Soilborne pathogens / Agents pathogènes telluriques

Influence of subsoiling on direct-seeded cereals in southeastern Idaho

Carl A. Strausbaugh and Juliet M. Windes

Abstract: The influence of shallow (20 cm deep) subsoil tillage on cereals planted with a no-till planter was investigated for 3 years at two locations in southeastern Idaho. Among *Fusarium* spp., *F. culmorum* was the primary fungus isolated from diffuse brown-black root lesions in the wetter location (Ririe), while *F. semitectum*, *F. reticulatum*, *F. equiseti*, and *F. acuminatum* were the dominant species isolated at the drier location (Arbon Valley). Increased yields resulting from methyl bromide fumigation indicated that biological factors were limiting the yield. However, subsoiling did not influence nematode populations or fungal root rots. The primary parasitic nematode found at both locations was *Pratylenchus neglectus*. Subsoiling had a tendency to increase soil moisture at depths between 61 and 90 cm, to increase organic matter, and to decrease nitrogen. Yield increased by 8% or more with subsoil tillage at both locations the first year. Yield increases were not significant in other years, when moisture was particularly limiting or abundant. Subsoiling may prove favorable for cereals planted in a soil-conservation tillage system, but the risk of fungal root rots may increase with such a practice. Additional study is warranted, as subsoil-tillage practices may increase yield and desirable soil parameters without compromising the benefits associated with cereal production in a soil-conservation tillage system.

Key words: Fusarium spp., fusarium root rot, direct seeding, dryland, subsoiling, no till, zero tillage.

Résumé : L'effet d'un sous-solage superficiel (20 cm de profondeur) sur des céréales plantées avec un planteur pour le semis direct a été étudié pendant 3 ans à deux sites du sud-est de l'Idaho. Parmi les espèces du *Fusarium*, le *F. culmorum* a été le principal champignon isolé de lésions racinaires floues brun noir au site le plus humide (Ririe), alors que les *F. semitectum*, *F. reticulatum*, *F. equiseti* et *F. acuminatum* ont été les espèces dominantes isolées du site le plus sec (vallée d'Arbon). Des augmentations de rendement résultant de fumigation au bromure de méthyle ont révélé que des facteurs biologiques limitaient les rendements. Par contre, le sous-solage n'a pas eu d'effet sur les populations de nématodes ou sur les pourritures racinaires fongiques. Le *Pratylenchus neglectus* fut le principal nématode parasite retrouvé aux deux sites. Le sous-solage avait tendance à augmenter la teneur en eau du sol aux profondeurs entre 61 et 90 cm, à augmenter la matière organique et à diminuer l'azote. Avec le sous-solage, les rendements ont augmenté de 8% ou plus aux deux sites au cours de la première année. Lors des autres années, les augmentations de rendement n'étaient pas significatives lorsque l'eau était particulièrement limitée ou abondante. Le sous-solage peut s'avérer profitable pour les céréales plantées dans un système de conservation des sols, mais une telle pratique pourrait accroître le risque de pourriture racinaire fongique. Des études supplémentaires sont souhaitables puisque les pratiques de sous-solage peuvent augmenter les rendements et améliorer les paramètres du sol sans mettre en péril les avantages de la production céréalière dans un système de conservation des sols.

Mots clés : Fusarium spp., pourriture racinaire fusarienne, semis direct, culture non irriguée, sous-solage, semis direct, culture sans travail du sol.

Introduction

In the Intermountain West (IMW) region from the Cascade Mountain range to the Rocky Mountains, small-grain cereals are produced in both dryland (rain-fed) and irrigated tillage-based production systems. To minimize crop inputs and reduce soil erosion from water and wind, growers have been encouraged to consider soil-conservation tillage in cereal production. Dryland fields planted with no tillage in southeastern Idaho are normally seeded annually to cereals. Some areas are too dry to produce high-quality malt barley and are therefore restricted to continuously cropped wheat.

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In high-elevation areas, winterkill and fungi causing snow mold further restrict growers to spring cereal production. Under such limited cropping options, soilborne diseases can limit yield.

Cereal foot-, crown-, and (or) root-infecting pathogens prevalent in the Pacific Northwest (PNW) at lower elevations (approximately 120–780 m) include rhizoctonia root rot and bare patch [*Rhizoctonia solani* Kühn AG8 and *Rhizoctonia oryzae* Ryker & Gooch], damping-off and pythium root rot [*Pythium* spp.], take-all [*Gaeumannomyces graminis* (Sacc.) Arx & D. Olivier var. *tritici* J. Walker], and fusarium foot and root rot [*Fusarium pseudograminearum* O'Donnell & T. Aoki and *Fusarium culmorum* (Wm.G. Sm.) Sacc.] (Cook 1968; Cook et al. 2002; Paulitz et al. 2002; Smiley 1996; Smiley and Patterson 1996; Smiley et al. 2005a). However, the pathogen responsible for crown and root rots can vary among sites in the PNW (Smiley et al. 2005a).

Fusarium culmorum and *Bipolaris sorokiniana* (Sacc.) Shoemaker are the primary root rot pathogens of concern at higher elevations in the IMW region (Strausbaugh et al. 2004, 2005). Recently, among the *Fusarium* spp., *F. acuminatum* Ellis & Everh., *F. reticulatum* Mont., and *F. semitectum* Berk. & Ravenel, normally considered minor pathogens, have been implicated as part of a *Fusarium* complex affecting crops in this production system (Strausbaugh et al. 2005).

In addition to fungal root and crown rots, root-lesion nematodes, particularly *Pratylenchus neglectus* (Rensch) Filipjev & Schuurmans-Stekhoven, are present in cereal fields planted without tillage in both the PNW and IMW regions (Smiley et al. 2005b; Strausbaugh et al. 2004). When dryland fields are shifted to higher-intensity cereal cropping, *Pratylenchus neglectus* can increase dramatically in dryland fields (Gair et al. 1969) and is associated with declining growth and yield (Smiley et al. 2005b).

Disease development associated with soilborne plant pathogens is influenced by factors in the soil environment such as soil physical and chemical composition and soil microflora (Rothrock 1992). There are conflicting reports on the influence of various tillage practices on root rots (Windels and Wiersma 1992). Previous work has focused on taking fields out of conventional tillage and into minimum- or no-till systems. Very little research has examined the impact of subsoiling on soilborne pathogens and cereal root rots in fields managed for a long term under no-till systems. Subsoiling had a positive influence in other cropping systems by reducing compaction (Henriksen et al. 2005). In no-till systems, soil compaction can occur, which may reduce water and root infiltration and increase root diseases (Hammel 1989). Shallow subsoiling may be a good solution for reducing soil compaction, but its influence on other soil parameters in the cropping system has not been thoroughly investigated.

By subsoiling with narrow shanks, producers can hope to break up compaction layers without negatively impacting the benefits associated with no-till cereal production. A series of subsoiling studies were initiated in southeastern Idaho in fields that had been in direct-seeded cereal production for 15 or more years. The objective was to determine the influence of subsoiling on soilborne pathogens, plant, and soil parameters, and on yield of cereals typically planted without tillage.

