconazole	25.0	0.19	Systemic	Syngenta

Table 1. Field experiments conducted for studying various aspects of the chemical suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) in carrot

Objective	Experiment	Cultivar	Planting date	Harvest date	Disease onset	
					Date	Days after planting
Fungicide efficacy	1997, autumn	Predor	9 July	27 October	28 August	50
	1998, autumn	Valor	16 August	15 December	19 October	74
Spray initiation	1996, autumn	Predor	9 June	10 October	23 August	45
	1997, spring	Predor	2 March	13 July	13 July	100
	1997, autumn	Presto	18 July	27 October	6 September	50
Spray termination	1998, spring	Presto	18 February	7 July	8 June	110
	1998, autumn	Presto	3 July	11 November	6 September	65
Validation	1998, autumn	Valor	16 August	15 December	19 October	74
	1999, spring	Predor	3 March	8 August	17 June	105

ments. The spray initiation experiments were factorial with two factors. The first factor (time of spray initiation) had three levels: (i) initiation of sprays according to the common management practice (that is, approximately 30 days after planting in the autumn season and 70 days after planting in the spring season), (ii) initiation of sprays 2 weeks after the common management practice, and (iii) initiation of sprays 4 weeks after the common management practice (this treatment was included in only two of the experiments). The second factor in the experiments was fungicide type and this factor included two levels: (i) mancozeb (a protectant fungicide) and (ii) tebuconazole (a systemic fungicide). Untreated control plots were also included in each experiment.

Experiments on spray termination were conducted in commercial fields. Until the beginning of the experiments, the crop was treated with the fungicide chlorothalonil, according to the common management practice. The first experiment (spring 1998) began 42 days before harvest and the second experiment (autumn 1998) began 24 days before harvest; sprays continued weekly until the times noted for each treatment. In treatment (i), sprays were terminated at 42 and 24 days before harvest in the spring and autumn experiments, respectively. In treatment (ii), sprays were terminated 29 and 19 days before harvest in the spring and autumn experiments, respectively. In treatment (iii), sprays were terminated 21 and 13 days before harvest in the respective experiments; and in treatment (iv), 14 and 7 days before harvest in spring and autumn, respectively. The spring experiment also included treatment (v), an untreated control, on which no spray was applied throughout the entire growing season.

Validation of the conclusions. Conclusions derived from the experiments described above on fungicide efficacy and time of spray initiation and termination were validated in two field experiments, conducted in autumn 1998 and spring 1999. Both experiments included four treatments: (i) an untreated control, (ii) treatment with fungicides throughout the season ("all-season" treatment), (iii) application of fungicides until the time of disease onset ("early-termination" treatment), and (iv) initiation of fungicide applications only after the onset of disease ("late-initiation" treatment). The first disease symptoms were observed 74 and 105 days after planting in autumn 1998 and spring 1999, respectively. The fungicide difenoconazole was applied in both experiments at 7- to 14-day intervals. Sprays were applied in the autumn 1998 experiment as follows: in treatment (ii), from 29 to 109 days after planting (eight sprays in total); in treatment (iii), from 29 to 65 days after planting (four sprays in total); and in treatment (iv), from 77 to 109 days after planting (four

sprays in total). Sprays were applied in the spring 1999 experiment as follows: in treatment (ii), from 64 to 142 days after planting (eight sprays in total); in treatment (iii), from 64 to 92 days after planting (four sprays in total); and in treatment (iv), from 106 to 142 days after planting (four sprays in total).

