Yield Responses of Direct-Seeded Wheat to Rhizobacteria and Fungicide Seed Treatments

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ABSTRACT

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Field trials were conducted with winter and spring wheat in eastern Washington and northern Idaho over several years to determine the benefit, as measured by grain yield, of seed treatments with rhizobacteria and formulated fungicides in cropping systems favorable to root diseases. The trials were conducted with wheat direct-seeded (no-till) in fields with a history of intensive cereals and one or more of the root diseases: take-all caused by *Gaeumannomyces graminis* var. *tritici*, Rhizoctonia root rot caused by *Rhizoctonia solani* AG8 and *R. oryzae*, and Pythium root rot caused mainly by *Pythium irregulare* and *P. ultimum*. The seed treatments included *Bacillus* sp. L324-92, *Pseudomonas fluorescens* Q69c-80, *Pseudomonas fluorescens* Q8r1-96, difenoconazole + metalaxyl (Dividend + Apron), difenoconazole + mefenoxam (Dividend + Apron XL = Dividend XL), tebuconazole + metalaxyl (Raxil XT), and tebuconazole + thiram (Raxil-thiram). Controls were nontreated seed planted into both nontreated (natural) soil and soil fumigated with methyl bromide just prior to planting. Although the data indicate a trend in higher wheat yields with two rhizobacteria treatments over the nontreated control (171 and 264 kg/ha, respectively), these higher yields were not significantly different from the nontreated control ($P = 0.06$). Fungicide seed treatments alone similarly resulted in yields that were 100 to 300 kg/ha higher than the nontreated control, but only the yield responses to Dividend on winter wheat (289 kg/ha) and Dividend + Apron on spring wheat (263 kg/ha) were significant ($P \leq 0.05$). The greatest yield increases over the nontreated control occurred with certain rhizobacteria-fungicide combinations, with three treatments in the range of 312 to 486 kg/ha (6.1 to 17.7%; $P \leq 0.05$). Some rhizobacteria-fungicide combinations brought average yields to within 85 to 90% of those obtained with soil fumigation. Only soil fumigation produced a measurable reduction in the incidence of take-all and Rhizoctonia root rot, as assessed on washed roots. No reliable method exists for visual quantification of Pythium root rot on wheat.

Additional keywords: no-till, soilborne pathogens

Root diseases, particularly take-all caused by *Gaeumannomyces graminis* (Sacc.) von Arx & Olivier var. *tritici* Walker, Rhizoctonia root rot caused by *Rhizoctonia solani* Kühn AG8 and *R. oryzae* Ryker & Gooch, and Pythium root rot caused by several *Pythium* species but mainly *P. irregulare* Buisman and *P. ultimum* Trow., are widespread on wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) in the U.S. Pacific Northwest (PNW). These diseases remain

prevalent because of the trends toward a higher frequency of cereals in the rotation, including, commonly, continuous cereals, and the use of less or no tillage (direct seeding). Both trends are likely to continue for mainly economical reasons. All varieties of wheat and barley are susceptible to these root diseases, and therefore their management depends on cultural practices. These practices include: (i) timely and effective management of volunteer and grass-weed hosts before planting (15); (ii) placement of fertilizer beneath the seed within easy access of diseased roots (5); (iii) soil disturbance below the seed at the time of planting (14); (iv) use of wide row spacing, including paired-rows, for a more open canopy, to favor warming and drying of soil beneath the crop residue (5); and (v) use of fresh seed for maximum seedling vigor (8).

Most wheat in the U.S. PNW is grown from seed treated with fungicides to control smut fungi and seedling diseases, e.g., *Pythium* damping-off, but the extent to

which these treatments also protect plants against root infections is mostly a matter of conjecture. Further, most research on seed treatments evaluates performance based on stands or disease incidence, but little has been done to determine the benefits of seed treatments in terms of yields in systems agronomically similar to modern, dryland, wheat-intensive cropping systems. Smiley and Patterson (16) reported a 5% (185 kg/ha) increase in grain yield for winter wheat grown in eastern Oregon in response to seed treatments intended mainly for smut control, namely Vitavax (carboxin) and Dividend (difenoconazole). Such a yield increase represents four- to fivefold return on the investment, even with wheat selling for less than US\$100/mt, but is still well short of yield increases demonstrated from either soil fumigation or a 3-year winter wheat/spring barley/pea rotation (2-6).

