Effect of Triadimenol Seed Treatment and Timing of Foliar Fungicide Applications on Onset and Extent of Powdery Mildew and Leaf Rust Epidemics

K. L. Everts and S. Leath

USDA, ARS, Department of Plant Pathology, North Carolina State University, Raleigh 27695-7616.
Present address of first author: Seed Research, Busch Agricultural Research, Inc., Ft. Collins, CO 80524.

Accepted for publication 22 January 1993.

ABSTRACT

Everts, K. L., and Leath, S. 1993. Effect of triadimenol seed treatment and timing of foliar fungicide applications on onset and extent of powdery mildew and leaf rust epidemics. Phytopathology 83:557-562.

Powdery mildew and leaf rust occur yearly in wheat-growing areas of the southeastern United States. However, the time of onset and peak severity differ between diseases, and consequently, wheat plants are subject to disease stress throughout a long period of the growing season. Three cultivars of winter wheat varying in their level of disease resistance and either seed treated with triadimenol or untreated were planted at Kinston and Plymouth, NC, during the fall of 1989 and 1990. Plots received foliar fungicide applications at different times during the two growing seasons to determine how cultivar, seed treatment, and time of foliar fungicide application affected development and severity of powdery mildew and leaf rust, yield components, and yield. The extent of mildew and leaf rust and their impact on yield components and yield varied between environments. At Kinston, where both powdery mildew and leaf rust were severe during 1989–1990 and 1990–1991, mildew positively influenced tiller number, and rust influenced 500-kernel weight and number of seeds per head. Powdery mildew was present only at low levels at Plymouth; leaf rust reduced 500-kernel weight and yield. Seed treatment reduced the extent of powdery mildew in all environments and reduced leaf rust at Kinston during 1989–1990 and at Plymouth during 1990–1991. When seed was treated with triadimenol, the optimum time of foliar fungicide application for maximum yield response was delayed in six of nine cultivar × environment combinations.

Powdery mildew and leaf rust usually occur yearly in wheat-growing areas of North Carolina and the southeastern United States, but the diseases differ in their time of onset and peak severity. Powdery mildew, caused by *Blumeria graminis* (DC.) E.O. Speer f. sp. *tritici* Em. Marchal (=*Erysiphe graminis* DC. f. sp. *tritici* Em. Marchal), is present on wheat (*Triticum aestivum* L.) during the fall and winter at low levels, and levels increase during early spring before high temperatures restrict the ability of *B. g. tritici* to grow and sporulate (1,6). At the same time that temperatures increase and powdery mildew severities decrease, severity of leaf rust, caused by *Puccinia recondita* Roberge ex Desmaz. f. sp. *tritici*, increases (1). Although leaf rust infection occurs early, epidemics are delayed in the Southeast until temperatures rise in late spring (12).

Early infection by powdery mildew and subsequent infection by leaf rust can cause substantial yield loss (1). Weather and disease intensity influence the magnitude of the total loss (3,6). Control of leaf rust and powdery mildew by seed treatment and foliar fungicide application generally has led to reduced disease and increased yield in the Southeast (1).

The conventional disease-control recommendation is to keep the flag and penultimate leaves disease-free by fungicide application at GS-8 and GS-10 (growth stages) on the Feekes scale (9); however, yield loss can occur from early-season disease (10). Triadimenol seed treatment can control early-season disease, but late-season leaf rust levels are not reduced in southeastern environments (1,10).

Triadimefon, a triazole fungicide that inhibits ergosterol biosynthesis, successfully reduced powdery mildew on susceptible cultivars in trials in North Carolina, Ohio, and Bulgaria (1,6, 7,11,14). Yield increases correlated to powdery mildew reductions occurred in North Carolina and Bulgaria (1,10,14). However, yield increases related to mildew reduction occurred during only 1 of 3 yr in Ohio (11).

In 12 trials in Pennsylvania during 1984–1985, leaf rust was reduced by foliar fungicide application of triadimefon and mancozeb (2). Triadimenol seed treatment reduced mildew in all 12 trials but was less effective in reducing leaf rust; reductions in leaf rust did occur in seven of the 12 trials, however. This may be a result of the presence of mildew in Pennsylvania during the fall, whereas leaf rust was present during the spring only. In additional trials in Pennsylvania during 1985–1986, reductions in leaf rust severity occurred when triadimefon was applied two and three times or with a single foliar spray at GS-7 or GS-9, respectively. Greater disease reductions and yield increases in Pennsylvania (2) have resulted from using combinations of seed treatment to control early-season powdery mildew and subsequent foliar fungicide application to control leaf rust.

Although treatment of seed is known to reduce early-season disease and increase yield in some environments, its influence on timing of late-season foliar fungicide application has not been studied. The objective of this study was to examine the effect of seed treatment on onset and extent of powdery mildew and leaf rust and subsequent timing of foliar fungicide sprays to maximize net yield.

MATERIALS AND METHODS

Plot establishment. Experiments were conducted during the 1989–1990 and 1990–1991 growing seasons at the Tidewater Research Station near Plymouth, NC, and at the Lower Coastal Plain Tobacco Research Station-Cunningham Farm near Kinston, NC. The factorial treatment designs were arranged in randomized complete blocks with five replications within each environment (location and year). Factors included three cultivars, two seed treatments, and six foliar fungicide applications.

