



## Can placement of seed away from relic stubble limit *Rhizoctonia* root rot in direct-seeded wheat?

Ryan A. Davis<sup>a,1</sup>, David Huggins<sup>b</sup>, R. James Cook<sup>a</sup>, Timothy C. Paulitz<sup>c,\*</sup>

<sup>a</sup> Department of Plant Pathology, Washington State University, Pullman, WA 99164-6430, United States

<sup>b</sup> USDA-ARS, Land Management and Water Conservation Research Unit Washington State University, Pullman, WA 99164-6421, United States

<sup>c</sup> USDA-ARS, Root Disease and Biological Control Research Unit, Room 363 Johnson Hall, Washington State University, Pullman, WA 99164-6430, United States

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### ABSTRACT

*Rhizoctonia* root rot of wheat can be a problem in no-till systems, especially during the transition from conventional tillage. There are no effective chemical controls or resistant varieties, leaving only cultural methods to manage this disease. In a no-till system, residue and inoculum of soilborne pathogens are not moved by cultivation, therefore the inoculum may be concentrated in the seeding row of the previous year. Using GPS tracking systems with sub-meter accuracy, the seeding row could be placed away from the row of the previous year. We tested the hypothesis that seeding away from the relic row may reduce *Rhizoctonia* root rot. In two field experiments, plants were sampled at three distances from the seed row, as well as from fumigated plots. Intact soil cores were also removed from the field, planted with seeds at various distances from the previous row, and grown in the greenhouse under controlled conditions. Pasteurized cores served as controls. Disease levels were higher in the field in the second year, but there was no consistent effect of seed row placement on disease or plant parameters. However, soil fumigation and pasteurization had significant effects, indicating that soilborne pathogens were active. Inoculum of *Rhizoctonia* is not produced in the crowns and lower stems of the plant, but the pathogen survives in living and dead roots of the previous year crop, volunteers, and grassy weeds. Thus, high inoculum densities may be present in between the relic rows, as well as within the rows. If this is the situation with *Rhizoctonia*, precision placement of seed rows would not be efficacious.

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### 1. Introduction

*Rhizoctonia* root rot of wheat and barley, also known as bare patch, and caused by *Rhizoctonia solani* AG-8, was first described in Australia in the 1930s and became a major problem there in the 1980s with the wide-spread adoption of no-till farming practices (Roget, 1995). *Rhizoctonia* root rot and bare patch caused by *R. solani* AG-8 was first described in the Intermountain Pacific Northwest (PNW) in 1986 (Weller et al., 1986) where it has become a major problem in no-till cropping systems (Weller et al., 1986; Pumphrey et al., 1987; Smiley et al., 1996). In areas with an annual rainfall >500 mm, typical disease symptoms include uneven stands, variable plant height, reduced tillering, and delayed maturity rather than patches of severely stunted plants, but otherwise the same diagnostic root pruning (spear-tipping) and

cortical rot of both seminal and crown roots occurs (Paulitz et al., 2002a). In addition to *R. solani* AG-8, *R. oryzae* (teleomorph = *Waitea circinata*) as well as other AG groups and binucleate *Rhizoctonia* spp. (telioform = *Ceratobasidium*) have been implicated as part of a disease complex (Paulitz et al., 2002b; Mazzola et al., 1996; Okubara and Paulitz, unpublished).

*Rhizoctonia* root rot remains one of the main impediments to wide-spread adoption of no-tillage, which provides growers with several environmental and economic benefits, including reduction in soil loss from erosion (Papendick, 2004), increased soil organic matter and associated improved soil structure (Dao, 1993; Douglas and Goss, 1982) and reduced fossil fuel usage, with as little as one-fourth the amount of fuel required to produce these crops compared to using conventional tillage operations (Cook, 2006; Baker et al., 1996). Recent work by Schroeder and Paulitz (2006) confirmed that *R. solani* is a major cause of yield reduction in years 3 and 4 of the conversion from conventional to no-tillage. At present, there are no resistant varieties among adapted cultivars of wheat (Smith et al., 2002a,b), and no chemical controls, although certain seed treatments can provide some early benefits to seedling health (Paulitz and Scott, 2006). Considerable progress

Abbreviations: AG, anastomosis group; GPS, global positioning system.

\* Corresponding author. Tel.: +1 509 335 7077; fax: +1 509 335 7674.

E-mail address: [paulitz@wsu.edu](mailto:paulitz@wsu.edu) (T.C. Paulitz).

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in the management of this disease has been made using a package of cultural controls. These include early and timely elimination of volunteer cereals and weeds that otherwise serve as a “green-bridge” for carryover and buildup of inoculum between crop harvest and planting of the next crop (Roget et al., 1996; Smiley et al., 1992), soil disturbance within the seed row at the time of planting (Roget et al., 1996), placement of fertilizer and especially relatively immobile phosphorus beneath the seed at planting that facilitates access by diseased roots (Cook and Veseth, 1991), and planting the crop in paired rather than uniformly spaced rows, thought to promote greater warming and drying of the top few centimeters of soil longer into the growing season (Cook et al., 2000). In general, crop rotation does not reduce disease incidence because of the wide host range of the pathogens (Cook et al., 2002).

