Influence of Host Resistance on Stewart's Wilt Forecasts and Probability of Exceeding Thresholds for Use of Seed-Treatment Insecticides on Sweet Corn

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ABSTRACT

Meyer, M. D., Pataky, J. K., Joos, D. K., Esgar, R. W., and Henry, B. R. 2010. Influence of host resistance on Stewart's wilt forecasts and probability of exceeding thresholds for use of seed-treatment insecticides on sweet corn. *Plant Dis.* 94:1111-1117.

Many sweet corn (*Zea mays*) hybrids commercially available today have higher levels of resistance to Stewart's disease (caused by *Pantoea stewartii* subsp. *stewartii*) than the cultivars from which Stevens developed the first forecast of this disease in the 1930s. Incorporating levels of host resistance into forecasts of the seedling wilt phase of Stewart's disease (i.e., Stewart's wilt) could improve control decisions for sweet corn which are made prior to planting. Incidence of systemic infection of seedlings was assessed on 27 sweet corn hybrids with a range of reactions to *P. stewartii*. In total, 741 observations were collected from 1998 to 2009 in 79 field trials at 15 locations throughout Illinois and one each in Kentucky and Delaware. Relative frequency distributions of the incidence of systemic Stewart's wilt were developed for combinations of hybrids with different levels of resistance and ranges of winter temperature from Stewart's wilt forecasts. The probability of exceeding thresholds of 1 or 5% incidence that warrant the use of seed-treatment insecticides on sweet corn grown for fresh market or processing, respectively, was determined from these frequency distributions. Levels of host resistance affected the incidence of systemic seedling wilt within ranges of winter temperatures used by Stewart's wilt forecasts. For moderate and resistant hybrids, frequency distributions of Stewart's wilt incidence and mean incidence ranging from 0.7 to 1.8% did not differ among three winter temperature ranges above -2.8°C . Conversely, distributions of Stewart's wilt incidence on susceptible hybrids differed among each of the four ranges of winter temperature from the Stevens-Boewe forecast (i.e., >0.6 , -1.1 to 0.6 , -2.8 to -1.1 , and $<-2.8^{\circ}\text{C}$), with mean incidence ranging from 0.5 to 8.5%. Occurrence of Stewart's wilt also differed among trials varying in number of winter months above -4.4°C , the criterion used by the Iowa State forecast of this disease. Levels of host resistance to *P. stewartii* also affected the occurrence of Stewart's wilt as predicted by the Iowa State method. The probability of exceeding economic thresholds of 1 or 5% incidence of systemic Stewart's wilt depended on levels of host resistance and winter temperature. Stewart's wilt is unlikely to exceed economic thresholds when the mean winter temperature is below -4.4°C . When mean winter temperature was above -2.8°C , the probability of exceeding 1% incidence of systemic Stewart's wilt was 0.59 for susceptible sweet corn hybrids and 0.28 for moderate and resistant hybrids. When mean winter temperature was below -2.8°C , the probability of exceeding 1% incidence of systemic Stewart's wilt was 0.22 for susceptible hybrids and 0.04 for moderate or resistant sweet corn hybrids. The probability of exceeding 5% incidence was less than 0.1, except when the mean winter temperature was above -2.8°C and susceptible hybrids were grown.

Plant disease forecasts can be used to guide disease management decisions. Forecasts have been developed for several economically important vegetable diseases such as Stewart's disease (caused by *Pantoea stewartii* subsp. *stewartii* (Smith) Mergaert et al. syn. *Erwinia stewartii*) of sweet corn (*Zea mays* L.) (2,7,18,28), late blight (caused by *Phytophthora infestans*) of potato (1), root rot (caused by *Aphanomyces euteiches* and *Fusarium solani* f. sp. *pisi*) of pea (27), and early blight (caused

by *Alternaria solani*) of tomato (15). Most forecasts are based on a single element of the disease triangle (14). Weather is the most commonly used predictor of disease occurrence because environmental factors affect the production or effectiveness of primary or secondary inoculum (5,9). Most

forecasts are developed with the assumption of uniform host susceptibility (10,14).

Host resistance affects the incidence and severity of disease and, therefore, can affect the accuracy of plant disease forecasts. For example, unwarranted fungicide applications were eliminated by accounting for levels of host resistance in two forecast models for late blight of potato (10). Similarly, separate models were developed to forecast stripe rust (caused by *Puccinia striiformis*) on different wheat cultivars (3). Host resistance also was incorporated into a model to predict gray leaf spot (caused by *Cercospora zae-maydis*) of maize in Iowa (26).