Wheat was planted mechanically with a small-plot grain drill. Plots were 3.35 × 2.4 m, consisting of 14 rows spaced 0.24 m apart. Plots were bordered on two sides with 1.67-m-wide plots of barley (*Hordeum vulgare* L. 'Anson') and with 1.2-m alleys on each end to reduce interplot interference.

Wheat was planted at Kinston on 17 and 31 October 1989 and 1990, respectively, and at Plymouth on 2 and 5 November 1989 and 1990, respectively. Preplant fertilizer was applied at Kinston at a rate of 336 kg/ha of 10-10-20 (N-P-K) during 1989 and 370 kg/ha of 10-10-20 (N-P-K) during 1990 and at Plymouth at a rate of 303 kg/ha of 10-15-30 (N-P-K) during 1989 and 336 kg/ha of 7-29-21 (N-P-K) during 1990. On 21 February 1990,

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112 kg/ha of nitrogen was applied as ammonium nitrate at both locations. On 13 February 1991, 112 kg/ha of nitrogen was applied as ammonium nitrate at Kinston. Ammonium nitrate (104 kg/ha) was applied at Plymouth on 25 February 1991.

Three wheat cultivars that are widely grown in North Carolina and that differ in their susceptibility to powdery mildew and leaf rust were planted. Coker 983 was moderately resistant to powdery mildew and moderately susceptible to leaf rust, Florida 302 was moderately resistant to both powdery mildew and leaf rust, and Saluda was susceptible to both powdery mildew and leaf rust (1,10).

Fungicide application. Seed for one-half of the plots was treated with triadimenol (Baytan 30F, Mobay Chemical Co., Kansas City, MO) at a rate of 2.59 g a.i./kg of seed. The remaining seed was not treated. Foliar fungicides triadimefon (Bayleton 50 DF, Mobay Chemical Co.) and mancozeb (Manzate 200 DF, E. I. Du Pont de Nemours & Co., Wilmington, DE) were applied during 1989–1990 and 1990–1991 at target rates of 68.04 g a.i. and 1.64 kg a.i./ha of formulation, respectively. Fungicides were applied with a CO_2 pressurized backpack sprayer delivering a volume of 234 L/ha at 240 kPa. The timings of foliar fungicide applications at both locations during both seasons were based on growth stage (Feekes scale) (Table 1).

Disease assessment. Incidence and severity of both powdery mildew and leaf rust was assessed on whole plots before the emergence of the flag leaf. Assessments were made on 11 January and 8 and 27 February at Kinston and on 12 January, 9 and 28 February, and 22 March at Plymouth during 1990. Assessments were made by estimating the number of plants infected and by estimating the approximate percentage of infected leaf area on each plant in 0.5 m of row in two to three locations within each plot. After flag leaf emergence, leaf rust severity, as the percentage of leaf tissue covered with pustules, was assessed on the flag and penultimate leaves of 10 randomly selected tillers per plot weekly (on 21 March, 4, 13, 18, and 25 April and 2 May at Kinston and on 5, 12, 20, and 26 April and 8 May at Plymouth) during 1990. Powdery mildew severity was assessed on the same 10 tillers by estimating the percentage of leaf area covered with pustules (on 21 March and 13 and 25 April at Kinston and on 5 and 20 April and 8 May at Plymouth). During 1991, whole-plot assessments of powdery mildew and leaf rust were made on 6 February and 20 March at Kinston and on 13 February and 6 and 21 March at Plymouth. Assessments on the flag and penultimate leaves of 10 randomly selected tillers per plot were made on 4, 9, 16, and 26 April and 8 May at Kinston and on 5, 12, and 17 April and 2 and 9 May at Plymouth.

Prior to harvest, the number of tillers per meter of row were counted, and 10 randomly selected heads per plot were collected to determine the number of kernels per head. Plants were harvested from a 1.7- × 2.4-m area of each plot with a combine. Total grain weight (kilograms per hectare) and 500-kernel weight (grams) were measured. Grain weight was adjusted to 13.5% moisture.

Data analyses. To determine treatment effects, analyses of variance were performed on the log of the areas under the powdery mildew progress curve (lAUMPC), the log of the areas under the leaf rust progress curve (lAURPC), yield (kilograms per hectare), and yield components (seeds per 10 heads, 500-kernel weight [grams], and tillers per meter of row). To allow simultaneous effects, general least squares analysis was performed for a system of equations. Covariance was estimated for variables and was used to produce regression analyses of the same equations (5).

TABLE 1. Growth stages (Feekes scale) of winter wheat at time of fungicide applications at Kinston and Plymouth, NC, during 1989–1990 and 1990–1991

Location	Season	Early	Mid-early	Mid-late	Late	Early + late
Kinston	1989–1990	8.0	10.1	10.5	11.0	8.0 and 11.0
	1990–1991	7.0	8.0	10.0	10.52	7.0 and 10.52
Plymouth	1989–1990	8.0	9.0	10.2	10.53	6.0 and 10.53
	1990–1991	7.0	8.0	10.2	10.52	7.0 and 10.52

In the models developed, yield, seeds per 10 heads, 500-kernel weight, tillers per meter of row, lAUMPC, and lAURPC were defined as endogenous variables whose values were determined, in part, by other variables in the system. Blocks, treatments, and treatment interactions were exogenous variables that affect endogenous variables but that have values determined outside the system (8).

Yield components and total yield were modeled by including all exogenous and endogenous variables that could affect them. Variables other than block and cultivar were individually dropped from the model until all remaining variables were significant ($P \leq 0.10$) (Table 2).

