Managing Foliar Blights on Carrot Using Copper, Azoxystrobin, and Chlorothalonil Applied According to TOM-CAST

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ABSTRACT

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Alternaria dauci and *Cercospora carotae* cause foliar blight on carrot, causing yield reductions in severely blighted fields. Currently, fungicides are used on either a 7-day schedule or according to the TOM-CAST disease forecasting system. Organic production prohibits applications of most fungicides for blight control but does allow select copper-based products. The objective of this study was to use the TOM-CAST weather forecasting system to (i) assess the efficacy of copper hydroxide treatments for organic operations and (ii) evaluate the efficacy of reduced-risk products in an alternating spray program. Chlorothalonil, azoxystrobin, and copper hydroxide were applied alone or in alternating programs in 2001 and 2002. Reapplications were made on a 7-day schedule or according to TOM-CAST using disease severity value (DSV) thresholds of 10, 15, and 20. Area under the disease progress curve (AUDPC) data revealed that all application intervals significantly limited disease incidence on the foliage and petioles, resulting in healthier petioles at harvest compared with the untreated. The 7-day and TOM-CAST 10 DSV programs had comparable rating values for all parameters assessed and were more effective than the TOM-CAST 15 and 20 DSV programs in limiting petiole disease and maintaining overall petiole health. Copper hydroxide treatments resulted in higher AUDPC values and significantly different petiole health ratings compared with other treatments, yet *P* values indicated significant disease control compared with the untreated. The TOM-CAST 15 DSV program reduced sprays up to 40% compared with a 7-day interval and produced mean savings of \$127/ha in 2001 and \$137/ha in 2002.

Blights caused by *Alternaria dauci* and *Cercospora carotae* are common diseases of carrot (*Daucus carota*) in all major production areas of the world (13). Symptoms of *A. dauci* infection include dark brown, irregularly shaped lesions with a yellow margin that typically occur on mature or senescing leaves. *C. carotae* can infect young, emerging tissue, resulting in small, circular lesions that enlarge into dark brown spots with a chlorotic border (17,31). Under environmental conditions that favor disease development, lesions coalesce to cover entire leaflets to the point of foliar necrosis and a girdling of petioles, resulting in a reduction of photosynthesis and overall yield. Because Michigan carrot growers harvest crops using mechanical equipment that grasps the foliage to lift roots out of the soil, diseased and weakened petioles break and prevent maximum harvest, thereby further reducing yield (13).

In 2006, Michigan growers harvested an estimated 2,270 ha of carrot for fresh mar-

ket, cut-and-peel, and processing uses (5). Depending on which of these three uses is intended, plant spacing and cultivars may vary for growers and can create challenges for management. Fungal foliar blights are currently managed by applying registered fungicides, including chlorothalonil, iprodione, azoxystrobin, pyraclostrobin, and copper-based products. Chlorothalonil and iprodione are classified as B2 carcinogens and may be impacted by the Food Quality Protection Act, as well as some processor restrictions. The strobilurin fungicide products (i.e., azoxystrobin and pyraclostrobin) offer a reduced risk to the applicator and the nontargeted environment (6). Some fixed-copper formulations are approved for use in organic crop production, according to the Organic Materials Review Institute (www.omri.org). Despite moderate control against *Alternaria* leaf blight when pathogen pressure is severe, copper treatments increase crop yields equivalent to several industry standard products (7).

Michigan carrot growers have shown interest in management techniques that reduce the reliance on B2 carcinogenic fungicides in order to retain future contracts with some restrictive processors, reduce production costs, and delay possible development of insensitivity of the pathogens (4). In a number of crops, focus has shifted to computerized forecasting systems that

identify periods when environmental conditions favor disease. FAST and TOM-CAST are examples of such a system used for diseases such as *A. solani* on tomato or *Stemphylium vesicarium* on pear, and has been shown to reduce fungicide applications from 28 to 38% compared with a 7-day schedule (22,25). The TOM-CAST model reduces the required number of sprays compared with applying fungicides weekly without compromising fruit quality or yield (11,15). The forecaster assigns a daily disease severity value (DSV) based on the duration of leaf wetness and the average temperature during periods with elevated moisture. When the cumulative DSV reaches a predetermined threshold, fungicide sprays are prompted (26). Studies have determined that the optimal DSVs for initiating sprays with TOM-CAST are 18 to 25 DSV for tomato (11,20,24), 15 DSV for purple spot (*S. vesicarium*) on asparagus (23), and 20 and 15 DSV for Wisconsin (28) and Michigan (8), respectively, for carrot foliar blights.

