Crop Sequence Effects on Leaf Spot Diseases of No-Till Spring Wheat

Joseph M. Krupinsky,* Donald L. Tanaka, Steven D. Merrill, Mark A. Liebig, Michael T. Lares,
and Jonathan D. Hanson

ABSTRACT

Crop sequence is an important management practice that may lower the risk for leaf spot diseases of spring wheat (*Triticum aestivum* L.). Field research was conducted near Mandan, ND, to determine the impact of crop sequences on leaf spot diseases of hard red spring wheat early in the growing season. Spring wheat was evaluated for disease severity following crop sequence combinations of 10 crops [buckwheat (*Fagopyrum esculentum* Moench), canola (*Brassica napus* L.), chickpea (*Cicer arietinum* L.), corn (*Zea mays* L.), dry pea (*Pisum sativum* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], lentil (*Lens culinaris* Medik.), oil seed sunflower (*Helianthus annuus* L.), proso millet (*Panicum miliaceum* L.), and hard red spring wheat). Spring wheat leaves with distinct lesions were collected for determination of lesion number and percentage necrosis data, which were used to estimate leaf spot disease severity. *Pyrenophora tritici-repentis* (Died.) Drechs., the cause of tan spot, and *Phaeosphaeria nodorum* (E. Müller) Hedjaroude, the cause of Stagonospora nodorum blotch, were the major leaf spot diseases and consistently present throughout the growing season. The frequency of isolation following alternative crops was generally lower compared with spring wheat following wheat. Leaf spot diseases on spring wheat were impacted by crop sequencing. Spring wheat following crop sequences with alternative crops for 1 or 2 yr had lower levels of disease severity compared with a continuous spring wheat treatment early in the growing season. Disease severity was apparently not related to the percentage of crop residue coverage on the soil surface associated with various crop sequence combinations. New alternative crops preceding spring wheat reduce levels of leaf spot diseases.

With a reduction in the traditional fallow–wheat system and adoption of reduced-till or no-till annual cropping systems, producers are including alternative crops such as oilseeds, pulses, and forages (Halvorson et al., 2000; Smith and Young, 2000; Tanaka and Anderson, 1997; Zentner et al., 2002). Such alternative crops have good potential for diversifying cropping systems in semiarid areas (Krupinsky et al., 2006; Miller et al., 2002, 2003; Zentner et al., 2002). Understanding how crops and management practices interact is essential in the development of practical, efficient, and cost-effective cropping systems capable of stabilizing crop production while minimizing deleterious effects on the environment (Hanson et al., 2003). To develop cropping systems that optimize crop and soil use options and attain production, economic, and resource conservation goals (Tanaka et al., 2002), more detailed information on multiple management components known to influence crop performance is required.

Proper sequencing of crops, which can accentuate positive synergistic interactions among crops, increase precipitation use efficiency, and reduce potential pest problems, is an important component of sustainable cropping systems (Anderson, 2005; Cook and Veseth, 1991; Krupinsky et al., 2006; Holtzer et al., 1996; Johnston et al., 2005; Kirkegaard et al., 2004; Peairs et al., 2005; Tanaka et al., 2002, 2005). Changes in the sequence of crops are known to enhance the yield of cereal crops such as wheat. Although there is variation in response depending on the site and weather conditions, wheat can yield 20% more following broad-leaf crops compared with wheat following wheat across broad regions of North America, northern Europe, and Australia (Kirkegaard et al., 2004). Generally, crops seeded on their own residue perform poorly compared with following different crops (Johnston et al., 2005; Krupinsky et al., 2006; Miller et al., 2003).

Crop sequence/rotation in combination with other management practices can be one of the most effective and inexpensive methods to manage a number of plant diseases (Holtzer et al., 1996; Krupinsky, 1999; Krupinsky et al., 2002; Turkington et al., 2003). Even though annual cropping systems may increase the complexity of pest management, crop diversification can moderate plant diseases through crop selection and interruption of disease cycles, particularly for disease organisms that are residue-borne (Krupinsky et al., 2002; Turkington et al., 2003). Crop sequences and crop rotations take advantage of the fact that plant pathogens important on one crop may not cause disease problems on another crop. Appropriate crop sequences or crop rotations lengthen the time between susceptible crops so that pathogen populations have time to decline. Crop rotation allows time for the decomposition of residue on which pathogens carryover, and natural competitive organisms reduce the pathogens on the remaining residue while unrelated crops are being grown (Cook and Veseth, 1991).

