Comparing Partial Resistance to *Puccinia sorghi* and Applications of Fungicides for Controlling Common Rust on Sweet Corn

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Research supported by the Illinois Agricultural Experiment Station as part of project 68-0323 and by Ciba-Geigy Corporation. We thank John Gantz, John Headrick, Payam Fallah, and Claude Nankam for technical assistance.
Accepted for publication 25 June 1993.

ABSTRACT

Pataky, J. K., and Eastburn, D. M. 1993. Comparing partial resistance to *Puccinia sorghi* and applications of fungicides for controlling common rust on sweet corn. Phytopathology 83:1046-1051.

Common rust, caused by *Puccinia sorghi*, can be controlled on sweet corn (*Zea mays*) by host resistance or fungicides. Different levels of partial rust resistance in sweet corn hybrids and levels of fungicidal control were compared in field trials from 1987 to 1992. The level of control provided by partial resistance depended, in part, on the effectiveness of fungicides. In the absence of fungicidal control, rust severity on the resistant, moderately resistant, and moderately susceptible hybrids was 15, 40, and 60%, respectively, of the amount of rust on the susceptible hybrid. When fungicide applications reduced rust severity on the susceptible hybrid by half, severity on the resistant, moderately resistant, and moderately susceptible hybrids was about 20, 55, and 80% of that on the susceptible hybrid. Thus, there was an interaction between fungicidal control and partial resistance. These relationships and previously derived yield loss models are used in a hypothetical example which compares the value of various methods of control.

Epidemics of common rust, caused by *Puccinia sorghi* Schwein, occur relatively frequently on sweet corn (*Zea mays* L.) grown late in the season in the midwestern and northeastern United States. When weather conditions are favorable for *P. sorghi*, rust can be epidemic in other areas where sweet corn is produced, such as southern and central Florida. Rust is particularly severe on highly susceptible hybrids, including some of the popular *sh2* and *su1* hybrids grown for fresh market and processing. Yields of susceptible hybrids have been reduced as much as 50%, according to some studies (4,7,14,19).

Rust can be controlled effectively by host resistance or fungicides. Several seed companies have recently released sweet corn hybrids that have *Rp* genes for resistance to *P. sorghi*, and breeders are developing new, *Rp*-resistant inbreds. Avirulent biotypes of *P. sorghi* do not sporulate on corn that carry these genes for resistance. The gene *Rp1d* has been effective against populations of *P. sorghi* surveyed in North America (6) except for one isolate collected in Kansas in 1990 (10). Nonetheless, the widespread use of hybrids with *Rp1d* probably will select for virulence within populations of *P. sorghi* in North America. Partial resistance to *P. sorghi*, which reduces the severity of rust but does not prevent infection and sporulation (13), is an alternative to *Rp* resistance. Several sweet corn hybrids (e.g., Esteem, Miracle, More, Patriot, Seneca Daybreak, Sweet Success, and Sweetie 82) have moderate levels of partial rust resistance (5,12,15). These hybrids are infected, and some yield loss occurs under moderate to severe disease pressure, but partially resistant hybrids are less likely to select for specific virulence within the pathogen population than are *Rp*-resistant hybrids.

The reactions of most sweet corn hybrids to common rust are intermediate to those of highly susceptible and partially resistant hybrids (16). Resistant (R), moderately resistant (MR), moderate (M), moderately susceptible (MS), and susceptible (S) categories have been created based on the variation that exists among commercially available sweet corn hybrids (15,19). Rust severity and subsequent reductions in yield are usually related to levels of partial resistance or susceptibility (5,16,19).

Fungicides sometimes are used to control rust when disease pressure is moderate to severe (4). Multiple applications of fungicides and partial resistance reduce the rate at which *P. sorghi* develops and thus limit the severity of rust (9,18); however, it is difficult to determine the level of control that is economically optimal, i.e., where profits are maximized and production is most efficient. Damage functions for common rust on sweet corn and outcomes of control actions might be used to accurately estimate optimal levels of control (1).

Damage functions are negative production functions that relate yield to levels of disease. Different methods of evaluating the effects of rust on sweet corn yield have resulted in relatively similar yield loss models (7,14,19). Based on the best estimates from regression models, sweet corn yield is reduced about 0.6% for each 1% increment of rust severity rated within 1 wk of fresh market harvest (14).