Michigan carrot growers use various management practices, including disease forecasters, to control foliar blights caused by *C. carotae* and *A. dauci*. Organic growers may be able to include additional fungicide tools such as copper-based products into their TOM-CAST program to reduce the seasonal number of sprays. Conventional growers can incorporate reduced-risk fungicides with TOM-CAST to maintain processor standards and maximize yield. Our objective was to test the TOM-CAST weather-forecasting system in combination with (i) copper hydroxide treatments for organic operations and (ii) a reduced-risk product for conventional growers seeking to reduce the use of fungicides classified as B2 carcinogens.

MATERIALS AND METHODS

Experimental design and spray applications. Plots were established at the Michigan State University Muck Soils Research Farm in Laingsburg on a Houghton muck field. Fresh market carrot seed ('Heritage') was sown at 65.6 seeds/m of row on 14 May 2001 and 21 May 2002 in muck soil previously planted with potato. Three rows spaced 0.5 m apart were seeded per raised bed. Beds were arranged in parallel and spaced 1.6 m on center. Treatment plots were one bed wide and 7.2 m long. Sections of unsprayed carrot plants were alternated with each treatment

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plot. Twenty-nine treatments, including an untreated control, were arranged in a randomized complete block design with four blocks measuring 49.4 m long and 15.2 m wide. The susceptible cultivar used was infected by naturally occurring *C. carotae* and *A. dauci* inoculum. Weed control and fertilization requirements were managed according to standard commercial practices (33) and plots were irrigated as needed.

The fungicides copper hydroxide (Kocide 2000 53.8DF at 0.91 kg a.i./ha; E. I. du Pont de Nemours and Co., Wilmington, DE), chlorothalonil (Bravo Ultrex 82.5WDG at 1.30 kg a.i./ha; Syngenta Crop Protection, Inc., Greensboro, NC), and azoxystrobin (Quadris 2.08SC at 0.11 kg a.i./ha; Syngenta Crop Protection, Inc.) were applied in the following programs: (i) untreated, (ii) copper hydroxide, (iii) copper hydroxide alternated with azoxystrobin, (iv) copper hydroxide alternated with chlorothalonil; (v) azoxystrobin, (vi) azoxystrobin alternated with chlorothalonil, (vii) chlorothalonil, and (viii) chlorothalonil alternated with azoxystrobin alternated with copper hydroxide. Fungicides were applied with a CO₂ backpack sprayer (R & D Sprayers, Opelousas, LA) equipped with three D3 hollow-cone nozzles (Teejet, Chicago) spaced 45.8 cm apart, operating at 2.8 kg/cm² and calibrated to deliver 473 liters/ha.

Treatments prompted according to the TOM-CAST program were based on duration of leaf wetness and average air temperature for each 24-h period (1100 to 1100) to determine a DSV value, from 0 to 4, that corresponded to a range of unsuitable to highly suitable environmental conditions for disease development (26). After DSV threshold values were reached, prompting spray applications, the sums of daily DSV values were reset to zero. Hourly averages of leaf wetness duration and temperature were acquired using a digital data logger (WatchDog Leaf Wetness and Temperature Logger 3610TWD; Spectrum Technologies, Inc., Plainfield, IL) that was positioned northward at a 45° angle and nested in the upper 75% of the crop canopy in the center of an unsprayed bed. Treatments were initiated on 29 June 2001 and 2 July 2002 at the onset of canopy closure within rows. Subsequent sprays were made at 7-day intervals or according to TOM-CAST thresholds of 10, 15, or 20 DSV.