Materials and methods

Field-study locations and soil types

Field studies were established from 2002 to 2004 in Idaho, near Ririe in Bonneville County and in Arbon Valley in Power County, in commercial dryland fields with 15 cm high standing stubble and natural cereal pathogen populations. These fields were chosen because they had been direct-seeded to wheat and (or) barley for at least the preceding 15 years and were representative of the moisture extremes (29–41 cm of annual precipitation, based on data from the Western Regional Climate Center, 2215 Raggio Parkway, Reno, NV 89512, United States; http://www.wrcc.dri.edu) of the IMW production area. Ririe is typical of the wetter production areas in soil-conservation tillage, while Arbon Valley is representative of drier areas. The soil type at Ririe was a Tetonia silt loam (coarse-silty, mixed, calcic, pachic cryoboroll) with pH 6.3 and 2.6% of organic matter. The soil type in Arbon Valley was a Newdale silt loam (coarse-silty, mixed, frigid, calciorthidic haploxeroll) with pH 7.6 and 1% of organic matter.

Experimental design and description of treatments

A split-plot design was used where the main plots (48.8 m × 14.63 m) with no tillage or shallow subsoil tillage were arranged in a randomized complete block design with four replicates. The subsoil-tillage treatment consisted of broadcast ripping with 2 cm wide rigid shanks with narrow (2.54 cm wide) points that were run through the ground 30 cm apart to a depth of 20 cm and perpendicular to the direction of planting. Within the main plots, subplots (3.78 m × 14.63 m) were either fumigated with methyl bromide or not (untreated). Fumigation was performed on 24 September 2002 by placing methyl bromide under a plastic tarpaulin at a rate of 45 g/m^2. The tarpaulin was removed after 7 days.

Because the 2002 data were collected prior to fumigation, these results provide a base-line data set for each location. The 2003 data set represents the first crop to be planted in the fall-fumigated ground. The fumigation was not repeated prior to the 2004 crop, so the 2004 data represent the second-year influence of the treatment. All seed planted at the Arbon Valley location was treated with Gaucho® 480 (48.7% imidacloprid; Gustafson, Plano, Texas) at 1.95 mL per kilogram of seed for insect control. Seed planted at Ririe was treated with Lindane 30C (30% lindane; Gustafson) at 0.91 mL/kg in 2002 and 2004 and with Gaucho 480 at 1.95 mL/kg in 2003. Within the untreated control and fumigated plots, a 1.52 m × 14.63 m area was reserved for harvest to collect yield data and was not subjected to sampling. The Ririe field was planted using a ATX Concord direct-seed drill (Case IH, Racine, Wisc.) in 2002 and 2004; in 2003, a custom-built drill with Conserva Pak® (Conserva Pak Seeding Systems, Indian Head, Sask.) openers was used. The Arbon Valley field was planted using a custom-built drill with Conserva Pak® openers. Both seeders placed fertilizer 3.81 cm below the seed in a one-pass operation.

Plots were harvested at maturity with a small-plot combine. Yield and test weight were determined.

Ririe field parameters

2002

The subsoil treatment was applied on 22 April 2002 and then the field was sprayed with Roundup® UltraMax (50.2% glyphosate; Monsanto, St. Louis, Mo.) at 1.17 L/ha for weed control. The field was planted at 89.6 kg/ha with the hard red spring wheat 'Jefferson' (*Triticum aestivum* L.) on 23 April 2002. Fertilizer placed below the seed included, per hectare, 89.6 kg of N, 22.2 kg of P_2O_5, and 16.8 kg of S.

2003

The subsoil treatment was applied on 19 September 2002 in the same direction and the same area previously subsoiled. Seed of the two-row spring malting barley 'Harrington' (*Hordeum vulgare* L.) was planted at 89.6 kg/ha on 21 April 2003. The fertilizer placed below the seed included, per hectare, 72.8 kg of N, 28.0 kg of P_2O_5, and 17.9 kg of S/ha. The weeds and volunteer wheat were controlled with a Roundup UltraMax) spray at 1.17 L/ha on 24 April 2003.

2004

The subsoil-tillage treatment in Ririe was applied on 15 October 2003 in the same direction and the same area previously subsoiled. The field was planted with hard white spring wheat 'Idaho 377s' (*T. aestivum*) at 67 kg/ha on 27 April 2004. The fertilizer placed below the seed included, per hectare, 84 kg of N, 28 kg of P_2O_5, and 18 kg of S. Weeds and volunteer wheat were controlled with Roundup UltraMax at 0.73 L/ha on 25 April 2004 and a 0.02 kg/ha application of Ally® Extra (37.5% thifensulfuron methyl, 18.75% tribenuron methyl, and 15% metsulfuron methyl; Dupont, Wilmington, Del.) on 21 May 2004.

Arbon Valley field parameters

2002

The subsoil treatment was applied on 24 April 2002 and then the field was sprayed with Roundup UltraMax at 1.17 L/ha for weed control. The field was planted with soft white spring wheat 'Whitebird' (*T. aestivum*) on 25 April 2002. Fertilizer placed below the seed included, per hectare, 67.2 kg of N, 16.8 kg of P_2O_5, and 6.7 kg of S.

2003

The subsoil treatment was applied on 19 September 2002 in the same direction and the same area previously subsoiled. The weeds and volunteer wheat were controlled with a Roundup UltraMax) spray at 1.17 L/ha on 11 October 2002. Seed of soft white winter wheat 'Eltan' (*T. aestivum*) was planted at 112 kg/ha on 15 October 2002. Fertilizer placed below the seed included, per hectare, 16.8 kg of N and 11.2 kg of P_2O_5.

2004

Subsoil-tillage treatment was applied on 15 October 2003 in the same direction and the same area previously subsoiled. The same day, an application of Roundup UltraMax was applied at 1.17 L/ha for weed control. The field was planted with soft white spring wheat 'Whitebird' at 67 kg/ha on 8 May 2004. Fertilizer placed below the seed included, per hectare, 45 kg of N and 11 kg of P_2O_5. Weeds and volunteer wheat were sprayed out with Roundup UltraMax at 1.17 L/ha on 8 May 2004.