The development of rust is greatly affected by local weather, therefore the economic value of rust-control actions differs considerably among locations and years depending on environmental factors influencing the amount of disease that would have occurred in the absence of control. Similarly, the value of one control action (e.g., fungicides) is dependent on the efficacy of other control actions (e.g., partial resistance). Thus, control actions that have similar effects on disease development need to be compared in combination. The objective of this study was to compare the efficacy of applications of fungicides and different levels of partial rust resistance currently available in sweet corn. Results from 1987 and 1988 were briefly summarized previously (18).

MATERIALS AND METHODS

Field trials were done from 1987 to 1992. Because of a drought, in 1991 the experiments were unsuccessful. There were two separate trials each year to evaluate treatments under different disease pressures (i.e., amount of inoculum and/or environments). The two trials were planted at different times in 1987 and 1988, resulting in different environments. Among all trials, planting dates varied from the first week of May until the last week of July. In 1989, 1990, and 1992, inoculation procedures differed between the two trials, as described below, resulting in different amounts of initial disease.

Each year the treatment design was a factorial of four hybrids and four to six fungicide applications. In 1989 and 1992, two fungicides were also part of the factorial treatment design. Representative hybrids were selected from our categories (15) of: resistant (R), moderately resistant (MR), moderately susceptible

(MS), and susceptible (S). Florida Staysweet and Sweetie 82 were grown in every trial as the susceptible and resistant hybrids, respectively. The moderately susceptible hybrids were Ivory and Gold in 1987 and How Sweet It Is in all other years. The moderately resistant hybrids were Phenomenal in 1987, Dinner Time in 1988, Honey and Pearl in 1989 and 1990, and XPH2688sh2 in 1992. The reactions of these hybrids to *P. sorghi* varied slightly among years when they were evaluated with other sweet corn hybrids in disease nurseries (15, Table 1).

Fungicide treatments differed slightly among years. During 1987, 1990, and 1992 there were six treatments: zero, one, two, three, four, and five applications. Fungicides were applied at approximately weekly intervals beginning at the three- to four-leaf stage and corresponding roughly to the three- to four-leaf, five- to six-leaf, seven- to eight-leaf, nine- to 10-leaf and early tassel growth stages for the first, second, third, fourth, and fifth applications, respectively. In 1988, there were five treatments: zero, one, two, three, and four applications from the three- to four-leaf through the nine- to 10-leaf stages. In 1989, there were four treatments: zero, one, two, and three applications from the three- to four-leaf through the seven- to eight-leaf stages.

Two fungicides were applied over the duration of the study. Dithane M-45 (mancozeb) was applied at a rate of about 180 g/ha in 1987, 1989, and 1992. Tilt 3.6E (propiconizol) was applied at a rate of about 50 ml/ha in 1988, 1989, 1990, and 1992. In all trials, fungicides were applied by a tractor-mounted spray boom equipped with six hollow-cone nozzles (Spraying Systems model 18x cone jet (Spraying Systems, Inc., Wheaton, IL) spaced 51 cm apart in order to cover four 76-cm rows. A tractor was driven approximately 6 km/hr and operated a Delavan 3/4-inch roller pump (Model 7-3110, Delavan Ag Spray, Lexington, TN) to deliver approximately 46 L of liquid per hectare. A Delavan electric boom control (P/N 37541) turned the spray boom off and on between experimental units in trials from 1989 to 1992.

The experimental design was a split-plot or a split-split plot of a randomized complete block with three replicates in 1987 and 1989 and four replicates in 1988, 1990, and 1992. Treatments that were applied to main plots or subplots differed among years, primarily to accommodate the movement of the tractor through fields with different dimensions. During 1987 and 1988, the number of applications varied among main plots and hybrids were planted in subplots. During 1989 and 1992, the two fungicides were applied to main plots, hybrids were planted in subplots, and number of applications varied among sub-subplots. In 1990, hybrids were planted in main plots and number of applications varied among subplots. Experimental units consisted of four-row plots about 3 m long with about 15 plants per row. All experimental units were bordered on one side by two "spreader" rows consisting of a mixture of susceptible hybrids and on the other side by two fallow rows, which allowed the tractor and spray equipment to move through the field without disturbing plants in the experimental units.

To establish initial levels of disease for trials with "high" and "low" disease pressure, treatment rows, or spreader rows were

TABLE 1. Reactions of sweet corn hybrids to *Puccinia sorghi*

Hybrid	Number of trials in a category[a] R	MR	M	MS	S	Resistance index[b]
Dinner Time	1	2	0	0	0	7.7
Florida Staysweet	0	0	2	0	6	2
Ivory and Gold	0	0	2	2	0	4
Honey and Pearl	0	2	1	0	0	6.3
How Sweet It Is	0	1	4	1	0	5
Phenomenal	0	2	2	4	0	4.5
Sweetie 82	4	2	0	0	0	8.3
PH2688BCsh2	1	3	0	0	0	7.5

[a] Number of previous trials in which hybrids were categorized resistant (R), moderately resistant (MR), moderate (M), moderately susceptible (MS), or susceptible (S) in disease nurseries (16).

