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WHEAT YIELD DEPRESSION ASSOCIATED WITH CONSERVATION TILLAGE CAUSED BY ROOT PATHOGENS IN THE SOIL NOT PHYTOTOXINS FROM THE STRAW

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Summary—Wheat planted directly into soil mulched with straw of a previous wheat crop (mulch or conservation tillage) typically grows and yields poorly relative to that planted into a prepared seedbed with straw residue burned or buried (clean tillage). This injurious effect associated with straw mulches has been greatest in the higher-rainfall wheat-growing areas, or in wet years in normally dry areas. Researchers have focused for the past 30 yr on putative phytotoxins thought to be liberated during microbial colonization or breakdown of the straw on or near the soil surface when wet. The results of experiments reported herein indicate that the causal microorganisms are in the soil and not the straw as would be required if phytotoxic straw decomposition products were important. The injury in these experiments resulted from at least three root diseases, all favored by the lack of crop rotation. The three root diseases were take-all caused by *Gaeumannomyces graminis* var. *tritici*, Rhizoctonia root rot caused mainly by *Rhizoctonia solani* AG8, and Pythium root rot caused by several *Pythium* spp. The effect of straw on, or mulched into, the soil surface possibly amounts to no more than helping to keep the top 10–15 cm of soil, the zone occupied by the root pathogens, more ideally moist for their activity. The results suggest that conservation tillage is feasible for wheat in the higher rainfall areas when used in combination with a break from wheat.

INTRODUCTION

Conservation (mulch) tillage leaves crop residue on the soil surface for protection against soil erosion and water evaporation. Direct drilling is the extreme whereby all residue of the previous crop is left on the soil surface and the crop is drilled directly through the residue and into the soil. Clean tillage is the other extreme, where the crop residue is buried, usually with a mold-board plow, prior to planting the next crop. The soil left without the protection of surface residues, and especially if also pulverized into a garden-type seedbed, is then prone to greater drying and to erosion. Systems that use less tillage also save soil organic matter, and direct drilling saves energy (Phillips *et al.*, 1980). Conservation tillage is therefore pivotal to making modern agriculture more resource-conserving and hence more sustainable.

In spite of the negative effects, fields cropped intensively to wheat (little or no crop rotation) in many wheat-growing areas of the world are still planted into seedbeds with straw from the previous crop buried by tillage or eliminated by open-field burning before planting. Wheat yields are commonly depressed when planted into a seedbed with straw of the previous crop still lying on the soil surface, a problem recognized since the introduction of stubble-mulch farming into North American Great Plains in the 1940s (McCalla and Army, 1961). Similar problems have been reported for wheat planted into wheat residue in Australia (Kimber, 1967) and England (Ellis *et al.*, 1975), and the U.S. Pacific Northwest (Zingg and Whitfield, 1957; Cook and Waldher, 1977; Papendick and Miller, 1977).

Zingg and Whitfield (1957) demonstrated that wheat yields are enhanced by mulch tillage in areas with low annual rainfall and high evaporative demand, such as in the northern Great Plains, presumably because the residues serve as a barrier to loss of precious water by evaporation. On the other hand, and for no apparent reason, yields in sub-humid areas such as the Palouse of eastern Washington and northern Idaho and parts of the southern Great Plains were depressed by mulch tillage, yet the principle of greater yield in response to more available water with less evaporation of water from the soil should apply across all of these ecosystems. Taking into account the lower actual yield compared with a higher attainable yield with mulch tillage compared with clean tillage in the higher-rainfall or wetter areas, the damage from this problem is significant.

