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Disease-Warning Systems for Processing Tomatoes in Eastern North America: Are We There Yet?

A disease-warning system predicts outbreaks or changes in intensity of one or more diseases on the basis of information about the weather, crop, pathogen(s), or some combination of the three (5). This article reviews the genesis of disease-warning systems for processing tomatoes, their refinement in various localities in eastern North America, and the impressive progress that has been made in bringing this new management strategy into grower use. We also highlight constraints that need to be overcome to sustain the successes that have been achieved.

The Disease Complex

Warm, moist weather conditions that typify summers in eastern North America make fungal diseases a potential limiting factor in the production of processing tomatoes. Although the relative impact of specific diseases varies across localities and years, here we highlight three widely distributed fungal diseases that have been the foci of efforts to develop disease-warning systems for processing tomatoes: early blight, caused by *Alternaria solani*; Septoria leaf spot, caused by *Septoria lycopersici*; and anthracnose fruit rots, caused primarily by *Colletotrichum coccodes*.

Early blight and Septoria leaf spot are primarily foliar pathogens in eastern North America. Both diseases typically appear first on older leaves after fruit set begins. Early blight causes dark brown leaf spots with concentric rings (Fig. 1A). Leaf spots caused by *S. lycopersici* are brown but much smaller and more numerous than those of early blight, and they lack concentric rings (Fig. 1B). The leaf yellowing and defoliation caused by these two diseases expose fruit to sunscalding, premature ripening, and accelerated decay.

Although *C. coccodes* is the pathogen most commonly associated with anthracnose fruit rot, *C. gloeosporioides* and *C. dematium* are of concern in some regions (26). As fruit ripen, infections cause small, depressed, circular lesions, often with visible acervuli (Fig. 1C). Secondary infection of anthracnose lesions by other fruit-rotting fungi is common. Anthracnose, in particular, can inflict large economic losses. In Ohio, for example, fruit "molds" such as anthracnose have resulted in losses of 34–45 metric tons per hectare, a yield loss of about 50%, on unprotected, susceptible cultivars (R. M. Riedel, *unpublished*). If the mold count of processing tomatoes exceeds a threshold set by the U.S. Food and Drug Administration, an entire semitrailer load of tomatoes, worth thousands of dollars, is rejected and becomes unsalable. In most locales, the fruit rots are the primary motivation for an intensive program of fungicide sprays. Defoliation of fresh-market cultivars caused by early blight or Septoria leaf spot may be quite extensive before yield is reduced (4,8), but similar studies of the impact of these diseases on processing tomatoes have not been reported.

The Problem

Traditionally, processing-tomato growers in eastern North America spray fungicides on their crops every 7–14 days from shortly after transplanting until harvest. This preventative strategy provides adequate disease protection but means that sprays are sometimes applied even when the threat of a disease outbreak is minimal.

Recent events have forced tomato growers to reconsider the preventative strategy. Intensifying public concern about pesticide contamination of produce and of the environment has forced greater government regulation of pesticides and pesticide applicators. The continuing loss of pesticide registrations for "minor use" fruit and vegetable crops has led to a situation in which the midwestern U.S. processing-tomato industry now depends primarily on a single fungicide, chlorothalonil, for control of fruit rots. Meanwhile, rising global competition is pressing tomato growers to maximize cost efficiency.

Pesticide restrictions and competitive pressures have awakened interest in adopting Integrated Pest Management (IPM) approaches. IPM makes systematic use of the full spectrum of available control options—cultural, genetic, biological, and chemical—to deliver acceptable pest and disease control with minimal use of chemical pesticides.

Techniques for biological and cultural control of early blight have shown some encouraging results in experimental trials (e.g., 39), but aside from traditional practices such as crop rotation, few of these techniques are presently used for processing tomatoes. Genetic resistance to anthracnose, early blight, or Septoria leaf spot varies among processing-tomato cultivars and is beginning to be incorporated into IPM strategies for processing tomatoes. Today, however, nonchemical alternatives alone cannot reduce the risk of crop loss to commercially acceptable levels in eastern North America. The need for at least some foliar fungicide sprays seems likely to remain for the foreseeable future.

Disease-Warning Systems

Disease-warning systems have proved successful in reducing fungicide inputs on processing tomatoes in eastern North America. Tomato disease-warning systems have evolved for more than two decades, incorporating modifications to improve disease-control efficacy, respond to regional variability in the disease complex, incorporate new technology, and encourage grower acceptance.

