e-**X**tra*

International Fungicide Efficacy Trials for the Management of Soybean Rust

M. R. Miles, United States Department of Agriculture–Agricultural Research Service (USDA-ARS), National Soybean Research Center, Urbana, IL 61801; **C. Levy,** Commercial Farmers Union of Zimbabwe, Harare, Zimbabwe; **W. Morel,** Ministerio de Agricultura y Ganadería, Centro Regional de Investigación Agrícola (CRIA), Capitán Miranda, Itapúa, Paraguay; **T. Mueller** and **T. Steinlage,** Department of Crop Sciences, University of Illinois, Urbana 61801; **N. van Rij,** KwaZulu-Natal Department of Agriculture and Environmental Affairs, Cedara, KwaZulu-Natal, South Africa; **R. D. Frederick,** USDA-ARS, Foreign Disease-Weed Science Research Unit, Ft. Detrick, MD 21702; and **G. L. Hartman,** USDA-ARS, National Soybean Research Center, Department of Crop Sciences, University of Illinois, Urbana 61801

ABSTRACT

Miles, M. R., Levy, C., Morel, W., Mueller, T., Steinlage, T., van Rij, N., Frederick, R. D., and Hartman, G. L. 2007. International fungicide efficacy trials for the management of soybean rust. Plant Dis. 91:1450-1458.

The efficacy of fungicides in managing soybean rust was evaluated in 12 environments in South America and southern Africa over three growing seasons from 2002 to 2005. There were differences in final soybean rust severity, defoliation, and yield among the treatments at most locations. In locations where soybean rust was not severe, all the fungicides evaluated reduced severity. In locations where soybean rust was severe, applications of triazole and triazole + strobilurin fungicides resulted in lower severity and higher yields compared with other fungicides. The strobilurin fungicides provided the highest yields in many locations; however, severity tended to be higher than that of the triazole fungicides. There also were differences in yield and severity between the trials with two and three applications of several fungicides, with three applications resulting in less severe soybean rust and higher yields. However, the third application of tebuconazole, tetraconazole, and the mixtures containing azoxystrobin and pyraclostrobin was not needed to maintain yield. These fungicides were among the most effective for managing soybean rust and maintaining yield over most locations.

The identification of soybean rust, caused by *Phakopsora pachyrhizi* Syd. & P. Syd., in Paraguay in 2001 (14) and its subsequent spread to over 95% of the soybean production in Brazil through the 2004 growing season (22,23) has heightened the awareness of this disease. The rapid spread of *P. pachyrhizi* and its potential to reduce yields makes this among the most destructive foliar diseases of soybean. Yield losses ranging from 20 to 60% have been reported in Asia, with losses up to 80% reported from experimental plots in Taiwan (7). Yield losses of 40 to 60% were reported in southern Africa, with reports of 100% loss in individual fields (2). During the 2003–04 growing season in Brazil, yield losses were estimated at 10% of the crop, an increase from the 5% yield loss reported for the previous growing season (23).

Soybean rust was identified for the first time in the United States in November 2004 (17). The commercial soybean cultivars available in the United States are susceptible to soybean rust, and incorporation of resistance into commercial cultivars is several years away (6). Soybean rust could have a major impact on both total soybean production and production costs in the United States.

The management of soybean rust has been primarily with fungicides (10,15, 19,20). Early research from Asia indicated that mancozeb was effective in reducing disease severity and providing some yield protection when compared with unprotected plots (10,19,20). Other compounds available at the time were compared with mancozeb and were effective, but results varied by test (1,19,20). Fungicide trials in India (15) and southern Africa (9) identified several triazole compounds that were effective against soybean rust. More recent trials in Africa and South America have identified additional triazoles, tebuconazole and tetraconazole, as well as several strobilurins and strobilurin + triazole mixtures, including azoxystrobin, pyraclostrobin, and trifloxystrobin + propiconazole, that were effective for managing soybean rust (3,11–13,22).

Recent studies from Zimbabwe and South Africa have found that fungicides were most effective when applied during early flowering through grain fill; applications made before flowering did not increase yields (3,9,10). These studies also showed that a single fungicide application was effective in reducing disease and protecting yield; however, the timing of the application was critical. Delaying fungicide application until after the disease was established resulted in significant yield losses (3,9,10).

There is limited information on the efficacy of fungicides that could be used in the United States. The Zimbabwe experiments were conducted with Punch Xtra (flusilazole plus carbendazim), which has not been available to U.S. producers. Several of the fungicides used in South America have formulations that differ from products available in the United States. The objective of these experiments was to obtain information on fungicide efficacy for products that are or could be available to producers in the United States in order to support management guidelines for soybean rust.

MATERIALS AND METHODS

Fungicides were evaluated in the soybean production areas of Paraguay, South Africa, and Zimbabwe during the 2002–03, 2003–04, and 2004–05 growing seasons (Table 1). The fungicides included in the trials differed in each of the three growing seasons (Tables 2, 3, and 4). There also were differences in the treatments evaluated in Paraguay and Zimbabwe within the 2003–04 and 2004–05 growing seasons (Tables 3 and 4). Azoxystrobin + cyproconazole was commercially available in Paraguay but not in Zimbabwe, whereas flusilazole + carbendazim was available in Zimbabwe but not Paraguay. Further differences were inclusion of oxycarboxin and triflumizole in Zimbabwe but not Paraguay and the inclu-

Corresponding author: M. R. Miles
E-mail: mrmiles@uiuc.edu

*The ***e*-X**tra logo stands for "electronic extra" and indicates that three supplemental figures not included in the print edition appear online.

Accepted for publication 18 June 2007.

---

doi:10.1094/PDIS-91-11-1450

sion of the azoxystrobin mixtures in Paraguay but not Zimbabwe in the 2003–04 season.

The experimental design was a split plot with four replications at each location. The main effect was fungicide treatment (products and rates) and the subplot treatments were two or three applications of the main effect treatment. The first application of each subplot treatment was between growth stages (GS) R1 and R2, between first and full bloom (4), with subsequent applications made 20 to 24 days apart. During the 2003–04 growing season, there were three treatments with subplots that differed from the two- and three-application protocol described above (Table 3). The first of these was azoxystrobin + propiconazole as the main effect with subplot treatments of a single application at 180 + 108 g a.i./ha applied at GS R1, compared with three applications at 90 + 54 g a.i./ha applied as described for the three-application protocol. The second treatment was a single application of tetraconazole (Domark 230ME) at 100 g a.i./ha; the subplot treatments were applications at GS R1 or GS R3. The third treatment that differed was trifloxystrobin + propiconazole applied at GS R1 followed by tebuconazole; the subplot treatments were either one or two applications of tebuconazole, and all applications spaced 20 days apart.

Row width and plot lengths varied by location to conform to local planting practices. All locations in Paraguay and South Africa had row widths of 40 cm; in Zimbabwe, row widths were 70 cm in the Gwebi Variety Testing Center (Gwebi) and 90 cm at Rattray Arnold Research Station (RARS). Plot lengths ranged from 6 to 9 m, with the center 5 m harvested at all locations except those in Paraguay in the 2003–04 growing season, where the center 6 m were harvested from plots 9 m in length. All plots were four rows wide, with all four rows treated with fungicide. The center two rows of each plot were used for all evaluations and harvested for yield. There were two to four nontreated rows between plots to act as a buffer between treatments and as spreader rows within the fields. All cultivars were commercially available and local production practices were followed throughout the growing season.

All locations in Paraguay were infested once or twice by placing infected leaves, collected from volunteer soybean plants near each field, in the spreader rows between plots after flowering. The Cedara location in South Africa was infested between the second and third fungicide application, after rust was found in the area. An early-maturing cultivar was planted 14 to 20 days in advance of the experimental cultivar as a border surrounding the test fields in both locations in Zimbabwe to provide additional inoculum.

In Paraguay, fungicides were applied in a single pass with a CO_2-pressurized backpack sprayer equipped with a spray wand with 4 TeeJet TJ8002 nozzles (Spraying Systems Co., Wheaton, IL) spaced 40 cm apart and calibrated to deliver water at 375 liters/ha. In South Africa, fungicides were applied in two passes per plot, with a battery-pressurized backpack sprayer equipped with two Lurmark hollow cone ceramic ATR80 nozzles (Lurmark Limited, Cambridge, UK) spaced 50 cm apart and calibrated to deliver water at 200 liters/ha. In Zimbabwe, fungicides were applied in four passes per plot, with a backpack sprayer pressurized by hand, fitted with a pressure regulator and a single Lurmark F110/1.6/3 flood-jet nozzle, and calibrated to deliver water at 400 liters/ha. In all locations, the application wands were held with nozzles centered over the plant row at a height of 20 to 30 cm above the canopy.