Early work considered that the surface residues caused nutrient deficiencies by immobilization of plant nutrients such as N, S or P, but this hypothesis is now dismissed (Ferguson and Gorby, 1964; Smika *et al.*, 1967; Kimber, 1973b). The greatest research effort has been directed at putative phytotoxins thought to be liberated from the rotting straw (Guenzi *et al.*, 1967; Norstadt and McCalla, 1967; Kimber, 1973a,b; Elliott *et al.*, 1978). This line of

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investigation started with a report (McCalla and Duley, 1949) that corn seedlings emerged poorly when the seeds were planted in pots of soil taken from the top 15 cm of a cultivated field in Nebraska if the soil was amended with wheat straw and maintained excessively wet, but grew well in the same soil not amended with straw or amended with straw but maintained in a well-drained condition. These results were interpreted as evidence that the straw in the wet soil is toxic to the corn. Norstad and McCalla (1968) later proposed that the injury results from patulin produced by *Penicillium urticae* on the wheat straw. Harris and Kimber (1983) considered the possibility that a residue-associated injury of wheat in Australia results from phenolic acids, and Lynch (1977, 1978) presented evidence that this, or a similar problem in England, results from acetic acid produced during anaerobic decomposition of the straw on the soil surface or in direct contact with the wheat plants.

Cook *et al.* (1990) showed that the injurious effect to wheat seedlings of fresh wheat straw added to wheat-field soil in pots can be explained by increased damage from *Pythium* species, which are virtually ubiquitous in agricultural soils (Wilhelm, 1965) and well-known to gain in inoculum potential when supplied with fresh plant material (Yarwood, 1966). Moreover, while substances extracted from straw may be injurious to seed germination or growth of seedlings of wheat (Guenzi *et al.*, 1967), few if any of the earlier studies of putative phytotoxins carried the work far enough to reproduce the symptoms observed in the field, namely, reduced tillering and stunting of plants during heading and more advanced stages of wheat development (Tanchandrophongs and Davidson, 1970; Davidson and Santleman, 1973; Papendick and Miller, 1977). None of the previous studies with putative phytotoxins have shown that phytotoxins are responsible for the lower yield of wheat associated with conservation tillage.

In the Pacific Northwest, there is no negative affect of straw mulches on wheat yield if the soil and straw are fumigated with methyl bromide before planting the wheat (Cook *et al.*, 1980; Moore and Cook, 1984). Such results demonstrate a role of deleterious microorganisms or their products in the yield depression but do not distinguish between root pathogens in the soil vs possible toxin-producing microorganisms in the straw. The experiments reported in this paper take a new approach by addressing the question: are the microorganisms responsible for this problem in the straw, presumably where they would need to be if the problem results from phytotoxic decomposition products from the straw, or are they in the soil? The results suggest that the organisms are in the soil. Preliminary accounts of these findings have been reported in recent reviews (Cook, 1990; Rovira *et al.*, 1990; Cook and Veseth, 1991).

MATERIALS AND METHODS

Experiments with deep placement of chloropicrin at the time of planting

Experiments were carried out in the 1985–1986 crop year in adjacent fields near Fairfield, Wash. (Spokane County) to determine whether the well-documented effect of fumigating both the soil and straw could be produced by placement of a fumigant deep enough to treat the soil but not the straw. One field had been cropped to spring wheat the previous year and the other to lentils. The spring wheat stubble and residual straw were burned to eliminate the surface residue in one area 30 × 70 m and left untouched (natural standing stubble) in an adjacent identical area 30 × 70 m. (Both the burned and adjacent unburned spring wheat sites were in uniform deep silt loam soil with 5% slope and south exposure.) The lentil site, in an adjacent field, was nearly bare because of the small amount of residue left by this crop.

Each of the three sites were drilled direct with winter wheat cv Lewjain in a north–south direction in paired rows (Fig. 1) using a commercially available "no-till" drill (Yielder Co., Spokane, Wash.) (Papendick, 1984). The seed was planted 3–4 cm deep at about 90 kg ha^{-1}, and nitrogen as aqua ammonia was injected simultaneously with the seeding operation as a band between each pair of rows (Fig. 1) about 12–13 cm deep to provide 120 kg N ha^{-1}. The

