Assessment of Methods of Determining Powdery Mildew Severity in Relation to Grain Yield of Winter Wheat Cultivars in Ohio

P. E. Lipps and L. V. Madden

Associate professors, Department of Plant Pathology, The Ohio State University, Ohio Agricultural Research and Development Center, Wooster, 44691.

Salaries and research support provided by state and federal funds appropriated to the Ohio Agricultural Research and Development center and The Ohio State University. Additional funding supplied by Mobay Chemical Corporation. Manuscript number 167-88.

We thank Audrey Weiker and John Nixon for their technical assistance.

Accepted for publication 31 October 1988 (submitted for electronic processing).

ABSTRACT

Lipps, P. E., and Madden, L. V. 1989. Assessment of methods of determining powdery mildew severity in relation to grain yield of winter wheat cultivars in Ohio. Phytopathology 79:462-470.

Powdery mildew severity was determined by estimating the percentage of leaf area covered by lesions on the upper three leaves of three winter wheat cultivars in 1985 and six cultivars in 1986 and 1987. Data obtained were used to evaluate five different disease assessment systems for estimating powdery mildew severity: a three-leaf additive system, a three-leaf weighted system, a two-leaf additive system, a two-leaf weighted system, and a 0–10 scale. The 0–10 scale was designed to account for leaf position and the percentage of leaf area covered by lesions, where 0 represents trace or no lesions on any leaf, and 10 represents lesions covering more than 15% of the flag leaf area. Disease severity evaluations using the 0–10 scale were highly correlated with those using the other four systems; e.g., *r* was 0.81–0.97 at growth stage (GS) 10.3. Linear regression analysis was used to determine the relationship between grain yield and powdery mildew severity. Depending on the growth stage, assessments of disease severity based on all assessment systems were significantly related to grain yield, although the coefficient of determination (R^2) varied with cultivar (e.g., at GS 10.3 in 1986, the highest R^2 was 0.87 to 0.90 for Becker, and the lowest was 0.15 to 0.32 for Caldwell), indicating that the assessment systems were nearly equal for assessing powdery mildew severity. Over the three years, yield was rarely correlated with disease severity before GS 10 ($P < 0.05$); disease at GS 10.3 was most consistently correlated with yield for all cultivars and years (R^2 values were 0.16 to 0.87). Further regression results were thus based on the disease severity from the 0–10 scale at GS 10.3 and the area under the disease progress curve (AUDPC) based on the 0–10 scale. Slopes and intercepts varied among cultivars within and across years, but the more susceptible cultivars had higher slope values each year (Adena, Becker, and Hart were susceptible; Caldwell, Cardinal, Scotty, and Tyler were less susceptible), indicating greater yield reduction per increase in disease severity. R^2 values for regression equations calculated for five of the six cultivars studied in 1986 and 1987 were relatively high (0.66 to 0.87 in 1986 and 0.50 to 0.83 in 1987). R^2 values for regression equations calculated from AUDPC data were marginally higher than those from the single assessment at GS 10.3 for some cultivars, but for others R^2 values from AUDPC were about the same as those from the GS 10.3 assessment or slightly lower. This was due to the high correlation between disease severity at GS 10.3 and AUDPC (*r* was 0.87–0.98). Covariance analysis indicated that fungicide treatment did not alter the relationship between yield and disease for any year or cultivar. Results indicated that linear regression equations calculated from disease assessments taken at GS 10.3 using the 0–10 scale adequately predicted the yield of the cultivars studied.

Additional keywords: epidemiology, *Erysiphe graminis* f. sp. *tritici, Triticum aestivum*, yield loss assessment.

Since the registration of the systemic, sterol-inhibiting, triazole-based fungicides in the eastern and midwestern United States, their use on wheat (*Triticum aestivum* L.) has been limited. The lack of information on actual yield losses caused by the major foliar diseases may be a major factor restricting growers from making firm economic decisions on disease control methods. Additionally, studies on the efficacy of fungicides for the control of diseases (3,11) and yield loss estimates (5,14,15) have used highly susceptible cultivars and may overestimate the yield loss of less susceptible but more commonly grown cultivars. Grain producers also have little or no experience assessing disease severity. Most disease assessments, especially those based on the percentage of leaf area affected, require some experience in order to obtain reproducible results (7,9,12). A disease assessment system that requires few trips to the field and has a relatively high level of accuracy, especially as it relates to yield loss, would best fit their needs.

Powdery mildew, caused by *Erysiphe graminis* DC. f. sp. *tritici* E. Marchal, is a prevalent disease in the eastern section of the United States (1,3–5,11,17,22,24). Disease severity is dependent on many factors, including cultural practices (1), variation in weather conditions (15), and the level of cultivar susceptibility (4,11,17,24). Fried et al (5) reviewed previous work and reported that yield losses attributed to powdery mildew varied from 0 to 45%. However, few studies have attempted to quantify the relationship between powdery mildew severity and the level of yield loss. In a 4-yr study, Large and Doling (15) determined the percentage of yield loss of two cultivars to be twice the square root of the percentage of disease severity on the upper four leaf blades assessed when the plants were completely headed, at Feekes growth stage (GS) 10.5 (13). This model predicted a yield loss of 3% at a mildew severity of 2.5% and a loss of 8% at a mildew severity of 16%. Fried et al (5) developed a model for predicting yield loss using single culms of the cultivar Chancellor. Their model, using kernels per head and 1,000-kernel weight to estimate yield and powdery mildew severity, was based on the mean percentage of disease on the flag leaf and the second leaf at the heading growth stage (GS 10.5.4). Their results indicated that a yield loss of 33% could be expected at 100% severity. Recently, Leath (16) demonstrated a linear relationship between wheat yield and powdery mildew severity on the flag leaf at GS 10.3 for a cultivar adapted to the southern United States. Yield loss predictions similar to these, based on disease severity at a given growth stage for a range of cultivars, would provide growers with information necessary for making management decisions for disease control.

A number of different disease assessment systems have been used to quantify the severity of powdery mildew in the field (8,14,23,24). These include systems that evaluate the whole plant, such as the 0–9 scale of Saari and Prescott (23), and those that evaluate the percentage of leaf area affected, such as the Horsfall-Barratt scale (7,24), the Large and Doling cereal mildew key (14,15), and the assessment keys developed by James (8). Most recent studies have used James's assessment keys to determine the percentage of leaf area affected on individual leaves, but considerable variation occurs among studies in the number of leaves and the position of the leaves on the plant that are assessed (1,3,22). However, most agree with earlier work (20) that carbohydrate production in the upper leaves (the penultimate leaf and the flag leaf) contribute significantly to grain yield. Since the upper leaves contribute more to grain filling, relative to lower leaves, Raymond et al (21) developed a weighted scale to take into account leaf position in evaluating the severity of tan spot (caused by *Pyrenophora tritici-repentis*). Each of the top four leaves was assessed for severity on a 0–5 scale, and the score for each leaf was then multiplied by the leaf number, with the flag leaf being 4, the penultimate leaf being 3, the third leaf down being 2, and the fourth leaf down being 1. A weighted mean disease severity score was obtained by adding the products and dividing by 4. Their results indicated that the weighted score was useful for quantifying disease severity and identifying resistant germ plasm. In order to develop any procedure for assessing the level of disease that correlates well with yield loss potential, the method must be accurate enough to be useful and simple enough to be used by those with little or no specific training. As James suggested (9), the simplest disease assessment method is usually the one least prone to error.

