A *Cercospora* Leaf Spot Model for Sugar Beet In Practice by an Industry

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Sugar beet (*Beta vulgaris* L.) is planted on nearly 268,000 ha in the Red River Valley (RRV) of Minnesota and North Dakota and in southern Minnesota. This geographic region is the leader in sugar beet production in the United States, representing about 45% of the hectares planted (17) and accounting for 50% of the tonnage produced annually (28). The most recent economic analysis by Bangsund and Leistritz (1) estimated that the 1992 sugar beet crop in Minnesota and North Dakota had direct impacts (production and processing) at \$575.5 million and secondary impacts at an additional \$1.06 billion.

The sugar beet industry in Minnesota and North Dakota consists of three grower-owned cooperatives (Fig. 1). American Crystal Sugar Company (186,810 ha) includes five districts, each with a factory where sugar is extracted. The Minn-Dak Farmers Cooperative (37,320 ha) and the Southern Minnesota Beet Sugar Cooperative (43,590 ha) are large districts, each with a single factory. The RRV includes the American Crystal and Minn-Dak cooperatives. Distance from the northern to the southern borders of the three cooperatives spans about 560 km.

This article reviews the history of *Cercospora* leaf spot in Minnesota and North

Dakota, which culminated in development of a leaf spot model. It also covers implementation and evolution of the model during 10 years of application by the sugar beet industry. Limitations and benefits of the *Cercospora* leaf spot model are presented.

Epidemic of 1981

Leaf spot, caused by *Cercospora beticola* Sacc., was not economically important to the sugar beet crop produced in the RRV and southern Minnesota before 1980. Several significant changes occurred earlier in the 1970s, however, that set the stage for an epidemic. In the fall of 1973, American Crystal Sugar Company (the only sugar company in Minnesota and North Dakota at that time) became a grower-owned cooperative. Policies previously set by agricultural management of the company now included input from sugar beet producers, since both groups were represented on the Board of Directors. Producers no longer wanted to plant American 2 Hybrid B, a widely planted "exclusive" cultivar that was moderately resistant to *Cercospora* leaf spot. Instead, they preferred an "open seed policy" that allowed commercial availability of high-yielding cultivars introduced into the United States from Europe in 1973. These cultivars rapidly gained popularity and were widely planted as the American Crystal cooperative expanded and as additional areas were planted with the establishment of Minn-Dak Farmers Cooperative in 1974 and the Southern Minnesota Beet Sugar Cooperative in 1975. The most popular cultivars (e.g., Beta 1345, Beta 1443, Hilleshog Mono 309) were highly susceptible to *C. beticola*, although several

cultivars (ACS ACH 30, G.W. Mono Hy M-8) had some resistance to the disease (27).

Despite a few reports of *Cercospora* leaf spot in the late 1970s, the disease in the RRV appeared to be a minor problem. In 1979, a few producers in the southern Minnesota cooperative applied the benzimidazole fungicides benomyl (Benlate) or thia-bendazole (TBZ or Mertect) when the disease occurred late in the season. *Cercospora* leaf spot was an economic problem in a few sugar beet fields in the southern RRV and in southern Minnesota in August 1980. These fields turned "tobacco brown" (Fig. 2) almost overnight, and producers and agricultural staff wondered if this was a new disease. Some panic spraying of fungicides was done in August, but these applications were too late to stop the epidemic.

Starting with the 1981 season, the cooperatives instituted an aggressive "calendar spray schedule" policy because of uncertainty as to when *Cercospora* leaf spot would develop and because of abundant inoculum from the previous season. The first application of fungicide was to occur "7 days before you see the first spot," with subsequent applications continuing at 10- to 14-day or at 21-day intervals (depending on the fungicide).

Cercospora leaf spot developed early in 1981. It was first noticed by mid-June in southern Minnesota, mid-July in the southern RRV, and in August in the northern RRV (5). The first fungicide applications were made by 10 July by some producers in the RRV and earlier in southern Minnesota. Overall, fungicides resulted in inconsistent control because some producers didn't start applications early enough, used

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Fig. 1. Location of sugar beet cooperatives and factory districts in Minnesota (MN) and North Dakota (ND).

low rates, and over-extended spray intervals. Protectant fungicides (ethylenebis-dithiocarbamate [EBDC] = maneb, mancozeb) were available but were not favored because they had to be applied every 10 to 14 days. The benzimidazole fungicides were widely used because their systemic activity stopped infections that had occurred during the previous 24 to 36 h and because application intervals could be extended from 14 to 21 days. Protection with systemic fungicides was generally good in the American Crystal cooperative (5), where at least one application resulted in an average yield increase of 2.5 Mg/ha. Overall, the Minn-Dak cooperative noted that the crop had a low sugar content and purity compared with previous years (5). In the southern Minnesota cooperative, *Cercospora* leaf spot affected 80% of the crop, and loss was estimated from 4.5 to 6.7 Mg/ha; sugar content averaged 13% (compared with a normal of 15%); and economic losses were from \$250 to \$285/ha (5).