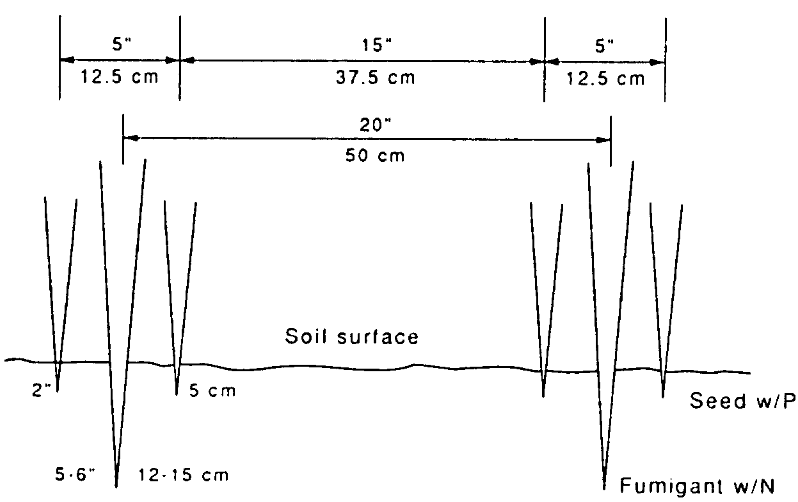

Fig. 1. Paired-row configuration used to direct drill wheat, showing depths, spacings, and relative positions of seeders, fertilizer placement and fumigant placement (when used).

drill was equipped to seed eight pairs of rows with a fertilizer band between (shared by) each pair of rows. Chloropicrin was metered through separate tubes into the deep bands (12–13 cm deep) with the nitrogen on one half of the drill (four adjacent pairs of rows) at either 9.4 or 18.8 l ha^{-1}. Nitrogen fertilizer only (check) was injected in the deep bands in the other half of the drill (four adjacent pairs of rows). Five 70 m long parallel drill strips were planted per rate of chloropicrin and accompanying fertilizer-only control in each experiment. The amount of fumigant was deliberately small to avoid injury to the wheat seed as the gas moved by diffusion through the soil, and also to ensure that any fumigation effect would likely be limited to soil and not the straw on or above the soil. Yields were determined by harvesting a 25 m length of the two center pairs of rows of both the treated and untreated halves of each drill strip using a Nurserymaster Wintersteiger combine. The data were analyzed by a paired-plot comparison and t-test for significance between the treated and untreated halves of the drill used to plant the experiment.

A similar experiment was carried out at Pullman, Wash. (Whitman Co.). Spring wheat (cv Fielder) was seeded with a plot-scale "no-till" drill (also made by Yielder, but equipped to plant only five pairs of rows) directly into standing stubble of winter wheat (stubble of the third consecutive direct-drilled crop of wheat grown on the site). Chloropicrin was injected about 12 cm deep between the five pairs of rows at the time of planting at 0 (fertilizer-only check), 9.4, 18.8, and 47.2 l ha^{-1} replicated five times in plots 30 m long in a complete randomized block design. The center three pairs of rows were harvested to determine yield and the data were analyzed by ANOVA.

Tests for influence of a 1 yr break to "chemical fallow"

Winter wheat was direct drilled at Pullman on 8 October 1987, on a site that had been direct drilled to winter wheat for 4 yr consecutively (1983–1986), and then left as undisturbed fallow (weeds controlled by herbicide treatment only and not by tillage, referred to as "chemical fallow") between termination of the 1986 crop and planting in the fall of 1987 (for a 1988 crop). The 1986 crop in this sequence was terminated early with a flail mower when the plants were still green but headed (not harvested for grain) because of severe damage from a combination of root diseases (take-all caused by *Gaeumannomyces graminis* var. *tritici*, Rhizoctonia root rot caused by *R. solani* AG8, and, Pythium root rot caused mainly by *P. irregulare* and *P. ultimum*), weeds, and possibly other problems. Most of the wheat and weed residue left on the soil surface had decomposed during the break, and the soil was nearly bare by the time of planting of our experiment.