RESULTS

Fungicide efficacy. The efficacy of various fungicides in the suppression of *Alternaria* leaf blight in carrots was determined in two field experiments. In 1997, the first disease symptoms were observed 50 days after planting and, within 6 weeks, disease severity in untreated plots exceeded 85% (Fig. 1A). Up to 90 days after planting, all the tested fungicides reduced disease severity significantly below that in the untreated control plots. Differences in

disease severity among the fungicide-treated plots were insignificant. However, from that time on, some of the fungicides were more effective than others and, by the end of the season, there were significant differences in disease severity among the fungicide-treated plots. Based on the final disease records and on RAUDPC values, the efficacy of the tested fungicides was determined (Fig. 1A; Table 3). The most effective were difenoconazole and chlorothalonil, both of which reduced the RAUDPC values (as compared with the untreated plots) by 86 to 88%. Less effective were copper hydroxide, tebuconazole, and mancozeb; these fungicides reduced RAUDPC values by 60 to 70%. Flutrifol and iprodione were the least effective among the tested fungicides and reduced the RAUDPC values over the untreated control by approximately 50%. Yields in

Fig. 1. Effects of various fungicides on suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) in carrot in two autumn experiments: **A**, autumn 1997 and **B**, autumn 1998. Untreated control (open square), mancozeb (open circle), iprodione (open diamond), flutrifol (cross), tebuconazole (solid square), copper hydroxide (line), chlorothalonil (open triangle), difenoconazole (solid diamond), propineb (star), trifloxystrobin (cross inside square). Vertical lines represent the least significant differences ($P \leq 0.05$) for each assessment date.

Table 3. Effects of various fungicides on suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) and on carrot yields in two experiments^w

Experiment, fungicide and rate (kg a.i./ha) ^x	Disease severity (%) ^y	RAUDPC (%) ^z	Yield (ton/ha)
1997, autumn			
untreated control	90.9 a	48.8 a	53.5 d
Iprodione (0.5)	72.0 b	23.1 b	78.1 bc
Mancozeb (2.0)	73.6 b	20.5 c	80.6 bc
Flutrifol (0.09)	66.5 bc	23.4 c	74.8 c
Tebuconazole (0.19)	60.5 c	19.7 cd	82.6 b
Copper hydroxide (1.5)	44.5 d	14.5 d	86.5 ab
Chlorothalonil (1.2)	14.2 e	6.1 e	93.0 a
Difenoconazole (0.19)	16.3 e	5.4 e	92.9 a
1998, autumn			
Untreated control	90.0 a	53.7 a	72.4 c
Iprodione (0.5)	72.0 b	35.5 b	76.1 bc
Propineb (1.7)	68.0 bc	34.5 b	79.3 bc
Trifloxystrobin (0.15)	56.0 cd	21.0 c	88.8 ab
Tebuconazole (0.19)	52.0 de	22.9 c	93.1 ab
Copper hydroxide (1.5)	42.0 e	17.1 cd	90.2 ab
Chlorothalonil (1.2)	24.0 f	10.7 de	89.2 ab
Difenoconazole (0.18)	24.0 f	7.4 e	94.4 a

^w Numbers (in each column, for each experiment) followed by different letters differ significantly as determined by a least significant difference test ($P \leq 0.05$).

^x Fungicides were applied at 7- or 7- to 14-day intervals in 1997 and 1998, respectively.

^y Disease severity at the last assessment date, just before harvest.

^z RAUDPC = relative area under the disease progress curve.

all fungicide-treated plots were significantly higher than those in the untreated control plots. The largest increases in yield were observed in plots treated with difenoconazole or chlorothalonil (39 ton/ha; 74% increase). In the other treatments, yield increases ranged from 12 to 33 ton/ha (25 to 61%; Table 3).

In 1998, disease severity increased from 7% (87 days after planting) to 87% within 4 weeks (Fig. 1B). All the tested fungicides reduced disease severity significantly as compared with untreated plots, but there were marked differences in efficacy among them. The most effective, as in 1997, were difenoconazole and chlorothalonil, both of which reduced RAUDPC values by 80 to 86% as compared with the untreated control. Less effective were copper hydroxide, tebuconazole, and trifloxystrobin. They reduced RAUDPC values by 57 to 68%. The least effective were propineb and iprodione, with 33 to 44% control efficacy (Fig. 1B; Table 3). The effects of the fungicides on yields resembled their efficacy in

disease suppression. Yields were increased significantly in plots treated with the most and the moderately efficacious fungicides, but not in those treated with the least efficacious ones. Yield increases ranged from 12 to 22 ton/ha. The largest yield increase was observed in plots treated with difenoconazole (22 ton/ha, 30% increase; Table 3).