[b] Resistance index—weighted mean where resistant categories have the values: R = 9, MR = 7, M = 5, MS = 3, S = 1.

inoculated. About 3 g of urediniospores suspended in 36 L of water and 5 ml of Tween 80 were sprayed into whorls of plants at the two-leaf stage 8–10 days before the first fungicide application. In the "high" disease pressure trials, all plants in the middle two rows of each experimental unit were inoculated so that uredinia resulting from inoculation had just passed through the incubation period when the first fungicide application was made. With this method, initial disease severity in the experimental units was estimated to be about 1–5% based on number of uredinia per plant (4,17). In "low" disease pressure trials, the two spreader rows bordering one side of each experimental unit were inoculated so that urediniospores from the spreader rows were just beginning to be produced when the first fungicide application was made. With this method, initial disease severity in experimental units was zero.

Severity of rust was rated on a row basis in the middle two rows of each experimental unit at 7- to 14-day intervals in most trials beginning with the initial application of fungicide. Two evaluators independently estimated severity as the percentage of the total leaf area infected using a modified Peterson scale (20). Final disease ratings were made within 1 wk of fresh market harvest (about 21 days after midsilk), except for the trial in 1989 when an early frost on September 18 killed plants soon after tassels emerged.

The final ratings of severity and of area under the disease progress curve (AUDPC) were analyzed by the ANOVA (SAS) that was appropriate for each trial. Main effects of hybrids and fungicide applications were compared by Waller-Duncan Bayesian least significant difference (BLSD) values when interactions involving those main effects were not significant. Combinations of hybrid-fungicide application treatments also were compared by BLSD values. When significant interactions occurred between compounds in 1989 and 1992, Dithane and Tilt were treated as separate trials.

Since the amount of disease varied greatly among trials, indices of rust severity and AUDPC values were calculated within each trial as the percentage of rust (severity or AUDPC) that occurred on the untreated susceptible hybrid. Frequency distributions of rust severity and the index of rust severity were compared among hybrid-fungicide application treatments by chi-square analyses. Indices also were averaged over all trials and compared among treatments. To compare the effects of partial resistance (hybrids) within fungicide treatments, the indices were calculated as a percentage of the index for the same fungicide treatment on the susceptible hybrid.

RESULTS

Severity of rust varied considerably among the 14 trials (Fig. 1). In two trials (1987-L and 1988-L), severity was less than 10% for all treatments. In the other 12 trials, severity on the untreated susceptible hybrid was between 20 and 30% in five trials, between 30 and 40% in one trial, between 40 and 50% in three trials, and greater than 50% in three trials (Fig. 2). Severity of rust on the untreated resistant hybrid was never above 20% and was above 10% in only two trials (1988-H and 1990-L).

In the analysis of rust severity, main effects of hybrids and fungicide applications were significant in all trials. Main effect means for severity were always less on the resistant hybrid than on the susceptible hybrid; however, the moderate hybrids (MR and MS) were not always different from one another. Likewise, main effects of fungicide applications always differed between no application and the maximum number of applications (three, four, or five depending on the trial); however, various numbers of applications did not always differ from one another. The hybrid-by-application interaction was significant in eight of 14 trials, including the three trials in which severity on the susceptible hybrid was above 50% and five of the nine trials in which severity on the susceptible hybrid was between 20 and 50%. The interaction was not significant when severity was below 10%. Increasing the number of fungicide applications usually had a larger effect on the susceptible hybrid than on the resistant hybrid in the trials where the interaction term was significant, such as 1987-H, 1988-H, and 1992-TL (Fig. 1). The results of the analyses of AUDPC values were similar to those of rust severity.

The index of rust severity averaged over all trials ranged from 100 to 46 on the susceptible hybrid, 61 to 36 on the moderately susceptible hybrids, 42 to 25 on the moderately resistant hybrids, and 17 to 10 on the resistant hybrid (Fig. 3). Thus, five applications of fungicide reduced rust about 55% on the susceptible hybrid and about 40% on the other hybrids as compared to no fungicidal control on the same hybrids. The index of AUDPC values were similar, ranging from 100 to 44 on the susceptible hybrid, 74 to 36 on the moderately susceptible hybrids, 60 to 36 on the moderately resistant hybrids, and 30 to 24 on the resistant hybrid. Based on these indices, the level of control provided by the moderately susceptible hybrids was equivalent to that of the susceptible hybrid with two or three applications of fungicide. The control provided by the moderately resistant hybrids was equivalent to that of the moderately susceptible hybrids with one to three fungicide applications. The control provided by the resistant hybrid was not matched by the other hybrids with as many as five applications of fungicides.