The seedling wilt phase of Stewart's disease (i.e., Stewart's wilt) is economically important on sweet corn. *Pantoea stewartii* is vectored by the corn flea beetle, *Chaetocnema pulicaria* Melsh. (6). Sweet corn hybrids experience significant yield losses when Stewart's wilt is prevalent, particularly when susceptible hybrids are infected at early stages of growth (29). Yield reduction is linearly associated with the incidence of systemic infection, which primarily results from the seedling wilt phase of the disease (8). Incidence of systemic infection is affected by levels of host resistance (16,21). In spite of potential yield losses, susceptible sweet corn hybrids may be grown because they possess other desirable traits, such as early maturity, proper ear shape, high yields, or kernel quality (8).

In the 1930s, Stevens (28) associated various levels of the seedling wilt phase of Stewart's disease with a temperature index based on mean daily temperatures in December, January, and February preceding planting (Table 1). Stevens' prediction of the seedling wilt phase is based on the abundance of primary inocula as affected by the presence and size of overwintering

Table 1. Stevens forecast for predicting the seedling wilt phase of Stewart's disease

Index ^a	Mean daily temperature ($^{\circ}\text{C}$)	Fahrenheit index ^b	Prevalence of Stewart's wilt
>100	>0.6	>33	Destructive
90–100	-1.1 to 0.6	30–33	Intermediate
<90	< -1.1	<30	Usually absent
<80 ^c	< -2.8	<27	Absent

^a Sum of the mean daily air temperature (F) in December, January, and February preceding planting (28).

^b Fahrenheit index = Stevens index divided by three and rounded to whole numbers to produce indices equivalent to degrees in Fahrenheit.

^c An additional temperature index was added when the Stevens forecast was expanded to include the leaf blight phase of Stewart's disease (2).

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Accepted for publication 16 May 2010.

doi:10.1094/PDIS-94-9-1111

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populations of corn flea beetles. *C. pulicaria* does not survive prolonged periods of cold weather (4). An additional temperature category was added when the forecast was expanded later to predict the leaf blight phase of Stewart's disease (2). Because the Stevens index is merely the sum of average temperatures from three winter months, dividing the index by three produces an index (which we refer to as the Fahrenheit Index) that is equivalent to the average temperature in degrees Fahrenheit (Table 1).

The Stevens forecast assumes host susceptibility and in-season weather conditions that are conducive for disease development and abundant populations of vectors. Stevens' original associations between winter temperatures and Stewart's wilt were based primarily on the occurrence of disease on open-pollinated sweet corn cultivars (e.g., 'Golden Bantam') known to be relatively susceptible to Stewart's wilt (12,20,22). Modern-day corn hybrids generally have much greater levels of resistance to *P. stewartii* than the cultivars grown in the 1930s. Also, factors other than winter temperature likely affect the abundance of flea beetles and the subsequent amount of Stewart's disease (2). After planting, corn flea beetle populations are affected by weather conditions such as wind, rain, and temperature (4). Incidence of Stewart's wilt usually decreases with later plantings, in association with a decline from April to early June in the size of populations of flea beetles that overwintered from the previous season (4,11,23).

Recently, a model was developed to predict the occurrence of Stewart's disease at the time of phytosanitary inspections in seed corn fields (7,18). This model, often referred to as the Iowa State method, predicts Stewart's disease from the number of winter months with mean monthly air temperatures above -4.4°C (Table 2). The presence or absence of Stewart's disease in seed production fields, which is predicted by the Iowa State method, is crucial to international marketing of corn seed because seedborne *P. stewartii* is regulated by quarantines in many countries. Seed-production fields must be free of the disease to pass phytosanitary inspections late in the season.

Stewart's wilt in sweet corn is controlled primarily through preplant decisions to

grow a resistant or moderately resistant hybrid or to use a seed-treatment insecticide. In previous evaluations, resistant hybrids had four times lower incidence of systemic infection than susceptible hybrids when plants were infected naturally under mild to severe occurrences of Stewart's wilt (16). Neonicotinoid insecticide seed treatments (e.g., imidacloprid, thiamethoxam, and clothianidin) reduced the incidence of Stewart's wilt on sweet corn by 50 to 90% (13,17,24,25). The decision to use a seed-treatment insecticide depends on crop value and the expected level of Stewart's wilt in the absence of control. The cost of neonicotinoid insecticide seed treatment of sweet corn is approximately equivalent to the value of sweet corn yield that is lost when the incidence of systemic Stewart's wilt is about 1% on crops grown for fresh market and about 5% on crops grown for processing (25). Thus, these seed treatments are cost effective above the thresholds of 1 and 5% incidence for fresh-market and processing crops, respectively.