Disease assessment. Foliar and petiole blight caused by *A. dauci* and *C. carotae* were assessed weekly from 2 August to 28 September 2001 and 22 July to 30 September 2002. Foliar and petiole disease assessments were based on carrot plants in the center 3 m of each treatment plot. Foliar blight was visually assessed according to an *Alternaria* leaf blight pictorial key (30) that assigns a value of 0, 1, 5, 10, 20, or 40% leaf blight. Petiole blight inci-

dence (≥ 1 infected petioles) was determined weekly as a percentage, with disease severity estimated according to the following scale: 1 = no lesions, 2 = 1 to 5 lesions, 3 = 6 to 20 lesions, 4 = 21 to 50 lesions, 5 = >50 lesions per plant, 6 to 9 = >50 lesions and increasing degrees of petiole necrosis, and 10 = petiole death. At harvest on 28 September 2001 and 2 October 2002, carrot roots from the center 3 m of each treatment plot were hand harvested, separated from their foliage at the crown, and weighed (kg) to determine yield. Area under the disease progress curve (AUDPC) was calculated to express the cumulative incidence of leaf and petiole infection occurring over a 57- and 70-day period in 2001 and 2002, respectively, according to the method of Shaner and Finney (29).

Statistical analysis. Each year of the TOM-CAST experiment represented a randomized complete block design. Data for all variables were analyzed with an analysis of variance (ANOVA) with a linear model that included treatment, year, treatment-year, and replicate nested within year as factors using the Proc GLM procedure of the Statistical Analysis System (SAS Institute, Cary, NC). The year-treatment interaction was not significant for any variable, so results were pooled over years. The design became a split plot in time when both years were combined. The assumptions of normality and equal variances were examined using the residuals from the ANOVA. Normality was examined using the Proc Univariate procedure of SAS. The equal variance assumption was examined using Levene's Robust Test (34) and by conducting an ANOVA on the absolute value of the residuals. All of the variables were transformed using $Y = \log(\text{variable} + 1)$. Although the other variables did not meet both assumptions, the transformed variables improved the fit to normality in all cases.

The 29 treatments examined in this experiment represent a seven (fungicide treatments) by four (application intervals) factorial, with an untreated control as the 29th treatment. All variables had significant differences among the 29 treatments. These differences were examined by decomposing the treatment sum of squares into four component sums of squares: (i) the difference between the mean of spray treatment programs and the untreated control, (ii) differences between fungicides, (iii) differences between application intervals, and (iv) an interaction between fungicides and application intervals. The interaction between fungicide and application intervals was not significant ($P > 0.05$) for all variables. As such, the main effects of fungicide and application interval were examined using Tukey's highly significant difference to determine which fungicide or application interval had the best mean.

The variability of yield within years was notably different. As a result, yield was analyzed separately by year, using an ANOVA of a randomized complete block experiment. The ANOVA was calculated using the Proc GLM procedure of SAS, and residuals were used to examine the assumptions of normality and equal variances as noted above. Yield data met both the assumptions of normality and equal variances without transformation. Differences in mean yield between the 29 treatments were examined in the same manner as the other variables.

RESULTS

Symptoms of infection caused by *A. dauci* and *C. carotae* were observed 77 days after planting in 2001 and 63 days after planting in 2002 on the fresh market cv. Heritage. Within 7 weeks, 78% (2001) and 100% (2002) of the untreated petioles were blighted (Table 1), showing that disease was more severe in 2002 (approximately 50 lesions/untreated plant) than the previous year (approximately 20 lesions/untreated plant). At the final disease assessment date, untreated plants had 25 and 33% blighted foliage in 2001 and 2002, respectively (Table 1).

According to AUDPC data, all application intervals significantly suppressed the incidence of disease on the foliage and petioles, resulting in healthier petioles at harvest compared with the untreated control ($P = 0.0001$; Table 2). The 7-day and TOM-CAST 10 DSV programs were statistically equivalent for all disease parameters measured and were more effective than the TOM-CAST 15 and 20 DSV programs in suppressing petiole disease and maintaining overall petiole health (Table 2). However, the TOM-CAST 15 DSV program was comparable with the 7-day and TOM-CAST 10 DSV programs in managing foliar blight. TOM-CAST 20 DSV was the least effective program in maintaining overall petiole health.

