Soilborne pathogens

Rhizoctonia root rot and take-all of wheat in diverse direct-seed spring cropping systems

R. James Cook, William F. Schillinger, and Neil W. Christensen

Abstract: The percent area of patches of wheat plants stunted by *Rhizoctonia solani* AG8 in years 3 and 4 of a direct seed (no-till) cropping systems study conducted under dryland conditions of Washington state was the same for continuous spring wheat (*Triticum aestivum*) (no crop rotation), spring wheat after spring barley (*Hordeum vulgare*), or first- or second-year spring wheat after consecutive crops of safflower (*Carthamus tinctorius*) and yellow mustard (*Brassica hirta*). Similar percent area of patches occurred in plots sown to spring barley after spring wheat and in the safflower and yellow mustard. Greenhouse studies confirmed that safflower and yellow mustard as well as several other broadleaf crops are susceptible to *R. solani* AG8. Between years 3 and 4, some patches increased in size, some new patches formed, and a few patches present in year 3 were not present in year 4. Seventy to 80% of the wheat plants sampled in year 4 of the study had at least 10% roots with take-all caused by *Gaeumannomyces graminis* var. *tritici*, including wheat after back-to-back safflower and yellow mustard (not susceptible to this pathogen). A one-time application of zinc at 1.1 kg/ha at planting provided no visual response of the stunted plants where the application passed through one side of a patch. The effect of crop rotation on grain yield of spring wheat related to water supply, with lower yield after the broadleaf crops because they extract more water (leaving less water for the next crop) than either wheat or barley.

Key words: no-till, soilborne plant pathogens, continuous cropping, rhizoctonia root rot, take-all.

Résumé : Le pourcentage de la surface en plaques de blé rabougri par le *Rhizoctonia solani* AG8 lors de la troisième et de la quatrième année d'une étude sur les systèmes de culture par semis direct (sans labour) menée en conditions sèches dans l'État de Washington fut le même pour des cultures successives de blé de printemps (*Triticum aestivum*) (sans rotation des cultures), de blé de printemps après de l'orge de printemps (*Hordeum vulgare*) et la première ou la deuxième année de blé de printemps après des cultures successives de tournesol (*Carthamus tinctorius*) et de moutarde (*Brassica hirta*). Un pourcentage semblable de surface en plaques fut trouvé pour des parcelles semées en orge de printemps après du blé de printemps, en tournesol et en moutarde. Des études en serre ont confirmé la sensibilité du tournesol et de la moutarde, de même que de plusieurs autres cultures dicotylédones, au *R. solani* AG8. De la troisième à la quatrième année, certaines plaques se sont agrandies, de nouvelles plaques se sont formées et quelques plaques que l'on trouvait à la troisième année ont disparu. De 70 à 80% du blé échantillonné lors de la quatrième année de l'étude avait au moins 10% des racines avec du piétin-échaudage causé par le *Gaeumannomyces graminis* var. *tritici*, y compris le blé après les cultures successives de tournesol et de moutarde (non sensibles à cet agent pathogène). Une application unique de zinc à 1,1 kg/ha lors du semis n'a pas eu d'effet visible sur les plantes rabougries lorsque l'application ne couvrait qu'une portion d'une plaque. L'effet de la rotation des cultures sur le rendement en grains du blé de printemps fut associé à l'approvisionnement en eau, des rendements plus faibles étant obtenus après la culture des dicotylédones qui extraient plus d'eau du sol (laissant moins d'eau pour la prochaine culture) qu'après des cultures de blé ou d'orge.

Mots clés : semis direct, agents phytopathogènes terricoles, culture ininterrompue, rhizoctone noir, piétin-échaudage.

Introduction

Dryland (rain-fed) cropping in the low-precipitation (less than 300 mm annual) region of the U.S. inland Pacific Northwest (PNW) is mostly a tillage-based winter wheat – summer fallow system where only one crop (winter wheat) is produced every 2 years. This dry region covers 1.6×10^6 cropland hectares in eastern Washington and adjacent

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R.J. Cook.[1] Department of Plant Pathology, Washington State University, Pullman, WA 99164, U.S.A.
W.F. Schillinger. Department of Crop and Soil Sciences, Washington State University, Pullman, WA 99164, U.S.A.
N.W. Christensen. Department of Crop and Soil Science, Oregon State University, Corvallis, OR 97331, U.S.A.

[1]Corresponding author (e-mail: rjcook@wsu.edu).

north-central Oregon. The main purpose of the 13-month fallow is to store in the soil a portion of the overwinter precipitation to allow successful establishment of winter wheat (*Triticum aestivum* L.), help ensure economic grain yields, and reduce the risk of crop failure from drought. However, summer fallow in this region is only about 30% efficient (Leggett et al. 1974), i.e., about 70% of annual mean precipitation received during the fallow year is lost because of runoff and evaporation before the winter wheat is planted. Moreover, intensive tillage during the fallow cycle frequently buries surface residue, pulverizes soil clods, and reduced surface roughness. Blowing dust from excessively tilled fallow fields leads to major soil losses and causes concerns for air quality.

Although precipitation in the region has historically been considered too low for annual cropping, a 3-year winter wheat – spring cereal – fallow rotation is practiced on about 10% of the cropland. Schillinger et al. (1999) reported that both direct seeded (no-till) and conventionally seeded spring cereals can be successfully produced in this low-precipitation area when overwinter water recharge occurs to a soil depth of 1 m or more and 130 mm of plant-available water is stored in the soil. Although continuous annual cropping is practiced on less than 1% of the land, there is interest by both growers and researchers in long-term annual cropping using direct seeding. Direct seeding reduces soil erosion, improves soil quality, provides other environmental benefits, and reduces variable costs because of fewer passes over each field. We define direct seeding as fertilizing and planting directly into the residue of the previous crop without any tillage operations that mix or stir the soil prior to fertilizing and planting.