Root evaluations

The roots of 20 plants per experimental unit were dug at Feeke's growth stage 10.1–10.5 (late "boot" to flowering) and evaluated for numbers of roots and tillers and for root diseases. The roots were initially placed in plastic bags in a cooler for transport to the laboratory; samples were then placed in a refrigerator at 4 °C until they were rated. Mainstem and seminal roots were evaluated for disease severity and assigned to one of the following root-lesion categories: (1) spear tips, (2) discrete black lesions, and (3) diffuse brown lesions. The spear-tip lesion type included roots with spear tips and lesions associated with reduced root diameter. These lesions are usually associated with *Rhizoctonia* spp., but the pathogen was difficult to isolate from mature root systems. The diffuse brown lesion type included roots with diffuse brown to dark-brown lesions, but no reduction in root diameter. Isolations from this lesion type were *Fusarium* spp. and *B. sorokiniana*. The discrete black lesion type had no reduction in root diameter and was normally associated with *G. graminis* var. *tritici*. When isolated, *G. graminis* var. *tritici* was always associated with this lesion type, but *Fusarium* spp. and *B. sorokiniana* were occasionally isolated. Disease severity was established for each lesion type individually, using a 0–4 scale: 0, no lesions; 1, fewer than 10% of the roots with lesions; 2, 10%–33% of the roots with lesions; 3, 34%–66% of the roots with lesions; and 4, more than 66% of the roots with lesions. A disease severity index was calculated for each plot, as follows: (% incidence × mean severity)/4. Isolations were made from root lesions (four lesions of each type per plot in each field) by disinfecting root tissues in a 0.5% sodium hypochlorite (NaOCl) solution for 30 s, splitting the root lesion in half, and placing one half on 1.8% Bacto agar (Becton Dickinson & Co., Sparks, Md.) and the other on Difco potato dextrose agar (PDA; Becton Dickinson & Co.). Both media were amended with streptomycin sulfate at 200 mg/L. Fungi growing from the roots were transferred to a plate of streptomycin-amended Difco PDA. All fungal isolates were then single-spored (hypha-tipped if no spores were present), using Bacto agar and then transferred to Difco PDA. Fungal identifications were performed using a light microscope. The *Fusarium* spp. isolates were also grown on synthetic nutrient-poor agar (Gerlach and Niremberg 1982) with pieces of sterile (autoclaved for 15 min at 121 °C) filter paper and carnation leaves placed on the agar surface prior to inoculation. The *Fusarium* spp. cultures were placed under fluorescent light for 3 weeks and identified as described by Nelson et al. (1983). Root isolation data from 2003 had been utilized previously to support the publication of a real-time polymerase chain reaction assay (Strausbaugh et al. 2005).

Reference cultures

Reference cultures were obtained from the Fusarium Research Center, University Park, Pennsylania, for the following *Fusarium* spp.: *F. culmorum* (R-9423), *F. pseudograminearum* (R-6563), *F. graminearum* Schwabe (R-7005), and *F. avenaceum* (Fr.:Fr.) Sacc. (R-6554). Representative cultures of the other *Fusarium* spp. (*F. culmorum*: F70, F82, F83, F99; *F. acuminatum*: F24, F59, F63, F146, F92; *F. equiseti* (Corda) Sacc.: F55, F61, F67, F98; *F. semitectum*: F159; *F. reticulatum*: F60) utilized in this research were submitted to the Fusarium Research Center for identification as part of a previous research project (Strausbaugh et al. 2004). These representative cultures were used for comparison to identify *Fusarium* spp. isolates on the basis of techniques and descriptions established by Nelson et al. (1983).

Samples for analyses of soil moisture and chemical and physical properties

Samples for analyses of soil moisture and chemical and physical properties were collected from the top 0.9 m of the soil profile in three 0.3 m deep increments, using a soil auger at the time of planting for spring cereals. Three sets of samples were collected from each experimental unit and combined prior to analysis. The moisture samples were weighed, dried in an oven at 110 °C for 3 days, allowed to cool to room temperature, and reweighed. The permanent wilting point for the silt-loam soils in these studies is 9.1% (McDole et al. 1974).

The complete soil analysis was conducted by AgSource Harris Laboratories, Lincoln, Nebraska, using established methods (Gavlak et al. 2003). After planting, soil samples were collected from the top 0.9 m of the soil profile two or three times to track the status of soil moisture through to anthesis.

Nematode samples

Nematode assays were performed by the Nematode Testing Service, Oregon State University, Corvallis, Oregon. Nematode samples were collected on 5 July 2002, 26 June 2003, and 21 May 2004 in the Ririe field and on 3 July 2002, 26 June 2003, and 3 June 2004 in the Arbon Valley field. Nematodes were extracted from 250 g of soil from a bulk sample (three subsamples from the top 30 cm of the soil profile per experimental unit), using wet sieving and sucrose density centrifugation (Ingham 1994). The sieving was initiated by washing the sample through a standard, 18-mesh soil sieve with 1 mm mesh into a bucket and allowing the mixture to settle for 2 min. The liquid was then poured through a 400-mesh screen held at a 45° angle to capture nematodes on the screen and leave the sediment in the bucket. The material was then rinsed from the screen into polycarbonate centrifuge tubes. The mixture was centrifuged at 3000 r/min (1383*g*) for 3 min and then one-half of the liquid was decanted. The tube was refilled with a sucrose solution at 900 g/L, shaken to resuspend the pellet, and centrifuged at 3000 r/min for 3 min. The nematodes were decanted from the sucrose solution onto a 500-mesh screen held at a 45° angle and partially immersed in water to disperse the nematodes and sucrose. The nematodes were identified and counted using a dissecting microscope, and numbers were adjusted on an oven-dry moisture basis.

Statistical analyses

Statistical analyses for all studies were performed using SAS version 8.2 (SAS Institute Inc. 1999). Data were analyzed using the general linear model procedure (Proc GLM; SAS Institute Inc. 1999) and the *F* test was used to detect significant ($P < 0.05$) differences between the tillage treatments for the response variables measured. Bartlett's test was used to determine the homogeneity of variance.

Results

Disease and pathogen evaluations

Data for diffuse brown-black root lesions are presented in Table 1, while data for the other two lesion types are not presented, since they were found in only trace amounts. At Ririe, there were no significant differences in diffuse root lesions between the no-till and subsoiled treatments for any root type (Table 1). In Arbon Valley, the only significant difference was that the disease-severity index was higher in main roots in association with subsoiling in 2003 (Table 1). There was significantly less disease with fumigation on all root types at Ririe, except for tiller roots in 2004. There was always less disease on roots with fumigation in Arbon Valley, even 2 years after the fumigation treatment.

Fusarium spp. were the predominant fungi isolated from root lesions at both locations (Table 2). At Ririe, *F. culmorum* was clearly the dominant species. Other fungi isolated from root lesions at Ririe included *B. sorokiniana*, which accounted for 7%–20% of the isolations, while *G. graminis* var. *tritici* and *Rhizoctonia* spp. were not isolated. In Arbon Valley, a number of *Fusarium* spp. (*F. equiseti*, *F. acuminatum*, *F. semitectum*, and *F. reticulatum*) that are normally considered weak pathogens were most frequently isolated. In Arbon Valley, *G. graminis* var. *tritici* isolations were 8% or fewer, and only 1% or fewer of the isolations were *B. sorokiniana* or *Rhizoctonia* spp.

Subsoil tillage did not influence nematode numbers (Tables 3 and 4), except in Arbon Valley in 2003, where more lesion nematodes were associated with subsoil tillage. Both the first and second crops following fumigation had significantly fewer parasitic nematodes at both locations. In 2004, the nonparasitic nematode population had rebounded in the fumigation treatment at Ririe, while they were still reduced with fumigation in Arbon Valley. The primary parasitic nematode species found at both locations was *Pratylenchus neglectus*.

