The Effect of Nitrogen Fertilization on the Expression of Slow-Mildewing Resistance in Knox Wheat

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ABSTRACT

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Powdery mildew development on the slow-mildewing wheat cultivar Knox was compared to that on the susceptible cultivar Vermillion over a period of 4 yr in the field at Lafayette, Indiana. Cultivars received three levels of nitrogen fertilizer to determine if high levels of N affected the expression of slow-mildewing in Knox wheat. Knox's resistance was evident under conditions favoring moderate to severe disease on Vermillion. Under low nitrogen fertility or unfavorable weather there was little difference in level of mildew on the two cultivars; under more favorable conditions disease severity increased greatly on Vermillion but increased little on Knox. The area under the disease progress curve had a lower error variance than statistics associated with the logit transformation of severity data and hence was a superior measurement of slow-mildewing. Slow-mildewing remains effective under the highest rates of nitrogen fertilization likely to be applied to wheat. In breeding for slow-mildewing, high rates of N provide optimal conditions for recognition of this resistance.

Additional key words: *Erysiphe graminis*, *Triticum aestivum*, epidemiology, general resistance, breeding for disease resistance, nitrogen fertilization effects.

Wheat *Triticum aestivum* L. em. Thell. 'Knox' has resistance to *Erysiphe graminis* f. sp. *tritici* that has been described as slow-mildewing to distinguish it from the resistance conferred by *Pm* genes (9). Because Knox has maintained its slow-mildewing character for many years over a wide geographical area, this resistance appears to be race nonspecific and to have value for wheat breeding programs (3, 9, 10). Slow-mildewing in Knox is characterized by fewer successful infections and lower spore production per colony, both of which restrict the rate of disease development in the field (10, 11). Unfortunately, slow-mildewing is only a partial resistance, it is not expressed in seedlings, and it behaves genetically as a quantitative trait (12). Moreover, Knox's slow-mildewing is a relative trait which can only be assessed by comparing mildew development on Knox with mildew development on a susceptible cultivar grown under the same conditions. Because the rate of mildew development depends on environment as well as host genotype, we would expect the measured level of slow-mildewing in Knox to vary among years and locations. Therefore, we measured the slow-mildewing in Knox over a range of conditions favorable or unfavorable for the disease to see if it would be expressed consistently. Mildew development on Knox was compared with that on the susceptible wheat cultivar Vermillion for 4 yr. Each year, three levels of nitrogen fertilizer were compared because farmers tend to use higher levels of nitrogen as cultivars with shorter and stiffer straw become available and because soil nitrogen level is an important factor in mildew development (1, 4, 5, 6, 7, 8, 14). An additional objective of this study was to find a way to measure slow-mildewing suitable for use in a wheat breeding program.

MATERIALS AND METHODS

Wheat cultivars Knox (C. I. 12798) and Vermillion (C. I. 13080) were grown in four-row plots, each 2.4 m long with 30 cm between rows. The plots were sown in September on a fine sandy loam soil on the Purdue Agronomy Farm, West Lafayette, Indiana. Potassium and phosphorus were applied uniformly to the plot area each fall in amounts adequate for high yield. Nitrogen (N) and cultivar treatments were arranged in a split-plot design with N levels as main plots and cultivars as subplots. Main plots were separated by four rows of the wheat cultivar Arthur, highly resistant to *E. graminis*. Shortly after emergence, a nitrogen topdress was applied as follows: High-N (N3) plots received N as ammonium nitrate at 100 kg/ha in 1971 and 1972 and 67 kg/ha in 1973 and 1974; intermediate-N (N2) plots received half that amount each year; and low-N (N1) plots received none. In the spring, plots were topdressed as follows: N3, 66 kg/ha in 1971 and 1972 and 90 kg/ha in 1973 and 1974; N2, half the amount applied to N3; and N1, none. About mid-April wheat seedlings infected with an *E. graminis* culture collected in the field at Lafayette, Indiana in 1970 were placed between rows in each plot as a source of inoculum. Beginning in early May and at weekly intervals

thereafter, mildew severity, as percent of leaf area covered, was recorded for each of the upper four leaves for five plants in each of the two center rows of each plot. The plot mean for each leaf position was the basic datum used in all subsequent analyses. The data for each year were analyzed separately.