In some fields in southern Minnesota, two to three applications of systemic fungicides were ineffective in controlling disease (Fig. 2). Strains of *C. beticola* with resistance to the benzimidazole fungicides were confirmed in 1981 (2), and systemic fungicides were no longer recommended (5). Many producers continued to apply benzimidazole fungicides, however, and within the next couple of years, resistance to these fungicides became widespread across the entire sugar beet growing area of Minnesota and North Dakota (18). Substantial shifts in fungicide use occurred by 1983 when protectant fungicides, primarily triphenyltin hydroxide (TPTH or Supertin), were applied on nearly all of the sugar beet crop compared with benzimidazole use on 7% of the crop (8).

Fig. 2. Severe leaf spot in a sugar beet field where *Cercospora beticola* is resistant to the fungicide benomyl (Benlate).

Cause and Symptoms

Leaf spot caused by *C. beticola* is the most common and destructive disease of sugar beet in Minnesota and North Dakota. Severity of *Cercospora* leaf spot varies from year to year, depending on weather conditions and effectiveness of disease control. If leaf spots cover at least 3% of the foliage by harvest, economic losses occur through reduced root tonnage and sucrose content and increased impurities. Also, roots of infected plants do not store as well as roots of healthy plants (15).

Individual leaf spots are circular, from 3 to 5 mm in diameter, and have tan to ash gray centers with dark brown to reddish purple borders (Fig. 3A). Stromata are visible in the necrotic spots as tiny black

dots (Fig. 3B). During periods of warm, wet, and humid weather, the lesions become steel blue to gray in color from the production of conidiophores and conidia on the stromata, and spots may coalesce (Fig. 3C). Severely infected leaves can wither, die, and fall to the ground, but they usually remain attached to the crown. Disease begins on the older leaves and progresses to younger foliage. *Cercospora* leaf spot also occurs on petioles.

The fungus overwinters on infected beet residue as stromata (19). During humid weather, conidiophores and conidia form on stromata, and conidia are spread by wind, water (irrigation and rain), and insects (16). Conidia and stromata also are carried on seed produced in regions where

disease is severe, but this source is of minor importance (16). Several common weed hosts, such as redroot pigweed, lamb's-quarters, mallow, and bindweed, also serve as minor sources of inoculum (20).

Sporulation, germination, and infection by *C. beticola* are favored by daytime temperatures of 25 to 35°C, night temperatures above 16°C, and extended periods of high humidity (90 to 95%) or free moisture on leaves (15,19,20). Conidia of *C. beticola* are produced most readily at temperatures from 20 to 26°C and relative humidity (RH) from 90 to 100%, but do not form at temperatures less than 10°C. Ideal conditions for germination and infection occur in free water on leaves when the temperature is 25 to 35°C for at least 8.5 h. Con-

idia germinate on the leaf surface and then penetrate through stomata. Symptoms develop from 5 to 21 days after infection, depending on weather conditions.

Disease Management

Integrated management of Cercospora leaf spot includes several cultural practices, cultivars that are moderately resistant, and the prediction model (scouting for disease and monitoring of weather conditions), which allows judicious application of foliar fungicides.

Cultural practices. Since *C. beticola* survives in infected beet leaves, cultural practices include deep tillage (to turn under residues) and a minimum rotation of beets every third year with nonhost crops. Also, beet fields are sown at least 100 m from fields planted to beets the previous year to avoid spread of conidia from infested debris (16).

Cultivar resistance. Following the epidemic of 1981, the cooperatives adopted a stringent selection policy for cultivars approved for sale to member producers. The most susceptible cultivars were not planted in 1982. New cultivars approved for commercial production required a leaf spot rating (averaged across five to seven evaluations from late July through late August) of 5.5 or less, based on the 1 to 9 Kleinwanzleber Saatzeit (KWS) scale (14). They also had to yield an average percentage of recoverable sucrose equal to or greater than the mean of all cultivars evaluated in 3 years of tests.

Evaluations for resistance to Cercospora leaf spot are performed annually at the Betaseed Cercospora Screening Nursery in Shakopee, Minnesota, where plots are

inoculated with *C. beticola* (Fig. 4). Coded trials for sugar beet quality and yield also are evaluated annually in commercial beet fields at multiple locations throughout Minnesota and North Dakota.