Similar inferences were made from chi-square analyses of frequency distributions of rust severity and rust indices (Table 2, Figs. 2 and 4). The distribution of rust severity on the untreated moderately susceptible hybrids was most similar to that of the susceptible hybrid with two applications of fungicides; and the distribution of the rust index on the untreated moderately susceptible hybrids was very similar to that of the susceptible hybrid with two or three fungicide applications. The distribution of severity on the untreated moderately resistant hybrids was most similar to that of the moderately susceptible hybrids with two applications, while the distribution of the rust index on the untreated moderately resistant hybrids was most like that of the moderately susceptible hybrids with four applications. Distributions for the untreated resistant hybrid were most similar to those for the moderately resistant hybrids with four or five applications.

When the rust indices were calculated as a percentage of the same fungicide treatment on the susceptible hybrid (Fig. 5), the value of partial resistance was apparent. In the absence of fungicides, severity of rust on the moderately susceptible, moderately resistant, and resistant hybrids was about 60, 40, and 15%, respectively, of that on the susceptible hybrid; and AUDPC values were about 75, 60, and 30% of those for the susceptible hybrid (Fig. 5). Differences between the susceptible and partially resistant hybrids were less when the number of fungicide applications increased, particularly for the moderate (MS, MR) hybrids. With five applications of fungicide, severity on the moderately susceptible, moderately resistant, and resistant hybrids was about 80, 55, and 20% of that on the susceptible hybrid, and AUDPC values were about 80, 80, and 55% of those for the susceptible hybrid (Fig. 5).