Determining when to make disease assessments is critical in developing any system that adequately relates disease severity to potential yield loss (9,12). The problems associated with models using one-time disease assessments (critical-point models) and those using several disease assessments made throughout the epidemic, such as the area under the disease progress curve (AUDPC), are recognized (9,26). Although AUDPC has frequently been used successfully in evaluating powdery mildew epidemics (4,24), evidence indicates that good correlations between grain yield and disease severity can be obtained when one-time assessments are made between head emergence (GS 10) and the stage at which kernels are milky ripe (GS 11.1) (22).

In order to make sound management decisions for the control of powdery mildew, more information is needed on disease assessment procedures and the yield loss of cultivars commonly grown in the area. Therefore, the purpose of this study was to evaluate different disease assessment methods as to their relationship with grain yield, determine the proper timing of disease assessments, compare the yield losses of several cultivars varying in susceptibility to *E. g. tritici*, and develop models for determining yield loss in relation to disease severity for the cultivars studied.

MATERIALS AND METHODS

Plots were established at the Ohio Agricultural Research and Development Center near Wooster, in fields that had been maintained under a corn-soybean-oat-wheat rotation (17). After plowing, the plots were fertilized with 336 kg of 6-24-24 (N-P-K) per hectare and then disked prior to planting. The plots were planted with 135 kg of seed per hectare, by means of a seven-row drill with 17.8 cm between rows, on 10 October 1984, 8 October 1985, and 10 October 1986. The plots were established in Ravenna silt loam in 1985 and in Wooster silt loam in 1984 and 1986. All plots were top-dressed with 100 kg of nitrogen per hectare, as ammonium nitrate, on 12 March 1985, 21 March 1986, and 18 March 1987. The plots were harvested with a plot combine on 23 July 1985, 15 July 1986, and 7 July 1987. Throughout the rest of this paper, all experiments are identified by the year in which they were harvested.

The wheat cultivars in this study and their relative levels of susceptibility to *E. g. tritici* in field trials during 1984 and 1985 (P. E. Lipps, *unpublished*) were Hart (CI 17426), susceptible; Becker (PI 494524), susceptible; Adena (PI 481852), moderately susceptible; Caldwell (CI 17897), moderately susceptible; Cardinal (PI 502973), moderately resistant; Tyler (CI 17899), resistant; and Scotty (PI 469294), resistant. Not all cultivars were tested each year of the study.

Different disease severity levels were obtained by the use of a systemic, ergosterol-biosynthesis-inhibiting seed treatment, triadimenol (Baytan, Gustafson Corp., Dallas, TX), and a closely related triazole, triadimefon (Bayleton, Mobay Chemical Corp., Kansas City, MO), formulated for foliar applications (17). These materials were used either alone or in combination. Seed was treated with either triadimenol (Baytan 30F, 30% a.i.) at 98 ml/100 kg of seed or a combination of carboxin (17% a.i.) and thiram (17% a.i.) (Vitavax 200, Gustafson Corp.) at 260 ml/100 kg of seed. The carboxin-thiram treatment was chosen because it had no activity against *E. g. tritici* but controlled other pathogens similar to those controlled by triadimenol. The foliar treatment consisted of one application of triadimefon (Bayleton 50W, 50% a.i., in 1985 and Bayleton 1.8EC, 22.5% a.i., in 1986 and 1987) at 140 g a.i./ha on 3 May 1985, 13 May 1986, and 10 May 1987. These dates corresponded to Feekes GS 9, GS 10, and GS 10 of the cultivar Becker, respectively. Triadimefon was applied as a foliar spray in 187 L of water per hectare with a CO_2-pressurized backpack sprayer with a constant boom pressure of 2.8 kg/cm^2.

Field plots were arranged in a strip-split plot design with four replicated blocks. Each block was divided in half, lengthwise, with foliar treatment randomly applied to one of the halves. Each block was also divided into sections, widthwise, with the cultivars randomly assigned to the sectors. Within each section (combination of foliar treatment and cultivar), one experimental unit consisted of triadimenol seed treatment, and the other consisted of carboxin-thiram seed treatment. Foliar treatment (triadimefon or no fungicide) and cultivar were strip plots; seed treatments (triadimenol or carboxin-thiram seed treatment) were subplots. The experimental units were one seven-row drill strip wide (125 cm) by 9, 11.4, and 19.5 m long in 1985, 1986, and 1987, respectively. All experimental units were adjacent to one another but separated by a 22-cm space between outside rows for traffic. No effort was made to restrict interplot interference (10) from adjacent plots.

Disease was evaluated at GS 6, GS 9, GS 10, GS 10.3, GS 10.5.1, and GS 10.5.4 in 1985 and 1986; at GS 6, GS 8, GS 9, GS 10, GS 10.3, and GS 10.5.4 in 1987; and also at GS 11.1 in 1986 and 1987. Ten tillers were selected at random from each plot, and ratings were conducted on all cultivars the same day. Although not all cultivars were at the same growth stage at each rating time, they varied no more than 2 to 3 days from the growth stage reported, except Caldwell, which reached flowering (GS 10.5.1) 3 to 4 days earlier than the other cultivars. In 1985 and 1986, powdery mildew was evaluated on the top two leaves (the penultimate and third leaves) at GS 6 and the top three leaves (the flag, second, and third leaves) at all later growth stages. The percentage of leaf area covered by lesions on each leaf was determined using disease assessment keys developed by James (8). These data were used to calculate disease severity based on five different systems: a two-leaf additive system, a three-leaf additive system, a two-leaf weighted system, a three-leaf weighted system, and a 0–10 scale. The two- and three-leaf additive systems were calculated as the sum of the percentage of leaf area covered by lesions on the top two or three leaves, respectively, on each tiller. The two- and three-leaf weighted systems were based on severity ratings proposed by Raymond et al (21) to take into account the relative importance of the top leaves for grain filling. Thus, for the two-leaf weighted system, the percentages of area covered by lesions on the flag and the second leaves were multiplied by 2 and 1, respectively, and for the three-leaf weighted system, the percentages of area covered on the flag, the second, and the third leaves were multiplied by 3, 2, and 1, respectively, before summation. A 0–10 scale was devised to take into account leaf position and to provide broader categories for the percentage of leaf area covered by lesions. The scale, leaves evaluated, and the percentage of leaf area affected in each category are presented in Table 1. The 0–10 scale was the only system used in 1987. In each rating system, the mean rating of the 10 tillers was calculated to represent powdery mildew severity for each experimental unit.