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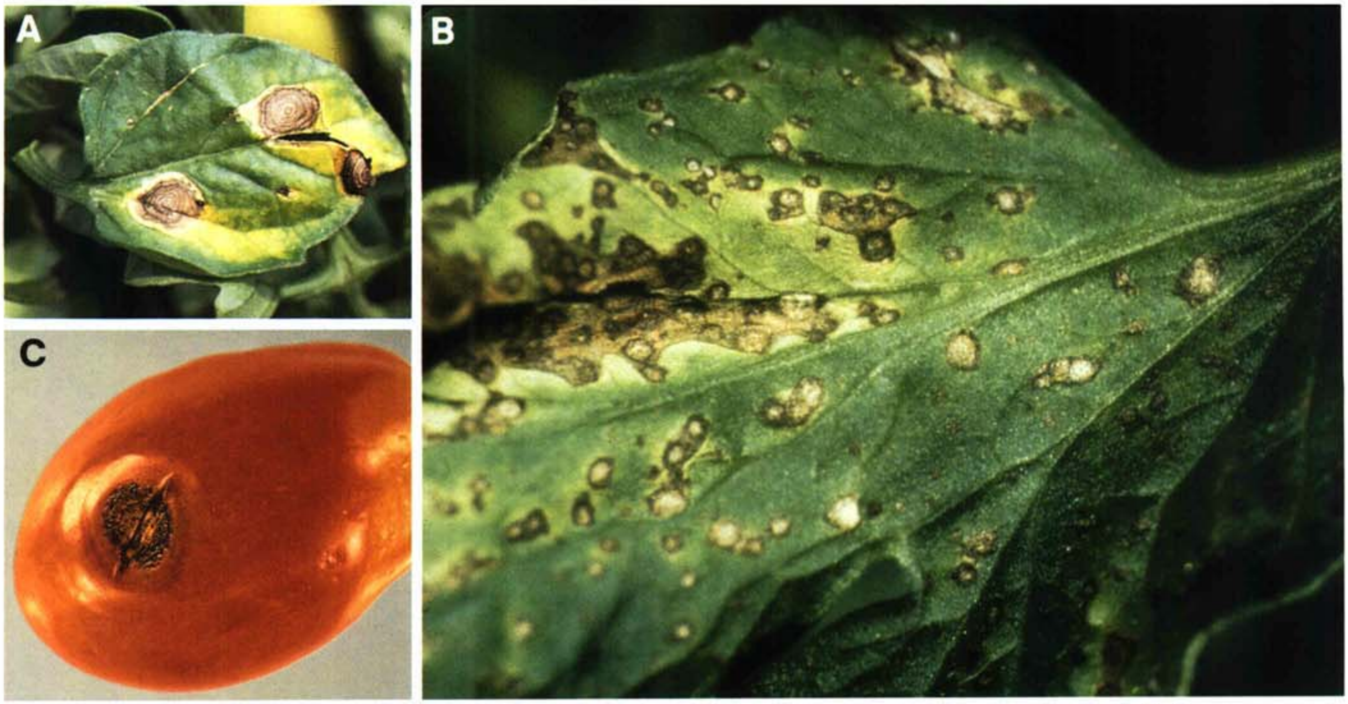

Fig. 1. Foliar symptoms of (A) early blight and (B) Septoria leaf spot. (C) Anthracnose symptoms on ripening fruit showing acervuli of *Colletotrichum coccodes*.

Table 1. The FAST models (35) for calculating daily ratings of the risk of an early blight outbreak

A. The dew model

Mean temp (C)	Leaf wetting time (hr) required to produce daily disease severity values (*S*)[a] of				
	0	1	2	3	4
13–17	0–6	7–15	16–20	21+	...
18–20	0–3	4–8	9–15	16–22	23+
21–25	0–2	3–5	6–12	13–20	21+
26–29	0–3	4–8	9–15	16–22	23+

[a]S = values range from 0 (environmental conditions unfavorable for *Alternaria solani* spore formation) to 4 (highly favorable conditions).

B. The rain model

Temperature average[a] (C)	Hours RH > 90[b]	Total rain[c]	R[d]
<22	<60	<2.5	0
>22	<60	<2.5	0
<22	>60	<2.5	1
<22	<60	>2.5	1
<22	>60	>2.5	1
>22	>60	<2.5	2
>22	<60	>2.5	2
>22	>60	>2.5	3

[a]Average temperature for past 5 days.
[b]Hours of RH > 90% during past 5 days.
[c]Total rainfall (cm) for past 7 days.
[d]Disease severity rating scale: 0 = environmental conditions unfavorable for *Alternaria solani* spore formation and infection of tomato; 3 = conditions highly favorable.

The FAST System

Publication of the FAST (Forecasting *Alternaria solani* on Tomatoes) model (35) was the seminal event in the evolution of tomato disease-warning systems. The FAST model, originally written in FORTRAN computer language, was an empirical model that synthesized some of the EPIDEM simulation model (45) and earlier work on the epidemiology of early blight on tomatoes (23) and potatoes (20,21). FAST's goals were to use environmental data to identify periods when early blight development was favored and to advise when fungicide sprays would be most useful in controlling the disease.

Development. Daily weather data (maximum and minimum air temperature, hours of leaf wetness, maximum and minimum air temperature during the wet period, hours of relative humidity [RH] > 90%, and daily rainfall) were the environmental inputs to FAST. The model assumed that inoculum was present initially. FAST's two submodels, the dew model and the rain model, each calculated a daily rating of the severity of risk of an early blight outbreak (Table 1). The dew model, based on the duration of wet periods and average air temperature during the wet periods, rated daily disease severity values (*S*) from 0 (conditions unfavorable for *A. solani* spore formation) to 4 (conditions highly favorable for spore formation). The rain model used average air temperature for the last 5 days, total hours during the past 5 days with RH > 90%, and total rainfall for the past 7 days to calculate disease severity rating values (*R*) from 0 (conditions unfavorable for *A. solani* spore formation and infection) to 3 (conditions highly favorable for spore formation and infection).