Today, many commercially available sweet corn hybrids have much greater levels of Stewart's wilt resistance than the cultivars from which Stevens developed his forecast in the 1930s. Incorporating levels of host resistance into forecasts of Stewart's wilt could improve preplant control decisions for sweet corn. The objective of this study was to develop and compare relative frequency distributions of the incidence of systemic Stewart's wilt on sweet corn hybrids with different levels of resis-

tance to *P. stewartii* within ranges of winter temperature from Stewart's wilt forecasts, and to use those distributions to determine the probability of exceeding the 1 and 5% incidence thresholds that warrant the use of seed-treatment insecticides.

MATERIALS AND METHODS

Observation of Stewart's wilt in field trials. Incidence of systemic Stewart's wilt infection was evaluated on sweet corn hybrids having different reactions to *P. stewartii* in 79 field trials from 1998 to 2009 at 15 locations throughout Illinois and 1 each in Kentucky and Delaware (Fig. 1). Planting dates varied among locations and years. In all, 10 to 12 sweet corn hybrids were planted at each trial location. The experimental design was a randomized complete block with two or three replicates. An experimental unit consisted of four 7-m-long rows of a sweet corn hybrid spaced 76 cm apart, with about 40 plants per row. Plants between the three- and seven-leaf stage were rated for incidence of systemic Stewart's wilt infection following early season feeding from naturally occurring populations of the corn flea beetle. Systemic infection was determined from symptoms of long, linear streaks of chlorotic leaf tissue on multiple leaves and on leaves emerging from leaf whorls. On some occasions, systemically infected plants were wilted. Randomly selected, systemically infected plants from each trial were examined microscopically for bacterial ooze.

Twenty-seven different hybrids were grown throughout the experiment. Seed were produced in Idaho or Chile, where *P. stewartii* does not occur. Hybrid reactions to Stewart's wilt ranged from susceptible to resistant based on multiple years of evaluation in disease nurseries (Table 3) (19). Reactions from individual disease nurseries were averaged over all years of evaluation. For this study, hybrids were grouped as resistant (1 to 3), moderate (4 to 6), or susceptible (7 to 9) based on mean reactions.

Winter weather data. Mean daily air temperature (i.e., mean of the daily high and low) during December, January, and February were obtained from the Midwestern Regional Climate Center (MRCC) (<http://mrcc.isws.illinois.edu/>) database. If temperature data were not available from a trial location, data from at least two MRCC locations within 25 km were averaged to estimate the daily air temperature at the trial location. Mean winter temperature preceding each growing season was then calculated as the mean of the daily air temperatures for December, January, and February. Trials were categorized by four ranges of winter temperature based on indices from the Stevens-Boewe forecast (Table 1) (2).

Relative frequency distributions and probability. Relative frequency distribu-

Fig. 1. Locations of field trials in which incidence of systemic Stewart's wilt was assessed on sweet corn hybrids from 1998 to 2009. Location in Delaware not shown.

Table 2. Iowa State method for predicting Stewart's disease of corn

No. of months $\geq -4.4^{\circ}\text{C}$	Predicted risk of occurrence
0	Negligible
1	Low to moderate
2	Moderate to high
3	High

^a Based on the mean daily air temperature in the December, January, and February preceding planting (18).

tions of incidence of systemic Stewart's wilt (0, >0 to <1, 1 to <3, 3 to <5, and $\geq 5.0\%$) on susceptible, moderate, and resistant hybrids were developed for each range of winter temperature. Contingency tables generated using the Proc Freq procedure of SAS (version 9.2; SAS Institute Inc., Cary, NC) were used in χ^2 analyses to test the homogeneity of relative frequency distributions for all possible pairwise combinations of distributions within each range of winter temperatures and each hybrid reaction. The probability of exceeding 1 and 5% incidence was determined from relative frequency distributions for all combinations of susceptible, moderate, or resistant hybrids and the four ranges of winter temperature. Binomial tests of pro-

portions ($P = 0.05$) were used to compare the probabilities of exceeding 1 or 5% Stewart's wilt incidence on hybrids with different levels of resistance within each temperature range.

