Diseases of Wheat in Long-Term Agronomic Experiments at Pendleton, Oregon

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ABSTRACT

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

Diseases of winter wheat were evaluated over 3 years in four long-term (27- to 60-year) cropping system experiments. Disease incidence and severity were evaluated with respect to seasonal precipitation and soil chemical and microbiological parameters. Take-all and eyespot were associated with increasing precipitation, and Rhizoctonia root rot and Fusarium crown rot were favored by drought. Eyespot and crown rot increased with rate of applied nitrogen and were inversely proportional to soil pH. Surface residue from previous crops had variable effects on diseases. Crown rot increased with amount of surface residue and was directly correlated with soil organic nitrogen and carbon. Surface residue also had a variable effect on Rhizoctonia root rot, depending on the magnitude of soil microbial respiration; root rot increased directly with amount of residue in a wheat–summer fallow rotation and was unaffected by residue or tillage in a wheat–pea rotation. Repeated burning of wheat stubble caused variable disease response, depending on precipitation and nitrogen rate. At high fertility, burning suppressed Pythium root rot and Rhizoctonia root rot, and enhanced eyespot and take-all. Effects of crop rotations on diseases appeared related to soil microflora effects on pathogen survival or virulence. Rhizoctonia root rot was most damaging in wheat–fallow rotation, Pythium root rot in wheat–fallow and annual wheat, and eyespot and crown rot in annual wheat. Diseases were collectively least prevalent where nitrogen in a wheat–fallow rotation was applied as pea vines or manure, rather than as inorganic fertilizer. Diseases also were generally less damaging in a wheat–pea rotation than in an annual wheat or wheat–fallow rotation. Soilborne plant pathogenic fungi appeared to suppress wheat yield by 3 to 12%. Long-term experiments provided insights to crop management and seasonal effects that are unlikely to be identified in short-term experiments.

Additional keywords: *Fusarium graminearum* Group 1, *Gaeumannomyces graminis* var. *tritici*, *Pisum sativum*, *Pseudocercosporella herpotrichoides*, *Pythium* spp., *Rhizoctonia solani* AG-8, *Triticum aestivum*

Most information on effects of crop and soil management practices on diseases of winter wheat (*Triticum aestivum* L.) has been developed from short-term (<5 years) experiments and observations of commercial fields. Comparative effects of management variables in long-term experiments with multiple pathogens are generally not known.

Five long-term experiments at the Columbia Basin Agricultural Research Center near Pendleton, Oregon, (27) represent a unique resource for sustainable crop production. Three experiments are among the oldest studies in the western United States and are included in the 13 oldest active long-term agronomic studies in North America (21). Information reported for soil chemical, physical, and microbiological properties in these plots (summarized in reference 27) was used to evaluate economic and biological sustainability of wheat–fallow production systems (12). Eyespot (29) and physiologic leaf spot (38) have been studied, but effects of long-term treatments on incidence and severity of other diseases remains unknown. Information on diseases caused by soilborne pathogens is becoming increasingly important as agriculture in the region shifts from inversion- to conservation-tillage systems, and is needed to direct further research on pathogen dynamics and disease epidemiology and control.

Objectives of this study were to: (i) identify and quantify diseases of winter wheat roots, crowns, and culms over 3 years in long-term management experiments at the Columbia Basin Agricultural Research Center; (ii) examine relationships between diseases and existing knowledge of soil organic carbon and N, soil pH, and soil microbial biomass; and (iii) compare incidence and severity of diseases in experiments featuring different cropping systems.

Oregon Agric. Exp. Stn. Technical Paper 10,235.

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Accepted for publication 13 April 1996.

Publication no. D-1996-0513-08R

MATERIALS AND METHODS

The Columbia Basin Agricultural Research Center is 13 km NE of Pendleton, at an altitude of 460 m. The climate is temperate with warm, dry summers and cool, wet winters. About 75% of the 414 mm mean annual precipitation occurs from November to May. Evaporative potential exceeds precipitation from March through October.

The soil is a Walla Walla silt loam (coarse-silty mesic Typic Haploxerolls), well drained, and with relatively level topography. The upper 10 cm of soil has a range of chemical, physical, and biological characteristics that depend on cultural practices. Examples include: soil pH = 4.4 to 6.4 (in 0.01 M $CaCl_2$), soil organic matter = 1.8 to 2.7%, organic N = 0.7 to 1.4 g/kg, organic C = 10 to 18 g/kg, bulk density = 1.1 to 1.3 Mg/m^3, and microbial biomass from 255 to 1,158 mg C/kg (5,26,27,30,31).

The soft-white winter wheat cultivar Stephens, used in all tests, was planted at 30-cm-wide row spacing. Weeds in wheat were controlled in the spring by applying bromoxynil + MCPA (0.56 + 0.56 kg/ha, as Bronate), metribuzin (0.22 kg/ha, as Sencor or Lexone), ethylmetribuzin (0.89 kg/ha, as Tycor), or 2,4-D amine + thifensulfuron + tribenuron (0.89 + 0.014 + 0.007 kg/ha, as 2,4-D Amine + Harmony Extra). The latter mixture was sometimes supplemented with diuron (0.22 kg/ha, as Karmex). Crop years for winter wheat in this study are designated by the year of harvest; e.g., 1989 refers to the 1988 to 1989 crop year.

Annual wheat. A continuous winter wheat experiment began in 1931 as eight 12 × 60 m nonreplicated plots. Plots were treated uniformly since 1951, and four plots sampled in this study were analyzed as replicates of a single treatment (annual winter wheat). After harvest, ammonium phosphate sulfate (23 kg N/ha) was broadcast and incorporated by moldboard plowing to 18-cm depth. An additional 88 kg N/ha, as ammonium nitrate, was broadcast on the surface and incorporated by rotary harrow, disking, and rod-weeding. Planting dates were 25 October 1988, 25 October 1989, and 10 November 1990.

Wheat–pea rotation. A winter wheat–green pea (*Pisum sativum* L.) rotation with four tillage treatments was initiated in 1963. Main plots are 7 × 36 m arranged in randomized blocks with eight replicates; four replicates are planted to peas and four to wheat each year. Two treatments were sampled during this survey, one conventional and one conservation tillage. Conventional tillage consists of moldboard plowing in the spring before planting peas and again in autumn before planting wheat (designated as tilled treatment). Conservation tillage consists of no tillage before planting peas and limited sweep tillage for wheat (designated as untilled). Plowing and sweeping are to depths of 15 and 5 cm, respectively. Wheat received 90 kg N/ha, as ammonium nitrate applied before planting, and peas received 23 kg N/ha as ammonium phosphate sulfate (16-20-0). Planting dates were 25 October 1988, 25 October 1989, and 10 November 1990.

Wheat–summer fallow rotation: residue management experiment. A crop residue management experiment, established in 1931, includes duplicate sets of treatments that allow data to be collected yearly. There are two replicates and nine 12 × 40 m treatments in each set. The north and south halves of each treatment vary in soil depth due to topography and bedrock. All treatments are moldboard plowed 20 cm deep in the spring after residue amendments have been added. Repeated shallow (5 to 8 cm) secondary tillage with a rod-weeder is used to conserve moisture and control weeds during fallow. Planting dates were 25 October 1988, 6 October 1989, and 13 November 1990. Eight treatments sampled for this survey included: (i) no added fertilizer since 1931; (ii) treatment one repeated except that wheat stubble is removed by burning in the spring; (iii) and (iv) application of 45 and 90 kg N/ha, respectively (ammonium nitrate broadcast from 1967 to 1988, and urea-ammonium nitrate banded 15 cm deep with 25-cm shank spacing from 1989 to present); (v) and (vi) treatments three and four repeated except that the wheat stubble is burned in the spring; (vii) cow manure (22.4 Mg/ha per crop, averaging 111 kg N/ha) applied 1 to 6 days prior to plowing; and (viii) pea vines (2.24 Mg/ha per crop, averaging 34 kg N/ha) applied 1 to 6 days prior to plowing. Disease data were collected from the north and south half of each treatment and, with two replicates, were analyzed as four replicates.

