Incorporation of chlorothalonil persistence on processing tomato into TOM-CAST

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Abstract

Measurements of chlorothalonil residue on tomato foliage are expensive and time consuming, yet knowledge of chlorothalonil persistence would assist in fungicide application scheduling. The objective of this study was to calibrate an existing chlorothalonil persistence model for processing tomatoes, and to incorporate the predictions of chlorothalonil residue into TOM-CAST. The Bruhn and Fry (1982b. A mathematical model of the spatial and temporal dynamics of chlorothalonil residues in a potato canopy. Phytopathology 72, 1306–1312) model for chlorothalonil persistence on potato foliage was calibrated for tomatoes using data from controlled rainfall experiments with a rainfall simulator. Field data consisting of chlorothalonil residue data and weather data from 1993 and 1995 field trials in Columbus, OH, was also used. Model evaluation was conducted using two data sets of chlorothalonil residue data and weather data from 1998 field trials in Columbus, OH. The chlorothalonil persistence predictions were within the 90% confidence interval of the observed chlorothalonil residues on upper canopy foliage for 11 of the 13 data points and nine of the 13 data points for the lower canopy foliage. The chlorothalonil persistence model and the TOM-CAST disease-forecasting algorithm were combined into an integrated fungicide application decision aid. The linked model predicted three spray applications were necessary compared to five predicted with the TOM-CAST-only program for the 1998 season in Columbus, OH.

Keywords: Processing tomatoes; Chlorothalonil; Persistence model; TOM-CAST; Computer decision aid; Fungicide
1. Introduction

Processing tomatoes in the Midwestern United States requires regular fungicide applications to maintain high-quality tomatoes. Concerns about fungicide residues on food, and environmental impact of fungicides, have prompted researchers to investigate alternative disease management strategies for processing tomatoes that focus on reducing fungicide use without increasing the risk of disease-related yield losses (Fulling et al., 1995). Achieving a balance between adequate protection and minimizing fungicide use is difficult. Traditionally, fungicide applications are initiated 2 weeks after transplanting and re-applied every 7–10 days until 2 weeks prior to harvest. While effective, this practice may use more fungicide than necessary.

There are several disease-forecasting systems (DFS) for tomatoes such as FAST (Madden et al., 1978), CU-FAST (Zitter and Sandlan, 1990), and TOM-CAST (Pitblado, 1988, 1992). These DFS have successfully reduced the amount of total season fungicide input without compromising yields. Among them, TOM-CAST is currently being used by many producers in the Midwest and Ontario, Canada (Gleason et al., 1995).

In the TOM-CAST algorithm, (1) hours of leaf wetness per day and (2) mean air temperature during the wet periods are determined from field data and used to select a daily Disease Severity Value (DSV), ranging between 0 and 4. A DSV of 4 is assigned for days with longer wet periods and higher temperatures than would occur on days when a lower DSV value is assigned. Daily DSVs are summed until the cumulative DSV reaches a predetermined action threshold (typically between 15 and 20) and the grower is advised to re-apply fungicide. During weeks when climatic conditions favoring fungal disease development exist, fungicide is applied more frequently. Midwest growers can obtain current DSV information via an internet web site (http://www.ag ohio state.edu/~vegnet/tomcats/tomfrm.htm) and a DSV hotline (+1-800-228-2905).

TOM-CAST recommends spray intervals based solely on climatic variables because fungal disease development is highly weather dependent. TOM-CAST does not, however, take into account the residual fungicide that may already be present on the plant from previous spray applications. For some conditions, persistence of fungicide (chlorothalonil) residues at effective concentrations on the plant could lengthen the spray interval beyond TOM-CAST recommendations (Patterson, 1999).

Chlorothalonil, available as Bravo and several other trade names, is an excellent broad spectrum fungicide against many leaf spots, blights, downy mildews, rusts, anthracnoses, scabs, and fruit rots of many vegetables, field crops, ornamentals, turf, and even trees (Agrios, 1997). Foliar chlorothalonil persistence studies have been performed on tomatoes (Lukens and Ou, 1976; Patterson, 1999), potatoes (Bruhn and Fry, 1982b), peanuts (Knudsen et al., 1988; Brenneman et al., 1990; Nokes and Young, 1992; Elliot and Spurr, 1993), and muskmelons (Suheri and Latin, 1991). Patterson (1999) demonstrated that chlorothalonil residue levels on processing tomato foliage were a significant factor to consider before making spray application decisions. They reported four of five spray intervals using the TOM-
CAST program (with a DSV action threshold of 18) which had chlorothalonil residues on upper and lower canopy foliage still at effective levels on the day fungicide re-applications were recommended.