Seed treatment fungicides currently available for use on cereals have systemic activity but apparently do not move downward into the roots. In contrast, strains of *Bacillus* and *Pseudomonas* species, selected for both rhizosphere competence (17) and ability to provide biological control of take-all (18), Rhizoctonia root rot (9), and Pythium root rot (1,19), have the ability to grow downward with elongating roots from a seed-applied source of inoculum (17). The objective of this research was to determine the benefit, as measured by an increase in grain yield, of select strains of rhizobacteria (11) applied alone and in combination with commercially available fungicides for root disease control in cropping systems characterized by intensive cereals with reduced or no tillage prior to planting.

MATERIALS AND METHODS

Locations and field histories. Twenty-four field trials were conducted during 1993 to 1999 at five locations in eastern Washington and adjacent northern Idaho. The five locations were the Steve Matsen farm near Bickleton, Klickitat Co., WA; the Robert Wigen farm near Dusty, Whitman Co., WA; the John Aeschliman farm near Colfax, Whitman Co., WA; the U.S. Department of Agriculture Palouse Conservation Field Station near Pullman, Whitman Co., WA; and the Nelson Bros. farm near Troy, Latah Co., ID (Table 1). The annual precipitation averages about

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30, 40, 45, 50, and 55 cm for the Bickleton, Dusty, Colfax, Pullman, and Troy sites, respectively. Typical of PNW dryland farming systems, no supplemental irrigation was used. The fields used for tests at the Bickleton, Colfax, and Pullman sites each had a history of continuous direct-seeded cereals for 5 years or longer. The fields near Dusty were direct-seeded for the first or second time after a long history of winter wheat planted conventionally into conventionally tilled fallow (2-year wheat/fallow rotation). The fields near Troy were in a 2-year rotation of winter wheat/lentils, typical of northern Idaho and adjacent northeastern Washington, and were direct-seeded for the first time after decades of conventional tillage. Tests at the Bickleton and Colfax sites were conducted in different fields of similar histories, usually winter wheat seeded directly into spring wheat stubble and spring wheat seeded directly into winter wheat stubble; this permitted tests with both spring and winter wheat each year. Tests at the Troy sites were also carried out in different fields of the same cropping history. Tests at the Dusty site all were with spring wheat planted into winter wheat stubble, in different fields each year. The tests conducted on the Palouse Conservation Field Station in 1996 to 1999 were on the same site each year, which was alternated between spring and winter wheat.

Varieties. All tests were conducted with either soft white spring wheat or soft white winter wheat, the two predominant kinds of wheat grown in the Pacific Northwest. The spring wheat variety was Penawawa through 1996 and Alpowa starting in 1997. Wawaiwai was used in place of Alpowa in 1999 at the Bickleton site because of its resistance to Hessian fly that rendered the 1998 yield results for Alpowa at this location unusable. The variety Madsen was used for all tests with winter wheat. In addition to Madsen, the test at Bickleton in 1999 also included seed treatments on the soft white winter wheat variety Eltan. All tests were carried out with current-year (i.e., fresh) certified seed (8).

Methods of seed treatment. Bacterial strains used in this study were *Bacillus* sp. L324-92 (10), *Pseudomonas fluorescens* Q69c-80 (12), and *P. fluorescens* Q8r1-96 (13). Wheat seeds were treated with bacteria as described by Pierson and Weller (12). Bacteria stored in glycerol at -20°C or -80°C were removed from storage and cultured on nutrient broth yeast extract agar (NBY) for 2 days at 27°C . The bacteria from these plates were then suspended in sterile, deionized water, and 1.0-ml aliquots of the suspension were introduced onto plates of King's medium B (KMB) (10). Cultures were incubated for 2 to 3 days at room temperature and the bacteria then scraped from the plates and suspended in a 1.0% (L324-92 and Q69c-80) or 0.5% (Q8r1-96) suspension (wt/vol) of methyl

cellulose (Sigma Chemical Co., St. Louis, MO). The bacterial suspension was applied uniformly to the seed as a slurry with thorough mixing in a glass beaker. Treated seeds were dried overnight under a stream of filtered air in a laminar flow hood. Dosages used throughout the study were approximately 5×10^6 for L324-92, 10^7 to 10^8 for Q69c-80, and 10^4 to 10^5 for Q8r1-96.