The FAST program maintained a cumulative total of all the *S* values since transplants were placed in the field (*TS*), a running total of the *S* values for the past 7 days (*CS7*), and a running total of the *R* values for the past 5 days (*CR5*). The program advised that the first fungicide spray be applied when *TS* reached 35 and the plants had been in the field for at least 5 weeks. Subsequently, when *CS7* exceeded a prespecified threshold, typically 13, a fungicide spray was advised unless an application had been made within the previous 7 days. When both the *CS7* threshold and the *CR5* threshold (typically 9) were exceeded, a fungicide spray was advised unless an application had been made within the previous 5 days.

Implementation. Over the last 15 years, operation of the FAST system in Pennsylvania has been modified as a result of feedback from commercial growers of both processing and fresh market tomatoes and of findings from experimental trials. These trials were promoted and supported by the Pennsylvania Vegetable Growers Association, the Pennsylvania Department of Agriculture, and Furman Canning Co. The results of modifications were increased reliability of disease control and greater convenience to growers.

When FAST was validated in 2 years of field experiments, the model controlled early blight as well as a weekly fungicide program but with substantially fewer sprays (38). In addition, a total of nine commercial-scale trials were conducted on grower farms in 1982 (34) and 1983 (33). Plots in each trial were sprayed according to FAST or a protectant schedule. Cooperators achieved good control of diseases with either spray schedule, but FAST required an average of 3.7 fewer fungicide applications, a 30% reduction from the protectant schedule.

Data from hygrothermographs, mechanical dew meters, and rain gauges were gathered by cooperating growers and extension agents at widely scattered locations in Pennsylvania and telephoned to the Pennsylvania State University (Penn State) as often as needed (usually at intervals of 1–3 days). FAST spray advisories were communicated by telephone to growers and by weekly newsletter to extension agents. Growers within a radius of about 80 km from a weather station made use of FAST advisories based on data from that station.

During the first year of the implementation phase, the FAST model was run on a mainframe computer at Penn State. The FAST program was rewritten, first in BASIC computer language for use with hand-held computers and later in spreadsheet programs for use with desktop computers. During the 1980s, growers ran FAST on hand-held computers and based calculations on weather data collected on their own farms. This system provided immediate feedback for them but resulted in a delay in communicating the information to growers in the same vicinity who lacked computers or weather instruments. To make the Pennsylvania system useful to the largest possible number of growers, centralized operation of FAST was restored to Penn State, and operation of the program was shifted to spreadsheet programs on desktop computers. The spreadsheet programs allowed easier entering and editing of weather data, provided clearer and more user-friendly output, and allowed more flexibility in modifying the program. Spray advisories are now communicated from Penn State by fax, electronic mail, telephone, and newsletter.

The model itself also was modified. The rain model sometimes reached an action threshold in Pennsylvania when the dew model was below its threshold. FAST decision rules were modified to allow the rain model threshold alone to trigger a spray advisory.

Additional modifications were incorporated to improve control of other components of the disease complex. Because FAST sometimes did not provide acceptable control of anthracnose and other fruit rots (38), a decision rule was added that advised switching from FAST to a weekly fungicide-spray schedule beginning when the first pink fruit appeared. Because epidemics of late blight (causal agent: *Phytophthora infestans*) sometimes appeared in Pennsylvania tomato fields, the BLITECAST model (27), a disease-warning model based on air temperature and hours of RH $> 90\%$, was run in tandem with the FAST model.

Decision rules adopted in the 1990s increased growers' margin of safety for disease protection by further incorporating crop stage, disease development, and cultural practices. The first fungicide spray of the season was now advised if any of the following conditions held: *TS* ≥ 35, the date was 1 July or later, any fruit had reached pea size, or any symptoms of early blight had appeared in the planting. Between the first spray and the appearance of pink fruit, the maximum interval between sprays was 14 days. The FAST program was recommended only for fields in which 1) neither tomatoes nor potatoes had been grown for 2 years, 2) the variety planted was not exceptionally susceptible to early blight, and 3) transplants were free of early blight and late blight symptoms.

Improved environmental-measurement technology developed since FAST's inception was incorporated into the Penn State system. The inked records of the original mechanical dew meters tended to wash out during rainfall periods and bleach out in bright sunlight. Electronic wetness sensors overcame these limitations; the sensors currently used in Pennsylvania are of the cylindrical type described by Gillespie and Duan (13). The addition of automated, battery-powered dataloggers greatly improved the convenience of collecting hourly temperature, wetness, RH, and rainfall data. During the growing season, the FAST model is run daily for each weather station in the system, and spray advisories are issued one to three times per week as needed.

Examples illustrating the extent to which FAST influences disease control in Pennsylvania include 70% of 729 ha (1,800 acres) devoted to mature green tomato production in northeastern Pennsylvania and 40% of 498 ha (1,230 acres) produced for one processor in the state. These percentages likely will increase in areas of concentrated tomato production when environmental input data is available in additional areas. Judging from experimental trials conducted over a 12-year period within Pennsylvania, growers using FAST would make an average of 6.2 applications per season, which represents a 30% reduction in fungicide use (2.7 fewer sprays per season) when compared with a 7-day interval program. At an estimated cost of from \$20.75 (mancozeb) to \$45.70 (chlorothalonil) per hectare per application, FAST would result in an average reduction in production cost from \$56.02 to \$123.38 per hectare.