In no-till systems, the seed is drilled directly into the soil and surface residues of previous crops with little soil disturbance other than that done by disk or hoe-type opener(s). The drill openers are designed to place fertilizer with the seed (3–5 cm depth), or deeper, banding it at 7–10 cm depth. Relic crowns, residues and roots of the previous crop remain concentrated within discernable rows in the absence of tillage that would physically fractionate and mix roots and residues. The relic stubble and associated roots that remain relatively intact in no-till systems, decompose more slowly and could harbor more root pathogens compared to conventionally tilled systems (Bockus and Shroyer, 1998). *R. solani* AG-8 survives primarily in dead root tissues as thick-walled moniloid hyphae and does not produce microsclerotia. *R. oryzae* also survives in root pieces, but produces abundant microsclerotia. Thus, the inoculum of these pathogens could be concentrated in localized positions in no-till systems: horizontally in the seed row of the previous year's crop, as well as vertically in the top few centimeters of soil, where the density of infected roots would be greatest and decomposition of the inoculum source slowed due to the lack of soil disturbance. This relic stubble and associated roots could also serve as an inoculum source for other root pathogens of wheat and barley in the PNW, notably *Fusarium culmorum* and *F. pseudograminearum*, several *Pythium* species, and *Gauemannomyces graminis* var. *tritici*.

One possible cultural control method where cereals follow cereals would be to plant each successive crop by placing the maximum amount of seed away from the seed row of the previous crop, thereby minimizing the potential exposure of the new crop to inoculum of root pathogens. Take-all caused by *G. graminis* var. *tritici* was progressively less severe as the distance from the seed to the inoculum source was increased (Kabbage and Bockus, 2002), and mathematical modeling estimated that planting parallel to and between the previous year's rows would cut yield loss almost in half (Garrett et al., 2004). The use of GPS-guidance systems with sub-meter accuracy as used in precision agriculture (reviewed by Bongioivanni and Lowenberg-Deboer, 2004) for variable-rate application of herbicides and insecticides could enable growers to precisely place seed (and fertilizer) between the rows of the previous crop based on maps from the previous year.

The objective of this research was to determine if there was a relationship between incidence and severity of root disease caused by *Rhizoctonia* species and seed placement in relation to the relic stubble row in an attempt to answer the question: can plants escape root infections by being planted away from the previous year's seed row?

## 2. Material and methods

### 2.1. Field trials

Field trials were conducted in each of 2001 and 2002 on the Washington State University Cook Agronomy Research Farm

(formerly known as the Cunningham Agronomy Farm), approximately 5 miles NE of Pullman, WA. In 2001, the experiment was conducted with spring wheat (cv. Hank) following spring barley (cv. Baronesse) and in 2002, with winter wheat (cv. Falcon) following spring wheat cv. Hank. The study was conducted in one field in locations with similar aspect and slope in order to minimize environmental variability introduced by the hilly terrain and diverse soils typical of this Palouse region. Sequences of spring wheat and barley alternated with winter wheat, i.e., continuous or near continuous cereals, are common in this region.

Field plots were laid out in a randomized split-block design with four replicates and six treatments. The main plots (1.5 m × 9.8 m in 2001 and 3.0 m × 9.8 m in 2002) consisted of three seed placement treatments and the subplots (1.5 m × 4.9 m in 2001 and 3.0 m × 4.9 m in 2002) consisted of fumigated and non-fumigated treatments. The three seed placement treatments were: (i) seed placed into relic stubble rows; (ii) seed placed as close as possible midway between the relic stubble rows (25-cm row spacing); and (iii) seed placed in rows diagonal to the relic stubble rows (approximately 6° angle), thereby producing a range of distances between seed placement and the relic stubble row.

The method of fumigation was as previously described by Cook and Haglund (1991). Briefly, fumigation treatment areas (1.5 m wide by 4.9 m long in 2001 and 3.0 m wide by 4.9 m in 2002) were covered with 6-mil clear plastic tarp with the edges buried in a shallow trench dug around the perimeter of each area. Methyl bromide (100% methyl bromide) at a rate of 50 g m<sup>-2</sup> was then released via plastic tubing beneath the plastic tarp where it moved by diffusion over the plot area and into the soil profile. Plots were left covered with the plastic tarp for 24 h and planted 2–4 days after fumigation.

The fumigated treatments were intended to provide pathogen-free checks and therefore an evaluation of environmental (microclimate) effects on plants growing within versus between the relic stubble rows. However, complete elimination of pathogen inoculum by a single methyl bromide treatment was not expected, particularly as cold, wet spring soils would limit diffusion. Consequently, fumigation essentially produced a lower level of root disease pressure for comparison of seed placement treatments.