All fungicide treatments significantly maintained petiole health in comparison with untreated plants. Copper hydroxide treatments resulted in higher AUDPC values and petiole health ratings compared with other fungicide treatments, yet P values indicated significant disease control compared with the untreated. AUDPC values for plants treated with azoxystrobin alone, or in alternation with copper hydroxide or chlorothalonil, were similar and more favorable than other treatment combinations. Applying chlorothalonil alone was more effective than copper hydroxide in suppressing disease. Alternating chlorothalonil with copper hydroxide resulted in AUDPC values that were not significantly different than using copper hydroxide alone in controlling foliar and petiole blight.

In 2001, an assessment of petiole blight severity values, petiole blight incidence,

and foliar blight percentages (Table 1) indicated similar control of disease across many of the fungicide treatments and application intervals, and significantly less disease than the untreated. Under heavier disease pressure than the previous year, spray programs using azoxystrobin (TOM-CAST 10-DSV interval) and azoxystrobin alternated with chlorothalonil (7-day interval) suppressed petiole blight incidence <10% of that of the untreated (100%) in 2002. Most treatment programs suppressed foliar blight (%) compared with the untreated control in 2002, with the following exceptions: copper hydroxide applied according to TOM-CAST 15 and 20 DSV and chlorothalonil applied at TOM-CAST 20 DSV.

Weights of untreated carrot roots had a significant yield reduction compared with roots subjected to fungicide treatments in 2001 (Table 3). However, differences were not detected between treated and untreated

carrot roots in 2002. An assessment of application intervals revealed that the 7-day spray program significantly increased yields compared with the TOM-CAST 15 and 20 DSV spray programs. Across fungicide programs, azoxystrobin/chlorothalonil/copper hydroxide, chlorothalonil, and azoxystrobin/copper hydroxide sprays produced the highest significant yields compared with copper hydroxide and chlorothalonil/copper hydroxide (Table 3). Although not significantly different from the other treatments, copper hydroxide-treated carrot plants had a greater yield quantity than other treatments in 2002.

The 7-day and TOM-CAST 10 DSV intervals prompted the most fungicide applications and, consequently, were the most costly programs (*data not shown*). The 7-day spray interval prompted 13 sprays during both years, whereas the TOM-CAST 10 DSV interval prompted 13 and 10 sprays for 2001 and 2002, respectively.

Although the TOM-CAST 20 DSV application interval prompted the least number of sprays, thereby reducing costs up to 50%, disease control was compromised in the majority of parameters analyzed in this study. Using a TOM-CAST 15 DSV interval reduced sprays up to 40% compared with a 7-day interval and produced an average savings of \$127/ha in 2001 and \$137/ha in 2002 (*data not shown*).

DISCUSSION

At the time of this study, copper hydroxide was selected based on its approval for organic production systems. Many copper-based products have been regulated over the past several years based on inert ingredients. Although no longer approved as of December 2008, the copper hydroxide product used in this study will be reviewed again in spring 2009 (Marcia Martin, DuPont, *personal communication*). Incorporating organically approved products,

Table 1. Mean summary of petiole and foliar blight caused by *Alternaria dauci* and *Cercospora carotae* at the final rating dates in 2001 and 2002, after applying foliar fungicides every 7-days or according to the TOM-CAST disease predictor^w