Replacement of the winter wheat – fallow system with continuous spring cropping eliminates several important diseases of wheat in the PNW, namely the snow molds, cephalosporium stripe (*Hymenula cerealis* Ellis & Everh. = *Cephalosporium graminearum* Nisikado & Ikata) and pseudocercosporella foot rot (*Tapesia yallundae* Wallwork & Spooner and *Tapesia acuformis* (Boerma, Pieters & Hamers) Crous = *Pseudocercosporella herpotrichoides* (Fron.) Deighton), all of which occur on winter wheat but not spring cereals (Cook and Veseth 1991). In contrast, rhizoctonia root rot caused by *Rhizoctonia solani* Kühn AG8 is rare or nonexistent on wheat following a 1-year break to fallow but occurs with continuous cereals, especially if volunteer cereals and grass weeds are allowed to grow within the stubble between crops (Smiley et al. 1992), and is exacerbated by direct seeding (Pumphrey et al. 1987; Weller et al. 1986). When severe, the disease occurs as patches of stunted plants and is referred to in early literature of Australia as "bare patch" and "purple patch". Because of its wide host range, rotation of cereals with a broadleaf crop has not controlled this disease. Thus, Rovira and Venn (1985) reported that lupines used in a 2-year rotation with wheat and direct seeding in South Australia controlled take-all caused by *Gaeumannomyces graminis* var. *tritici* but not rhizoctonia root rot caused by *R. solani* AG8.

As part of a larger long-term study of the potential for continuous direct-seed cropping in the low-precipitation area of eastern Washington, we compared the incidence and severity of rhizoctonia root rot and take-all in response to 4 years of (i) continuous wheat, (ii) a 2-year wheat–barley rotation, and (iii) a 4-year safflower – yellow mustard – wheat – wheat rotation. While primarily intended to evaluate the agronomic and economic potential of these three spring cropping systems, the 4-year rotation was designed specifically to test the effects of back-to-back broadleaf crops on the epidemiology of rhizoctonia root rot. Thongbai et al. (1993a, 1993b) reported that zinc applications to South Australian soils deficient in zinc provided some control of rhizoctonia root rot. We, therefore, also tested the effects of zinc application in a year when patches of stunted plants caused by this disease were particularly common.

Materials and methods

Treatments and field layout

A study of direct-seed annual spring-cropping systems was established starting in 1997 on the Ron Jirava farm near Ritzville, Adams County, Wash. The cropping systems were (i) a 4-year safflower – yellow mustard – wheat – wheat rotation, (ii) a 2-year wheat–barley rotation, and (iii) continuous wheat. The experiment covered 8 ha, and the soil is a Ritzville silt loam (Orthic Brown Chernozem; U.S. equivalent, coarse-silty, mixed, superactive mesic Calcidic Haploxeroll). Soil depth is >2 m, and slopes are <1%. The field where the experiment was established had been direct seeded to spring wheat in 1996 following decades of the traditional winter wheat – fallow system. Mean annual precipitation at the site is 290 mm.

The experimental design was a randomized complete block with four replications. Each crop in each rotation occurred each year in 20 × 150 m plots, making a total of 28 plots. Four of the seven crops planted in year 1 in each replication were wheat; one represented the continuous-wheat cropping system, and three represented the rotations intended, respectively, as first- and second-year wheat after broadleaf crops and wheat after barley. Similarly, in the second year of the study (1998), four of the seven crops were wheat representing, respectively, the continuous-wheat cropping system, wheat after barley, and the rotations representing first- and second-year wheat after broadleaf crops. In this year, the first-year wheat followed one broadleaf crop, yellow mustard, grown in the same plots in 1997. In the third year of the study, the seven plots of each replicate were planted, respectively, to yellow mustard, safflower, first-year wheat after two consecutive broadleaf crops, second-year wheat after yellow mustard, wheat after barley, barley after wheat, and continuous wheat. Completed cycles of all seven cropping systems were represented in year 4 (2000).

During the first 3 years (1997, 1998, and 1999), all plots were planted and fertilized in one pass directly into the undisturbed soil and residue left by the previous crop using the grower's Flexi-Coil 6000 (Flexi-Coil Ltd., Saskatoon, Sask.) air seeder equipped with Barton II™ dual-disk openers on 19-cm spacing for simultaneous and precision placement of seed and fertilizer in the same row. In 2000, all plots were planted and fertilized in one pass using a custom-built drill equipped with Cross-slot™ (Baker Manufacturing, Christchurch, N.Z.) notched-coulter openers on 20-cm spacing for simultaneous and precision placement of seed and fertilizer in the same row. Both openers are low disturbance and place fertilizer beneath and slightly to one side of the seed. Glyphosate (Round-up®) was applied 2–4 weeks before planting in the spring at 0.43 kg acid equivalent per hectare to control weeds and limit the build-up of inoculum of *R. solani* AG8 on living hosts between harvest and planting (Roget et al. 1987; Smiley et al. 1992). Seeding rate averaged across years was 78, 78, 23, and 10 kg/ha for wheat, barley, safflower, and yellow mustard, respectively. Solution 32 (NH_4NO_3 + urea) provided the base for liquid fertilizer to supply a mean of 40 kg/ha N, 11 kg/ha P (aqueous solution of $NH_4H_2PO_4$), and 17 kg/ha S (aqueous solution of $(NH_4)_2S_2O_3$). The quantity of available soil moisture and residual N, P, and S was measured in all rotations each spring to determine fertilizer needs based on a yield goal. Between the tillering and stem elongation phase of growth of wheat and barley, in-crop broadleaf weeds were controlled with 2,4-D at 0.7 kg acid equivalent per hectare plus Harmony Extra® (50% thifensuluron + 25% tribenuron) at 0.9×10^{-2} L active ingredient per hectare. In-crop herbicides were not used in safflower or yellow mustard plots as no legally labeled broadleaf weed herbicides were available for these crops in Washington.