The formulated fungicides used for the seed treatments were difenoconazole + metalaxyl (Dividend + Apron, Syngenta Crop Protection, Greensboro, NC), difenoconazole + mefenoxam (Dividend + Apron XL = Dividend XL, Syngenta), tebuconazole + thiram (Raxil-thiram, Gustafson LLC, Dallas, TX), and tebuconazole + metalaxyl (Raxil XT, Gustafson LLC).

All fungicide formulations were applied to the seed according to the manufacture's specifications at standard recommended rates. These rates as product per kg of seed were: 0.33 ml of Dividend and 1.2 ml of Apron for Dividend + Apron; 0.65 ml of Dividend XL; 2.3 ml of Raxil-thiram; and 0.01 g of Raxil XT. The amount of product needed to treat 10 kg of seed was mixed with 200 ml of water, and this solution was then added slowly as a slurry to seed in a rotating drum. The uniformly treated seed was spread as a thin layer on clean paper overnight for drying and then transferred to a paper bag left open at the top until the time of planting, usually within 24 to 48 h after treatment. For tests conducted with Raxil-thiram and Raxil XT during the years 1997, 1998, and 1999, seed was treated by the manufacturer and returned by overnight mail within 1 or 2 days of planting. The same seed was held back for planting the nontreated controls.

For combinations of rhizobacteria and fungicide treatments, the desired rhizobacteria or fungicide mixture was mixed at the desired rate with the bacterial suspension in methyl cellulose and applied to the seed in the same way used to apply the rhizobacteria alone. Each combination treatment included the appropriate controls of rhizobacteria and fungicide treatments alone and a nontreated control, all with the same variety and seed lot.

Plot design and methods of soil fumigation, fertilization, and planting. All trials were randomized complete block designs with either four (Dusty, Pullman, and Troy locations) or six (Bickleton and Colfax) replicates per treatment. Each plot was 2.3×8 m. Plots intended for soil fumigation were located within each experimental layout, trenched around their perimeters, covered with 6-mil clear plastic tarp, and fumigated with methyl bromide at 45 g/m^2 (4). The tarps were removed and the trial was planted 2 or 3 days after fumigation. Each trial was planted directly (no-till) into the undisturbed soil and standing stubble of the previous crop, which was either wheat (Bickleton, Colfax, Dusty, and Pullman sites) or lentil residue (Troy site). A burn-down herbicide (glyphosate = Roundup) was applied at least 2 weeks and more commonly 1 month or longer before planting wheat after wheat to eliminate volunteer and grass weed hosts of the root pathogens (14,15).

The drill used to plant the trials was described by Cook and Haglund (4) and Cook et al. (5). Briefly, it is equipped to place fertilizer as a liquid mixture of nitrogen, phosphorus, and sulfur (NPS) directly beneath the seed at the time of planting in eight rows spaced uniformly at 30 cm (2.3

Table 1. Average yields of spring and winter wheats at the indicated years and locations with and without (control) soil fumigation

Location	Year	Spring wheat		Winter wheat	
		Control ^a (kg/ha)	Fumigated ^a (kg/ha)	Control ^a (kg/ha)	Fumigated ^a (kg/ha)
Bickleton, WA	1998	1,438		2,632	4,077
	1999	2,556		2,584	3,237
	2000	1,910		2,362	3,550
Dusty, WA	1993	3,202	3,813		
	1994	2,570	3,577		
	1996	2,500	2,473		
	1999			5,869	5,230
Colfax, WA	1993			4,369	5,987
	1995			6,383	7,335
	1996	3,521		5,036	6,786
	1997	4,271	6,848	5,459	5,550
	1998	3,188	4,223	3,730	5,758
	1999	4,160	5,348	6,063	
Pullman, WA	1996			5,709	
	1997	4,806			
	1998				
	1999	4,438			
Troy, ID	1994			6,945	
	1995			5,737	
	1996			5,925	
Average		3,213	4,380	4,914	5,279

^a Each value is the average yield for four (Dusty, Pullman, and Troy) or six (Bickleton and Colfax) replicates, where individual plots were 2.3×8 m.

m total width per plot). The rates of N, P, and S were set for each location based on a commercially available soil test and yield goal for that site and year following standard industry recommendations (7). These rates of N, P, and S were typically in the range of 60, 20, and 10 kg/ha, respectively, for the low precipitation areas (e.g., Bickleton), 120, 40, and 10 kg/ha, respectively, for the high-precipitation areas (e.g., Pullman and Troy), and proportionally intermediate for the intermediate-precipitation areas (e.g., Dusty and Colfax). Exact rates varied with the amount of residual N, P, and S and percentage of organic matter at the respective sites (7). The drill is also equipped with a cone designed to deliver all the seed of any given treatment within a predetermined length of plot, which in these trials was 8 m. Nontreated seed was planted in the fumigated plots.

