Effects of Cropping Systems on Root Diseases and Nematodes in a Long-term Experiment at Moro, OR (2004-2012)

Richard Smiley and Stephen Machado
October 17, 2012

SYNOPSIS

Dryland cropping systems in the Pacific Northwest are slowly changing from a 2-year rotation of winter wheat and cultivated fallow to direct-seed (no-till) systems that include chemical fallow, spring cereals, and pulse and brassica crops. Little information is available regarding effects of these changes on diseases. Eight cropping systems were compared over nine years at Moro, Oregon. Root-lesion nematodes were more numerous in cultivated than in chemical fallow and became greater with increasing frequency of host crops. Highest numbers occurred following mustard, spring wheat, winter wheat and winter pea. Lowest numbers occurred following camelina, spring barley and spring pea. Winter wheat selected for a higher density of *Pratylenchus neglectus* and spring wheat and winter pea selected for a higher density of *Pratylenchus thornei*. Fusarium crown rot of winter wheat was more prevalent for cultivated fallow than for chem-fallow. Rhizoctonia root rot was more severe when winter wheat was rotated with chemical fallow than with no-till winter pea. Take-all was more severe on annual spring wheat than on annual spring barley. The concentration of inoculum (DNA/g of soil) for each pathogen differed among cropping systems. *Phoma medicaginis* var. *pinodella* was detected only where winter pea was planted frequently. This is the first report of this pathogen as a component of the dryland stem rot complex of pulse crops in north-central Oregon.

Root and crown diseases are common on field crops in the low-rainfall region of the Pacific Northwest. Fusarium crown rot (*F. culmorum* and *F. pseudograminearum*) becomes most damaging in the lowest rainfall regions particularly when winter wheat is sown deeply into warm soil during late summer to early fall, which is common in cultivated fallow systems, and when wheat is sown shallowly into fields that have a high level of crop residue remaining on the surface, as is common in direct-seed systems. Rhizoctonia root rot (*R. solani* AG-8) is most prevalent in direct-seed systems and particularly in spring barley and in fields that are planted annually. *Pythium* diseases caused by multiple species are particularly prevalent in direct-seed systems when seed is planted into cool, wet soil. Take-all (*Gaeumannomyces graminis* var. *tritici*) occurs regularly and is most prevalent in annual crops and in direct-seed systems. Root-lesion nematode (*Pratylenchus neglectus* and *P. thornei*) is increased in proportion to the frequency of host crops and is more prevalent following wheat compared to barley.

Pulse crops in low-rainfall regions are affected by a root and stem rot complex that includes Fusarium root rot (*F. solani*), Rhizoctonia seedling rot (*R. solani*), Pythium damping-off, root rot and root-tip necrosis (*Pythium* sp.), and black root rot (*Thielaviopsis basicola*). Pulse crops in higher rainfall and irrigated areas are also affected by black stem rot and foot rot (*Phoma medicaginis* var. *pinodella*), Aphanomyces root rot (*Aphanomyces euteiches*) and Fusarium wilt (*F. oxysporum*). Several of these pathogens are typically present where pulse crops are grown.

Optimal grain yields for cereal crops depend on the health of the root systems which extract water and nutrients throughout the soil profile. Most fallow in the PNW is still managed as a cultivated ‘dust mulch’ that provides comparatively high winter wheat yields because it retains as much as 30% of the precipitation occurring during the fallow winter. Each winter wheat crop therefore has access to water equivalent to as much as 60% of precipitation occurring during the 24-month sequence. Direct-seeding into non-tilled chemical fallow is becoming increasingly popular. Most direct-seeded annually-planted fields in the low-precipitation region are planted repeatedly to spring wheat or barley although other crops include mustard, canola, camelina, or winter pea. Three year rotations of winter wheat, a spring crop and chemical fallow are also practiced in higher rainfall regions.

A long-term experiment was established at Moro, OR during 2003 to examine eight cropping systems. The diversity of fungal and nematode pathogens at the site was representative of production systems throughout the region. This paper summarizes three technical manuscripts that reported effects of cropping systems on diseases and nematodes from 2004 to 2012.

METHODS

The long-term experiment (LTE) was performed at the OSU Columbia Basin Agricultural Research Center near Moro, in Sherman County, OR. Annual precipitation averages 11 inches and the soil is a Walla Walla silt loam.

Cropping systems. A uniform crop of spring wheat was planted over the intended experimental area during 2003. The experimental area was mapped into 42 plots of 48 × 350 feet, arranged as 14 treatments of eight crop rotations, randomized within each of three blocks. Crops, varieties, or the type of fallow are shown in Table 1.

Rotation 1. Two-year rotation of winter wheat and cultivated fallow - Each phase (1A and 1B) of the rotation was present each year to allow data for each treatment to be collected every year. After harvest, the field was not cultivated until mid-April of the following (fallow) year. Glyphosate was applied as needed in the fall and spring. In April, primary tillage was conducted to a depth of 6 inches using a John Deere 1600 cultivator fitted with chisel plow turning points, followed by sweep cultivation to a depth of 5 inches using the same cultivator equipped with 12-inch wide sweeps. Plots were rod-weeded at a depth of 3 to 4 inches whenever necessary to maintain weed control and to break capillary continuity between the dust mulch fallow and under-lying moist soil. Plots were generally rod-weeded two or three times from May to August. Anhydrous ammonia and gypsum were incorporated into fallow during September. Soft-white winter wheat varieties were planted in mid-September using a John Deere 7616 HZ drill with 16-inch row spacing. In-crop herbicides were applied as necessary.