Exponential decay models have been used to predict chlorothalonil persistence on plant foliage (Knudsen et al., 1988; Patterson, 1999). Exponential decay models make the assumption that loss of fungicide residues is a function of time only. Rainfall has been found to affect removal of fungicide from the plant more than any other weather factor (Bruhn and Fry, 1982b). Temperature also has been found to affect persistence of fungicide residues (Bruhn and Fry, 1982b). A more complete simulation model that includes the effects of rainfall and temperature is necessary to better characterize the persistence of chlorothalonil on tomato foliage. Weather-driven chlorothalonil persistence predictive models have been developed and used on potatoes (Bruhn and Fry, 1982b) and peanuts (Nokes and Young, 1992), but not tomatoes.

Incorporation of a weather-driven chlorothalonil persistence model into a DSV-based spray program would provide a mechanism to delay spray recommendations if an effective concentration of chlorothalonil persists on the plant. This would allow spray intervals to be lengthened beyond the DSV-based spray recommendations. The TOM-CAST disease-forecasting program and a weather-driven chlorothalonil persistence and efficacy prediction model could be linked into an integrated decision aid. Reduced fungicide use while maintaining fungal control would result in lower cost to producers and reduced fungicide use.

As in other Integrated Disease Management programs, we mainly want to reduce the number of applications of fungicide by considering the residual amount of active ingredient. The main objectives of this study were: (1) to calibrate for tomato the Bruhn and Fry (1982b) chlorothalonil persistence model; (2) to evaluate the model using independent field data; and (3) to incorporate the model into the existing disease-forecasting program (TOM-CAST).

2. Methods and materials

2.1. Laboratory data

Two controlled rainfall experiments were performed. The first experiment evaluated the effect of rainfall on foliar chlorothalonil persistence after varying rainfall duration periods (10, 20, 30, 68, and 150 min) at rainfall intensities of 2.5 cm/h or greater. For each experimental test, four potted tomato plants (cv. Ohio 8245) grown under greenhouse conditions, 5–6 weeks old, were treated with chlorothalonil (2.6 g active ingredient (a.i.)/l, Bravo Weather Stik, ISK Biosciences Corporation, Mentor, OH). After drying for 5 h, three of these plants were placed under the rainfall simulator and exposed to the rainfall treatment. The fourth plant did not experience rainfall and was used as a control to quantify the initial foliar chlorothalonil concentration. After the rain event, the plants were left under the rainfall simulator to dry, and 10 leaf disks (1.7 cm diameter each) were taken from upper
and lower canopy foliage on each plant. Pooled samples (for upper and lower canopy foliage separately) were analyzed using the chlorothalonil magnetic particle-based enzyme immunoassay technique (Lawruk et al., 1995) to determine residual chlorothalonil concentration. The three plants were considered replications for each experimental test. The proportion of chlorothalonil residue remaining was computed by dividing the residue concentration on the test plant by the initial concentration on the control plant.

The second laboratory experiment evaluated the effect of time since chlorothalonil application on the persistence of chlorothalonil on the tomato foliage. Nine potted tomato plants (cv. Ohio 8245) grown under greenhouse conditions, 5–6 weeks old, were treated with chlorothalonil (2.6 g a.i./l, Bravo Weather Stik) at the same time. After 5 h of drying, three plants were exposed to rainfall at an intensity level of 2.5 cm/h on the same day (day 0), three other plants on the next day (day 1), and the remaining three plants 1 week later (day 7). Within a group of three plants placed under the rainfall simulator, individual plants were randomly removed after experiencing 10, 30, or 60 min of rainfall. Ten leaf disks were taken from upper canopy foliage on each plant before and after each rainfall event. Pooled samples were analyzed to determine residual chlorothalonil concentration using the chlorothalonil magnetic particle-based enzyme immunoassay technique (Lawruk et al., 1995). The experiment was repeated three times. The proportion of chlorothalonil residue remaining was computed by dividing the residue concentration observed after rainfall by the initial concentration on the same plant prior to the rain event.