Plant and yield parameters

There were no consistent significant differences or distinct trends in numbers of roots or tillers with subsoiling or fumigation (Table 5). Grain yield was significantly higher with subsoil tillage at both locations in 2002 (Table 6), but lower in Arbon Valley in 2003. Yield in Arbon Valley was likely reduced by subsoiling, because of severe drought conditions, which limited recharge of soil moisture after the larger 2002 crop. In 2004, yield was unaffected by subsoiling. Test weight was not influenced by the subsoil treatment in any location or year. Fumigation increased yields at both locations in 2003, within a year of treatment, indicating that yield was limited by biological factors. No residual effect of fumigation on yield was evident in 2004.

At Ririe, moisture was adequate for plant growth throughout the top 90 cm of the soil profile at the time of planting in 2002 and 2004 (Table 7). The 2003 data indicated that only the top 30 cm of soil had adequate moisture at planting.

Table 1. Disease-severity indices for diffuse brown-black lesions associated with *Fusarium* spp. and *Bipolaris sorokiniana* on cereal* roots in response to tillage and methyl bromide fumigation in two southeastern Idaho fields, at Ririe in Bonneville County and in Arbon Valley in Power County, in 2002–2004.

	Disease-severity index					
	Tillage treatment[†]			Fumigation treatment[‡]		
Crop parameter	None	Subsoiled	$P > F$	No	Yes	$P > F$
Ririe						
Seminal roots	18	24	0.1735	32	14	0.0112
Main-stem roots	25	25	0.7512	32	16	0.0043
Tiller roots						
2002	4	4	0.5617	na	na	na
2003	20	16	0.5754	25	11	0.0015
2004	6	8	0.6355	11	4	0.2172
Arbon Valley						
Seminal roots						
2002	11	19	0.3622	na	na	na
2003	19	20	0.8353	35	4	0.0008
2004	44	39	0.5550	60	23	0.0021
Main-stem roots						
2002	38	35	0.6887			
2003	24	32	0.0006			
2004	21	18	0.6305			
2003–2004				40	8	0.0003
Tiller roots						
2002	4	4	0.7086			
2003	6	16	0.0544			
2004	14	6	0.0731			
2003–2004				17	4	0.0049

Note: The disease-severity indices, (% incidence × mean severity)/4, are for plants collected at Feeke's growth stage 10.1–10.5. Parameters for which only one line of data is given were not significantly different ($P > 0.05$) between years or interactions, and variances were homogeneous. The data for these parameters were therefore analyzed across years. $P > F$ denotes the probability associated with the F value when data were analyzed using Proc GLM procedure (SAS Institute Inc. 1999).

*Ririe site was planted with hard red spring wheat 'Jefferson' (*Triticum aestivum*), two-row spring malting barley 'Harrington' (*Hordeum vulgare*), and hard white spring wheat 'Idaho 377s' (*T. aestivum*) in 2002, 2003, and 2004, respectively. Arbon Valley site was planted with soft white spring wheat 'Whitebird' (*T. aestivum*) in 2002 and 2004 and with soft white winter wheat 'Eltan' (*T. aestivum*) in 2003.

[†] "None" indicates no tillage, and "subsoiling" indicates broadcast ripping with rigid shanks 1.9 cm wide with narrow (2.5 cm wide) points run through the ground 30.5 cm apart to a depth of 20.2 cm perpendicular to the direction of planting.

[‡] "No" denotes no fumigation, and "yes" denotes fumigation with methyl bromide at a rate of 45 g/m^2 on 24 September 2002. "na" indicates not applicable because no fumigation was performed for the first year; the data under tillage treatment for this year were used to establish a base line.

In 2003, subsoiling increased ($P < 0.10$) soil moisture at depths between 61 and 90 cm on 23 April and 10 and 25 June. Drought conditions in 2003 were severe and, by anthesis, they resulted in moisture-limiting conditions for crop growth in the upper 90 cm of the soil profile in the no-till plots. Shortly after grain fill, the plants in the no-till plots, the untilled alleyways, and the grower's commercial field surrounding the plots all died and the subsoiled plots were still green, confirming the availability of subsoil moisture. The trend for moisture to increase at depths between 61 and 90 cm with subsoiling was also evident in 2004 for the later sampling dates (Table 7).

In Arbon Valley, the soil moisture profile level was good in the spring of 2002 and 2004, but the soil was very dry in 2003 and moisture was depleted to a depth of 90 cm (Table 8). In the winter of 2002–2003, the soil moisture profile did not totally recharge. The wilting point for the upper 90 cm occurred by 10 June. In contrast to 2004, soil moisture was still available at depths between 61 and 90 cm on 22 July. Under these drier conditions in Arbon Valley, subsoiling did not increase subsoil moisture.

Soil analysis

At Ririe after 2 years, organic matter significantly increased in the top 30 cm and at depths between 61 and 90 cm with subsoiling, but the same trend was present at all soil depths, regardless of subsoiling (Table 9). In contrast, there was a reduction in nitrogen in the upper 30 cm with both treatments (subsoiled and with no tillage) after 2 years. In Arbon Valley over the 3 years (Table 10), organic matter increased

Table 2. Percentages of *Fusarium* spp. isolated from cereal* roots collected from fields at Ririe and in Arbon Valley, Idaho, in 2002–2004.

	% *Fusarium* sp.					
	Ririe			Arbon Valley		
	2002	2003	2004	2002	2003	2004
F. culmorum	33	67	61	9	1	7
F. equiseti	20	7	29	9	20	38
F. acuminatum	13	4	0	0	18	18
F. semitectum	13	1	4	36	11	23
F. reticulatum	7	1	0	27	31	0
Fusarium spp. unidentified	7	0	6	18	10	14

*Ririe site was planted with hard red spring wheat 'Jefferson' (*Triticum aestivum*), two-row spring malting barley 'Harrington' (*Hordeum vulgare*), and hard white spring wheat 'Idaho 377s' (*T. aestivum*) in 2002, 2003, and 2004, respectively. Arbon Valley site was planted with soft white spring wheat 'Whitebird' (*T. aestivum*) in 2002 and 2004 and with soft white winter wheat 'Eltan' (*T. aestivum*) in 2003.

Table 3. Nematode counts in cereal* roots in response to tillage and methyl bromide fumigation at Ririe field, Idaho, in 2002–2004.