Assessments for soybean rust were made before each fungicide application and at 14- to 24-day intervals after the final application; evaluations continued until defoliation in the control plots interfered with assessment. The severity rating from the latest evaluation was used as the final soybean rust severity. On each date of evaluation, severity was rated as a percentage of leaf area covered with uredinia and associated chlorosis within the canopy. These ratings were either a single assessment encompassing the full canopy or were the mean of assessments from the lower, middle, and upper canopy, each taken at five locations within the plot. The single assessment was obtained by visually evaluating severity on fully developed trifoliates from 5 to 10 plants within the plot. When there were three or more dates with soybean rust present, an area under the disease progress curve (AUDPC) was calculated (18). Defoliation was evaluated visually across the entire plot as percent defoliation.

All plots were hand harvested and mechanically threshed, and seed weights and moistures were obtained. Yields were calculated as kilograms per hectare at 13% moisture. Analysis of variance was performed using JMP statistical software (ver-

Table 1. Country and location of the fungicide efficacy trials within each growing season, with cultivar name, cultivar growth habit and planting date of the field where the experiment was conducted, days after planting to first application (First appl.), first observation of soybean rust (First obsn.), final severity evaluation (Final eval.) and harvest, the mean final soybean rust severity (%) from untreated control plots, and mean yield (Yield) for each location

					Days after planting to					
Season, country	Location name	Cultivar	Growth habit[a]	Planting date	First appl.	First obsn.	Final eval.	Harvest	Severity (%)[b]	Yield (kg/ha)
2002–03										
Paraguay	Romero, Pirapo[c]	Conquista	D	11/20/2002	58	58	128	136	27	1,616
Paraguay	Sato, Pirapo[c]	Nidera 9000	I	12/17/2002	73	73	127	145	28	1,870
Paraguay	Yasu, Pirapo[c]	Nidera 7636	D	11/7/2002	63	63	114	142	26	2,319
2003–04										
Paraguay	Sato-1, Pirapo[c]	Nidera 7500	D	2/5/2004	59	59	112	118	15	1,130
Paraguay	Sato-2, Pirapo[c]	Nidera 7500	D	2/7/2004	59	59	112	116	27	1,015
Paraguay	Yomo, Pirapo[c]	Mercedes 70	D	11/1/2003	88	88	133	113	6	5,656
Zimbabwe	Gwebi[d]	Safari	I	12/11/2003	50	79	121	143	94	3,554
Zimbabwe	RARS[d]	Storm	D	12/16/2003	50	107	114	128	94	3,796
2004–05										
Paraguay	Krauss, Bella Vista[c]	Asgrow 8000	I	12/23/2004	55	121	135	151	82	2,301
South Africa	Cedara, KuaZulu Natal[e]	Prima 2000	I	11/4/2004	69	93	140	157	80	3,565
Zimbabwe	Gwebi[d]	Safari	I	11/26/2004	50	102	117	146	76	4,448
Zimbabwe	RARS[d]	Storm	D	12/17/2004	50	83	97	133	60	3,301

[a] I = indeterminate growth habit and D = determinant growth habit.

[b] Final rust severity was the last severity assessment taken before defoliation of control plots interfered with the evaluation.

[c] All locations in Paraguay were in the soybean production area in the Itapúa District of southern Paraguay, and are identified by the producer's name followed by closest city.

[d] Both locations in Zimbabwe are research stations in the main soybean production area near Harare in central Zimbabwe. Gwebi = Gwebi Variety Testing Center and RARS = Rattray Arnold Research Station.

[e] The location in South Africa was in KwaZulu-Natal, near the Cedara Research Station in the midlands between Pietermartsberg and Durbin.

sion 5.1; SAS Institute Inc., Cary, NC). Students' least significant difference test was used to compare means, where $\alpha = 0.05$. Treatments varied each year and in some cases between countries within a year; therefore, data sets were combined for analysis only when treatments were the same. In the 2004–05 growing season, data from treatments common across locations were used for the cross-location analyses. Because the location–treatment interactions were significant, single location data sets were analyzed for comparison of treatments. Single degree-of-freedom contrasts were used to compare two- and three-application protocol subplots within each treatment using the appropriate error from the analysis of variance.

RESULTS

2002–03 Growing season. Soybean rust was present prior to the first fungicide application at Romero, Sato, and Yasu in Paraguay during the 2002–03 growing season but the disease development was low, with mean final severities of 26 to 28% in the nontreated control (Table 1). AUDPC was not calculated for these locations because soybean rust severity did not differ among treatments until the final assessment. Differences were detected between the mean soybean rust severity of the two- and three-application protocols at Romero and Sato but not at Yasu (Table 2). The mean yields at the three locations were low (Table 1) and there were no differences in yield between the application protocols within each location (Table 2).

Final soybean rust severity at all three locations differed among treatments and all fungicide treatments had less disease than the nontreated control (Table 2). Pyraclostrobin and trifloxystrobin + propiconazole were among the treatments that had low soybean rust severity at all three locations, while flutolanil was among the treatments that consistently had high rust severity. Single degree-of-freedom contrasts identified differences between the two and three applications of two and five treatments at Romero and Yasu, respectively, but in nine treatments at Sato. In each comparison, severity was less with three applications compared with two applications of the same fungicide. There were no treatments where differences between application protocols were identified at all three locations, and only pyraclostrobin had low severity with both protocols at all three locations. There were few differences for yield among the fungicide treatments (Table 2). The only treatment to provide yields that differed from that in the nontreated control was boscalid at the Sato location. There also were no differences in yield between the two and three applications within individual treatments. Final disease severity was not correlated with yield at any of the three locations.

2003–04 Growing season. Soybean rust was present prior to the first fungicide application at Sato-1, Sato-2, and Yomo in Paraguay during the 2003–04 growing season; however, the disease development was low, with final severities of 6 to 27% in the nontreated control (Table 1). In Zimbabwe, soybean rust was first detected 79 and 107 days after planting at Gwebi and RARS, respectively (Table 1). Disease development was high, with a final disease severity of 94% in the nontreated control at both locations (Table 1). Differences were detected between the mean soybean rust severity and mean yields of the two- and three-application protocols at Gwebi and RARS in Zimbabwe, but not at Sato-1, Sato-2, and Yasu in Paraguay (Table 3).

Table 2. Final soybean rust severity and yield of treatments in the fungicide efficacy trials from three locations in Paraguay during the 2002–03 growing season

Active ingredient (product)[c]	Rate (g a.i./ha)	Severity (%)[a]						Yield (kg/ha)[b]		
		Romero		Sato		Yasu		Romero	Sato	Yasu
		2-A	3-A	2-A	3-A	2-A	3-A	Mean	Mean	Mean
Azoxystrobin (Priori 250EC)[d]	109	8	9	4	2	14	12[a]	1,582	1,780	2,230
Azoxystrobin (Priori 250EC)[d]	163	9	8	3	3	6	5	1,648	1,942	2,062
Boscalid (Endura 38WG)[e]	224	10	8	2	6	3	3	1,651	2,071	2,254
Chlorothalonil (Bravonil Ultro 82.5%)[d]	1,683	12	9	7	7	17	12[a]	1,593	2,007	2,164
Chlorothalonil (Echo 720SC)[f]	1,440	8	8	2	4	2	1	1,480	2,021	2,255
Fenbuconazole (Enable 2F)[g]	75	11	10	19	10[a]	1	1	1,662	1,837	2,094
Fenbuconazole (Enable 2F)[g]	100	11	9	12	6[a]	1	1	1,788	1,750	2,404
Flutolanil (Moncut 70)[h]	343	18	13[a]	15	12	17	11[a]	1,521	1,845	2,472
Mancozeb (Dithane 75DF)[g]	2,400	10	10	14	6[a]	14	9[a]	1,658	1,930	2,501
Myclobutanil (Laredo 2EC)[g]	100	10	10	11	5[a]	1	0	1,544	1,628	2,369
Myclobutanil (Systhane 20EW)[g]	100	13	11	8	4	2	1	1,633	1,830	2,303
Propiconazole (Propimax 3.6EC)[g]	120	15	14	16	10[a]	12	7[a]	1,605	1,785	2,251
Propiconazole (Tilt 3.6EC)[d]	126	16	12[a]	13	8[a]	12	13	1,612	1,817	2,316
Pyraclostrobin (Headline 250EC)[e,i]	170	4	4	1	1	2	2	1,529	2,003	2,352
Pyraclostrobin + boscalid (Pristine)[e,i]	170 + 168	11	11	17	12[a]	14	11	1,533	1,793	2,403
Tebuconazole (Folicur 3.6F)[j]	94	12	11	7	4	1	1	1,731	1,926	2,684
Tetraconazole (Eminent 125SL)[f]	100	10	7	17	3[a]	1	0	1,456	1,756	2,409
Trifloxystrobin + propiconazole (Stratego 2.08EC)[i,j]	128	5	8	3	3	2	1	1,717	1,911	2,189
Undeclared (AMS 21619 480SC)[j]	100	11	8	9	3[a]	1	1	1,742	2,028	2,215
Nontreated control	…	29	25	30	25	26	25	1,626	1,741	2,448
Application protocol mean	…	12	10[k]	10	7[k]	7	6	…	…	…
LSD 0.05[l]	…	3	3	5	5	4	4	295	305	515

[a] Significant differences between the means of the two-application (2-A) and three-application (3-A) protocols for each treatment were identified using a single degree of freedom contrast, $P = 0.05$, and indicated with an "a" following the late protocol mean. For each treatment, the first application of both protocols was applied after first flower and subsequent applications spaced 20 to 24 days apart.