2.2. Field data

Tomatoes were grown at The Ohio State University Horticulture Farm (Columbus, OH) in a Kokomo silty loam soil. The fields are tile-drained, and the tomatoes were grown on raised beds. Standard cultural practices were performed with the exception of chlorothalonil application.

2.2.1. 1993 and 1995 field trials

Tomato plants (cv. Heinz 8704) were transplanted on 8 June 1993 and 6 June 1995 at a plant density of approximately 30,000 plants per ha, into twin-row plots (1.52×9.14 m) with a buffer plot between each spray plot. Chlorothalonil (Bravo 720, ISK Biosciences Corporation, Mentor, OH) was applied at the rate of 2.52 kg a.i. per ha with a CO2-powered, tractor-mounted sprayer (Opelousas, LA) (481 kPa) using five Delavan (Delavan Inc., West Des Moines, IA) hollow cone #8 nozzles. Chlorothalonil was applied on a 10-day calendar spray program. Foliage samples from the upper and lower canopy layers were collected prior to chlorothalonil re-application, and several samples were collected directly after application. Leaf samples were frozen in zip-lock bags, packed in dry ice, and mailed overnight to The National Food Laboratory (The National Food Laboratory, Inc., Dublin, CA) where chlorothalonil residue concentrations were determined by the multiresidue procedure in the “Pesticide Analytical Manual, Vol. 1” (Luke et al., 1983). For
individual spray cycles, the proportion of chlorothalonil residue remaining was computed by dividing the observed residue concentration prior to chlorothalonil re-application by the concentration at the start of the spray cycle. Three replications were used to determine the mean and standard error of the mean for all data samples, except 28 July 1993, 29 July 1993, and 5 August 1993 which consisted of two replications for both upper and lower canopy.

2.2.2. 1998 field trial

Tomato plants (cv. Peto 696) were transplanted 5 June 1998 at a plant density of approximately 30,000 plants per ha, into single row plots (1.52×9.14 m). Chlorothalonil (Bravo Ultrex, ISK Biosciences Corporation, Mentor, OH) was applied at a rate of 3.08 kg a.i. per ha with a single row tractor mounted CO₂-powered (414 kPa) boom with five HC-12 nozzles. Chlorothalonil was applied on separate single rows on either a 7-day calendar spray program or TOM-CAST-advised sprays at a DSV interval of 18. Foliage samples from the upper and lower canopy layers were collected prior to chlorothalonil re-application. Leaf samples were frozen in zip-lock bags, packed in dry ice, and taken to the Biosystems and Agricultural Engineering Department at the University of Kentucky (Lexington, KY) where chlorothalonil residue concentrations were determined by the chlorothalonil magnetic particle-based enzyme immunoassay technique (Lawruk et al., 1995). Three replications were used to determine the mean and standard error of the mean for all data samples.

2.2.3. Weather data

Cumulative daily rainfall was recorded at the weather station located at the Ohio State University Horticulture Farm in Columbus, OH. During the 1993 and 1995 field trials, an Omnidata Datapod (Model DP223, Omnidata International, Logan, UT) with an air temperature probe (Campbell Scientific, Logan, UT, Model 108) and a coated leaf wetness sensing grid (Campbell Scientific, Logan, UT, Model 237) was used to record and store hourly temperatures and leaf wetness values. During 1998, a CR-10 unit (Campbell Scientific, Logan, UT) was used to record air temperature and leaf wetness, using sensors identical to the Omnidata Datapod.

2.3. Bruhn and Fry chlorothalonil persistence model

The Bruhn and Fry (1982b) chlorothalonil persistence model is described by a matrix of parameters that determine chlorothalonil loss due to weathering and chlorothalonil redistribution from upper to lower canopy layers. Chlorothalonil weathering from upper canopy foliage is described by the following equation:

\[ r_t (1) = [g_t, d_t] r_{t-1} (1), \]

where \( r_t (1) \) is the residue on layer 1 (upper canopy) at time \( t \), and \( r_{t-1} (1) \) is the residue on layer 1 at time \( t-1 \). Also, \( g_t \) and \( d_t \) are the reduction factors quantifying effects of
rainfall and temperature, respectively, on weathering of chlorothalonil from upper canopy foliage.