Rotation 2. Two-year rotation of winter wheat and chemical fallow - Each phase (2A and 2B) of the rotation was present each year. Glyphosate was applied to control weeds three to four times during the chemical fallow phase. The fallowed plots were direct-seeded using a Fabro Drill during late September or early October. Urea was banded 1 inch below the seed and ammonium sulfate was applied with the seed. In-crop herbicides were applied as necessary.

Rotation 3. Annual winter wheat - Plots were sprayed in late September or early October with glyphosate to control summer weeds. Plots were then direct-seeded using the Fabro disk-type drill with 12-inch row spacing. A blend of urea and ammonium sulfate was banded 1 inch below the seed during planting and herbicides were applied as necessary.

Rotations 4 and 5. Annual spring wheat and spring barley - Plots were sprayed with glyphosate in late September or early October. In April the plots were direct-seeded using the Fabro drill to plant soft-white spring wheat and 2-row feed barley varieties. Fertilizer and herbicide applications were as described for annual winter wheat.

Rotation 6. Three-year rotation of winter wheat, spring barley and chemical fallow - Each phase (6A, 6B and 6C) of the rotation was present each year. Management practices for winter wheat following chemical fallow were the same as in the 2-year direct-seed rotation and practices for spring barley were the same as for the annual spring barley treatment.

Rotation 7. Two-year rotation of winter wheat and winter pea - Each phase (7A, and 7B) of the rotation was present each year. Following winter wheat harvest, plots were sprayed with glyphosate during late September to early

Table 1. Crop and management treatments in a long-term experiment (LTE) at Moro; 2004-2012.

Treatment sequence	Rotation No.	Rotation Phase	Crop and variety or fallow type during each harvest year [a] 2004	2005	2006	2007	2008	2009	2010	2011	2012
WW/CuF	1	1A	WW	CuF	WW	CuF	WW	CuF	WW	CuF	WW
		1B	CuF	WW	CuF	WW	CuF	WW	CuF	WW	CuF
WW/ChF	2	2A	WW	ChF	WW	ChF	WW	ChF	WW	ChF	WW
		2B	ChF	WW	ChF	WW	ChF	WW	ChF	WW	ChF
Annual WW	3	3	WW	WW	WW	WW	WW	WW	WW	WW	WW
Annual SW	4	4	SW	SW	SW	SW	SW	SW	SW	SW	SW
Annual SB	5	5	SB	SB	SB	SB	SB	SB	SB	SB	SB
WW/SB/ChF	6	6A	WW	SB	ChF	WW	SB	ChF	WW	SB	ChF
		6B	SB	ChF	WW	SB	ChF	WW	SB	ChF	WW
		6C	ChF	WW	SB	ChF	WW	SB	ChF	WW	SB
WW/WP	7	7A	WW	WP	WW	WP	WW	WP	WW	WP	WW
		7B	WP	WW	WP	WW	WP/SP	WW	WP/SP	WW	WP
Flex crops [b]	8	8A	SB	SW	SM	SW	SC	SP	SW	SC	WW
		8B	SW	SB	ChF	WW	SP	SW	SP	SW	SC

[a] ChF = chemical fallow, CuF = cultivated fallow, SB = spring barley, SC = spring camelina, SM = spring mustard, SP = spring pea, SW = spring wheat, WP = winter pea, WW = winter wheat. The experimental area was planted uniformly to spring wheat in 2003. All rotational sequences were performed without tillage (no-till) except Rotations 1A and 1B, which were cultivated between WW crops. Varieties: WW included Tubbs, Stephens, ORCF101 and ORCF102; SW included Zak and Louise; SB included Camas and Haxby; WP included 706, Specter, Austrian and Windham; SP was Universal; SM was Tilney; SC was Calina.

[b] Flex crop = Decisions regarding rotational sequences were made annually to adjust to availability of stored water, crop prices, and occurrences of weeds or diseases.

November. Plots were then seeded with feed-type winter field pea varieties during October or November using the Fabro drill. Granular inoculant was applied with the seed. Starter fertilizer was banded below the seed, at a depth of 3 inches. Herbicides were applied in accordance with standard practice. If winter pea plants died during the winter the plots were replanted to spring pea, as shown in Table 1. After the pea crop was harvested in late July or early August glyphosate was applied to prepare plots for planting winter wheat. In November, winter wheat was seeded using the Fabro drill. Urea was banded 1 inch below the seed during planting and starter fertilizer (ammonium sulfate) was applied with the seed. In-crop herbicides were applied as necessary.

Rotation 8. Flexible cropping sequences (Flex crop) - Two direct-seed flexible cropping treatments (8A and 8B) were examined. Each treatment allowed independent and complete annual flexibility in selecting the crop species produced, with decisions based upon market prices, soil moisture available before planting, and occurrences of weeds and diseases. Cropping decisions were made by consensus of scientists and farmers who served on an advisory committee for the experiment. Crops grown in these rotations (Table 1) were winter wheat or spring-planted wheat, barley, yellow mustard, canola or camelina. Management was as described for direct-seed annual crops.