Because of increasingly severe disease pressure in recent years, the maximum KWS value for commercial cultivars has been lowered. The cooperative in southern Minnesota reduced their acceptance threshold of resistance to Cercospora leaf spot to a maximum KWS rating of 5.3 in the early 1990s and then lowered it to 5.0 in 1996. The Minn-Dak Farmers Cooperative is lowering their acceptance value to 5.2 in 1998. American Crystal Sugar Company is phasing in cultivars with a KWS rating of 5.3 or lower by 1999.

Fungicide management. Fields are monitored for disease, and fungicides are applied at disease onset or when weather favors disease. When conditions favor disease, or if disease already is prevalent, fungicide applications are more frequent than when disease pressure is low. Use of protectant fungicides (TPTH, EBDCs, and fixed copper [which provides limited control]) sometimes requires reapplication on a 10- to 14-day schedule to prevent disease. Registered systemic fungicides include benomyl and thiophanate methyl (Topsin M).

In 1994, tolerance to TPTH was first confirmed in southern Minnesota (3). Tolerance to TPTH is defined as reduced linear mycelial growth of *C. beticola* on potato dextrose agar (PDA) amended with 0.2 or 1 ppm TPTH (concentrations that completely inhibit growth of sensitive strains) compared with an unamended PDA control (3). Subsequently, agriculturists employed by the cooperatives have submitted diseased sugar beet leaves collected from fields under their supervision to the USDA, Agricultural Research Service, Northern Crop Science Laboratory at North Dakota State University, Fargo. Cultures of *C. beticola* isolated from these diseased leaves are assessed for tolerance to TPTH and for resistance to thiophanate methyl. Tolerance to TPTH is prevalent in southern Minnesota and in the southern RRV and is fairly prevalent in the central and northern RRV (26). Isolates of *C. beticola* with resistance to benomyl (3) and thiophanate methyl are widespread in southern Minnesota and in the southern RRV and are uncommon in the central and northern RRV (26).

Cross-resistance of *C. beticola* to thiophanate methyl and TPTH was detected in 1996 and 1997 (L. G. Campbell, G. A. Smith, and H. A. Lamey, unpublished). Plots treated with thiophanate methyl (three applications at 14-day intervals) resulted in a significant increase in isolates of *C. beticola* resistant to thiophanate methyl and tolerant to TPTH compared with the untreated control. There is no obvious explanation for this phenomenon

Fig. 3. *Cercospora beticola* on sugar beet: (A) individual leaf spots, (B) stomata, and (C) leaf spots coalescing and killing large areas of leaf tissue.

Fig. 4. Screening germ plasm for resistance to *Cercospora* leaf spot at the Betaseed Nursery in Shakopee, Minnesota; a resistant cultivar (right) and susceptible cultivar (left).

since thiophanate methyl is a benzimidazole fungicide and TPTH is an organo-metallic fungicide.

Tolerance to TPTH and resistance to the benzimidazole fungicides has limited options for management of *Cercospora* leaf spot. One strategy is to tank mix TPTH with an EBDC fungicide (producers usually select mancozeb). Another approach is to select an EBDC fungicide (full label rate) for the first one or two applications, followed by a tank mix of an EBDC with TPTH, and then mancozeb at the end of the season, if needed. Benzimidazole fungicides are recommended only in the Hillsboro district and north (Fig. 1) as a single early-season application in a tank mix with mancozeb.

Prediction Model: Original Version

From 1982 to 1985, the Sugarbeet Research and Education Board of Minnesota and North Dakota funded the research of William W. Shane and Paul S. Teng, Department of Plant Pathology, University of Minnesota, St. Paul, to develop a *Cercospora* leaf spot prediction model. The intent of the prediction model was to provide information for timing applications of protectant fungicides so a producer could tailor fungicide application programs to specific fields and years rather than rely on a fixed-calendar schedule. Information on the development and use of the model was published in a series of annual reports distributed to producers and the sugar industry in 1983 to 1986 (21–23,25) and was summarized in 1991 (12).

The *Cercospora* leaf spot prediction model developed by Shane and Teng (21–

23,25) consisted of two integrally related components: percent severity of disease based on field monitoring and a *Cercospora* Advisory based on weather information. Fungicide applications were recommended at certain ratings of disease severity when weather was favorable for disease development.