Treatment ^z	Petiole blight							
	No. of sprays		Incidence (%)		Disease severity ^x		Foliar blight (%) ^y	
			2001	2002	2001	2002	2001	2002
Untreated	...	...	77.86 c	100.00 h	2.75 d	4.50 g	25.00 c	32.50 f
Copper								
7-day	13	13	10.05 ab	44.32 cdef	1.00 bc	2.25 abc	7.75 b	5.25 abc
TOM-CAST 10-DSV	13	10	7.73 ab	47.04 def	1.00 bc	2.75 bcd	1.00 a	9.00 abc
TOM-CAST 15-DSV	8	7	14.38 ab	76.82 gh	1.25 c	3.50 def	4.25 ab	22.50 def
TOM-CAST 20-DSV	6	5	22.92 b	78.81 gh	1.25 c	4.00 fg	5.75 ab	25.00 ef
Azoxy/copper								
7-day	13	13	1.21 a	27.70 bcde	0.50 ab	2.00 ab	3.00 ab	3.00 ab
TOM-CAST 10-DSV	13	10	0.79 a	25.20 abcd	0.50 ab	2.00 ab	2.00 ab	4.00 ab
TOM-CAST 15-DSV	8	7	2.65 a	52.63 efg	0.75 abc	2.25 abc	3.00 ab	5.25 abc
TOM-CAST 20-DSV	6	5	3.89 a	64.27 fg	0.75 abc	2.75 bcd	3.00 ab	12.50 abcd
Chloro/copper								
7-day	13	13	9.73 ab	29.54 abcde	1.00 bc	2.25 abc	3.25 ab	5.75 abc
TOM-CAST 10-DSV	13	10	2.32 a	43.98 bcdef	1.00 bc	2.25 abc	1.00 a	4.25 ab
TOM-CAST 15-DSV	8	7	2.96 a	69.07 fg	0.75 abc	3.00 cde	4.25 ab	14.00 abcde
TOM-CAST 20-DSV	6	5	15.44 ab	67.68 fg	1.25 c	3.00 cde	5.75 ab	10.25 abc
Azoxy								
7-day	13	13	0.55 a	32.91 abcde	0.50 ab	2.00 ab	2.00 ab	5.75 abc
TOM-CAST 10-DSV	13	10	2.23 a	6.29 a	0.75 abc	2.00 ab	1.00 a	6.75 abc
TOM-CAST 15-DSV	8	7	2.22 a	45.43 cdef	1.00 bc	2.25 abc	1.00 a	4.00 ab
TOM-CAST 20-DSV	6	5	1.51 a	41.94 bcdef	1.00 bc	2.25 abc	4.00 ab	3.25 ab
Azoxy/chloro								
7-day	13	13	1.19 a	8.40 a	0.25 a	2.00 ab	1.00 a	2.00 a
TOM-CAST 10-DSV	13	10	0.76 a	10.85 a	0.75 abc	2.00 ab	2.00 ab	2.00 a
TOM-CAST 15-DSV	8	7	1.07 a	50.36 defg	0.50 ab	2.25 abc	2.00 ab	4.25 ab
TOM-CAST 20-DSV	6	5	2.51 a	50.44 defg	0.75 abc	2.75 bcd	4.25 ab	16.25 cde
Chloro								
7-day	13	13	1.47 a	17.84 abc	0.75 abc	1.75 a	1.00 a	3.25 ab
TOM-CAST 10-DSV	13	10	1.97 a	12.03 a	0.50 ab	1.75 a	0.75 a	1.00 a
TOM-CAST 15-DSV	8	7	4.86 a	32.23 abcde	0.75 abc	2.50 abc	2.00 ab	10.50 abc
TOM-CAST 20-DSV	6	5	7.27 a	64.40 fg	1.00 bc	3.75 efg	3.00 ab	30.25 f
Azoxy/chloro/copper								
7-day	13	13	0.57 a	26.71 abcde	0.50 ab	2.00 ab	2.00 ab	6.25 abc
TOM-CAST 10-DSV	13	10	0.70 a	15.50 ab	0.50 ab	2.00 ab	1.00 a	3.00 ab
TOM-CAST 15-DSV	8	7	2.38 a	11.87 a	0.75 abc	2.00 ab	2.00 ab	2.00 a
TOM-CAST 20-DSV	6	5	2.34 a	67.13 fg	0.75 abc	3.00 cde	4.25 ab	9.00 abc

^w Means within a column followed by the same letter are not significantly different according to Fisher's least significant difference ($\alpha = 0.05$).

^x Cumulative incidence of petiole disease severity, pooled over 2001 and 2002, according to the following rating scale: 1 = no lesions, 2 = 1–5 lesions, 3 = 6–20 lesions, 4 = 21–50 lesions, and 5 = >50 lesions per plant, 6–9 = >50 lesions and increasing degrees of petiole necrosis, and 10 = petiole death.

^y Severity was visually assessed using an *Alternaria* leaf blight pictorial key that assigns values of 0, 1, 5, 10, 20, or 40% leaf blight.