Time of spray initiation. The effect of the time of spray initiation on fungicide efficacy was determined in three field experiments. Disease severity in untreated plots intensified from less than 5% to more than 85% within 3 to 5 weeks. By the end of the season, disease severity in untreated plots was $\geq 90\%$ in all experiments (Fig. 2). In most cases, disease severity was significantly lower and yield was significantly higher in fungicide-treated plots than in the untreated control plots. In general, postponing the time of spray initiation from that used under common management practice resulted in a gradual decrease in control efficacy, as reflected in final dis-

ease severity and RAUDPC values as compared with the common management treatment. Yield was higher in these treatments in five out of the six comparisons (Table 4).

The relative efficacy of tebuconazole and mancozeb was determined by comparing treatments in which sprays were initiated at the same time. In six (based on final disease severity) or five (based on RAUDPC values) out of eight comparisons, tebuconazole was significantly more effective than mancozeb (Table 4).

Multiple regression analysis of the results recorded in the three experiments enabled us to test the hypothesis that fungicide efficacy is governed by the time of spray initiation. The efficacy of tebuconazole was generally significantly higher than that of mancozeb; therefore, a dummy variable was included in the analysis, representing the effect of fungicide type. In the first analysis, effects on fungicide efficacy (dependent variable) were determined in relation to the time of dis-

Fig. 2. Effects of the time of spray initiation on suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) in carrot in three field experiments: **A** and **B**, autumn 1996, **C** and **D**, spring 1997, **E** and **F**, autumn 1997. Application of **A**, **C**, and **E**, the protectant fungicide mancozeb (2.0 kg a.i./ha) and **B**, **D**, and **F**, the systemic fungicide tebuconazole (0.18 kg a.i./ha). Untreated control (open square), sprays initiated at the common timing (solid square), sprays initiated 2 weeks after the common timing (open triangle), sprays initiated 4 weeks after the common timing (solid triangle). Vertical lines represent the least significant differences ($P \leq 0.05$) for each disease assessment date.

ease onset and fungicide type (the independent variables). The regression equation was $CE = 36.6 + 19.0 \times Fu - 0.82 \times To$, where CE = fungicide efficacy (%), Fu = fungicide type (a dummy variable, 0 = mancozeb, and 1 = tebuconazole), and To = time between spray initiation and disease onset (days). The regression equation was highly significant ($R^2 = 0.59$, $P = 0.0028$). The earlier the spray initiation, relative to the time of disease onset, the higher the fungicide efficacy achieved (Fig. 3A). In the second analysis, effects on fungicide efficacy (the dependent variable) were determined in relation to the time that passed since planting. Disease onset in the spring crop occurred later than in the autumn crop; therefore, a dummy variable was included in the analysis, representing the effect of the season. The independent variables in the analysis were time, fungicide type, and the season. The regression equation was $CE = 83.4 + 19.2 \times Fu + 46.9 \times S - 0.98 \times Tp$, where: CE = fungicide efficacy (%); Fu = fungicide type (a dummy variable, 0 = mancozeb, and 1 = tebuconazole); S = the season (a dummy variable, 0 = autumn, and 1 = spring), and Tp = time between planting and spray initiation (days). The regression equation was highly significant ($R^2 = 0.69$, $P = 0.0022$). For both crops, the earlier the spray initiation after the time of planting, the greater was the efficacy of the fungicides (Fig. 3B).

Time of spray termination. The optimal time for spray termination, in relation to the time of harvest, was evaluated in two field experiments. In spring 1998, disease appeared late in the season (29 days before harvest) but increased rapidly thereafter and, by the time of harvesting, disease severity in untreated plots was 92% (Fig. 4A). In autumn 1998, the first disease symptoms were observed in the experimental site 34 days before harvest. When the experiment started 10 days later, disease severity in the experimental site was 7.4% (Fig. 4B). In both experiments, the earlier the spray termination, the greater the disease severity by the end of the season. However, termination of sprays 14 days before harvest (or later) still resulted in adequate disease suppression. Yield was not reduced significantly, even in plots where sprays were terminated up to 29 days before harvest (Table 5).