To determine if the optimum time for a fungicide application was influenced by the presence of a seed treatment, growth stage at time of fungicide application was regressed on kilograms of grain per hectare in each environment. Block, seed treatment, cultivar, fungicide application time, and all interactions of these treatments were used as predictors of yield. The growth stage (*GS*) at which the fungicide was applied and a growth stage by growth stage (GS^2) variable were included in the model so the yield response could increase and then decrease as growth stage increased.

The optimum time (growth stage) of fungicide application based on total grain yield (Y_j kg/ha) was calculated by $Y = B_{0i} - 1/5(b_1 + b_2 + b_3 + b_4 + b_5) + B_{1i}(GS) + B_{2i}(GS^2)$ and by taking the derivative to solve for growth stage:

$$\frac{-B_{1i}}{2B_{2i}} = GS$$

in which B_0 = intercept; B_1 and B_2 are regression coefficients; $b_x = rep_x$; and i = 1–6 seed treatment by cultivar combinations.

RESULTS

Environment. The four environments differed in their patterns of powdery mildew and leaf rust epidemics. Powdery mildew was detected on 11 January 1990 and 6 February 1991 at Kinston, where mildew severity peaked on 11 and 26 April 1990 and 1991, respectively, and began to decline by 1 May (Fig. 1). Powdery mildew severity was less at Plymouth than at Kinston during both seasons. Only the cultivar Saluda and Saluda and Florida 302 sustained more than 1% powdery mildew severity at Plymouth by April during 1990 and 1991, respectively. Leaf rust severity was greatest at Plymouth during 1989–1990 and ranged between 15 and 30% on Coker 983 in the other three environments. Tiller numbers varied between environments and were greater at Plymouth than at Kinston during both years (Table 3).

Cultivar. Leaf rust severity in cultivars Saluda and Coker 983 was higher than in Florida 302 at Kinston during 1989–1990 and at Plymouth during 1989–1990 and 1990–1991 (Fig. 1). Yield components also varied by cultivar. Tiller numbers were greatest for cultivar Coker 983 and lowest for cultivar Florida 302 at Plymouth during 1990–1991 (Table 3). Florida 302 had higher kernel weight at Plymouth both years and at Kinston during 1990–1991 than had Coker 983 or Saluda (Table 3). Total grain yield was highest for Florida 302 at Kinston during 1989–1990, for Saluda at Plymouth during 1989–1990, for Florida 302 and Coker 983 at Kinston during 1990–1991, and for Florida 302 at Plymouth during 1990–1991 (Table 3).

Seed treatment. The lAUMPC of Saluda was reduced in wheat grown from treated seed compared to untreated seed at Kinston during both seasons (Table 4). At Kinston during 1989–1990, the lAURPC was less in plots in which seed was treated than in plots in which seed was untreated (Table 4).

Seed treatment affected tiller numbers at Kinston during 1990–1991, where Coker 983 had fewer tillers from treated seed (Table 4). The number of seeds per head was higher in Saluda grown from treated compared to untreated seed at Kinston and Plymouth during 1990–1991; Coker 983 and Florida 302 did not show the same effect (Table 4). Coker 983 and Florida 302 yielded more when grown from treated seed than from untreated seed during 1989–1990 (Table 4). Likewise, at Kinston and Plymouth during 1990–1991, Saluda and Florida 302 yielded more when grown from treated than from untreated seed.

Fungicide. At Kinston during 1989–1990 and 1990–1991, early, mid-early, and early plus late fungicide applications reduced lAUMPC (Table 3). Fungicide timing had similar effects on powdery mildew-susceptible Saluda at Plymouth during 1989–1990, where the lAUMPC was reduced after fungicide application before GS-10.2 (early or mid-early) but not when applied at GS-10.2 (mid-late) and 10.53 (late) (Table 3).

TABLE 2. Three-stage least squares model-parameter estimates of the effect of the log of the area under the powdery mildew (lAUMPC) and leaf rust progress curves (lAURPC) on yield components and yield in four environments in North Carolina