The net effect of changes to the FAST system in Pennsylvania since 1980 has been a broader spectrum of disease control, improved responsiveness to crop stage and cultural control practices, an increased margin of safety for growers, and more reliable and rapidly accessible spray advisories. System usage has increased slowly but steadily; about 20% of Pennsylvania processing-tomato growers currently use it and report increasing confidence in the system (A. A. MacNab, *unpublished*).

FAST in New York: The CU-FAST system. For processing-tomato growers in central New York State, the most important fungal diseases are anthracnose and early blight. Research and extension specialists at Cornell University began an effort in 1989 to adapt FAST for New York. A key difference from other tomato disease-warning systems was that the New York system, named CU-FAST, estimated the duration of wetness periods rather than measuring them directly (46). Daily wetness-duration estimates were calculated from an algorithm based on rainfall amount, duration of periods with RH $> 90\%$, and minimum daily RH on two consecutive preceding days. This method took advantage of the fact that many New York growers already possessed hygrothermographs but that very few had wetness-sensing equipment. The CU-FAST system, written in an expert system format for IBM-compatible personal computers, was used by about 20 growers on approximately 405 ha of tomatoes during 1989–1992; reported spray savings compared with conventional schedules ranged from 20 to 30%. Since 1992, Cornell University has sold the software to private crop consultants, who in turn charge growers a fee for the service.

The TOM-CAST System

In 1992, the 10,638-ha crop in southern Ontario had a farm gate value of $75,457,000 ($55,084,000 U.S.). The disease complex for which fungicides are applied annually includes Septoria leaf spot in addition to early blight and anthracnose. In the mid-1970s, Ontario processing-tomato growers applied fungicides at intervals of 7–10 days from 1 week after transplanting until harvest, a total of 10 to 12 sprays per season.

Development. In 1979, an initial attempt to use FAST met with poor response from growers. The model was perceived as complex and difficult to understand, and the mechanical dew meters and hygrothermographs were seen as awkward to use and prone to problems. The major impetus to try FAST again, in 1983, came from the commercialization of affordable, automated dataloggers. Cylindrical wetness sensors (13), manufactured at Ridgetown College in Ontario, provided acceptable accuracy at lower cost than commercially available, flat-plate sensors (6).

In 1985, after 7 years of experimental trials, it was concluded that the modified FAST program, called TOM-CAST (Tomato Forecaster), could be used, not only for early blight prediction, but also to advise growers when to apply fungicides to control anthracnose and Septoria leaf spot. To simplify data gathering, the rain model of FAST was eliminated, and disease severity values (*DSV*s) were calculated solely on the basis of the dew model. Another departure from the FAST model was to sum *DSV*s, after the first fungicide spray, from the date of the last spray rather than over a 5- or 7-day time window as in FAST. Field experiments over the next several years established early-season and midseason *DSV* thresholds for the target diseases and compared the efficacy of various fungicides (R. E. Pitblado, *unpublished*). A fallback initial spray date of 11 July—i.e., the first spray was applied on 11 July if TOM-CAST had not advised an earlier spray—was found valuable for the control of fruit anthracnose. On the basis of these experiments, the following recommendations were devised: 1) the first fungicide spray of the season should be applied when 35 *DSV*s had accumulated after transplanting on or before 23 May, at 45 *DSV*s if transplanting occurred after 23 May, or on 11 July if the early-season threshold had not yet been reached; and 2) after the first spray, additional sprays should be applied until harvest after every 20 *DSV* for chlorothalonil (Bravo 500) and after every 15 *DSV* for mancozeb fungicides.

Implementation. With assistance from the Ontario Vegetable Growers' Marketing Board, H.J. Heinz Co. of Canada, and other tomato-processing companies, grower trials began in 1987. Eleven cooperating growers timed fungicide sprays on 2-ha plots according to TOM-CAST or to the standard, fixed-interval schedule on the rest of their plantings. Weather data were collected by scouts from dataloggers deployed in growers' tomato fields, and *DSV*s were calculated by personnel at Ridgetown College. The cooperators achieved excellent control of foliar diseases and anthracnose and equivalent yield with either spray schedule, but TOM-CAST required an average of only 5.3 applications, compared with 8.0 applications for the fixed-interval schedule.

Beginning in 1989, TOM-CAST was implemented for large numbers of Ontario growers. Thirteen dataloggers equipped with leaf wetness and air temperature sensors were deployed in tomato fields in Essex, Kent, and Norfolk counties (Fig. 2). Growers called a toll-free telephone number to receive a recorded message listing the *DSV*s for the last 7 days for each zone of their county; each noted only the *DSV*s derived from the datalogger nearest to his or her farm, which was less than 16 km away. The messages for Essex and Kent counties were updated by research personnel at Ridgetown College and, for the Norfolk region, by Horticultural Crop Advisors employed by the Ontario Ministry of Agriculture and Food. Growers summed the *DSV*s themselves and applied fungicide sprays on the basis of specified action thresholds.