Leaf rust (caused by *Puccinia recondita* Rob. ex Desm.) and Septoria nodorum blotch (caused by *Leptosphaeria nodorum* Müller) were assessed at the same time as powdery mildew. Leaf rust was present on the flag leaves of Tyler in 1985 by GS 10.5.1, so data from this cultivar were dropped from the test. Septoria nodorum blotch did not move above the third leaf by GS 11.1 in any year of the study.

Data analysis. Correlation and regression analyses were used to determine the relationships between assessment scales and the relationship between yield and disease severity. For each year, cultivar, and assessment time, correlation coefficients (r) between all possible pairs of assessment scales were determined.

Critical-point regression models were developed, of the form

$$Y = b_0 - b_1 X_t \quad (1)$$

in which Y is yield (in kilograms per hectare), X_t is disease severity at growth stage t, and b_0 and b_1 are parameters. The Y-intercept parameter (b_0) represents yield when disease severity is 0 ($X_t = 0$), and the slope (b_1) represents the change in yield with a unit change in disease severity. Equation 1 was fitted to the data from each assessment time and cultivar. Multiple-point models also were tested for each cultivar as described by Teng (25), to develop a model for Y as a function of more than one X_t. Stepwise regression techniques were used to eliminate nonsignificant disease variables. Finally, yield was related to AUDPC by means of equation 1, in which AUDPC (6) was substituted for X_t. All regression models were evaluated as discussed elsewhere (18,25).

The effects of seed and foliar fungicide treatments on the relationship between yield and disease were determined with covariance analysis. After the best disease predictor (X_t) was identified, the following model was fitted to the data for each cultivar:

$$Y = b_0 - b_1 X_t + b_2 S + b_3 F + b_4 X_t S + b_5 X_t F \quad (2)$$

in which $S = 1$ if seed was treated with triadimenol, $S = 0$ otherwise, $F = 1$ if plants were treated with triadimefon, and $F = 0$ otherwise. If either fungicide treatment affected the change in yield with a change in disease severity (b_1), then b_4 or b_5 would be significant. If overall yield level was determined by fungicide treatment independent of disease severity, then b_2 or b_3 would be significant.

Programs of the BMDP computer system were used for all analyses (2).

TABLE 1. The 0–10 disease severity scale used to assess the level of powdery mildew

Scale	Leaf evaluated[a]	Percentage of leaf area affected
0	Any	0 to <1%
1	Fourth	1–50%
2	Third	1–5%
3	Third	5–15%
4	Third	>15%
5	Second	1–5%
6	Second	5–15%
7	Second	>15%
8	Flag	1–5%
9	Flag	5–15%
10	Flag	>15%

[a] Individual tillers were evaluated by assessment of the uppermost leaf with lesions. Leaf position designations were the flag or top leaf, the penultimate or second leaf, the third leaf, and the fourth leaf down.

RESULTS

Powdery mildew assessments. Coefficients of correlation between the five assessment scales for disease severity were very high and always significant ($P < 0.01$) for each assessment time and cultivar. Therefore, only the data from the GS 10.3 rating time are presented (Table 2). At this growth stage, correlation coefficients for the 1–10 scale compared with the other four systems ranged from 0.81 to 0.92 in 1985 and from 0.87 to 0.97 in 1986. Regression analysis and assessment of residuals (18) indicated an approximately linear relationship between the scales. In 1985, the 0–10 scale had the highest correlation with the two-leaf weighted system (r = 0.92, 0.85, and 0.92 for the three cultivars) and the lowest correlation with the three-leaf additive system (r = 0.81, 0.82, and 0.88). In 1986, there were consistently high correlation coefficients for the correlations between the 0–10 scale and all four other scales. There was also a very high and significant correlation ($P < 0.01$) between the 0–10 scale assessed at GS 10.3 and the AUDPC calculated from the 0–10 scale at all assessment times. Correlations between the other four scales were very similar to those shown in Table 2.

Time of assessment. Linear regression equations for the relationship between grain yield and disease severity assessed with each of the assessment scales at each assessment time were developed to determine the time that best correlated with yield (Table 3). Only the results for the 0–10 scale are presented. Over all cultivars, the coefficients of determination (R^2) calculated for the 1985 data were lower than those calculated for 1986 and 1987. In 1985, the highest R^2 values for the cultivars Hart, Becker, and Adena were calculated for data taken at GS 10, GS 10.5.1, and GS 10, respectively. In both 1986 and 1987, the highest R^2 values, or values equal to the highest, were calculated at GS 10.3 for four of the six cultivars studied. The highest R^2 values, or values equal to the highest, for the remaining cultivars occurred at GS 10.5.1 and GS 10.5.4 in 1986 and at GS 10.5.4 and GS 11.1 in 1987. In 1985 and 1986, no significant R^2 values ($P < 0.05$) were determined

TABLE 2. Correlation coefficients (r) for the relationships between the 0–10 severity scale at growth stage 10.3 and four additional powdery mildew rating systems and between the 0–10 scale and the area under the disease progress curve (AUDPC)

Year	Rating system	Cultivar					
		Hart	Becker	Adena	Caldwell	Cardinal	Tyler
1985	3-leaf additive[a]	0.81[f]	0.82	0.88			
	3-leaf weighted[b]	0.87	0.83	0.91			
	2-leaf additive[c]	0.90	0.84	0.91			
	2-leaf weighted[d]	0.92	0.85	0.92			
	AUDPC for 0–10 scale[e]	0.97	0.98	0.95			
1986	3-leaf additive	0.91	0.96	0.97	0.94	0.96	0.94
	3-leaf weighted	0.92	0.95	0.97	0.93	0.96	0.87
	2-leaf additive	0.93	0.95	0.96	0.92	0.95	0.94
	2-leaf weighted	0.92	0.94	0.95	0.92	0.94	0.91
	AUDPC for 0–10 scale	0.98	0.98	0.98	0.95	0.98	0.87

[a] Sum of the percentage of leaf area affected on the flag, second, and third leaves down the stem.
[b] Percentage of leaf area affected on the third leaf plus double the percentage of leaf area affected on the second leaf plus triple the percentage of leaf area affected on the flag leaf.
[c] Sum of the percentage of leaf area affected on the flag and second leaves.
[d] Percentage of leaf area affected on the second leaf plus double the percentage of leaf area affected on the flag leaf.
[e] AUDPC was determined from assessments of powdery mildew at Feekes growth stages 6, 9, 10, 10.3, 10.5.1, and 10.5.4 in both years and also 11.1 in 1986. Powdery mildew severity was assessed on the basis of the 0–10 scale, described in Table 1.
[f] All correlation coefficients are significant at $P = 0.01$.

before GS 10 and GS 10.3, respectively. In 1987, the first significant R^2 was as early as GS 6 for Becker or as late as GS 10.5.4 for Caldwell. The R^2 values for yield in relation to AUDPC, calculated from the 0–10 scale, were similar to those for individual assessments (Table 3).