Yield determinations. All plots were harvested with a Wintersteiger Nursery Master plot combine (Wintersteiger, Salt Lake City, UT). Each 8-m-long plot was trimmed to 7 m by mowing 50 cm off each end, and then five of the eight rows were harvested with borders of one row and two rows, respectively, on the two sides of each plot. The grain was cleaned and weighed to determine the yields on the basis of 12 to 13% grain moisture.

Assessment of root diseases. A representative sample of plants taken during mid-May to mid-June (Feeke's stages 6 to 8 [7], which varied from year to year) was assessed for the incidence of Rhizoctonia root rot and take-all in both 1996 and 1998. No reliable method is available to quantitatively rate wheat roots for incidence or severity of Pythium root rot. Plants were dug from approximately 15 cm of row at each of five places in each plot, shaken gently to remove the loose soil, and then bulked in a new plastic bag for transport to

the laboratory and storage at 4°C (if necessary) before processing. The roots on these plants were thoroughly washed under a high-pressure stream of water and then 15 plants were selected randomly from each bulk sample for assessment. The measurements included: (i) length of the mainstem (pseudostem), measured from the crown to the tip of the longest leaf; (ii) number of seminal roots; and (iii) number of seminal roots with Rhizoctonia root rot and take-all lesions. Where a single root had lesions characteristic of both diseases, the same root was counted as positive for both diseases.

Statistical analysis. Significant seed-treatment effects were identified with the Means Procedure of Windows SAS version 6.12 using the Windows NT operating system. By this procedure, the yield for each replicate of each seed treatment of each test was subtracted from the mean yield of the nontreated (control) for each test to obtain a mean yield increase or decrease in response to that treatment. If there was no seed treatment effect, the resultant mean difference would be no yield change. The percent difference from the yield for nontreated seed planted into nontreated soil (control) was calculated by dividing the difference between the seed treatment and this control by the average yield of this control for each plot.

Data on length of the mainstem, total number of seminal roots, and percentage of seminal roots with lesions characteristic of Rhizoctonia root rot and take-all were analyzed by ANOVA using SAS, and significantly different treatments were identified by Fisher's protected LSD method at $P = 0.05$.

RESULTS

General performance of crops at different sites. As expected, yields at each

location each year were lowest at Bickleton (the driest location) and progressively higher with increasing annual rainfall (Dusty, Colfax, Pullman, Troy locations) (Table 1). Also typical of the two kinds of wheat, spring wheat yields averaged only about 65% of the yields of winter wheat (Table 1).

Failure to effectively control volunteer spring wheat in the winter wheat made it necessary to abandon the Colfax site in 1994 and made the data unusable for the statistical analysis at the Bickleton, Colfax, and Pullman sites in 1998 (Table 1). In addition, one or more individual plots was lost due to damage from rodents. Yield data from these plots likewise were dropped from the analyses, reducing the number of replicates for certain treatments. Similarly, an outbreak of Hessian fly on the spring wheat at Bickleton in 1999 precluded the use of these yield data in the statistical analysis.

Yield responses to soil fumigation.

Combining the data across all tests (Table 2), the yields in response to soil fumigation were approximately 1,000 kg/ha higher for spring wheat and 900 kg/ha higher for winter wheat compared with nontreated seed planted in nontreated soil, both significant at $P = 0.01$. Actual yields for nontreated seed in either nonfumigated or fumigated soil for the different years and sites are given in Table 1. The yield depression in response to fumigation at the Colfax site in 1993 (Table 1) was associated with an acute leaf necrosis starting about the heading stage specifically in the plots treated with methyl bromide. This necrosis occurred after an obvious increased growth response of the winter wheat to the fumigation of these plots. Fumigated plots at the Troy site in 1994 showed extremely severe injury from the methyl bromide treatment, such that this