Wheat–fallow rotation: tillage × fertility experiment. This experiment was established in a winter wheat–fallow rotation in 1940, with the wheat crop harvested in odd-numbered years. The experiment contains three main plot tillage variables and six subplot levels of N application, five of which were sampled. Subplots are 6 × 40 m and are replicated three times in a randomized complete block design. Tillage treatments include moldboard plow (23 cm deep, 95% of crop residue buried), offset disk (15 cm deep, 60% of residue buried), and 30-cm subsurface sweeps (15 cm deep, 35% of residue buried). Urea-ammonium nitrate was banded 15 cm deep with 25-cm shank spacing at rates of 0, 45, 90, 135, and 180 kg N/ha. Planting dates were 10 October 1988 and 11 October 1990.

Disease survey. The annual wheat, wheat–pea, and wheat–fallow experiments were sampled each spring (April to May) in 1989, 1990, and 1991. The tillage × fertility wheat–fallow experiment was sampled in 1989 and 1991. Samples were collected when plants were about Haun growth stage 8 (eight fully extended leaves on the main stem; 7). All plants in three randomly selected 1-m rows were removed from each plot during 1989, and at least 20 randomly selected plants per plot were collected during 1990 and 1991. Soil was washed from the roots, and plants were stored up to one day at 4°C until evaluated. Disease parameters included severity of cortical and vascular necrosis on seminal and coronal root main axes caused by Rhizoctonia root rot (*Rhizoctonia solani* Kühn AG-8), percentage of plants with symptoms of Rhizoctonia root rot, percentages of roots and plants with lateral root pruning caused by Pythium root rot (*Pythium* spp.), percentages of roots and plants with vascular or cortical blackening caused by take-all (*Gaeumannomyces graminis* (Sacc.) Arx & D. Olivier var. *tritici* J. Walker), percentages of culms and plants with eyespot lesions caused by *Pseudocercosporella herpotrichoides* (Fron.) Deighton, and percentages of plants with dark lesions on the subcrown internode caused by a crown and root rot complex (primarily *Fusarium graminearum* Schwabe Group 1 but including *F. culmorum* (Wm.G. Sm.) Sacc. and *Cochliobolus sativus* (Ito & Kuribayashi) Drechs. ex Dastur). Percentages of prematurely ripened wheat heads (whiteheads) were assessed for two adjacent 3-m segments of row during July 1989 and 1991. The primary reason for development of whiteheads was determined by inspecting wheat roots, crowns, and culms.

Rhizoctonia root rot severity of seminal roots was evaluated by a 0 to 5 scale, where 0 = no lesions, 1 = lesions on <25% of first-order and <50% of second-order lateral branches, 2 = lesions on 25 to 50% of first-order and >50% of second-order lateral branches, 3 = lesions on >50% of first-order lateral branches, 4 = lesions on one to two main axes, and 5 = lesions on three or more main axes. Rhizoctonia root rot severity of coronal roots (0 to 4 scale) was based on percentage of main root axes with lesions: 0 = none, 1 = <25%, 2 = 26 to 50%, 3 = 51 to 75%, and 4 = >76%.

Periodic isolations were made from symptomatic roots, subcrown internodes, crowns, and culms. Tissue segments were washed under running water for 3 h and then, without surface-disinfection, placed in petri dishes containing 2% water agar amended with rifampicin at 50 µg/ml. Incubations were at 24°C. Pure cultures were obtained by transferring hyphae onto 0.5-strength commercial potato-dextrose agar and were identified.

Relationships between diseases and selected soil chemical parameters were evaluated by using reported data for soil pH, soil organic matter (g C/kg and g N/kg), and soil microbial biomass (mg

Table 1. Disease incidence and grain yield for annual winter wheat experiment at Pendleton, Oregon

Crop year	Rhizoctonia root rot[a]	Pythium root rot[a]	Take-all[a]	Eyespot[b]	Fusarium crown rot[c]	Yield (kg/ha)
1989	18.1	ND[d]	4.2	63.6	3.8	4,797
1990	21.2	36.7	5.7	46.3	7.4	2,733
1991	45.2	7.6	6.1	23.7	5.8	3,780
LSD (0.05)	10.3	12.1	ns	11.4	ns	892

[a] Percentage of main root axes with symptoms of Rhizoctonia root rot, Pythium root rot, or take-all.
[b] Percentage of culms with eyespot lesions.
[c] Percentage of plants with subcrown internode lesions caused primarily by *Fusarium graminearum*.
[d] ND = not determined, ns = not significant.

Table 2. Disease incidence and grain yield for winter wheat in tilled or untilled treatments of a wheat–pea rotation at Pendleton, Oregon

Tillage Crop year	Rhizoctonia root rot[a]	Pythium root rot[a]	Take-all[a]	Eyespot[b]	Fusarium crown rot[c]	Yield (kg/ha)
Tilled						
1989	17.2	ND[d]	10.2	2.4	0.5	5,033
1990	21.1	0.4	16.5	10.1	4.1	4,127
1991	18.4	6.1	19.1	3.8	2.3	6,160
LSD (0.05)	ns	ns	ns	ns	ns	968
Untilled						
1989	19.2	ND	11.3	5.2	1.3	5,192
1990	18.1	0.3	17.1	12.1	6.2	3,546
1991	4.7	2.5	8.6	0.4	3.3	5,155
LSD (0.05)	9.8	ns	ns	7.2	ns	661

[a] Percentage of main root axes with symptoms of Rhizoctonia root rot, Pythium root rot, or take-all.
[b] Percentage of culms with eyespot lesions.
[c] Percentage of plants with subcrown internode lesions caused primarily by *Fusarium graminearum*.
[d] ND = not determined, ns = not significant.

C/kg) during fallow or in-crop cycles (5,26,30,31). During 1988, soil pH for each treatment was measured in a 1:2 suspension of soil in 0.01 M $CaCl_2$ (2).

RESULTS

Environmental conditions. This survey began with wheat planted after an abnormally dry winter (1988 crop year), leading to suboptimal water storage in the fallow cycle of wheat–fallow rotations and for both wheat and peas in the wheat–pea rotation. Precipitation during September and October each year of this experiment was lower than the 20-year mean. Two winters (crop years 1990 and 1991) were significantly drier than normal, and one (1989) was wetter than normal. Precipitation during May and June each year was above the 20-year mean and, for the 1991 crop, was more than twice the norm. The winter and spring of 1990 and 1991 were colder than other years, but mean monthly temperatures were otherwise comparable each year and did not deviate markedly from the 20-year norm.