^z Duration of leaf wetness and ambient temperature for 24-h intervals, which determines a disease severity value (DSV) that corresponds to varying conditions suitable for disease development. Treatment (a.i./ha): copper hydroxide (Copper) at 0.91 kg, azoxystrobin (Azoxyc) at 0.11 kg, and chlorothalonil (Chloro) at 1.3 kg.

which should be referenced at the Organic Materials Review Institute prior to use, with a TOM-CAST weather forecasting system would allow growers to manage foliar blight in conjunction with other management and cultivation tactics, to compete with the rapidly growing organic segment of U.S. agriculture (3).

Using reduced risk (i.e., azoxystrobin) and biocontrol products to control foliar diseases on carrot offers an alternative to relying on fungicides containing B2 carcinogens. Despite this, biological agents like harpin protein and *Bacillus subtilis* did not show consistent control in different evaluations, especially against *Cercospora* leaf blight (12,27). Compost teas are another reduced-risk alternative where plant-pathogenic organisms were shown to have been suppressed when extracts are applied directly to plant surfaces (10,32), yet a Michigan study in 2004 proved that, when compost tea was applied every 7 days, foliar blight on carrot was not significantly limited (14).

Already integrated as a management tool by Michigan growers (8), the TOM-CAST program has effectively reduced grower reliance on spraying prematurely or too frequently, thereby decreasing seasonal costs (8,28). In our study, the TOM-CAST 10 DSV program only differed from the weekly spray interval in 2002, with 10 sprays triggered compared with 13. According to Table 2 data, this program had statistically similar results to the 7-day program for petiole blight incidence, petiole health, and foliar blight. TOM-CAST

at 15 DSV prompted 8 (2001) and 7 (2002) sprays compared with the 13 used by the calendar-based weekly interval, cutting spray costs by \$55 and \$66/ha, respectively. Similarly, Rogers and Stevenson (28) showed that using the TOM-CAST 15

DSV program allowed them to reduce sprays by four compared to the 7-day interval. Bounds et al. (8) also confirmed that the 15 DSV program prompted fewer sprays (between five and seven) than the 7-day program. Despite the TOM-CAST 20

Table 3. Average weight (kg) of carrot roots harvested during 2001 and 2002 growing seasons after applying foliar fungicides every 7 days or according to the TOM-CAST disease predictor^v

Treatment ^w	Yield (kg)/3 m					
	2001 ^x	F value	P value	2002 ^y	F value	P value
Application interval						
7-day	13.02 b	...	...	14.08 a	...	...
TOM-CAST 10 DSV	12.67 ab	...	...	13.23 a	...	...
TOM-CAST 15 DSV	12.22 a	...	...	14.00 a	...	...
TOM-CAST 20 DSV	12.18 a	...	...	13.30 a	...	...
Fungicide						
Copper	11.60 a	...	...	14.75 a	...	...
Azoxycopper	13.02 b	...	...	13.88 a	...	...
Chloro/copper	11.55 a	...	...	13.86 a	...	...
Azoxyc	12.44 ab	...	...	13.53 a	...	...
Azoxyc/chlorol	12.73 b	...	...	13.53 a	...	...
Chloro	13.05 b	...	...	13.11 a	...	...
Azoxyc/chloro/copper	13.26 b	...	...	12.60 a	...	...
Contrast						
Untreated	...	25.02	<0.0001	...	0.12	0.7290
Fungicide	...	6.77	<0.0001	...	1.97	0.0790
Application interval	...	3.84	0.0125	...	1.65	0.1847
Fungicide–interval ^z	...	1.61	0.0756	...	0.69	0.8325

^v Means within a column followed by the same letter or no letter are not significantly different according to Tukey's highly significant difference ($\alpha = 0.05$).

^w Duration of leaf wetness and ambient temperature for 24 h intervals, which determines a disease severity value (DSV) that corresponds to varying conditions suitable for disease development. Treatment (a.i./ha): copper hydroxide (Copper) at 0.91 kg, azoxystrobin (Azoxyc) at 0.11 kg, and chlorothalonil (Chloro) at 1.3 kg.

^x In 2001, untreated yield (8.72 kg) differed significantly from the other treatments ($P = 0.0001$).