[b] The difference between the 2-A and 3-A protocols was not significant, and there were no significant differences between protocols for individual treatments; therefore, data was combined to obtain means for each treatment.

[c] Active ingredient with product name and formulation.

[d] Syngenta Crop Protection, Greensboro, NC.

[e] BASF Ag Products, Research Triangle Park, NC.

[f] Sipcam Agro, Atlanta, GA.

[g] Dow Agricultural Science, Indianapolis, IN.

[h] Nichino America, Wilmington, DE.

[i] A nonionic surfactant (0.125%) was included in the treatment.

[j] Bayer Crop Science, Research Triangle Park, NC.

[k] Difference between means of the application protocols were significant at this location, $P < 0.05$.

[l] Students' least significant difference (LSD), where $P < 0.05$.

The final soybean rust severity differed among treatments at all five locations (Table 3). In Sato-1 and Sato-2, all treatments had less severe soybean rust than the nontreated control. At Yomo, where the soybean rust severity was low, all treatments were similar to the nontreated control. There were 16 treatments at Gwebi and 12 at RARS, where severity was less with three applications than with two applications of the same fungicide. Two products, tebuconazole and tetraconazole (Domark 230ME and Eminent 125SL), resulted in severities of 0% for both the two- and three-application protocols at Gwebi and RARS. When tetraconazole (Domark 230ME) at 100 g a.i./ha was applied once at GS R1 or GS R3, the soybean rust severity was 0%, as were the two and three applications at 85, 100, and 115 g a.i./ha. However, at one location, Gwebi, the GS R1 application had a severity of 69% and was similar to the nontreated control. When a single application of azoxystrobin + propiconazole at 180 + 108 g a.i./ha applied at GS R1 was compared with three applications at 90 + 54 g a.i./ha spaced 20 days apart, the disease severity from the single application was similar to that of the nontreated control, whereas the three applications had lower soybean rust severity at both locations. Final rust severity and AUDPC (*data not presented*) were highly correlated at Gwebi ($r = 0.95$, $P = 0.0001$), RARS ($r = 0.95$, $P = 0.0001$), Sato-1 ($r = 0.92$, $P = 0.0001$), Sato-2 ($r = 0.97$, $P = 0.0001$), and Yomo ($r = 0.37$, $P = 0.0001$).

Yields differed among treatments at all five locations (Table 3). Mean yields were low at both Sato locations, ranging from 713 to 1,263 kg/ha, but were high at Yomo, ranging from 4,609 to 6,489 kg/ha. At Yomo, where disease severity was low, most treatments were similar in yield to the nontreated control; the exceptions included azoxystrobin + propiconazole, myclobutanil at 100 g a.i./ha, pyraclostrobin, and tetraconazole (Domark 230ME) at 115 g a.i./ha with three applications. In Gwebi, where disease severity was high, all treatments provided higher yield than the nontreated control except two applications of azoxystrobin + propiconazole, oxycarboxin, and tetraconazole (Domark 230ME) at 115 g a.i./ha. At RARS, all treatments provided higher yields than the nontreated

Table 3. Final soybean rust severity and yield of treatments in the fungicide efficacy trials in Paraguay and Zimbabwe during the 2003–04 growing season

Active ingredient[c]	Rate (g a.i./ha)	Severity (%)							Yield (kg/ha)							
		Paraguay			Zimbabwe[a]				Paraguay				Zimbabwe[a]			
		Sato-1	Sato-2	Yomo	Gwebi[b]		RARS[b]		Sato-1	Sato-2	Yomo[b]		Gwebi[b]		RARS[b]	
		Mean[c]	Mean[c]	Mean[c]	2-A	3-A	2-A	3-A	Mean[c]	Mean[c]	2-A	3-A	2-A	3-A	2-A	3-A
Azoxystrobin[d]	110	13	40	5	87[e]	37[a]	90	65[a]	1,087	1,002	6,650	6,327	3,556	3,776[m]	3,677	4,088
Azo + cypro[d]	60 + 24	8	16	5	…	…	…	…	1,097	1,172	4,541	4,678	…	…	…	…
Azo + propi[d]	125	11	24	6	90[e]	28[a,m]	82	37[a]	1,095	968	5,096	7,507[a]	3,014	3,330[m]	2,758	3,859[a]
Boscalid[e]	168	22	37	6	88	44	94	94	1,098	854	5,316	6,462[a]	3,555	3,951[a]	3,120	3,404
Chlorothalonil[d]	1,262	24	40	6	88	34[a]	93	88	1,002	911	5,439	6,268	2,910	3,329[a]	3,592	3,977[a]
Chlorothalonil[f]	1,440	28	48	5	69	0[a]	63	0[a]	1,087	875	5,882	6,425	3,440	3,770[a]	3,647	3,980
Flusi + carb[g]	100 + 50	…	…	…	60	0[a]	47	0	…	…	…	…	3,247	3,405	3,873	4,288[a]
Mancozeb[h]	2,400	27	43	6	94	46[a]	94	85	1,090	957	4,330	5,991	3,597	3,665	3,134	3,662[a]
Myclobutanil[h]	100	11	17	7	82	0[a]	60	0[a]	1,079	1,136	5,390	7,073[a]	3,668	3,719	3,766	4,009
Myclobutanil[h]	125	11	16	6	60	0[a]	0	0	1,169	1,168	4,650	4,795	3,363	3,439	4,129	4,016
Oxycarboxin[i]	1,000	…	…	…	87	0[a]	91	56[a]	…	…	…	…	3,160	3,394	3,599	3,901
Propiconazole[h]	120	13	19	8	93	0[a]	88	34[a]	1,263	1,083	4,781	5,884[a]	3,602	3,841	3,899	4,172
Propiconazole[h]	190	13	29	5	91	16[a]	93	46[a]	1,283	981	4,900	4,744	3,741	3,836	3,488	3,661
Propiconazole[d]	126	14	28	5	93	37	76	44[a]	1,206	937	5,304	5,501	3,409	3,956[a]	3,737	3,886
Pyraclostrobin[e,j]	170	15	31	5	88	0[a]	60	0[a]	1,262	1,107	5,614	7,141[a]	3,828	4,466[a]	3,840	4,345[a]
Pyraclo + bosc[e,j]	170 + 168	17	39	5	85	0[a]	61	9[a]	1,248	989	5,773	6,246	3,291	3,807[a]	3,589	4,102[a]
Tebuconazole[l]	100	10	13	5	0	0	0	0	1,147	938	5,386	4,689	3,736	4,038	3,874	4,065
Tetraconazole[k]	85	12	14	6	0	0	0	0	1,186	1,009	5,700	6,719[a]	3,647	4,224[a]	3,936	4,083
Tetraconazole[k]	100	10	16	6	0	0	0	0	1,194	1,146	5,360	5,319	3,418	3,711	3,901	4,170
Tetraconazole[k]	115	10	15	5	0	0	0	0	1,047	1,135	5,536	6,893[a]	3,107	3,658[a]	3,990	4,150
Tetraconazole[f]	100	10	14	5	0	0	0	0	988	1,075	5,040	5,784	3,513	3,619	4,160	4,430
Triflox[j,l] fb tebuc[l]	128 then 94	12	28	5	…	…	…	…	1,127	991	5,504	4,752	…	…	…	…
Triflox + propi[l]	128	11	28	5	…	…	…	…	1,180	1,026	6,477	6,113	…	…	…	…
Triflumizole[i]	350	…	…	…	78	0[a]	91	44[a]	…	…	…	…	3,205	3,381	3,705	3,873
Single application treatments																
Azo + propi R1	180 + 108	13	20	7	94[e]	…	95	…	1,168	1,045	4,899	…	3,708[m]	…	3,750	…
Azo + propi 3-A	90 + 54	13	22	6	…	25[a,m]	…	40[a]	1,032	916	…	5,402[a]	…	4,343[a,m]	…	3,986
Tetracon R1[k]	100	10	18	6	69	…	0	…	1,148	1,055	4,771	…	3,514	…	3,511	…
Tetracon R3[k]	100	10	17	7	…	0[a]	…	0	1,142	1,042	…	5,801[a]	…	3,379	…	4,068[a]
Nontreated control	…	35	58	6	94	94	94	94	1,007	713	5,071	5,555	2,687	2,634	2,608	2,742
Protocol mean	…	…	…	…	66	15[n]	57	31[n]	…	…	5,236	5,906	3,426	3,682	3,637	3,955
LSD 0.05[o]	…	6	6	2	48	48	36	36	193	162	1,290	1,290	512	512	335	335

[a] Gwebi = Gwebi Variety Testing Center and RARS = Rattray Arnold Research Station.