Annual wheat. The incidence of Rhizoctonia root rot did not differ for crop years with the wettest (1989) and driest (1990) autumn and winter months, but was significantly higher following the driest year (Table 1). The severity of Rhizoctonia root rot was less ($P < 0.05$) during the wettest than during the two drier years; root rot ratings on seminal roots were 0.8 in 1989 and 2.3 during 1990 and 1991, and on coronal roots were 0.3 during 1989 and 1.0 and 1.7 in 1990 and 1991 (LSD = 1.5 for seminal roots and 0.8 for coronal roots).

The incidence of Pythium root rot was less in 1991 than in 1990 (driest year) but was not evaluated during the wettest year (1989) (Table 1). Eyespot incidence was highest during the wettest year and less in years with drier autumn and winter periods. The incidence of take-all and crown rot, caused primarily by *F. graminearum* Group 1, was always low and did not vary from season to season. Grain yield was highest during the wettest year and lowest during the driest year (Table 1).

Wheat–pea rotation. The incidence and severity of Rhizoctonia root rot and take-all did not differ between tillage treatments during 2 of 3 years. In 1991, the incidence of both diseases was higher in tilled than in untilled soil (Table 2). Incidence of Rhizoctonia root rot was equivalent during years with the wettest (1989) and driest (1990) autumn and winter months. Severity of Rhizoctonia root rot in both tilled and untilled soil was lowest during the wettest year (ratings of 0.6 to 0.7), highest during the driest year (ratings of 2.2 in both treatments), and intermediate during a year of intermediate precipitation (ratings 1.1 to 1.3).

Pythium root rot was not evaluated during the wettest year and did not differ during the other 2 years. Eyespot, take-all, and crown rot did not differ significantly during the wettest and driest years.

When averaged over years, wheat yields for the two tillage systems differed significantly ($P = 0.03$), and there was no year × tillage interaction. Yield in tilled soil exceeded that in untilled soil during 2 of 3 years.

Wheat–fallow rotation: residue management experiment. Incidence of Rhizoctonia root rot was highest during the driest crop years (1990 and 1991) ($P = 0.02$; data not shown). When averaged over seasons (Table 3), root rot incidence was less ($P < 0.05$) when pea vines, manure, or no N were applied than when 45 or 90 kg N/ha were applied from an inorganic source. When organic treatments were excluded from the data, the burn treatment significantly ($P < 0.01$) reduced the incidence of Rhizoctonia root rot at each level of applied N (0, 45, or 90 kg N/ha).

Severity of Rhizoctonia root rot on seminal and coronal roots was low to intermediate each year in all treatments (data not presented), and there was a significant ($P = 0.007$) treatment × year interaction. Mean ratings on seminal roots did not reach 3, at which point main root axes are severed by this disease. Rhizoctonia root rot was less severe during the wettest crop year (1989) than in the driest (1990), and was variable and intermediate during 1991. Averaged over years, root rot severity ratings (Fig. 1) tended to be less in the 0 N, pea, and manure treatments than in the unburned 90 N treatment. Root rot severity increased with N rate in unburned treatments and was unresponsive to N rate when stubble was burned. The burn treatment reduced the severity of Rhizoctonia root rot in the 90 N treatment.

The distribution of Rhizoctonia root rot severity class ratings on seminal roots in the residue management experiment was affected by treatment (Fig. 1). A larger proportion of severe root rot ratings (classes 4 and 5) occurred in 0 N and 90 N than in other treatments. Removal of wheat

Table 3. Disease incidence and grain yield in a crop residue management experiment (wheat–summer fallow rotation) at Pendleton, Oregon; means of assessments during 1989, 1990, and 1991

Treatment[a]	Rhizoctonia root rot[b]	Pythium root rot[b]	Take-all[b]	Eyespot[c]	Fusarium crown rot[d]	Yield (kg/ha)
0 N	63.2	6.4	0.4	5.9	0	2,964
0 N, burn	56.1	5.9	0.1	14.6	5.1	2,799
45 N	82.3	12.9	0.2	14.0	3.2	4,598
45 N, burn	77.8	15.1	0.5	15.9	1.5	4,311
90 N	83.3	17.0	0.4	15.3	2.1	5,628
90 N, burn	72.9	12.4	6.5	24.3	0	5,070
Pea vine	65.3	4.8	2.5	12.0	0	4,371
Manure	57.1	1.7	0.3	23.1	0	6,362
LSD (0.05)	14.6	4.5	3.5	13.0	ns	449

[a] Application rate for inorganic nitrogen fertilizer (0, 45, or 90 kg N/ha), pea vines (2.24 Mg/ha), or cow manure (22.4 Mg/ha), and either burning or not burning stubble from the previous wheat crop.
[b] Percentage of main root axes with symptoms of Rhizoctonia root rot, Pythium root rot, or take-all.
[c] Percentage of culms with eyespot lesions.
[d] Percentage of plants with subcrown internode lesions caused primarily by *Fusarium graminearum*.

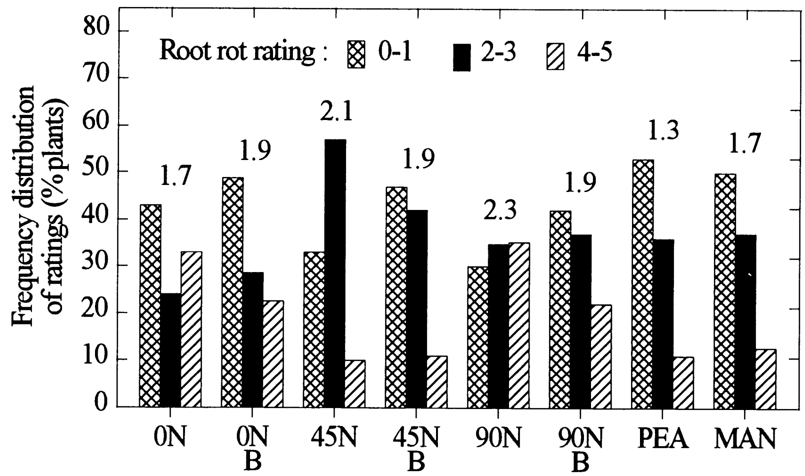

Fig. 1. Distribution of Rhizoctonia root rot severity rating classes (described in text; 0 = none, 5 = severe; means of 3 years of assessment) on seminal roots of wheat in the residue management experiment in a wheat–summer fallow cropping system (since 1931) at Pendleton, Oregon. Treatments applied to fallow preceding each wheat crop included pea vines (2.24 Mg/ha), animal manure (22.4 Mg/ha), or inorganic nitrogen at 0, 45, or 90 kg N/ha, with burning (B) or without burning stubble of the previous wheat crop. The mean severity rating is shown for each group of rating classes, $LSD_{0.05}$ = 0.4.

Table 4. Disease incidence and yield of winter wheat in a tillage × fertility interaction experiment (wheat–summer fallow rotation) during 1989 and 1991 at Pendleton, Oregon

		Nitrogen application rate (kg/ha)						
Tillage	**Variable**	**0**	**45**	**90**	**135**	**180**	**Mean**	**LSD (0.05)**
Plow	Eyespot[a]	16	40	62	68	56	48	16
	Crown rot[b]	2.1	3.1	4.7	5.4	4.4	3.9	ns
	Grain yield[c]	3,564	4,580	5,516	5,232	5,764	4,931	1,013
Sweep	Eyespot	20	16	22	34	40	26	10
	Crown rot	3.9	5.1	10.0	12.5	13.3	9.0	7.8
	Grain yield	3,244	4,200	4,874	4,731	4,677	4,345	ns
Disk	Eyespot	10	22	38	49	37	32	12
	Crown rot	6.6	6.4	6.1	12.0	10.8	8.1	3.5
	Grain yield	3,569	4,649	5,168	5,388	5,189	4,793	804

[a] Percentage of culms with eyespot lesions during 1989.
[b] Percentage of tillers with prematurely dying heads (whiteheads) caused primarily by *Fusarium graminearum* (crown rot) during 1989.
[c] Grain yield (kg/ha) during 1989 and 1991.