Chlorothalonil weathering from lower canopy foliage and redistribution from the upper canopy to lower canopy foliage is described by the following equation:

\[ r_t(2) = [ g_t, d_t ]^r r_{t-1}(2) + [1 - g_t, d_t ] z r_{t-1} (1). \]  

where \( r_t(2) \) is the residue on layer 2 (lower canopy) at time \( t \), and \( r_{t-1}(2) \) is the residue on layer 2 at time \( t-1 \). Also, parameter \( s \) describes chlorothalonil weathering from lower canopy foliage. Parameter \( z \) is defined as the proportion of fungicide that is removed from the upper canopy and re-deposited onto foliage in the lower canopy. In the model, \( z \) equals zero if precipitation on day \( t \) \( (p_t) \) equals zero or if \( p_t > 1.0 \) cm (model assumes when rainfall high, no chlorothalonil re-deposited on lower foliage). It is assumed that no fungicide is redistributed upward within the canopy.

The proportion of chlorothalonil deposit remaining after rain on day \( t \), \( g_t \), is described by the following equation:

\[ g_t = \exp[a p_t^{1/3} + b(p_t(t_{app} - 1))^{1/3}] \text{ for } p_t \geq 0.1 \text{ cm} \]  

\[ g_t = 1.0 \text{ for } p_t < 0.1 \text{ cm} \]

where \( p_t \) is the amount of rain (cm) on day \( t \), \( t_{app} \) is the number of days since the fungicide was applied, and \( a \) and \( b \) are parameters.

The proportion of chlorothalonil deposit remaining due to volatilization on day \( t \), \( d_t \), is described by the following equation:

\[ d_t = \exp[c(T - T')] \text{ for } T > T' \]  

\[ d_t = 1.0 \text{ for } T \leq T' \]

where \( T \) is the average daily temperature (°C), and \( c \) and \( T' \) are parameters.

### 2.4. Chlorothalonil persistence model development

The Bruhn and Fry (1982b) chlorothalonil persistence model was programmed using MATLAB (1992), to evaluate individual spray intervals. Total daily rainfall (cm), average daily temperature (°C), and the number of days since chlorothalonil application were input variables to the model. The initial chlorothalonil concentration (µg/cm²) for upper and lower canopy layers and the number of days since being modeled were given in the program for each spray interval used in the calibration. Residual chlorothalonil concentrations (µg/cm²) were calculated for two canopy layers, upper and lower, by the model. Data collected from the laboratory experiments and field trials in 1993 and 1995 were used to calibrate the model for tomatoes. Six model parameters were fit: \( a, b, c, T', s, \) and \( z \).
2.4.1. Chlorothalonil deposit estimates

When initial chlorothalonil concentration measurements were not available for the field data, a standardized method of determining an estimate of the initial chlorothalonil concentration was needed. Data were available during each of the 1993 and 1995 seasons for a spray interval when little or no rainfall was recorded. Two spray events (spray application 28 July 1993 and 19 July 1995) provided residue data immediately before and several hours after a spray occurred. The difference in chlorothalonil concentration before and after each spray event gave an estimate of the amount of chlorothalonil deposited on the upper and lower canopy foliage. Data from periods when no rainfall occurred eliminated concern over potential chlorothalonil loss if rainfall occurred shortly after a spray.

From 1993 data, the mean residues deposited were 11.8 μg/cm² for the upper canopy and 4.46 μg/cm² for the lower canopy. From 1995 data, the mean residues deposited were 11.0 μg/cm² for the upper canopy and 4.44 μg/cm² for the lower canopy. These mean residue deposits were averaged to get 11.4 and 4.4 μg/cm² as chlorothalonil deposit estimates for the upper and lower canopies, respectively. These estimates were based on an application rate of 2.52 kg a.i. per ha.

The chlorothalonil application rate for the 1998 field trial was 3.08 kg a.i. per ha. To account for the increase in application rate for the 1998 season, a scaling factor of 1.2 μg/cm²/(kg a.i. per ha) was used for the upper canopy estimate. For upper canopy foliage, the chlorothalonil deposit estimate was increased to 13.7 μg/cm², and the lower canopy deposit estimate remained at 4.4 μg/cm² (Bruhn and Fry, 1982a).