As one criterion of resistance, percentage severities were converted to logits (15) and the regression of logit on time was calculated. The slope of this regression line (b), which is an estimate of the apparent infection rate (15), was calculated for each subplot and these were analyzed by analysis of variance to estimate effects of N-level, cultivar and N-level × cultivar interactions. Two regression lines may have the same slope (apparent infection rate) yet differ in position if one epidemic begins at a later date than the other. To characterize the position of the transformed disease progress curve, we used the time required for severity to reach 10% (T_{10}). The T_{10} measure was used as an alternative to the Y-intercept because it is easier to visualize a difference in time than a difference in logits. In this case, mildew damage would be less on the treatment that requires more time for severity to reach 10%.

As a second method of measurement of resistance, the area under the disease-progress curve was calculated for each subplot and these were analyzed by analysis of variance. The area under the disease progress curve (ADPC) was calculated as follows:

$$\text{ADPC} = \sum_{i=1}^{n} [(Y_{i+n1} + Y_i)/2] [X_{i+1} - X_i]$$

in which Y_i = mildew severity (per unit) at the *ith* observation, X_i = time (days) at the *ith* observation, and n = total number of observations.

RESULTS

Of the 4 yr of this study, 1972 was most favorable for spread of *Erysiphe graminis* (Fig. 1), followed in order by 1971, 1974, and 1973. In each year, disease was most severe on Vermillion in the N3 plots. Considerable mildew developed on Vermillion in the N2 plots except in 1974. The amount of mildew on Vermillion in N1 plots ranged from essentially none in 1973 and 1974, to a moderate amount in 1971 and 1972. Nitrogen also