In the northern Great Plains, spring wheat can be impacted by a variety of fungal leaf spot diseases, which act together as a leaf spot disease complex. Major diseases are tan spot [*P. tritici-repentis*, anamorph = *Drechslera tritici-repentis* (Died.) Shoemaker] and Stagonospora nodorum blotch [*P. nodorum*, anamorph = *Stagonospora nodorum* (Berk.) Castellani & E.G.

J.M. Krupinsky, D.L. Tanaka, S.D. Merrill, M.A. Liebig, and J.D. Hanson, USDA-ARS, Northern Great Plains Research Lab., Box 0459, Mandan, ND 58554-0459; and M.T. Lares, Univ. of Mary, 7500 University Dr., Bismarck, ND 58504. Received 24 Apr. 2006. *Corresponding author (krupinsj@mandan.ars.usda.gov).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: AGDD, accumulated growing degree days; GLM, general linear model.

Germano]. Other leaf spot diseases present on wheat in this region include Stagonospora avenae blotch [*Phaeosphaeria avenaria* (G.F. Weber) O. Eriksson, anamorph = *Stagonospora avenae* Bissett f. sp. *triticea* T. Johnson], Septoria tritici blotch [*Mycosphaerella graminicola* (Fuckel) J. Schrt. in Cohn, anamorph = *Septoria tritici* Roberge in Desmaz], and spot blotch [*Cochliobolus sativus* (Ito & Kuribayashi) Drechs. ex Dastur., anamorph = *Bipolaris sorokiniana* (Sacc.) Shoemaker] (Fernandez et al., 1998a, 1998b; Gilbert and Woods, 2001; Krupinsky et al., 2004 and 2007a; Krupinsky and Tanaka, 2001; McMullen, 2003; Wang et al., 2002). These fungi easily carry over on crop residues (Duczek et al., 1999). In Manitoba, Gilbert and Woods (2001) indicated that crop rotation does not appear to have a significant effect on the isolation of *P. tritici-repentis* or *S. nodorum*.

The influence of previous crops and crop residues on plant diseases needs to be understood to develop effective crop sequences that minimize leaf spot diseases in spring wheat in diverse cropping systems. In a previous crop sequence project (Krupinsky et al., 2004), spring wheat was direct-seeded (no-till) in the crop residue of 10 crops and evaluated for leaf spot diseases when the flagleaf (the uppermost leaf) was identifiable. The risk for leaf spot disease was lower when wheat was grown after canola, barley (*Hordeum vulgare* L.), crambe (*Crambe abyssinica* Hochst. ex R.E. Fr.), and flax (*Linum usitatissimum* L.) compared with wheat grown after wheat. Furthermore, differences among crop sequence treatments were more evident with evaluations when the flagleaf was first evident compared with later in the season (Krupinsky et al., 2004, 2006). More testing with new and emerging crops and additional crop sequences earlier in the season will help further the understanding of crop sequence effects on leaf spot diseases of spring wheat. The objective of the present study was to determine the influence of new and emerging crops and crop sequences on the development of leaf spot diseases in spring wheat especially earlier in the season, and determine to what extent fungi present are influenced by crop sequence under the semiarid environmental conditions of the northern Great Plains.

MATERIALS AND METHODS

The research project was located at the Area IV Soil Conservation Districts/Agricultural Research Service Cooperative Research Farm southwest of Mandan, ND (Site 1, 46°46′ N, 100°56′ W; Site 2, 46°45′ N, 100°55′ W; and 518 m elevation). The two sites, occupying ≈6.1 ha each, were located ≈2 km apart. Predominant soils at the sites are Temvik–Wilton silt loams (fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls). Long-term annual precipitation averages 409 mm, with 79% of the total received during the growing season from April through September. Annual temperature averages 4°C, though daily averages range from 21°C in the summer to −11°C in the winter.