2.4.2. Calibration of rainfall reduction factor, g₁

Data from the rainfall intensity and duration experiment were used to calibrate parameter a in Eq. (3). Since rainfall occurred on the same day as chlorothalonil application in the laboratory experiments, the second term in Eq. (3) was equal to zero and a could be calibrated independently of b. The mean proportion of chlorothalonil remaining on the upper canopy foliage after rainfall was compared to the total rain amount the plants experienced after each simulated rain event (Fig. 1). MATLAB was used to determine the best fitting parameter value of the non-linear equation for the data by the Gauss-Newton method using the function nlinfit. The Bruhn and Fry (1982b) parameter value (a = -1.9091) was used as an initial estimate, and a = -0.4555 (standard error of a = 0.05) was determined the best fitting parameter (Fig. 1).

Data from the time-effect rainfall experiment were used to calibrate parameter b in Eq. (3). Data were statistically analyzed using a completely randomized full factorial treatment structure that compared the three time periods after chlorothalonil application before rain occurred (0, 1, and 7 days), and the three rainfall duration periods (10, 30, and 60 min) that the plants experienced. Data were analyzed using the PROC GLM procedure of SAS® (1987). From analysis of variance, there was not sufficient evidence to conclude a significant difference between mean residual chlorothalonil concentrations for the treatment main effect of time since chlorothalonil application (P = 0.66). Based on results from this experiment, removal of this chlorothalonil formulation from tomato foliage by rainfall was not dependent
on the number of days since chlorothalonil application that the rainfall occurred, and parameter $b$ was set to 0 in Eq. (3).

2.4.3. Calibration of temperature reduction factor, $d_t$

The average proportion of chlorothalonil residue remaining per day and the corresponding average daily temperature over five individual spray intervals (the number of complete spray intervals available) during 1993 and 1995 field trials (spray intervals beginning 28 July 1993, 9 August 1993, 6 July 1995, 29 July 1995, and 17 August 1995) were evaluated to calibrate parameters $T'$ and $c$ in Eq. (4) (Fig. 2). Complete spray intervals were those with observed initial and residual chlorothalonil concentrations and complete weather data over the entire interval. For two of the five spray intervals (spray intervals beginning 9 August 1993 and 29 July 1995), the initial chlorothalonil concentration was unknown and was estimated by adding the deposit estimates to the residual chlorothalonil concentrations from the previous interval. The average proportion of chlorothalonil remaining per day over the spray interval was computed by averaging the proportions remaining at the beginning and end of the interval. A linear equation relating the natural logarithm of the average proportion of chlorothalonil remaining per day to the corresponding average daily temperature was determined using the function `regress` in MATLAB (Fig. 2). The intercept of the linear equation when the proportion remaining per day was equal to 1 gave an estimated lower boundary temperature of $T' = 16.5^\circ C$. 

Fig. 1. Effect of rainfall on removal of chlorothalonil from processing tomato foliage, comparing the mean proportion of chlorothalonil remaining after rainfall and the total amount of rainfall applied. +, Mean observed proportion of chlorothalonil remaining after rainfall; — , non-linear equation fitted to data by Gauss-Newton method ($g_t = \exp(-0.46 p_t^{1/3})$).
The estimate of parameter \( c \) in Eq. (4) was evaluated by considering the spray interval beginning 28 July 1993. Only one rain event (0.95 cm) occurred during this period, which allowed the effect of rainfall on chlorothalonil loss to be minimal. The mean observed proportion of chlorothalonil remaining on the eighth day after application was 0.4. The average proportion of chlorothalonil being lost per day was 0.07. By estimating the daily temperature reduction factor \( (d_t) \) to be 0.93 \((1 - 0.07)\) and using the lower temperature boundary determined above \( (T' = 16.5^\circ C) \) and the average temperature during the spray cycle \( (T = 22^\circ C) \), parameter \( c \) was computed directly from Eq. (4) and found to be equal to \(-0.01\).