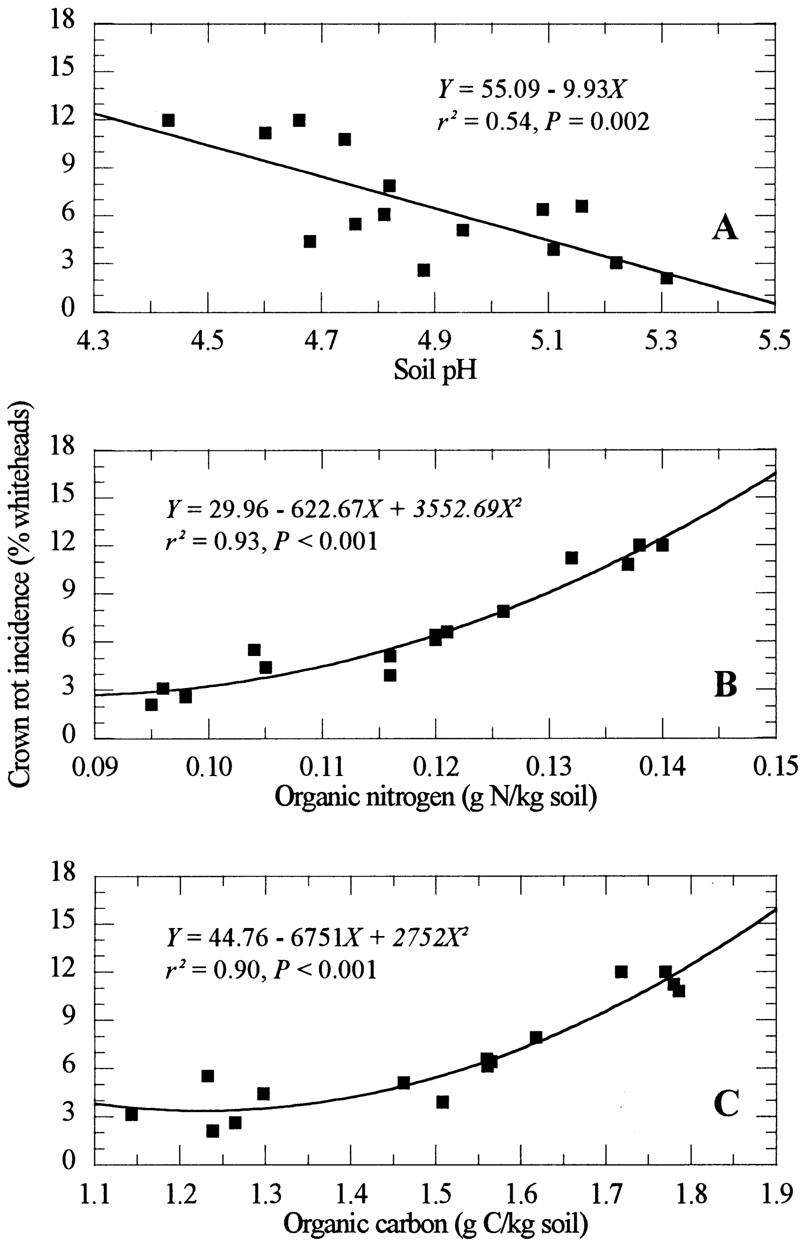

Fig. 2. Relationship of **(A)** soil pH, **(B)** soil organic nitrogen, and **(C)** carbon during 1989 to incidence of Fusarium crown rot (3-year mean; 1989 to 1991) in a long-term tillage × fertility experiment (moldboard plow, disk, or sweep, and application of 0, 45, 90, 135, or 180 kg N/ha) in a winter wheat–summer fallow rotation near Pendleton, Oregon.

residue by burning shifted severity ratings from higher to lower classes. The fewest ratings in classes 4 and 5 occurred in the 45 N, pea, and manure treatments; and intermediate ratings (classes 2 and 3) were higher for 45 N than for either organic treatment.

Pythium root rot was most prevalent in treatments with inorganic N fertilizer and lowest in unfertilized treatments or those with organic amendments (manure or peas) (Table 3). Burning the stubble in the 90 N treatment reduced the incidence of Pythium root rot. Disease incidence did not vary between wet and dry seasons (P = 0.88).

Incidence of take-all was low in the residue management experiment (Table 3), and there was a significant year × treatment interaction ($P < 0.001$). An exception occurred in the stubble-burn 90 N treatment in the 1989 crop, where 19% of plants had symptoms.

Eyespot incidence in the residue management experiment was highly dependent on crop management and year. Eyespot was more prevalent ($P < 0.001$) during the wettest (1989 and 1991) than during the driest (1990) spring periods, and the year × treatment interaction was not significant (P = 0.27). Eyespot was consistently low in the unfertilized, unburned treatment. Averaged over years, eyespot tended to be increased by N (P = 0.08) and by burning crop residue (P = 0.07), especially during years with the wettest winters and springs.

Incidence of crown rot was low (Table 3), and there were no treatment or seasonal differences.

Grain yields (Table 3) were approximately proportional to the amount of N added from organic or inorganic sources. Highest yields always occurred in the manure treatment, which supplied the highest rate of N. There was no significant effect of year (P = 0.50) or year × treatment interaction (P = 0.86). The effect of burning stubble was examined after deleting organic N treatments from the data set. The effect of burning was significant (P = 0.004), with yields higher in unburned than in burned plots (means of 4,330 versus 4,060 kg/ha; $LSD_{0.05}$ = 157). Application rates of inorganic N also affected grain yield, and there was a significant N × year interaction (P = 0.03). Mean yields during the 3 years were 2,881, 4,454, and 5,249 kg/ha for 0 N, 45 N, and 90 N treatments, respectively.

Wheat–fallow rotation: tillage × fertility experiment. Principal diseases were eyespot during 1989, the year with the wettest autumn and winter, and crown rot during 1991, the crop preceded by a dry summer, autumn, and winter, and finishing with unusually high precipitation during May and June.

The incidence of eyespot was higher (P < 0.05, LSD = 8) in the plow than in the disk or sweep treatments (Table 4). Eyespot was also higher ($P < 0.01$) in all tillage treatments at N application rates of 135 to 180 kg N/ha than at 0 to 45 kg N/ha. There was no tillage × N interaction. Percentages of whiteheads also increased with N rate ($P < 0.001$; data not presented). There was no effect of tillage or tillage × N interaction for whiteheads.

The incidence of whiteheads caused by crown rot was significantly affected by N ($P < 0.001$, $LSD_{0.05} = 3.0$) and tillage ($P = 0.03$, $LSD_{0.05} = 3.5$), and there was no significant tillage × N interaction ($P = 0.40$). Percentages of whiteheads increased with increasing N rate and amount of surface residue remaining on the summer fallow before planting.