An experimental crop × crop residue matrix design was used to allow the simultaneous evaluation of numerous crop sequences under similar weather and soil conditions. Three crops were used to prepare the research sites and provide a similar residue background. Oil seed sunflower was grown for 1 yr followed by 2 yr of hard red spring wheat under no-till management (Table 1). An additional 2 yr were required to form the crop × crop residue matrix (referred to hereafter as crop matrix) in which 10 crops were direct-seeded into the residue of the same 10 crops. During Project Year 1 (Table 1), four replicates of 10 crops (buckwheat, canola, chickpea, corn, dry pea, grain sorghum, lentil, oil seed sunflower, proso millet, and hard red spring wheat) were direct-seeded in 9-m-wide strips into spring wheat residue. All crops, except corn and sunflower, were seeded with a no-till drill (John Deere 750) with 19-cm row spacing. Seeding of corn and sunflower was accomplished with a no-till row-crop planter with 76-cm row spacing. The 10 cultivars were Koto buckwheat, 357RR canola, B-90 chickpea, TF2183 corn, DS Admiral dry pea, DK28E grain sorghum, Richlea lentil, Earlybird proso millet, 63M91 sunflower, and Amidon spring wheat. During Project Year 2 (Table 1), the same 10 crops were direct-seeded perpendicular over the residue of the previous year's crops. This established a 10 by 10 crop matrix with 100 crop sequence combinations, where each crop was grown on 10 crop residues (Fig. 1 in Tanaka et al., 2007). The crop matrix was replicated four times each year following a randomized strip-block design with individual 9- by 9-m plots considered as experimental units.

Nitrogen was applied as a mid-row (between every other row) band application of NH_4NO_3 at 78 kg N ha^{-1} during seeding except for chickpea, dry pea, or lentil. Phosphorus was applied with the seed as 0–44–0 at 11 kg P ha^{-1} during the seeding of all crops. Sulfur was applied as ammonium sulfate during the seeding of canola at 11.2 kg S ha^{-1} and N source adjusted to obtain 78 kg N ha^{-1}. Recommended seed inoculants were applied to dry pea, lentil, and chickpea before seeding. Weed control was accomplished using no-till techniques appropriate for each crop. In Project Year 3 (Table 1), spring wheat was uniformly seeded over a crop matrix on 13 April 2004 and 20–21 April 2005, providing a spring wheat crop following four replicates of 100 crop sequences for two consecutive years.

Evaluation of Leaf Spot Disease Severity

The severity of leaf spot disease was visually assessed for individual leaves (10 leaves per plot for each evaluation) by quantifying the number of lesions and visually assessing the total percentage of necrosis and chlorosis. Leaves with distinct lesions surrounded by green tissue were arbitrarily collected from near the center of the treatment plots (at least 3 m from

Table 1. Project years with crops and sites used to evaluate the influence of crops and crop sequence on leaf spot diseases of spring wheat.

Project Year	Crop	Site 1†		Site 2†	
0	sunflower	1999		2000	
0	spring wheat crop	2000		2001	
0	spring wheat crop	2001		2002	
1	10 crops‡	2002		2003	
2	Crop matrix‡	2003		2004	
3	spring wheat crop§	2004	Leaf spot diseases evaluated	2005	Leaf spot diseases evaluated

† Two locations, ≈2 km apart, provided two sites.

‡ Two years were required to establish a crop matrix (crop × crop residue matrix). During Project Year 1, 10 crops were seeded in strips to provide residue into which 10 crops were seeded during Project Year 2. During Project Year 2, a crop matrix was formed by seeding 10 crops perpendicular over the crop residue from the first year. Crops were direct-seeded (no-till).

§ During Project Year 3, a spring wheat crop ('Amidon') was direct-seeded (no-till) over the crop reside from the crop matrix (100 crop sequences).

edge of plot) for determination of lesion number and percentage necrosis of spring wheat leaves. Since leaves with distinct lesions were selected, leaves with coalescing lesions or emerging leaves without lesions were avoided to be able to quantify lesions and to obtain the same number of leaves with distinct lesions from each treatment for fungal isolations.

Evaluations were done early in the growing season (Table 2) before the flagleaf (uppermost leaf) was clearly identifiable. The third through sixth leaves produced on the main stem (out of a possible eight to nine leaves produced) were rated for disease severity. A 6.0 on the Haun growth stage of spring wheat occurs when the sixth leaf is fully extended (Bauer et al., 1983). Number of lesions counted and percentage necrosis were used as indicators of disease severity, which was used to compare crop sequence treatments. For some evaluations, leaves were measured and number of lesions per area was calculated. Results from lesion number per leaf area data were similar to above data and are not presented.

Spring Wheat Seeded after Crop Matrix, Three Groups of Crop Sequence Treatments Evaluated

In Project Year 3, spring wheat was uniformly seeded over the crop matrix at both sites (Table 1). Spring wheat, following different crop sequence treatments, was evaluated for leaf spot disease severity a number of times. At site 1, evaluations began on 3 June 2004 and continued through 28 June 2004 (Table 2). At site 2, evaluations began on 6 June 2005 and continued through 28 June 2005 (Table 2).