Disease severity assessment. Disease monitoring began at canopy closure (usually late June to early July) and continued weekly until mid-September. Disease severity was assessed by inspecting plants throughout the field and along two sides bordering last year's beet field, windbreaks, ditches, or other protected areas (12). *Cercospora*-free plants were recorded as zeros. If leaf spot was present, a lower leaf was randomly selected, and its category of damage was estimated and recorded on an assessment form (Fig. 5). A total of 100 plants was rated according to a spot-percentage scale and assigned to a category (1 to 10) based on disease severity: 1 to 5 spots per leaf = 0.10% (category 1), 6 to 12 spots = 0.35% (category 2), 13 to 25 spots = 0.75% (category 3), 26 to 50 spots = 1.50% (category 4), and 51 to 75 spots = 2.50% (category 5). At higher disease incidences, the average affected area per leaf was estimated from standard area diagrams, and categories 6 through 10 represented 3, 6, 12, 25, and 50% severity, respectively (12,21). An average severity value was calculated and compared with Action Zones for *Cercospora* leaf spot (25) (Fig. 6). As long as the average percent disease severity remained within the safety zone for a given calendar date, fungicide applications were not economical. As soon as the average percent severity value en-

tered the caution zone, an initial fungicide application was made.

***Cercospora* Advisory.** The Advisory (22) described the potential for infection by *C. beticola* that existed during the previous 48 h as a single whole number between 0 and 14 based on a Daily Infection Value (DIV). The DIVs ranged from 0 to 7 and were calculated from the number of hours per day (midnight to midnight) with RH greater than 90% and the average temperature during those hours (Table 1). Shane and Teng (22) developed the DIV table from greenhouse trials (sugar beet plants inoculated with *C. beticola* at various temperatures and humidities, as measured by a hygrothermograph) in combination with published data (29). In the field, infection periods may last longer than 1 day, so the *Cercospora* Advisory consisted of adding the DIVs for the two preceding 24-h periods. If the sum of two adjacent days was less than 6, the likelihood of infection was low; a sum of 6 was marginal; and sums of 7 to 14 indicated conditions favorable for infection.

After the first fungicide application, subsequent applications differed with location (12). In the northern RRV, second and subsequent fungicide applications were based on average percent disease severity (determined by field monitoring), *Cercospora* Action Zones (Fig. 6), and the *Cercospora* Advisory. In the southern RRV and especially in southern Minnesota, where weather conditions tend to be favorable for leaf spot development, the second fungicide application was made at the end of the first spray interval based on the product label. Then, field monitoring was resumed to determine percent disease severity, and

Damage category	SE	NW	Border	NE	SW	Border	Total	Severity (%)	Average severity
0							76	0.00	0.00
1							20	0.10	2.00
2			1		1		2	0.35	0.7
3							2	0.75	1.5
4								1.50	
5								2.50	
6								3	
7								6	
8								12	
9								25	
10								50	
							100		4.20
									0.042

Fig. 5. Assessment form for calculating average severity of *Cercospora* leaf spot based on examination of 100 sugar beet plants. Damage categories (0 to 10) correspond to percent disease severity: 0 = no leaf spot, 1 to 5 spots per leaf = 0.10% (category 1), 6 to 12 spots = 0.35% (category 2), 13 to 25 spots = 0.75% (category 3), 26 to 50 spots = 1.50% (category 4), and 51 to 75 spots = 2.50% (category 5). At higher disease incidences, the average affected area per leaf is estimated from standard area diagrams and categories 6 through 10 represent 3, 6, 12, 25, and 50% severity, respectively (12,21).

among fields. When conditions for *Cercospora* leaf spot are marginal but inoculum is readily available, a low incidence of successful infections can result in development of considerable disease.

According to agriculturists (33 of 38) surveyed in November 1996, the rationale for recommending the first fungicide application varied with the cooperative (Table 2). The most frequent response from agriculturists at the American Crystal and Minn-Dak cooperatives was when *Cercospora* leaf spot was detected in a field or in nearby fields (61 and 86%, respectively); the most popular determinant in the southern Minnesota cooperative (75%) was when the canopy closed the row (Table 2). Other important criteria included weather conditions (recent, current, predicted), DIVs (often used together with current and predicted weather), susceptibility of cultivar, and field location or history (proximity to sheltered areas, crop development). Prioritization of these criteria, however, varied with the cooperative. Calendar date (application of fungicide at a set time each season) was identified as having limited value in the American Crystal and southern Minnesota cooperatives but was not noted by agricultural staff at Minn-Dak.

Over the last 10 years, calculation of DIVs and employment of the *Cercospora* Advisory have been modified. The DIVs, when calculated at 90% RH, did not account for the incidence of *Cercospora* leaf spot observed in the field, particularly in southern Minnesota and the southern RRV. To reduce the risk of untreated disease, the southern Minnesota cooperative began calculating DIVs based on 87% RH readings starting in 1988. This change was a conservative educated guess to more closely match field observations. The same change in calculation of the DIV was adopted by American Crystal in 1993 and by Minn-Dak in 1995.