Soil water content was measured in the soil profiles during the 2006 and 2007 growing seasons. Access tubes were inserted and water soil moisture content (% volume) was measure at 4-, 8-, 16-, 24-, and 40-inch depths using a PR2 probe from Delta-T Devices Ltd. (Cambridge, England). All crops were harvested using a commercial combine and a weigh wagon.

Nematodes. Soil from each of the 42 plots was collected each year during the spring to determine the number of nematodes/lb of soil. Samples were processed by Western Laboratories (Parma, ID), which identifies root-lesion nematodes to the genus level; e.g., "*Pratylenchus* species". During 2012 the soil samples were divided and half was sent to Western Labs and the other half was sent to the Root Disease Testing Service (RDTS) in Adelaide, Australia. The RDTS extracted DNA from soil and reported numbers and identities of individual nematode species; e.g., “*Pratylenchus neglectus”* or “*P. thornei*.”

Diseases. Plants with intact root systems were dug from plots during May for winter crops and mid-June for spring crops. Roots were washed and then evaluated for incidence and/or severity of disease symptoms on roots, subcrown internodes, crowns and stems. Diseases of small grains that we detected in this study were Fusarium crown rot, Rhizoctonia root rot and take-all. Disease incidence describes the percentage of plants showing symptoms of a disease. Disease severity rates the intensity of the disease symptom, usually on a scale from 0 to 4 or 5.

Fusarium crown rot was rated by plants that had subcrown internodes darkened by the disease and also by plants that had a brown dry rot inside the crown tissue, as revealed when crowns were cut open. Severity was rated on a 0 to 4 scale; 0 = no lesion on the subcrown internode and 4 = >75% lesion area. Rhizoctonia root rot was rated by plants having roots with a brown cortical rot or a characteristic "spear tip" symptom. Severity was rated on 0 to 5 scale; 0 = no root rot and 5 = extensive rotting on most roots. Take-all was rated as plants which had seminal roots with a characteristic blackening of the root cortex or vascular system, using a 0 to 5 scale; 0 = none, 5 = extensive blackening of most roots. Percentages of plants that had a pruning of branch roots were also recorded. Since at least three pathogens (*Pratylenchus*, *Pythium*, and *Rhizoctonia*) were capable of causing this symptom, no attempt was made to identify which was most important.

Soil samples were collected from each plot during May 2012 and sent to the RDTS in Australia, as described above for nematodes. DNA extracted from soil by also revealed the concentration of fungal inoculum (picograms DNA/g of soil) for *Bipolaris sorokiniana*, *Fusarium culmorum*, *F. pseudograminearum*, *Gaeumannomyces graminis* var. *tritici*, *Phoma medicaginis* var. *pinodella*, *Pythium* species, and *Rhizoctonia solani* AG-8.

RESULTS

Annual precipitation over the 9-year experimental period averaged 11.4 inches and ranged from 7.1 inches in 2008 to 15.6 inches in 2010. Precipitation during the over-winter and early-spring period (November - March) was considered to be most indicative of potential nematode activity. Precipitation during this 5-month period averaged 4.4 inches over the 9-years, including two particularly dry years (2.3 in 2007; 3.3 inches in 2008), and three comparatively wet years; 4.9, 6.7 and 5.2 inches in 2004, 2010 and 2012, respectively.

Nematodes. *Main rotations* **-** The density of root-lesion nematodes averaged over the 9 years (Table 2) was higher in annual spring wheat and annual winter wheat than in annual spring barley, the 3-year rotation, the flexible cropping treatment, and the winter wheat/fallow rotations.

Table 2. Average density of root-lesion nematodes in 8 cropping systems from 2004 to 2012. The number of times each crop or fallow occurred over the 9 years is shown in parenthesis.

Rota-tion	Rotation name	Nema./ lb of soil
4	Annual SW (27)	1,371
3	Annual WW (27)	1,048
1	WW/CuF (54)	751
7	WW/WP (54)	675
2	WW/ChF (54)	587
8	Flex crop (54)	565
6	WW/SB/ChF (81)	307
5	Annual SB (27)	160

Rotation phases **-** To identify changes in root-lesion nematode density within phases of individual rotations, analyses were performed for each phase of each of the four main rotations (Table 3). The nematode density was greater in cultivated fallow than in chemical fallow, and also declined more rapidly in cultivated than in chemical fallow. In cultivated fallow (Rotation #1) the density of root-lesion nematodes diminished by about 50% during the 14-month fallow period; from 1,128/lb of soil during the spring following the winter wheat crop to 581/lb during the spring of the winter wheat crop that had been planted six months earlier but was still small and would continue to grow for another four months before being harvested. In chem-fallow (#2), the nematode decreased in density by 21% during that period; from 662 to 523/lb.

Table 3. Density of root-lesion nematodes in the spring following specific crop sequences in 9 phases of 2- and 3-year rotations during the final 8 years of the LTE; averages of 24 plots.