All plots were sprayed with glyphosate at 0.24 L ha<sup>-1</sup> in the fall and spring prior to planting, to minimize the potential for a “greenbridge” effect and maximize the importance of the relic stubble and associated root residue as a source of pathogen inoculum. In both years the plots were seeded with a 2.4-m-wide custom-built drill equipped with Cross-slot openers (Baker No-tillage Ltd., New Zealand) on 25-cm spacings into rows of standing stubble seeded the previous year with a Great Plains 1520 CPH no-till drill with double disk openers also spaced 25 cm apart. Each Cross-slot opener is a single notched-coulter that places seed at one depth on one side of the disk and fertilizer slightly deeper on the other side of the disk. The drill seeds with minimal soil disturbance, thereby maintaining pre-planting soil and residue characteristics. In 2001, the study was planted on March 22 with hard red spring wheat (cv. Hank) at 112 kg ha<sup>-1</sup> and fertilized with 157 kg N ha<sup>-1</sup>, 23 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and 34 kg S ha<sup>-1</sup>. The second year of the study was planted on October 23, 2001 with hard red winter wheat (cv. Falcon) at 112 kg ha<sup>-1</sup> and fertilized with 180 kg N ha<sup>-1</sup>, 23 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and 23 kg S ha<sup>-1</sup>. Post-plant weed control followed University recommendations with commercially available herbicides used at labeled rates.

The incidence and severity of root diseases were assessed only on plants obtained from plots seeded diagonally. Plant samples were taken at three distances (0–3.8, 3.8–8.9 and 8.9–12.7 cm) from relic stubble rows three times in 2001 and twice in 2002. Twenty-five plants were removed with roots to a depth of at least

10 cm from each position using a small shovel. Plants were washed free of adhering soil in the lab and rated for total height, number of tillers, number of crown and seminal roots and the number of crown or seminal roots with symptoms of infection caused by *Rhizoctonia* species.

Grain yield was determined from harvesting a 2-m<sup>2</sup> area in treatments that were seeded parallel to, but either within or between the relic rows. Only 2002 grain yields were evaluated as the 2001 study had a prohibitive number of missing rows due to poor drill performance.

## 2.2. Greenhouse study with intact soil cores from the field

A greenhouse study was conducted to determine the effect of seed placement on disease incidence and severity in a more controlled environment. In the fall of 2001, after harvest, a modified tractor-mounted Giddings Probe (Giddings Machine Company, Windsor, CO) was used to sample ninety 15-cm-diameter by 25-cm deep soil cores from a no-tillage spring barley (cv. Baroness) field located at the WSU Cook Agronomy Farm. The cores were contained in sections of PVC sewer pipe (5-mm wall thickness) ground on one end to produce a sharp edge and facilitate insertion into the soil. The Cook Agronomy Farm has been continuously direct-seeded since 1999, and cores were taken from a field where continuous cereals had been grown for at least the previous 10 years. Each sample core was collected to maximize the amount of relic stubble retrieved. Once cores were removed, a fiberglass mesh screen (1.5 mm) was secured to the core bottom in order to hold the soil intact while allowing for drainage.

The intact soil cores were placed on a greenhouse bench where 75 of 90 were selected based on the amount of intact soil and relic stubble (least evidence of disturbance) and the uniformity of soil depth within cylinders. The soil cores contained sufficient water at the time of sampling to support immediate growth of volunteer cereals and weeds once in the greenhouse, where the temperature was held at 14–16 °C. After growth of volunteer plants, the cores were sprayed with a 2% solution of glyphosate and then randomly divided into three groups of 25 in preparation for an experiment consisting of three soil or seed treatments, with winter wheat seed (cv. Madsen) planted at four distances from relic stubble, replicated five times.

The three soil or seed treatments were: (i) moist soil pasteurized at 60 °C for 30 min and planted with non-treated seed; (ii) natural soil planted with non-treated seed; and (iii) natural soil planted with seed treated with Dividend XL (30 mL/45 kg seed). Soil pasteurization was accomplished by placing individual cores double-wrapped in polyethylene bags into a hot water bath so that the water came at least to the height of the soil in cylinder. This bath was constructed using a Behlen stock tank (60 cm × 30 cm × 122 cm) and two immersion heaters (Polyscience model 71) placed on each end of the stock tank where they heated and circulated the water. Once the cores were placed into the water bath, the top of the stock tank was covered with aluminum foil to retain heat. When the center of the soil cores reached 60 °C (approximately 3 h) cores were held in the bath for another 30 min before cooling to room temperature.

Seed placement distances were 0, 2, 4, and 6 cm from the relic stubble. Accurate seed placement was achieved by using forceps to create a hole in the soil where individual seeds were planted at the specified distances from relic stubble. This technique minimized soil disturbance.

Following planting, cores were watered to bring soil moisture content to approximately 28% volume by weight (roughly field capacity or –0.03 MP). Cores were fertilized with Miracle Gro<sup>®</sup> plant fertilizer (7.5 g/L) at planting and two other times during the

experiment. Cores were watered as needed to maintain field capacity. Greenhouse photoperiod was 12 h and temperature ranged from 14 to 16 °C.

After 56 days, plants within each pot were marked according to their position/distance relative to the relic stubble. The soil cores were then removed from the cylinders and the plants and their associated root systems gently separated from the soil. Plant development was rated using the Haun scale (Haun, 1973) to assess the total number of fully emerged leaves on the main stem, the fraction-emergence (to nearest 10%) of the newest leaf, and the respective tillers formed in the leaf axils on the main stem.

After the number of crown and seminal roots and the number of roots with evidence of root lesions caused by *Rhizoctonia* species were visually counted, the roots were severed from the stem bases, dried at 60 °C for 24 h, and then weighed. This experiment was conducted once.