The southern Minnesota and Minn-Dak cooperatives have encountered conditions extremely favorable for *Cercospora* leaf spot in the last few seasons. In southern Minnesota, the DIV is interpreted in a very conservative manner (and the *Cercospora* Advisory usually is not implemented). The agriculture staff notes DIVs over a 5-day period. If DIVs are 1 or 2, there is a low potential for disease development. When DIVs increase to 3 or 4 for 1 day, conditions are favorable for *Cercospora* leaf spot. During these periods, sugar beet leaves often remain wet until noon (although RH readings may be low); a fungicide application is advised if the interval of the previously applied fungicide is starting to lapse. In 1996, the Minn-Dak Farmers Cooperative also stopped using the *Cercospora* Advisory and started providing their producers with DIVs for the preceding 7 days. DIVs that fall between 0 and 4 are interpreted as indicating low disease potential, 5 and 6 indicate medium

potential, and 7 indicates high potential. To use DIVs successfully, however, producers also are advised to monitor fields for leaf spot and to consult with agricultural staff.

Criteria used as a basis to decide when to apply the second (and subsequent) fungicide application varied with the cooperative, according to a survey of agriculturists in November 1996. The most popular criterion was the length of interval recommended on the fungicide label by the manufacturer (Table 2). The DIV was ranked as the second most important criterion at American Crystal (56%) but was of less importance among agriculturists at the Minn-Dak (29%) and southern Minnesota (25%) cooperatives. Criteria listed as more important than DIVs by agriculturists at Minn-Dak were weather and cultivar susceptibility to *C. beticola*, and at the southern Minnesota cooperative were weather and incidence of disease. Among the least important factors were density of canopy, time before harvest, and recommendations from chemical company representatives.

Implementation

Implementation and evaluation of the *Cercospora* leaf spot prediction model commenced as it was being developed and involved cooperation of the sugar beet industry, producers, and university personnel. Two key ingredients promoted adoption of the model: (i) education programs for the potential advocates (agricultural staff of the cooperatives) and producers and (ii) establishment of weather monitoring networks to provide data on RH and

temperature on a 24-h basis for calculation of the DIV (to determine the *Cercospora* Advisory).

Education programs. Education efforts initiated in the 1980s continue today. Extension and research faculty from the University of Minnesota and North Dakota State University participate in annual seminars for producers and other personnel involved in sugar beet production. They present information on the biology, identification, and control of *Cercospora* leaf spot and explain the leaf spot prediction model. This information also is distributed to all sugar beet producers through research and extension publications. In addition, the sugar beet cooperatives hold training sessions for their agricultural staff and new producers. They also distribute newsletters to producers to emphasize and explain field monitoring, DIVs, and the *Cercospora* Advisory.

Early response by the sugar beet industry and producers to the original prediction model was mixed because of uncertainty as to how and if it worked. Many producers thought the model should not entail extra work, but instead provide a single numerical value indicating whether a fungicide application was needed. Problems with weather monitoring stations that resulted in inaccurate DIVs and *Cercospora* Advisories also raised questions about credibility of the model. Some agriculturists had many of the same concerns. The southern Minnesota and Minn-Dak cooperatives encouraged adoption of the prediction model. The American Crystal cooperative

Table 2. Factors identified by agriculturists employed by three sugar cooperatives as the basis for recommending fungicide applications to control *Cercospora* leaf spot

Criteria	Agriculturists identifying each factor ^a (%)		
	Am. Crystal	Minn-Dak	So. Minn.
First application			
<i>Cercospora</i> leaf spot found ^b	61	86	38
Weather	45	43	63
Row closure	36	29	75
Daily Infection Value	33	43	25
Cultivar susceptibility	27	57	50
Field location/history ^c	27	29	63
Calendar date	12	0	38
Second (and subsequent) application			
Label recommendation ^d	61	71	63
Daily Infection Value	56	29	25
Disease incidence	50	29	38
Weather	33	86	75
Cultivar susceptibility	11	57	0
Canopy density	11	14	13
Time remaining to harvest	7	0	13
Other sources of recommendations ^e	8	0	0

^a Responses from 18 of 23 agriculturists at American Crystal Sugar Company, 7 of 7 at Minn-Dak Farmers Cooperative, and 8 of 8 at the Southern Minnesota Beet Sugar Cooperative in a survey conducted during November 1996. For each cooperative, values are more than 100% because agriculturists identified multiple factors.

^b In field and/or geographic area.

^c Includes planting date, proximity to sheltered areas, crop rotations.

^d Length of interval recommended on the fungicide label by the manufacturer.