Rotation	Treatment	Current year	Previous year	Nema./ lb of soil
1	WW/CuF	CuF	WW	1,128
		WW	CuF	581
2	WW/ChF	ChF	WW	662
		WW	ChF	523
6	WW/SB/ChF	WW	ChF	190
		SB	WW	541
		ChF	SB	266
7	WW/WP	WW	WP	547
		WP	WW	1,162

Table 4. Density of root-lesion nematodes during the spring following production of a specific crop or fallow management treatment during 9 years (2004 to 2012) of the LTE. The number of times each crop or fallow occurred over the 9-year interval is shown in parenthesis.

Previous crop or treatment	Nema./ lb of soil
Mustard (3)	1,269
Winter pea (18)	1,931
Winter wheat (123)	893
Spring wheat (84)	624
Cultivated fallow (24)	581
Chemical fallow (51)	331
Camelina (6)	300
Spring barley (54)	244
Spring pea (15)	171

In the 3-year direct-seed rotation (#6) the density of nematodes was very low (190/lb) during the winter wheat cycle, was significantly higher when the spring barley was planted following winter wheat (541/lb), and began diminishing again during the chemical fallow following the spring barley cycle (20/lb). This cycling indicated that winter wheat led to amplification of the nematode density and that it decreased during the years when a poor host (barley) was present and was further diminished during chemical fallow. Only a single year of winter wheat was required to amplify densities of nematodes to values comparable to those following winter wheat in the 2-year rotations with fallow. In the winter wheat/winter pea rotation (#7) it was apparent that both crops were good hosts for root-lesion nematodes.

Crop species **-** The influence of crops and treatments was evaluated based upon the preceding crop or treatment, without regard to the current crop (Table 4). Greatest densities of root-lesion nematodes occurred following mustard, winter pea, winter wheat and spring wheat, and the lowest densities occurred following camelina, spring barley, and spring pea.

DNA assays **-** During 2012 soil samples were sent to both Western Labs and the RDTS in Australia. Estimates of density were higher from DNA extractions than from traditional extractions but the correlation between methods was very good ($R^2 = 0.70$, $P < 0.01$). DNA data indicated that winter wheat had a greater density of *P. neglectus* and that spring wheat and winter pea had a greater density of *P. thornei* (Table 5). These trends also occurred in the annual cereal crop sequences (#3, #4 and #5), in the 2-year rotations of winter wheat with fallow (#1 and #2) or with winter pea (#7), in the 3-year rotation that includes winter wheat as one of the two crops (#6), and in the flex-crop rotations (#8). It was notable that in Rotation 7, there was a greater inoculum density of *P. neglectus* when the current crop was winter wheat and a greater inoculum density of *P. thornei* when the current crop was winter pea, yet the density of generic '*Pratylenchus* species' was equivalent in each phase of the rotation (Table 5). These DNA assays revealed that different cropping systems are selecting for different species of this nematode.

Small grain diseases. On winter wheat, Fusarium crown rot was more prevalent and more severe in the winter wheat/cultivated fallow (#1) than in other rotations (Table 6). Rotting of internal crown tissue occurred on less than 3% of plants, and was mostly only found in the cultivated fallow rotation and in the annual winter wheat. On spring cereals, crown rot was significantly more prevalent and severe on annual spring barley than on annual spring wheat (Table 6). Rotting of crown tissue generally was not observed on spring cereals but was present during the driest year (2008) in

Table 5. Density of root-lesion nematode species during the final spring season (2012) of 14 rotational phases of 8 cropping systems in the LTE at Moro

Rota-tion	Treatment	Current year	Previous year	Nema./lb of soil [a] Pn	Pt	Total
1	WW/CuF	WW	CuF	814	150	964
		CuF	WW	907	352	1,259
2	WW/ChF	WW	ChF	535	238	773
		ChF	WW	529	558	1,087
3	Annual WW	WW	WW	4,960	852	5,812
4	Annual SW	SW	SW	505	3,618	4,123
5	Annual SB	SB	SB	144	16	160
6	WW/SB/ChF	WW	SB	338	125	463
		SB	ChF	83	134	217
		ChF	WW	455	257	712
7	WW/WP	WW	WP	1,118	276	1,394
		WP	WW	616	868	1,484
8	Flex crop	WW	Cam	190	683	873
		Cam	SW	457	3,536	4,093

[a] Pn = *Pratylenchus neglectus*, Pt = *P. thornei*. For Rotations 3 and 4, the ratio of *P. neglectus* to *P. thornei* was 5.8 in winter wheat (#3) and 0.2 in spring wheat (#4). For *P. neglectus* the ratio of winter wheat to spring wheat was 9.8. For *P. thornei* the ratio of winter wheat to spring wheat was 0.2.

Table 6. Severity (Sev) and incidence (Inc) of wheat and barley root and crown diseases [a] averaged over 9 years (2004-2012) in the LTE at Moro; 27 plots of all except one treatment.