Iowa State method. Mean winter temperatures preceding planting also were grouped according to the Iowa State method for predicting the occurrence of Stewart's disease. Mean daily air temperatures during December, January, and February were calculated and used to group trials by the number of winter months preceding planting with mean daily air temperatures above -4.4°C . Occurrence of Stewart's wilt at each location (i.e., the number of trials where Stewart's wilt was observed divided by total number of trials)

was determined within each category of the Iowa State method. The occurrence of systemic Stewart's wilt (i.e., the presence or absence) on hybrids with susceptible, moderate, and resistant reactions also was compared using the Iowa State method.

RESULTS

Summary statistics. Mean winter temperature preceding planting ranged from -5.8 to 5.7°C and averaged -1.1°C . There were 17 to 25 trials with 153 to 216 hybrid observations for each of the four ranges of winter temperature (Table 4). Stewart's wilt occurred in 59 of 79 trials and on 330 of 741 hybrids observed in those trials (Table 4). Among the 20 trials without Stewart's wilt, 11 occurred in 2008 and 2009, when mean winter temperature for all trial locations was -2.6 and -2.8°C , respectively. Five occurred in 2005, when daily low temperatures from mid-April to mid-May were below 4.4°C for at least 11 and 7 days at central and southern Illinois locations, respectively, and daily low temperatures were below 0°C at least once. Incidence ranged from 0 to 77% and averaged 2.6% for all hybrid observations. Mean incidence was 5.7, 1, and 0.8% for susceptible, moderate, and resistant hybrids, respectively. Mean incidence was 0.3% when the winter temperature was below -2.8°C , and ranged from 2.2 to 4.3% for the other three ranges of winter temperature.

Stewart's wilt was more prevalent at trial locations in southern Illinois and Kentucky than in northern or central Illinois. Stewart's wilt did not occur in 11, 3, and 1 trials each in northern, central, and southern Illinois, respectively. When winter temperature was below -2.8°C , Stewart's wilt was not observed on 80% of the hybrids evaluated (154 of 192 observations). When winter temperature was above -2.8°C , Stewart's wilt was observed on 53% of the hybrids evaluated (292 of 549 observations).

Comparisons of relative frequency distributions. Relative frequency distributions of incidence of systemic Stewart's wilt differed among hybrid reactions and ranges of winter temperature (Tables 5 and 6; Fig. 2). Frequency distributions did not differ between moderate and resistant hybrids within each of the four ranges of winter temperature, whereas frequency

Table 3. Sweet corn hybrids classified from resistant to susceptible to Stewart's wilt based on reactions in disease nurseries

Reaction, hybrid	Seed source ^b	Stewart's wilt reaction ^a		No. of years evaluated
		Mean	SD	
Resistant (1–3)				
Bonus	Rog	1.2	0.4	13
Terminator	Cr	1.7	1.0	11
Ambrosia	Cr	1.8	0.9	18
Summer Sweet 7630	AC	2.0	1.3	12
182A	IFS	2.2	0.6	7
GH 2628	Rog	2.3	1.0	4
Moderate (4–6)				
Crisp and Sweet 710	Cr	3.5	1.5	16
Incredible	Cr	3.5	1.6	19
Crisp and Sweet 710A	Cr	4.0	1.1	8
Shimmer	Sem	4.3	1.4	14
GH 1829	Rog	4.4	1.0	9
Bodacious	Cr	4.6	1.5	20
Even Sweeter	Sem	5.3	1.6	12
273A	IFS	5.3	1.1	10
Honey Select	Rog	5.5	1.1	8
GH 2690	Rog	5.6	2.2	5
Rival	Sem	5.7	1.6	11
Marvel	Cr	6.0	1.1	11
Double Gem	MM	6.1	1.4	8
Temptation	Sem	6.3	0.7	8
Susceptible (7–9)				
Royal Sweet	Rog	6.5	1.9	4
Snow White	HM	6.9	1.7	19
Coho	HM	7.3	1.5	9
Lumina	HM	7.6	1.1	11
Supersweet Jubilee Plus	Rog	8.1	1.2	8
Jubilee	Rog	8.7	0.6	24
Supersweet Jubilee	Rog	8.9	0.3	12

^a Reaction to infection by *Pantoea stewartii* in University of Illinois sweet corn disease nurseries (19), where 1 = resistant, 3 = moderately resistant, 5 = moderate, 7 = moderately susceptible, and 9 = susceptible. SD = standard deviation.