Yield components	Kinston 1989–1990		Kinston 1990–1991		Plymouth 1989–1990		Plymouth 1990–1991	
Yield (kg/ha)								
Intercept	−0.015	±0.070	−0.017	±0.060	0.005	±0.072	0.015	±0.068
Blocks	0.284	±0.142	−0.988	±0.147	0.444	±0.148	−0.823	±0.198
C1[z]	−0.612	±0.104	1.338	±0.264	0.219	±0.102	−0.491	±0.235
C2	−0.193	±0.010	1.996	±0.198	1.592	±0.270	0.018	±0.394
Tillers/m of row	...	...	...	...	...	...	1.044	±0.348
Seeds/10 heads	−0.279	±0.160	1.756	±0.231	...	...	...	...
500-kernel weight (g)	...	...	1.391	±0.222	1.765	±0.254	0.850	±0.296
Tillers/m of row								
Intercept	−0.004	±0.059	−0.003	±0.044	0.004	±0.065	0.012	±0.045
Blocks	−0.793	±0.119	−0.772	±0.089	1.198	±0.131	1.001	±0.090
C1	...	...	0.134	±0.062	−0.188	±0.093	0.234	±0.063
C2	...	...	0.495	±0.063	−0.025	±0.092	0.713	±0.063
Seeds/10 heads								
Intercept	0.021	±0.091	0.007	±0.039	0.008	±0.039	0.014	±0.049
Blocks	−0.194	±0.185	0.957	±0.146	−0.452	±0.094	0.459	±0.116
C1	−1.515	±0.284	−0.681	±0.079	−0.677	±0.062	−0.265	±0.087
C2	−0.876	±0.219	−1.037	±0.113	−0.505	±0.055	−0.463	±0.178
Tillers/m of row	...	...	0.831	±0.182	0.319	±0.155	−0.428	±0.231
lAUMPC	...	...	−0.155	±0.056	...	...	...	...
lAURPC	1.816	±0.347	...	...	...	...	...	...
500-kernel weight								
Intercept	0.011	±0.092	0.018	±0.043	−0.003	±0.052	0.022	±0.040
Blocks	0.298	±0.315	0.375	±0.146	−0.574	±0.184	−0.007	±0.082
C1	−0.632	±0.306	−0.721	±0.067	−0.432	±0.286	−0.438	±0.063
C2	−0.239	±0.223	−0.300	±0.133	−1.190	±0.265	−0.626	±0.057
Tillers/m of row	1.243	±0.365	0.568	±0.172	0.626	±0.276	...	...
Seeds/10 heads	...	...	...	...	−0.849	±0.398	...	...
lAURPC	0.734	±0.374	−0.717	±0.129	−0.287	±0.122	−0.319	±0.073

[z] $C_x = (C_x - C_3)$, in which $x = 1$ (Saluda) or 2 (Coker 983), and C_3 = Florida 302.

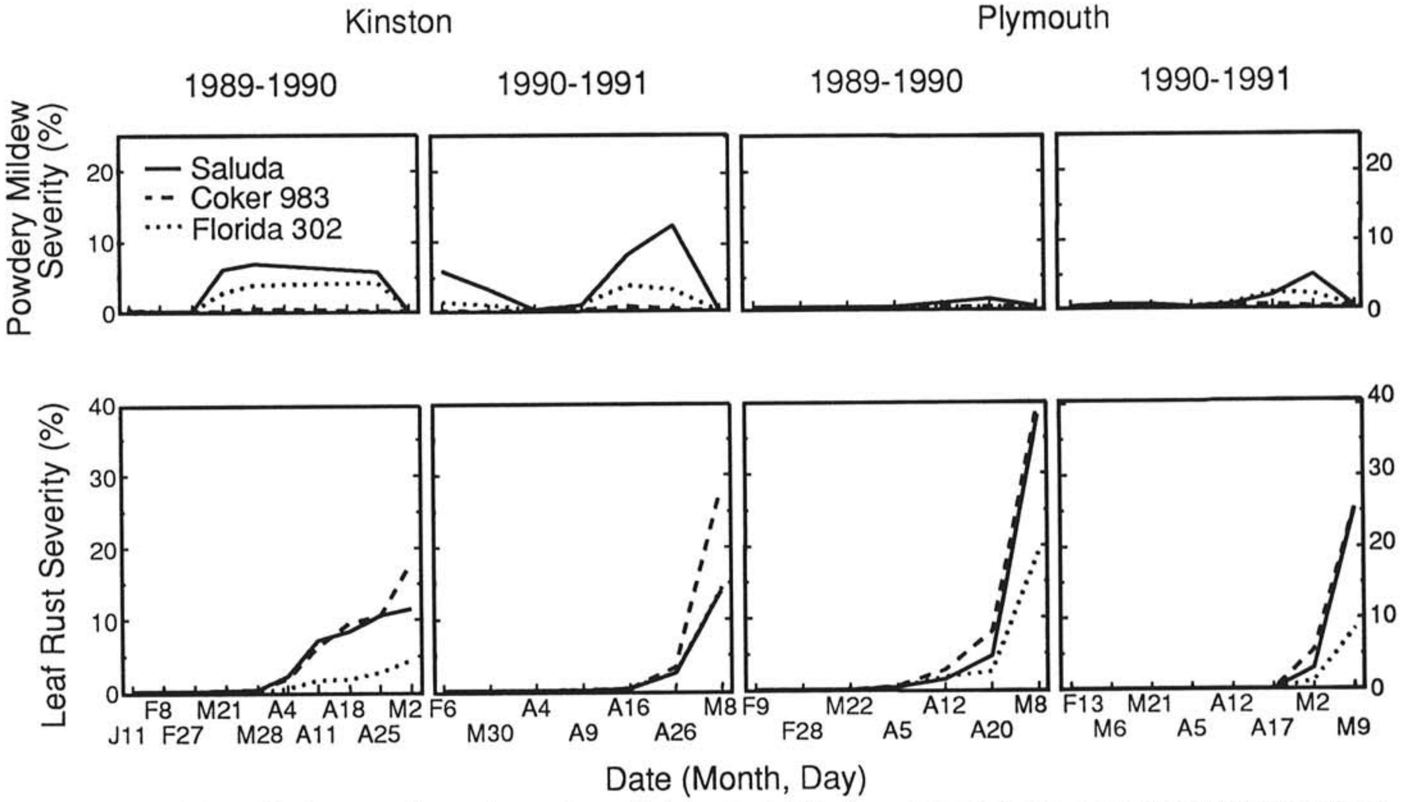

Fig. 1. Powdery mildew and leaf rust severities on three cultivars of winter wheat at Kinston and Plymouth, NC, during 1989–1990 and 1990–1991.