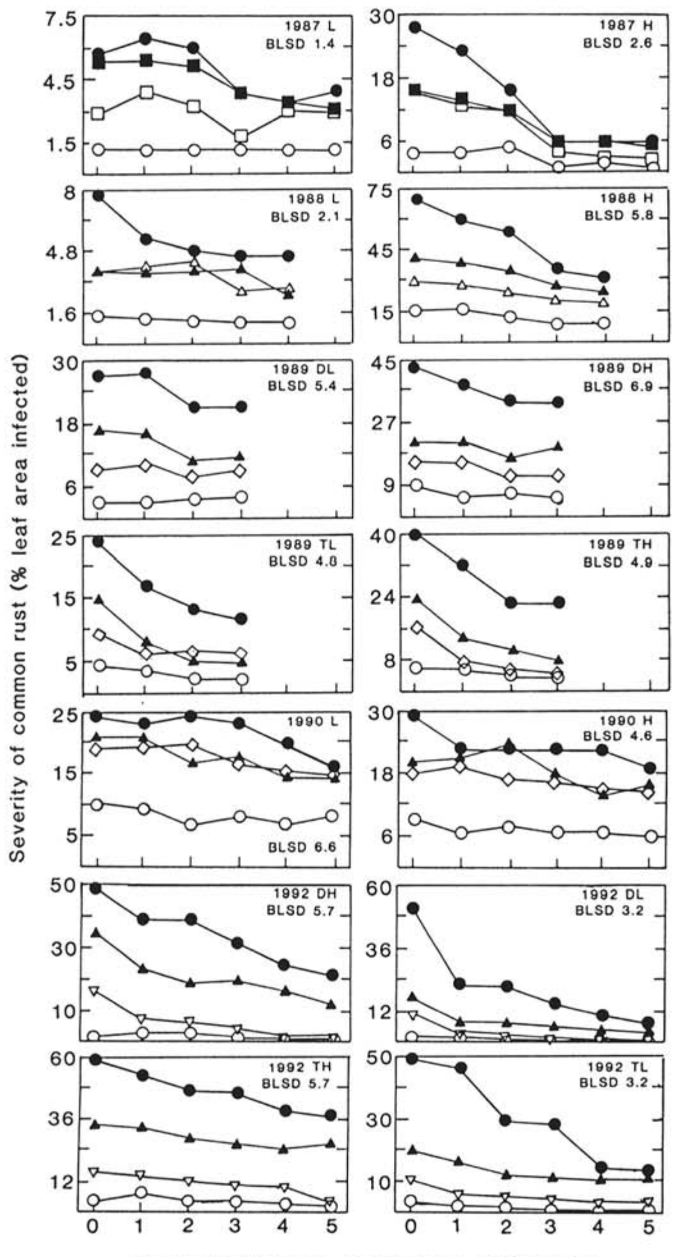

Fig. 1. Severity of rust on sweet corn as affected by level of partial rust resistance and number of fungicide applications. Hybrids are: Florida Staysweet (●), Ivory and Gold (■), Phenomenal (□), Sweetie 82 (○), How Sweet It Is (▲), Dinner Time (△), Honey and Pearl (◇), and XPH2688BCsh2 (▽). BLSD values are for comparisons of hybrid-fungicide treatments. L = Low disease pressure, H = high disease pressure, D = dithane, T = tilt (see Materials and Methods for further explanation).

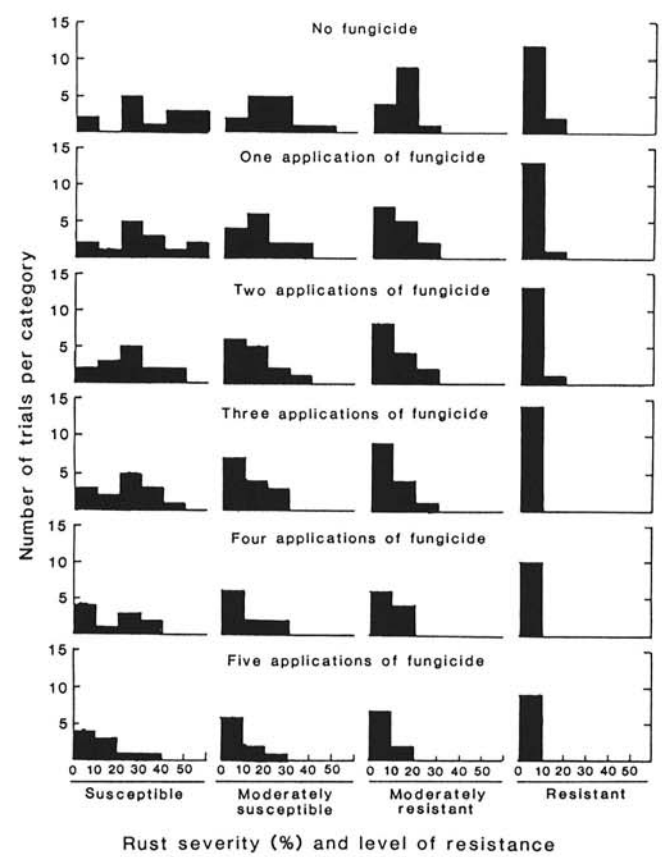

Fig. 2. Frequency distributions of rust severity on sweet corn hybrids with different levels of partial rust resistance to which zero to five applications of fungicide were made. Distributions are based on results from 14 field trials from 1987 to 1992.

DISCUSSION

Different levels of partial resistance to *P. sorghi* in sweet corn hybrids provided varied amounts of control for common rust which depended, in part, on the effectiveness of fungicidal control. When comparisons were made in the absence of fungicides, severity of rust on the resistant, moderately resistant, and moderately susceptible hybrids was about 15, 40, and 60%, respectively, of that on the susceptible hybrid. When fungicides were used to control rust, the value of partial resistance decreased, particularly for the moderately susceptible and moderately resistant hybrids. When hybrids received five weekly applications of fungicide, rust severity on resistant, moderately resistant, and moderately susceptible hybrids was about 20, 55, and 80% of that on the susceptible hybrid. Thus, there was an interaction between fungicidal control and partial resistance. Theoretically, the value of partial resistance is zero if fungicides control rust completely, but in this study where the maximum number of applications of fungicides on the susceptible hybrid reduced rust by about half, all levels of partial resistance (even the moderately susceptible hybrids) provided additional control beyond that of fungicides.

Yield losses attributable to rust are proportional to disease severity, and thus, to the levels of control provided by partial resistance and fungicides. Level of control observed from this study and results from previous yield loss studies (7,14,19) can be used to make simple comparisons of the economic value of control, as illustrated in a hypothetical example (Table 3). If severity of rust at harvest is 60% on an untreated susceptible

TABLE 2. Chi-square values for comparing frequency distributions of rust severity (%) and an index of rust severity among 14 field trials in which sweet corn hybrids with different levels of partial rust resistance received zero to five applications of fungicide

Comparison of treatments[a]	Chi-square values: Actual severity (Fig. 2)	Severity index (Fig. 4)
MS-0 vs		
S-0	9.00	21.00
S-1	5.67	8.52
S-2	1.17	0.19
S-3	2.49	0.67
S-4	6.01	2.57
MR-0 vs		
MS-0	6.48	8.50
MS-1	2.93	5.27
MS-2	2.88	3.67
MS-3	3.74	2.11
MS-4	4.65	1.54
R-0 vs		
MR-2	3.45	6.07
MR-3	2.10	5.00
MR-4	2.06	2.61
MR-5	0.24	4.71

[a] S, susceptible; MS, moderately susceptible; MR, moderately resistant; R, resistant; 0, 1, 2, 3, 4, 5 = number of applications of fungicide.