This site provided an opportunity to confirm that wheat can grow and yield well when direct drilled if provided first with at least a 1 yr break. Subplots arranged within the site in a randomized block design were fumigated with methyl bromide beneath a clear plastic tarp (to produce a "pathogen-free" check) or left nonfumigated (natural soil). The site was direct drilled to winter wheat cv Hill-81 on 9 October 1987, using a custom-made plot seeder equipped with double-disk openers (ACRA-Plant, Garden City, Kan.) and with fertilizer shanks (Riper-Shooter, McGregor Co., Colfax, Wash) positioned in front of each opener to inject liquid N, P, and S within each row and 12–14 cm deep (7–8 cm below the seed) all as a one-pass operation. The rate of fertilization was based on results of a standard soil test for available nutrients and a target yield goal of 8000 kg ha^{-1} as determined by available water and expected precipitation (see below).

Experiments with fumigated soil or fumigated straw or both

Two nearly identical field experiments were made near Fairfield and Pullman, Wash., respectively, in fields cropped to wheat for each of the 3 previous years, with treatments arranged in complete randomized block designs of fumigated or natural soil with fumigated, natural or no straw on the soil surface, in all possible combinations and five replications. The Fairfield site had been in spring wheat the previous year and was burned immediately prior to fumigation. The Pullman site had been in winter wheat the previous year and was made bare by hand raking as much straw as possible from the plot area about 1 week before fumigation. Subplots were fumigated or left natural, direct drilled (using the custom-made one-pass plot seeder with rows spaced 30 cm apart and fertilizer solution injected directly beneath the seed at the time of planting) with cv Hill-81 winter wheat, and immediately (same day) covered uniformly with fumigated or natural straw at about 2 t ha^{-1} or left bare. The straw was from a local field harvested 2 months earlier and was fumigated under a clear plastic tarp at each site with methyl bromide. Each plot was direct drilled with the soft white winter wheat cv Hill-81 in rows 30 cm apart and with N, P, and S injected below each row as a liquid solution for targeted yields of 7400 ha^{-1} at the Fairfield site and 8000 ha^{-1} at the Pullman site. Yields were determined by harvesting five of the eight rows in each plot. The data were analyzed by ANOVA, and significant differences among treatments were determined by Duncan's multiple range test.

Estimation of fertilizer requirements based on soil tests and yield goals

A standard commercially-available soil test was used to estimate available N as NO_3 in the top 120-cm depth of soil and N as NH_4, P and PO_4, and S as SO_4 in the top 30 cm of soil. Based on local experiences and recommendations to wheat growers in this region, we assumed average mineralization of N for nontilled (except at planting) soil, namely, that an addition 20 kg N ha^{-1} would become available for the crop for each 1% organic matter content of the soil up to 3% (Steve Reinertsen, McGregor Co., Colfax, Wash., pers. commun.). Available water was also determined for the 120 cm depth of soil at the time of planting, and this value together with the value for average rainfall during the growing season was used to set a yield goal, from which the amount of N, P and S needed as fertilizer to reach this yield goal was calculated. Again, based on local experience and recommendations, we used the figure of 190 kg ha^{-1} attainable yield for each 1-cm available water after the first 10 cm of water (Cook, 1986). Thus, with a total estimated available water of 50 cm, discounting 10 cm (as adequate to support some plant growth but not grain formation), the yield goal would be 7500 kg ha^{-1}. We used the N:yield relationship of 45 kg N:1000 kg grain, so that to reach a yield goal of 7500 kg ha^{-1} would require a total (residual, mineralized, and applied) of 340 kg N ha^{-1}.

Assessment of inoculum density and incidence of infections

Inoculum density was estimated only for *Pythium* spp and only for soil taken from the top 15 cm. The method of sampling, processing the soil samples, and dilution-plate counting was as described by Cook *et al.*, (1990). We used the *Pythium*-selective medium of Mircetich (1971).

The incidence of *Pythium* infection of seedlings was determined on plants in the 1- to 2-leaf stage by plating the scutellum and adjoining tissue representing the region of root–shoot transition from at least 25 seedlings dug from each replicate. The method of obtaining and washing this segment from each seedling was as described (Hering *et al.*, 1987). The segments were plated on 2% water agar, five segments per plate, and incubated for 24 h at 20°C. The incidence of *Pythium* infection was calculated from the number of segments that scored positive for growth of *Pythium* onto the water agar.