Validation of the conclusions. The main conclusions derived from the experiments were: (i) the most effective fungicides are difenoconazole and chlorothalonil, (ii) sprays should be initiated before disease onset, and (iii) disease severity does not increase markedly until 14 days after the last application. These conclusions were validated in two field experiments conducted in autumn 1998 and spring 1999.

In autumn 1998, the first disease symptoms were observed 74 days after planting.

Disease in untreated plots developed slowly at first; from 87 days after planting onward, disease developed more rapidly and disease severity reached 85% 3 weeks later. In plots treated with fungicides throughout the growing season, disease severity was significantly lower (fungicide efficacy 86.2%, based on RAUDPC), and yield was significantly higher (an additional 22.1 ton/ha; 30.7% increase) than in the untreated plots (Table 6). In the early-termination treatment, sprays were terminated 65 days after planting, before the onset of disease. In that treatment, disease severity remained lower than 10% 35 days

after the last spray. By that time, disease severity in untreated plots was 66%. Although sprays in the early-termination treatment were not applied after disease onset, the RAUDPC value was significantly lower and yield was significantly higher in this treatment than in the late-initiation treatment, where the crop was protected throughout the entire epidemic. Fungicide efficacy in the latter treatment was only 37.1% and yield was not significantly higher than the untreated control plots (Table 5).

In the spring 1999 experiment, the first disease symptoms were observed 105 days

Table 4. Effects of the time of spray initiation on suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) and on carrot yields in three field experiments^w

Experiment, treatment ^x	Disease severity (%) ^y	RAUDPC (%) ^z	Yield (ton/ha)
1996, autumn			
Untreated control	96.2 a	37.6 a	26.9 e
Mancozeb, C	75.0 b	20.7 bc	36.5 d
Mancozeb, C+2	53.0 c	14.5 cd	43.6 bc
Mancozeb, C+4	74.4 b	24.1 b	38.1 cd
Tebuconazole, C	42.3 c	9.1 d	52.1 a
Tebuconazole, C+2	48.0 c	12.1 d	48.4 ab
Tebuconazole, C+4	51.5 c	15.8 cd	45.0 abc
1997, spring			
Untreated control	90.0 a	37.6 a	84.8 c
Mancozeb, C	54.0 c	17.2 c	96.7 b
Mancozeb, C+2	58.4 c	20.2 c	95.2 b
Mancozeb, C+4	73.2 b	29.2 b	95.9 b
Tebuconazole, C	16.2 e	4.2 e	108.8 a
Tebuconazole, C+2	30.6 d	10.4 d	96.6 b
Tebuconazole, C+4	63.1 c	27.3 b	93.4 b
1997, autumn			
Untreated control	98.6 a	51.9 a	39.0 c
Mancozeb, C	92.3 ab	29.6 b	57.2 ab
Mancozeb, C+2	92.0 ab	36.0 b	48.9 bc
Tebuconazole, C	76.0 c	19.3 c	64.7 a
Tebuconazole, C+2	86.3 b	30.2 b	55.2 ab

^w Numbers (in each column, for each experiment) followed by different letters differ significantly as determined by a least significant difference test ($P \leq 0.05$).

^x The protectant fungicide mancozeb was applied at a rate of 2.0 kg a.i./ha and the systemic fungicide tebuconazole at 0.19 kg a.i./ha. Sprays were initiated according to the common management practice (C), 2 weeks later (C+2), or 4 weeks later (C+4). Subsequent sprays, until the end of the season, were applied at 7-day intervals.

^y Disease severity at the last assessment date, just before harvest.

^z RAUDPC = relative area under the disease progress curve.