## 2.3. Statistical analyses

Statistical analyses were performed using the SAS system version 9.1 (SAS Institute, Cary, NC). Data were analyzed using the general linear model (GLM) procedure of SAS to generate an ANOVA table with means separations performed using Fischer's least-significant-difference *t*-tests. Both main effects and interactions between variables were analyzed using the GLM procedure.

In the field study, data for 2001 and 2002 were normal and no transformation was needed to complete the analysis. However, in the greenhouse study, data were not normally distributed and were transformed using the Boxcox transformation in the TRANREG procedure of SAS.

## 3. Results

### 3.1. Field trials

In 2001, fumigation significantly increased the number of tillers and crown roots and reduced crown root infection by *Rhizoctonia* (Table 1). Significant interaction between seed placement and fumigation occurred for plant height and number of crown roots (Table 1). In fumigated plots, plants grown away from the stubble row were taller and had more crown roots, while in the non-fumigated plots, plants were taller and had more crown roots growing within the relic stubble rows. The numbers of seminal roots were not significantly different across all treatments.

The percentage of roots with lesions characteristic of *Rhizoctonia* infections was similar for both seminal and crown roots and was significantly lower ( $P = 0.04$ ) in response to fumigation only for crown roots. Percentages of roots with lesions were more or less similar regardless of seed placement relative to the relic stubble, except for seminal roots in fumigated soil where percentages of infection were greatest on plants within the relic stubble and the interaction between placement and fumigation was highly significant ( $<0.0001$ ).

In 2002, measured plant growth and development all responded positively to fumigation (Table 2), indirect evidence of the negative influence of *Rhizoctonia* species and other root pathogens on root health. Additionally, in non-fumigated plots, plants located within relic stubble rows in 2002, were shorter than plants in treatments between relic stubble rows ( $P = 0.02$ ), whereas this trend was not as pronounced in fumigated plots (Table 2). Also in 2002, soil fumigation resulted in more tillering for plants positioned between relic stubble rows than positioned within the relic rows ( $P = 0.006$ ) and, overall greater numbers of seminal roots ( $P = 0.03$ ) and less roots infected with *Rhizoctonia* ( $P = 0.008$ ). Contrary to 2001 results, the number of crown roots

**Table 1**  
Plant growth responses and percentages of roots with *Rhizoctonia* lesions in response to seed placement relative to relic stubble rows, with and without preplant fumigation, and the interaction between seed placement and fumigation for 2001

Treatment	Distance <sup>a</sup>	Height	Tiller	# of seminal roots	% seminal roots w/rhizoc	# of crown roots	% crown roots w/rhizoc
Non-fumigated	1	27.4 b <sup>b</sup>	2.3 a	5.4 a	6.4 a	5.8 b	6.56 a
	2	25.5 a	2.0 a	5.6 ab	12.7 ab	5.2 ab	9.35 a
	3	24.3 a	1.8 a	5.4 a	7.5 a	5.1 a	9.47 a
Fumigated	1	27.0 a	4.1 ab	5.6a	10.8 b	7.9 a	5.93 a
	2	28.1 ab	3.4 ab	5.6 a	3.7 a	7.3 ab	2.66 b
	3	28.2 b	3.9 a	5.5 a	4.8 a	8.2 b	7.44 a
ANOVA P-values							
Seed placement		0.0552	0.0035	0.1259	0.1582	0.0439	0.0836
Fumigation		0.1336	0.0026	0.3876	0.0900	0.0369	0.0430
Placement × fumigation		<0.0001	0.2404	0.2620	<0.0001	0.0505	0.0306

<sup>a</sup> Distance from relic stubble row: 1 = 0–3.8 cm; 2 = 3.8–8.9 cm; 3 = 8.9–12.7 cm.

<sup>b</sup> Means with the same letter within each fumigation treatment are not significantly different,  $P = 0.05$ .

**Table 2**  
Plant growth responses and percentages of roots with *Rhizoctonia* lesions in response to seed placement relative to relic stubble rows, with and without preplant fumigation, and the interaction between seed placement and fumigation for 2002

	Distance <sup>a</sup>	Height	Tiller	# of seminal roots	% seminal roots w/rhizoc	# of crown roots	% crown roots w/rhizoc
Non-fumigated	1	37.5 a <sup>b</sup>	1.8 a	3.4 a	88.0 b	11.8 b	21.01a
	2	40.8 b	2.3 a	3.4 a	58.7 a	9.3 a	41.61 b
	3	40.0 b	2.1 a	3.2 a	74.7 ab	13.1 b	13.69 c
Fumigated	1	47.2 a	2.9 a	3.6 a	24.0 a	16.0 b	8.15 a
	2	46.9 a	2.8 a	3.7 a	25.3 a	13.9 a	9.95 a
	3	47.6 b	3.4 b	3.7 a	26.7 a	17.6 b	9.33 a
ANOVA P-values							
Seed placement		0.0191	0.0856	0.8301	0.3482	<.0001	<.0001
Fumigation		0.0015	0.0061	0.0338	0.0084	0.0214	0.0353
Placement × Fumigation		0.0163	0.0297	0.2786	0.1690	0.9582	<.0001

<sup>a</sup> Distance from relic stubble row: 1 = 0–3.8 cm; 2 = 3.8–8.9 cm; 3 = 8.9–12.7 cm.