	No. of nematodes[‡]/100 g of soil corrected for soil moisture level		
Treatment[†]	Root-lesion nematode	Stunt nematode	Nonparasitic nematodes
2002			
No tillage	22	1.8	93
Subsoiled	34	1.0	94
P >F	0.5630	0.4860	0.9886
2003			
No tillage	145	3	153
Subsoiled	62	6	132
P >F	0.1110	0.3302	0.7612
No fumigation	202	9	260
Fumigation	5	1	25
P >F	0.0151	0.0038	0.0020
2004			
No tillage	276	16	421
Subsoiled	263	20	346
P >F	0.9497	0.7090	0.6867
No fumigation	536	35	423
Fumigation	3	0	343
P >F	0.0167	0.0193	0.4500

*Ririe site was planted with hard red spring wheat 'Jefferson' (*Triticum aestivum*), two-row spring malting barley 'Harrington' (*Hordeum vulgare*), and hard white spring wheat 'Idaho 377s' (*T. aestivum*) in 2002, 2003, and 2004, respectively.

[†] Subsoiling was achieved by broadcast ripping with rigid shanks 1.9 cm wide with narrow (2.5 cm wide) points run through the ground 30.5 cm apart to a depth of 20.2 cm perpendicular to the direction of planting. Fumigation was performed by placing methyl bromide under a plastic tarpaulin at a rate of 45 g/m^2 on 24 September 2002. *P >F* denotes the probability associated with the *F* value when data were analyzed using Proc GLM procedure (SAS Institute Inc. 1999).

[‡] Root-lesion nematodes (*Pratylenchus neglectus*), stunt nematodes (*Tylenchorhynchus* spp.), and undetermined species of nonparasitic nematodes.

Table 4. Nematode counts in wheat* roots in response to tillage and methyl bromide fumigation in Arbon Valley field, Idaho, in 2002–2004.

	No. of nematodes[‡]/100 g of soil corrected for soil moisture level		
Treatment[†]	Root-lesion nematode	Stunt nematode	Nonparasitic nematodes
2002			
No tillage	123	140	288
Subsoiled	127	76	304
P >F	0.8281	0.1922	0.8448
2003			
No tillage	11	108	302
Subsoiled	28	49	224
P >F	0.0039	0.5052	0.6007
No fumigation	37	157	492
Fumigation	1	0	33
P >F	0.0018	0.0568	0.0053
2004			
No tillage	256	70	254
Subsoiled	412	58	246
P >F	0.2068	0.6255	0.9212
No fumigation	654	128	340
Fumigation	15	0	161
P >F	0.0007	0.0030	0.0219

*Arbon Valley site was planted with soft white spring wheat 'Whitebird' (*Triticum aestivum*) in 2002 and 2004 and with soft white winter wheat 'Eltan' (*T. aestivum*) in 2003.

[†] Subsoiling was achieved by broadcast ripping with rigid shanks 1.9 cm wide with narrow (2.5 cm wide) points run through the ground 30.5 cm apart to a depth of 20.2 cm perpendicular to the direction of planting. Fumigation was performed by placing methyl bromide under a plastic tarpaulin at a rate of 45 g/m^2 on 24 September 2002. *P >F* denotes the probability associated with the *F* value when data were analyzed using Proc GLM procedure (SAS Institute Inc. 1999).

[‡] Root-lesion nematodes (*Pratylenchus neglectus*), stunt nematodes (*Tylenchorhynchus* spp.), and undetermined species of nonparasitic nematodes.

at all sampling depths over time in both treatments. At times, there was also a decrease in nitrogen in the upper 60 cm at both sites. There were no differences in phosphorus and potassium levels at either location.

Discussion

Shallow subsoil tillage in two fields that had been in continuous cereal production without tillage for at least 15 years increased yield by at least 8% the first year. In subsequent years, yield was highly influenced by wide fluctuations in available soil moisture. Except in a few instances, subsoiling had no influence on root-disease severity or nematode populations. Subsoiling was at times associated with an increase in soil moisture at depths between 61 and 90 cm, an increase in organic matter, and a slight decrease in available nitrogen. The primary pathogen responsible for fungal root disease at the wetter Ririe location was *F. culmorum*, while at the drier Arbon Valley location, other *Fusarium* spp. normally considered saprophytic or minor pathogens predominated. The primary pathogenic

Table 5. Influence of tillage and methyl bromide fumigation on numbers of roots and tillers in cereal* crops in two southeastern Idaho fields, at Ririe and in Arbon Valley, in 2002–2004.

	Numbers of roots or tillers					
	Tillage treatment[†]			Fumigation treatment[‡]		
Crop parameter	None	Subsoiled	*P* >*F*	No	Yes	*P* >*F*
Ririe						
Seminal roots						
2002	8.2	6.3	0.0276			
2003	4.6	5.2	0.1138			
2004	5.0	4.3	0.0727			
2003–2004				4.8	4.8	0.5165
Main-stem roots						
2002	6.6	6.7	0.8609	na	na	
2003	10.6	11.1	0.3664	10.7	11.0	0.7113
2004	14.3	14.2	0.6494	13.6	14.9	0.0685
Tiller roots						
2002	12.8	16.0	0.0919			
2003	18.6	19.6	0.7888			
2004	23.4	22.1	0.4195			
2003–2004				21.2	20.6	0.7453
Tillers						
2002	6.2	6.2	0.9412	na	na	
2003	6.9	7.5	0.5846	6.8	7.5	0.2843
2004	5.1	5.1	0.9674	5.0	5.2	0.5862
Arbon Valley						
Seminal roots						
2002	6.2	6.0	0.7550	na	na	
2003	4.8	4.6	0.8437	4.8	4.6	0.4345
2004	5.2	5.4	0.5314	5.2	5.4	0.0642
Main-stem roots						
2002	7.4	7.4	1.0000	na	na	
2003	7.7	8.7	0.0087	8.4	8.0	0.4880
2004	12.5	12.2	0.6926	12.4	12.3	0.9682
Tiller roots						
2002	6.7	8.7	0.0275			
2003	3.7	5.2	0.1090			
2004	5.5	4.5	0.3015			
2003–2004				4.2	5.2	0.1723
Tillers						
2002	2.5	3.0	0.0558	na	na	
2003	2.5	3.1	0.1224	2.6	3.0	0.3952
2004	2.2	1.8	0.1324	1.8	2.2	0.0843

Note: Parameters for which only one line of data is given were not significantly different ($P > 0.05$) between years or interactions, and variances were homogeneous. The data for these parameters were therefore analyzed across years. *P* >*F* denotes the probability associated with the *F* value when data were analyzed using the Proc GLM procedure (SAS Institute Inc. 1999).

*Ririe site was planted with hard red spring wheat ‘Jefferson’ (*Triticum aestivum*), two-row spring malting barley ‘Harrington’ (*Hordeum vulgare*), and hard white spring wheat ‘Idaho 377s’ (*T. aestivum*) in 2002, 2003, and 2004, respectively. Arbon Valley site was planted with soft white spring wheat ‘Whitebird’ (*T. aestivum*) in 2002 and 2004 and with soft white winter wheat ‘Eltan’ (*T. aestivum*) in 2003.

[†] “None” indicates no tillage, and “subsoiling” indicates broadcast ripping with rigid shanks 1.9 cm wide with narrow (2.5 cm wide) points run through the ground 30.5 cm apart to a depth of 20.2 cm perpendicular to the direction of planting.