Wheat yields for 1989 and 1991 were averaged because there was no significant effect of year on yield ($P = 0.26$) or of interactions for year × tillage, year × N, tillage × N, or tillage × N × year. Yield increased with N rate ($P < 0.001$, $LSD_{0.05} = 217$) and was higher in the moldboard plow than in the sweep or disk treatments ($P = 0.04$, $LSD_{0.05} = 471$). The effect of tillage was further examined for the 90 N treatment that approximates the commercial practice in the area; there was no significant ($P > 0.5$) influence of tillage, year, or interactions. Wheat yield during 1989 was inversely correlated with soil pH ($P = 0.002$, $r^2 = 0.55$) and incidence of eyespot ($P = 0.002$, $r^2 = 0.53$). Wheat yield was not correlated with percentages of whiteheads caused by crown rot during 1991.

Soil pH varied from 4.6 to 5.2 and was inversely proportional ($P < 0.001$, LSD = 0.1) to the rate of applied N. Soil pH differed slightly ($P = 0.001$, LSD = 0.01) among tillage treatments (plow = 5.0, disk = 4.8, sweep = 4.9), but there was no tillage × fertility interaction. Soil pH was inversely proportional to quantity of organic N ($P = 0.01$, $r^2 = 0.35$) and organic carbon ($P = 0.03$, $r^2 = 0.27$), and incidence of eyespot ($P = 0.03$, $r^2 = 0.26$). Percentages of whiteheads caused by crown rot were inversely proportional to soil pH and directly proportional to organic N and carbon (Fig. 2).

Comparisons among experiments. The collective spectrum of diseases was less in wheat–pea rotation than when wheat was the only crop produced, either annually or during alternate years (Fig. 3). Eyespot was much more prevalent in annual wheat than in wheat–pea and wheat–fallow rotations, and Pythium root rot was more prevalent in annual wheat and wheat–fallow rotation (90 N treatment) than in wheat–pea rotation.

Rhizoctonia root rot was more prevalent in wheat–fallow than in wheat–pea rotation and in annual wheat (Fig. 3). Fewer class 0 and 1 root rot ratings occurred in the 90 N treatment of the wheat–fallow rotation than in the wheat–pea rotation and the annual wheat with comparable amounts of N (Fig. 4). Similarly, rating classes 4 and 5 were more prevalent in the wheat–fallow 90 N treatment than in the wheat–pea rotation and annual wheat. With one exception, plants in all experiments had more than 80% of roots in severity classes 0 and 1, and less than 20% in classes 2 and 3 (unpublished data). The 90 N treatment of the wheat–fallow rotation had 68% of roots in classes 0 and 1, and 32% in classes 2 and 3.

Six treatments were included in both this survey and an earlier study of microbial dynamics (5). They were 0 N, 0 N + burn, 90 N, and manure treatments of the residue management experiment, tilled treatment of the wheat–pea rotation, and annual wheat. Microbial biomass was inversely correlated with incidence and severity of Rhizoctonia root rot each year ($P < 0.05$, $r^2 > 0.7$) and for 3-year means (Fig. 5).

DISCUSSION

The timing and amount of precipitation affected most diseases in a predictable manner (6,14,33). Take-all was most intense during the year with the wettest autumn and winter, and Rhizoctonia root rot was most prevalent during years that were particularly dry during the autumn and winter. Eyespot was most detrimental during years with a wet autumn and spring, particularly in annual wheat. The higher incidence of eyespot in annual wheat than in wheat–pea rotation during 1989 suggests that the inoculum density and potential were highest in the annual wheat during the severe drought of 1988, and were therefore more able to increase disease incidence rapidly during the very wet autumn of 1989. Crown rot was most important during 1991, in which the autumn and winter were drier than normal and the late spring was much wetter than normal. Infection of seedlings by *F. graminearum* Group 1 is restricted to soil water potentials between –0.1 and –1.5 MPa (17). Moisture stress between anthesis and maturity favors development of crown rot symptoms (16).

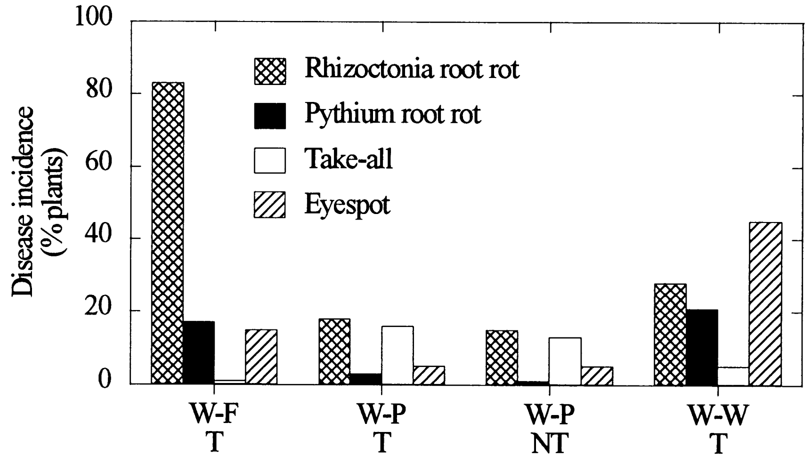

Fig. 3. Percentage of winter wheat plants with symptoms of four root or culm diseases (means for 3 years of assessment) in three long-term crop management experiments, either tilled (T) by moldboard plow or untilled (NT), at Pendleton, Oregon. W-F = wheat–summer fallow rotation (90 kg N/ha treatment), W-P = wheat–pea rotation, and W-W = annual winter wheat.

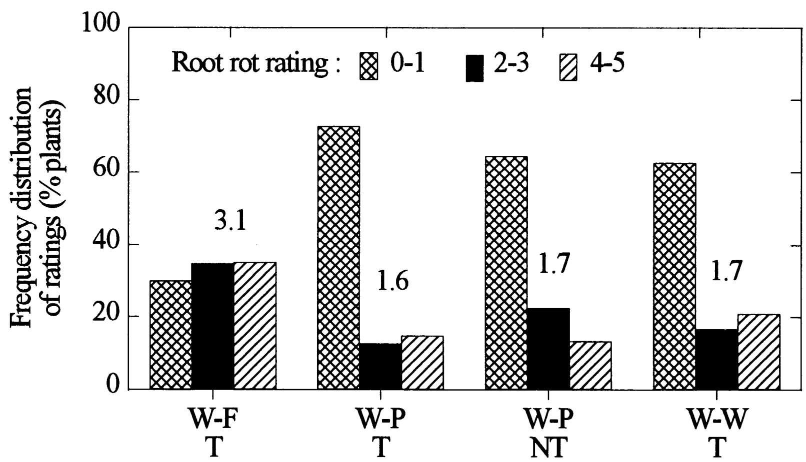

Fig. 4. Distribution of Rhizoctonia root rot severity rating classes (described in text; 0 = none, 5 = severe; means of 3 years of assessment) on seminal roots of wheat in three long-term crop management experiments, either tilled (T) by moldboard plow or untilled (NT), at Pendleton, Oregon. W-F = wheat–summer fallow rotation (90 kg N/ha treatment), W-P = wheat–pea rotation, and W-W = annual winter wheat. The mean severity rating is shown for each group of rating classes, $LSD_{0.05} = 0.7$.

Conditions favored infection of seedlings each year of this study. Since water was not limiting from anthesis to maturity, either moisture stress before anthesis or very wet conditions from anthesis to maturity was responsible for development of severe crown rot in this study. Crown rot commonly occurs in Australia, northern Europe, and the central and eastern United States, in regions where rainfall is prevalent during the summer (4,7,15).