[b] Significant differences between the means of the two-application (2-A) and three-application (3-A) protocols for each treatment were identified using a single degree-of-freedom contrast, $P = 0.05$, and indicated with an "a" following the 3-A mean; … = treatment not included at the location. For each treatment, the first application of both protocols was applied after first flower and subsequent applications spaced 20 to 24 days apart.

[c] The difference between the 2-A and 3-A protocols was not significant; therefore, data were combined to obtain means for each treatment.

[d] Azoxystrobin (Quadris 2.08SC), Azo + cypro = azoxystrobin + cyproconazole (Priori Xtra 280SC), Azo + propi = azoxystrobin + propiconazole (Quilt 200SE), chlorothalonil (Bravo 720 SE), propi = propiconazole (Tilt 3.6EC) from Syngenta Crop Protection, Greensboro, NC. Azo + propi R1 = single application of azoxystrobin + propiconazole (Quilt 200SE) applied at R1 which was compared to three applications (Azo + propi 3-A).

[e] Boscalid (Endura 38 WG), pyraclostrobin (Headline 250EC) and Pyraclo + bosc = pyraclostrobin + boscalid (Pristine) from BASF Ag Products, Research Triangle Park, NC.

[f] Chlorothalonil (Echo 720 SC) and tetraconazole (Eminent 125SL) from Sipcam Agro, Atlanta, GA.

[g] Flusi + carb = flusilazole + carbendazim (Punch Xtra SC) from Dupont Crop Protection, Wilmington, DE.

[h] Mancozeb (Dithane 75DF), myclobutanil (Systhane 20EW) propi = propiconazole (Propimax 3.6EC) from Dow Agricultural Science, Indianapolis, IN.

[i] Oxycarboxin (Plantvax 75WP) and triflumizole (Procure 50WS) from Crompton Corp., Middlebury, CN.

[j] Tebuconazole (Folicur 3.6F) Triflox = trifloxystrobin + propiconazole (Stratego 250EC), Triflox fb tebuc = trifloxystrobin + propiconazole (Stratego 250EC) at R1 followed by tebuconazole (Folicur 3.6F) in subsequent applications from Bayer CropScience, Research Triangle Park, NC.

[k] Tetraconazole (Domark 230ME) from ISAGRO, Milan, Italy. Tetracon R1 = a single application of tetraconazole (Domark 230ME) at R1 and Tetracon R3 was a single application at R3.

[l] A nonionic surfactant (0.125%) was included in the treatment.

[m] Means were from three replications; data were discarded due to uneven field conditions that affected plant development.

[n] Difference between means of the application protocols were significant at this location, $P < 0.05$.

[o] Students' least significant difference (LSD), where $P < 0.05$.

control except for two applications of azoxystrobin + propiconazole. When compared across locations, pyraclostrobin was consistently among the treatments providing the highest yield, whereas boscalid, chlorothalonil (Bravo 720SC and Echo 720SC), mancozeb, oxycarboxin, and triflumizole tended to be among the treatments providing lower yield.

Differences in yield between the two- and three-application protocols were identified in nine, seven, and nine treatments at Gwebi, RARS, and Yomo, respectively; in each comparison, three applications provided higher yields. Pyraclostrobin was the only treatment where a difference in yield between two and three applications was identified at all three locations. At RARS with tebuconazole and tetraconazole (Domark 230ME and Eminent 125SL), the treatments with 0% disease severity for both two and three applications were among the higher yielding treatments and there were no differences in yield between two and three applications for any treatment of both fungicides. At Gwebi, there were differences in yield between the two and three applications of tetraconazole (Domark 230ME) at 85 and 115 g a.i./ha and, in each comparison, three applications provided higher yields.

The single GS R3 application of tetraconazole (Domark 230ME) at 100 g a.i./ha was similar in yield to the two and three applications at 85, 100, and 115 g a.i./ha at Gwebi, RARS, and Yomo. However, at one location, Gwebi, the yield provided by three applications at 85 g a.i./ha was higher. The GS R3 application also provided a higher yield than the single application at GS R1 at RARS and Yomo but not at Gwebi. When a single application of azoxystrobin + propiconazole at 180 + 108 g a.i./ha applied at GS R1 was compared with three applications at 90 + 54 g a.i./ha spaced 20 days apart, three applications provided higher yield at Gwebi and Yomo but not at RARS. Both treatments provided higher yield than the nontreated control at Gwebi and Yomo but not at RARS. Final rust severity was inversely correlated with yield at Gwebi ($r = -0.21$, $P = 0.003$), RARS ($r = -0.58$, $P = 0.0001$), and Sato-2 ($r = -0.39$, $P = 0.0001$) but was not correlated at Sato-1 and Yomo. The correlations between yield and AUDPC were similar, with an inverse correlation at Gwebi ($r = -0.30$, $P = 0.003$), RARS ($r = -0.63$, $P = 0.0001$), and Sato-2 ($r = -0.34$, $P = 0.0001$), but the correlations were not significant at Sato-1 and Yomo.

Defoliation was recorded at Sato-1, Sato-2, Gwebi, and Yomo and there were differences among treatments at all four locations. However, no treatment was consistently among those with the lowest defoliation across all locations (*data not presented*). All treatments differed from the nontreated control in Sato-2 and Yomo. At Yomo, the treatment that resulted in the lowest defoliation was azoxystrobin followed by trifloxystrobin + propiconazole; however, in Sato-2, treatments that resulted in the lowest defoliation included azoxystrobin, myclobutanil, propiconazole, tebuconazole, and tetraconazole (Domark 230ME and Eminent 125SL). In Sato-1, the treatments that resulted in the lowest defoliation included azoxystrobin, pyraclostrobin, and trifloxystrobin + propiconazole, whereas the treatments with boscalid, chlorothalonil, mancozeb, and tetraconazole were similar to the nontreated control. Differences in defolia-

Table 4. Final soybean rust severity and yield of treatments in the fungicide efficacy trails in Paraguay, South Africa, and Zimbabwe during the 2004–05 growing seasons