^b Cr = Crookham Co.; HM = Harris Moran Seed Co.; IFS = Illinois Foundation Seeds Inc.; MM = Mesa Maize; Rog = Syngenta Seeds, Rogers Brands; and Sem = Seminis Vegetable Seeds.

Table 4. Occurrence and incidence of systemic Stewart's wilt in 79 trials from 1998 to 2009 grouped by four ranges of winter temperature

Temperature ($^\circ\text{C}$) ^c	FI ^d	Trials		Hybrid observations ^a		Stewart's wilt incidence (%) ^b	
		Total	With wilt	Total	With wilt	Mean	Range
>0.6	>33	25	24	216	112	3.9	0–77
–1.1 to 0.6	30–33	19	15	153	91	4.3	0–62
–2.8 to –1.1	27–30	17	12	180	89	2.2	0–73
<–2.8	<27	18	8	192	38	0.3	0–16

^a Hybrid observations = 741 hybrid observations in 79 trials.

^b Stewart's wilt incidence (%) = percentage of plants of a hybrid in a trial with symptoms of systemic Stewart's wilt.

^c Mean winter daily air temperature for December, January, and February.

^d Fahrenheit index (FI) = Stevens index divided by three and rounded to whole numbers to produce indices equivalent to degrees in Fahrenheit.

distributions for susceptible hybrids differed from those of moderate and resistant hybrids within each winter temperature range (Table 5; Fig. 2). For susceptible hybrids, frequency distributions were different for each of the four ranges of winter temperature (Table 6; Fig. 2). For moderate and resistant hybrids, frequency distributions did not differ among the three ranges of winter temperature above -2.8°C . Distributions of incidence on moderate and resistant hybrids for each of the three temperature ranges above -2.8°C were significantly different from the distributions when the winter temperature was below -2.8°C (Table 6; Fig. 2).

Probability of 1 and 5% Stewart's wilt incidence. The probability of exceed-

ing 1 or 5% incidence of systemic Stewart's wilt differed among hybrids with different reactions to *P. stewartii* and among ranges of winter temperature (Fig. 3). The probability of exceeding 1 or 5% Stewart's wilt incidence was greatest on susceptible hybrids and did not differ significantly between moderate and resistant hybrids. For susceptible hybrids, the probability of exceeding 1% incidence was 0.22 when the winter temperature was below -2.8°C , and ranged from 0.5 to 0.66 when mean winter temperature was above -2.8°C (Fig. 3A). For moderate and resistant hybrids, the probability of exceeding 1% incidence was 0.06 or 0 when mean winter temperature was below -2.8°C , and ranged from 0.15 to 0.39 when mean win-

ter temperature was above -2.8°C (Fig. 3A). When data were combined for frequency distributions that did not differ among moderate and resistant hybrids or among ranges of winter temperatures above -2.8°C , the probability of exceeding 1% incidence of systemic Stewart's wilt was 0.59 and 0.22 for susceptible hybrids when winter temperature was above or below -2.8°C , respectively; and 0.28 and 0.04 for moderate and resistant hybrids when winter temperature was above or below -2.8°C , respectively (Table 7).

Probabilities of exceeding 5% incidence of systemic Stewart's wilt were similar to but lower than those for 1% incidence. For all hybrids, incidence did not exceed 5% when the mean winter temperature was below -2.8°C . For susceptible hybrids, the probability of exceeding 5% incidence ranged from 0.24 to 0.48 when winter temperature was above -2.8°C (Fig. 3B). For moderate and resistant hybrids, the probability of exceeding 5% incidence ranged from 0.02 to 0.1 when winter temperature was above -2.8°C (Fig. 3B). When data were combined for frequency distributions with ranges of winter temperature above -2.8°C , the probability of exceeding 5% incidence of systemic Stewart's wilt was 0.34 for susceptible hybrids and 0.07 for moderate and resistant hybrids (Table 7).