Rota-tion	Treatment	Fusarium crown rot Sev	Inc	Rhizoctonia root rot Sev	Inc	Take-all Sev	Inc	Root pruning Inc
	<u>Winter wheat</u>							
3	Annual WW	1.6	33	1.0	38	0.8	8	11
1	WW/CuF	2.5	57	0.9	37	0.9	14	7
2	WW/ChF	1.9	41	1.2	47	0.8	16	15
7	WW/WP	1.5	21	0.7	35	1.0	14	10
6	WW/SB/ChF (WW only)	1.5	30	1.1	46	0.8	16	12
	<u>Spring cereals</u>							
4	Annual SW	0.9	14	1.4	56	0.8	17	2
5	Annual SB	1.2	28	1.9	66	0.5	9	4
6	WW/SB/ChF (SB only)	0.9	23	2.0	65	0.8	13	7
8	Flex crop (SB & SW)	0.6	4	1.6	53	0.5	4	6

[a] Severity (Sev) ratings and incidence (Inc) of symptomatic plants for diseases caused by *Fusarium culmorum* and/or *F. pseudograminearum*, *Rhizoctonia solani* AG-8, and *Gaeumannomyces graminis* var. *tritici*. Root pruning was the incidence of plants with roots terminated by effects of *Pythium*, *Rhizoctonia* and/or *Pratylenchus*.

annual spring wheat (3% of plants), annual spring barley (7%), and spring barley in the 3-year rotation (10%).

DNA analysis showed that both *F. culmorum* and *F. pseudograminearum* were present (Table 7). *F. culmorum* was detected at a high level in chemical fallow following winter wheat (2B), winter wheat following chemical fallow (6A), annual spring barley (#5), spring barley following winter wheat (6B), and

Table 7. Concentration of fungal DNA in 14 treatments of 8 cropping systems during 2012.

Rota-tion	Treatment	Current year	Previous year	Concentration of pathogen DNA [a]						
				Ggt	Rs	Fp	Fc	Bs	Pyth	Pmp
1A	WW/CuF	WW	CuF	0	14	23	4	0	71	0
1B	WW/CuF	CuF	WW	1	6	19	6	0	74	0
2A	WW/ChF	WW	ChF	1	10	29	2	0	83	0
2B	WW/ChF	ChF	WW	0	19	33	26	0	31	0
3	Annual WW	WW	WW	0	13	5	1	0	70	0
4	Annual SW	SW	SW	1	49	4	7	0	145	0
5	Annual SB	SB	SB	1	35	25	28	1	115	0
6A	WW/SB/ChF	WW	ChF	1	31	4	79	0	40	0
6B	WW/SB/ChF	SB	WW	1	43	13	18	0	93	0
6C	WW/SB/ChF	ChF	SB	0	37	4	3	0	173	0
7A	WW/WP	WW	WP	1	29	1	9	0	82	76
7B	WW/WP	WP	WW	1	48	3	3	0	445	114
8A	Flex crop	WW	Cam	1	22	1	1	0	386	0
8B	Flex crop	Cam	SW	1	30	5	15	0	143	0

[a] Quantity of fungal DNA (pg/g of soil) reported by the Root Disease Testing Service (Adelaide, Australia). Pathogens were *Gaeumannomyces graminis* var. *tritici* (Ggt), *Rhizoctonia solani* AG-8 (Rs), *Fusarium pseudograminearum* (Fp), *Fusarium culmorum* (Fc), *Bipolaris sorokiniana* (Bs), *Pythium* species (Pyth), and *Phoma medicaginis* var. *pinodella* (Pmp).

camelina recently planted into soil previously cropped to spring wheat (8B). The greatest detection of *F. pseudograminearum* occurred in treatments where winter wheat was rotated with cultivated or chemical fallow (1A, 1B, 2A, 2B), in annual spring barley (#5), and in spring barley following winter wheat (6B), and in winter wheat following spring barley (6A). Detections of both pathogens were high in treatments that included spring barley (#5 and 6B) and in the fallow phase of the winter wheat/chemical fallow treatment. DNA of both *Fusarium* sp. was higher in annual spring barley (#5) compared to annual winter wheat (#3) or annual spring wheat (#4). The common root rot pathogen *B. sorokiniana* was detected at a low concentration only in the annual spring barley treatment (#5).

Rhizoctonia root rot on winter wheat was most prevalent and most severe in the chemical fallow rotation (#2) and the 3-year rotations (#6) and least prevalent and least severe in the winter wheat/winter pea rotation (#7) (Table 6). Inoculum of *R. solani* AG-8 was at a high level in most of the treatments (Table 7). On spring cereals, the incidence of Rhizoctonia root rot was uniform among crop rotations but severity was greater for spring barley than for spring wheat (Table 6). DNA of the pathogen was high in all treatments where direct-seeded spring cereals occurred (Table 7).

Symptoms of take-all on winter wheat did not differ among rotations (Table 6) and DNA of *G. graminis* var. *tritici* was low throughout the trial area (Table 7). Root pruning on winter wheat was greatest in rotations with the greatest amount of surface residue between and within crops and least in the rotation of winter wheat with cultivated fallow (Table 6). DNA from the most likely pathogens (*Pythium*, *Rhizoctonia* and *Pratylenchus*) was high in most of these treatments. The incidence of root pruning did not differ among treatments of spring cereals.