Evaluation of \( c \) in Eq. (4) was conducted by holding constant the rainfall parameter values \((a = -0.46\) and \(b = 0.0)\) and the lower temperature boundary \( (T' = 16.5^\circ C) \). Only three spray intervals during 1993 and 1995 field trials (spray intervals beginning 28 July 1993, 6 July 1995, and 17 August 1995) had both observed chlorothalonil concentrations after application and immediately prior to re-application, and were appropriate for evaluating the model. Model-predicted chlorothalonil residues were compared to the mean observed chlorothalonil residue on upper canopy foliage at the end of each spray interval. Minimizing sums of squares of residuals (observed minus predicted values) confirmed parameter \( c = -0.01 \).

Fig. 2. Effect of temperature on the loss of chlorothalonil from processing tomato foliage in the field, comparing the average proportion of chlorothalonil residue remaining per day and the corresponding average daily temperature. +, Average observed proportion of chlorothalonil remaining per day; —, linear equation fitted to data by regression \((\ln(d_t) = -0.0544(T + 16.47))\).
2.4.4. Calibration of lower canopy weathering and redistribution

Calibration was performed for the exponent \( s \) in Eq. (2) by varying the parameter value in the chlorothalonil persistence model between 0.10 and 0.471, while holding constant the rainfall parameter values \((a = -0.46\) and \( b = 0.0)\) and the temperature parameter values \((c = -0.01\) and \( T' = 16.5^\circ \mathrm{C})\). The value used by Bruhn and Fry (1982b) \((s = 0.471)\) was used as an initial estimate, then values of \( s \) were reduced by increments of 0.05. Concurrently, parameter \( z \) in Eq. (2) was varied in the chlorothalonil persistence model at two proportion levels, 0.05 and 0.2, as was done in the Bruhn and Fry model (1982b). Two spray intervals were used in the calibration (spray intervals beginning 6 July 1995, and 17 August 1995). Predicted chlorothalonil residues were compared to the mean observed chlorothalonil residue on lower canopy foliage at the end of each spray interval. Minimizing sums of squares of residuals gave parameter \( s = 0.15 \) for both levels of parameter \( z \). The sum of squares of residuals were equivalent for both levels of parameter \( z \) when parameter \( s = 0.15 \). A parameter value of \( z = 0.05 \) was chosen because it represents a conservative estimate of redistribution from upper to lower canopy foliage.

2.5. Chlorothalonil persistence model evaluation

The chlorothalonil persistence model was evaluated using two data sets from the 1998 field trial. These data were not used to develop the model. Initial chlorothalonil deposit estimates and 1998 weather data were used in the model. Model-predicted chlorothalonil residue concentrations were compared to mean observed residues on upper and lower canopy foliage at the end of each spray interval for either a 7-day calendar spray program or a TOM-CAST program with DSV threshold of 18. The following parameters were used in the chlorothalonil persistence model: \( a = -0.46, b = 0.0, c = -0.01, T' = 16.5, s = 0.15, \) and \( z = 0.05 \).

The chlorothalonil persistence model was evaluated over the entire 1998 season for both spray programs. Initial chlorothalonil concentrations were not collected during the 1998 season and were estimated for each spray interval. For the first spray application, chlorothalonil deposit estimates of 13.7 and 4.4 \( \mu \mathrm{g/cm}^2 \) were used as model input initial chlorothalonil concentrations for the upper and lower canopy layers, respectively. For each subsequent spray re-application, model initial chlorothalonil concentrations were estimated by adding the deposit estimates to the model-predicted residual chlorothalonil from the previous spray interval for the upper and lower canopy layers.

The 90% confidence interval of the mean observed residual chlorothalonil concentrations at the end of each spray interval were used to evaluate model quality.

2.6. Chlorothalonil persistence–TOM-CAST-linked model

A MATLAB program was created that combined the chlorothalonil persistence model for tomatoes and the TOM-CAST algorithm. Hourly weather information from a field data logger was input directly as a text file into the linked model program. The user would input the desired DSV action threshold, chlorothalonil
application rate, and number of days since the first chlorothalonil application. The program computes a chlorothalonil deposit estimate for upper canopy foliage based on the chlorothalonil application rate using a scaling factor, and uses a default value of 4.4 \( \mu \text{g/cm}^2 \) as a deposit estimate for lower canopy foliage. The program also computes the cumulative DSVs and predicts chlorothalonil residue concentrations for upper and lower canopy foliage each day. The program recommends chlorothalonil be re-applied when both the DSV action threshold and the critical chlorothalonil concentration (1.2 \( \mu \text{g/cm}^2 \); Patterson, 1999) in either the upper or lower canopy have been reached.