TOM-CAST has met with impressive grower acceptance in Ontario. In Essex and Kent counties, for example, 3,000 calls were made to the toll-free telephone line in 1989, and 4,170 in 1990. Judging by experimental trials at Ridgetown College, growers using TOM-CAST during 1988–1991 applied an average of 2.75 fewer fungicide sprays per season than recommended by the traditional spray program (5.25 sprays compared with eight per season, a 34% reduction) (R. E. Pitblado, *unpublished*). At an estimated cost of $44.50 Canadian ($34.40 U.S.) per spray per hectare, which included both fungicide and application costs, TOM-CAST resulted in an average cost reduction of $122 Canadian ($95 U.S.) per year for 1 ha of processing tomatoes. In 1990–1993, it was estimated (J. Elmhirst, Ridgetown Collge, Ridgetown, Ontario, Canada, *personal communication*) that 80% of growers used TOM-CAST to time their first spray application and that 50% used it all season. On the basis of estimated spray savings of zero to three sprays in various zones of the tomato-producing counties, Ontario growers saved a total of $2,115,000 Canadian ($1,543,950 U.S.) in 1990–1993 by using TOM-CAST.

Recent technological changes to the Ontario TOM-CAST system have improved the efficiency of information gathering and delivery. The weather-sensing network has now been automated more fully through the use of dataloggers linked to telephone lines. The result is large savings in labor costs. In addition to the phone-message system,

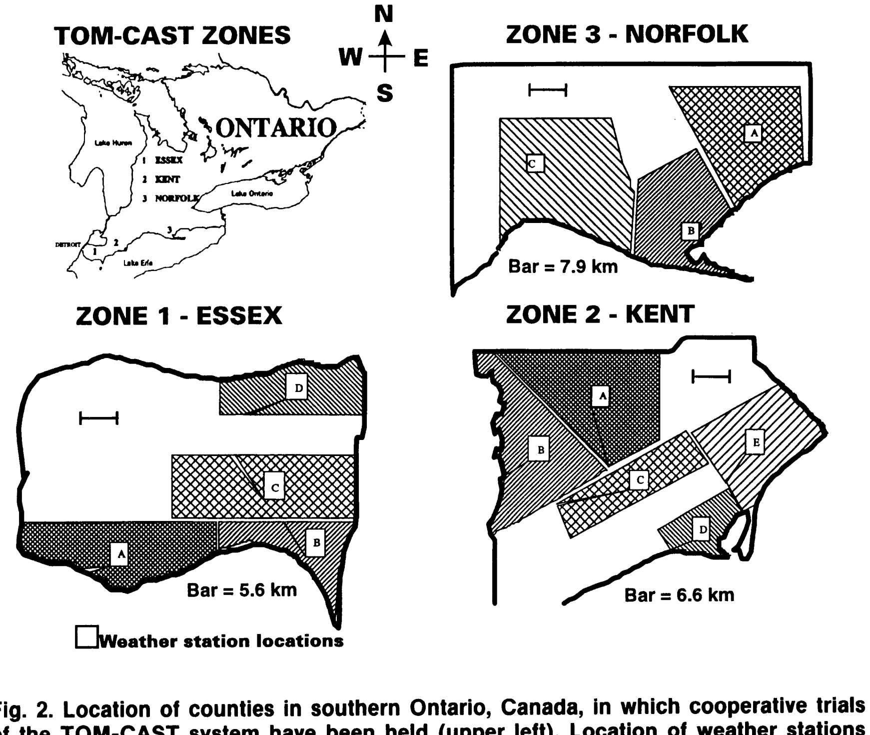

Fig. 2. Location of counties in southern Ontario, Canada, in which cooperative trials of the TOM-CAST system have been held (upper left). Location of weather stations in these counties devoted to the TOM-CAST network, and of the zones (shaded areas) served by each station.

DSV totals are now faxed to local agrichemical dealers and some growers.

TOM-CAST in the midwestern United States. A total of 11,069 ha of processing tomatoes grown in Ohio, Michigan, and Indiana in 1992 had a farm value of approximately $60 million. The fungal disease complex in these states is similar to that in southern Ontario.

Between 1988 and 1991, separate field trials to validate TOM-CAST in the midwestern United States were conducted by the Ohio State University, Heinz U.S.A., Campbell Soup Co. (3), Michigan State University, Purdue University, and Iowa State University. For example, studies at Ohio State University compared TOM-CAST on cultivars with a range of susceptibility to anthracnose and tested the potential for TOM-CAST to reduce fungicide residues on harvested fruit and processed products (2,41).

In 1992, a consortium including Ohio State University, Michigan State University, Purdue University, Heinz U.S.A., and Campbell Soup Co., funded by the the Mid-America Food Processors Association, the Fremont Pickle and Tomato Growers Association, and the USDA Extension Service, began a 3-year TOM-CAST implementation program. The TOM-CAST weather monitoring sites in Ohio, Michigan, and Indiana were supplied with Omnidata DP-223 Datapods. Volunteers downloaded data manually at each station and telephoned it to Ohio State University, where *DSV*s were calculated and disseminated via a toll-free telephone service. Cooperating growers were advised to apply their first fungicide spray at 25 *DSV* or on 15 June, whichever occurred first, if transplanting occurred on or before 20 May. Tomatoes transplanted after 20 May were sprayed each time 15 or 20 *DSV*s accumulated. Cooperators logged 1,740 and 1,411 calls to receive recorded *DSV* information on the toll-free phone line during 1992 and 1993, respectively. In 1992, cooperators saved an average of approximately 2.5 fungicide sprays per season compared with a protectant spray schedule that required nine sprays, with no loss of fruit tonnage or quality (D. A. East, *unpublished data*).