Active ingredient[c]	Rate (g a.i./ha)	Severity (%)[a]								Yield (kg/ha)[a]						
		Cedara[b]		Krauss[b]		Gwebi[b]		RARS[b]		Cedara[b]		Krauss[b]	Gwebi[b]		RARS[b]	
		2-A	3-A	2-A	3-A	2-A	3-A	2-A	3-A	2-A	3-A	Mean[c]	2-A	3-A	2-A	3-A
Azo + cypro[d]	60 + 24	61	63	18	4	…	…	…	…	3,613	3,796	2,392	…	…	…	…
Azo + propi[d]	125 + 75	77	72	58	18[a]	…	…	…	…	3,713	3,755	2,375	…	…	…	…
Chlorothalonil[e]	1,440	74	75	80	65[a]	53	37[a]	32	8[a]	3,206	3,634	2,352	3,804	4,263[a]	3,065	3,260
Fenarimol[f,g]	96	79	76	58	25[a]	26	10[a]	0	0	3,276	3,525	2,351	4,173	4,199	3,157	3,082
Flusilazole[h]	90	69	66	58	20[a]	21	0[a]	4	1	3,620	3,619	2,301	4,130	4,452	3,365	3,209
Flusilazole[h]	125	70	66	38	8[a]	10	0	0	0	3,171	4,023[a]	2,234	4,509	4,861	2,984	3,345[a]
Flutrifol[i]	63	69	64	5	5	0	0	0	0	3,738	3,292	2,465	4,312	4,726	3,317	3,625[a]
Metconazole[j]	54	73	69	35	14[a]	1	0	37	11[a]	3,937	3,723	2,275	4,271	4,646	3,278	3,285
Met + pyraclo[j]	40 + 65	69	64	15	3	2	0	4	4	3,575	3,452	2,361	4,548	5,212[a]	3,491	3,195
Met + pyraclo[j]	52 + 65	63	56	15	4	1	0	29	1[a]	3,633	4,027	2,190	4,454	4,732	3,232	3,598[a]
Met + pyraclo[j]	54 + 90	65	51[a]	15	1	3	0	12	1[a]	3,638	3,507	2,422	4,401	4,445	3,488	3,475
Met + pyraclo[j]	60 + 75	65	60	10	0	5	0	0	0	3,540	4,027[a]	2,420	4,437	4,570	3,695	3,561
Oxycarboxin[k]	750	…	…	…	…	48	24[a]	0	0	…	…	…	3,745	4,221[a]	2,888	3,125
Propiconazole[d]	189	76	68[a]	65	30[a]	…	…	…	…	3,710	3,709	2,325	…	…	…	…
Propiconazole[d]	125	79	69[a]	55	43[a]	…	…	…	…	3,250	3,181	2,247	…	…	…	…
Pyraclostrobin[g,i]	170	74	67	20	3[a]	0	0	0	0	3,903	3,921	2,408	4,336	4,530	3,628	3,981[a]
Tebuconazole[l]	94	72	69	15	9	0	0	6	0	3,983	3,959	2,301	4,203	4,609	3,218	3,089
Tebuconazole[l]	100	67	67	8	4	0	0	4	0	3,680	3,250	2,431	4,379	4,417	3,227	3,400
Tebuconazole[e]	125	70	65	3	4	0	0	0	0	3,975	3,541	2,284	4,404	4,768	3,131	3,131
Tetraconazole[m]	85	69	68	4	3	0	0	0	0	3,587	3,640	2,370	4,456	4,533	3,260	3,075
Triflox + propi[g,l]	182	70	65	30	15[a]	13	0	7	0	2,855	4,283[a]	2,341	4,359	4,455	3,024	3,367[a]
Triflox + propi[g,l]	146	76	65[a]	43	18[a]	5	0	24	10[a]	3,222	3,317	2,271	4,538	4,781	3,348	3,343
Triflumizole[i]	350	…	…	…	…	37	22[a]	22	4[a]	…	…	…	4,141	4,340	3,104	3,003
Nontreated control	…	80	80	73	85	77	75	55	64	2,597	2,582	1,713	4,130	4,088	2,981	2,910
Protocol mean	…	71	66[n]	29	16[n]	12	7[n]	12	5[n]	3,580	3,550	…	4,325	4,572[n]	3,272	3,330
LSD 0.05[o]	…	8	8	21	21	14	14	16	16	625	625	279	426	426	375	375

[a] Significant differences between the means of the two-application (2-A) and three-application (3-A) protocols for each treatment were identified using a single degree-of-freedom contrast, $P = 0.05$, and indicated with an "a" following the 3-A mean; … = treatment not included at the location. For each treatment, the first application of both protocols was applied after first flower and subsequent applications spaced 20 to 24 days apart.

[b] Cedara = Cedara, South Africa, Krauss = Krauss, Prarguay, Gwebi = Gwebi Variety Testing Center, Zimbabwe and RARS = Rattray Arnold Research Station, Zimbabwe.

[c] The difference between the 2-A and 3-A protocols was not significant; therefore, data were combined to obtain means for each treatment.

[d] Azo + cypro = Azoxystrobin + cyproconazole (Priori Xtra 280SC), Azo + propi = azoxystrobin + propiconazole (Quilt 200SE), chlorothalonil (Bravo 720 SE), propi = propiconazole (Tilt 3.6EC) from Syngenta Crop Protection, Greensboro, NC.

[e] Chlorothalonil (Echo 720 SC) and tebuconazole (SA 120 210EC) from Sipcam Agro, Atlanta, GA.

[f] Fenarimol (Rubigan EC) from Gowan Co., Yuma, AZ.

[g] A nonionic surfactant (0.125%) was included in the treatment.

[h] Flusilazole (Punch 40EC) from Dupont Crop Protection, Wilmington, DE.

[i] Flutrifol (Impact 125SC) from Cheminova, Wayne, NJ.

[j] Metconazole (Carumba 90SL), pyralcostrobin (Headline 250EC) and Met + pyraclo = metconazole + pyraclostrobin from BASF Ag Products, Research Triangle Park, NC.

[k] Oxycarboxin (Plantvax 75WP) and triflumizole (Procure 50WS) from Crompton Corp., Middlebury, CN.

[l] Tebuconazole (Folicur 3.6F), Triflox + propi = trifloxystrobin + propiconazole (Stratego 250EC), from Bayer CropScience, Research Triangle Park, NC.

[m] Tetraconazole (Domark 230ME) from ISAGRO, Milan, Italy.

[n] Difference between means of the application protocols were significant at this location, $P < 0.05$.

[o] Students' least significant difference (LSD), where $P < 0.05$.

tion between two and three applications were detected with tetraconazole (Eminent 125SL) and myclobutanil, where three applications resulted in lower defoliation than two applications, 85 versus 98 and 86 versus 94%, respectively. In Gwebi, three applications of all products, except boscalid, resulted in less defoliation than the nontreated control (Fig. 1), and there were 12 treatments where defoliation was greater with two applications compared with three applications of the same treatment. Flusilazole + carbendazim, tebuconazole, and tetraconazole were among the treatments that provided the lowest defoliation in both application protocols. The single application of azoxystrobin + propiconazole applied at GS R1 and the three applications at 90 + 54 g a.i./ha were similar to the nontreated control, with 92 and 82% defoliation, respectively. The single applications of tetraconazole (Domark 230ME) at 100 g a.i./ha applied at either GS R1 or GS R3 differed with 80 and 68% defoliation, respectively. The defoliation observed with the single GS R3 application was similar to that observed with two or three applications of tetraconazole at 85, 100, or 115 g a.i./ha. Final rust severity was correlated with defoliation at Gwebi ($r = 0.55$, $P = 0.0001$), Sato-1 ($r = 0.31$, $P = 0.0001$), and Sato-2 ($r = 0.67$, $P = 0.0001$) but not at Yomo. Correlations between AUDPC and defoliation were similar at each location. The inverse correlation between yield and defoliation was low at Gwebi ($r = –0.19$, $P = 0.0007$), Sato-1 ($r = –0.33$, $P = 0.0001$), Sato-2 ($r = –0.44$, $P = 0.0001$), and Yomo ($r = –0.15$, $P = 0.0001$).

2004–05 Growing season. Soybean rust first was observed between the second and third fungicide applications at Cedara and RARS, but not until after the third application at Gwebi and Kraus (Table 1). The final soybean rust severity was over 75% for the nontreated control at all locations except RARS, where it was 60%. However, the lower severity at RARS was due to the short time period, 14 days, between first observation of the disease and recording of final severity. A later severity assessment was taken, but high levels of defoliation did not allow for an accurate evaluation. When combined across treatments within a location, the differences between the means of the two- and three-application protocols were detected at all four locations for final soybean rust severity (Table 4), at Gwebi and RARS for defoliation (Fig. 2), and only at Gwebi for yield (Table 4). Soybean rust severity differed among treatments at all four locations (Table 4). The lowest severities were observed with metconazole + pyraclostrobin, flutriafol, and azoxystrobin + cyproconazole, followed by flusilazole, tebuconazole, and tetraconazole (Domark 230ME). Differences were detected between the two- and three-application protocols for 4, 11, 5, and 6 treatments at Cedara, Krauss, Gwebi, and RARS, respectively. At Cedara, three applications of metconazole + pyraclostrobin at 54 + 90 g a.i./ha, trifloxystrobin + propiconazole at 146 g a.i./ha, and propiconazole at 125 and 189 g a.i./ha resulted in lower severities compared with two applications of the same fungicide. At Krauss, lower severities were observed with three applications of metconazole, pyraclostrobin, and flusilazole at both 90 and 125 g a.i./ha; fenarimol and trifloxystrobin + propiconazole at both 146 and 182 g a.i./ha; and propiconazole at both 125 and 189 g a.i./ha. At Gwebi and RARS, for all treatments where two applications resulted in greater than 20% severity, a third application provided decreased severity. At Gwebi, these included chlorothalonil, fenarimol, flusilazole, oxycarboxin, and triflumizole whereas, at RARS, these were metconazole, metconazole + pyraclostrobin at 52 + 65 and 54 + 90 g a.i./ha, oxycarboxin, trifloxystrobin + propiconazole, and triflumizole. AUDPC followed a pattern similar to the final disease severity, with all treatments different from the nontreated control (*data not presented*). Final disease severity and AUDPC (*data not presented*) were correlated at Cedara ($r = 0.61$, $P = 0.0001$), Gwebi ($r = 0.58$, $P = 0.0001$), and RARS ($r = 0.37$, $P = 0.0001$). AUDPC was not calculated at Krauss because the final disease severity was the only assessment with rust present.