Cultivar also influenced regression results. In 1986 and 1987, Becker had some of the highest R^2 values for the relationship between yield and disease severity at GS 10.3 and for AUDPC (0.87 and 0.87 in 1986 and 0.83 and 0.81 in 1987, respectively). The cultivar Caldwell had the lowest R^2 values during these two years (0.32 and 0.40 in 1986 and 0.16 and 0.27 in 1987) (Table 3). The ranking of cultivars according to R^2 values for assessments at GS 10.3 and AUDPC were generally consistent in 1986 and 1987, except that two cultivars shifted position in 1986 for the AUDPC regressions. For 1986 and 1987, the most consistent R^2 values across all cultivars were for GS 10.3.

Yield loss assessment. Differences between the rating systems were similar at each assessment time; therefore, only the regression results for GS 10.3 are presented (Table 4). Coefficients of determination were lower in 1985 than in 1986 (the largest values were 0.38 and 0.90, respectively). In 1985, the highest R^2 values for two of the three cultivars studied were calculated from the 0–10 scale, and the three-leaf additive system had the highest R^2 value for the other cultivar. The 0–10 scale had the highest R^2 values, or values equal to the highest, for four of the six cultivars studied in 1986. The three-leaf additive system had the highest R^2 values, or values equal to the highest, for three of the six cultivars studied. Differences in R^2 values were greater between cultivars than

TABLE 3. Coefficients of determination (R^2) from regression of grain yield on powdery mildew severity assessed with the 0–10 severity scale at various growth stages and the area under the disease progress curve (AUDPC) for three cultivars in 1985 and six in 1986 and 1987[a]

Year	Growth stage[b]	Cultivar						
		Hart	Becker	Adena	Caldwell	Cardinal	Tyler	Scotty
1985	6	0.05	0.01	0.19				
	9	0.15	0.00	0.22				
	10	0.44**[d]	0.10*	0.25*				
	10.3	0.36*	0.25*	0.21				
	10.5.1	0.26*	0.34*	0.24				
	10.5.4	0.20	0.30*	0.17				
	AUDPC[c]	0.38**	0.31*	0.30*				
1986	6	0.00	0.01	0.01	0.07	0.00	0.00	
	9	0.06	0.05	0.16	0.05	0.02	0.01	
	10	0.00	0.00	0.04	0.13	0.02	0.17	
	10.3	0.84**	0.87**	0.79**	0.32*	0.77**	0.66**	
	10.5.1	0.77**	0.87**	0.61**	0.41**	0.72**	0.44**	
	10.5.4	0.72**	0.87**	0.67**	0.29*	0.79**	0.37**	
	11.1	0.77**	0.81	0.72**	0.32*	0.72**	0.27**	
	AUDPC	0.90**	0.87**	0.75**	0.40**	0.77**	0.54**	
1987	6	0.25	0.91*	0.61**	0.07	0.20		0.00
	8	0.15	0.26*	0.43	0.00	0.32*		0.50**
	9	0.26*	0.17	0.04	0.08	0.23		0.40**
	10	0.31*	0.74**	0.69**	0.19	0.59**		0.53**
	10.3	0.51**	0.83**	0.68**	0.16	0.61**		0.50**
	10.5.4	0.18	0.71**	0.49**	0.35*	0.55**		0.40**
	11.1	0.36*	0.71**	0.58**	0.24	0.58**		0.58**
	AUDPC	0.43**	0.81**	0.67**	0.27*	0.65**		0.54**

[a] The 0–10 severity scale is described in Table 1.
[b] Feekes growth stages (13).
[c] AUDPC was calculated according to Fry (6) on the basis of the 0–10 scale (Table 1).
[d] Asterisks indicate statistical significance of R^2; * indicates significance at $P = 0.05$, and ** indicates significance at $P = 0.01$ (14 degrees of freedom).

TABLE 4. Coefficients of determination (R^2) from the regression of grain yield on powdery mildew severity from five assessment systems at growth stage 10.3 for three cultivars in 1985 and six in 1986

Year	Rating system	Cultivar					
		Hart	Becker	Adena	Caldwell	Cardinal	Tyler
1985	3-leaf additive[a]	0.30[f]	0.24	0.38			
	3-leaf weighted[b]	0.31	0.23	0.35			
	2-leaf additive[c]	0.27	0.24	0.26			
	2-leaf weighted[d]	0.27	0.22	0.27			
	0–10 scale[e]	0.36	0.25	0.21			
1986	3-leaf additive	0.58	0.90	0.79	0.17	0.79	0.50
	3-leaf weighted	0.56	0.90	0.77	0.15	0.77	0.45
	2-leaf additive	0.55	0.88	0.79	0.19	0.76	0.58
	2-leaf weighted	0.52	0.88	0.76	0.18	0.74	0.55
	0–10 scale	0.84	0.87	0.79	0.32	0.77	0.66

[a] Sum of the percentage of leaf area affected on the flag, second, and third leaves down the stem.
[b] Percentage of leaf area affected on the third leaf plus double the percentage of leaf area affected on the second leaf plus triple the percentage of leaf area affected on the flag leaf.
[c] Sum of the percentage of leaf area affected on the flag and second leaves.
[d] Percentage of leaf area affected on the second leaf plus double the percentage of leaf area affected on the flag leaf.
[e] The 0–10 scale is described in Table 1.
[f] Coefficients of determination (R^2) of 0.25 or larger are significant at $P = 0.05$; coefficients of 0.38 or larger are significant at $P = 0.01$ (14 degrees of freedom).

between rating systems within cultivars. For example, in 1986 the R^2 value calculated from the 0–10 scale was 0.87 for Becker and 0.32 for Caldwell, whereas the range of R^2 values across the five rating systems was 0.87 to 0.90 for Becker and 0.15 to 0.32 for Caldwell.

Because of the high correlations between the 0–10 rating scale and the other four assessment scales (Table 2) and the strong relationship between yield and the 0–10 scale at GS 10.3 (Table 3), only final regression results for this scale and growth stage are presented (Table 5). Grain yield varied considerably among cultivars and years. Becker was the highest-yielding cultivar tested, and Adena was generally the lowest, but this varied with year. The highest yields occurred in 1985 and the lowest in 1986 (Figs. 1 and 2). Regression equations for assessments prior to GS 10.3 were highly influenced by one or two relatively large disease values, and no confidence could be placed in the adequacy of the models. This also could be seen in the cultivar Scotty at GS 10.3 in 1987 (Fig. 2F). Regression equations for late assessments (e.g., GS 10.5.4 and GS 11.1) were based on fitting a line through two distinct clusters of points. Thus, again, little confidence could be placed in the adequacy of the models. This also could be seen in the cultivar Caldwell in 1986 (Fig. 2A).