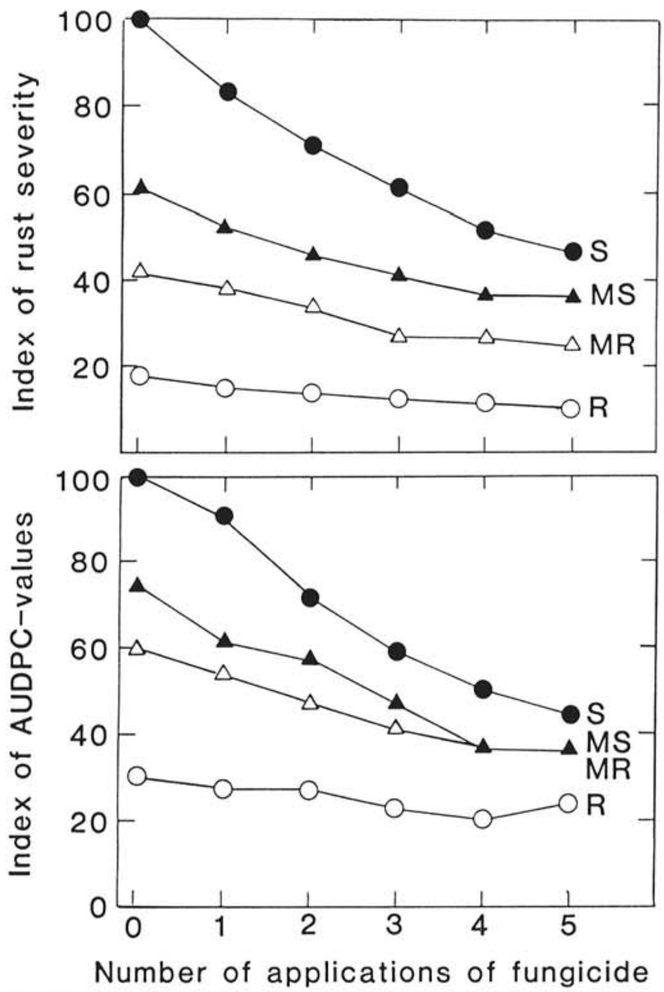

Fig. 3. Indices of rust severity and AUDPC values for sweet corn hybrids with different levels of partial rust resistance which received zero to five applications of fungicide. Indices, calculated within trials as the percentage of the severity or AUDPC value on the untreated susceptible hybrid, are means of 14 trials.