Table 2. Yield changes (+/-) from a nontreated control in response to soil fumigation and seed treatments for spring and winter wheats at five locations (Bickleton, Dusty, Colfax, and Pullman, WA, and Troy, ID) over the years 1993 to 1996

Treatment	Spring wheat				Winter wheat			
	% ^a	(No.) ^b	kg/ha ^c	P value ^d	% ^a	(No.) ^b	kg/ha ^c	P value ^d
Fumigation (methyl bromide)	32	35	1,049	<0.01	24	39	907	<0.01
Dividend	-3.6	23	-92	0.56	5.2	43	289	0.01
Dividend + Apron	8.1	20	263	0.03	3.1	32	191	0.10
Dividend XL	-0.8	16	-26	0.91	4.0	26	153	0.10
Raxil-thiram	4.6	21	268	0.31	6.6	12	301	0.16
Raxil XT	5.7	16	167	0.32	9.5	33	219	0.13
L324-96	5.4	54	171	0.06	2.0	49	76	0.49
L324-96 + Dividend					6.1	31	312	0.01
L324-96 + Dividend XL	1.1	16	20	0.93	10.2	12	328	0.11
L324-96 + Raxil-thiram	-6.0	11	-278	0.24	5.0	17	230	0.21
L324-96 + Raxil XT					9.8	12	314	0.27
Q69c-80	3.2	28	37	0.81	1.2	49	82	0.35
Q69c-80 + Dividend	17.7	8	486	<0.01	8.4	23	438	<0.01
Q8r1-96	5.6	11	187	0.52	6.2	21	264	0.06
Q8r1-96 + Dividend XL					15.2	12	479	0.05
Q8r1-96 + Raxil-thiram					5.6	22	293	0.07

^a Percent change in grain yield from nontreated control.

^b Number of paired comparisons.

^c Actual change in grain yield compared to nontreated control.

^d P value based on a *t* test that compared the treated with its corresponding nontreated control for each year, location, and replicate.

treatment was discontinued at this location. No such damage was observed at the other locations, although it has been observed in other studies within this region (5).

Yield responses to the rhizobacteria seed treatments. Two rhizobacteria treatments used alone produced a trend of higher wheat yields compared with the nontreated control, but the differences were not significant. Yields in response to *Bacillus* sp. L324-92 were 171 kg/ha higher than the nontreated control (Table 1), but this difference was not significant ($P = 0.06$). Likewise, yields in response to *P. fluorescens* Q8r1-96 were 264 kg/ha higher than the nontreated control (Table 1), but this difference was not significant ($P = 0.06$).

Yield responses to the fungicide seed treatments. With the exceptions of Dividend and Dividend XL on spring wheat, all fungicide seed treatments resulted in a yield response in the range of 3 to 8% (100 to 300 kg/ha) greater yield compared with the nontreated control (Table 2). Only the yield responses to Dividend on winter wheat and Dividend + Apron on spring wheat were significant ($P < 0.05$).

Yield responses to rhizobacteria + fungicide seed treatments. The greatest yield responses to the seed treatments occurred with combinations of rhizobacteria and fungicides (Table 2). Yields were higher than the nontreated control by 6.1% ($P = 0.01$) in response to strain L-324-92 combined with Dividend. Yields in response to Q69c-80 combined with Dividend were 17.7% higher than the nontreated control for spring wheat ($P < 0.01$) and 8.4% higher than the nontreated control for winter wheat ($P < 0.01$). The combination of Q8r1-96 and Dividend XL produced a 15.2% higher yield ($P = 0.05$).

Root disease assessments. Assessment of Rhizoctonia root rot and take-all revealed remarkably uniform amounts of these diseases (Table 3), with the least take-all at the driest sites (e.g., Bickleton and spring wheat at Colfax). However, in both 1996 (data not shown) and 1998, only soil fumigation resulted in a significant reduction in the incidence of these two diseases on the seminal roots compared with the nontreated control (Table 3). Further, with the exception of L324-92 on winter wheat at Colfax in 1998, only soil fumigation produced an increased growth response as measured by length of the mainstem compared with the same nontreated seed planted into nontreated soil. Two seed treatments, namely L324-92 + Raxil-thiram on spring wheat at Colfax and Raxil-thiram alone on winter wheat at Pullman resulted in an increase (28.1% compared with 18.5%; $P < 0.05$) in lesions characteristic of Rhizoctonia root rot (Table 3). Raxil-thiram also resulted in a decrease (9.9% compared with 15.9%; $P < 0.05$) in the incidence of seminal roots with Rhizoctonia lesions on winter wheat at the Colfax site.