The incidence and severity of root infections by *Pythium* spp, *R. solani*, and *G. graminis* var. *tritici* was estimated on a subjective scale by examining washed roots of plants dug from the plots in early spring (just prior to onset of stem extension), at heading, near maturity, or on stubble just after harvest. The occurrence of take-all was recognized as typical black lesions or blackened bases of the mainstems and tillers. The occurrence of Rhizoctonia root rot was recognized as reddish brown cankerous lesions or more commonly as "spear-tips" (Rovira, 1986; Weller *et al.*, 1986). The occurrence of Pythium root rot was recognized as general browning of the cortical tissues and absence of fine laterals (Chamswarng and Cook, 1985).

RESULTS

Influence of deep placement of chloropicrin to fumigate the soil but not the straw

Without deep-band fumigation (controls), yields averaged 1600 and 1300 kg ha^{-1} greater on the lentil and burned spring wheat sites, respectively, than on the unburned spring wheat site (Table 1). Within sites, the wheat was uniformly dense and deep green in both the lentil and burned spring wheat sites with or without deep-band fumigation, and yields were also the same on these two sites with or without fumigation. In contrast, the wheat on the unburned spring wheat site was uniformly dense and deep green only in the rows treated with chloropicrin, and these rows yielded 700 kg ha^{-1} or about 14% more (significant at $P = 0.05$) in response to deep-band placement of the chloropicrin.

The wheat in the unburned nonfumigated rows showed the symptoms typical of direct drilled wheat after wheat (no crop rotation) in the area, namely, uneven height of adult plants, smaller heads, more open canopy (more space between the rows) and light green color with some yellowing of the flag leaves. These are typical symptoms of root diseases, namely take-all and Pythium root rot, both of which were diagnosed on these plants. Moreover, these are the symptoms eliminated by methyl bromide fumigation of soil and straw under a tarp (Cook *et al.*, 1980; Moore and Cook, 1984; Cook *et al.*, 1987), or in some past experiments with metalaxyl applied in the seed furrow with wheat direct drilled into wheat stubble (Cook *et al.*, 1980). All rows treated with chloropicrin in the deep band stood out as distinctly healthier than the adjacent rows without chloropicrin in the unburned spring wheat site, but the treatments could not be distinguished (because of the much healthier checks) in either the lentil or burned spring wheat site. The response in the unburned spring wheat site was the same whether the rate was 9.4 or 18.8 l ha^{-1}.

Likewise in the experiment at Pullman, where cv Fielder spring wheat was direct drilled into standing winter wheat stubble (becoming the fourth consecutive direct-drilled wheat crop), yields averaged 3000 kg ha^{-1} with N only (checks), 3700 kg ha^{-1} with chloropicrin in the deep band at 9.4 l ha^{-1} (14% increase, significant at $P = 0.05$), 3600 kg ha^{-1} with chloropicrin at 18.8 l ha^{-1}, and 3400 kg ha^{-1} with chloropicrin at 47.2 l ha^{-1}. The yields in response to the three rates of chloropicrin were not significantly different from each other at $P = 0.05$.

Influence of a 1 yr break to chemical fallow

A soil test revealed a total of about 200 kg N ha^{-1} as NO_3 and NH_4 (combined) residual in the 120-cm profile *ca.* 3 months before this site was to be planted.

Table 1. Yields of soft white winter wheat in response to the in-soil placement of chloropicrin with the fertilizer solution at the time of direct drilling into sites with different crop histories and amounts of surface residues

Site history	Yield (t ha^{-1}) per fumigation rate			
	Control	9.4 l ha^{-1}	Control	18.8 l ha^{-1}
Previous crop: spring lentils; natural lentil residue	6.19	6.27	6.18	6.32
Previous crop: spring wheat; natural wheat residue	4.55	5.10**	4.52	5.27**
stubble burned	5.84	5.98	5.81	5.81

Rows were in pairs spaced 12.5 cm apart, with 37.5 cm between pairs. Nitrogen as aqua ammonia was injected as a band 12–13 cm deep between the paired rows and chloropicrin at the indicated rates was metered through separate tubes into the fertilizer deep-band. Each drill strip of eight pairs of rows 30 m long received chloropicrin on one half (4 adjacent pairs) and fertilizer only in the other half (check). Significant differences are indicated by the double asterisk ($P = 0.01$) according to the student *t* test for five comparisons (drill strips) per site and rate of fumigation (reading across).