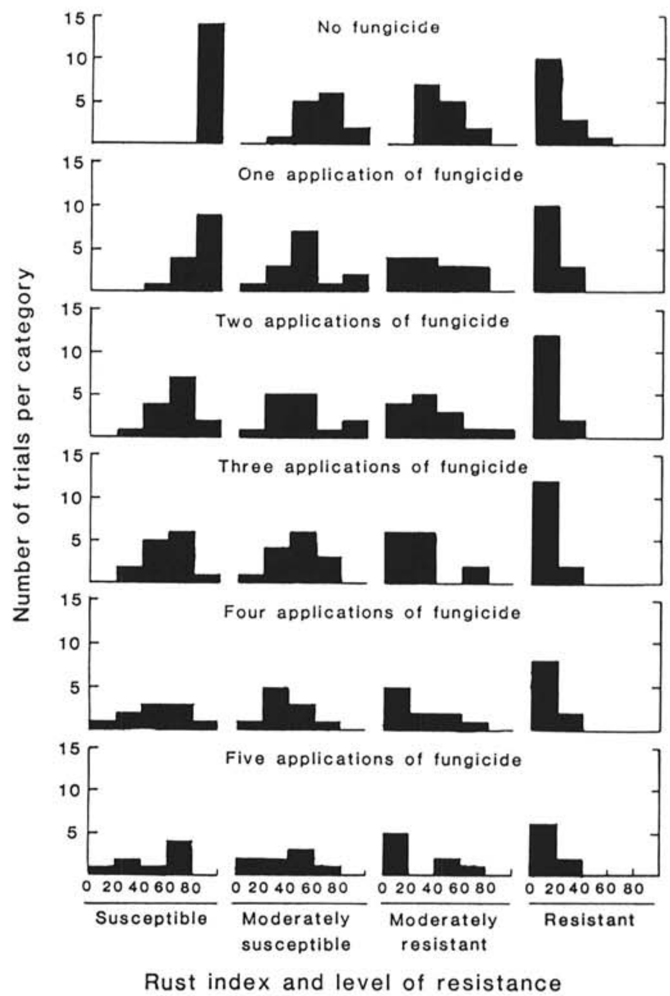

Fig. 4. Frequency distributions of an index of rust severity on sweet corn hybrids with different levels of partial rust resistance which received zero to five applications of fungicides. Distributions are based on indices calculated within trials as the percentage of rust severity on the untreated susceptible hybrid and include results from 14 field trials from 1987 to 1992.

hybrid, severity would be about 9% (15% of the susceptible) on a hybrid with partial resistance equal to that observed in this experiment, about 24% (40% of the susceptible) on a moderately resistant hybrid and about 36% (60% of the susceptible) on a moderately susceptible hybrid. If fungicidal control reduced rust by half (to 30% severity) on the susceptible hybrid, severity would be about 6% (20% of the susceptible) on the resistant hybrid, about 17% (55% of the susceptible) on the moderately resistant hybrid, and about 24% (80% of the susceptible) on the moderately susceptible hybrid. Since rust reduces yield of sweet corn about 0.6% for each 1% increment in severity (14), percent yield reductions and severity are directly proportional; however, all hybrids may not yield the same in the absence of disease. To estimate the economic value of control, yield of susceptible and resistant hybrids must be estimated in the absence of disease. In the hypothetical example (Table 3), yield is lowered by about 3.6%

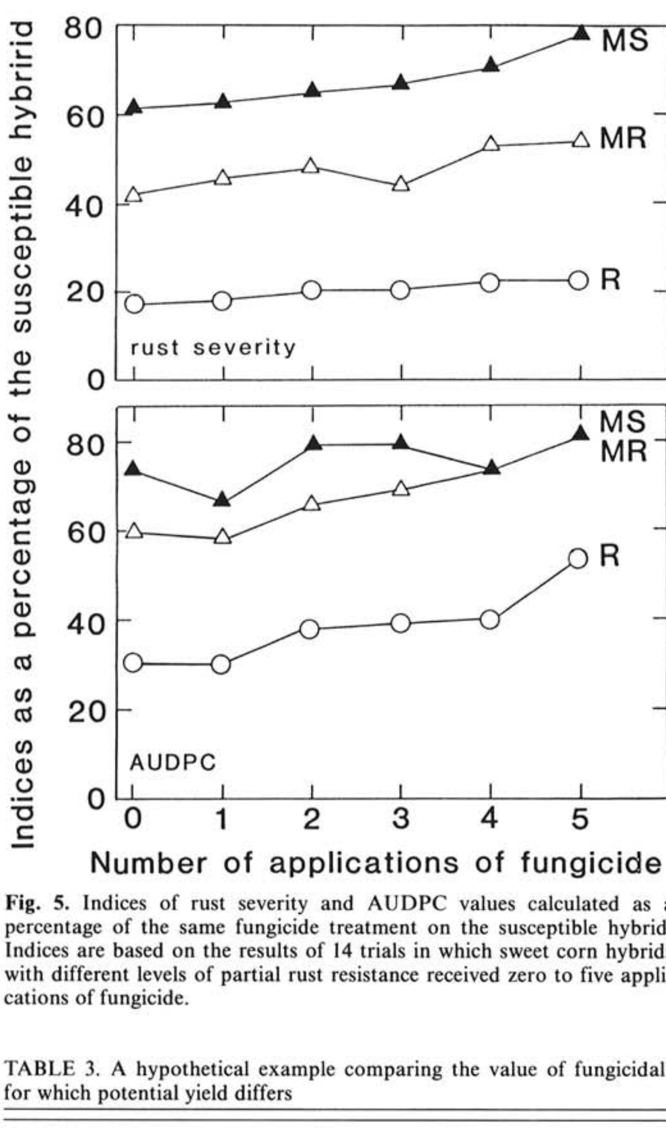

Fig. 5. Indices of rust severity and AUDPC values calculated as a percentage of the same fungicide treatment on the susceptible hybrid. Indices are based on the results of 14 trials in which sweet corn hybrids with different levels of partial rust resistance received zero to five applications of fungicide.