Pulse diseases. Dark lesions occurred on cotyledons and upper taproots of winter pea each year. Primary pathogens revealed by DNA analysis during 2012 included *R. solani* AG-8, *Pythium* species, *Phoma medicaginis* var.

pinodella, and *Pratylenchus* species (Tables 5 and 7), each of which was more prevalent in the rotation phase currently planted to winter pea than in the rotation phase currently planted to winter wheat. Disease severity ratings on both cotyledons and roots were always relatively low (<2 on a 0-4 scale) but the disease incidence from year to year varied from 5% to 88% on cotyledons and from 3% to 100% on roots. During 2008, the year with the driest spring, we also detected a reduction in root branching on 65% of the plants. On spring pea the dark lesions were present on more than 60% of the plants but the severity ratings were low (1.5 or less) and did not differ among years. DNA for pathogens capable of causing symptoms on spring pea (Table 7) included *R. solani* AG-8 and *Pythium* species.

Brassica diseases. No diseases were detected on roots or stems of mustard during 2006 in Rotation 8A. Lesions occurred on the lower stems of camelina during each of the three years it was grown and were very prevalent (70% of plants) during the driest year (2008) and barely detectable (< 2% of plants) in 2011 and 2012. However, even in 2008 the severity rating was low (1.2 on a 0 to 4 scale). Similar observations occurred for the incidence of lesions on roots of camelina; 82%, none, and 12% during 2008, 2011 and 2012, respectively. The severity of root lesion symptom was minor; 1.3 during 2008 and 0.7 during 2012. DNA of pathogens capable of causing symptoms on brassica crops included *R. solani* AG-8, *Pythium* species, and *Pratylenchus* species (Tables 5 and 7).

Grain yields. Data for yield are not presented in this summary. Average yields over four years (2005 to 2008) were highest for winter wheat in the 3-year rotation (#6) and in the winter wheat/cultivated fallow (#1), followed in order by winter wheat/chem-fallow (#2), winter wheat/winter pea (#7), annual spring barley (#5), and spring barley in the 3-year rotation (#6). The lowest mean yields were for annual winter wheat (#3) and annual spring wheat (#4). The yields for winter wheat in five crop sequences (all except the flex-crops) were strongly and negatively correlated with the density of root-lesion nematodes (Fig. 1). The lowest yields shown in the figure correspond to the datum points for annual winter wheat.

Soil water. Soil water content during the spring and summer of 2006 is shown in Fig. 2. Greater moisture was present at the end of the growing season for the three fallow treatments compared to all winter wheat treatments. Compared to winter wheat in other crop sequences, the annual winter wheat extracted much less water and had the highest density of root-lesion nematodes and lowest grain yield. A similar result occurred when water was monitored in 2007.

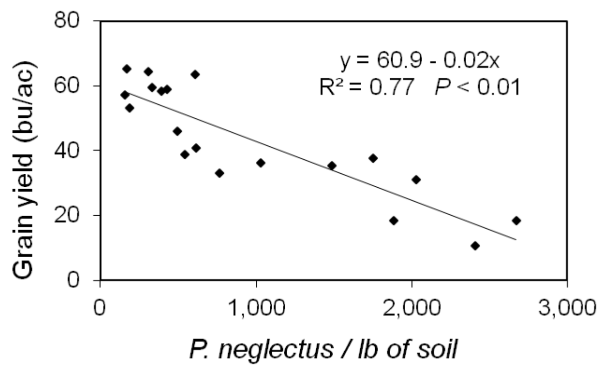

Figure 1. Relationship of *Pratylenchus neglectus* density and yield of winter wheat in five crop rotations averaged over a 4-year period (2005-2008) in the LTE at Moro

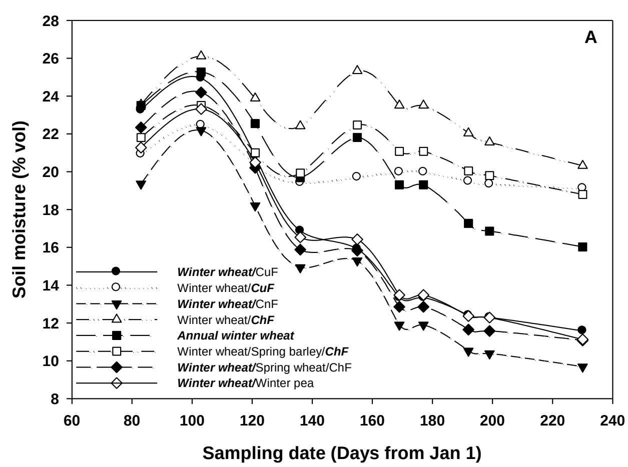

Figure 2. Mean soil water content under all rotations in the 0 to 40-inch depth profile at Moro from March to September during 2006. Data is for the crop or treatment shown in boldface and italics of a crop or management sequence.

HIGHLIGHTS

Nematodes:

1. Root-lesion nematodes increased in prevalence as the frequency of wheat or winter pea was increased.
2. Root-lesion nematodes were at a high density following a mustard crop and at a low density following spring barley, spring pea, and camelina.
3. Root-lesion nematodes were in lower numbers in chemical fallow compared to cultivated fallow systems.
4. There was an inverse relationship between yield of winter wheat and the density of root-lesion nematodes during the spring.
5. In plots with the greatest densities of root-lesion nematode the wheat roots were least capable of extracting water (and nutrients?) from the soil profile.
6. Different crops selected from different species of the root-lesion nematode.