From the 100 crop sequence treatments available for assessment, three groups of crop sequence treatments were selected for evaluation. The continuous spring wheat treatment was included in each group because it was considered to be most favorable for disease development and was used for comparison. Group 1 consisted of nine crop sequence treatments in which spring wheat followed one season of an alternative crop [spring wheat (Project Year 1)/alternative crop (Project Year 2)/spring wheat (Project Year 3); e.g., spring wheat/canola/spring wheat], plus the continuous spring wheat treatment.

Table 2. Groups of crop sequence treatments were evaluated for leaf spot disease severity (percentage necrosis and number of lesions) after spring wheat was uniformly seeded (13 April 2004 at Site 1 and 20–21 April 2005 at Site 2) over the crop matrix in Project Year 3.

Site	Group 1†	Group 2‡	Group 3§
1		3 June 2004	
1		4 June 2004	
1	9 June 2004	7 June 2004	
1		14 June 2004	
1	15 June 2004	16 June 2004	16 June 2004
1	21 June 2004	23 June 2004	23 June 2004
1	28 June 2004		
2	06 June 2005	10 June 2005	
2	14 June 2005	16 June 2005	16 June 2005
2	21 June 2005	23 June 2005	23 June 2005¶
2	28 June 2005	28 June 2005	

† Group 1 = nine crop sequence treatments in which spring wheat followed one season of an alternative crop (spring wheat [Project Year 1]/alternative crop [Project Year 2]/spring wheat [Project Year 3]; plus the continuous spring wheat treatment.

‡ Group 2 = nine crop sequence treatments in which spring wheat followed an alternative crop grown on its own residue (alternative crop [Project Year 1]/same alternative crop [Project Year 2]/spring wheat [Project Year 3]), plus the continuous spring wheat treatment.

§ Group 3 = 25 crop sequence treatments in which spring wheat followed alternative crop sequences associated with different levels of crop residue coverage of soil, plus the continuous spring wheat treatment.

¶ Only percentage necrosis data was collected with this evaluation.

Group 2 consisted of nine crop sequence treatments in which spring wheat followed an alternative crop grown on its own residue [alternative crop (Project Year 1)/same alternative crop (Project Year 2)/spring wheat (Project Year 3); canola/canola/spring wheat], plus the continuous spring wheat treatment. Even though seeding a crop on its own crop residue is not a recommended management practice (Johnston et al., 2005; Krupinsky et al., 2006), these treatments provided a more uniform crop residue for a particular crop by reducing the possible residue carryover from another crop.

Disease severity of spring wheat following 2 yr of an alternative crop (Group 2) was also compared with spring wheat following 1 yr of an alternative crop (Group 1). Evaluations done within a day or two of one another were analyzed together. For example, data from the 9 June 2004 (Group 1) and 7 June 2004 (Group 2) evaluations (Table 2) were analyzed together, data from the 15 June 2004 (Group 1) and 14 June 2004 (Group 2) were analyzed together, and data from the 21 June 2004 (Group 1) and 23 June 2004 (Group 2) were analyzed together to detect differences between the 2-yr and 1-yr treatments in 2004.

Group 3 consisted of 25 crop sequence treatments in which spring wheat followed alternative crop sequences associated with different levels of crop residue coverage of soil, plus the continuous spring wheat treatment, which averaged 93% crop residue coverage of soil (Krupinsky et al., 2007b). The 25 treatments in Group 3 included all possible combinations of two alternative crops associated with higher surface residue coverage of soil (proso millet and grain sorghum) and three alternative crops associated with lower surface residue coverage (corn, sunflower, and chickpea) (Krupinsky et al., 2007b). Group 3 compared crop sequence combinations that provide a range of surface residue coverage [lower (first year of crop sequence)/lower (second yr of crop sequence), lower/higher, higher/lower, and higher/higher]. Crop residue coverage of soil ranged from 57% following the chickpea/chickpea treatment to 97% following the grain sorghum/grain sorghum treatment (Krupinsky et al., 2007b). In addition to comparing disease severity following crop sequence treatments of alternative crops with a continuous spring wheat treatment, the alternative crop sequences were also analyzed without the continuous spring wheat treatment to determine if the various levels of crop residue coverage of soil associated with the alternative crop treatments can impact disease severity early in the season.