(10 boxes of 50 ears per 0.4 ha) for each level of resistance. The value of resistance in the absence of fungicidal control is considerable in this example because yields of untreated susceptible and resistant hybrids are 179 and 238 boxes, respectively. When fungicides are used to reduce severity on the susceptible hybrid by half, resistance has a relatively small effect on yield because yields of the treated susceptible and resistant hybrids are 230 and 241 boxes, respectively. In this situation, the costs of fungicidal control, the price of seed of resistant and susceptible hybrids, and quality differences among hybrids may have a greater influence than yield on the economic value of control decisions, i.e., partial resistance and/or fungicides. Other hypothetical situations which include levels of fungicidal control from 0 to 50%, hybrids with different potential yield, various costs of fungicidal control, and different prices of seed can be examined using the relationships derived from our studies.

Direct comparisons between levels of partial resistance and applications of fungicide can be made from our results with certain limitations or qualifications. In our study, each higher level of resistance was equivalent to about two or three weekly applications of fungicide. For example, the untreated moderately susceptible hybrid had levels of rust similar to the susceptible hybrid with two or three fungicide applications. Likewise, the untreated moderately resistant hybrid had levels of rust similar to the moderately susceptible hybrid with two or three fungicide applications. While these relationships were relatively consistent among the various environments in our trials, they may not be the same when different methods of fungicidal control are used, such as: Applications that are made more frequently than 1-wk intervals, different methods of application, different compounds, different rates, and different formulations. As the efficacy of fungicidal control changes, the exact relationship between the value of fungicides and partial resistance will vary; however, the relative response of resistant, moderately resistant, moderately susceptible, and susceptible hybrids should be consistent. The need for fungicidal control decreases with higher levels of partial resistance, and vice versa.

We had three reasons for dropping applications of fungicides at later host growth stages instead of delaying initial applications or deleting applications in the middle of a weekly spray program. First, we believe that to effectively control rust, populations of *P. sorghi* must be maintained at manageable levels as inferred by the six-uredinia-per-leaf action threshold proposed by Dillard and Seem (3). Second, we felt that adult plant reactions observed by Headrick and Pataky (8) may provide a minimal amount of control at later growth stages if *P. sorghi* has been controlled adequately at earlier growth stages. Third, earlier applications of fungicides may result in lower levels of fungicidal residues when sweet corn is harvested. Additional research is required to determine if different action thresholds are applicable for hybrids with different levels of partial resistance and if schedules of fungicides with fewer applications at middle growth stages are more efficacious than those used in this study.

The highest level of partial rust resistance evaluated in this study was that of the hybrid, Sweetie 82. Although Sweetie 82 is among the most resistant sweet corn hybrids available (other than those with *Rp* genes), Sweetie 82 is not as resistant as some

TABLE 3. A hypothetical example comparing the value of fungicidal control and partial resistance to *Puccinia sorghi* among sweet corn hybrids for which potential yield differs

	Rust severity (%)		Yield reductions (%)[b]		Hypothetical yields[c] (boxes per 0.4 ha)		
	No control	Fungicide[a]	No control	Fungicide[a]	No disease	No control	Fungicide[a]
Susceptible	60	30	36	18	280	179	230
Moderately susceptible	36	24	22	14	270	212	226
Moderately resistant	24	17	14	10	260	223	234
Resistant	9	6	5	4	250	238	241

[a] Fungicidal control sufficient to reduce rust by half on the susceptible hybrid. Control on the partially resistant hybrids (MS, MR, R) is not 50% because of the interaction between partial resistance and fungicidal control (see text and Fig. 3).
[b] Yield reductions of 0.6% for each 1% severity based on previous results (14).
[c] Hypothetical yields (boxes of 50 ears per 0.4 ha) of S, MS, MR, and R hybrids assuming that susceptible hybrids have higher yields in the absence of rust.

Zea mays, particularly highly resistant tropical genotypes (2,11,12). As higher levels of partial resistance are incorporated into acceptable sweet corn hybrids, these hybrids will need to be evaluated in comparison to fungicides and current levels of resistance. Similarly, a range of reaction occurs among the hybrids classified as moderately resistant or moderately susceptible. In fact, one hybrid (Phenomenal) that we used as a moderately resistant treatment in 1987 later proved to be more similar to moderately susceptible hybrids. Thus, there is a need to repeatedly evaluate hybrids and other methods of control to obtain the best estimate of the level of control provided by any method.

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