TABLE 3. Mean yield (kilograms per hectare), mean yield components, and mean area under the powdery mildew (lAUMPC) and leaf rust progress curves (lAURPC) of three cultivars of winter wheat treated with six foliar fungicide applications[z] at Kinston and Plymouth, NC, during 1989–1990 and 1990–1991

	Saluda						Coker 983						Florida 302						
Location	None	Early	Mid-early	Mid-late	Late	Early + late	None	Early	Mid-early	Mid-late	Late	Early + late	None	Early	Mid-early	Mid-late	late	Early + late	St
Kinston 1989–1990																			
Tillers/m of row	75.1	84.7	72.6	83.5	81.7	79.2	75.0	75.6	79.4	73.3	77.5	86.9	76.2	85.0	78.7	79.3	75.9	70.6	4.4
Seeds/10 heads	371.9	391.1	358.0	397.8	363.7	350.9	440.1	383.8	356.7	381.2	405.2	378.7	441.6	403.5	398.4	373.3	399.5	351.8	21.8
500-kernel weight (g)	17.4	18.8	17.8	17.9	17.5	17.5	18.4	17.4	17.3	17.7	18.6	17.3	18.3	17.9	17.8	17.8	17.8	17.6	0.5
Yield (kg/ha)	3,572	4,089	3,662	3,699	3,665	4,261	3,561	4,324	4,061	3,703	4,152	4,640	4,248	4,937	4,595	4,683	4,912	5,355	143
lAUMPC	4.95	4.38	4.70	4.79	4.79	4.27	0.90	0.75	0.62	0.81	0.85	0.85	4.63	3.61	4.16	4.22	4.24	3.93	0.16
lAURPC	5.46	4.97	5.60	5.24	5.41	4.69	5.39	4.76	4.91	4.99	5.22	4.48	3.27	2.24	2.53	2.74	2.77	1.86	0.19
Plymouth 1989–1990																			
Tillers/m of row	107.6	87.3	113.0	99.1	110.3	102.2	99.4	107.3	113.3	103.2	108.0	99.9	108.5	119.8	107.4	107.0	114.8	110.6	8.0
Seeds/10 heads	346.5	320.0	319.1	335.7	347.4	332.1	348.4	352.0	354.7	357.9	338.9	357.2	493.4	483.2	436.1	469.8	475.5	465.9	10.7
500-kernel weight (g)	17.3	17.8	18.1	17.9	17.9	18.3	15.8	16.4	16.6	16.5	16.2	16.5	18.5	18.7	19.8	19.1	19.4	19.8	0.3
Yield (kg/ha)	4,598	4,457	4,863	4,849	4,788	5,176	3,956	4,514	4,700	4,488	4,351	4,577	4,071	4,464	4,651	4,468	4,389	4,846	185
lAUMPC	1.54	0.36	0.72	1.59	1.54	0.06	0.00	0.05	0.06	0.00	0.00	0.00	0.06	0.13	0.06	0.16	0.09	0.03	0.13
lAURPC	5.76	5.47	5.15	5.22	5.22	4.50	5.96	5.65	5.45	5.63	5.39	5.02	5.26	4.72	4.60	4.82	4.34	3.46	0.12
Kinston 1990–1991																			
Tillers/m of row	80.2	81.6	84.5	80.9	79.0	84.2	86.4	94.2	88.2	90.4	86.3	80.0	62.6	67.1	67.2	65.4	65.4	66.5	3.6
Seeds/10 heads	358.0	368.2	384.6	361.0	363.8	379.0	384.6	389.3	379.0	364.4	385.0	377.2	483.8	467.5	476.3	473.2	479.1	464.4	8.2
500-kernel weight (g)	15.1	15.4	16.0	15.7	15.6	16.1	15.4	15.8	16.4	16.3	15.8	16.3	18.5	19.4	19.9	19.8	19.6	19.9	0.2
Yield (kg/ha)	3,856	4,286	4,393	4,093	4,032	4,481	4,720	4,923	5,037	4,917	4,791	5,082	4,580	4,985	5,259	5,009	5,126	5,245	104
lAUMPC	4.93	4.42	4.21	4.44	5.03	4.37	1.60	1.58	1.64	1.69	1.82	1.11	3.71	2.57	3.19	3.93	3.63	2.51	0.21
lAURPC	4.77	4.62	4.66	4.68	4.63	4.25	5.26	5.12	4.74	5.13	4.86	4.63	4.58	4.02	4.08	4.00	3.68	3.51	0.13
Plymouth 1990–1991																			
Tillers/m of row	105.8	119.2	114.1	114.8	109.6	122.5	115.2	127.9	134.4	128.6	122.4	126.7	82.6	73.3	79.4	82.2	77.7	80.2	4.7
Seeds/10 heads	370.3	371.5	348.3	346.7	347.4	362.1	343.5	331.4	334.1	334.1	334.5	331.2	442.7	444.1	441.1	450.4	446.7	432.8	9.8
500-kernel weight (g)	15.2	16.0	15.9	16.2	16.2	16.3	15.2	15.5	16.0	16.0	16.2	16.0	17.9	18.4	18.8	18.4	18.8	19.1	0.2
Yield (kg/ha)	4.708	5,362	5,113	5,046	5,220	5,432	5,252	5,554	5,689	5,501	5,600	5,358	5,316	5,949	5,739	5,687	5,646	6,069	120
lAUMPC	3.86	2.94	2.15	3.33	3.70	2.78	1.19	0.89	1.17	1.55	1.36	1.01	3.37	1.75	0.98	2.48	2.52	1.13	0.26
lAURPC	4.61	4.26	3.89	4.06	3.88	3.43	4.82	3.98	3.26	3.65	4.16	3.38	3.89	3.65	2.97	3.43	3.25	2.54	0.17

[z] Foliar fungicide treatments consisted of 68.05 and 1.64 kg a.i./ha of triadimefon and mancozeb, respectively, applied at or near GS-6–8, early; GS-9–10, mid-early; GS-10.2–10.5, mid-late; GS-10.53–11.0, late; and GS-6–8 and GS-10.53–11.0, full, growth stages.