Crown rot increased proportionately with N, as reported previously (7,11). There was a trend for incidence of eyespot also to increase with increasing N in both wheat–fallow experiments, which contrasts with an earlier report from the crop residue experiment (29). During the earlier study, incidence of eyespot (84 to 89% infected culms) and precipitation (>600 mm) were very high. Response of eyespot to applied N is apparently masked when the disease is severe.

Nitrogen fertilizers are applied to all wheat crops in eastern Oregon, with rates proportional to soil productivity and annual precipitation. Soils in the Pacific Northwest are being acidified at rates that depend on the rate of N applied, rainfall, and soil buffering (1,20,24,27). Earlier studies on the long-term plots at Pendleton established a direct relationship between both the amount of surface residue and applied N with soil organic N, carbon, and acidification (1,26,30,32). Soil pH values measured in this study were as low as 4.6. Wheat growth becomes impeded as soil pH values (in 0.01 M $CaCl_2$) become less than 4.7 (2,11,22). This appears to be the first report of an inverse relationship between soil pH and the incidence of both crown rot and eyespot. It is important to determine if *F. graminearum* and *P. herpotrichoides* have higher capacities for saprophytic survival in acid soils, are more virulent to wheat in acid soils, or both. It is also important to determine if these diseases, as for Cephalosporium stripe (18), are early biological indicators of reduced plant vitality by becoming measurable before effects of low soil pH directly reduce wheat growth or yield in the absence of disease.

Crown rot severity increased in proportion to the amount of surface residue, as has been reported (39). Proportionately more N becomes available through mineralization as the soil organic N and carbon content increase (P. E. Rasmussen, *unpublished*). Our results appear to be the first report of a direct relationship between incidence of crown rot and soil organic N and carbon.

Rhizoctonia root rot is also recognized for causing the most damage in management systems that retain the highest amount of cereal residue at or near the soil surface (25,41). In the present study, Rhizoctonia root rot was more severe with stubble mulch than with inversion tillage in the wheat–fallow rotation, but was unaffected by tillage in the wheat–pea rotation. This apparent discrepancy appears related to the inverse correlation between microbial biomass and incidence and severity of Rhizoctonia root rot. Microbial biomass was much higher in wheat–pea than in wheat–fallow rotations (5). Where inoculum potential of *R. solani* remains high, as in the wheat–fallow rotation, saprophytic survival of the pathogen is greatly reduced by inversion tillage (33).

Incidence of take-all in the wheat–pea rotation was higher in tilled than in untilled soil during 1991, the year in which spring rainfall was higher than normal, and in other years did not differ between tillage systems. This observation is opposite tillage relationships reported for take-all in eastern Oregon (37), Washington (23), and South Australia (34), but is consistent with the many contradictory reports of tillage effects on take-all (13,43). Pythium root rot was also unaffected by tillage in the wheat–pea rotation, which contrasts with reports (10,37) that this disease was more damaging in untilled than in tilled cropping systems where wheat is grown under irrigation or in a region where precipitation is 35% more than at Pendleton.

Cook (8) summarized literature pertaining to lower wheat yields with conservation than with inversion tillage systems. Yield-suppressing effects previously attributed to straw-derived phytotoxins or lower temperature and higher moisture in conservation tillage systems were reascribed as damage from take-all and Pythium and Rhizoctonia root rots. The relative importance of these diseases in different wheat production areas of North America was estimated by examining the ratio of wheat yields in moldboard plow versus mulch tillage systems, as plotted against a precipitation–evaporation index for each region. Ratios above 1.0 occur in semiarid regions and below 1.0 in subhumid regions. A yield ratio of 0.85 was reported for Pendleton. In the present study, the yield ratio was 0.91 in the wheat–pea rotation, and 0.97 and 0.88 with the disk and sweep treatments, respectively, of the tillage × fertility experiment. Although yield was generally not correlated with disease incidence or severity in this study, the yield ratios suggest that soilborne pathogens restricted the achievement of potential yields by 3 to 12%. Additional strategies are clearly needed for managing root, crown, and culm diseases of winter wheat.

Burning the stubble after harvest, under certain conditions, influenced the occurrence of diseases. This effect was particularly apparent at the highest rate of N application, where Pythium root rot, Rhizoctonia root rot, and take-all were suppressed by burning wheat stubble and eyespot was enhanced. More residue is produced as the N rate increases, but it is not known whether the N-rate effect was due to residue quantity, quality, or both.

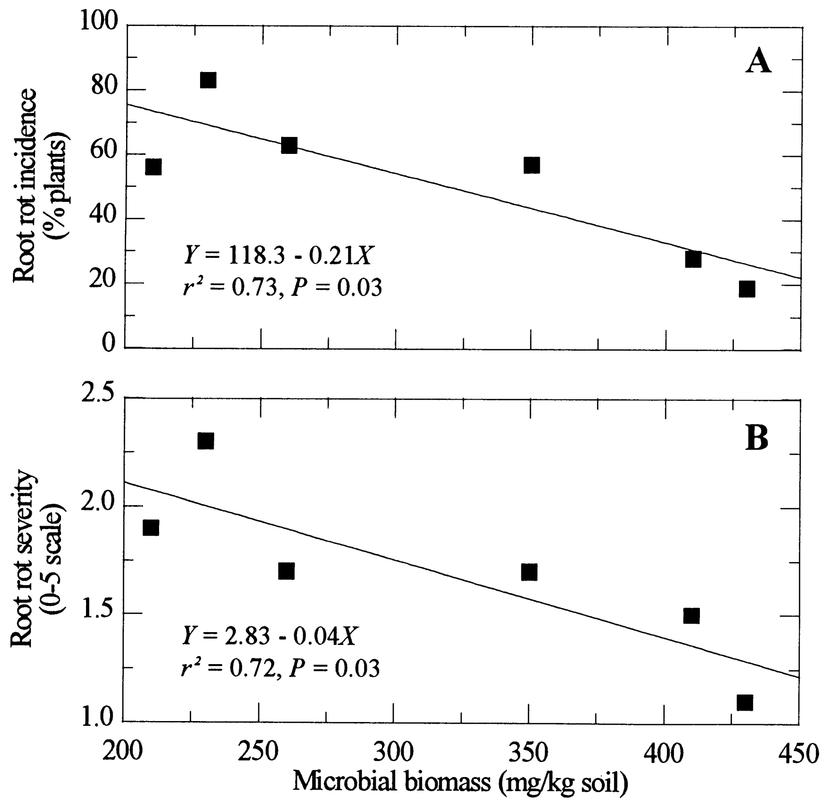

Fig. 5. Relationship of soil microbial biomass (during 1988; 5) to **(A)** incidence and **(B)** severity of Rhizoctonia root rot (3-year mean; 1989 to 1991) on wheat seminal roots in tilled soils of a wheat–fallow rotation (treated with 0 N, 0 N + burn stubble, 90 N, or manure), wheat–pea rotation, and annual wheat.

Burning stubble reduced Pythium root rot when 90 kg N/ha but not lower N rates were applied. It has been reported (9,10) that burning reduces *Pythium* inoculum density and increases wheat plant growth. Our results extend existing knowledge by demonstrating an interaction of N fertility with the efficiency of Pythium root rot suppression by burning stubble. Comparable fuel loads (9,28) were burned in the earlier and present studies. This therapeutic effect is unlikely to be due to thermal heating in the root zone (28), where most *Pythium* propagules reside, but may be associated with a reduced microbial biomass (5) and less diverse microbial composition in long-term burn compared to stubble incorporation treatments (H. P. Collins, *unpublished*).