All plots were harvested with the grower's combine, and grain yield was determined on site by auguring grain into a truck mounted on weigh pads. When postharvest broadleaf weeds were present in cereals (1999 only) and broadleaf crops (all years), Surefire® herbicide (paraquat + diuron) was applied 7–10 days after harvest to prevent seed production and halt soil water use by these weeds.

Quantification of rhizoctonia root rot and take-all on plants in the field

In 1998, before the appearance of patches of stunted plants, the number and percentage of seminal and crown roots with rhizoctonia root rot and take-all was determined for 100 plants in the stem elongation stage of growth dug on 5 June (Feekes 5; Large 1954) from each plot and transported under refrigeration to the laboratory for processing. The plants from each plot represented a larger bulked sample in excess of 100 plants selected from intermittent locations across the entire length and breadth of each plot. The roots and adhering soil were dug at least 15 cm deep as clusters of four to five plants per sample. The plants when freshly dug were shaken gently to dislodge some of the soil and then placed in a large new plastic bag. In the laboratory, the roots were washed free of soil and the total number of seminal and crown roots and the numbers with rhizoctonia root rot and (or) take-all were counted while floating the roots in a thin layer of water against a white background. The 100 plants selected for these assessments were selected randomly from the bulked samples.

As a variation on this method, in 2000, a take-all index (TAI) was determined for 20 adult (headed) plants representing a larger bulked sample obtained from random locations in each plot using the indexing method of Beal et al. (1998). Briefly, plants with roots washed free of soil were placed into one of five categories according to whether the percentage of all roots with lesions typical of take-all was zero (0) trace to 10% (1), >10% and ≤30% (2), >30% and ≤60% (3), and >60% (4).

Patches appeared in 1999 and 2000. A Pathfinder Pro XR (Trimble Navigation Ltd., Sunnyvale, Calif.), global positioning systems (GPS) equipped with mapping software was used to determine the location, size, and area of these patches. These measurements were obtained in all wheat and barley plots in 1999 and 2000 and in safflower and yellow mustard plots in 2000 by circling each clearly visible rhizoctonia patch with the backpack-mounted GPS mapping unit in early June. The GPS unit had a degree of accuracy of <1 m.

Tests for susceptibility of plant species to *Rhizoctonia solani* AG8

Greenhouse studies were conducted to determine the relative susceptibility of several broadleaf plant species to *R. solani* AG8. The plant species were canola (*Brassica napus* L.), yellow mustard, safflower, pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medik), and chickpea (*Cicer arietinum* L.), all potential rotation crops with wheat in the PNW. A virulent isolate (C-1; Weller et al. 1986) of the pathogen obtained originally from barley from a field near Clyde, Wash., and grown on sterilized oat grains was used as the source of inoculum. Plastic Conetainers (Ray Leach Conetainer, Canby, Oreg.) 4 cm in diameter at the opening (SuperCells™) were filled two-thirds full with a local silt loam soil that had been pasteurized with moist heat at 60°C for 30 min and then air dried. Two *Rhizoctonia*-infested oat grains were placed on the soil surface and covered with a 2 cm thick layer of the same pasteurized soil. The soil was then moistened with water applied from the top and incubated beneath clear plastic sheeting (to prevent drying) for 1 week; this allowed time for the pathogen to colonize the pasteurized soil from the oat-grain food base. Seeds of the different crop plant species were then planted one seed per Conetainer for large-seeded plants and two seeds per Conetainer for small-seeded crops, covered with a 2-cm-thick layer of the pasteurized soil, watered from the top, and incubated on a greenhouse bench at 12–15°C with natural light supplemented with overhead mercury-halide lights. Pasteurized soil of the same quantity per Conetainer and incubated in the same fashion but without oat-grain inoculum of the pathogen served as checks. A total of seven Conetainers with and seven without *Rhizoctonia* inoculum were used per plant species. The plants were watered as necessary and allowed to grow for 3–4 weeks at which time the amount of disease was assessed based on appearance of the tops (plant stunting) and the roots (girdled or severed by *Rhizoctonia* lesions). The tests were done three times.

Evaluation of the effects of zinc application on severity of rhizoctonia root rot

An application of zinc was superimposed on the continuous spring wheat treatment in 2000 (year 4) to determine whether the stunting caused by rhizoctonia root rot could be abrogated by this plant nutrient. Two composite soil samples were collected to a depth of 15 cm from within each of the four replications of the continuous-wheat treatment in the spring just prior to planting. One sample was taken from within a 1999 rhizoctonia patch, and one was taken from a nearby 1999 apparently healthy area. The soil samples were air dried for 10 days and then submitted to the Central

Analytical Laboratory (CAL) at Oregon State University. The samples were analyzed for pH (1:2 in water); phosphorus ($NaHCO_3$ extractable); potassium, calcium, and magnesium (NH_4 acetate extractable); copper, manganese, and zinc (diethylenetriaminepentaacetic acid extractable); sulfate–sulfur (calcium phosphate extractable); and total nitrogen (Leco CNS-2000 Macro Analyzer).