Fungal pathogens:

1. Fusarium crown rot was more severe and prevalent when winter wheat was planted into cultivated fallow than into chemical fallow.
2. DNA of *F. pseudograminearum* was generally higher than for DNA of *F. culmorum* in winter wheat-fallow rotations and in spring wheat, and the DNA concentration of these species was more equivalent in cropping systems that included spring barley.
3. Rhizoctonia root rot was more prevalent and more severe when winter wheat was rotated with chemical fallow than cultivated fallow.
4. Take-all was present even during the driest year and was more severe on annual spring wheat than on annual spring barley.
5. *Phoma medicaginis* var. *pinodella* was a previously overlooked pathogen in the complex of fungi that cause lower stem and upper root lesions on pulse crops.

OVERALL SUMMARY:

Previously, we believed that only *P. neglectus* was dominant at Moro. The use of DNA extracts for real-time PCR during the last year of the study revealed that there was far more *P. thornei* in certain treatments than we had realized. We learned that effects of crop rotations are far more complex than we had previously believed. In particular, winter wheat promoted higher densities of *P. neglectus* than *P. thornei* and the reverse was true for spring wheat and winter pea. More research is required to understand this observation, particularly since we already know that wheat varieties differ in their ability to tolerate invasion by each these species. For instance, *P. thornei* reproduces very effectively on Louise. We also reported previously that *P. thornei* reproduced twice more effectively on Tubbs and Tubbs'06 than on ORCF102, and that ORCF101 was intermediate. We also showed that *P. neglectus* reproduced prolifically on ORCF102 and ORCF101, and slightly less on Tubbs and Tubbs'06. Compared to winter wheat varieties used in the LTE at Moro, popular varieties such as Stephens and Madsen were much poorer hosts of *P. neglectus* but very good to excellent hosts of *P. thornei*. The choice of wheat variety will clearly have an impact on the density and dominance of these two species of root-lesion nematodes.

We previously reported that higher numbers of *Pratylenchus* sp. were typically detected in fallow following wheat than during the spring during the growth of winter wheat. In this study we found twice as many *Pratylenchus* sp. in the cultivated fallow than in the chemical fallow treatment nearly eight months after harvest. We also noted that the density of *Pratylenchus* sp. tended to decline more rapidly during cultivated (50%) than of chemical fallow (21%). It has been reported by others that the density of *P. neglectus* is reduced more by a combination of tillage and fallow than by fallow alone.

When the densities of *Pratylenchus* sp. were averaged over the 42 plots for each year of this experiment there was an inverse relationship between density of nematodes and the amount of rainfall that occurred during the five months (November through March) before soil samples were collected. We hypothesize that, compared to drier soil, the wetter soil during the winter months reduced survival of nematodes produced on crop roots the previous year. It is likely that the number of wetting and drying cycles during the winter months are fewer during the driest winters. If so, the drier periods during late fall and early winter could favor longer periods of dormancy induced by cold temperature or they could reduce mortality from parasitism by bacteria and fungi. There are other possibilities but further research will be required.

Lowest densities of *Pratylenchus* species were detected following spring barley, spring pea, or camelina and highest densities occurred following winter wheat, spring yellow mustard or winter pea. We also confirmed previous observations that *Pratylenchus* species become more numerous as host-crop frequency is increased. It is unclear as to why winter field pea was a good host of *P. thornei* and spring field pea appeared to be resistant. This will require further study.

Soilborne fungi and nematodes that cause the root and crown diseases survive either in a dormant state in soil or in root, crown or basal stem tissues of plants that were infected while they were living. Pathogen inoculum declines over time as dormancy structures are subjected to multiple wetting and drying cycles that stimulate activity of the soil microbiota and reduce the mass of residue available for harboring pathogen inoculum. In the low-rainfall areas of the PNW the lack of effective rotational diversity or rotation length provides an opportunity for efficient survival of pathogen inoculum from one crop to the next. In our study, the persistence of pathogen inoculum during the 14-month period of fallow was revealed by results of DNA analyses. In particular, inoculum levels remained quite high during fallow periods for *Rhizoctonia solani* AG-8, *Fusarium culmorum*, *F. pseudograminearum*, and species of *Pythium*.

We found Fusarium crown rot to be more severe and more prevalent when winter wheat was planted into cultivated fallow than into chemical fallow. It is well known that there is a strong relationship between the date of planting and the occurrence of Fusarium crown rot. In this study, winter wheat was planted as much as three weeks earlier into cultivated fallow than into chemical fallow. Moreover, when wheat is planted into cultivated fallow it is planted into warm, moist soil beneath the dust mulch. Wheat planted into chemical fallow is either placed shallowly into dry soil in anticipation of the onset of fall rains or is placed shallowly into moist soil following the onset of fall rain or while soil is still moist during the spring. The *Fusarium* species that cause crown rot can infect any tissue but often invade the coleoptile as it elongates from the seed to the soil surface (it becomes the subcrown internode). These fungi may also invade the crown tissue as the outer leaf sheath tissue is ruptured during emergence of crown roots. As compared to direct-seed cropping systems, winter wheat planted into cultivated fallow is typically planted into a soil environment that is more favorable for invasion by *Fusarium* species.