Burning reduced Rhizoctonia root rot incidence and severity by 62% where 90 kg N/ha was applied during the season with the wettest autumn and winter. Although this fertilizer treatment exemplifies commercial practice in the region, the value of this information is limited because seasonal rainfall is unpredictable and Rhizoctonia root rot is most severe during the driest years, when this disease is unresponsive to burning.

Removal of stubble by burning typically does not enhance or suppress the incidence or severity of take-all in short-term experiments (35,43). In the long-term crop residue management experiment, take-all became damaging where 90 kg N/ha was applied to soil after stubble had been removed by burning. Modification of the microbial biomass and soil chemical and physical qualities by repetitive burning (5,24,26,29) may have resulted in microbe–host–parasite interactions quite different than those in short-term investigations.

Burning stubble after harvest was reported to either increase or have no effect on the occurrence of eyespot (29,42). Burning led to increased eyespot in this experiment, which contrasts with a report (29) that eyespot was not affected by burning stubble from this same experiment during 1980 and 1983. The earlier study quantified eyespot during the first and second crops after burning was initiated in 1979; whereas the present study was conducted on the fifth and sixth crops after burning was initiated. The mass of infected culms and inoculum density were apparently reduced by repetitive burning.

A report that incidence of crown rot was reduced by burning (39) was not confirmed in this study. A supportive trend occurred at N rates considered normal for this region, but our results were inconclusive because crown rot incidence was low in the experiment where stubble burning was examined.

Crop sequences affected the occurrence and severity of diseases. Although these effects could not be tested with statistics, these observations provide important insights for disease management strategies. Rhizoctonia root rot, for instance, caused little damage in annual wheat and wheat–pea rotation, compared to damage in the wheat–fallow rotation. This disease often becomes devastating when annual cropping is first initiated (25,33,41). Rhizoctonia root rot decline, similar to take-all decline (35), was induced (19) by repeatedly planting wheat into intact cores of soil collected from the tillage × fertility experiment (wheat–fallow rotation), which is not considered to exhibit the decline phenomenon.

Pythium root rot was more prevalent when wheat was produced annually or in rotation with fallow, as compared to a wheat–pea rotation. Microbial biomass in these plots (5) was equal in annual wheat and wheat–pea rotation, and both had higher microbial activity (soil respiration) than the wheat–fallow rotation. It appears possible that suppression of Pythium root rot was responsive to a combination of greater microbial biomass plus a more diverse microbial species distribution (H. P. Collins, *unpublished*) in wheat–pea compared to annual wheat or wheat–fallow systems. Evidence taken from the crop residue study supports this hypothesis; Pythium root rot was much more prevalent when high rates of N were supplied by inorganic fertilizer compared to organic sources (pea vines or animal manure).

Bruehl et al. (3) reported that the winter wheat–fallow system was more conducive to eyespot than were annual cropping systems because planting generally occurs earlier with wheat following fallow than with annual wheat or wheat following peas. In the present study, eyespot and crown rot were more prevalent in annual wheat than in either of the rotations. A common planting date was used for each system in this study during 1989 and 1991. In this study, eyespot and crown rot were associated with the frequency of producing a susceptible host. *P. herpotrichoides* and *F. graminearum* Group 1 both survive mostly as mycelium in infested wheat tissues, and eyespot and crown rot are suppressed by crop rotation (3,4,11,36,40). Although both diseases are favored by early planting, it is also true that they are favored by recurrent host crops and an absence of surface residue (3,7,11,14).

Long-term agronomic experiments provided unique insights into relationships among wheat diseases, crop and soil management, and soil characteristics. Some relationships could not have been identified by short-term experiments. For example, examination of relationships between diseases and organic N, C, and microbial diversity under similar soil and climatic conditions requires application of experimental treatments over several decades in semiarid regions with winter-dominant precipitation (32).

These experiments were located in the transition zone between traditional wheat–fallow and wheat–pea rotations. Rhizoctonia root rot, Pythium root rot, take-all, and eyespot were collectively least prevalent in a wheat–pea rotation and in a wheat–fallow rotation where pea vines or manure were the only source of added nutrients. The wheat–pea rotation, with either conventional or conservation tillage, had fewer diseases than wheat produced annually. Where annual cropping is traditional, the wheat–pea rotation appears the best choice for minimal damage from diseases. The management system considered standard for the wheat–fallow region (90 kg N/ha) was among treatments having the highest overall prevalence of diseases, dominated by Rhizoctonia root rot. Results of this study suggest that annual wheat would be feasible, with respect to disease management, in the traditional wheat–fallow region. Eyespot was the most damaging disease in annual wheat and is now controlled by planting resistant cultivars. Annual cropping systems will eventually be required to sustain soil productivity in the wheat–fallow region (12,27). This research indicated that diseases are not likely to be a major hindrance to production after the transition from alternate year to annual production of wheat.

ACKNOWLEDGMENTS

We thank Robert Ramig, Karl Rhinhart, Wakar Uddin, Lisa Patterson, and Roger Goller for assisting in this study. Financial support was provided by the USDA-CSRS-Pacific Northwest Regional LISA Research Program and Oregon Wheat Commission.

LITERATURE CITED

1. Allmaras, R. R., Ward, K., Rasmussen, P. E., and Rohde, C. R. 1978. Soil acidification from long-term use of ammonium-type nitrogen fertilizers. Oreg. State Univ. Agric. Exp. Stn. Misc. Bull. 78-4:55-58.
2. Black, C. A. 1968. Soil-Plant Relationships. John Wiley & Sons, New York.
3. Bruehl, G. W., Nelson, W. L., Koehler, F., and Vogel, O. E. 1968. Experiments with Cercosporella foot rot (strawbreaker) disease of winter wheat. Wash. Agric. Exp. Stn. Bull. 694.
4. Burgess, L. W., Dodman, R. L., Pont, W., and Mayers, P. 1981. Fusarium diseases of wheat, maize and grain sorghum in eastern Australia. Pages 64-76 in: *Fusarium*: Diseases, Biology and Taxonomy. P. E. Nelson, T. A. Toussoun, and R. J. Cook, eds. Pennsylvania State University, University Park.
5. Collins, H. C., Rasmussen, P. E., and Douglas, C. L., Jr. 1992. Crop residue management effects on soil carbon and microbial dynamics. Soil Sci. Soc. Am. J. 56:783-788.
6. Cook, R. J. 1981. The effect of soil reaction and physical conditions. Pages 343-352 in: Biology and Control of Take-all. M. J. C. Asher and P. J. Shipton, eds. Academic Press, London.
7. Cook, R. J. 1981. Fusarium diseases of wheat and other small grains in North America. Pages 39-52 in: *Fusarium*: Diseases, Biology and Taxonomy. P. E. Nelson, T. A. Toussoun, and R. J. Cook, eds. Pennsylvania State University, University Park.
8. Cook, R. J. 1990. Diseases caused by root-infecting pathogens in dryland agriculture. Adv. Soil Sci. 13:215-239.