Yields differed among treatments at all four locations (Table 4). At Cedara and Krauss, yields were low and, although all

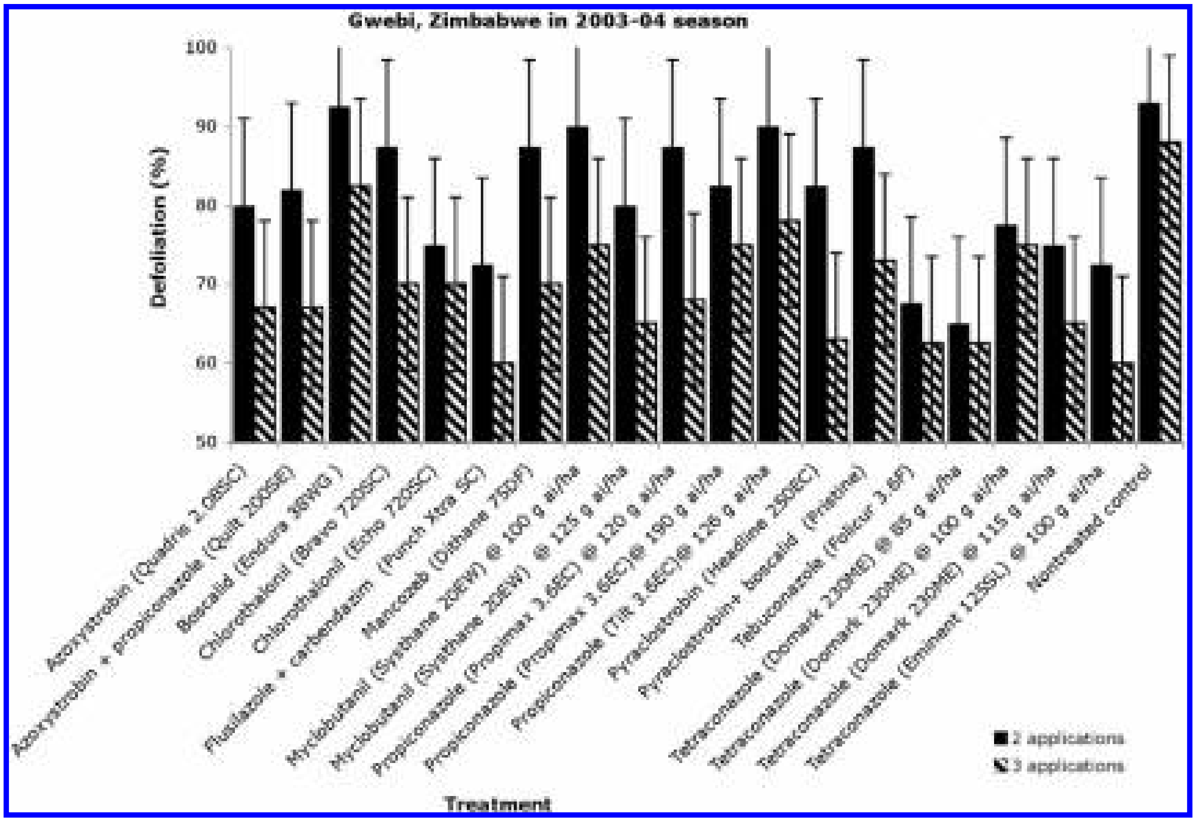

Fig. 1. Percent defoliation observed after two and three applications of each fungicide treatment evaluated in Gwebi, Zimbabwe during the 2003–04 growing season. Means separated by Students' LSD, $P = 0.05$, represented by bars.

treatments provided higher yields than the nontreated control, there was little difference among treatments. At Cedara, the highest yields were those provided by three applications of flusilazole, metconazole + pyraclostrobin at 52 + 65 and 60 + 75 g a.i./ha, and trifloxystrobin + propiconazole at 182 g a.i./ha, as well as both the two and three applications of pyraclostrobin and tebuconazole at 94 g a.i./ha, followed by azoxystrobin + cyproconazole and azoxystrobin + propiconazole. At Krauss, flutriafol provided the highest yield, followed by metconazole + pyraclostrobin at 54 + 90 and 60 + 75 g a.i./ha, pyraclostrobin, and tebuconazole at 100 g a.i./ha. Yields were higher in the Zimbabwe locations, but there were several treatments in each location that were similar to the nontreated control, including chlorothalonil, fenarimol, flusilazole, oxycarboxin, tebuconazole at 94 g a.i./ha, trifloxystrobin + propiconazole, and triflumizole. Flutriafol, metconazole, metconazole + pyraclostrobin, and pyraclostrobin had the highest yields across both locations. Differences in yield between two and three applications were identified in three, three, and five treatments at Cedara, Gwebi, and RARS, respectively. At Cedara, the treatments included flusilazole, metconazole + pyraclostrobin at 60 + 74 g a.i./ha, and trifloxystrobin + propiconazole at 182 g a.i./ha. At Gwebi, chlorothalonil, metconazole + pyraclostrobin at 40 + 65 g a.i./ha, and oxycarboxin provided higher yields with three applications compared with two applications. At RARS, flutriafol, flusilazole at 125 g a.i./ha, metconazole + pyraclostrobin at 60 + 75 g a.i./ha, pyraclostrobin, and trifloxystrobin + propiconazole at 182 g a.i./ha provided higher yield with three applications compared with two applications. Final rust severity was inversely correlated with yield at Krauss ($r = –0.28$, $P = 0.0003$), Gwebi ($r = –0.38$, $P = 0.0001$), and RARS ($r = –0.27$, $P = 0.0006$) but was not correlated at Cedara. Yield and AUDPC also were inversely correlated at Gwebi ($r = –0.37$, $P = 0.0001$) and RARS ($r = –0.27$, $P = 0.0006$) but not at Cedara.

The percent defoliation was recorded at Krauss (*data not presented*), Gwebi, and RARS and there were differences among treatments in all three locations. At both Krauss and Gwebi, defoliation was lower in all treatments compared with the nontreated control; however, at RARS, fenarimol, flusilazole, oxycarboxin, and tetraconazole at 85 g a.i./ha were similar to the nontreated control. There were no differences in defoliation between two and three applications of the treatments at Krauss, but differences were identified in 15 and 5 treatments at Gwebi and RARS, respectively (Fig. 2). Defoliation was lower with three applications of chlorothalonil, fenarimol, metconazole + pyraclostrobin at 60 + 75 g a.i./ha, tebuconazole at 94 g a.i./ha, and triflumizole compared with two applications in both locations. Pyraclostrobin was among the treatments with the lowest defoliation at both Gwebi and RARS, and defoliation did not differ between two and three applications of the fungicide. Final rust severity was correlated with defoliation at Krauss ($r = 0.28$, $P = 0.0003$), Gwebi ($r = 0.58$, $P = 0.0001$), and RARS ($r = 0.3$, $P = 0.0001$). There also was a correlation between AUDPC and defoliation at Gwebi ($r = 0.59$, $P = 0.0001$) and RARS ($r = 0.37$, $P = 0.0001$). Yield and defoliation were inversely correlated at Krauss ($r = –0.28$, $P = 0.0003$), Gwebi ($r = –0.34$, $P = 0.0001$), and RARS ($r = –0.46$, $P = 0.0006$).