With 3.9% organic matter content in the soil, we estimated conservatively (because the site would not be tilled, except as part of the planting operation) that another 60 kg N ha^{-1} would become available to the crop by mineralization. Based on available water in the profile and anticipated precipitation, we set a yield goal of 8000 kg ha^{-1}, which would require an estimated 360 kg N ha^{-1} to produce. With 260 kg N ha^{-1} already available or anticipated, another 100 kg N ha^{-1} together with 10 kg P ha^{-1} and 20 kg S ha^{-1} was applied as a solution mixture below the seeds at the time of planting to reach the yield goal.

The yields in the natural and fumigated plots were outstanding (for the region) and remarkably uniform at an average of 8710 kg ha^{-1} (109% of targeted yield), with no significant difference between fumigated and nonfumigated plots. The soil contained an estimated 326 propagules (mainly oospores) of *Pythium* spp g^{-1} in the top 15 cm at the time of planting. However, the fall of 1987 was one of the driest on record for eastern Washington, and fortuitously the seed zone apparently was only wet enough for wheat seed germination but too dry for infection by *Pythium*; seedling emergence was excellent throughout the plot area but a random collection of wheat seedlings in the 1-leaf stage revealed <5% embryo infection, compared with the more typical 30–90% embryo infection by *Pythium* spp in wet seedbeds (Hering *et al.*, 1987; Fukui, 1988). Symptoms of Pythium root rot but only rarely of take-all or Rhizoctonia root rot were found at later stages of plant development.

A soil test with samples taken from the 120-cm depth at this same site on 19 September 1988 (about 1 month after harvest of the 1987–1988 winter wheat crop), revealed 64 kg N ha^{-1} of available NO_3 and NH_4 combined, about half of which was a NO_3 in the top 30 cm. In other words, the outstanding crop produced on this site left relatively little available N as residual in the soil profile.