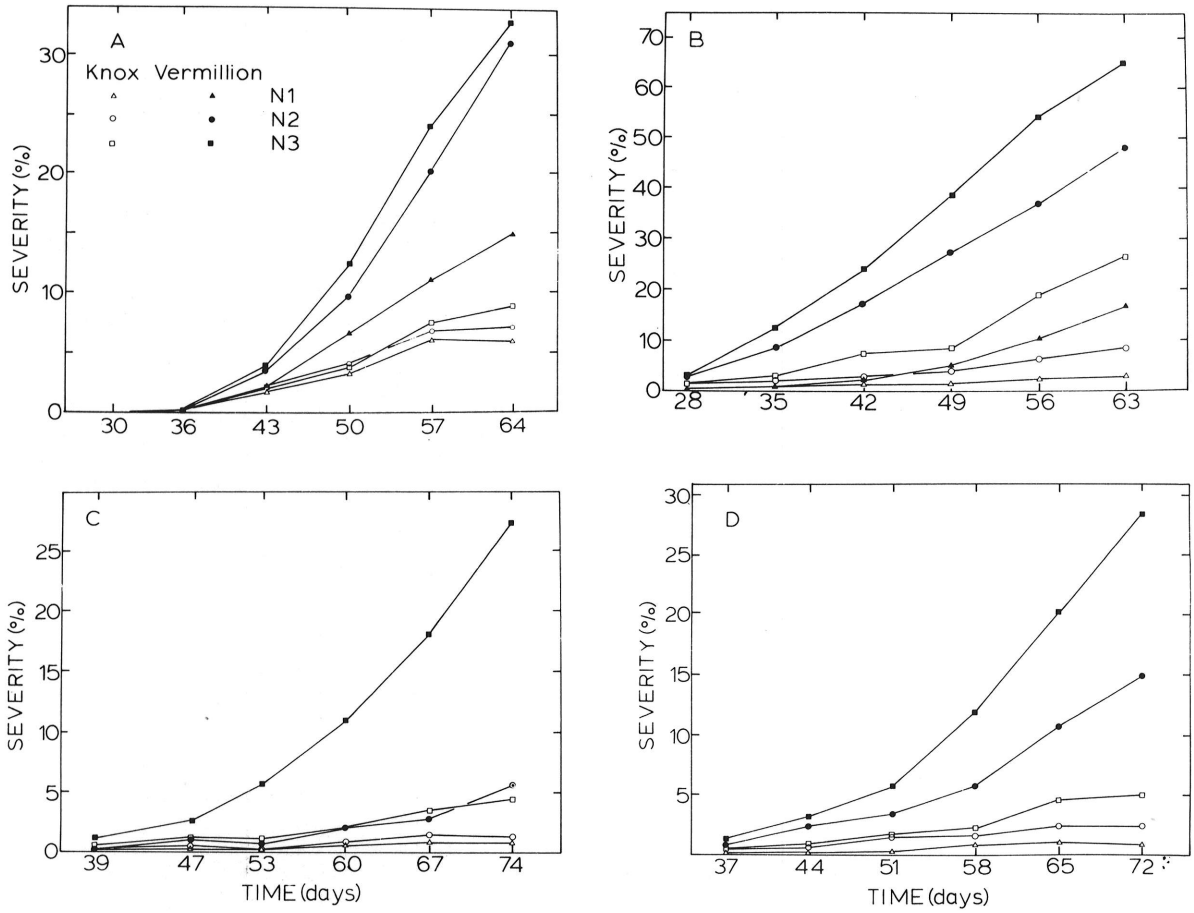

Fig. 1-(A to D). Disease progress curves for spread of *Erysiphe graminis* on Knox and Vermillion wheats, Purdue University Agronomy Farm, Lafayette, Indiana. Severities are means for the upper four leaves. Each point is the mean of four replications. Day 1 = 1 April. **A)** 1971. **B)** 1972. **C)** 1973. The curve for Vermillion N1 matches that of Knox N1 and is not plotted. **D)** 1974. The curve for Vermillion N1 matches that of Knox N1 and is not plotted.

increased mildew severity on Knox, but the response in this cultivar was less than in Vermillion. Even in the N3 plots the level of disease on Knox was low. In the favorable years 1971 and 1972 the level of mildew on Knox-N3 was only half that on Vermillion-N2.

Over the four years there were 72 combinations of cultivar, N, and leaf position. Analysis of these data indicated that there were no important interactions of the various factors with leaf position and that data averaged over leaf position revealed the same trends seen within leaf positions. Therefore, we are presenting only averaged data here. Data within leaf position averaged over N level are included to illustrate the vertical pattern of mildew development within the canopy. The leaf positions cannot be compared directly because they are based on observations over different periods of time. The disease

TABLE 1. Apparent infection rates (b)[a] for spread of *Erysiphe graminis* on Knox and Vermillion wheats at Lafayette, Indiana, averaged over: (A) the upper three leaves, or (B) three nitrogen levels

	(A) Apparent infection rate per year and cultivar[b]									
Nitrogen	1971		1972		1973		1974		Mean	
kg/ha	K	V	K	V	K	V	K	V	K	V
0	.086A	.142*[c]A	.070A	.082 A	.053A	.055 A	.032A	.017 A	.061	.074
81	.075A	.157*A	.068A	.140*B	.044A	.106*B	.042A	.074*B	.057	.119
162	.091A	.162*A	.091A	.169*C	.063A	.120*B	.078B	.092 B	.081	.136
Mean	.084	.154*	.076	.130*	.053	.094*	.051	.061	.066	.110

	(B) Apparent infection rate per year and cultivar[b]									
leaf[d]	1971		1972		1973		1974		Mean	
	K	V	K	V	K	V	K	V	K	V
F	.113	.208*	.062	.118*	.061	.123*	.033	.045	.067	.124
F-1	.077	.137*	.072	.123*	.067	.090	.062	.078	.070	.107
F-2	.062	.115*	.094	.150*	.033	.068*	.057	.059	.062	.098
Mean	.084	.153*	.076	.130*	.053	.094*	.051	.061	.066	.110

[a]b is the linear regression coefficient of logit severity plotted against time.
[b]K = Knox; V = Vermillion.
[c]Within a given year and either N level or leaf, the asterisk symbol (*) indicates Knox and Vermillion differ significantly at $P=0.05$. Within a given year and cultivar in part A, means followed by the same letter do not differ significantly at $P=0.05$ (Duncan's multiple range test).
[d]F = flag leaf, F-1 = first leaf below flag leaf, etc.