Iowa State method. Mean temperatures were above -4.4°C for 1, 2, or 3 months in 8, 28, and 43 trials, respectively. Mean temperatures were not below -4.4°C for all 3 months in any of the 79 trials. Occurrence of Stewart's wilt varied among trials having different numbers of months with mean temperatures above -4.4°C and among hybrids with different reactions to *P. stewartii* (Table 8). Stewart's wilt occurred in 38, 71, and 84% of the trials with one, two, or three winter months above -4.4°C , respectively (Table 8). Stewart's wilt was present only half as often on resistant hybrids as on susceptible hybrids for each of the three categories from the Iowa State method (Table 8). Among hybrids with susceptible reactions to *P. stewartii*, Stewart's wilt occurrence was 33, 60, and 71% when mean temperature was above -4.4°C for one, two, and three winter months, respectively. Stewart's wilt occurred on 9, 31, and 35% of the hybrids with resistant reactions to *P. stewartii* when mean winter temperature was above -4.4°C for 1, 2, and 3 months, respectively (Table 8).

DISCUSSION

For nearly 75 years, the Stevens or Stevens-Boewe forecast has been used as a rule of thumb to predict the prevalence of Stewart's wilt based on the effects of winter temperatures on overwintering populations of corn flea beetles, the vector of *P. stewartii* (2,28). Based on 12 years of field observations from which our data set was

Table 5. χ^2 Test of homogeneity of distributions of Stewart's wilt incidence on sweet corn hybrids with susceptible, moderate, and resistant reactions to *Pantoea stewartii* within four ranges of mean winter temperature^a

Comparison of hybrid reactions within temperature ranges	χ^2 value	P^b
$>0.6^{\circ}\text{C}$		
Susceptible vs. moderate	26.28	<0.01
Susceptible vs. resistant	39.34	<0.01
Moderate vs. resistant	4.15	0.39
-1.1 to 0.6°C		
Susceptible vs. moderate	27.16	<0.01
Susceptible vs. resistant	21.47	<0.01
Moderate vs. resistant	1.42	0.84
-2.8 to -1.1°C		
Susceptible vs. moderate	13.57	<0.01
Susceptible vs. resistant	16.85	<0.01
Moderate vs. resistant	3.37	0.50
$<-2.8^{\circ}\text{C}$		
Susceptible vs. moderate	10.04	0.02
Susceptible vs. resistant	12.53	0.01
Moderate vs. resistant	3.12	0.21

^a Reactions as described previously (19). Mean daily air temperature measured in the December, January, and February preceding planting.

^b Probability of exceeding the χ^2 value when the hypothesis of homogeneity is true.

Table 6. χ^2 Test of homogeneity of distributions of Stewart's wilt incidence at four ranges of mean winter temperature within groups of sweet corn hybrids with susceptible, moderate, and resistant reactions to *Pantoea stewartii*^a

Comparison of temperature ranges within hybrid reactions	χ^2 value	P^b
Susceptible		
>0.6 vs. -1.1 to 0.6°C	21.2	<0.01
>0.6 vs. -2.8 to -1.1°C	11.2	0.03
>0.6 vs. $<-2.8^{\circ}\text{C}$	40.6	<0.01
-1.1 to 0.6 vs. -2.8 to -1.1°C	10.6	0.03
-1.1 to 0.6 vs. $<-2.8^{\circ}\text{C}$	41.9	<0.01
-2.8 to -1.1 vs. $<-2.8^{\circ}\text{C}$	20.4	<0.01
Moderate		
>0.6 vs. -1.1 to 0.6°C	4.6	0.33
>0.6 vs. -2.8 to -1.1°C	3.2	0.53
>0.6 vs. $<-2.8^{\circ}\text{C}$	17.5	<0.01
-1.1 to 0.6 vs. -2.8 to -1.1°C	1.4	0.84
-1.1 to 0.6 vs. $<-2.8^{\circ}\text{C}$	28.2	<0.01
-2.8 to -1.1 vs. $<-2.8^{\circ}\text{C}$	20.7	<0.01
Resistant		
>0.6 vs. -1.1 to 0.6°C	4.7	0.31
>0.6 vs. -2.8 to -1.1°C	8.7	0.07
>0.6 vs. $<-2.8^{\circ}\text{C}$	14.7	0.01
-1.1 to 0.6 vs. -2.8 to -1.1°C	5.9	0.21
-1.1 to 0.6 vs. $<-2.8^{\circ}\text{C}$	22.4	<0.01
-2.8 to -1.1 vs. $<-2.8^{\circ}\text{C}$	11.5	0.02

^a Reactions as described previously (19). Mean daily air temperature measured in the December, January, and February preceding planting.