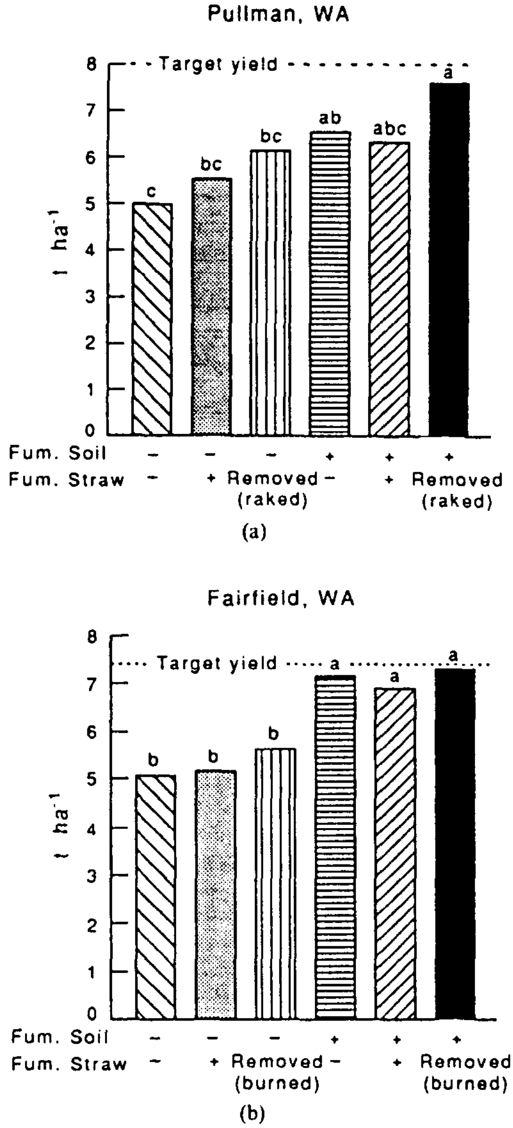

Fig. 2. Yields of soft white winter wheat cultivar Hill 81 direct drilled into a site cropped the previous year to spring wheat (Fairfield) or winter wheat (Pullman) with soil either fumigated (+) or not fumigated (−) and straw either fumigated (+) or not fumigated (−). Straw was removed from one set of plots by burning at Fairfield site and by hand raking at Pullman site. The fumigated or natural straw was layered on the soil surface at about 2 t ha^{-1} immediately after planting. Bars with the same lower case letter are not significantly different at $P = 0.05$.

Direct evidence that the responsible microorganisms are in the soil

In both the Pullman and Fairfield experiments, wheat yields were highest in plots with fumigated soil, whether the soil was covered with natural or fumigated straw, and were lowest in plots with natural soil, whether or not the straw on the soil was fumigated (Fig. 2). Yields were slightly but not significantly ($P = 0.05$) higher in plots with no straw than with straw, regardless of the method by which the straw was removed. This rules out any unique effects of burning *per se*. The yields in plots made both bare and fumigated averaged 7370 kg ha^{-1} or 92% of the targeted yield at the Pullman site, and 7300 kg ha^{-1} or 99% of the targeted yield at the Fairfield site. By comparison, the yields in nonfumigated plots covered with either natural or fumigated straw averaged 4960 kg ha^{-1} or 62% of the targeted yield at the Pullman site and 5030 kg ha^{-1} or 68% of the targeted yield at the Fairfield site.

Root diseases were severe in the nonfumigated plots at both the Pullman and Fairfield sites. At the Pullman site, take-all was the dominant root disease and was evident at the Fairfield site as both a high frequency (80–90%) of plants with infected seminal and crown roots and about half of the plants with blackened tiller bases that extended 2–3 cm up the stems. Some take-all was also evident on roots and lower stems of plants in the fumigated plots at Pullman, but not until the plants were headed. Pythium root rot was the second most important root disease at the Pullman site but was observable only on roots without take-all. At the Fairfield site, take-all and Rhizoctonia root rot occurred in roughly equal severities on the same plants and often on the same roots. Pythium root rot was third in importance among the three root diseases at this site. Take-all was evident as a high frequency of infected seminal roots followed by crown roots but relatively low frequency of blackened stem bases and these were nearly all mainstems. This is typical of take-all development under conditions represented by wet soils during early stages of plant development followed by relatively dry surface soil beginning with stem extension and subsequent stages of plant development (Cook, 1981). The incidence of white heads (prematurely dead wheat), typical of severe take-all, occurred at ~10% in the nonfumigated plots at Pullman but <1% at Fairfield.

DISCUSSION

Burning the stubble and associated straw residue can give relief from the yield depression associated with planting wheat into soil otherwise left covered with the residue of the previous wheat crop. However, our results indicate, and for the first time, that the microorganisms responsible for the disappointingly poor performance of wheat grown in these management systems probably are in the soil and not in the straw where they would need to be if phytotoxic straw-decomposition products played a role in the etiology of this problem. All of our experiments were conducted in the field, which helps insure that the problem we studied was not an artefact. Previous evidence that straw is injurious to wheat when mixed with natural soil in pots incubated under controlled conditions can be explained by increased *Pythium* damage promoted by the saprophytic increase of this pathogen in response to energy sources from the straw (Cook *et al.*, 1990). These findings collectively call into question some 30 yr of research on putative phytotoxins from rotting straw and proposed as the cause of the common injury to wheat long associated with straw mulches.

It is unlikely that the small amount of fumigant injected 12–13 cm deep, and that produced a yield response exclusively for wheat direct drilled into standing stubble, would have affected microorganisms in the straw and standing stubble above the soil. Moreover, if the increased growth and yield response of wheat to chloropicrin was the result of direct stimulation of the wheat plants, inhibition of nitrification, or increased mineralization of N, then the response should have occurred in all three experiments rather than just the one experiment with wheat planted directly into the stubble.