Over the three years, there was generally a linear relationship between yield and disease severity at GS 10.3 (Figs. 1 and 2). Relatively high R^2 values were calculated for five of the six cultivars studied in 1986 (values of 0.66–0.87) and in 1987 (values of 0.50–0.83) (Table 5). The cultivar Caldwell had the lowest R^2 value of the cultivars studied in both 1986 and 1987. The low R^2 values calculated for the three cultivars studied in 1985 were indicative of the high variability in the yield data, as detected by the high values of the mean square error for that year (Table 5 and Fig. 1A, D, and G).

Estimated slopes (b_1) were greater in 1986 than in 1985 or 1987 (Table 5), indicating a greater yield reduction in response to powdery mildew severity in 1986. Becker, for example, had slopes of 144, 237, and 141 kg per disease severity unit in 1985, 1986, and 1987, respectively. The cultivars also varied greatly in slopes within a year. In 1986, slopes ranged from 85 kg per disease severity unit (for Caldwell) to 249 kg per disease severity unit (for Tyler). Variation among cultivars was greatest in 1986, if one ignores the unreliable slope for Scotty in 1987, which was due to the separation of one observation from a cluster of points near disease severity of 0 (Fig. 2F). The ranking of cultivars according to slope value was generally consistent across years. For instance, Cardinal and Caldwell had the lowest values in 1986 and 1987. The cultivars tested over all three years, ranked according to slope value, were Becker, Hart, and Adena in 1985 and 1986; however, Adena had the greatest slope of these three in 1987.

TABLE 5. Regression statistics for the relationship between grain yield (in kilograms per hectare) and powdery mildew severity recorded at Feekes growth stage 10.3 for wheat cultivars tested in 1985, 1986, and 1987[a]

		Statistics[b]					
Year	Cultivar	b_0	$s(b_0)$	b_1	$s(b_1)$	R^2	MSE ($\times 10^4$)
1985	Hart	5,414	129	97	35	0.36	12.4
	Becker	6,375	269	144	62	0.25	55.3
	Adena	4,936	175	94	50	0.21	22.8
1986	Hart	4,022	116	180	22	0.84	4.4
	Becker	4,768	69	237	24	0.87	3.8
	Adena	3,396	122	175	24	0.79	3.7
	Caldwell	3,981	135	85	30	0.32	5.2
	Cardinal	4,082	100	114	17	0.77	2.1
	Tyler	4,553	99	249	48	0.66	8.1
1987	Hart	4,560	109	120	32	0.51	10.9
	Becker	5,434	70	141	17	0.83	3.8
	Adena	4,808	95	153	28	0.68	7.3
	Caldwell	5,266	90	50	31	0.16	7.7
	Cardinal	4,613	70	108	23	0.61	5.1
	Scotty	4,990	53	801[c]	213	0.50	4.2

[a]Powdery mildew severity was assessed on the basis of the 0–10 scale, described in Table 1.

[b]b_0 and b_1 are the intercept and the slope, respectively; $s(b_0)$ and $s(b_1)$ are their standard errors; R^2 is the coefficient of determination; MSE is the mean square error. There were 16 data points in each regression analysis (14 degrees of freedom).

[c]Abnormally high slope value resulting from a single high data point, or outlier (see Fig. 2).

The intercepts (b_0), i.e., yield when disease severity was 0, varied considerably among years and among cultivars within a year. The highest values of b_0 were in 1985, and the lowest in 1986. Becker had the largest b_0 in each year, but Adena's ranking varied with the year.

The regression equations for yield as a function of AUDPC (Table 6) fit the data about as well as the equations based on disease at GS 10.3 (Table 5). Some R^2 values were marginally larger when AUDPC was used (e.g., 0.90 versus 0.84 for Hart in 1986), some were virtually equal (e.g., 0.87 for Becker in 1986), and some were marginally smaller (e.g., 0.43 versus 0.51 for Hart in 1987). Residual plots indicated that the linear AUDPC equations were acceptable for describing yield. The ranking of cultivars based on their slopes for AUDPC (Table 6) agreed with the ranking based on assessment at GS 10.3 for 1986 and 1987. The values of b_0 for the AUDPC equations also were very similar to the values for the GS 10.3 equations over all three years.

The predicted percentage of yield loss (L) at a given level of disease severity (X_t) is given by $100X_tb_1/b_0$, in which b_0 and b_1 are the parameters in Table 5. The standardized slope (b_1*) is given merely by $100b_1/b_0$, and therefore additional regressions are not necessary. There was strong agreement between b_1 (Table 5) and b_1* (Table 7); i.e., if b_1 was large, then so was b_1*. Estimates of L for disease severities of 2, 5, and 8 at GS 10.3 varied considerably between years (Table 7). For instance, on the basis of the greatest severity recorded (approximately 8 at GS 10.3), estimated when no foliar fungicide was used, Becker had losses of 18, 40, and 21% in 1985, 1986, and 1987, respectively. At a severity of 2, Becker had losses ranging from 4.5 to 9.9%.

Stepwise regression generally provided a model with only a single disease predictor of yield (results not shown). This was attributed to the high correlation in disease severity between assessment times. In the few cases in which more than one assessment time (e.g., GS 10.3 and GS 10.5.4) was significant, the increase in R^2 was minimal.

Equation 2 was fitted to the data for each year and cultivar, with disease severity at GS 10.3 used for X_t. In all cases, the estimated b_2, b_3, b_4, and b_5 were not significant ($P > 0.20$) when entered into the model after X_t. This indicated that the fungicide treatments did not affect the relationship between yield and disease severity, even though the treatments, especially the foliar fungicide, reduced disease severity (17).

DISCUSSION

The high correlation of the four disease assessment systems with the 0–10 scale (Table 2) and the relatively high association of each assessment system with grain yield (Table 4) indicated that all may equally describe powdery mildew severity. Accurately estimating the percentage of leaf area covered by lesions on each of the top three leaves may be necessary for studies that require a high degree of precision in order to detect differences in powdery mildew severity between some treatments. However, in field tests or other experiments with relatively large biological variation, especially those with treatment or cultivar effects as they relate to yield (9), or where highly reproducible assessments are needed among investigators (12), a system such as the 0–10 scale may be more useful or practical. The 0–10 scale accounted for both leaf position and the percentage of leaf area affected, both factors that may influence plant performance and yield (9,14). This assessment system permitted rapid evaluation of individual tillers, since only the uppermost leaf with lesions was assessed. The 0–10 scale had the additional advantage of incorporating broad categories for the percentage of leaf area covered by lesions, permitting evaluation decisions to be made quickly with minimum error. Although it