^b Probability of exceeding the χ^2 value when the hypothesis of homogeneity is true.

generated, levels of host resistance appear to affect the incidence of systemic seedling wilt within ranges of winter temperatures used by these forecasts. Frequency distributions of Stewart's wilt incidence and mean incidence ranging from 0.7 to 1.8% on moderate and resistant hybrids did not differ among three temperature ranges above -2.8°C . Conversely, distributions of Stewart's wilt incidence on susceptible hybrids differed among each of the four ranges of winter temperature from the Stevens-Boewe forecast with a mean incidence of 8, 8.5, 4.8, and 0.5% when mean winter temperature was above 0.6, -1.1 to 0.6, -2.8 to -1.1 , and below -2.8°C , respectively.

Stevens proposed his forecast based on observed associations between winter temperature and the occurrence of Stewart's disease on open-pollinated sweet corn cultivars in the early 1930s (28). Because many of those cultivars were relatively susceptible to *P. stewartii* (12,20,22), it is

not surprising that the ranges of winter temperature which define Stevens' indices have a similar association with Stewart's wilt incidence on modern, commercial sweet corn hybrids that are classified as moderately susceptible to susceptible. Similarly, it is not surprising that incidence of Stewart's wilt on hybrids with greater levels of resistance cannot be differentiated as distinctly by these temperatures. Host resistance has been shown to influence disease forecasts of other crops (3,10,26). In this and a previous study (16), incidence of naturally occurring, systemic Stewart's wilt at vegetative growth stages was lower on resistant and moderately resistant hybrids than on susceptible hybrids.

Host resistance also appears to affect the Iowa State method, which predicts the risk of the occurrence of Stewart's disease assessed later in the growing season. In this study, the occurrence of the seedling wilt phase of Stewart's disease was more frequent as the number of winter months

with average temperature above -4.4°C increased and as levels of resistance decreased. Stewart's wilt was present only half as often on resistant hybrids compared with susceptible hybrids for each of three categories of the Iowa State method. Although overwintering and summer generations of corn flea beetles both contribute to the occurrence of Stewart's disease at the time of phytosanitary inspections, a higher incidence of the seedling wilt phase of this disease caused by the overwintering generation of the vector is likely to be related to a higher risk of any occurrence of this disease. Thus, similar to the Stevens-Boewe forecast, accounting for the Stewart's wilt reaction of a hybrid or inbred could improve the ability of the Iowa State method to predict the occurrence of Stewart's disease at the time of phytosanitary inspection.

The cost of neonicotinoid seed treatments (e.g., imidacloprid, thiamethoxam, and chlothianidin) has previously been

Fig. 2. Frequency distributions of incidence of systemic Stewart's wilt on sweet corn hybrids with susceptible, moderate, and resistant reactions to *Pantoea stewartii* grouped by four ranges of mean winter temperature.

shown to be equivalent to yield reductions resulting from about 1% systemic Stewart's wilt infection of sweet corn grown for fresh market and about 5% systemic Stewart's wilt infection of sweet corn grown for processing (8,24,25). Based on data from this study, the probability of exceeding 1 or 5% incidence of systemic Stewart's wilt depends on the Stewart's wilt reaction of the hybrid being grown and winter temperatures. For fresh-market growers, the decision to treat or not to treat seed with these insecticides seems clear cut in three

cases. Neonicotinoid seed treatments would not be warranted when the mean winter temperature is below -4.4°C , based on a recent summary of data on the occurrence of Stewart's wilt from seed-production fields in Iowa (7,18). Similarly, using a seed-treatment insecticide on moderate and resistant hybrids would not be economical when the mean winter temperature is below -2.8°C because the probability of exceeding 1% incidence of systemic Stewart's wilt is only about 0.04 (i.e., 4% chance). Conversely, moderately

susceptible to susceptible sweet corn hybrids should be treated with a seed-treatment insecticide when mean winter temperature is above -2.8°C in order to avoid yield losses from Stewart's wilt because the probability of exceeding 1% incidence of systemic Stewart's wilt is greater than 0.5. In two other cases, the decision to treat or not to treat is less obvious and probably depends on the risk aversion of the grower. Use of a seed-treatment insecticide on moderate and resistant hybrids would not be economical in the long run when the mean winter temperature is above -2.8°C or on susceptible hybrids when the mean winter temperature is below -2.8°C because the probability of exceeding 1% incidence is below 0.5. However, in both of these situations, there may be utility in using a seed-treatment insecticide as an insurance against substantial fluctuations in production when the disease exceeds 1% incidence, which has about a 25% chance of occurring.