Testing of telephone-linked, fully automated weather stations was begun in 1993 by Ohio State University. Five of the 10 weather-monitoring stations in Ohio, Michigan, and Indiana were converted to automated stations in 1994.

Overcoming Constraints

To be acceptable to growers, a disease-warning system should be reliable, affordable, convenient, available on a real-time basis, and possess multipurpose applicability (5). Despite the impressive strides made to date, disease-warning systems must do a better job of meeting the needs of processing-tomato growers if their success is to be sustained. The following discussion highlights progress toward meeting these needs and suggests ways that current constraints can be overcome.

Incorporation of other IPM practices and diseases. Decision rules for disease-warning systems are being modified to account for the effects of cultural practices such as conservation tillage (F. Louws, Michigan State University, East Lansing, *personal communication*), crop rotation (28,29), and the use of disease-resistant cultivars (9,10,11,29,31,32). IPM approaches such as these could help convince growers that disease-warning systems can be customized to the specific practices and pest situations on their own farms.

Although FAST and TOM-CAST usually provide acceptable control of the target diseases, they incorporate information about the epidemiology of only one disease, early blight. Anthracnose and Septoria leaf spot can be controlled by FAST and TOM-CAST, but their epidemiology differs substantially from that of early blight (7,22,37). For example, the results of Parker et al (37) indicated that the spread of Septoria leaf spot occurred predominantly during rain rather than dew periods, but the TOM-CAST model does not distinguish between rain and dew. Additional research is needed to assess whether the accuracy of current models would be improved by incorporating aspects of the epidemiology of anthracnose and/or Septoria leaf spot.

Other tomato diseases can further complicate the management picture. Where late blight is a threat, as in Pennsylvania, the BLITECAST model (27) can be incorporated into the disease-warning system. Bacterial diseases present a different challenge. Bacterial spot (pathogen: *Xanthomonas campestris* pv. *vesicatoria*) and bacterial canker (*Clavibacter michiganensis* subsp. *michiganensis*) occur sporadically but can sometimes cause serious economic losses. Chemical controls for these diseases are marginally effective at best, so IPM practices focus on avoidance of inoculum by such practices as crop rotation and use of certified seed and transplants (16,17).

Incorporation of genetic resistance. Host resistance represents another control option that may enhance the performance of disease-warning systems. Recent research by Fulling et al (11) showed that fewer fungicide applications were required on resistant than on susceptible cultivars to achieve similar levels of anthracnose control. Their field studies defined a linear relationship between cultivar-specific resistance indices and TOM-CAST-derived fungicide application intervals required to achieve a given level of anthracnose control. Results suggested that, if resistance to fruit anthracnose could be indexed, fungicide application intervals could be prescribed for specific cultivars (Table 2).

Several reports (30,31,43) support the premise that, to achieve a predetermined level of control, fewer fungicides may be applied to tomato cultivars with more resistance. However, delivery of decision rules for incorporating resistance into the TOM-CAST system may be slow for several reasons. Many tomato cultivars are planted by each of a dozen or more processors operating in eastern North America, and new cultivars are introduced annually. Although the bulk of the area contracted by a processor in a given year may be planted to only four or five cultivars, the number of processors, cultivars, and the rate of cultivar turnover make a labor-intensive process such as resistance indexing a continual research challenge that can consume considerable resources. Also, acceptable levels of fruit anthracnose differ, depending on the tomato product. For example, tomatoes destined for paste cans or ketchup bottles may have higher levels of infection than do tomatoes canned whole. Finally, there seems to be little or no association between resistance to fruit anthracnose and resistance to early

Table 2. Resistance index values, anthracnose coefficients, and prescribed fungicide application intervals for three varieties of processing tomatoes

Cultivar[a]	Resistance index[b]	Anthracnose coefficient[c]	Prescribed application interval (*CSV*)[d]
Ohio 8245	0.216	0.563	24
Peto 696	0.329	0.675	20
Ohio 7814	1.000	0.970	14

[a] Selected from a more extensive list for demonstration purposes.
[b] Resistance index = (% fruit anthracnose of test cultivar) ÷ (% fruit anthracnose of the standard susceptible cultivar).
[c] Anthracnose coefficient = slope of the no intercept regression of percent infected fruit on the fungicide application interval (based on TOM-CAST) for each cultivar in fungicide trials.
[d] Estimated appropriate application intervals (in units of accumulated TOM-CAST severity values) for each cultivar based on the resistance index and the anthracnose coefficient.

blight and Septoria leaf spot. Such resistance, however, has been evaluated on only a few cultivars by public institutions. Development of rapid and quantitative resistance screening procedures may result in a more complete description of host resistance to these diseases and hasten its integration with disease-warning systems.