TABLE 2. Days[a] required for powdery mildew (*Erysiphe graminis*) severity to reach 10% (T_{10}) on Knox and Vermillion wheats at Lafayette, Indiana, averaged over: (A) the upper three leaves, or (B) three nitrogen levels

	(A) T_{10} per year and cultivar[b]									
Nitrogen	1971		1972		1973		1974		Mean	
kg/ha	K	V	K	V	K	V	K	V	K	V
0	72A	65*[c]A	84A	79*A	132A	126 A	120A	139*A	102	102
81	71AB	58*B	77A	56*B	125A	95*B	112A	72*B	96	70
162	68B	57*B	80A	51*B	101B	71*C	88B	59*C	82	60
Mean	70	60*	80	62*	119	97*	107	90*	94	77

	(B) T_{10} per year and cultivar[b]									
leaf[d]	1971		1972		1973		1974		Mean	
	K	V	K	V	K	V	K	V	K	V
F	81	70*	97	76*	120	96*	129	102*	105	86
F-1	69	61*	79	60*	115	97*	97	88	90	76
F-2	61	49*	65	50*	125	99*	94	80*	86	70
Mean	70	60*	80	62*	119	97*	107	90*	94	77

[a]The number of days was calculated by solving the regression equation $\{\ln[0.10/(1-0.10)]-a\}/b = X$ for X, using values of a and b determined from logit analysis (15) of disease progress curves. The regression coefficient, b, is the apparent infection rate. Day 1 = 1 April. Values of X that exceeded 150 days were reduced to 150 days before analysis of variance. Each value is the mean of four replications.
[b]K = Knox, V = Vermillion.
[c]Within a year and either N level or leaf, the asterisk symbol (*) indicates Knox and Vermillion differ significantly at $P=0.05$. Within a year and cultivar in part A, means followed by the same letter do not differ significantly at $P=0.05$ (Duncan's multiple range test).
[d]F = flag leaf, F-1 = first leaf below flag leaf, etc.

symptoms always appeared first on lower leaves and spread up the plant so that the epidemic for each leaf position occurred at successively later periods. Consequently, the statistics characterizing these epidemics reflect not only physiological conditions peculiar to each leaf position, but weather conditions as well.

Apparent infection rate.—Apparent infection rates [slope (b) of the line of logit severity vs. time] tended to increase with N level (Table 1-A). However, b for Knox was less sensitive to N than b for Vermillion. Nitrogen increased b on Knox significantly in only one year, whereas it increased b on Vermillion significantly in three years. Within year and N level, b for Vermillion was greater than b for Knox in 11 of 12 comparisons, significantly in eight of them. Averaged over all treatments, b for Vermillion was 1.7 times greater than b for Knox.

The values of b for different leaves averaged over N level do not bear any consistent relation to leaf position (Table 1-B). Values for Vermillion within each year and leaf were always greater than those for Knox, significantly in 8 of 12 comparisons.

Time required for severity to reach 10 percent (T_{10}).—As N level increased, T_{10} decreased for Vermillion (Table 2-A). In 1971 and 1972 the only significant difference was between N1 and N2; in 1973 and 1974 the values for all N levels were significantly different. Conversely, N level only shortened T_{10} for Knox significantly between N2 and N3. Values of T_{10} were much higher in 1973 and 1974 than in 1971 and 1972. In 10 of 12 comparisons, T_{10} for Vermillion was significantly less than T_{10} for Knox; in one case it was significantly greater. T_{10} was consistently lower for each leaf position on Vermillion compared with Knox (Table 2-B). Averaged over all treatments, 17 more days were required for severity to reach 10% on Knox than on Vermillion.

Area under the disease progress curve (ADPC).—Nitrogen significantly increased the ADPC for both cultivars in all years (Table 3-A). Each increment in N caused a significant increase in ADPC for Vermillion, but this was not always so for Knox. Judged by ADPC, disease was most severe in 1972 and least severe in 1973. In 9 of 12 comparisons within year and N level, ADPC for Vermillion was significantly greater than ADPC for Knox. In no case was ADPC less on Vermillion than on Knox. Averaged over all treatment combinations, ADPC for Vermillion was 2.9 times greater than ADPC for Knox.

Summarized by leaf position, the ADPC's reflect the greater development of mildew on the lower leaves, especially when disease was severe (Table 3-B). The difference between the cultivars was greater lower in the canopy, indicated by increasing ratios of ADPC for Vermillion to ADPC for Knox. Averaged over years these ratios were 2.2, 2.7, and 3.2 for F, F-1, and F-2 respectively.