Fig. 3. Effects of the time of spray initiation in relation to **A**, the onset of disease or **B**, the time that passed after planting on fungicide efficacy of *Alternaria* leaf blight (caused by *Alternaria dauci*) in carrot. Experiments were conducted in the autumn of 1996 and 1997 (solid symbols) and in the spring of 1997 (open symbols). The protectant fungicide mancozeb (solid lines, square symbols) was applied at 2.0 kg a.i./ha and the systemic fungicide tebuconazole (broken lines, circles) was applied at 0.18 kg a.i./ha. Regression equations are presented in the text.

after planting. Disease in untreated plots developed slowly at first but more rapidly from 123 days after planting onward, and disease severity reached 75% 4 weeks later. In plots treated throughout the growing season, disease was significantly lower (control efficacy 96.4%, based on

RAUDPC) than in the untreated plots (Fig. 5B). In the early-termination treatment, the last spray was applied 92 days after planting and disease severity remained lower than 10% for another 52 days. By that time, disease severity in untreated plots was 41% (Fig. 5B). In the late-initiation

treatment, the first spray was applied 106 days after planting, just after the onset of disease. Control efficacy in that treatment was high until the end of the season (Fig. 5B, Table 6).

DISCUSSION

Effects of *Alternaria* leaf blight on carrot yield are devastating. Yield in fungicide-treated plots was increased (as compared with untreated plots) by up to 24 ton/ha (28%) in the spring season and by up to 39 ton/ha (74%) in the autumn season. Carrots in our experiments were harvested manually. Thus, these values reflect only the effects of the pathogen on the actual yield. It is likely that these differences would have been larger if mechanical harvesting had been applied, because leaves weakened by blight often break off when gripped by a mechanical harvester and the roots are not collected. Average yields in Israel in commercial fields range from 60 to 80 ton/ha. Assuming that potential loss from the disease is 20 to 40 ton/ha and that the value of the yield is \$0.4/kg, the potential damage from *Alternaria* leaf blight ranges from \$8,000 to \$16,000/ha. The cost of one fungicide application is \$50/ha on the average (including the cost of the product, which ranges from 10 to \$60/ha, and the cost of spraying, which is approximately \$20/ha). Thus, the cost of one spray is 0.3 to 0.6% of the potential damage. In situations where the potential cost of damage is much higher than that of chemical protection, growers tend to use chemical control as an insurance measure and to apply fungicides whether they are needed or not (10). This is indeed the situation for *Alternaria* leaf blight in carrots in Israel. Currently, carrot growers in Israel initiate sprays as a prophylactic measure before disease symptoms appear, apply subsequent sprays frequently, and continue to protect the crop until harvest. The outcome is that many of the applied sprays are not needed. In the present study, we attempted to optimize the chemical management of the disease. Such optimization would enable growers to reduce the number of sprays without increasing the risks of uncontrolled epidemics.

In the first step of the research, the relative efficacy of several fungicides was evaluated. Currently, more than 25 different compounds are registered in Israel for use against *Alternaria* leaf blight in carrots, but no reliable information on their relative efficacy is available. In the present study, the efficacy against *Alternaria* leaf blight of nine fungicides from several chemical groups was evaluated. All the fungicides suppressed *Alternaria* leaf blight significantly as compared with untreated plots, but there were marked differences in efficacy among them. The most effective fungicides were chlorothalonil and difenoconazole. Difenoconazole also has been found to be the most effective fungicide

Fig. 4. Effects of the time of spray termination (in relation to the date of harvest) on suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) in carrot in two field experiments. **A**, Spring 1998; untreated control (open square); last sprays applied 42 (solid square), 29 (solid triangle), 21 (open triangle), or 14 (no symbol) days before harvest. **B**, Autumn 1998; last sprays applied 24 (open square), 19 (solid square), 13 (solid triangle), or 7 (open triangle) days before harvest. Vertical lines represent the least significant differences ($P \leq 0.05$) for each disease assessment date.