At planting, one pass was made the full length of each 150-m-long plot with the 2.4-m-wide Cross-slot drill equipped to apply zinc at 1.1 kg/ha as zinc chelate (aqueous solution of zinc–EDTA chelate) mixed with the liquid fertilizer. All other drill passes were made using the same drill and same fertilizer rate but without the zinc. Plant samples were taken when wheat was in the stem elongation phase (Feekes 7) from areas within each of the four replicate plots from (i) healthy plants where no zinc was applied, (ii) healthy plants where zinc was applied, and (iii) within patches (stunted plants) where zinc was applied. These samples, submitted to CAL, were oven-dried prior to microwave digestion and analysis for P, K, Ca, Mg, Mn, Cu, B, and Zn using a Perkin-Elmer Optima 3000DV inductively coupled plasma emission spectrometer. Samples were also analyzed for total N and S using the Leco CNS-2000 macro analyzer.

Analysis of data

Grain yield, percent area as patches of plants (stunted by rhizoctonia root rot), and nutrient concentration data were subjected to analysis of variance and means were compared using least significant differences (LSD) when the F test indicated significance at $P < 0.05$. Root infection data were compared using standard deviations from means for percentage infections.

Results

Incidence and severity of root diseases in the field

A low level of rhizoctonia root rot occurred on both seminal and crown roots of both the wheat and barley in year 2 of the study (Table 1). The percentage of roots with lesions typical of rhizoctonia root rot was three to four times higher for seminal roots than crown roots. Both the lowest and highest percentages of seminal and crown roots with rhizoctonia root rot in 1998, significant at $P < 0.05$, occurred in the treatments where wheat had been grown in both year 1 and year 2 of the study. One of these two wheat–wheat sequences was to be followed in 1999 and 2000 by the consecutive broadleaf crops and the other was the continuous wheat cropping system. The incidence of take-all was very low on seminal roots (Table 1) of both wheat and barley and essentially nonexistence on crown roots (no data recorded).

Patches of plants stunted because of rhizoctonia root rot were apparent in all wheat and barley plots starting in year 3 (1999), and the area in patches was even greater in year 4 (2000) of the study (Table 2, Figs. 1 and 2). Poor stands of both the yellow mustard and safflower in 1999 made it unreliable to quantify the patches for those crops that year. When all data on percentage area of patches for a given year were analyzed together, there was no significant difference ($P < 0.05$) in area of patches among any of the rotations, including first-year wheat after two consecutive broadleaf crops in 2000 (Table 2). On the other hand, when the area of patches was analyzed for wheat plots only, the 4.5% area as patches in first-year wheat after the two consecutive broadleaf crops was significantly less ($P < 0.05$) than the 11.9% area as patches in the continuous spring wheat plots (Table 2).

An overlay of patched areas in 2000 with that in 1999 showed that some new patches had appeared and others had disappeared in 2000 compared with 1999 (Figs. 1 and 2). Averaged across treatments, 73% of the land area with

Table 1. Incidence of rhizoctonia root rot caused by *Rhizoctonia solani* AG8 and take-all caused by *Gaeumannomyces graminis* var. *tritici* on spring wheat and spring barley in the second year (1998) of different planned crop sequences.

Crop		Percentage of roots with lesions*		
1997	1998	Root rot seminal	Root rot crown	Take-all seminal
Yellow mustard	Wheat	10.8 b	2.2 b	1.3 a
Wheat[†]	Wheat	18.5 a	5.3 a	0.6 a
Wheat	Barley	17.0 a	5.2 a	1.7 a
Barley	Wheat	17.2 a	5.3 a	1.0 a
Wheat[†]	Wheat	7.3 b	2.2 b	0.9 a

*Each value is for 100 plants taken randomly from each of four replicates. Within column percentages followed by a different letter are significantly different at $P < 0.05$ based on Fisher's LSD.

[†]The wheat–wheat cropping system in the second row of the table was preliminary to safflower in 1999 and yellow mustard in 2000. The wheat–wheat cropping system in the fifth row of the table was a continuous wheat system. Thus, as of 1998, these two cropping systems were still identical.

Table 2. Percentage plot area with patches of stunted plants caused by *Rhizoctonia solani* AG8 in the different cropping systems and years.

Cropping system	Percentage of plot area with patches	
	1999*	2000
Four-year rotation		
Safflower	nd	7.3 a
Yellow mustard	nd	11.1 a
First-year wheat	3.4	4.5 a B
Second-year wheat	6.6	9.2 a AB
Two-year rotation		
Wheat	3.2	5.8 a B
Barley	7.3	9.1 a
Continuous wheat	6.5	11.9 a A

Note: Within-column values for *Rhizoctonia*-incited patches in wheat followed by a different letter are significantly different at $P < 0.05$. There were no significant differences in area of *Rhizoctonia*-incited patches when all treatments for a given year were analyzed together (lowercase letters). However, when the data for area of patches in the wheat plots only were analyzed, the differences between first-year wheat and continuous wheat were significant at $P < 0.05$ (uppercase letters).

*Measurements of area with *Rhizoctonia*-incited patches were not done (nd) in safflower or yellow mustard in 1999.

Fig. 1. Distribution of *Rhizoctonia*-incited patches in 1999 (A) and 2000 (B) as affected by cropping system and based on documentation by global positioning system (GPS). Yellow, patches in 1999; black, patches common in both 1999 and 2000; red, new patches in 2000. Note that *Rhizoctonia*-incited patches were not measured in treatments 1 and 2 in 1999. Rep., replicate.