<sup>b</sup> Means with the same letter within each fumigation treatment are not significantly different,  $P = 0.05$ .

was the same on plants located within and 8.9–12.7 cm away from the relic stubble rows and lowest on plants in between these two positions (3.8–8.9 cm away from the relic stubble). Overall percentages of root infections were considerably higher in 2002 than in 2001 for both seminal and crown roots (Table 1 compared to Table 2).

In non-fumigated plots, the highest percentages of infected seminal roots were within relic stubble rows. In contrast, percentages of seminal and crown root infections characteristic of *Rhizoctonia* species were the same at all positions in fumigated plots. Despite treatment effects on shoot and root characteristics, grain yield was not significantly affected by seed placement or soil fumigation in 2002 (Table 3).

### 3.2. Greenhouse study with intact soil cores from the field

Plant position with respect to relic stubble had no significant effect on either tiller development or root weight of wheat grown in soil cores taken from the field (Table 4). On the other hand, soil pasteurization had a significant positive effect on tiller development in the axils of leaf 1 ( $P = 0.0032$ , leaf 2 ( $P = 0.0004$  and leaf 4

**Table 3**  
Yields (kg/ha) of spring wheat (cv. Hank) in response to seed placement and soil fumigation relative to relic stubble row in 2002

Seed placement relative to relic stubble row	Yield (kg/ha)	
	Fumigated	Non-fumigated
Within	5323 a	5045 a
Between	5651 a	4705 a

( $P = 0.0002$ ), and also on root weight ( $P = 0.005$ ) (Table 4). Dry root biomass was 0.502 g in pasteurized soil compared to 0.448 and 0.443 g in natural soil with and without seed treated with Dividend XL, respectively (data not shown). The use of Dividend XL as a seed treatment provided no apparent benefit to tillering.

## 4. Discussion

The purpose of this study was to determine if seed row placement away from the relic stubble row could increase plant growth and reduce *Rhizoctonia* disease. This effect could be due to differences in environmental conditions (microclimate) or to differences in inoculum density. To separate these effects, soil fumigation and pasteurization treatments were included to provide a measure of plant responses to differences in the microclimate in the absence of root disease. Thus, if seed placement had an effect on one or more of the plant growth parameters in both fumigated (or pasteurized) and non-treated soils, this would indicate that the environment and not root disease was the cause of the effect. Conversely, if seed placement had an effect in non-fumigated soil but not in fumigated or pasteurized soil, then root disease must be considered the likely cause for the effect on the growth parameters. While the pasteurization treatment used for the greenhouse study was effective, fumigation with methyl bromide in the two field experiments served instead to produce a lower or different level of root disease pressure. Within the non-fumigated plots, only two datasets, namely plant height and percent infected crown roots in 2002 (Table 2), showed the expected trend of reduced plant growth and higher disease within than between relic stubble rows.

**Table 4**

P-values for effect of soil and seed treatment and seed placement on tiller development or root weight under greenhouse conditions, 2001

	Tiller 0	Tiller 1	Tiller 2	Tiller 3	Tiller 4	Tiller 5	Root weight
Soil/seed treatment	0.0985	0.0032	0.0004	0.2977	0.0002	0.3692	0.005
Seed placement distance <sup>a</sup>	0.5523	0.5600	0.6266	0.7162	0.9817	0.3932	0.8786
Treatment × Distance	0.2507	0.6960	0.4609	0.8096	0.8759	0.4255	0.8696

<sup>a</sup> Plant distance from relic stubble row.

In the other treatments within the field trials and greenhouse experiment, seed placement with respect to relic stubble and associated roots of the previous crop had no consistent effect on either plant height or tillering (both indications of the severity of root disease), or the incidence of *Rhizoctonia* root rot on seminal and crown roots in either the field or in the greenhouse. In fact, plants were taller and had more crown roots in the relic stubble row in 2001, which could be due to residual fertilizer (NPS were placed within the seed row and below the seed to produce the crop represented by relic stubble) or due to phytochrome mediated responses to less light, resulting in less tillering and taller plants. There could also be more moisture within than between the stubble rows. Residue can serve as a mulch to reduce evaporation from the soil, and standing stubble can trap drifting snow in the winter. The year 2001 was much drier than 2002, with 50% more precipitation from November to May for 2002 (National Weather Service, Spokane, WA) than during this same period in 2001.

Tiller formation is another particularly sensitive indication of root health (Cook et al., 1987), especially health of the seminal roots since crown root formation follows tiller formation (Klepper et al., 1998). Again, there was no significant difference in tiller formation on plants in non-fumigated plots in either field experiment, nor did seed placement relative to relic stubble influence tiller formation in soil cores taken from a field with standing stubble but planted to wheat and incubated in the greenhouse.

Apart from an anticipated gradient in inoculum potential extending outward from the relic stubble and associated roots, plants located between the relic rows would be also expected to benefit from reduced levels of residue away compared to within the stubble row, which could result in higher average soil temperature in the top few centimeters of soil during the day and in lower average surface soil temperatures during the night. Moreover, while the Cross-slot opener used for direct seeding in the field experiments provides the least soil disturbance of any drill used in the PNW (Baker et al., 1996), even the slightest “blackening” of the soil surface during the seeding operations would favor more drying as well as warming of the top few centimeters of soil within this narrow zone during the day. Warmer soil temperatures in these narrow zones could result in faster emergence and increased tillering between relic stubble rows, while the shading and mulch effect within the stubble rows would result in less radiation-warming, trap more snow and reduce wind velocity (Papendick, 2004; Papendick and McCool, 1994).