Table 5. Effects of the time of spray termination on suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) and on carrot yields in two field experiments^x

Experiment, spray termination (days before harvest) ^y	Disease severity (%) ^z	Yield (ton/ha)
1998, spring		
Untreated control	92.3 a	112.5 b
42	48.8 b	130.6 ab
29	25.6 c	134.9 a
21	14.4 cd	128.6 ab
14	5.1 d	135.1 a
1998, autumn		
24	66.0 a	101.7 a
19	42.0 b	102.7 a
13	32.5 c	98.5 a
7	25.0 c	99.3 a

^x Numbers (in each column, for each experiment) followed by different letters differ significantly as determined by a least significant difference test ($P \leq 0.05$).

^y Chlorothalonil was applied according to the common management practice until a certain date before harvest, after which the plots were not treated with fungicides. Fungicides were not applied to the untreated plots.

^z Disease severity at the last assessment date, just before harvest.

Table 6. Effects of the times of spray initiation and termination on suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) in carrots in two field experiments^w

Experiment, treatment ^x	Disease severity (%) ^y	RAUDPC (%) ^z	Yield (ton/ha)
1998, autumn			
Untreated control	91.3 a	48.0 a	71.9 c
All season	24.4 c	6.6 d	94.0 a
Early termination	62.1 b	21.1 c	85.2 b
Late initiation	69.8 b	30.2 b	72.4 c
1999, spring			
Untreated control	83.0 a	36.3 a	...
All season	4.6 c	1.3 c	...
Early termination	45.0 b	10.5 b	...
Late initiation	6.6 c	2.2 c	...

^w Numbers (in each column, for each experiment) followed by different letters differ significantly as determined by a least significant difference test ($P \leq 0.05$).

^x Difenoconazole was applied throughout the growing season according to the common management practice (all season), terminated before the onset of disease (early termination), or initiated soon after the onset of disease (late initiation).

^y Disease severity at the last assessment date, just before harvest.

^z RAUDPC = relative area under the disease progress curve.

against *Alternaria* leaf blight in Belgium (19). Analysis of the results of the present field experiments enabled two points to be emphasized. First, although it has been demonstrated for different crops (13,15) and is generally accepted by the carrot industry in Israel, that systemic fungicides are more effective than protectant fungicides against *Alternaria* diseases, this was not the case in *Alternaria* leaf blight. Chlorothalonil (a protectant fungicide) was found to be significantly more effective than some of the systemic fungicides (e.g., tebuconazole and flutriafol). Studies of the persistence, deposition, and distribution of chlorothalonil within the plant canopy, by several authors, have shown that chlorothalonil is relatively resistant to degradation and that it retains its efficacy for long periods as compared with other fungicides (2,4). Lukens and Ou (6), for example, concluded that the intervals between applications on tomato could be increased to 10 days and still ensure adequate control of early blight. The second point is that there were significant differences in efficacy among fungicides of the same chemical group that share same mode of action. Tebuconazole, difenoconazole, and flutriafol are all systemic fungicides that belong to the triazole group of fungicides and all inhibit the C¹⁴ demethylation step in ergosterol biosynthesis (DMI fungicides). Nevertheless, difenoconazole was significantly more effective than the other two DMI fungicides. These results were not unexpected because it is well documented that the biological activity of pesticides is influenced by various parameters, such as the application technique, plant characteristics, the physiochemical characteristics of active ingredients, and environmental conditions (1).

In the second step of the research, the time of spray initiation was examined.

Currently, sprays are initiated in carrots as a prophylactic measure before disease symptoms appear in the field. We attempted to develop an action threshold model for spray initiation (i.e., a system for initiating sprays only after disease symptoms are observed; 20). Qualitative analyses of the data (by ANOVA) revealed that initiating sprays after the onset of disease reduced fungicide efficacy, although this reduction was significant only in part of the comparisons. However, quantitative analyses of the data (by regression analysis) revealed that the earlier the initiation of sprays, relative to the onset of disease, the higher the fungicide efficacy achieved. This relationship was valid for both compounds used and for both growing seasons. The highest fungicide efficacy was observed when sprays were initiated 28 days before the first disease symptoms were observed in the field. On the assumption that the length of the *A. dauci* disease cycle is 8 to 12 days under field conditions (8,16), this finding implies that the highest fungicide efficacy was achieved when sprays were initiated 2 to 3 disease cycles before the observers were able to find the first disease symptoms in the field. Different results have been reported from Ontario, Canada, where spray initiation after disease severity had risen above 1 to 2% still gave adequate disease suppression (3). Differences between the two countries in disease dynamics and epidemic intensity (i.e., disease severity increases more rapidly and epidemics are more severe in Israel) are probably the reason for the differing results. Nevertheless, the conclusion is that initiating sprays according to an action threshold model is not applicable for *Alternaria* leaf blight in carrots in Israel. Therefore, spray initiation should remain prophylactic.