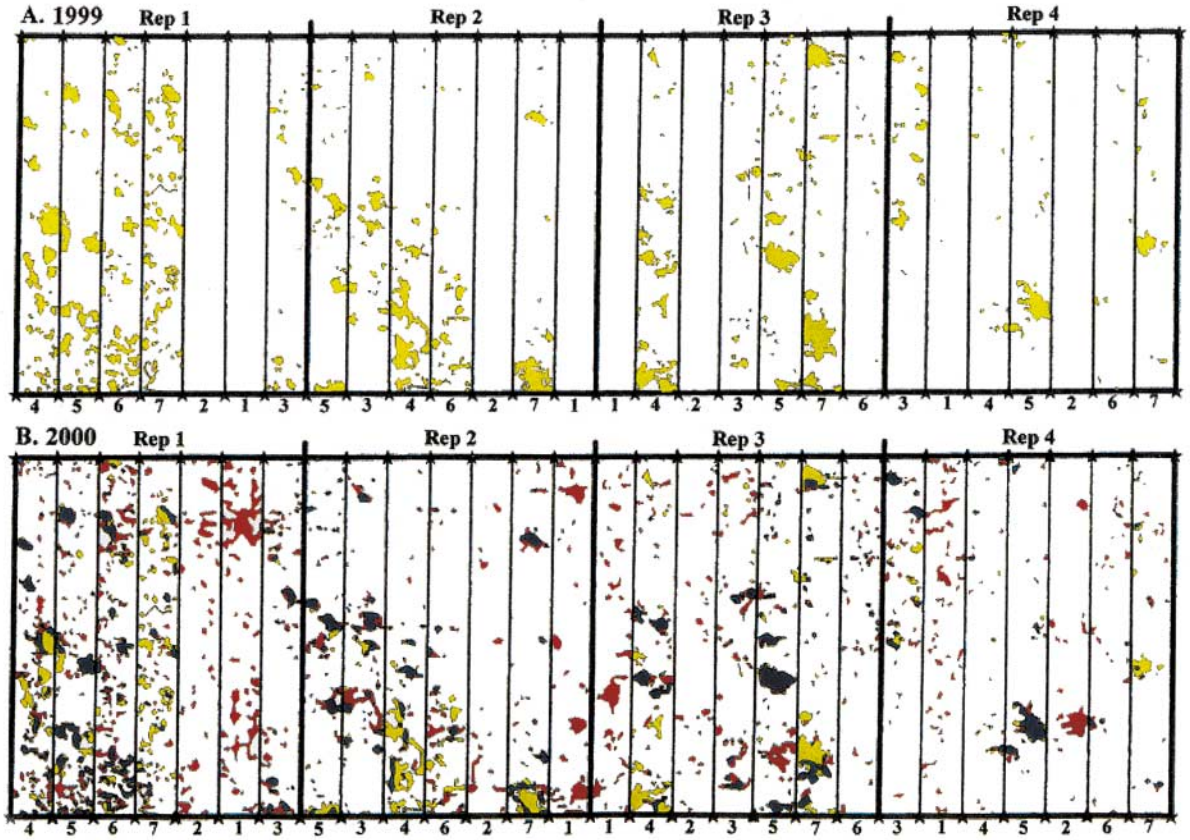
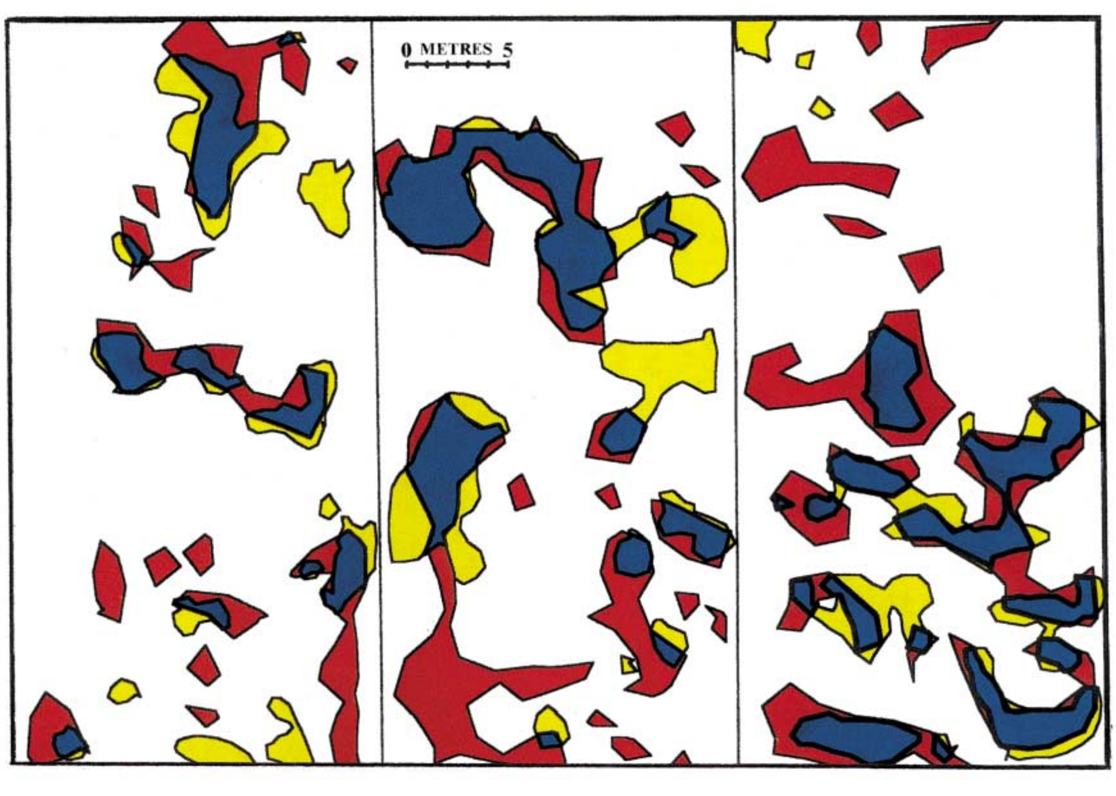