^y In 2002, untreated yield (10.71 kg) did not differ significantly from the other treatments ($P = 0.7290$).

^z Fungicide–application interval interaction.

Table 2. Evaluation of fungicide applications (appl.) against *Alternaria dauci* and *Cercospora carotae* using different disease thresholds based on a TOM-CAST forecasting system on 'Heritage' carrot^v

Treatment ^y	No. of appl.		AUDPC (disease–day) ^w						Petiole disease severity ^x		
	2001	2002	Petiole	F value	P value	Foliar	F value	P value	Severity	F value	P value
Application interval											
7-day	13	13	53.83 a	...	...	52.63 a	...	...	3.39 a	...	...
TOM-CAST 10 DSV	13	10	54.92 a	...	...	49.39 a	...	...	3.43 a	...	...
TOM-CAST 15 DSV	8	7	122.25 b	...	...	70.51 ab	...	...	4.02 b	...	...
TOM-CAST 20 DSV	6	5	219.70 b	...	...	104.65 b	...	...	4.88 c	...	...
Fungicide											
Copper	...	...	359.90 c	...	...	149.39 b	...	...	5.13 b	...	...
Azoxyc/copper	...	...	67.36 ab	...	...	63.42 ab	...	...	3.72 a	...	...
Chloro/copper	...	...	162.99 bc	...	...	86.72 ab	...	...	4.13 a	...	...
Azoxyc	...	...	85.30 ab	...	...	48.41 a	...	...	3.75 a	...	...
Azoxyc/chloro	...	...	47.24 a	...	...	50.90 a	...	...	3.97 a	...	...
Chloro	...	...	84.29 ab	...	...	54.33 a	...	...	3.44 a	...	...
Azoxyc/chloro/copper	...	...	50.27 a	...	...	50.43 a	...	...	3.38 a	...	...
Contrasts											
Untreated	...	...	...	40.58	<0.0001	...	107.33	<0.0001	...	11.43	<0.0001
Fungicide	...	...	...	7.38	<0.0001	...	13.40	<0.0001	...	8.74	<0.0001
Interval	...	...	...	11.52	<0.0001	...	16.19	<0.0001	...	21.73	<0.0001
Fungicide–interval ^z	...	...	...	0.59	0.9037	...	1.35	0.1613	...	1.28	0.2068

^v Mean values were pooled over 2001 and 2002. Means within a column followed by the same letter are not significantly different according to Tukey's highly significant difference ($\alpha = 0.05$).

^w Cumulative incidence of leaf and petiole infection expressed as area under the disease progress curve (AUDPC) for petiole blight incidence (Petiole) and foliar blight (Foliar).

^x Cumulative incidence of petiole disease severity, pooled over 2001 and 2002, according to the following rating scale: 1 = no lesions, 2 = 1–5 lesions, 3 = 6–20 lesions, 4 = 21–50 lesions, and 5 = >50 lesions per plant, 6–9 = >50 lesions and increasing degrees of petiole necrosis, and 10 = petiole death.

^y Duration of leaf wetness and ambient temperature for 24-h intervals, which determines a disease severity value (DSV) that corresponds to varying conditions suitable for disease development. Treatment (a.i./ha): copper hydroxide (Copper) at 0.91 kg, azoxystrobin (Azoxyc) at 0.11 kg, and chlorothalonil (Chloro) at 1.3 kg.

^z Fungicide–interval interaction.

DSV triggering less than half the sprays of the 7-day program, unacceptable disease control resulted. When environmental conditions are favorable for disease to occur early and progress rapidly, as in our 2002 study, application intervals may need to be shortened to a 7-day or TOM-CAST 10 DSV program. In such situations, reducing the number of sprays may still be obtainable when using effective scouting methods and initiating sprays based on trace amounts of foliar blighting, as Bounds et al. (9) validated when screening varying disease thresholds in conjunction with TOM-CAST.