The effect of fungicide on the lAUMPC at Plymouth during 1990–1991 depended on seed treatment (Table 5). lAUMPC was reduced in plants grown from triadimenol treated seed if fungicide was applied at GS-7, GS-8, GS-10.2, or GS-10.52 alone. In the same environment, however, the lAUMPC of plants grown from untreated seed was not reduced when fungicide was applied after GS-8.

In all environments, lAURPC was reduced most by early plus late fungicide applications (Table 3). The single application that reduced lAURPC varied between environments. At Kinston during 1989–1990, the early (GS-8) application reduced lAURPC as much as the early plus late application. At Plymouth during 1989–1990 and at Kinston during 1990–1991, the late application (after GS-8) was often more effective. For example, lAURPC of Coker 983 was reduced when fungicide was applied mid-early and late (Table 3). At Plymouth during 1990–1991, all foliar fungicide applications resulted in lower lAURPC except for Saluda and Florida 302 grown from untreated seed with an early fungicide application (Table 3).

Early and mid-early fungicide application (GS-8 and GS-10) increased tiller numbers in plots grown from untreated seed compared to plots that received no fungicide application at Kinston during 1989–1990 ($P < 0.10$). In plots with treated seed, fungicide applications at GS-8, GS-10.5, and GS-11 increased tiller numbers compared to plots that received no fungicide application. The number of seeds per head was decreased by some foliar fungicide applications in all environments (e.g., Florida 302 and Coker 983 at Kinston during 1989–1990) (Table 3). None of the treatments influenced the weight of 500 kernels (grams) at Kinston during 1989–1990 (Table 5). Kernel weight varied across cultivar and environment, and all fungicide applications increased kernel weight at Kinston and Plymouth during 1990–1991 (Tables 3 and 5). All foliar fungicide applications increased yield at all locations compared to unsprayed plots (Tables 3 and 5).

Variation in both lAUMPC and lAURPC resulted from variation in exogenous variables or variation in all exogenous interaction variables, except those containing seed-treatment by cultivar interactions (when tests comparing the models indicated the smaller model adequately described [$P \leq 0.05$] disease level). When the regression to determine the optimum time for fungicide application was performed, a smaller model that did not include any cultivar by seed-treatment interactions also predicted the yield

TABLE 4. Difference in yield components, yield, and powdery mildew and leaf rust progress curves (lAUMPC and lAURPC, respectively) of three cultivars of winter wheat at Kinston and Plymouth, NC, during 1989–1990 and 1990–1991 resulting from seed treatment with triadimenol

Location	Saluda	Coker 983	Florida 302	SE
Kinston 1989–1990				
Tillers/m of row	−5.1	2.9	−1.9	2.5
Seeds/10 heads	27.8	−26.5	0.6	12.6
500-kernel weight (g)	0.1	−0.1	0.1	0.3
Yield (kg/ha)	1,044.0	424.0	311.0	82.0
lAUMPC	−1.4	−0.8	−1.0	0.1
lAURPC	−0.2	−0.7	−0.4	0.1
Plymouth 1989–1990				
Tillers/m of row	0.3	1.0	9.5	4.7
Seeds/10 heads	6.8	10.4	0.3	6.3
500-kernel weight (g)	0.1	0.3	0.3	0.2
Yield (kg/ha)	124.0	494.0	351.0	111.0
lAUMPC	−0.8	0.0	−0.0	0.1
lAURPC	−0.0	−0.1	−0.2	0.1
Kinston 1990–1991				
Tillers/m of row	4.3	−6.2	2.2	2.1
Seeds/10 heads	33.8	−1.3	6.3	4.8
500-kernel weight (g)	0.1	0.0	0.6	0.1
Yield (kg/ha)	566.0	−62.0	294.0	61.0
lAUMPC	−1.7	−1.2	−2.2	0.1
lAURPC	0.1	−0.1	−0.2	0.1
Plymouth 1990–1991				
Tillers/m of row	2.1	−2.5	3.1	2.8
Seeds/10 heads	18.9	9.6	5.3	5.8
500-kernel weight (g)	0.1	0.0	0.4	0.1
Yield (kg/ha)	198.0	−139.0	305.0	69.0
lAUMPC	−1.0	−0.8	−0.5	0.2
lAURPC	−0.1	−0.5	−0.1	0.1

TABLE 5. Analysis of variance (Type III, sum of squares) of the natural log area under the powdery mildew (lAUMPC) and leaf rust progress curves (lAURPC) and yield data from three wheat cultivars grown with or without triadimenol seed treatment and different timings of triadimefon- and mancozeb-fungicide applications near Kinston and Plymouth, NC, during 1989–1990 and 1990–1991