The magnitude of Knox's slow-mildewing relative to Vermillion.—Originally, we analyzed means for each year, N level, and leaf position separately. There are therefore 36 means representing all combinations of year, N level, and leaf position for each cultivar. To compare the magnitude of slow-mildewing in Knox relative to Vermillion under conditions increasingly favorable for mildew, the regression of b (apparent infection rate) for Knox on b for Vermillion and the regression of ADPC for Knox on ADPC for Vermillion were calculated for these 36 pairs of means. The relations are as follows:

$$b_K = 0.3603\ b_V + 0.0275 \qquad r^2 = 0.51709$$

$$ADPC_K = 0.2700\ ADPC_V + 0.1270 \qquad r^2 = .90909$$

TABLE 3. Area under the disease progress curve (ADPC)[a] for spread of *Erysiphe graminis* on Knox and Vermillion wheats at Lafayette, Indiana, averaged over: (A) the upper three leaves, or (B) three nitrogen levels

Nitrogen kg/ha	(A) ADPC per year and cultivar[b]									
	1971		1972		1973		1974		Mean	
	K[b]	V	K	V	K	V	K	V	K	V
0	0.80A	1.26*[c]A	0.30A	0.56 A	0.08A	0.14 A	0.11A	0.15 A	0.32	0.53
81	1.00B	2.32*B	0.61A	2.08*B	0.16A	0.44*B	0.35B	1.41*B	0.53	1.56
162	1.01B	2.47*C	1.90B	6.93*C	0.35B	1.26*C	0.59C	2.26*C	0.96	3.23
Mean	0.94	2.02*	0.94	3.19*	0.20	0.61*	0.35	1.27*	0.61	1.77
leaf[d]	(B) ADPC per year and cultivar[b]									
	1971		1972		1973		1974		Mean	
	K	V	K	V	K	V	K	V	K	V
F	0.19	0.30*	0.32	0.51*	0.10	0.27*	0.23	0.81*	0.21	0.47
F-1	0.89	1.31*	0.80	2.86*	0.22	0.64*	0.54	1.85*	0.61	1.66
F-2	1.74	4.45*	1.68	6.19*	0.27	0.94*	0.28	1.17*	0.99	3.19
Mean	0.94	2.02	0.94	3.19	0.20	0.61	0.35	1.27	0.61	1.77

[a] $ADPC = \sum_{i=1}^{n} [(Y_{i+1} + Y)/2][X_{i+1} - X_i]$ in which Y_i = mildew severity (per unit) at the *ith* observation, X_i = time (days) of the *ith* observation, and n = total number of observations.

[b] K = Knox; V = Vermillion.

[c] Within a year and either N level or leaf, the asterisk symbol (*) indicates Knox and Vermillion differ significantly at $P = 0.05$. Within a year and cultivar in part A, means followed by the same letter do not differ significantly at $P = 0.05$ (Duncan's multiple range test).

[d] F = flag leaf, F-1 = first leaf below flag leaf, etc.

The regression equation relating b_K to b_V shows that as b_V increases, the ratio b_V/b_K likewise increases. Thus, if we use the apparent infection rate as the criterion for slow-mildewing, Knox's resistance improves in a relative sense as conditions become more favorable for mildew. A similar situation exists for ADPC.

DISCUSSION

Disease development depends on environment as well as genes in the host and pathogen. Genetic resistance, adverse weather, or a less suitable plant owing to insufficient nitrogen in the soil may all have the same effect on *E. graminis*, namely, interference with its reproduction. Resistance conferred by *Pm* genes, in which development of the pathogen in the host usually ceases before production of new inoculum occurs, is relatively insensitive to environment. Essentially no disease develops. Slow-mildewing is a quantitative resistance that interferes with, but does not completely prevent, an epidemic. *Erysiphe graminis* f. sp. *tritici* has a lower reproductive efficiency on Knox than on Vermillion (11); consequently, the population of the pathogen builds up more slowly on Knox (10). Beacuse slow-mildewing does not completely inhibit reproduction of *E. graminis*, disease severity on a cultivar with this resistance does increase with time. One would expect that this rate of increase would be subject to environment just as is the rate of increase on a susceptible cultivar. Consequently, environment would exert a greater effect on the expression of slow-mildewing than it does on the expression of race-specific, monogenic resistance. The greater influence of environment on slow-mildewing means a larger experimental error associated with measurements of this kind of resistance (12).