^e Direct recommendation by a chemical company representative.

left this option to the discretion of each producer, but on 17 June 1987, it departed from the traditional calendar preventative spray program and announced a policy "to implement the *Cercospora* prediction model as a guide to starting the first fungicide spray as well as when succeeding sprays are needed." Acceptance of this policy had improved by then, especially in the northern RRV, where *Cercospora* leaf spot had been a minor problem in previous years and validity of the calendar spray program was questioned.

Weather monitoring networks. Because the DIVs and *Cercospora* Advisory depend on the availability of accurate weather data, particularly RH and temperature, the cooperatives established weather stations in commercial sugar beet fields. The model was originally designed and tested with hygrothermographs installed in standard meteorological enclosures and placed just above the ground between rows (24). In 1983, these units were installed at pilot sites in the southern Minnesota, Minn-Dak, and American Crystal cooperatives. Several problems developed that compromised accuracy of the data. Periodic maintenance and quality control of the units was difficult because soil, water, rodents, etc., interfered with operation of the instruments. Some weather stations did not function for long periods of time, resulting in major gaps of data. Some units consistently peaked at night at apparent RH values as low as 85% or as high as 110%. This meant that the DIV was underestimated if the RH reading was too low or overestimated if the RH reading was too high. Also, considerable time was required to travel to and from the weather stations and to calculate DIVs.

In 1985, the cooperatives installed automated weather stations (Fig. 7A) (Models CR-21, CR-21X, and later, CR-10; Campbell Scientific Co., Logan, UT).

By 1988, seven stations were located in commercial fields throughout the RRV, and three were in southern Minnesota. The weather stations were moved to different fields each season. When leaves covered the row, humidity and temperature probes were set 5 cm below the top of the leaf canopy (Fig. 7B and C). Data were recorded every minute for 24 h (midnight to midnight), downloaded daily to each cooperative, and used to calculate the DIV. The agricultural staff at each factory prepared a daily *Cercospora* Advisory.

Automatic weather stations have greatly improved accuracy of the *Cercospora* Advisory, but problems still occur when sensors for RH and temperature are not placed in the canopy or when they are dirty. Currently, agricultural staff at the Minn-Dak and southern Minnesota cooperatives maintain two and four automated weather stations, respectively. Since 1995, The American Crystal cooperative has maintained six factory weather stations as part of the North Dakota Agricultural Weather Network (NDAWN) through North Dakota State University. NDAWN weather stations are solar powered, and data are downloaded daily by phone. The top of the shield for the RH sensor is placed 40 cm above the soil, and the sensing element is 30.5 cm above the soil surface. Every spring, the sensors are calibrated with a laboratory standard dew point generator at 25, 50, and 90% RH; accuracy of the sensor is $\pm 2\%$ when RH is below 90% and $\pm 3\%$ when RH is above 90% (J. W. Enz, North Dakota State University, *personal communication*). Without a full leaf canopy, however, RH in the canopy is significantly underestimated (9).

All weather stations currently maintained by the three cooperatives are located at permanent sites in commercial fields that represent the macroclimate of the area as much as possible. Cooperatives estab-

lish a sugar beet crop near or around the weather stations so sensors can be placed in the plant canopy. This requires good husbandry of the crop. Most sites have been well maintained, but weather data at other sites are not reliable because of weeds and low populations of sugar beet plants. Also, planting continuous beets at permanent sites is not always possible; therefore, the Minn-Dak cooperative has started to grow rhubarb at the weather station sites, because rhubarb simulates a sugar beet canopy and is easier to maintain.

Initially, DIVs and the *Cercospora* Advisory were accessible to producers and crop consultants through dedicated telephone hot lines and by contact with sugar beet industry agricultural staff. Later, DIVs and the *Cercospora* Advisory were expanded to a special page on the Data Transmission Network (DTN, Omaha, NE) by the cooperatives (Minn-Dak in 1987, American Crystal in 1992, and southern Minnesota in 1993). A survey of sugar beet producers in October 1996 revealed that 71% (of 566 respondents) accessed DIVs and the *Cercospora* Advisory by the DTN, 17% contacted agricultural staff, and 12% used the telephone hot line (7).

Fungicide Application Problems

The timing of the initial application, as well as application intervals, is critical to control *Cercospora* leaf spot. If disease is not detected early at onset, then the first fungicide application may be too late and a large population of conidia develops to infect new, unprotected foliage before the next fungicide application. The greater the disease pressure, as indicated by the DIV and severity of leaf spot, the shorter the application interval required. Inclement weather and the unavailability of commercial aerial applicators when needed can delay timely application of fungicides.

Fig. 7. (A) A CR-10 automated weather station. (B) Stakes show position of temperature and humidity probes (noted by an arrow) placed incorrectly above the canopy and (C) placed properly within the canopy.