The linked model evaluated the 1998 season in Columbus, OH. Hourly weather data were collected by a CR-10 data logger (Campbell Scientific, Logan, UT). The DSV action threshold was set at 18 and the chlorothalonil application rate was 3.08 kg a.i. per ha.

3. Results and discussion

3.1. Chlorothalonil persistence model evaluation

Mean observed chlorothalonil foliar concentrations prior to fungicide re-application and model-predicted chlorothalonil residues on the upper and lower canopy foliage and corresponding weather data for the 1998 7-day calendar spray program are presented in Fig. 3. Similar information for the TOM-CAST DSV-based spray program is presented in Fig. 4.

The model accurately predicted residual chlorothalonil concentrations observed during the 1998 season on upper and lower canopy processing tomato foliage. Predicted chlorothalonil residue concentrations generally fell near observed mean values and within the confidence intervals. For the 1998 7-day calendar spray program, model-predicted residual chlorothalonil concentrations were within the confidence interval of the observed mean for eight of the eight spray intervals on upper canopy foliage, and for five of the eight spray intervals on lower canopy foliage. For the 1998 TOM-CAST DSV-based spray program, model-predicted chlorothalonil residue concentrations were within the confidence interval of the observed mean for three of the five spray intervals on upper canopy foliage, and for four of the five spray intervals on lower canopy foliage.

The Bruhn and Fry (1982b) chlorothalonil persistence model was calibrated for tomato using methods similar to those used by Bruhn and Fry. One major difference in experimental results between the current and Bruhn and Fry (1982b) studies regarded the effect of time since fungicide application on the ability of rainfall to remove chlorothalonil from foliage. Bruhn and Fry (1982b) found that rainfall on the day of fungicide application had the greatest impact on removal of chlorothalonil from potato foliage, but the effect declined with aging of the fungicide deposit. In the current study, however, results indicated that when time was greater than or equal to 5 h since fungicide application, time until the rain event did not influence the impact of rainfall on removing chlorothalonil from tomato foliage.
This result was not expected, but may be explained by the difference in plant species or improvements in fungicide adsorption with chlorothalonil formulations as used in the current study.

In developing and evaluating the chlorothalonil persistence model, the chlorothalonil deposition estimates for the initial chlorothalonil concentrations are reasonable compared to literature values. Bruhn and Fry (1982a) studied the effect of rate of chlorothalonil application on the initial deposit. They found that doubling the application rate resulted in a twofold increase in the amount of chlorothalonil on potato foliage in the top half of canopy, but no significant difference for the lower half of the canopy. Courshée (1967) reported similar results on cotton and suggested that leaves in bottom part of canopy were more likely to be concealed from the fungicide spray than leaves located near the top of the canopy. Brenneman et al. (1990) applied chlorothalonil at the rate of 1.26 kg a.i. per ha to peanuts and determined the foliar chlorothalonil deposit after application was 6.74 μg/cm² for the upper canopy and 4.43 μg/cm² for the middle canopy. Since the spray rate for model
development was 2.52 kg a.i. per ha, by doubling the upper canopy value found by Brenneman et al. (1990) on peanut foliage, the corresponding fungicide deposit according to the findings of Bruhn and Fry (1982a) would be 13.5 µg/cm² for the upper canopy and 4.4 µg/cm² would remain for the lower canopy. Also, Elliot and Spurr (1993) determined the average initial deposition of chlorothalonil in the upper canopy of peanut foliage at a spray rate of 1.26 kg a.i. per ha to be 5.8 µg/cm². Doubling the concentration gives 11.6 µg/cm². Based on these findings, using a scaling factor to estimate the chlorothalonil deposit on upper canopy foliage from a known application rate is well founded.