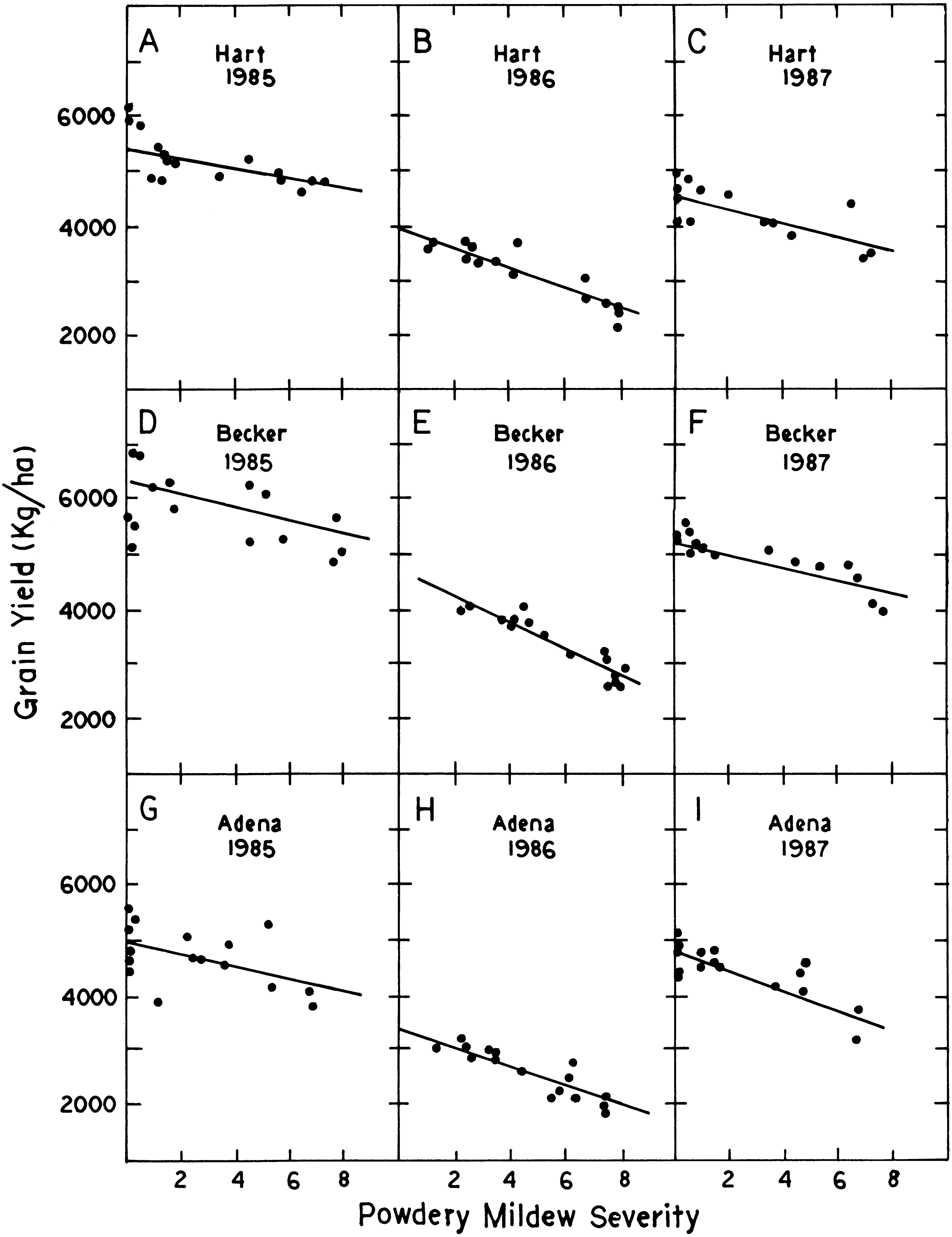

Fig. 1. Observed and predicted (Table 5) grain yield of winter wheat in relation to powdery mildew severity, assessed with the 0–10 scale (Table 1) at growth stage 10.3, on the cultivars Hart, Becker, and Adena in 1985, 1986, and 1987. One data point is not present in D (Becker, 1985), representing powdery mildew severity of 0 and grain yield of 8,260 kg/ha.

would appear that evaluating only the uppermost leaf for disease would limit the accuracy of predicting yield from such assessments, only rarely were tillers evaluated during the years of this study that had little or no disease on the lower leaves. Different results may occur if disease develops late in the season and only the flag leaf becomes infected.

Results indicated that regression equations calculated for the relationship between grain yield and powdery mildew severity assessed at GS 10.3 provided a model for precise yield estimates for most cultivars studied. This growth stage was the same or nearly the same as the one identified in other studies (5,15,16). Regression equations with coefficients of determination above 0.50 were considered adequate for the individual cultivar models. With this as a guide, regression equations for five of the six cultivars in both 1986 and 1987 were adequate (Table 5). Caldwell, the one cultivar with low R^2 values both years, had relatively little yield loss for the level of mildew recorded. It is known that the magnitude of the slope is directly proportional to the R^2 value (19). The high variability of the yield data in 1985 and the lower slopes were responsible for the low R^2 values and high mean square errors for that year. Coefficients of determination for regression equations