9. Cook, R. J., Sitton, J. W., and 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.
10. Cook, R. J., Sitton, J. W., and Waldher, J. T. 1980. Evidence for *Pythium* as a pathogen of direct-drilled wheat in the Pacific Northwest. Plant Dis. 64:102-103.
11. Cook, R. J., and Veseth, R. J. 1991. Wheat Health Management. American Phytopathological Society, St. Paul, MN.
12. Duff, B., Rasmussen, P. E., and Smiley, R. W. 1994. Wheat/fallow systems in the semi-arid regions of Pacific Northwest America. Pages 85-111 in: Agricultural Sustainability: Economic, Environmental and Statistical Considerations. V. Barnett, R. Payne, and R. Steiner, eds. John Wiley & Sons, London.
13. Folwell, R. J., Cook, R. J., Heim, M. N., and Moore, D. L. 1991. Economic significance of take-all on winter wheat in the Pacific Northwest USA. Crop Prot. 10:391-395.
14. Herrman, T., and Wiese, M. V. 1985. Influence of cultural practices on incidence of foot rot in winter wheat. Plant Dis. 69:948-950.
15. Kane, R. T., and Smiley, R. W. 1987. Relative pathogenicity of selected *Fusarium* species and *Microdochium bolleyi* to winter wheat in New York. Plant Dis. 71:177-181.
16. Liddell, C. M., and Burgess, L. W. 1985. Wax layers for partitioning soil moisture zones to study the infection of wheat seedlings by *Fusarium graminearum.* Pages 206-208 in: Ecology and Management of Soilborne Plant Pathogens. C. A. Parker, A. D. Rovira, K. J. Moore, and P. T. W. Wong, eds. American Phytopathological Society, St. Paul, MN.
17. Liddell, C. M., and Burgess, L. W. 1988. Wax partitioned soil columns to study the influence of soil moisture potential on the infection of wheat by *Fusarium graminearum* Group 1. Phytopathology 78:185-189.
18. Love, C. S., and Bruehl, G. W. 1987. Effect of soil pH on Cephalosporium stripe in wheat. Plant Dis. 71:727-731.
19. Lucas, P., Smiley, R. W., and Collins, H. P. 1993. Decline of Rhizoctonia root rot on wheat in soils infested with *Rhizoctonia solani* AG-8. Phytopathology 83:260-265.
20. Mahler, R. L., Halvorson, A. R., and Koehler, F. E. 1985. Long-term acidification of farmland in northern Idaho and eastern Washington. Commun. Soil Sci. Plant Anal. 16:83-95.
21. Mitchell, C. C., Westerman, R. L., Brown, J. R., and Peck, T. R. 1991. Overview of long-term agronomic research. Agron. J. 83:24-29.
22. Mohebbi, S., and Mahler, R. L. 1989. The effect of soil pH on wheat and lentils grown on an agriculturally acidified northern Idaho soil under greenhouse conditions. Commun. Soil Sci. Plant Anal. 20:359-381.
23. Moore, K. J., and Cook, R. J. 1984. Increased take-all of wheat with direct drilling in the Pacific Northwest. Phytopathology 74:1044-1049.
24. Pikul, J. L., Jr., and Allmaras, R. R. 1986. Physical and chemical properties of a haploxeroll after fifty years of residue management. Soil Sci. Soc. Am. J. 50:214-219.
25. Pumphrey, F. V., Wilkins, D. E., Hane, D. C., and Smiley, R. W. 1987. Influence of tillage and nitrogen fertilizer on Rhizoctonia root rot (bare patch) of winter wheat. Plant Dis. 71:125-127.
26. Rasmussen, P. E., Allmaras, R. R., Rohde, C. R., and Roager, N. C., Jr. 1980. Crop residue influences and soil carbon and nitrogen in a wheat-fallow system. Soil Sci. Soc. Am. J. 44:596-600.
27. Rasmussen, P. E., Collins, H. C., and Smiley, R. W. 1989. Long-term management effects on soil productivity and crop yield in semi-arid regions of eastern Oregon. Oregon Agric. Exp. Stn. Bull. 675.
28. Rasmussen, P. E., Rickman, R. W., and Douglas, C. L., Jr. 1986. Air and soil temperatures during spring burning of standing wheat stubble. Agron. J. 78:261-263.
29. Rasmussen, P. E., and Rohde, C. R. 1988. Stubble burning effects on winter wheat yield and nitrogen utilization under semiarid conditions. Agron. J. 80:940-942.
30. Rasmussen, P. E., and Rohde, C. R. 1988. Long-term tillage and nitrogen fertilization effects on organic nitrogen and carbon in a semiarid soil. Soil Sci. Soc. Am. J. 52:1114-1117.
31. Rasmussen, P. E., and Rohde, C. R. 1989. Soil acidification from ammonium-nitrogen fertilization in moldboard plow and stubble-mulch wheat-fallow tillage. Soil Sci. Soc. Am. J. 53:119-122.
32. Rasmussen, P. E., and Smiley, R. W. Soil nitrogen and carbon change in long-term agricultural experiments at Pendleton, Oregon. In: Soil Organic Matter in Temperate Agro-ecosystems Workshop. K. Paustian, ed. W. K. Kellogg Biol. Stn., Hickory Corners, MI. In press.
33. Rovira, A. D. 1986. Influence of crop rotation and tillage on Rhizoctonia bare patch of wheat. Phytopathology 76:669-673.
34. Rovira, A. D., and Venn, N. R. 1985. Effect of rotation and tillage on take-all and Rhizoctonia root rot in wheat. Pages 255-258 in: Ecology and Management of Soilborne Plant Pathogens. C. A. Parker, A. D. Rovira, K. J. Moore, and P. T. W. Wong, eds. American Phytopathological Society, St. Paul, MN.
35. Shipton, P. J. 1975. Take-all decline during cereal monoculture. Pages 137-144 in: Biology and Control of Soilborne Pathogens. G. W. Bruehl, ed. American Phytopathological Society, St. Paul, MN.
36. Sitton, J. W., and Cook, R. J. 1981. Comparative morphology and survival of chlamydospores of *Fusarium roseum* 'Culmorum' and 'Graminearum'. Phytopathology 71:85-90.
37. Smiley, R. W., Ingham, R. E., Uddin, W., and Cook, G. H. 1994. Crop sequences for managing cereal cyst nematode and fungal pathogens of winter wheat. Plant Dis. 78:1142-1149.
38. Smiley, R. W., Uddin, W., Zwer, P. K., Wysocki, D. J., Ball, D. A., Chastain, T. G., and Rasmussen, P. E. 1993. Influence of crop management practices on physiologic leaf spot of winter wheat. Plant Dis. 77:803-810.
39. Summerell, B. A., Burgess, L. W., and Klein, T. A. 1989. The impact of stubble management practices on the incidence of crown rot of wheat. Aust. J. Exp. Agric. 29:91-98.
40. Wearing, A. H., and Burgess, L. W. 1977. Distribution of *Fusarium roseum* 'Graminearum' Group 1 and its mode of survival in eastern Australian wheat belt soils. Trans. Br. Mycol. Soc. 69:429-442.
41. Weller, D. M., Cook, R. J., Macnish, G., Bassett, E. N., Powelson, R. L., and Peterson, R. R. 1986. Rhizoctonia root rot of small grains favored by reduced tillage in the Pacific Northwest. Plant Dis. 70:70-73.
42. Yarham, D. J. 1979. The effect on soil-borne diseases of changes in crop and soil management. Pages 371-383 in: Soil-Borne Plant Pathogens. B. Schippers and W. Gams, eds. Academic Press, London.
43. Yarham, D. J. 1981. Practical aspects of epidemiology and control. Pages 353-384 in: Biology and Control of Take-all. M. J. C. Asher and P. J. Shipton, eds. Academic Press, London.