The concentration of *F. pseudograminearum* DNA was generally higher than for *F. culmorum* in winter wheat-fallow rotations and in spring wheat, but the DNA concentrations of these species were more equivalent in treatments that included spring barley. The greater DNA concentration in the spring barley coincided with higher crown rot ratings in spring barley than in spring wheat. Selection of *Fusarium* species by different crop systems requires further study.

Rhizoctonia root rot is generally most damaging to spring barley than to spring or winter wheat, and is generally more damaging in annual crops in direct-seed than cultivated cropping systems. In agreement with previous research, we also found that Rhizoctonia root rot was more prevalent and more severe when winter wheat was rotated with chemical fallow than cultivated fallow. Moreover, when winter wheat was grown in a 2-year direct-seed system, Rhizoctonia root rot was less prevalent and less severe when the wheat was rotated with winter pea than with chemical fallow. DNA evidence provided support for the hypothesis that inoculum density of *R. solani* AG-8 declines during the fallow phase of rotations. However, it was notable that DNA of this pathogen was present in rather high inoculum densities in most of the rotations. These results support previous reports that *R. solani* quickly becomes a limiting factor when dryland wheat is converted to irrigation, and when a winter wheat-fallow system is changed from cultivated to direct-seed.

The classical symptom of take-all is a blackening of roots, the crown and the lower stem. This symptom occurs in where rainfall is plentiful or when cereals are irrigated. In low-rainfall dryland production take-all symptoms are restricted to the seminal roots and, while restricting water uptake particularly from deep-feeding seminal roots, the plants are not noticeably stunted and it is difficult to demonstrate a reduction in grain yield or grain quality. In this study, 'dryland take-all' occurred even during the driest of the nine years and was more severe on annual spring wheat than on annual spring barley. The chronic occurrence of 'dryland take-all', with a very low level of inoculum occurring in most treatments, explains why take-all quickly becomes severe when land is converted to irrigation.

Diseases caused by species of *Pythium* are well known in the low rainfall regions but an absence of visually diagnostic symptoms makes it difficult to evaluate differences among treatments. Nevertheless, the problem is so important that all commercial seed treatments sold in the PNW contain a fungicide capable of suppressing seed rot and seedling damping-off by *Pythium*. DNA of *Pythium* species occurred at rather high inoculum densities in most rotations, underscoring the need to treat seed with a fungicide to protect seed and seedlings from *Pythium*.

Root and lower stem diseases of pulse crops are chronic and sometimes severe. Lower stem and upper root lesions on peas were thought to be caused by pathogens such as *F. solani*, *R. solani* AG-8, *Pythium* species, and *Thielaviopsis basicola*. DNA analysis was not available for *F. solani* or *T. basicola* but supported our earlier belief regarding *R. solani* AG-8 and *Pythium* species. Moreover, we also learned that *Phoma medicaginis* var. *pinodella* was another pathogen that we had previously overlooked. This pathogen had been reported in higher rainfall regions of western Oregon and eastern Washington but not from the dryland low-rainfall environment of north-central Oregon.

This study revealed new findings that will provide guidance for research to improve the efficiency of crop production in the PNW. These findings have important implications regarding the refinement of farming practices that can be used to more effectively manage the disease process without necessarily attempting to reduce the inoculum density of these pathogens.

Potential associations between fungal pathogens and root-lesion nematodes must also be considered in future research. Current studies in Australia and Iran are each revealing that wheat varieties that have the least tolerance to the nematode express the greatest yield losses from Fusarium crown rot pathogens even when environmental conditions are not particularly conducive to development of crown rot. The co-existence of the nematode and the fungal pathogen leads to a considerably greater amount of plant damage and yield loss than that caused by either pathogen alone. This could provide important guidelines for maximizing the efficiency of wheat production in the PNW.

ACKNOWLEDGEMENTS

The authors thank Sandra Easley, Jennifer Gourlie, Erling Jacobsen, Larry Pritchett, Jason Sheedy, Anthony Spence, Alison Thompson and Dr. Guiping Yan for technical assistance, and Dr. Steve Petrie and farmers who served on the advisory committee for this long-term experiment. This research was partially funded by the USDA-ARS Root Disease and Biological Control Unit, at Pullman, and by the USDA-CSREES-STEEP Program.

TECHNICAL PUBLICATIONS:

Smiley, R. W., and Machado, S. 2009. *Pratylenchus neglectus* reduces yield of winter wheat in dryland cropping systems. Plant Dis. 93:263-271.

Smiley, R. W., Machado, S., Gourlie, J. A., Pritchett, L. C., Yan, G. P., and Jacobsen, E. E. 2013. Influence of semi-arid cropping systems on root diseases and inoculum density of soilborne pathogens. Plant Disease 97: (submitted for peer review).

Smiley, R. W., Machado, S., Gourlie, J. A., Pritchett, L. C., Yan, G. P., and Jacobsen, E. E. 2013. Effects of crop rotation and tillage on *Pratylenchus* species in the semi-arid Pacific Northwest USA. Plant Disease 97: (submitted for peer review).