DISCUSSION

Clearly, seed treatments with certain commercially available formulations of fungicides are worth the investment as a means to raise yields of both spring and winter wheat more nearly to the full potential of these crops when grown intensively in direct-seed systems. Although highly variable, average yield responses in the range of 263 to 289 kg/ha, e.g., Dividend + Apron on spring wheat and Dividend on winter wheat, over the diversity of locations and years provides a gross return to the grower of \$25 to \$30/ha (\$10 to \$12/A). These returns are several times the cost of the fungicides and their application to the seed. These yield responses are similar to or slightly greater than the increases

reported by Smiley and Patterson (16) for carboxin (Vitavax) and difenoconazole (Dividend) on winter wheat grown with conventional tillage and seeding in Oregon.

All yield increases in response to the fungicide seed treatments fall far short of the potential yields as indicated by the yields achieved when the soil was treated with methyl bromide just prior to planting. The yield increase in response to soil fumigation averaged 35 and 24% greater than the nontreated controls for spring and winter wheat, respectively. Even the "best" yield increase in response to a fungicide seed treatment, e.g., 8.1% average yield response of spring wheat to Dividend + Apron, is only 80% of the potential for spring wheat as revealed by soil fumiga-

Table 3. Influence of rhizobacteria and fungicide seed treatments, soil fumigation, and no seed treatments (controls) on wheat growth (length of mainstem and number of seminal roots) and percentage of seminal roots with lesions of Rhizoctonia root rot or take-all in 1998

Treatments	Mainstem length ^a (cm)	Seminal roots ^a (no./plant)	% seminal roots with Rhizoctonia root rot ^b	% seminal roots with take-all lesions ^b
Winter wheat, Bickleton				
Control	52.0	3.5	14.6	0.6
Fumigated soil	59.5	3.7	4.4	0.0
L324-92	51.2	3.7	17.6	0.0
L324-92 + Dividend/Apron	51.8	3.6	14.1	0.4
L324-92 + Raxil-thiram	53.5	3.5	11.3	0.6
Q8r1	54.2	3.6	14.8	1.5
Q8r1 + Dividend/Apron	52.0	3.7	14.1	0.2
Q8r1 + Raxil-thiram	53.6	3.9	11.7	0.8
Dividend/Apron	53.5	3.7	9.7	0.4
Raxil-Thiram	53.3	3.5	14.1	1.8
LSD ($P = 0.05$)	2.3	0.2	5.4	1.3
Spring wheat, Colfax				
Control	65.7	4.76	18.5	0.0
Fumigated soil	74.0	4.88	11.7	0.0
L324-92	66.2	4.90	15.9	0.0
L324-92 + Dividend XL	67.5	4.30	16.1	0.3
L324-92 + Raxil-thiram	65.0	4.57	28.1	0.0
Q8r1-96	65.3	4.71	16.4	2.2
Q8r1-96 + Dividend XL	67.9	4.82	21.3	0.4
Q8r1-96 + Raxil-thiram	66.7	4.71	14.2	1.5
Dividend XL	66.8	4.67	22.9	0.5
Raxil-Thiram	66.6	4.74	18.3	0.0
LSD ($P = 0.05$)	2.3	0.24	5.9	1.2
Winter wheat, Pullman				
Control		4.6	24.1	3.1
L324-92		4.9	28.5	6.1
L324-92 + Dividend/Apron		4.6	32.7	3.0
L324-92 + Raxil-thiram		4.5	26.6	2.0
Dividend/Apron		5.1	29.4	4.3
Raxil-thiram		4.8	44.6	3.4
LSD ($P = 0.05$)		0.4	10.1	3.4
Winter wheat, Colfax				
Control	66.8	4.6	15.9	19.0
Fumigated soil	76.7	4.6	5.3	11.8
L324-92	71.9	4.7	11.1	15.2
L324-92 + Dividend/Apron	62.9	4.5	11.9	19.8
L324-92 + Raxil-thiram	65.7	4.4	12.8	17.3
Q8r1-96	68.1	4.3	11.2	22.2
Q8r1-96 + Dividend/Apron	60.3	4.5	11.5	21.3
Q8r1-96 + Raxil-thiram	67.2	4.7	12.0	22.4
Dividend/Apron	67.1	4.6	17.0	17.4
Raxil-thiram	68.5	4.6	9.9	17.6
LSD ($P = 0.05$)	3.9	0.3	5.4	7.5