Fig. 2. Magnified view of a portion of the experiment area showing *Rhizoctonia*-incited patches in 1999 only (yellow), patches common in both 1999 and 2000 (blue), and new patches in 2000 (red).



patches in 2000 were in the same areas that were in patches in 1999; the remaining 27% of 2000 patches were in areas not stunted in 1999 (data not shown). Similarly, 25% of the total land area with patches in 1999 showed no *Rhizoctonia* symptoms in 2000. An example of these patterns is shown in Fig. 2.

A low but uniform incidence of take-all also occurred in all plots planted to spring wheat in 2000, regardless of the crop sequence (Table 3). Most plants rated 1 (trace to ≤10% roots with lesions) or 2 (>10% to ≤30% roots with lesions). However, a small number of plants from each rotation rated 3 (>30% to ≤60% roots with symptoms) and the occasional plant had more than 60% of roots with lesions, again, with no effect of crop rotation.

Susceptibility of plant species to *R. solani* AG8 in the greenhouse

All broadleaf plant species exposed to inoculum of *R. solani* AG8 were stunted relative to the check plants grown in pasteurized soil without this pathogen. Inspection of the roots revealed the roots girdled and severed by the lesions diagnostic of this disease on wheat and barley. Figure 3 shows the severity of rhizoctonia root rot of safflower and mustard in this test, which typifies the results obtained with all five plant species tested for susceptibility to this disease.

Influence of zinc applications on rhizoctonia root rot

Zinc applications had no visible effect on rhizoctonia root rot as indicated by no response in any of the areas where the application passed through one side of a patch. Further, the soil test for DTPA-extractable zinc indicated that wheat was unlikely to respond to a zinc application, and an adequate supply of zinc for wheat was confirmed based on the concentrations in plant tissue (Table 4) and the absence of any visual response of the plants outside the patches to the zinc application.

Laboratory analyses revealed only minor chemical differences between soil samples collected within and outside of *Rhizoctonia*-incited patches (Table 4). Soil pH and extractable potassium both were lower and manganese was higher in areas where patches were observed in 1999, but despite statistical significance, these differences were not agronomically significant. Nutrient concentration within the plant tissues all were within the sufficiency range reported for small grains (Westfall et al. 1990). Tissue concentrations of zinc in response to zinc applications were not higher in healthy plants but were higher along with manganese and boron in diseased plants (Table 4).

Grain yields during 2 years with severe rhizoctonia root rot

Yields of wheat were higher by 49–58% and barley by 71% in year 4 (2000) than in year 3 (1999) of the 4-year study. In addition, yields of wheat in 2000 averaged about 10% more in the continuous wheat and barley–wheat cropping system compared with wheat after the broadleaf crops, but only the 15% higher yield of wheat after barley compared with second-year wheat after consecutive broadleaf crops was significant ($P < 0.1$) (Table 5). There was about 4 cm less water available in the 180-cm soil profile at the time of planting wheat where broadleaf crops had been grown in years 1 and 2 of the study (data not shown).

Table 3. Incidence and severity of take-all caused by *Gaeumannomyces graminis* var. *tritici* on spring wheat in the fourth year (2000) of three different crop sequences.

	Rating scale†					
Crop sequence*	0	1	2	3	4	Mean
SW–Saf–YM–SW	3	35	37	4	1	1.56
Saf–YM–SW–SW	12	28	37	3	0	1.38
SW–SW–SW–SW	9	37	25	7	2	1.45
SB–SW–SB–SW	10	35	30	4	1	1.34

*SW, spring wheat; SB, spring barley; Saf, safflower; YM, yellow mustard.

†Values are numbers of plants per rating for take-all. Rating scale after Beal et al. (1998) was: (0) no visual evidence of take-all; (1) trace to <10% roots with take-all; (2) ≥10% but <30% roots with take-all; (3) ≥30% but <60% roots with take-all; and (4) ≥60% roots with take-all. Each value is the total for plants taken randomly from each of four replicates.

Discussion

Rhizoctonia root rot occurred at a low but uniform level on both wheat and barley in the second year of the cropping sequence, occurred as patches starting in the third year, and produced the largest area of patches in the fourth year in all three cropping systems. The larger percent area of patches in year 4 than in year 3 could have resulted from any one or a combination of at least three factors: (i) the higher precipitation in 2000 compared with 1999 could have provided more favorable conditions for the disease; (ii) the use of a lower disturbance drill in year 4 compared with years 1–3 could have favored the disease (MacNish 1985); and (or) (iii) the pattern reflects a natural and progressive increase in disease with years of annual direct-seed cropping. Roget (1995) similarly reported for direct-seed continuous wheat and wheat alternated in 2-year rotations with volunteer pasture, peas, or medic, all direct seeded, that the severity of rhizoctonia root rot based on a root rating increased during years 1–3 of the study and the percent area of patches caused by this disease increased during years 1–4 of the study regardless of the crop rotation. Interestingly, the severity rating and percentage area of patches declined progressively in all four cropping systems tested by Roget (1995) after years 3 and 4, respectively, confirming the report of Lucas et al. (1993) from Oregon of a decline in rhizoctonia root rot with continuous cropping of wheat. It is still too early in the cropping sequence to expect rhizoctonia root rot decline in our study.