Carrot growers experience yield losses when the petioles become weakened. During mechanical harvesting, machinery that lifts the roots by grasping the foliage will cause diseased petioles to snap, leaving unharvested roots in the ground (33). Despite not experiencing an effect of treatment programs, we recorded that fungicide-treated plot yields were 31% (2001) and 22% (2002) higher compared with untreated plots. Langenberg (21) discussed a correlation between yield reduction and leaf blight severity, caused by *A. dauci*, in a study that showed that a progressively higher percentage of mechanically harvested plants had snapped at the petiole as leaf blighting increased above 10%. In 2001 of our study, foliar blighting was limited to $\leq 7.75\%$ with fungicide treatment programs. However, in 2002, we saw that multiple fungicide treatments under the TOM-CAST 15 and 20 DSV programs exceeded the 10% threshold of foliar blighting highlighted by Langenberg (21), which may have affected yield losses during a mechanical harvest (Table 1). Similarly, petiole blight severity in 2002 was 50% higher than the previous year, which may explain the insignificant yield totals compared with the untreated (Table 3).

Based on grower surveys in Michigan and Wisconsin (M. K. Hausbeck, *unpublished data*), chlorothalonil is the primary foliar fungicide used on commercially grown carrot to manage *A. dauci* and *C. carotae*. In order to minimize toxicity to nontarget organisms and the environment, our study evaluated the efficacy of alternating chlorothalonil sprays with a reduced-risk product. Similar studies in Michigan, Indiana, and Maryland were successful in their investigations, whereby the TOM-CAST system prompted fewer applications of chlorothalonil to control *A. solani* and *Stemphylium lycopersici* on marketable yields of tomato (11,24). Based on our AUDPC and petiole disease severity data, alternating azoxystrobin with either copper hydroxide or chlorothalonil significantly controlled disease at a commercially acceptable level, which has been corroborated by other studies (12,17–19). A spray program alternating all three products was equally effective for all parameters assessed under a 7-day interval, which re-

duces exposure to carcinogenic ingredients. Moreover, growers can further reduce toxicity exposure when alternations are combined with a TOM-CAST DSV program that could prompt fewer sprays. This was substantiated by Rogers and Stevenson (28) when they alternated azoxystrobin and chlorothalonil on a TOM-CAST 15 and 20 DSV spray schedule, showing that toxicity values were reduced by 55 to 80% when compared with a 7-day schedule using chlorothalonil alone.

As a result of the final ruling of the National Organic Program, organic carrot producers are able to use copper-based products, as outlined by the United States Department of Agriculture, as long as users minimize copper accumulation in the soil. In this study, we observed less control of lone applications of copper hydroxide compared with the other fungicides. Despite this, our AUDPC data shows that it was significantly better in controlling disease progression than the untreated under the 7-day and TOM-CAST 10 DSV spray programs. Furthermore, using a copper-based fungicide is inexpensive (costing 50% less than chlorothalonil) and does provide a certain degree of control when compared with the absence of treatment, which has been validated by several other studies on carrot crops (1,2,7,16). A 2001 study by Ben-Noon et al. (7) shows that copper hydroxide treatments significantly controlled *A. dauci* up to 55% better than the untreated. Additional examples of foliar blight control with copper hydroxide can be seen in reports by Abawi and Ludwig (1), where average leaf blight severity was reduced by 40 to 50% compared with the untreated plants. Although trends were observed, these researchers saw a decline in efficacy in 2003 and 2004 compared with earlier studies. These differences could be attributed to the frequent rainfall experienced in Geneva, NY over the duration of their experiments, which often occurred within 1 to 4 h following fungicide applications (2,16).

Managing foliar blights on carrot requires multiple management tactics used concurrently. TOM-CAST has shown the potential to significantly reduce the number of fungicide applications necessary to provide economic control of foliar blight on Michigan carrot operations. If this forecasting system is integrated with other substantiated measures, growers can maximize their pest management strategies more efficiently. Because it is standard practice for Michigan carrot growers to routinely scout for pests, prolonging spray initiation until trace amounts of foliar blight is found can reduce the number of applications from one to five while providing a savings of up to \$140/ha, as was confirmed by Bounds et al. (9). When carrot growers combine these management practices with planting disease-resistant cultivars, they may be able to reduce their

seasonal costs of controlling foliar blight more than if utilizing a single tactic. Future management studies may continue to screen other organically approved fungicidal materials or other reduced risk fungicides, with differing modes of action, to avoid reliance on a particular mode of action.

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