[‡] “No” denotes no fumigation, and “yes” denotes fumigation with methyl bromide at a rate of 45 g/m^2 on 24 September 2002. “na” indicates not applicable because no fumigation was performed for the first year; the data under tillage treatment for this year were used to establish a base line.

Table 6. Influence of tillage and methyl bromide fumigation on test weight and yield in cereal* crops in two southeastern Idaho fields, at Ririe and in Arbon Valley, in 2002–2004.

	Tillage treatment†			Fumigation treatment‡		
Crop parameter	None	Subsoiled	*P* >*F*	No	Yes	*P* >*F*
Ririe						
Test weight (kg/m^3)						
2002	700	699	0.8913	na	na	na
2003	559	580	0.2493	574	564	0.1052
2004	787	782	0.8639	782	787	0.4340
Grain yield (kg/ha)						
2002	3079	3376	0.0322	na	na	na
2003	1417	2199	0.3905	1494	2122	0.0037
2004	6682	6560	0.6926	6528	6730	0.5943
Arbon Valley						
Test weight (kg/m^3)						
2002	712	741	0.1379	na	na	na
2003	662	660	0.8560	644	678	0.8885
2004	730	729	0.9308	732	726	0.1193
Grain yield (kg/ha)						
2002	695	1178	0.0245	na	na	na
2003	1070	727	0.0011	750	788	0.0004
2004	1810	1850	0.8611	1808	1852	0.6746

Note: *P* >*F* denotes the probability associated with the *F* value when data were analyzed using the Proc GLM procedure (SAS Institute Inc. 1999).

*Ririe site was planted with hard red spring wheat 'Jefferson' (*Triticum aestivum*), two-row spring malting barley 'Harrington' (*Hordeum vulgare*), and hard white spring wheat 'Idaho 377s' (*T. aestivum*) in 2002, 2003, and 2004, respectively. Arbon Valley site was planted with soft white spring wheat 'Whitebird' (*T. aestivum*) in 2002 and 2004 and with soft white winter wheat 'Eltan' (*T. aestivum*) in 2003.

†"None" indicates no tillage, and "subsoiling" indicates broadcast ripping with rigid shanks 1.9 cm wide with narrow (2.5 cm wide) points run through the ground 30.5 cm apart to a depth of 20.2 cm perpendicular to the direction of planting.

‡"No" denotes no fumigation, and "yes" denotes fumigation with methyl bromide at a rate of 45 g/m^2 on 24 September 2002. "na" indicates not applicable because no fumigation was performed for the first year; the data under tillage treatment for this year were used to establish a base line.

nematode at both locations was *Pratylenchus neglectus*. Fumigated control plots confirmed that biological factors were limiting the yield. Isolation data also confirmed that the fumigation treatment reduced the incidence of fungal root rots in all locations, years, and root types, except for tiller roots in 2004 at Ririe. The fumigation treatment also reduced the populations of root-lesion nematodes and stunt nematodes (*Tylenchorhynchus* spp.) in both locations and years, except for a borderline response by stunt nematodes in 2003 in Arbon Valley.

Subsoiling increased yield at both locations in 2002 in fields that had been in continuous cereal production without tillage for at least 15 years. At Ririe in 2003, under severe drought conditions, yield differences were not significant, but there was a trend for subsoiling to increase yield. In Arbon Valley in 2003, the soil moisture profile was not recharged to 90 cm depth. The larger preceding subsoiled crop may have depleted soil moisture to a greater soil depth, which then contributed to lower yields. In 2004, there were no significant yield differences at either location. Over the six location-years, subsoiling increased yield in the first 2 years, it was associated with a trend for yield to increase in 2 other years and with a decrease or a trend for yield to decrease in the remaining 2 years. Given these varying yield responses, additional research will be needed to determine whether consistent yield benefits are gained beyond the first year of subsoiling.

Yield responses to subsoiling were not a response to changes in fungal root pathogen or nematode populations. Yield increases may have been influenced by breaking up soil compacted from years of continuous direct-seeding. Soil bulk density and impedance have increased in surface layers under soil-conservation tillage management practices for 10 years in northern Idaho (Hammel 1989). With spring cereals, weed control and planting are conducted during moist soil conditions, potentially aggravating compaction (Hammel 1989). Research conducted in other areas and soil types also indicates that subsurface compaction can occur with soil-conservation tillage practices (Fabrizzi et al. 2005; Ferreras et al. 2000; Henriksen et al. 2005; Oussible et al. 1992).

Soil moisture content is almost always greater under no-till or other soil-conservation tillage systems than under conventional tillage, as a result of increased infiltration rates, reduced runoff, and lower evaporation (Rothrock 1992; Veseth 1986). In Saskatchewan, the soil moisture content in the 0–60 cm profile was found to be 9% higher in no-till plots than in those under conventional tillage (Lafond et al. 1992). Our research from Ririe indicates that shallow subsoiling has the potential to increase soil moisture availability

Table 7. Soil moisture in the upper 90 cm of the soil profile in cereal* plots at Ririe, Idaho, in 2002–2004.

Sampling date and tillage treatment†	Soil moisture (%) at various depths		
	0–30 cm	31–60 cm	61–90 cm
29 April 2002			
None	23.4	24.0	23.2
23 April 2003			
None	24.2	19.6	15.1
Subsoiled	24.2	22.5	21.2
P >*F*	0.9575	0.1960	0.0793
30 May 2003			
None	17.8	18.8	16.3
Subsoiled	18.8	18.7	20.1
P >*F*	0.6206	0.9548	0.1143
10 June 2003			
None	11.8	15.4	15.1
Subsoiled	10.9	15.2	18.3
P >*F*	0.3025	0.8779	0.0494
25 June 2003			
None	9.4	10.5	11.8
Subsoiled	10.2	11.4	16.6
P >*F*	0.4777	0.6062	0.0653
2 April 2004			
None	24.7	24.2	24.1
Subsoiled	24.4	24.0	23.7
P >*F*	0.8465	0.9051	0.6936
21 May 2004			
None	22.4	21.6	20.2
Subsoiled	22.6	22.1	24.6
P >*F*	0.8985	0.8004	0.07
23 June 2004			
None	14.2	17.4	18.4
Subsoiled	16.8	18.9	20.9
P >*F*	0.1717	0.0616	0.1015

*Ririe site was planted with hard red spring wheat 'Jefferson' (*Triticum aestivum*), two-row spring malting barley 'Harrington' (*Hordeum vulgare*), and hard white spring wheat 'Idaho 377s' (*T. aestivum*) in 2002, 2003, and 2004, respectively.

†Subsoiling was achieved by broadcast ripping with rigid shanks 1.9 cm wide with narrow (2.5 cm wide) points run through the ground 30.5 cm apart to a depth of 20.2 cm perpendicular to the direction of planting. *P* >*F* denotes the probability associated with the *F* value when data were analyzed using the Proc GLM procedure (SAS Institute Inc. 1999).