While soil fumigation failed to completely eliminate root disease, the most consistent response for all plant growth and development parameters was the responses to the soil fumigation and pasteurization treatments. Previous and extensive studies of wheat growth and development in response to soil fumigation and pasteurization have consistently pointed to a primary if not exclusive role of improvements in root health as accounting for the responses, and have experimentally ruled out a role of either more available nitrogen or nitrogen remaining in the ammonium form to account for this response (Cook, 1992; Cook and Haglund, 1991; Cook et al., 1987, 1990). We found significantly lower levels of

*Rhizoctonia* root rot in fumigated compared to non-fumigated plots in 2002, which was consistent with the increased growth response of wheat to fumigation in this year. Moreover, soil pasteurization in the greenhouse had a consistent positive effect on the number of tillers 0, 1, 2 and 4 in spite of the optimal nutrient solution applied to both pasteurized and natural soil. One complication of this type of work is the inability to accurately distinguish between plant growth and development responses such as stunting and less tiller formation caused by *Rhizoctonia* root rot from the same or similar responses caused by other soilborne pathogens, particularly *Pythium* species (Cook et al., 1987). Indeed, it is virtually impossible to conduct a field trial in natural soil in the absence of *Pythium* species in the soil, shown to eliminate the root hairs and fine rootlets of wheat (Cook et al., 1987). Nevertheless, we are confident of our data on percentages of roots with *Rhizoctonia*-incited lesions based on the distinct root pruning and diagnostic spear-tipping rated in this study when assessing the incidence of *Rhizoctonia* root rot. Moreover, recent surveys and collections of *Rhizoctonia* groups made on this farm based on sequencing of the ITS region of the rDNA (Okubara, 2006) have identified *R. solani* AG 2-1, AG-10, binucleate *Rhizoctonia* spp., and *R. oryzae* in addition to low populations of *R. solani* AG-8. (Paulitz et al., 2006; Paulitz and Rossi, 2004). However, *Pythium* spp. are also uniformly present in the soil on this farm, typical of the Palouse region more generally (Cook et al., 1987), and are eliminated or greatly reduced by fumigation and pasteurization (Cook et al., 1987, 1990). Later analysis of soil at the Cook Farm, using molecular techniques for the quantification of *Pythium* spp. (Schroeder et al., 2006), have revealed significant populations of *P. irregulare* Group IV, *P. abappressorium*, *P. paroecandrum*, *P. heterothallicum*, and *P. rostatifingens*, often from a single soil sample (Schroeder and Paulitz, 2005). *Rhizoctonia* species may also interact with *Pythium*, resulting in a more complex and highly variable disease complex.

Our initial hypothesis was that placement of the seed and fertilizer in rows at an angle to the previous crop in no-till systems would minimize exposure of the next crop to carryover inoculum. This would be a relatively simple and inexpensive cultural practice, to limit the severity of *Rhizoctonia* root rot of no-till spring wheat. But our hypothesis was not supported by this field trial. This is contrary to results of Kabbage and Bockus (2002) and Garrett et al. (2004) for take-all. However, *G. graminis* var. *tritici*, the causal agent of take-all, survives in tiller bases (crowns) as well as roots of wheat. But *R. solani* AG-8 does not infect the crowns, but survives as resistant mycelium (dark, thick-walled moniloid hyphae) in the roots of the previous crop, volunteer cereals and grassy weeds. In addition, *R. oryzae* forms abundant microsclerotia in and outside of the root. In both cases, however, the pathogen is associated with old roots, which may spread more or less uniformly between as well as within the relic stubble row. Interestingly, take-all was essentially nonexistent on either the spring or winter wheat in our trials, including in the relatively wet 2002, probably due to the spontaneous take-all decline that occurs with monoculture or near-monoculture cereals in this and many other regions of the world (Cook, 2006, 2007) or because of the low pH of these soils (approximately 5.0).

Most inoculum of *Rhizoctonia* is in the upper few centimeters of soil (MacNish and Dodman, 1987). Studies of bare patches caused by *Rhizoctonia* species using intact soil cores from a site near Ritzville, WA cropped to continuous direct-seeded cereals for the previous 7 years revealed inoculum of *R. solani* AG-8 evenly distributed in the top 20 cm and that of *R. oryzae* mostly in the top 10 cm (Paulitz et al., 2003). In either case, most direct-seed openers would place the seed into this inoculum zone.

Another consideration in no-till systems is the observation that roots follow the channels of previous root growth and the activity of earthworms (Watt et al., 2006). In the absence of tillage, these channels provide pathways of least resistance, and roots of wheat can extend to depths of 3 m (Hamblin and Tennant, 1987), but mostly extend to 1–2 m in depth (Canadell et al., 1996). Thus, in no-till systems, roots may preferentially follow old root channels at a distance from the stubble row, where they could be exposed to relatively high levels of inoculum of root pathogens left from previously colonized roots. Thus, planting away from the stubble row would not necessarily minimize exposure to either *Rhizoctonia* or *Pythium* inoculum from relic roots. However, further testing is needed in other cropping and rainfall zones, so see if these principles apply. Our testing was done in a continuous cropping area of eastern Washington, with 500–800 mm precipitation per year. In lower rainfall zones of eastern Washington with lighter soils; soil moisture, root biomass, microbial activity and decomposition rates are different, which may affect the outcome of any cultural control technique.