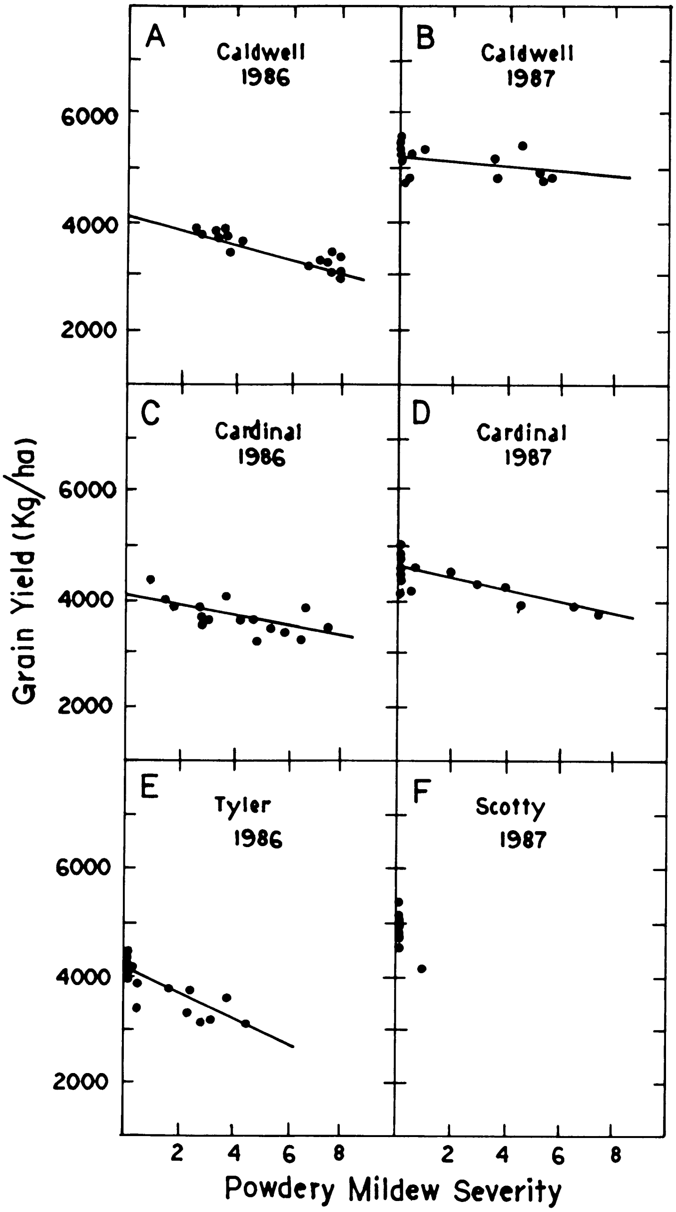

Fig. 2. Observed and predicted (Table 5) grain yield of winter wheat in relation to powdery mildew severity, assessed with the 0–10 scale (Table 1) at growth stage 10.3, on the cultivars Caldwell and Cardinal in 1986 and 1987, Tyler in 1986, and Scotty in 1987.

calculated using AUDPC (Table 6) were somewhat higher in 1985 than for regression equations using the single GS 10.3 assessment time (Table 5). This was not necessarily the case in 1986 and 1987, since some R^2 values were lower and others higher, and there was no consistency among cultivars. This indicates that the regression equations calculated from the single assessment time (GS 10.3) were as precise as those calculated from AUDPC data.

Model predictions that accurately predict yield (or loss) would be useful in making economically sound disease management decisions. It is often assumed that AUDPC and multiple-point models provide more precise estimates of yield (or loss) than critical-point models because information on a larger part of the epidemic is used in the former models (9,18,26). Multiple-point and AUDPC models are limited in practice by the large amount of data that must be collected, especially late in the epidemic. Attempts to develop a multiple-point model generally resulted in disease severity at only one assessment time being significant, probably because of the high correlation between disease ratings at the different times. Likewise, equations based on AUDPC, in most cases, were no more precise than equations using a single assessment time. Possibly this was because AUDPC gives equal weight to disease levels from all assessment times when predicting yield.

Analysis of the relationship between yield and disease severity assessed with the 0–10 scale at various growth stages generally indicated that the highest R^2 values, or values equal to the highest, were obtained for assessments made at GS 10.3 (Table 3). These high R^2 values were calculated for four of six cultivars in 1986 and 1987. In 1985, the highest R^2 values for two cultivars were calculated from data obtained at GS 10 and for one cultivar at GS 10.5.1. The R^2 values for these three cultivars at GS 10.3 were only slightly lower. Later assessments resulted in the separation of disease severities into two distinct groups. Earlier assessments usually exhibited one or two relatively high severities, and the rest were near 0. Both situations produce poorly behaved estimated

TABLE 6. Regression statistics for the relationship between grain yield (in kilograms per hectare) and the area under the disease progress curve (AUDPC) for powdery mildew of wheat cultivars tested in 1985, 1986, and 1987[a]

		Statistics[b]					
Year	Cultivar	b_0	$s(b_0)$	b_1	$s(b_1)$	R^2	MSE ($\times 10^4$)
1985	Hart	5,562	175	147	50	0.38	12.0
	Becker	6,617	330	236	94	0.31	52.5
	Adena	5,084	197	162	67	0.30	20.2
1986	Hart	4,163	102	267	25	0.90	2.8
	Becker	4,667	140	294	30	0.87	3.8
	Adena	3,329	126	211	33	0.75	4.5
	Caldwell	3,995	121	108	36	0.40	4.6
	Cardinal	4,035	91	151	22	0.77	2.0
	Tyler	4,230	124	476	117	0.54	11.0
1987	Hart	4,627	136	239	73	0.43	12.4
	Becker	5,535	83	246	32	0.81	4.1
	Adena	4,862	105	312	59	0.67	7.6
	Caldwell	5,319	91	129	56	0.27	6.7
	Cardinal	4,640	69	192	38	0.65	4.6
	Scotty	5,057	57	405[c]	99	0.54	3.8

[a] AUDPC was calculated (6) from disease assessments at Feekes growth stages 6, 9, 10, 10.3, 10.5.1, and 10.5.4 in 1985 and 1986; at GS6, GS8, GS9, GS10, GS10.3 and GS10.54 in 1987; and 11.1 in 1986 and 1987. Powdery mildew severity was assessed on the basis of the 0–10 scale, described in Table 1. AUDPC values were standardized by dividing the calculated value by the duration of disease assessments. This results in AUDPC values in the range of 0–10.

[b] b_0 and b_1 are the intercept and the slope, respectively; $s(b_0)$ and $s(b_1)$ are their standard errors; R^2 is the coefficient of determination; MSE is the mean square error. There were 16 data points in each regression analysis (14 degrees of freedom).

[c] Abnormally high slope value resulting from a single high data point, or outlier (see Fig. 2).

TABLE 7. Estimates of the percentage of yield loss at three levels of powdery mildew severity assessed at the head emergence growth stage (GS 10.3) with the 0–10 severity scale and regression statistics for wheat cultivars tested in 1985, 1986, and 1987

Year	Cultivar	Estimated percentage of yield loss: Disease severity level 2[a]	Disease severity level 5	Disease severity level 8	Statistics[b]: b_1*	$s(b_1*)$
1985	Hart	3.5	9.0	14.3	1.79	0.65
	Becker	4.5	11.3	18.1	2.26	0.98
	Adena	3.8	9.5	15.2	1.90	1.02
1986	Hart	9.0	22.4	35.8	4.48	0.56
	Becker	9.9	24.8	39.8	4.97	0.51
	Adena	10.3	25.8	41.2	5.15	0.73
	Caldwell	4.3	10.7	17.1	2.14	0.76
	Cardinal	5.6	14.0	22.3	2.79	0.42
	Tyler	10.9	27.3	43.8	5.47	1.06
1987	Hart	5.2	13.2	21.0	2.63	0.70
	Becker	5.2	13.0	20.8	2.59	0.31
	Adena	6.4	15.9	25.5	3.18	0.59
	Caldwell	1.9	4.7	7.6	0.95	0.59
	Cardinal	4.7	11.7	18.7	2.34	0.50
	Scotty	—[c]	—	—	—	—

[a] Disease severity levels according to the 0–10 scale, described in Table 1.
[b] b_1* and $s(b_1*)$ are, respectively, the slope and the estimated standard error for predicting the percentage of yield loss in relation to disease. $b_1* = 100b_1/b_0$, where b_1 and b_0 are as given in Table 5; $s(b_1*)$ was calculated from the asymptotic formula (19) based on $s(b_0)$ and $s(b_1)$ as given in Table 5.
[c] Estimate not valid because of low disease severities (Fig. 2).

regression parameters (19). Our results and those of others (5,14,22) indicate that one-time disease assessments can provide reliable disease severity estimates for predicting yield loss to powdery mildew. However, we found a linear relation, in agreement with Fried et al (5), not a square-root relation, which was found by Large and Doling (14,15). Unfortunately, disease severity estimates obtained at GS 10.3 may not be early enough to provide sufficient time for the application of appropriate control measures (11,22). Future research should focus on predicting disease severity at GS 10.3 on the basis of an earlier assessment and weather data.