		Mean squares					
Factor	df	lAUMPC	lAURPC	Tillers/ m of row	Seeds/ 10 heads	500-kernel weight (g)	Yield (kg/ha)
Kinston 1989–1990							
Replicate	4	0.6	0.4	9,133**	2,536	2.6	$1.1 \times 10^{6\,**}$
Cultivar (C)	2	261.9$^{**\,z}$	126.9**	59	8,627	0.1	$1.5 \times 10^{7\,**}$
Seed treatment (ST)	1	52.6**	9.1**	86	18	0.1	$1.6 \times 10^{7\,**}$
Fungicide timing (F)	5	1.4**	4.0**	137	11,471^{+}	0.4	$3.4 \times 10^{6\,**}$
C × ST	2	1.3	1.1	238	11,047*	2.4	$2.3 \times 10^{6\,*}$
C × F	10	0.3	0.3	278	4,554	1.6	1.8×10^{5}
ST × F	5	0.0	0.3	467^{+}	4,586	0.3	2.1×10^{5}
C × ST × F	10	0.1	0.2	357	4,309	2.3	2.2×10^{5}
Plymouth 1989–1990							
Replicate	4	0.2	0.2	10,637**	3,034*	3.0**	$5.2 \times 10^{6\,**}$
Cultivar (C)	2	16.7**	7.3**	1,058	331,735**	121.3**	$2.2 \times 10^{6\,*}$
Seed treatment (ST)	1	3.5**	0.2	590	1,518	2.6*	$4.6 \times 10^{6\,**}$
Fungicide timing (F)	5	1.6**	2.6**	380	2,136^{+}	4.0**	$1.5 \times 10^{6\,**}$
C × ST	2	3.3**	0.1	393	402	0.1	5.0×10^{5}
C × F	10	1.5**	0.2	514	1,843	0.5	1.9×10^{5}
ST × F	5	0.3	0.2	507	372	0.7	1.8×10^{5}
C × ST × F	10	0.2	0.1	732	537	0.5	5.0×10^{5}
Kinston 1990–1991							
Replicate	4	0.5	0.3	9,198**	18,797**	0.6	$5.5 \times 10^{5\,**}$
Cultivar (C)	2	134.7**	14.6**	7,713**	200,361**	270.0**	$1.2 \times 10^{7\,**}$
Seed treatment (ST)	1	127.4**	0.2	1	7,596*	2.8*	$3.5 \times 10^{6\,**}$
Fungicide timing (F)	5	4.1**	1.8**	107	613	5.1**	$1.1 \times 10^{6\,**}$
C × ST	2	3.5	0.2	466*	5,125**	0.8	$1.7 \times 10^{6\,*}$
C × F	10	0.9	0.3^{+}	99	895	0.3	9.1×10^{4}
ST × F	5	0.3	0.1	139	779	0.4	2.3×10^{4}
C × ST × F	10	0.3	0.1	70	848	0.3	7.8×10^{4}
Plymouth 1990–1991							
Replicate	4	1.8*	2.1**	10,556**	6,857	1.0*	5.8×10^{4}
Cultivar (C)	2	104.2**	8.5**	34,964**	192,311**	140.8**	$5.2 \times 10^{6\,**}$
Seed treatment (ST)	1	23.4**	1.4*	38	5,626	1.6	$6.6 \times 10^{5\,+}$
Fungicide timing (F)	5	9.2**	5.8**	366	482	4.1**	$1.2 \times 10^{6\,**}$
C × ST	2	1.2	0.8	133	679	0.5	$8.0 \times 10^{5\,*}$
C × F	10	1.7*	0.4	259	689	0.3	2.3×10^{5}
ST × F	5	1.9**	0.3	291	1,186	0.9	4.0×10^{5}
C × ST × F	10	0.9	0.7*	123	194	0.5	5.1×10^{4}

[z] *, **, and + indicate significant treatment effects at the 0.05, 0.01, and 0.10 levels of probability, respectively.

TABLE 6. Predicted optimum growth stage (Feekes scale) of fungicide application (triadimefon plus mancozeb) for maximizing yield from three cultivars of winter wheat, as influenced by seed treatment in three environments in North Carolina, based on a quadratic model of actual fungicide-application stages and total grain yields

Cultivar	Seed treatment	Kinston 1990–1991	Plymouth 1989–1990	Plymouth 1990–1991
Saluda	None	7.8	10.2	4.5
	Triadimenol	8.4	9.9	8.0
Coker 983	None	8.6	8.9	8.4
	Triadimenol	8.3	9.4	8.7
Florida 302	None	8.8	8.8	2.9
	Triadimenol	8.7	9.5	7.8

(kilograms per hectare) ($P \leq 0.05$) at Plymouth during both seasons.

The number of seeds per 10 heads was negatively associated with yield at Kinston during 1989–1990 (Table 5). Seeds per 10 heads and 500-kernel weight were positively associated with lAURPC. At Plymouth during 1989–1990 and 1990–1991, 500-kernel weight was positively related to yield. The number of tillers per meter of row was positively associated with yield at Plymouth during 1990–1991. Yield was indirectly influenced by lAURPC, through its negative relationship with 500-kernel weight at Plymouth during both seasons. Seeds per 10 heads and 500-kernel weight were positively associated with yield at Kinston during 1990–1991. Tillers per meter of row influenced yield indirectly through its positive effect on seeds per 10 heads and 500-kernel weight. Seeds per 10 heads were reduced by powdery mildew, and 500-kernel weight was reduced by leaf rust severity.