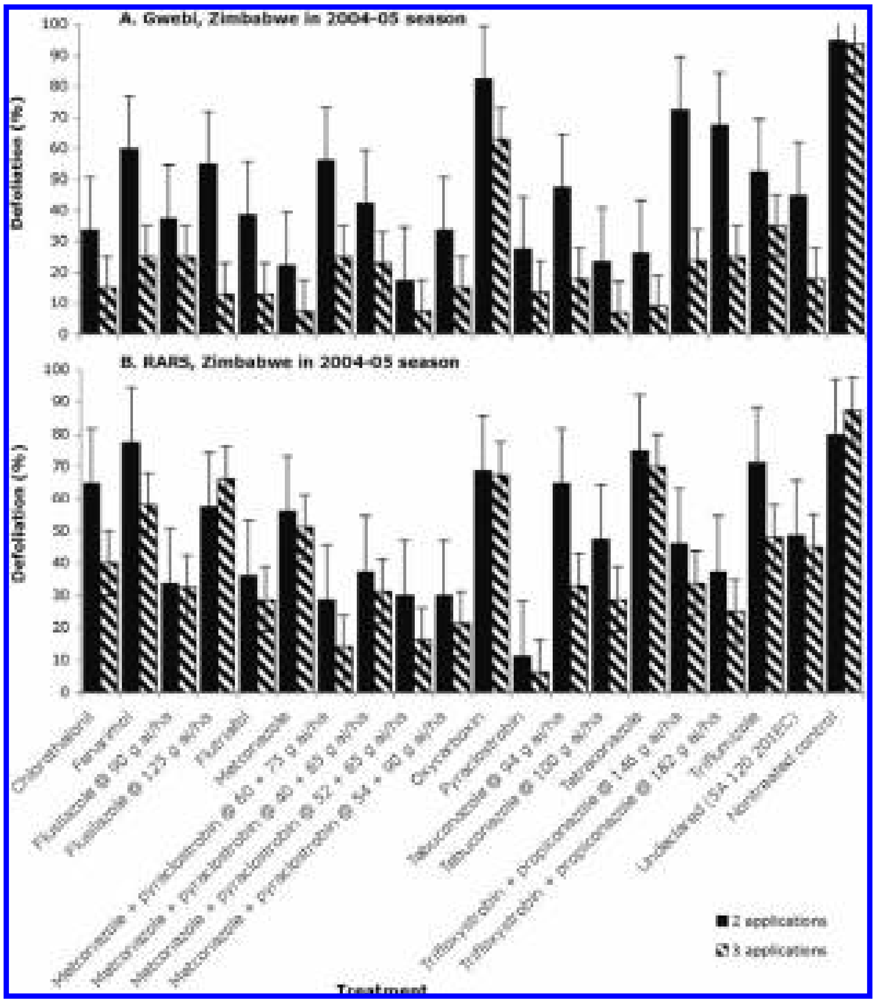

Fig. 2. Percent defoliation observed after two and three applications of each fungicide treatment evaluated in Gwebi and Rattray Arnold Research Station (RARS), Zimbabwe during the 2004–05 growing season. Means separated by Students' LSD, $P = 0.05$, represented by bars.

DISCUSSION

In previous studies, chlorothalonil was shown to be as effective as mancozeb for managing soybean rust (1,15,19,20). Chlorothalonil and mancozeb are protectant fungicides which remain on the surface of the leaf and generally are most effective when applied prior to infection. In our studies in the locations where soybean rust severity remained low, the yields provided by the protectant fungicides were higher than that of the nontreated control, even when applied after the disease had been observed in the field. However, in locations where soybean rust severity was high, the protectant fungicides were not among the most effective treatments.

The strobilurin fungicides interfere with spore germination and germ tube development, are absorbed into the leaf tissue, and move in a translaminar manner (8,16). Like chlorothalonil and mancozeb, the strobilurin fungicides are most effective when applied before infection occurs. In Paraguay during the 2002–03 growing season, where soybean rust was observed in the field prior to the first fungicide application and disease severity remained low, the strobilurin fungicides were among the treatments with the lowest severity. During the 2003–04 and 2004–05 growing seasons, where final severity in the nontreated control was over 50%, the strobilurin fungicides were not as consistent, and three fungicide applications were needed to maintain low soybean rust severity. Azoxystrobin, azoxystrobin + propiconazole, and pyraclostrobin tended to be among the treatments providing higher yields in locations with severe disease, even when final soybean rust severity recorded for those treatments was high. Further confounding comparisons between treatments are reports that strobilurin fungicides produce a physiological response that may result in increased yields in some environments (5,8,16). In locations with low soybean rust severity, the strobilurin fungicides did not consistently provide yields higher than those provided by the triazole fungicides; therefore, no growth regulatory effect on yield in soybean was inferred. However, the strobilurin fungicides tended to be among the treatments where the lowest defoliation was observed. Delayed senescence is a side effect of strobilurin fungicides reported in other crop species (5,8,16).

The triazole fungicides are sterol inhibitors that interfere with sterol biosynthesis in fungal membranes and are absorbed into the leaf tissue and, like the strobilurins, move in a translaminar manner through the leaf (21). In general, the treatments containing triazole fungicides, alone or in a mixture, performed more consistently than other chemistries. In Zimbabwe, where soybean rust severity was high, low severities were attained with the triazole fungicides flutriafol, metconazole, tetraconazole, and tebuconazole in both the two- and three-application protocols. In locations with high disease severity, the triazole fungicides (tebuconazole and tetraconazole, for example) provided control of soybean rust but were not always among the treatments providing the highest yield. In a previous study, two post-flowering applications of propiconazole were effective in reducing soybean rust and provided yields 33% greater than the nontreated control (15); in our studies, propiconazole was among the least effective of the triazole fungicides. The treatments with strobilurin-triazole mixtures tended to provide yields similar to or higher than that of the triazole in the mixture. Less severe soybean rust and less defoliation also were observed with the mixture when compared with the triazole alone.

The soybean cultivars in our trials included both determinate and indeterminate growth habits. Although there were no apparent patterns related to the growth habit of the cultivars, the difference between the two growth habits may have contributed to the location–treatment interaction, as well as a difference between the two- and three-application protocols with some treatments. These effects can be seen in Paraguay in 2003, where there were differences detected between two and three applications of nine treatments at the Sato location, but there were differences detected in two and five treatments at Romero and Yasu, respectively. The cultivar planted in Sato had an indeterminate growth habit whereas the cultivars planted in Romero and Yasu had a determinant growth habit.

Correlations between soybean rust severity, defoliation, and yield differed by location. The lowest correlations were in locations with low yield or low severity, or were in locations where yields did not differ among treatments even though there were differences in severity. The highest correlations between disease severity and yield were observed in Zimbabwe during the 2003–04 growing season, where a severe epidemic developed late in the season. At Gwebi, soybean rust first was observed before the plots had reached GS R5; however, at RARS, the first observation was late in GS R5, and the final soybean rust severity in the nontreated control was similar in both locations, 94%. The nontreated control had 30% lower yield compared with treatments that provided the highest yield within each location. These results indicate that, if the epidemic is severe and develops rapidly, yield losses can be significant even when soybean rust arrives late in the growing season. Further research is needed to quantify the impact of late-season soybean rust epidemics on yield loss and to determine the stage of maturity at which fungicides are no longer needed for yield protection.

The application protocols, two versus three applications with the first application timed at GS R1, were used as subplot treatments to allow for comparisons of the efficacy of the fungicides without the need to time the fungicide applications to disease onset. These protocols were not developed for commercial soybean production in the United States, but were used to simplify implementation and management of the experiments. There were differences between the two and three applications of several of the fungicides, including boscalid, chlorothalonil, flusilazole + carbendazim, myclobutanil, and propiconazole, where the third application was needed to maintain low severity or provide higher yields. The yield and final disease severity provided by azoxystrobin and pyraclostrobin, alone or in mixtures, also tended to differ between the two- and three-application protocols, with three applications resulting in less severe soybean rust and higher yields. However, in many of the locations, the two applications of azoxystrobin and pyraclostrobin were among the treatments providing the highest yields when compared among other two-application treatments. Treatments of tebuconazole and tetraconazole were among the treatments that were most consistent, with low disease severity and similar yield provided by both two and three applications.

The differences in yield and disease severity provided by two or three applications of several of the fungicides also support results from previous studies, where the timing of the fungicide applications was critical in managing soybean rust (3,9). Disease onset was observed after the third fungicide application was made in RARS during the 2003–04 growing season as well as at Krauss and Gwebi in the 2005–06 growing season. Within these locations, three applications of many fungicides were needed to maintain reduced disease severity and provide higher yields. However, two applications of flutriafol, metconazole + pyraclostrobin, myclobutanil, pyraclostrobin, tebuconazole, and tetraconazole maintained low severity and provided yields among the highest in these locations. The effect of application timing was further reinforced by the comparison of the single applications of tetraconazole at GS R1 or GS R3 with two and three applications, all at 100 g a.i./ha. The single application at GS R3 was similar to two and three applications and was more effective in reducing disease severity and providing higher yield than the application at GS R1. These result indicate that a poorly timed application made too far in advance of disease onset will not provide the protection needed to manage soybean rust. The products that were effective in maintaining disease severity when applied 20 or more days in advance of disease onset were limited to a small set of fungicides, among which tebuconazole and tetraconazole were the most consistent, followed by pyraclostrobin and pyraclostrobin + metconazole. Further research under U.S. production practices will be needed to identify the length of time prior to disease onset that the fungicides approved for use in the United States are effective for management of soybean rust.