Cultivars with the greatest yield loss in relation to powdery mildew severity may provide economic returns when expensive control measures, such as fungicides, are used. The slope values from equation 1 can be considered a measure of the tolerance of the cultivar; smaller values indicate greater tolerance (25). Slope values for the different cultivars varied with the year, and some cultivars shifted in rank order during the 3-yr study (Tables 5 and 7). Yet, those cultivars considered most susceptible prior to this study (Hart, Becker, and Adena) had higher slope values than those considered less susceptible (Cardinal and Caldwell). This was true for slopes calculated for absolute and relative yields. In this study, however, even the less-susceptible cultivars had some treatments with severities of 8 at GS 10.3 and predicted losses of 8–22% (Table 7). The cultivars Tyler and Scotty were considered to be resistant when placed in the study, but slopes for these two cultivars were the highest calculated for the cultivars evaluated. Scotty had only one experimental unit with a disease severity as high as 1 (Fig. 2F). This single observation biased the regression calculations (Table 5) and, therefore, was considered to be an inconsequential artifact. In the case of Tyler, an apparently new race of *E. g. tritici* became prevalent in plots for the first time (Lipps, *unpublished*), but disease severity did not reach as high a level on this cultivar as on some of the others studied.

Regardless of the inherent problems with variation among years and cultivars, the regression models provided guidelines for yield loss of the different cultivars and some representation of the variation that must be expected. The differences between cultivars for disease severity and yield without disease (b_0) and yield reduction in relation to disease (b_1) indicated that models must be constructed for each cultivar and that models based on data from one cultivar would be of little practical use for estimating the yield loss of most cultivars. Perhaps, when more cultivars are evaluated, they could be grouped into categories according to expected yield loss for disease control management considerations.

LITERATURE CITED

1. Broscious, S. C., Frank, J. A., and Frederick, J. R. 1985. Influence of winter wheat management practices on the severity of powdery mildew and Septoria blotch in Pennsylvania. Phytopathology 75:538-542.
2. Dixon, W. J., ed. 1985. BMDP Statistical Software. University of California Press, Berkeley.
3. Frank, J. A., and Ayers, J. E. 1986. Effect of triadimenol seed treatment on powdery mildew epidemics on winter wheat. Phytopathology 76:254-257.
4. Fried, P. M., MacKenzie, D. R., and Nelson, R. R. 1979. Disease progress curves of *Erysiphe graminis* f. sp. *tritici* on Chancellor wheat and four multilines. Phytopathol. Z. 95:151-166.
5. Fried, P. M., MacKenzie, D. R., and Nelson, R. R. 1981. Yield loss caused by *Erysiphe graminis* f. sp. *tritici* on single culms of "Chancellor" wheat and four multilines. Z. Pflanzenkrankh. Pflanzenschutz 88:256-264.
6. Fry, W. E. 1978. Qualification of general resistance of potato cultivars and fungicide effects for integrated control of potato late blight. Phytopathology 68:1650-1655.
7. Horsfall, J. G., and Barratt, R. W. 1945. An improved grading system for measuring plant diseases. (Abstr.) Phytopathology 35:655.
8. James, W. C. 1971. An illustrated series of assessment keys for plant diseases, their preparation and usage. Can. Plant Dis. Surv. 51:39-65.
9. James, W. C. 1974. Assessment of plant diseases and losses. Annu. Rev. Phytopathol. 12:27-48.
10. Jenkyn, J. F., Bainbridge, A., Dyke, G. U., and Todd, A. D. 1979. An investigation into interplot interactions, in experiments with mildew on barley, using balanced designs. Ann. Appl. Biol. 92:11-28.
11. Kingsland, G. C. 1982. Triadimefon for control of powdery mildew of wheat. Plant Dis. 66:139-141.
12. Kranz, J. 1988. Measuring plant disease. Pages 35-50 in: Experimental Techniques in Plant Disease Epidemiology. J. Kranz and J. Rotem, eds. Springer-Verlag, New York.
13. Large, E. C. 1954. Growth stages in cereals: Illustration of the Feekes scale. Plant Pathol. 3:128-129.
14. Large, E. C., and Doling, D. A. 1962. The measurement of cereal mildew and its effect on yield. Plant Pathol. 11:47-57.
15. Large, E. C., and Doling, D. A. 1963. Effect of mildew on yield of winter wheat. Plant Pathol. 12:128-130.
16. Leath, S., and Bowen, K. L. 1989. Effects of powdery mildew, triadimenol seed treatments, and triadimefon foliar sprays on yield of winter wheat in North Carolina. Phytopathology 79:152-155.
17. Lipps, P. E., and Madden, L. V. 1988. Effect of triadimenol seed treatment and triadimefon foliar treatment on powdery mildew epidemics and grain yield of winter wheat cultivars. Plant Dis. 72:887-892.
18. Madden, L. V. 1983. Measuring and modeling crop losses at the field level. Phytopathology 73:1591-1596.
19. Neter, J., Wasserman, W., and Kutner, M. H. 1983. Applied Linear

Regression Models. Richard D. Irwin, Homewood, IL. 547 pp.

20. Porter, H. K., Pal, N., and Martin, R. V. 1950. Physiological studies in plant nutrition. XV. Assimilation of carbon by the ear of barley and its relation to the accumulation of dry matter in the grain. Ann. Bot. (London) 14:55-68.
21. Raymond, P. J., Bockus, W. W., and Norman, B. L. 1985. Tan spot of winter wheat: Procedures to determine host response. Phytopathology 75:686-690.
22. Royse, D. J., Gregory, L. V., Ayers, J. E., and Cole, H., Jr. 1980. Powdery mildew of wheat: Relation of yield components to disease severity. Can. J. Plant Pathol. 2:131-136.
23. Saari, E. E., and Prescott, J. M. 1975. A scale for appraising the foliar intensity of wheat diseases. Plant Dis. Rep. 59:377-380.
24. Shaner, G. 1973. Evaluation of slow-mildewing resistance of Knox wheat in the field. Phytopathology 63:867-872.
25. Teng, P. S. 1985. Construction of predictive models. II. Forecasting crop losses. Pages 179-206 in: Advances in Plant Pathology, Vol. 3: Mathematical Modeling of Crop Diseases. C. A. Gilligan, ed. Academic Press, London.
26. Teng, P. S., and Johnson, K. B. 1988. Analysis of epidemiological components in yield loss assessments. Pages 179-189 in: Experimental Techniques in Plant Disease Epidemiology. J. Kranz and J. Rotem, eds. Springer-Verlag, New York.