The size, shape, and distribution of patches mapped by GPS in our study are remarkably similar to the size, shape, and distribution of patches caused by rhizoctonia root rot in cereals and mapped by MacNish (1985a) in Western Australia. MacNish (1985b) also observed that some years favored more or larger patches than other years, and that with years, some patches expanded, some remained the same in size and shape for at least two seasons, some disappeared completely, and new patches appeared. He proposed that a changing balance of conducive and suppressive factors over space and time, interacting with nonrandom distribution of

Fig. 3. Seedlings of safflower (upper panel) and yellow mustard (lower panel) showing the severe stunting when grown in pasteurized soil infested with *Rhizoctonia solani* AG8 compared with the same pasteurized soil without *R. solani* AG8.

primary inoculum, can explain the patterns observed where these patches are mapped in the same field year after year.

The wide host range of *R. solani* AG8 has been well documented (Rovira 1986; Rovira and Venn 1985). Nevertheless, different kinds of crops have diverse effects on the soil environment, they have tap versus fibrous root systems, and they produce various amounts of crop residue or the residue decomposes at different rates when left on the soil surface

Table 4. Soil pH and plant nutrient concentrations in soil (A) before application of zinc and in plants (B) after application of zinc with the nitrogen fertilizer solution across areas with healthy plants and plants in patches caused by *Rhizoctonia solani* AG8.

(A) Means and ranges in soil before zinc application.

	pH	P (mg/kg)	K (mg/kg)	Ca (cmol/kg)	Mg (cmol/kg)	Cu (mg/kg)	Mn (mg/kg)	Zn (mg/kg)	SO_4-S (mg/kg)	C (g/kg)	N (g/kg)	C/N ratio
Mean												
Healthy	6.2	30	464	3.5	1.3	2.3	9.7	1.5	1.5	9.0	0.7	13.0
Patch	6.1	34	407	3.3	1.2	2.6	10.8	1.7	2.3	8.5	0.7	13.1
LSD 5%	0.07	ns	35	ns	ns	ns	0.64	ns	ns	ns	ns	ns
Range												
Minimum	6.0	26	285	2.8	1.1	1.9	9.1	0.9	1.1	8.2	0.6	11.4
Maximum	6.4	42	562	4.1	1.5	3.2	11.2	2.4	3.7	10.3	0.9	14.0

(B) Means in plants after zinc application.

	P (g/kg)	K (g/kg)	Ca (g/kg)	Mg (g/kg)	Cu (mg/kg)	Mn (mg/kg1)	Zn (mg/kg)	B (mg/kg)	N (g/kg)	S (g/kg)	N/S ratio
No Zn, healthy	2.1	23.2	1.9	1.3	5	49	17	3.7	20.8	1.4	15.6
With Zn, healthy	2.5	23.4	1.9	1.2	5	52	19	4.0	20.7	1.5	14.0
With Zn, patch	2.3	21.8	1.7	1.2	6	63	25	5.3	25.0	1.6	15.5
LSD 5%	ns	ns	ns	ns	ns	10	4.9	1.6	ns	ns	ns

Note: ns, not significant.

Table 5. Spring crop yields in three rotations in Adams County, Wash.: a 4-year safflower – yellow mustard – wheat – wheat rotation; a 2-year wheat–barley rotation; and continuous wheat.

	Yield (kg/ha)			
	1997*	1998	1999	2000
Four-year rotation				
Safflower	1590	806	1165	672
Yellow mustard	1602	381	123	549
First-year wheat	—	2762	1794	2667 ab
Second-year wheat	—	—	1700	2560 bc
Two-year rotation				
Wheat	—	2708	1868	2956 a
Barley	5152	2531	1702	2912 a
Continuous wheat	4320	2721	1807	2856 ab

Note: All crops were planted with a Flexi-Coil 6000 drill in 1997, 1998, and 1999 and with a Cross-slot drill in 2000. Wheat and barley grain yields among treatments were not significantly different at $P < 0.1$ in 1998 nor in 1999. Within columns, cereal yield means in 2000 followed by different letters are significantly different at $P < 0.10$.

*All crops were sown into spring wheat stubble in 1997, which was the first year of the study.

in direct-seed systems. Depending on the extent of these differences, the amount of disease in this low-precipitation area could also differ, at least between cropping systems as dissimilar as our 4-year rotation and continuous-wheat system. The 4-year rotation in our study was designed to augment any benefit of broadleaf crops for control of root disease by including two broadleaf crops back-to-back before returning to wheat. Previous studies on rotational effects of broadleaf crops have been limited to a single broadleaf crop as a break crop before wheat (Roget 1995; Rovira and Venn 1985). In spite of the differences in crops and rotations, the incidence and severity of both rhizoctonia root rot and take-all were similar if not the same on wheat whether the cropping system was continuous wheat, a 2-year barley–wheat rotation, or a 4-year safflower – yellow mustard – wheat – wheat rotation.