When wet weather persists, it is impossible to apply fungicides by ground, and aerial applicators often have a backlog of orders to apply fungicides to beets. This situation can delay the first application or extend intervals between applications, either of which results in reduced disease control.

Uniform coverage of foliage with fungicide, either by air (Fig. 8A) or ground application (Fig. 8B), is vital for control of leaf spot. Careless application of fungicide or defective equipment can result in strips and patches of foliage with severe *Cercospora* leaf spot (Fig. 9). Some aerial applicators rely on the Global Positioning System to assure thorough application of pesticides over a field. Coverage under power lines, along shelter belts, and near trees, however, is difficult for aerial applicators. Operators must pull up their aircraft over such obstacles and thus do not provide adequate coverage near them. Many aerial applicators routinely side-dress along power lines and shelter belts to assure adequate coverage. In 1997, 62% of fungicide treatments were applied by airplane and 38% by ground equipment (6).

Effectiveness of fungicide application is reduced by improper calibration of spray equipment, improper spacing of nozzles, and worn and plugged nozzles. The type of application equipment, operating pressure, and amount of water carrier also affects efficacy of fungicides (4,11). Coverage of foliage with fungicides applied by ground equipment is most effective when the pressure is more than 6.9×10^5 Pa, but 1.4×10^6 Pa or greater does not enhance coverage (4). The best coverage for ground application ranges from 187 to 374 liters/ha; amounts of less than 187 liters/ha do not cover leaves adequately, and 561 liters/ha results in run off (4).

Inadequate control of *Cercospora* leaf spot usually occurs because of problems related to fungicide application, according to a survey of agriculturists in November 1996 (Table 3). Agriculturists also identified other fungicide-related problems, including selection of tolerance to the tin fungicides and early cessation of fungicide programs. Inadequate control of *Cercospora* leaf spot also was attributed to planting the most susceptible cultivars available, prolonged weather conditions favorable for disease, delay of the first fungicide application until disease severity was too high to regain control of the disease, and close rotation of sugar beet crops.

Benefits of the Model

Economic benefits gained from the *Cercospora* leaf spot model are difficult to determine directly. In annual surveys of 14 to 33 sugar beet fields in the southern Minnesota and Minn-Dak cooperatives, the average number of fungicide applications was 3.7 in 1982, 4.0 in 1983, 3.7 in 1984, and then dropped to 2.1 when the model was implemented in 1985 (24). When fun-

gicide use from 1986 through 1988 was evaluated across the fields of the American Crystal cooperative, the number of fungicide applications was reduced by 1.5, representing a \$4.2 million annual savings to producers (10). These years were unseasonably dry, but many producers would have continued to apply fungicides on a calendar spray program without the prediction model. The prediction model was designed for nonirrigated beets in Minnesota and North Dakota, but when evaluated on irrigated sugar beets in the panhandle of

Nebraska, it resulted in reduction of fungicide applications (13).

A variable pattern in number of fungicide applications per season has prevailed across the sugar beet-growing regions of Minnesota and North Dakota (Fig. 10) since these data were first collected in 1983 (A. G. Dexter, North Dakota State University, *personal communication*). Every year, the lowest fungicide use generally has occurred in the northern RRV compared with intermediate use in the southern RRV and highest use in southern

Fig. 8. Fungicides are applied by (A) airplane and (B) ground spray equipment to control *Cercospora* leaf spot of sugar beet.

Fig. 9. Severe *Cercospora* leaf spot on a few rows of sugar beet plants that were missed when fungicide was applied by ground equipment.

Minnesota. These trends reflect increasingly favorable temperature and moisture conditions for development of *Cercospora* leaf spot from the northern to the southern beet-growing areas (Table 4).

Since 1991, weather conditions compared with previous seasons have been

more favorable for development of *Cercospora* leaf spot (especially in the southern RRV and in southern Minnesota), and the number of fungicide applications has increased (Fig. 10). In these seasons, adoption of the model has been especially important because it takes only a modest

return in yield to offset the costs of fungicide and application. Average costs per hectare for each fungicide application are about \$13.30 for TPTH and \$14.80 for an EBDC fungicide, with an additional expense to apply the chemical by custom airplane (\$9.90), custom ground equipment (\$8.65), or with producers' ground equipment (\$3.70). When use of the model extends the length of a spray interval and results in one less fungicide application on 50% of the hectares, savings in input costs (fungicide and application) are about \$3.2 million annually.

Fewer fungicide applications are made when cultivars that are least susceptible to *Cercospora* leaf spot are planted, but they usually yield lower amounts of recoverable sucrose compared with more susceptible cultivars. Consequently, cultivars with moderate susceptibility to *Cercospora* leaf spot are preferred, because even with additional fungicide applications, they are more profitable than the less susceptible cultivars.