Table 8. Soil moisture in the upper 90 cm of the soil profile in wheat* plots in Arbon Valley, Idaho, in 2002–2004.

Sampling date and tillage treatment†	Soil moisture (%) at various depths		
	0–30 cm	31–60 cm	61–90 cm
29 April 2002			
None	21.1	21.4	21.4
25 March 2003			
None	19.2	18.4	16.4
Subsoiled	20.0	19.4	14.3
P >*F*	0.3120	0.1621	0.2605
19 May 2003			
None	16.8	17.2	16.4
Subsoiled	17.5	17.0	15.2
P >*F*	0.4919	0.7841	0.3670
10 June 2003			
None	7.7	9.0	11.4
Subsoiled	7.7	8.6	10.1
P >*F*	0.9808	0.8040	0.1568
5 April 2004			
None	19.9	20.2	20.7
Subsoiled	20.7	20.7	20.5
P >*F*	0.3599	0.5994	0.7782
3 June 2004			
None	17.6	17.3	18.2
Subsoiled	18.1	18.1	18.1
P >*F*	0.4893	0.5052	0.9489
22 July 2004			
None	9.8	9.5	12.5
Subsoiled	9.7	9.6	10.7
P >*F*	0.9807	0.9319	0.2446

*Arbon Valley site was planted with soft white spring wheat 'Whitebird' (*Triticum aestivum*) in 2002 and 2004 and with soft white winter wheat 'Eltan' (*T. aestivum*) in 2003.

†Subsoiling was achieved by broadcast ripping with rigid shanks 1.9 cm wide with narrow (2.5 cm wide) points run through the ground 30.5 cm apart to a depth of 20.2 cm perpendicular to the direction of planting. *P* >*F* denotes the probability associated with the *F* value when data were analyzed using the Proc GLM procedure (SAS Institute Inc. 1999).

at depths between 61 and 90 cm of the soil profile at anthesis, when precipitation is available to recharge the upper 90 cm. At our drier location in Arbon Valley, where the soil profile always started the season with less moisture and where the upper 90 cm was never recharged in 2003, the moisture level did not respond to subsoiling. These data seem to contradict previous research (Dao 1993; Fabrizzi et al. 2005; Ferreras et al. 2000; Veseth 1986), but our subsoiling treatment with narrow rigid shanks and points leaves stubble on the soil surface virtually undisturbed. Our results are not comparable with those from other research on soil moisture involving considerably different tillage systems.

In semiarid areas of the PNW, about 70% of the total annual precipitation occurs between November and April, which provides most of the soil water recharge for the wheat crop (Pannkuk et al. 1997). Subsequent summer rainfall is rarely sufficient to contribute to stored water, but temporarily reduces loss of stored water (Pannkuk et al. 1997). Thus, a shallow subsoiling operation in late fall may reduce soil compaction and increase soil moisture for direct-seeded spring cereals. In an 11-year Canadian tillage study (Conner et al. 1987), yield differences were more affected by weed control, seed placement, or soil moisture content than by root rot; these results are consistent with our findings.

A shift to reduced-tillage management from conventional tillage affects factors such as soil moisture, soil temperature, soil physical structure, and the density and structure of surface residue. These factors can in turn alter the status of

Table 9. Influence of tillage on analysis of soil chemical properties at three depths at spring planting near Ririe, Idaho, in 2002–2004.

	Quantification of soil chemical parameter					
	No tillage			Subsoiled*		
	0–30 cm	31–60 cm	61–90 cm	0–30 cm	31–60 cm	61–90 cm
Organic matter (%)						
2002	2.25	1.70	1.32	2.25 b	1.70	1.32 b
2003	2.55	1.73	1.55	2.18 b	1.75	1.32 b
2004	2.58	2.00	1.65	2.80 a	1.98	1.85 a
P >*F*	0.5479	0.4633	0.5314	0.0087	0.2832	0.0288
Nitrogen (ppm)						
2002	21 a	8	20	21 a	8 ab	20
2003	23 a	17	12	12 b	13 a	12
2004	6 b	9	14	8 b	6 b	17
P >*F*	0.0056	0.2025	0.3291	0.0105	0.0472	0.1500
Phosphorus (ppm)						
2002	41	29	22	41	29	22
2003	45	24	17	37	26	23
2004	40	25	14	38	21	16
P >*F*	0.7342	0.7965	0.5499	0.3822	0.4496	0.1076
Potassium (ppm)						
2002	334	278	232	334	278	232
2003	279	263	234	298	292	253
2004	317	286	242	341	246	232
P >*F*	0.2938	0.7538	0.9633	0.4580	0.2748	0.6496

Note: *P* >*F* denotes the probability associated with the *F* value when data were analyzed using the Proc GLM procedure (SAS Institute Inc. 1999). When means are compared across years within a parameter and depth, those followed by a different letter are significantly different at $P \leq 0.05$.

*Subsoiling was achieved by broadcast ripping with rigid shanks 1.9 cm wide with narrow (2.5 cm wide) points run through the ground 30.5 cm apart to a depth of 20.2 cm perpendicular to the direction of planting.

soil microbial populations (Rothrock 1992). In most instances, retention of crop stubble coupled with reduced or no tillage leads to increases in soil carbon and nitrogen and an accompanying increase in microbial biomass and activity (Pankhurst et al. 2002). Even though both tillage systems used in our studies fall into this category, subsoiling tended to increase soil organic matter and decrease nitrogen. The long-term implications of these changes are not clear, on the basis of yield parameters from the present study, but increasing soil moisture and organic matter is desirable.

Methyl bromide fumigation resulting in increased yields indicated that yield was limited because of biological factors such as fungal root rots and nematodes, but subsoiling had little influence on root-disease severity or nematode numbers. Although changes in soil chemical and microbiological properties have been linked to a reduction in root-disease severity, when no tillage is compared with conventional tillage (Pankhurst et al. 2002), the two systems compared at Ririe and Arbon Valley are very similar, since almost no disturbance of stubble occurred when the subsoiling treatment was applied. Because of this similarity between the two systems, perhaps the lack of change in root-disease severity and nematode populations should have been expected. In the PNW, *G. graminis* var. *tritici*, *Rhizoctonia* spp., and *Pythium* spp. all increased under straw mulches and reduced tillage (Cook and Haglund 1991). In Oregon, the influence of reduced tillage was found to vary within a region, since *G. graminis* var. *tritici* was found to be either reduced or increased by reduced tillage, depending on the location studied (Smiley and Wilkins 1993). In Saskatchewan, Bailey and Duczek (1996) observed that damage caused by common root rot [*B. sorokiniana* and *Fusarium* spp.] led to average yield losses of 21% with conventionally tilled plots and 5% with no-till plots. This greater yield loss with conventional tillage was consistent with their fungal isolations showing decreased disease pressure in no-till plots (Bailey and Duczek 1996). In another Canadian study, no consistent differences in common root rot ratings were found when wheat was grown under conventional tillage and minimum tillage (Conner et al. 1987). Bailey et al. (2000, 2001) found that no tillage was associated with reduced populations of *B. sorokiniana* and increased incidence of *Fusarium* spp. in roots. Most of the *Fusarium* spp., such as *F. equiseti* and *F. acuminatum*, identified in their plots are considered to be weak pathogens or saprophytes (Bailey et al. 2000). Fewer than 20% of the species identified were serious pathogens of cereals, such as *F. culmorum* (Bailey et al. 2000). Even though *B. sorokiniana* populations decreased and *Fusarium* spp. populations increased, there was no effect on root-disease severity or yield loss (Bailey et al. 2001). These results are similar to those we describe for our drier location in Arbon Valley. In studies at Crookston, Minnesota, tillage treatment (minimum till, chisel plow, or moldboard plow) had no effect on root-rot indices for wheat and barley and did not affect the frequencies of isolation of *F. acuminatum* or *F. culmorum* (Windels and Wiersma 1992). These results are also similar to those we found with the subsoil treatments. In Minnesota, *F. graminearum* and *F. avenaceum*