The response of some crops to *Alter-*

naria changes with their physiological age. For example, potato plants are highly resistant to *A. solani* until the initiation of tuberization, and cotton plants are highly resistant to *A. macrospora* until the initiation of flowering. Following these phenological stages, the responses of both crops change and they become gradually more and more susceptible during the reproductive stage. Accordingly, it was found that sprays applied for the suppression of *Alternaria* before tuber initiation in potatoes (11,12,14) or before flowering in cotton (9,11) did not contribute to overall disease suppression. In carrots, the time that has passed since planting provides a rough indication of the development stage of the carrot roots (although there are differences among cropping seasons). Comparison of the effects of time of spray initiation (in terms of the time since planting) on fungicide efficacy in the autumn and spring seasons suggests that the crop growth stage at the time of spray initiation was not important in carrots. In both seasons, early initiation of sprays was advantageous. What apparently was important was the time of disease onset, and that is governed by the availability of inoculum and by environmental conditions rather than by the crop developmental stage (E. Ben-Noon, unpublished data). The conclusion is that initiation of sprays according to the phenological development stage of the crop is not applicable for *Alternaria* leaf blight in carrots.

The next step was to determine when sprays could be terminated. In potatoes, it has been reported that terminating sprays against early blight 14 to 17 days before the end of the season did not affect the overall control efficacy significantly (12,14). Similar results were observed in the present study for *A. dauci*. The conclusion from these findings is that it is not necessary to continue to apply protection against *Alternaria* leaf blight in carrots until harvest. Sprays may be terminated earlier and 2 to 6 unnecessary sprays may be saved.

The main conclusions derived from the experiments described above were validated and corroborated in two additional field experiments. In both experiments, there was a treatment in which difenoconazole was applied only until the onset of disease (the early-termination treatment). Sprays in that treatment prevented the very first disease cycles that were below the observation capability of the scouts. Sprays were terminated before disease onset; therefore, plants in that treatment were not protected with fungicides for the duration of the entire epidemic. Nevertheless, disease development was suppressed significantly as compared with untreated control plots and disease severity remained below 10% for 35 to 52 days after application of the last spray. Initiating sprays after the onset of disease resulted in poor dis-

Fig. 5. Effects of the time of spray initiation and termination on suppression of *Alternaria* leaf blight (caused by *Alternaria dauci*) in carrot in two field experiments. **A**, Autumn 1998; untreated control (open square); sprays applied according to the commercial management practice from 29 to 109 days after planting (solid square), terminated before the onset of disease, 65 days after planting (solid triangle), or initiated after the onset of disease, 77 days after planting (open triangle). **B**, Spring 1999; untreated control (open square); sprays applied according to the commercial management practice from 64 to 142 days after planting (solid square), terminated before the onset of disease, 92 days after planting (solid triangle), or initiated just after the onset of disease, 106 days after planting (open triangle). Vertical lines represent the least significant differences ($P \leq 0.05$) for each disease assessment date.

ease suppression. These results emphasize the importance of early sprays in the overall suppression of *Alternaria* leaf blight in carrots. Apparently, early sprays prevent the first disease cycles and delay the establishment of the pathogen in the crop. The validation experiments demonstrated that adequate suppression of *Alternaria* leaf blight could be achieved with application of only four to eight sprays in a growing season. The results of this study were adopted by carrot growers in Israel and have enabled them to save a large number of sprays in a growing season.

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