The estimated optimum growth stage for fungicide application for maximizing yield varied from GS-2.9 (Florida 302 at Plymouth, 1990–1991) to GS-10.2 (Saluda at Plymouth, 1989–1990) (Table 6). At Kinston during 1989–1990, GS^2 was not significant, and the optimum time of fungicide application could not be determined. At Kinston during 1990–1991, the optimum time of fungicide application was delayed because of the seed treatment for the cultivar Saluda, which is susceptible to powdery mildew, but not for Coker 983 or Florida 302, which were moderately resistant. At Plymouth, where powdery mildew was present at low levels and leaf rust was present at higher levels late in the season, the estimated optimum time of fungicide application for maximum yield generally was later when seed had been treated with triadimenol (Table 6).

DISCUSSION

The total area planted to wheat in the southeastern United States has increased over the last 20 yr. Powdery mildew and leaf rust can result in large yield losses, but economics dictate minimal use of fungicide. Triadimenol seed treatment represents a new approach to chemical disease control and is effective at reducing fall epidemics of powdery mildew, leaf rust, and Septoria blotch. To reduce the need for foliar fungicide applications, use of a resistant cultivar or a susceptible cultivar treated with triadimenol is often recommended.

The effect of triadimenol seed treatment on yield of resistant cultivars and leaf rust severities at these locations previously was thought to be minimal. However, yield was higher in triadimenol treated plots than in untreated plots of Coker 983 at both Kinston and Plymouth, 1989–1990, where powdery mildew and leaf rust onset were early. Thus, moderately resistant cultivars as well as susceptible cultivars may benefit from triadimenol seed treatment in years when disease onset is early. Triadimenol seed treatment in this study may have resulted in reduced powdery mildew severity, which resulted in reduced tiller initiation and less competition between unproductive tillers. In recent studies (6), yield increases were shown with triadimenol seed treatment and were the result, in part, of a delay or reduction in tiller initiation and a subsequently higher survival rate of existing tillers. Because triadimenol affects growth-regulator activity, it may have reduced or delayed tiller formation in some of these environments, again reducing competition between tillers (6).

We observed a larger yield response to triadimenol seed treatment than has been reported previously in North Carolina (10). This may have been the result of closer row spacing and early onset of powdery mildew and leaf rust during 1989–1990 than have been found in other environments. We also observed reductions in leaf rust severities in triadimenol-treated plots at Kinston during 1989-1990 and at Plymouth during 1990-1991, reductions that previously had not been reported in our environment. Leaf rust primarily occurs late in the season and rust-infected leaves below the flag and penultimate leaves contribute relatively little to yield (13). At Kinston, 1989–1990, this reduction in leaf rust may have been the result of early disease onset and did not result in increased yield. Although reductions in leaf rust resulting from triadimenol have only been observed in some environments in the Southeast, use of larger plot sizes in experiments may reduce interplot interference, resulting in more definitive information.

In many statistical analyses, one-way causality is assumed, but some economic models allow examination of interrelationships among variables and simultaneous affects (8). Disease-yield loss relationships may be appropriately modeled in this way because they contain simultaneous effects of treatments on disease level and of disease level on yield components and total yield. Because of compensation, yield components can influence each other.

Relationships between yield components varied between environments. Tiller number was positively associated with kernel weight in three environments and with seeds per head in two environments. Formation of vigorous tillers earlier in the season (because of lower disease levels or other environmental factors) may result in a better seed set and larger kernel size. Compensation for low tiller numbers by increasing numbers of seeds per head occurred at Plymouth during 1990–1991. This was the location where the highest number of tillers remained at harvest, indicating that only when large numbers of tillers survive will competition between tillers limit kernel production.

Because triadimenol affects growth-regulator activity (6), seed treatment was included in the models developed in this study to predict tillers per meter of row. In the four environments studied, seed treatment never directly influenced tiller number at harvest and only influenced yield indirectly through its effect on powdery mildew. Similar tiller numbers in plots with varying levels of disease must be interpreted cautiously, however, because more tillers may be initiated in response to early-season mildew but subsequently die, utilizing carbohydrate reserves of the plant.

When plants were grown from seed treated with triadimenol, fungicide application usually resulted in higher yields in Saluda and Florida 302. In addition, when seed was treated with triadimenol, the estimated optimum growth stage for fungicide application was delayed in six of nine cultivar × environment combinations (Table 6). This was true for Coker 983 in two of the three environments, even though this cultivar was moderately resistant to powdery mildew. The estimated optimal growth stage for fungicide application for maximum-yield response usually was delayed at Plymouth, where powdery mildew was low. In environments in which mildew is severe, early fungicide application may be necessary for maximum-yield response, whether seed is treated with triadimenol or left untreated. Although seed treatment may not delay the time of optimal fungicide application under these conditions, it did result in significantly higher yields at Kinston during both seasons, except on Coker 983 during 1990–1991. Reductions in powdery mildew and increases in yield of susceptible cultivars treated with triadimenol has been previously reported (1,2,6,11). Based on these studies, yield increases also may occur when moderately resistant cultivars are treated with triadimenol. Finally, the timing of foliar fungicide application may be delayed when wheat seed has been treated with triadimenol; resulting foliar fungicide applications are more likely to reduce late-season diseases, such as leaf rust and Septoria leaf and glume blotch.

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