Table 10. Influence of tillage on soil chemical properties at three depths at spring planting in Arbon Valley, Idaho, in 2002–2004.

	Quantification of soil chemical parameter					
	No tillage			Subsoiled*		
	0–30 cm	31–60 cm	61–90 cm	0–30 cm	31–60 cm	61–90 cm
Organic matter (%)						
2002	1.50 b	1.12 b	0.90 b	1.50 b	1.12 b	0.90 b
2003	1.50 b	0.98 b	0.85 b	1.45 b	1.12 b	0.92 b
2004	1.75 a	1.38 a	1.10 a	1.78 a	1.48 a	1.22 a
P >*F*	0.0046	0.0129	0.0406	0.0252	0.0062	0.0007
Nitrogen (ppm)						
2002	7 a	8 ab	12	7	8 b	12
2003	6 ab	10 a	10	8	15 a	9
2004	4 b	4 b	4	5	4 b	7
P >*F*	0.0399	0.0428	0.1023	0.1960	0.0019	0.4732
Phosphorus (ppm)						
2002	17	9	9	17	9	9
2003	14	4	4	16	8	5
2004	16	6	4	20	8	6
P >*F*	0.4409	0.2180	0.2948	0.3905	0.7003	0.4291
Potassium (ppm)						
2002	390	306	209	391	306	209
2003	452	362	292	425	335	198
2004	345	325	231	376	329	236
P >*F*	0.0750	0.6449	0.3604	0.3552	0.8344	0.8159

Note: *P* >*F* denotes the probability associated with the *F* value when data were analyzed using the Proc GLM procedure (SAS Institute Inc. 1999). When means are compared across years within a parameter and depth, those followed by a different letter are significantly different at $P \leq 0.05$.

*Subsoiling was achieved by broadcast ripping with rigid shanks 1.9 cm wide with narrow (2.5 cm wide) points run through the ground 30.5 cm apart to a depth of 20.2 cm perpendicular to the direction of planting.

were isolated more frequently from subcrown internodes of plants in minimum-tillage plots than in moldboard-plowed plots (Windels and Wiersma 1992). *Bipolaris sorokiniana* was isolated more frequently from subcrown internodes in moldboard-plowed plots than in minimum-tillage plots (Windels and Wiersma 1992). In Czechoslovakia, no-till treatments on spring wheat were associated with a 20% increase in *Fusarium* spp., especially *F. culmorum* (Herman 1984). A fourfold increase in *Fusarium* spp. in the rhizosphere, rhizoplane, and roots was noted in plants from no-till plots. In Australia, crown rot caused by *F. pseudograminearum* (syn. *F. graminearum* group I) in wheat and barley resulted in 54% diseased tillers when residues were retained, while fewer than 10% diseased tillers occurred when stubble was burned (Dodman and Wildermuth 1989). Increased stubble retention also increased the incidence of fusarium crown rot, whereas stubble burning usually reduced the disease incidence (Summerell et al. 1989). The finding that *Fusarium* spp. were predominantly isolated from root lesions in our cereal plots is consistent with previous research on no-till systems.

The predominant fungal pathogens in the Ririe field were *F. culmorum* and *B. sorokiniana*. These results are consistent with previous observations from this higher-moisture IMW area (Strausbaugh et al. 2004). Cook (1980) noted that *F. culmorum* was the main cause of fusarium foot rot in the northwestern United States and that water stress predisposes wheat plants to this disease. Although our work focused on root rot, root infections can progress to become crown and foot rot (Cook 1980). The fact that *F. semitectum*, *F. reticulatum*, *F. equiseti*, and *F. acuminatum* were the dominant species isolated from the drier Power County location is also consistent with previous observations from this county (Strausbaugh et al. 2004). Some of the same species are known to be associated with cereal roots in the PNW (Smiley and Patterson 1996) and have been shown to be associated with root and crown infections (Fedel-Moen and Harris 1987; Strausbaugh et al. 2004, 2005). The importance of the role these *Fusarium* spp. play in our drier locations in the IMW dryland system remains to be proved.

The root-lesion nematode *Pratylenchus neglectus* was the predominant parasitic nematode found at both locations, which is also consistent with previous observations for the IMW (Strausbaugh et al. 2004). In the PNW, *Pratylenchus neglectus* has been shown to be associated with declining wheat growth and up to 71% reductions in grain yield (Smiley et al. 2005b). *Pratylenchus* populations exceeding 2500/kg of soil in the surface 20 cm of the soil profile occur in 20% of intensively cropped fields in the PNW (Smiley et al. 2004), and populations exceeding 2000/kg of soil were responsible for limited grain yield in Oregon (Smiley et al. 2005b). *Pratylenchus neglectus* populations in our study averaged from 220 to 5360/kg of soil in nonfumigated plots. There were no differences in *Pratylenchus neglectus* populations between no-till and subsoiled treatments, but numbers were lower where fumigation had been applied. These differences, along with the fungal root rots, could help explain why the biology of the system was important, since fumigation resulted in higher yields in 2003 and a trend towards higher yields in 2004.

Given the current increase in research and significant advancements in no-till farming, the large-scale adoption of direct-seeding of cereals by growers in dryland areas is anticipated in the coming decade (Shillinger et al. 2003). In the western United States, dryland growers must concentrate their tillage and residue-management efforts on efficient soil water storage to have the greatest impact on yield potential (Veseth 1986). Aggregate stability in soil declines with increasingly intensive tillage, thus reducing the rate of water infiltration (Veseth 1986). Organic matter plays a key role in maintaining a stable soil structure and thus is important for keeping macropores open for water infiltration (Veseth 1986). Our research indicates that utilizing a fall-applied shallow subsoiling operation in the production of direct-seeded spring cereals did not influence fungal root rots or nematode populations but will potentially increase soil moisture, organic matter, and yield. Further research into optimizing this shallow fall subsoiling operation should be considered for spring cereals in a soil-conservation tillage system.

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