Evaluation of the chlorothalonil persistence model for tomato demonstrated that residual chlorothalonil concentrations could be predicted accurately under a different set of field conditions from that which the model was developed. Differences in tomato variety, cultural practices, chlorothalonil formulation, chlorothalonil application rate, and weather existed between the data sets used for calibration and evaluation of the model. The accurate model predictions demonstrated the robustness of the model for different conditions. Generally, if predictions were in error, the
upper canopy portion of the model under-predicted residue. Chlorothalonil is lost most rapidly from foliage in the top of the plant (Bruhn and Fry, 1982b), so the model provides a conservative estimate of the residual chlorothalonil on upper canopy foliage. A slower decline of residue occurs on lower canopy foliage due to the increased protection of lower foliage and redistribution of fungicide from top leaves onto lower foliage (Bruhn and Fry, 1982b). Except for the final spray interval of the 1998 calendar spray program, the lower canopy portion of the model predicted the trend of residue accumulation on lower canopy foliage with time accurately.

Generally, when a chemical agent is applied the formulation contains some kind of spreader or sticker to aid in adhering of active ingredients to the crop foliage for a longer period of time. The specific formulation could make a considerable difference in residual chlorothalonil concentrations, particularly during wet periods. Chlorothalonil residue data used for model development came from using two different chlorothalonil formulations (Bravo 720 and Bravo Weather Stik), and for model evaluation a third chlorothalonil formulation (Bravo Ultrex). Differences in chlorothalonil formulation were not evaluated in this study; however, the accurate model-predictions of residual chlorothalonil concentrations demonstrated model robustness when using the three different chlorothalonil formulations in this study.

3.2. Chlorothalonil persistence–TOM-CAST-linked model predictions

The chlorothalonil persistence–TOM-CAST-linked model predictions of residual chlorothalonil concentrations and corresponding cumulative DSVs are presented in Fig. 5. In addition, predicted chlorothalonil residues using the unlinked model are presented in Fig. 5 for comparison. The linked model predicted four spray re-applications were necessary for the 1998 season. Cultural practice limits the final spray application to be made no more than 14 days before harvest. Since the linked model predicted the final fungicide re-application to occur near harvest, in practice only three spray re-applications would have been recommended using the linked program. Five sprays were actually applied using only the DSV-based program and nine spray re-applications were made using the calendar method.

Midwestern processing tomato growers rely on fungicides to maintain production of high-quality tomatoes. The TOM-CAST program has been shown under some conditions to reduce fungicide spray applications while still maintaining adequate fungal disease protection compared to fixed-interval spray programs (Gleason et al., 1995). Previously, it was shown that chlorothalonil can persist at effective concentrations when fungicide re-application is being recommended by the TOM-CAST program (Patterson, 1999). If enough chlorothalonil persists on the plant to provide adequate protection against fungal disease, spray intervals could be lengthened. The chlorothalonil persistence–TOM-CAST-linked model developed in this study predicted fewer spray applications were necessary per season compared to using just the TOM-CAST program. Being able to extend the spray interval beyond the TOM-CAST recommended spray date gives growers the possibility to reduce the number of spray applications per season even further.
4. Conclusions

A chlorothalonil persistence model to predict the foliar chlorothalonil concentration on tomato based on rainfall, temperature and time since last fungicide application was developed and successfully evaluated. The chlorothalonil persistence model and the TOM-CAST algorithm were combined into an integrated fungicide application decision aid. The linked model predicted fewer spray applications were necessary per season compared to the TOM-CAST program alone.

The results of this study show that the potential of reducing chlorothalonil re-applications per season using the chlorothalonil persistence–TOM-CAST-linked model is possible. However, field data were not available to evaluate the linked model-predictions. Further research is necessary to compare the new chlorothalonil persistence–TOM-CAST-linked model to actual chlorothalonil residues throughout the season. Ideally, disease protection must be maintained without compromising yield. Evaluation of fungal disease levels using the linked fungicide-scheduling
program is necessary to determine the model’s reliability for disease protection under varying field conditions.

The chlorothalonil persistence model was evaluated under a different set of conditions (chlorothalonil formulation, cultural practices, tomato variety, etc.) than were used for model development. The accurate model predictions demonstrated the robustness of the model for different conditions. However, using different chlorothalonil formulations, or other fungicide active ingredients altogether, may result in model predictions that are not as precise. Further research is necessary to evaluate the extent of model robustness and the potential for model calibration when using other formulations.

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