## 5. Conclusions

Soilborne pathogens produce inoculum in the roots and stubble of the previous year's crop, and in direct-seed systems, the relic seed row from the previous year is left intact. In 2-year field trial in a continuous cereal cropping zone of eastern Washington, precision placement of the seed row away from the old row did not reduce *Rhizoctonia* root rot, although fumigation did reduce disease levels. This indicates that *Rhizoctonia* inoculum is not in the above-ground stubble, but primarily survives in the old roots, which may be uniformly distributed between the seed rows, at a normal seeding depth.

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## References

Baker, C.J., Saxton, K.E., Ritchie, W.R., 1996. No-tillage Seeding: Science and Practice. CAB International, Wallingford, Oxon, UK.

Bockus, W.W., Shroyer, J.P., 1998. The impact of reduced tillage on soil borne plant pathogens. *Annu. Rev. Phytopathol.* 36, 485–500.

Bongioanni, R., Lowenberg-Deboer, J., 2004. Precision agriculture and sustainability. *Precision Agric.* 5, 359–387.

Canadell, J., Jackson, R.B., Ehleringer, J.R., Mooney, H.A., Sala, O.E., Schulze, E.D., 1996. Maximum rooting depth of vegetation types at the global scale. *Oecologia* 108, 583–595.

Cook, R.J., 1992. Wheat root health management and environmental concern. *Can. J. Plant Pathol.* 14, 76–85.

Cook, R.J., 2006. Toward cropping systems that enhance productivity and sustainability. *Proc. Natl. Acad. Sci.* 103, 18389–18394.

Cook, R.J., 2007. Take-all decline: a model system in biological control and clue to the success of intensive cropping. In: Vincent, Charles, Goettel, Mark, Lazarovits, George (Eds.), *Biological Control on a Global Perspective: Case Studies From Around the World*. CAB Publishing, UK, pp. 399–414.

Cook, R.J., Haglund, W.A., 1991. Wheat yield depression associated with conservation tillage caused by root pathogens in the soil not phytotoxins from the straw. *Soil Biol. Biochem.* 23, 1125–1132.

Cook, R.J., Veseth, R.J., 1991. *Wheat Health Management*. American Phytopathological Press, St. Paul, MN.

Cook, R.J., Chamswarn, C., Tang, W.-H., 1990. Influence of wheat chaff and tillage on *Pythium* populations and *Pythium* damage to wheat. *Soil Biol. Biochem.* 22, 939–947.

Cook, R.J., Sittou, J.W., Haglund, W.A., 1987. Influence of soil treatments on growth and yield of wheat and implications for control of *Pythium* root rot. *Phytopathology* 77, 1192–1198.

Cook, R.J., Ownley, B.H., Zhang, H., Vakoch, D., 2000. Influence of paired-row spacing and fertilizer placement on yield and root diseases of direct-seeded wheat. *Crop Sci.* 40, 1079–1087.

Cook, R.J., Schillinger, W.F., Christensen, N.W., 2002. *Rhizoctonia* root rot and wheat take-all in diverse direct seed cropping systems. *Can. J. Plant Pathol.* 24, 349–358.

Dao, T.H., 1993. Tillage and winter wheat residue management effects on water infiltration and storage. *Soil Sci. Soc. Am. J.* 57, 1586–1595.

Douglas, J.T., Goss, M.J., 1982. Stability and organic matter content of surface soil aggregates under different methods of cultivation and in grassland. *Soil Till. Res.* 2, 155–175.

Garrett, K.A., Kabbage, M., Bockus, W.W., 2004. Managing for fine-scale differences in inoculum load: seeding patterns to minimize wheat yield loss to take-all. *Precision Agric.* 5, 291–301.

Hamblin, A., Tennant, D., 1987. Root length density and water uptake in cereals and grain legumes: how well are they correlated? *Aust. J. Agric. Res.* 38, 513–527.

Haun, J.R., 1973. Determination of wheat growth-environment relationships. *J. Agron.* 65, 813–816.

Kabbage, M., Bockus, W.W., 2002. Effect of placement of inoculum of *Gaeumannomyces graminis* var. *tritici* on severity of take-all in winter wheat. *Plant Dis.* 86, 298–303.

Klepper, B., Richman, R.W., Waldman, W., Chevalier, P., 1998. The physiological cycle of wheat: its use in breeding and crop management (reprinted from wheat: prospects for global improvement, 1998. *Euphytica* 100, 341–347).

MacNish, G.C., Dodman, R.L., 1987. Vertical distribution of root damage caused by *Rhizoctonia solani* in wheat. *Plant Pathol.* 36, 328–332.

Mazzola, M., Wong, O.T., Cook, R.J., 1996. Virulence of *Rhizoctonia oryzae* and *R. solani* AG-8 on wheat and detection of *R. oryzae* in plant tissue by PCR. *Phytopathology* 86, 354–360.