For sweet corn grown for processing, the use of seed-treatment insecticides to control Stewart's wilt would not be economical on moderate and resistant hybrids

Table 7. Probability of exceeding 1 or 5% incidence of systemic Stewart's wilt on sweet corn hybrids with susceptible (Susc) or moderate to resistant (M and R) reactions to *Pantoea stewartii* when mean winter temperature was above or below -2.8°C based on 741 observations of hybrids in 79 field trials from 1998 to 2009

Mean winter temperature ^a		Systemic Stewart's wilt incidence			
		$\geq 1\%$		$\geq 5\%$	
Celsius	Fahrenheit index ^b	Susc	M and R	Susc	M and R
$> -2.8^{\circ}\text{C}$	> 27	0.59	0.28	0.34	0.07
$< -2.8^{\circ}\text{C}$	< 27	0.22	0.04	0	0

^a Mean daily air temperature in the December, January, and February preceding planting.

^b Fahrenheit index = Stevens index divided by three and rounded to whole numbers to produce indices equivalent to degrees in Fahrenheit.

Fig. 3. Probability of exceeding **A**, 1% incidence or **B**, 5% incidence of systemic Stewart's wilt on hybrids with susceptible, moderate, and resistant reactions to *Pantoea stewartii* following one of four ranges of mean winter temperatures. Within levels of resistance, probabilities followed by the same letter are not significantly different at $P = 0.05$.

Table 8. Occurrence (Occur) of systemic Stewart's wilt in 79 field trials from 1998 to 2009 when mean winter temperatures are grouped by the Iowa State method of forecasting the occurrence of Stewart's disease on sweet corn hybrids with susceptible, moderate, or resistant reactions to *Pantoea stewartii*

Trials			Hybrid reaction to Stewart's wilt					
			Susceptible		Moderate		Resistant	
No. of months	<i>n</i>	Occur (%)	<i>n</i>	Occur (%)	<i>n</i>	Occur (%)	<i>n</i>	Occur (%)
1	8	38	30	33	32	16	22	9
2	28	71	98	60	105	40	72	31
3	43	84	139	71	133	41	110	35

^a Occurrence = presence or absence, calculated as number of trials with Stewart's wilt divided by the total number of trials within a temperature range.

^b Number of winter months (December, January, or February) where mean daily air temperature was above -4.4°C .

regardless of mean winter temperature, because the probability of exceeding 5% incidence of systemic Stewart's wilt is very low. Similarly, if mean winter temperature is below -2.8°C , the use of a seed-treatment insecticide would not be economical on susceptible sweet corn hybrids. However, if mean winter temperature is above -2.8°C and a susceptible sweet corn hybrid is grown, the use of a seed-treatment insecticide may have utility for a risk-averse grower as an insurance against more severe occurrence and yield losses due to Stewart's wilt.

Other factors besides winter temperature undoubtedly affect the prevalence of Stewart's wilt (2). As proposed previously (4,7), the occurrence of Stewart's wilt the previous growing season and the size of the flea beetle population at the end of the previous season may be important indicators of the amount of local inoculum for the following season. Planting date and in-season weather also may affect the development of Stewart's wilt (11,25). Stevens (28) did not identify relationships between Stewart's wilt incidence and total rainfall during the growing season or temperature during the growing season. However, Cook et al. (4) observed that weather affects corn flea beetle populations. Further examination of the effects of in-season weather conditions may explain some of the variation in Stewart's wilt forecasts that is not a result of host resistance. However, because Stewart's wilt control decisions are made prior to planting, in-season prediction has limited value with regard to disease management.

ACKNOWLEDGMENTS

A portion of this project was supported by grants from the Midwest Food Processors Association. We thank Abbott & Cobb Inc.; Crookham Company; Harris Moran Seed Co.; Illinois Foundation Seeds Inc.; Mesa Maize; Seminis Vegetable Seeds Inc.; and Syngenta Seeds Inc., Rogers Brands for providing seed for this study; and J. Hawk, University of Delaware, for assistance with a trial in Newark, DE.

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