Because slow-mildewing interferes with, but does not completely inhibit spread of the pathogen, it is difficult to obtain dependable measurements of this resistance based on readings at any one time. Readings made early in the season may underestimate the susceptibility of many genotypes, whereas readings made later may be confounded by natural senescence of lower leaves which cannot be distinguished from death from disease. The seasonal vagaries of weather preclude selection of one best time for taking notes. Differences in growth rates among genotypes means that mildew severities observed at one calendar time may not reflect the eventual severity and associated yield loss as accurately as severities observed at another time. To reduce experimental error, it is necessary to make sequential observations and to express slow-mildewing in terms of statistics associated with the disease progress curve.

We used three statistics associated with the disease progress curve to compare treatment effects in this study. Analysis of variance revealed significant differences between Knox and Vermillion for these three statistics under certain environmental conditions. The first of these statistics, the apparent infection rate, was calculated as the slope (b) of a straight line fitted to points plotted on a graph of logit severity versus time. To the extent that these points did not fall on a straight line, the apparent infection rate obscured some of the true variation in rate of disease development. Berger (2) reported considerable variation in the apparent infection rate during the course of epidemics. In our study, in 1971, 1972, 1973, and 1974, 13%, 3%, 43%, and 47%, respectively, of the coefficients of determination associated with the calculation of apparent infection rates were less than 0.8. Thus, some of the information in a disease progress curve is lost in calculation of an apparent infection rate and this evidently increases experimental error, because analyses of variance detected fewer differences among treatments than did analyses of T_{10} or ADPC.

Aside from errors introduced by lack of linearity in $\ln[Y/(1-Y)]$ plotted against X, there is another significant source of error in calculating b. The value of the apparent infection rate is strongly influenced by minor differences in disease severity early in the season when severities are low. Small differences in severity at the first observation time become much larger when transformed to $\ln[Y/(1-Y)]$ and can lead to large error terms associated with means of b's. The apparent infection rate is useful in analyzing epidemics and predicting the effect of various disease control practices, but it has serious drawbacks as a statistic for studying slow-mildewing in small plots. Wilcoxson et al. (16) reached the same conclusion in studying slow-stem-rusting in wheat.

The T_{10} is not independent of b because it is calculated from the regression equation relating $\ln[Y/(1-Y)]$ to X. It is perhaps superior to b for discriminating treatments because it embodies both position and slope of the transformed disease progress curve. Nonetheless, it is time consuming to calculate and offers no advantage over ADPC.

Calculation of ADPC uses all data available and does not obscure the variation in rate of disease development because of transformations. Moreover, minor differences in disease severity early in the season have little effect on ADPC. One disadvantage to the use of ADPC, however, is that it must be calculated from a common time base in order to compare treatments, because it is a product of time and severity. If the total time interval is not greatly different from one treatment to another, a relative ADPC can be calculated. This permits comparisons of years or locations where it may not have been possible to make observations on all treatments at the same time.

The other objective of this study was to determine whether the slow-mildewing resistance of Knox remains effective under conditions that favor a severe epidemic. Although the amount of mildew on Knox varied among years and levels of nitrogen, as indicated by the apparent infection rate or ADPC, slow-mildewing was always evident in Knox by comparison with Vermillion. With no supplemental nitrogen, little mildew developed on either cultivar. As more nitrogen was supplied or in seasons of more favorable weather, the different levels of resistance in the two cultivars became evident. At the highest level of nitrogen (N3) Knox still exhibited considerable slow-mildewing. Our highest N is twice the amount of nitrogen currently recommended for wheat in Indiana. At the recommended rate (N2) the mean severity on the upper four leaves of Knox never exceeded 8%, whereas severity on Vermillion at N2 was as high as 48% (Fig. 1). Thus the expression of slow-mildewing in Knox is variable, but it does not "break down" under conditions favorable for an epidemic. Indeed, in a relative sense, the resistance of Knox improves as conditions become more favorable for

an epidemic. Whereas a susceptible cultivar may show a yield reduction owing to increased disease severity (13), a short, stiff-strawed cultivar with slow-mildewing may show a yield response to high levels of nitrogen.

Our results have implications for breeding for this kind of resistance. They indicate that high levels of nitrogen should be applied to breeding material to magnify disease severity differences between slow-mildewing and susceptible lines. The ADPC is easily calculated and should be a useful criterion for selection. Finally, slow-mildewing is clearly expressed in small plots, offering encouragement that it can be selected in early generations in single 1-m rows.

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