Smiley et al. (1996) concluded that differences in severity of rhizoctonia root rot of winter wheat in 2-year wheat–fallow and wheat–pea rotations at Pendleton, Oreg. (400 mm annual precipitation), could be explained by an inverse correlation between microbial biomass and severity of rhizoctonia root rot, with higher microbial biomass and less rhizoctonia root rot (presumably because of greater disease suppression) in the wheat–pea than in the wheat–fallow rotation. Microbial biomass at the site where our work was done, although not measured, would be low in all treatments, in spite of being cropped every year, because of low amounts of crop biomass produced under the dry conditions of this site. This might account for the highly conducive nature of the site to this disease.

The occurrence of take-all on the first wheat crop following two broadleaf crops is probably due to carryover of inoculum in the stem bases of one or more previous wheat crops through 2 years of non-host crops. Infested tiller bases are slow to decompose in the semi-arid inland PNW when left undisturbed on or near the soil surface where, owing to the combination of northerly latitude (47°N) and Mediterranean climate, soils wet enough for microbial activity are usually then cold, or when warm enough for microbial activity they are usually then dry. Ramsey et al. (2000) found that 75% of PNW fields planted to wheat had sufficient take-all to be yield limiting, including fields in a 2-year winter wheat–fallow rotation where the pathogen must survive without a host for 13–15 months. Likewise, Smiley et al. (1996) observed similar amounts of take-all in long-term plots at Pendleton, Oreg., whether planted to wheat every year or every other year (wheat–pea or wheat–fallow rotations). The potential for *G. graminis* var. *tritici* to carry over in old wheat stem bases is even greater in direct-seed systems where the crop residue is disturbed only at the time of planting, and is greater still in the low-precipitation area where our experiment was conducted. Grass hosts were virtually absent from these plots, and volunteer wheat plants were controlled well in advance of planting the safflower in the 4-year rotation. The fact that the incidence and severity of take-all was no greater for wheat after wheat or barley could mean that the limiting factor to disease development at this location was weather (suitable moisture and temperature) and not inoculum. Take-all is well known to depend on cool moist soil conditions while the crop is growing. The uniform occurrence of this disease in this dry area can explain why take-all is commonly devastating already in the first year and almost always by the second year of wheat when fields historically cropped to dryland wheat are then irrigated.

In contrast to take-all, it is highly unlikely that the severe patches caused by *R. solani* AG8 in the first wheat crop following two consecutive broadleaf crops were due to survival of the pathogens in old wheat residue over the 2 years since wheat was last grown in these plots. Even a short period of fallow can greatly reduce the severity of this disease (Roget et al. 1987; Smiley et al. 1992). It seems more likely that, since all crops in these systems are hosts and since the period of time from planting (mid-March to early April) to harvesting (August for mustard, barley, and wheat and September for safflower) was approximately the same, the amount of primary inoculum for production of rhizoctonia root rot in the next crop was also then approximately the same.

There was no visual plant response to zinc applied at 1.1 kg/ha below the seed at planting, including where the application passed through just one side of the patches. We expected no plant growth response in the apparently healthy areas, since the zinc concentration in the soil was within the range considered adequate for wheat growth but did expect a response to zinc within the patches if this nutrient has any potential for an ameliorating effect on this disease. Since this study was done only once, on a site with no apparent soil deficiency in zinc, it is possible that the same test on a zinc-deficient site would show evidence of mitigation of rhizoctonia root rot. Conceivably some as yet unidentified factor, but not zinc deficiency, may be predisposing crops to severe rhizoctonia root rot at this site.

Not surprisingly, since the amount of rhizoctonia root rot and take-all on wheat and barley were generally the same in all cropping systems, the yields of these crops also were generally the same. There were differences in soil water content, especially in year 4 where plots planted to safflower and yellow mustard the previous 2 years had about 4 cm less water available for wheat compared with continuous cereals, and this was reflected in a mean of 10% lower yields of wheat in the 4-year rotation than in either the 2-year barley–wheat rotation or continuous wheat (Table 5). Safflower and yellow mustard are among the few broadleaf crops available for use in crop rotations in this low-precipitation area.

The production of spring wheat and spring barley grain yields in the range of 3000 kg/ha averaged over 4 years of continuous cereals is about 65% of grain yield achieved by farmers in neighboring fields during the study period when growing one crop every other year in the 2-year winter wheat – fallow rotation. Since the yields of spring cereals are produced every year, total production over each 2-year period would be 130% of the yield of winter wheat alternated with fallow. Grain yield in years 3 and 4, when rhizoctonia root rot was most severe, could have been 5–10% higher without the *Rhizoctonia*-incited patches. These yields were produced using just four or five field operations per year: a pre-plant application of glyphosate herbicide; one pass to plant and fertilize; an in-crop broadleaf herbicide application; harvest with a combine; and a postharvest herbicide application (1999 only for cereals). The winter wheat – fallow system, on the other hand, uses eight or more tillage operations to prepare a seedbed, control weeds, fertilize, and plant in addition to in-crop herbicide application and harvest. Excessively tilled fallow is a major source of dust in the region and also leaves the land vulnerable to water erosion when soils are frozen in the winter months. In contrast, direct-seeded cropland is protected from erosion by the standing stubble and other undisturbed residue of the previous cereal crop.

There are reports that *Brassica* species, such as yellow mustard and canola, and other deep-rooted broadleaf crops reduce disease pressure and enhance grain yield of the subsequent wheat crop (Angus et al. 1991). However, considering that these broadleaf crops provide no apparent benefit for rhizoctonia root disease control and leave less soil water available for the ensuing one or two cereal crops, growers in low-precipitation areas on the inland PNW are probably better off to plant continuous cereals.

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