^a Plants sampled on 19 May 1998 for root rating on 27 May 1998 for Bickleton; 24 June 1998 for spring wheat, Colfax; 19 May 1998 for Pullman; and 21 May 1998 for winter wheat, Colfax. Fifteen plants were harvested from four replicate plots for each treatment.

^b Number of seminal roots with Rhizoctonia root rot or take-all lesions divided by total number of seminal roots.

tion. On the other hand, yields with no seed treatment but using best management practices available for intensive cereals and direct seeding are only about 75% of the potential for spring wheat and 80% of the potential for winter wheat.

Of the three rhizobacteria seed treatments, none produced a significant yield increase on either spring or winter wheat when used alone. On the other hand, the 5.4% yield response of spring wheat to strain L324-92 ($P = 0.06$) and the 6.2% yield response of winter wheat to strain Q8r1-96 are within the range of yield responses obtained with the best fungicide combination treatments. However, the greatest responses occurred with combinations of rhizobacteria and fungicide seed treatments, especially with treatments containing Dividend. Whereas Q69c-80 by itself had no measurable yield effect, Q69c-80 + Dividend resulted in average yield responses of 17.7% (486 kg/ha) on spring wheat and 8.4% (435 kg/ha) on winter wheat, both highly significant ($P = 0.01$). Similarly, Q8r1-96 + Dividend XL resulted in an average yield response over the nontreated control of 15.2% (479 kg/ha; $P = 0.05$). For strain L324-92, the average yield response of winter wheat was 6.1% (312 kg/ha; $P = 0.01$) when combined with Dividend. These results are not surprising, considering that root diseases occur as a mixture on wheat in the dryland PNW, and only control of most or all members of the mixture is likely to produce a yield response. Yield responses of 10 and 15% bring the attainable yields to within 85 to 90% of the potential for these sites and years as revealed by soil fumigation.

We routinely score seminal roots for take-all and Rhizoctonia root rot since these are the first roots to be exposed to soilborne inoculum of the pathogens and their protection is key to early plant vigor reflected in the length of the mainstem, among other indicators of plant health. However, of all the treatments for which root ratings were made (Table 3), only soil fumigation resulted in a consistently lower percentage of seminal roots with symptoms of these root diseases. The incidence of take-all on seminal roots was high enough to detect differences only in the test with winter wheat at Colfax in 1998, but the incidence of roots with Rhizoctonia root rot was high enough to detect differences in all four tests that year. It seems likely that the protocol used to evaluate take-all and Rhizoctonia root rot was not sufficiently sensitive to pick up treatment ef-

fects where the corresponding yield response is only 5 to 10% or where the corresponding increase in length of mainstem in response to seed treatment is only 1 to 2 cm. Length of mainstem is a sensitive indicator of root disease pressure (6). Possibly, a larger sample size would improve ability to detect treatment effects. For example, an average increase of 1 to 2 cm in length of the mainstem, as occurred in several of the tests with Q8r1-96, might have been statistically significant if a larger number of plants had been evaluated. In addition, we have no visual method by which to rate roots for incidence or severity of Pythium root rot, yet length of the mainstem is a sensitive indicator of the severity of this disease (4,6).

The large yield responses to soil fumigation with methyl bromide are consistent with previous results in this region for intensive wheat (3,5,6). A summary of earlier work with soil fumigation revealed an average response of 70, 22, and 7% greater yields in the PNW for winter wheat planted every year (no break; included some fields under irrigation), every other year (2-year crop rotations), and every third year (3-year crop rotations), respectively (2). Since all but the tests at Troy, ID, were conducted in fields cropped the previous several years to a cereal grain, and based on the average responses of 24 and 35% for winter and spring wheat, respectively, there is little doubt that the tests for efficacy of the seed treatments were conducted under conditions of high pressure from the root disease complex present in this area. Even the tests conducted at Troy were in fields cropped every other year to winter wheat where, based on earlier tests, we could expect a 22% average yield response to soil fumigation (6).

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