Okubara, P.A., 2006. Characterization of pathogenic *Rhizoctonia solani* and *R. oryzae* of the Pacific Northwest using real-time PCR. In: Annual Meeting of the American Phytopathological Society Pacific Division, Abstract #31, Boise, ID, June 15, p. 9.

Papendick, R.I., 2004. *Farming with the Wind II: Wind Erosion and Air Quality Control on the Columbia Plateau and Columbia Basin*. University Publishing, Washington State University, Pullman, WA.

Papendick, R.I., McCool, D.K., 1994. Residue management strategies: Pacific Northwest. In: Hatfield, J.L., Stewart, B.A. (Eds.), *Crop Residue Management*. Lewis Publ., Boca Raton, FL, pp. 1–14.

Paulitz, T.C., Okubara, P.A., Schillinger, W.F., 2006. First report of damping-off of canola caused by *Rhizoctonia solani* AG 2-1 in Washington State. *Plant Dis.* 90, 829.

Paulitz, T.C., Rossi, R., 2004. Spatial distribution of *Rhizoctonia solani* and *Rhizoctonia oryzae* a three different scales in direct-seeded wheat. *Can. J. Plant Pathol.* 26, 419.

Paulitz, T.C., Schillinger, W.F., Cook, R.J., 2003. Greenhouse studies of *Rhizoctonia* bare patch disease in soil cores from direct-seeded fields. [CD-ROM] In: American Society of Agronomy Annual Meeting, ASA, CSSA, and SSSA Abstracts, 2–6 Nov., Denver, CO.

Paulitz, T.C., Scott, R.B., 2006. Effect of Seed Treatments for Control of *Rhizoctonia* Root Rot in Spring Wheat, 2005. *Fungicide and Nematicide Reports*, 61, ST014.

Paulitz, T.C., Smiley, R., Cook, R.J., 2002a. Insights into the prevalence and management of soilborne cereal pathogens under direct seeding in the Pacific Northwest, USA. *Can. J. Plant Pathol.* 24, 416–428.

Paulitz, T.C., Smith, J., Kidwell, K., 2002b. Virulence of *Rhizoctonia oryzae* on wheat and barley cultivars from the Pacific Northwest. *Plant Dis.* 87, 51–55.

Pumphrey, F.V., Wilkins, D.E., Hane, D.C., Smiley, R.W., 1987. Influence of tillage and nitrogen fertilizer on *Rhizoctonia* root rot (bare patch) of winter wheat. *Plant Dis.* 71, 125–127.

Roget, D.K., 1995. Decline in root rot (*Rhizoctonia solani* AG-8) in wheat in a tillage and rotation experiment at Avon, South Australia. *Aust. J. Exp. Agric.* 35, 1009–1013.

Roget, D.K., Neate, S.M., Rovira, A.D., 1996. Effect of sowing point design and tillage practice on the inoculum of *rhizoctonia* root rot, take-all and cereal cyst nematode in wheat and barley. *Aust. J. Exp. Agric.* 36, 683–693.

Schroeder, K.L., Okubara, P.A., Tambong, J.J., Lévesque, C.A., Paulitz, T., 2006. Identification and quantification of pathogenic *Pythium* spp. from soils in eastern Washington using real-time PCR. *Phytopathology* 96, 637–647.

Schroeder, K.L., Paulitz, T.C., 2005. Quantification of *Pythium* species in soils of a dryland cereal-based cropping system using real-time PCR. *Phytopathology* 96, S105.

Schroeder, K.L., Paulitz, T.C., 2006. Root diseases of wheat and barley during the transition from conventional tillage to direct seeding. *Plant Dis.* 90, 1247–1253.

Smiley, R.W., Collins, H.P., Rasmussen, P.E., 1996. Diseases of wheat in long-term agronomic experiments at Pendleton, Oregon. *Plant Dis.* 80, 813–820.

Smiley, R.W., Ogg, A.G., Cook, R.J., 1992. Influence of glyphosate on *Rhizoctonia* root rot, growth, and yield of barley. *Plant Dis.* 76, 937–942.

- Smith, J.D., Kidwell, K.K., Evans, M.A., Cook, R.J., Smiley, R.W., 2002a. Evaluation of spring cereal grains and wild *Triticum* relatives for resistance to *Rhizoctonia solani* AG 8. *Crop Sci.* 43, 701–709.
- Smith, J.D., Kidwell, K.K., Evans, M.A., Cook, R.J., Smiley, R.W., 2002b. Assessment of spring wheat genotypes for disease reaction to *Rhizoctonia solani* AG 8 in controlled environment and no-till field conditions. *Crop Sci.* 43, 694–700.
- Watt, M., Silk, W.K., Passioura, J.B., 2006. Rates of root and organism growth, soil conditions, and temporal and spatial development of the rhizosphere. *Ann. Bot.* 97, 839–855.
- Weller, D.M., Cook, R.J., MacNish, G., Bassett, E.N., Powelson, R.L., Petersen, R.R., 1986. *Rhizoctonia* root rot of small grains favored by reduced tillage in the Pacific Northwest. *Plant Dis.* 70, 70–73.