Environmental monitoring. Although the accuracy of wetness-duration measurements is questionable, it is seldom considered, let alone quantified, by pathologists. Wetness duration is a key input to all disease-warning systems for tomatoes, but despite proliferation of sensor types, there is no consensus on appropriate sensor design, calibration method, or placement relative to the crop canopy. Scattered reports comparing performance of different wetness-sensor sizes and shapes (13,24), surface coatings (14,24), orientation (14), and calibration methods (40) found variability of up to several hours per night in wetness-duration measurements.

Dew is the most difficult component of wetness to measure accurately. Even supposedly identical sensors, placed 1 m apart on an unobstructed site in the same orientation and connected to the same datalogger, varied by up to 5.5 hours in recording nightly dew duration (40). For TOM-CAST, the average of the difference in measured dew duration between sensors in this study, 2.4 hours, could result in a difference of one *DSV* per dew event. Assuming five dew events per week from 1 July through 15 September and a spray threshold of 18 *DSV*s, this variation could result in a difference of three fungicide sprays per season (40). To minimize variability, individual sensors should be calibrated in the field with visual observations of vegetative wetness during the onset of dew periods on several nights. This is a laborious, inconvenient, but necessary process (44).

Networks of weather stations. Networks of weather stations have some potent advantages over stations owned by individual growers, including lower cost per grower, greater convenience, and less labor. The issue of appropriate spacing between weather stations in a disease-warning network is a crucial one, however. Because automated weather stations are expensive, fewer stations mean a more affordable system. Mesoscale variation in wetness duration, rainfall, relative humidity, and air temperature are influenced by terrain, prevailing weather patterns, and a host of other factors. Unfortunately, studies of the influence of distance from the tomato field to a weather station on performance of disease-warning models are almost nonexistent. Results of a field experiment using a conservative version of the TOM-CAST model (*DSV* threshold = 15 after the first fungicide spray) in the relatively flat terrain of Iowa suggested that a weather station could be located at least 24 km from a processing tomato field without compromising foliar disease control or marketable yield (Fig. 3) (19). Similar tests need to be performed over several years in other tomato-growing regions to determine the optimum spacing of weather stations for each region.

Moving toward mesoscale weather monitoring. A system that obtained its environmental inputs from existing, publicly owned and operated weather-monitoring stations might offer cost and convenience advantages over networks of weather stations dedicated exclusively to tomato disease-warning systems. Virtually none of the hundreds of public-domain weather stations in the United States and Canada (36) measures wetness duration. Huber and Gillespie (25) reviewed attempts to estimate daily wetness duration from standard meteorological parameters, such as rainfall, relative humidity, and wind, which are measured routinely at these stations. The CU-FAST model, for example, calculates daily wetness duration from rainfall and relative humidity data (46). An empirical model based on relative humidity, dew point difference, and wind speed estimated dew-period duration at 13 sites