Overview and Outlook

The *Cercospora* leaf spot model has been integrated with other control options for more than 10 years. When the model was developed, it was evaluated in select fields with moderate levels of disease, but when implemented on a wide scale, several uncertainty factors emerged. For instance, the model was untested under a wide range of concentrations of inoculum, under prolonged environmental conditions favorable for disease, and when DIVs varied from 0 to 6 on adjacent days. When seasons very favorable for development of *Cercospora* leaf spot were encountered, and adherence to the model resulted in inadequate disease control, the industry made several modifications in the model: adjustment of RH values from 90 to 87% to calculate DIVs; employment of DIVs and the *Cercospora* Advisory to determine the second and subsequent fungicide applications but not the first; and use of DIVs rather than the *Cercospora* Advisory in geographic regions where inoculum concentrations are high and weather conditions are extremely favorable for disease. These changes have improved reliability of forecasting *Cercospora* leaf spot and reduced risk of disease, but they should be confirmed or fine-tuned by scientific investigation. Also, reliable environmental data are needed as well as information on the geographic area reasonably covered by a weather station. Perhaps weather data currently collected from distant specific sites are robust and useful in many fields but are inadequate when disease is sporadic or when disease pressure is low but cumulative.

Two factors will allow for broader adoption of the *Cercospora* model: a simpler and easier means to monitor and assess sugar beet fields for disease severity and a reliable measurement of RH and

Table 3. Factors identified by agriculturists employed by three sugar cooperatives as responsible for inadequate control of *Cercospora* leaf spot of sugar beet

Factors	Agriculturists identifying each factor ^a (%)		
	Am. Crystal	Minn-Dak	So. Minn.
First application delayed	83	100	75
Fungicide application poor ^b	50	14	88
Intervals too long ^c	39	57	88
Fungicide rates too low	17	14	0
Cultivar susceptibility	11	29	38
Weather	11	29	13
Disease incidence	11	0	13
Other ^d	6	29	25

^a Responses from 18 of 23 agriculturists at American Crystal Sugar Company, 7 of 7 at Minn-Dak Farmers Cooperative, and 8 of 8 at the Southern Minnesota Beet Sugar Cooperative in a survey conducted during November 1996. For each cooperative, values are more than 100% because agriculturists identified multiple factors.

^b Fungicide application problems include poor coverage, plugged nozzles, no spray on edges of fields or near windbreaks and power lines.

^c Intervals delayed beyond fungicide label recommendations, fungicide removed by heavy rain.

^d Fungicide application stopped too early, tolerance to tin fungicides developed, producer decided not to invest in fungicide for cost/benefit reasons, poor rotations.

Fig. 10. Mean number of fungicide applications per season in Renville County and surrounding counties in the Southern Minnesota Beet Sugar Cooperative (So. MN); Richland County in the Minn-Dak Farmers Cooperative, southern portion of the Red River Valley (So. RRV); and Pembina County in American Crystal Sugar Co., northern portion of the Red River Valley (No. RRV). Figure compiled from annual surveys conducted by A. G. Dexter (North Dakota State University, *personal communication*).

Table 4. Average 30-year (1967 to 1996) precipitation and maximum and minimum temperatures during summer months at three sugar beet factory locations in the Red River Valley (RRV) and southern Minnesota

Location Factory district	Mean 30-year average values per month ^a								
	Precipitation (mm)			Maximum temp (°C)			Minimum temp (°C)		
	July	Aug	Sept	July	Aug	Sept	July	Aug	Sept
North RRV									
Drayton, N.D.	68	49	52	24	19	19	11	7	5
South RRV									
Moorhead, Minn.	72	57	49	28	27	21	15	14	8
Southern Minnesota									
Renville, Minn.	98	87	66	29	28	23	17	15	10

^a Data provided by Mark Seely, Climatologist, University of Minnesota, St. Paul.

temperature. These factors define the limits of the model and thus affect disease control and economic benefits. The possibility of site-specific weather data appears promising, but current resolution (1 km²) by satellite is inadequate to predict where hot spots of disease might develop. Availability of site-specific weather data on a smaller scale, directly or by simulation, would open exciting new possibilities for *Cercospora* leaf spot management by the sugar beet industry. Regardless of how weather data are collected, each producer needs to know what happens in his or her fields—whether it be an early-morning shower or a dew that remains until noon—to make an intelligent decision on leaf spot control.

Despite some limitations and modifications in the *Cercospora* leaf spot model, it has increased grower awareness of environmental conditions that favor disease. This knowledge has signaled a logical basis for departure from fungicide applications based on calendar dates and has resulted in judicious application of fungicides, improved leaf spot control, and frequently, reduced production costs.

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