The fungicides that were registered and labeled for soybean rust management or included in the Section 18 Emergency Exemption request in the United States were effective against the disease. All fungicides reduced soybean rust and provided higher yields in at least some of the locations. However, the fungicides differed in effectiveness in reducing disease severity and providing higher yield. Among the fungicides that were evaluated in these studies, the mixtures of triazole + strobilurin tended to be most consistent, providing higher yields with less severe soybean rust, lower AUDPC, and less defoliation. The triazole fungicides (tebuconazole and tetraconazole, for example) tended to have low soybean rust severity but did not always provide the highest yields at each location. The strobilurin fungicides (azoxystrobin, pyraclostrobin, and trifloxystrobin) tended to have higher soybean rust severities but provided greater yield with less defoliation. This study provides information to develop guidelines for management of soybean rust using fungicides available in the United States.

ACKNOWLEDGMENTS

This research was supported by the United Soybean Board as Projects 2229, 3217, and 4217, and

CSREES Critical Issues Grant 2004-05458 and supports the goals of the USDA National Strategic Plan for the Coordination and Integration of Soybean Rust Research**.** We thank the field crews in Paraguay, South Africa, and Zimbabwe for managing the fields and conducting the experiments, without whose efforts this work would not have been completed; T. Herman for reviewing the early drafts of the manuscript; and the many companies who supplied products, shipped them to the locations, and funded portions of this research.

LITERATURE CITED

1. AVDRC. 1992. Annotated bibliography of soybean rust (*Phakopsora pachyrhizi* Syd.). AVRDC Library Bibliography Series 4-1. G. L. Hartman, E. M Saddoui, and A. T. Tschanz, eds. Tropical Vegetable Information Service, Asian Vegetable Research and Development Center, Taipei, Taiwan.
2. Caldwell, P., and McLaren, N. W. 2004. Soybean rust research in South Africa. Pages 354-360 in: Proc. VII World Soybean Res. Conf., IV Int. Soybean Processing and Utilization Conf., III Congresso Mundial de Soja (Brazilian Soybean Conf.). F. Moscardi, C. B. Hoffman-Campo, O. Ferreira Saraiva, P. R. Galerani, F. C. Krzyzanowski, and M. C. Carrão-Panizzi, eds. Embrapa Soybean, Londrina, Brazil.
3. Du Preez, E. D., and Caldwell, P. M. 2004. Chemical control of soybean rust (*Phakopsora pachyrhizi*) in South Africa. Pages 431-435 in: Proc. VII World Soybean Res. Conf., IV Int. Soybean Processing and Utilization Conf., III Congresso Mundial de Soja (Brazilian Soybean Conf.). F. Moscardi, C. B. Hoffman-Campo, O. Ferreira Saraiva, P. R. Galerani, F. C. Krzyzanowski, and M. C. Carrão-Panizzi, eds. Embrapa Soybean, Londrina, Brazil.
4. Fehr, W. R., Caviness, C. E., Burmood, D. T., and Pennington, J. S. 1971. Stage of development descriptions for soybeans, *Glycine max* (L) Merr. Crop Sci. 11:929-931.
5. Grossmann, K., and Retzlaff, G. 1997. Bioregulatory effects of the fungicidal strobilurin kresoxim-methyl in wheat (*Triticum aestivum*). Pestic. Sci. 50:11-20.
6. Hartman, G. L., Miles, M. R., and Frederick, R. D. 2005. Breeding for resistance to soybean rust. Plant Dis. 89:664-666.
7. Hartman, G. L., Wang, T. C., and Tschanz, A. T. 1991. Soybean rust development and the quantitative relationship between rust severity and soybean yield. Plant Dis. 75:596-600.
8. Koehle, H., Grossmann, K., Jabs, T., Stierl, R., Gerhard, M., Kaiser, W., Glaab, J., Conrath, U., Seehaus, K., and Herms, S. 2002. Physiological effects of the strobilurin fungicide F 500 on plants. Pages 61-74 in: Modern Fungicides and Antifungal Compounds, III. H. Lyr, P. E. Russell, H. W. Dehne, and H. D. Sisler, eds. Intercept, Andover, UK.
9. Levy, C. 2004. Zimbabwe—a country report on soybean rust control. Pages 340-348 in: Proc. VII World Soybean Res. Conf., IV Int. Soybean Processing and Utilization Conf., III Congresso Mundial de Soja (Brazilian Soybean Conf.). F. Moscardi, C. B. Hoffman-Campo, O. Ferreira Saraiva, P. R. Galerani, F. C. Krzyzanowski, and M. C. Carrão-Panizzi, eds. Embrapa Soybean, Londrina.
10. Miles, M. R., Hartman, G. L., Levy, C., and Morel, W. 2003. Current status of soybean rust control by fungicides. Pestic. Outlook 14:197-200.
11. Miles, M. R., Levy, C., and Hartman, G. L. 2004. Summary of the USDA fungicide efficacy trials to control soybean rust in Zimbabwe 2003–2004. USDA National Information System for the Regional IPM Centers. Online publication.
12. Miles, M. R., Morel, W., and Hartman, G. L. 2003. Summary of the USDA fungicide efficacy trials to control soybean rust in Paraguay 2002–2003. USDA National Information System for the Regional IPM Centers. Online publication.
13. Miles, M. R., Morel, W., Steinlage, T. A., and Hartman, G. L. 2004. Summary of the USDA fungicide efficacy trials to control soybean rust in Paraguay 2003–2004. USDA National Information System for the Regional IPM Centers. Online publication.
14. Morel, W., Scheid, N., Amarilla, V., and Cubilla, L. E. 2004. Soybean rust in Paraguay, evolution in the past three years. Pages 361-364 in: Proc. VII World Soybean Res. Conf., IV Int. Soybean Processing and Utilization Conf., III Congresso Mundial de Soja (Brazilian Soybean Conf.). F. Moscardi, C. B. Hoffman-Campo, O. Ferreira Saraiva, P. R. Galerani, F. C. Krzyzanowski, and M. C. Carrão-Panizzi, eds. Embrapa Soybean, Londrina.
15. Patil, P. V., and Anahosur, K. H. 1998. Control of soybean rust by fungicides. Indian Phytopathol. 51:265-268.
16. Sauter, H., Steglich, W., and Anke, T. 1999. Strobilurins: evolution of a new class of active substances. Angew. Chem. Int. Ed. Engl. 38:1328-1349.
17. Schneider, R. W., Hollier, C. A., Whitman, H. K., Palm, M. E., McKemy, J. M., Hernandez, J. R., Levy, L., and DeVries-Paterson, R. 2005. First report of soybean rust caused by *Phakopsora pachyrhizi* in the Continental United States. Plant Dis. 89:774.
18. Shaner, G., and Finney, R. E. 1977. The effect of nitrogen fertilization on the expression of slow-mildewing resistance in Knox wheat. Phytopathology 67:1051-1056.
19. Sinclair, J. B. 1977. Control of soybean rust by means other than breeding for resistance. INTSOY Ser. Int. Soybean Program 12:85-88.
20. Sinclair, J. B., and Hartman, G. L. 1995. Management of soybean rust. Pages 6-11 in: Soybean Rust Workshop. J. B. Sinclair and G. L. Hartman, eds. College of Agriculture, Consumer, and Environmental Sciences, National Soybean Research Laboratory Publ. No. 1, Urbana, IL.
21. Tsuda, M., Itoh, H., and Kato, S. 2004. Evaluation of the systemic activity of simeconazole in comparison with that of other DMI fungicides. Pest Manage. Sci. 60:875-880.
22. Yorinori, J. T. 2004. Country report and rust control strategies in Brazil. Pages 447-455 in: Proc. VII World Soybean Res. Conf., IV Int. Soybean Processing and Utilization Conf., III Congresso Mundial de Soja (Brazilian Soybean Conf.). F. Moscardi, C. B. Hoffman-Campo, O. Ferreira Saraiva, P. R. Galerani, F. C. Krzyzanowski, and M. C. Carrão-Panizzi, eds. Embrapa Soybean, Londrina, Brazil.
23. Yorinori, J. T., Paiva, W. M., Frederick, R. D., Costamilan, L. M., Bertagnolli, P. F., Hartman, G. L., and Nunes, J. Jr. 2005. Epidemics of soybean rust (*Phakopsora pachyrhizi*) in Brazil and Paraguay from 2001 to 2003. Plant Dis. 89:675-677.