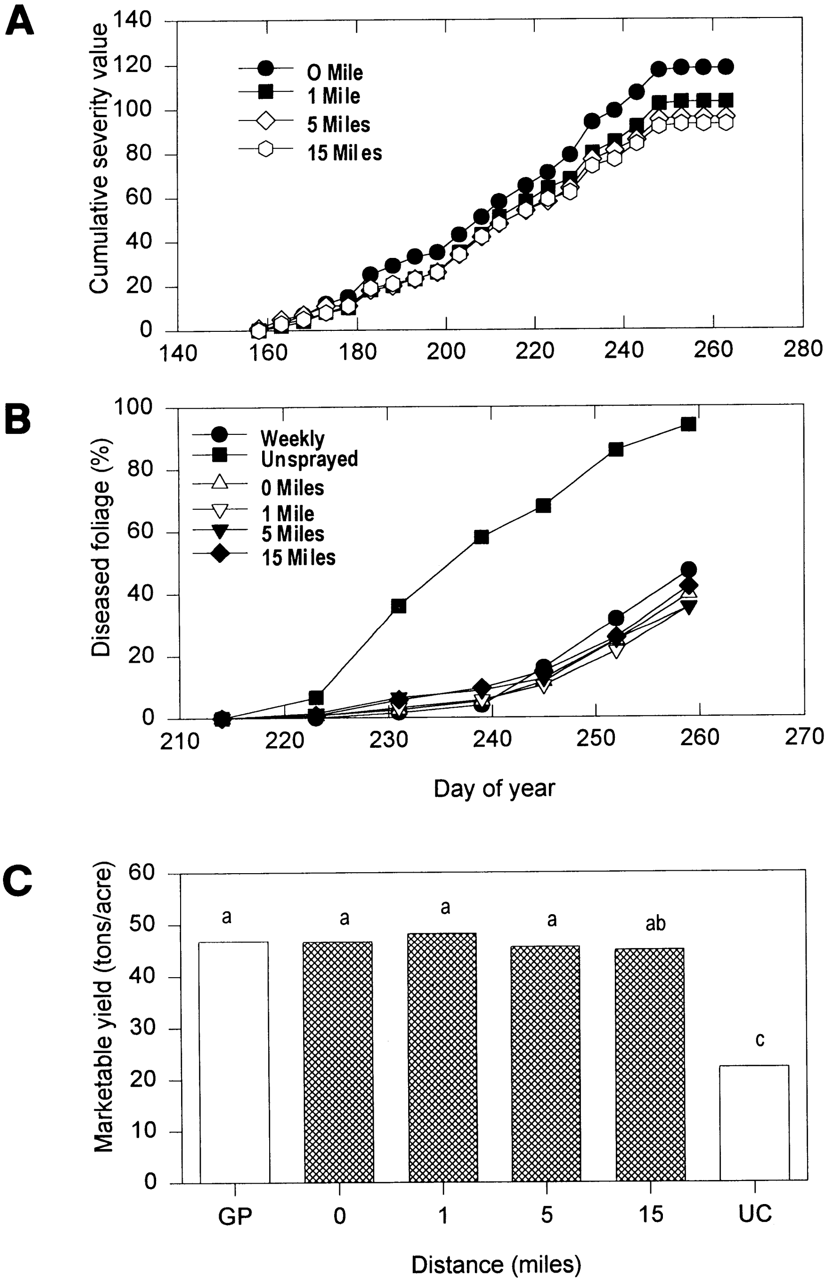

Fig. 3. TOM-CAST (A) cumulative severity values, (B) percent foliage infected by early blight and Septoria leaf spot, and (C) marketable yield of processing tomatoes (cv. Heinz 6004) near Gilbert, Iowa, in 1991, for an experiment in which weather stations 0, 1.6, 8.1, or 24.2 km (0, 1, 5, or 15 mi) from the tomato plot provided input data for TOM-CAST. In (C), GP = weekly fungicide treatment and UC = unsprayed treatment. The *DSV* threshold was 35 for the early season and 15 from the first spray until harvest. Bars with the same letter are not significantly different (DMRT, *P* = 0.05). n = 5. (19).

in the midwestern United States with better accuracy than a model based solely on relative humidity (18). These efforts all have the common aim of circumventing the need for measuring wetness duration.

Although public-domain weather stations in eastern North America are still widely and unevenly scattered, progress is being made in developing methods to estimate wetness duration in the areas between weather stations. In Ontario, for example, a regional wetness-estimation model to drive TOM-CAST, based on air temperature and dew-point depression and calibrated with wetness measurements at several base stations, resulted in disease control equivalent to that achieved with measured wetness duration (15). Geographic Information Systems technology also has potential for extending the useful domain of wetness estimates to locations within 50 km of a weather station (42). Remote sensing with ground-based radar has been used to detect the timing and location of rainfall (1) and the presence of dew on crop canopies (12). An exciting development is the recent commercialization (e.g., WSI Inc., Billerica, MA, and ZedX Inc., Boalsburg, PA) of services that offer high-spatial-resolution, real-time estimates of wetness timing and duration on the basis of U.S. National Weather Service radar scans and meteorological models. Although these services will require extensive validation, they offer the enticing prospect of disease-warning systems driven entirely by remotely sensed data.

Summary

The progress described represents one of the greatest sucesses yet achieved in implementing a disease-warning system in North American agriculture. Cooperating growers in five states and Ontario have used FAST and its descendants to reduce the frequency of fungicide spraying by up to 50% compared with conventional, calendar-based schedules. Clearly, a grower who uses fewer pesticide sprays to attain fruit yield and quality equivalent to conventional spray programs saves money and is a stronger economic competitor. Implementation of these systems has spread beyond eastern North America; in 1994, for example, TOM-CAST was used successfully on commercial processing tomatoes in New Zealand (M. D. Ricker, *unpublished*).

A key ingredient of this success is the close relationship between growers and processing companies. Because processors contract with growers for their crops, the growers are highly responsive to the advice and concerns of their sole customer. When processors perceived the need to reduce fungicide use, rapid implementation of disease-warning systems was assured. Both growers and processors benefited from strong links to plant pathologists in land-grant and agricultural colleges and universities in the United States and Canada who developed and refined the systems and introduced them to the tomato industry. Private consultants have begun to take an active role in some regions, too. Close cooperative relationships have helped to push these IPM systems into wide use in a relatively short period of time; although the FAST model is nearly 20 years old, implementation in much of eastern North America has advanced most rapidly during the last 5 years.

Outlook

Will past successes in implementing disease-warning systems on processing tomatoes be sustained and expanded, or will they be scrapped? The history of other IPM systems in North American agriculture is mixed. Many initially promising efforts collapsed or became dormant after grant funds and early enthusiasm ebbed, whereas others are thriving several decades after their inception. Disease-warning systems must continue to improve in reliability, affordability, convenience, and compatibility with other tomato IPM techniques to remain relevant in the future.

Socioeconomic questions also hover over the future of these systems. Grants and other short-term funds have fueled startup implementation efforts, but who should pay to sustain the systems? Who should operate them? Close cooperative links among growers, processors, private consultants, and university and government personnel have been the glue holding technology transfer together; how can these links be nurtured and strengthened in an era of rapid change in the tomato industry and budget shrinkage in the public sector? Answers to these questions must be found so that disease-warning systems can continue to enhance the competitiveness of eastern North American processing tomatoes in the global marketplace.

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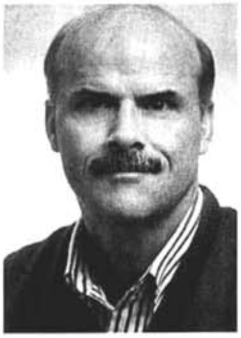

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