In previous work (Cook and Haglund, 1982; Cook *et al.*, 1987), we showed experimentally that the small flush of N and the inhibition of nitrification associated with soil fumigation cannot explain the increased growth and yield response of wheat to soil fumigation. In our present study, we present more evidence in favor of the importance of root pathogens to account for the growth and yield response to soil fumigation by showing that yields were increased specifically in response to fumigating the soil, regardless of whether the soil was covered with fumigated or natural straw. Crookston and Kurle (1989) took a similar experimental approach in field trails designed to reveal whether corn residue was responsible for the relatively lower yield of corn after corn than corn after soybean, by moving corn residue to plots after harvest of soybeans and then planting corn. Soybeans yielded better after corn than after soybeans, and conversely corn yielded better after soybeans than after corn, regardless of whether corn residue was added to the plots prior to planting the next crop.

The most overlooked feature of the problem of low wheat yields with mulch tillage is that wheat seeded into wheat straw is also wheat grown without benefit of a break, i.e. crop rotation. There is no other practical way for farmers to plant wheat directly into wheat stubble. Tillage and associated seedbed preparation was not a prerequisite to high yield of wheat on the site where no crop other than wheat had been planted for 4 yr consecutively followed by a 15-month break to chemical fallow; the crop was devastated by root diseases and weed competition the year before the break but yielded 8700 kg ha^{-1} or 109% of the targeted yield the year after the break and with no increased-yield response to methyl bromide fumigation.

Of the several wheat root pathogens favored when wheat is grown without benefit of crop rotation, *G. graminis* var. *tritici*, *R. solani*, and *Pythium* species singly or collectively can produce the same symptoms ascribed to phytotoxins, namely, stunted spindly plants, yellowing of the leaves, and poor tillering (Cook *et al.*, 1980; Moore and Cook, 1984; Rovira and Venn, 1985; Rovira, 1986; Weller *et al.*, 1986). Most significantly, each of these three root diseases are widespread, and each has been shown experimentally in field plots, both in the U.S. Pacific Northwest (Cook *et al.*, 1980; Moore and Cook, 1984; Pumphrey *et al.*, 1987; Weller *et al.*, 1987) and in the southern Australian wheat belt (Rovira and Venn, 1985; Rovira 1986), to be more severe when wheat is planted directly into undisturbed soil covered with wheat residue than when planted into a prepared seedbed. In the present study, take-all, Rhizoctonia root rot, and Pythium root rot occurred as mixtures at both the Fairfield and Pullman sites. However, it was necessary to examine washed roots to document these diseases. Above-ground symptoms were mainly or almost entirely (depending on the site) evident as stunting, uneven plant height, and more open canopy (more open space between the rows). The major responses of wheat to soil fumigation are more tillers with heads (which results in a more dense canopy), taller plants, and more even plant height (Cook and Haglund, 1982; Cook *et al.*, 1987).

These results confirm a vast experience and literature showing that the effects of wheat root diseases can be controlled and yields of wheat can be enhanced significantly by a break from wheat for as little as 1 yr. The effects of surface residues on root diseases in the absence of a break can be explained by the commonly wetter and cooler soil environment, especially in the top 10–15 cm of soil where the root pathogens of wheat are concentrated and most active. *G. graminis* var. *tritici*, *R. solani*, and *Pythium* spp all grow best at relatively high water potentials (reviewed in Cook and Papendick, 1972). *Pythium* attack of wheat is dependent on soil matric potentials of −0.04 mPa or wetter (Hering *et al.*, 1987). Removal of straw by burning has long been practised in certain humid or subhumid wheat-growing areas, e.g. the inland Pacific Northwest and U.K., but is not an acceptable alternative over the long term. Soil fumigation is a valuable research tool but is not economical as a means to control the root pathogens of wheat. Other methods, including crop rotation, must be used to control these root diseases and thereby open the way for wider use of conservation tillage.

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