Identification of Fungi Present

Fungi were identified from Group 1 and Group 2 collections to determine the major components of the leaf spot disease complex and determine if the composition of the leaf spot disease complex was influenced by crop sequence or varied during the growing seasons. Green leaves with distinct lesions, which were rated during the disease severity evaluations, were pressed, allowed to dry, and stored in a refrigerator at 2 to 4°C until they were processed, 1 to 12 wk after collection in 2004, and 17 to 28 wk after collection in 2005. Fungi were identified on eight leaf sections (with distinct lesions) from each plot processed. In 2004, 320 leaves (8 leaves × 4 replicates × 10 treatments) were normally processed from each leaf collection. Considering the results of fungal isolations in 2004, fewer assessments were done with the 2005 collections. For each leaf collection processed in 2005, 160 leaves (8 leaves × 2 replicates × 10 treatments) were used.

Leaf sections (2 cm long, one per individual leaf) were surface-sterilized for 3 min in a 1% sodium hypochlorite solution containing a surfactant (Tween 20, polyoxyethylenesorbitan monolaurate, Sigma Chemical Co., St. Louis, MO), rinsed in sterile distilled water, plated on water agar (18%) in plastic Petri dishes, and incubated under a 12-hr photoperiod (cool-white fluorescent tubes) at 18/24°C (dark/light). After an incubation of 6 to 7 d, leaf sections were microscopically examined to detect fungi present. Fungal spores were transferred from leaf tissue to a glass slide, stained with cotton blue or aniline blue, and microscopically identified. The number of leaf sections infected with a particular fungus was used as an indicator of the relative importance of that fungus in causing leaf spot disease in a particular plot (Gilbert and Woods, 2001; Krupinsky et al., 2004, 2007a; and Krupinsky and Tanaka, 2001).

In 2004, when four replicates of data were available, the frequency of fungal isolation following spring wheat grown after 1 yr (Group 1) and 2 yr (Group 2) of alternative crops was compared with wheat after continuous spring wheat. Data from collections made at a similar date were analyzed together: 7 June (Group 2, Table 2) and 9 June (Group 1), 15 June (Group 1) and 16 June (Group 2), and 21 June (Group 1) and 23 June (Group 2) were compared with the continuous wheat treatment collected at the same time.

Statistical Analysis

The crop matrix was replicated four times each year following a randomized strip-block design. Lesion numbers counted and percentage necrosis of spring wheat leaves associated with various crop sequence treatments were analyzed as square-root transformed lesion number data and arcsin square-root-transformed percentage necrosis data, respectively, using the general linear model (GLM) procedure (SAS Institute, 2003) for each evaluation. Data sets analyzed for comparing disease severity for spring wheat after 1 yr (Group 1) and 2 yr of alternative crops (Group 2) were collected at a similar time (evaluations done within a day or two of one another). The number of leaf sections infected with a particular fungus was analyzed using the GLM procedure. When making statistical comparisons for frequency of isolation after continuous spring wheat, and 1 yr (Group 1) and 2 yr (Group 2) of alternative crops, data sets that were collected at a similar time were analyzed together. Statistical comparisons within individual evaluations were made with Dunnett's one-tailed test and Student-Newman-Keuls' test. Dunnett's one-tailed test was used to make comparisons between the crop sequence treatments and the continuous spring wheat treatment, which was considered to be the most favorable for leaf spot disease development. All statistical differences were evaluated at a probability level of $P \leq 0.05$.

RESULTS AND DISCUSSION

During the research project, monthly precipitation and air temperature varied during the growing season (Fig. 1). In general, 2004 was a cooler and drier year compared with 2005 (Fig. 1), especially during the month of June when disease severity was evaluated. The accumulated growing degree days (AGDD) for June was 511 AGDD with 5 cm of precipitation in 2004 compared with 585 AGDD and 12.3 cm of precipitation in 2005.

Identification of Fungi Present

Several fungal pathogens were often present on individual wheat leaves processed. In 2004 at Site 1, 74% of 3040 leaves processed were infected with *D. tritici-repentis*, 14% with *S. nodorum,* 3% with *S. avenae* f. sp. *triticea,* and 2% with *B. sorokiniana*. In 2005 at Site 2, 66% of 960 leaves processed were infected with *D. tritici-repentis*, 21% with *S. nodorum*, 15% with *S. avenae* f. sp. *triticea*, and 3% with *B. sorokiniana*. *Drechslera tritici-repentis* and *S. nodorum* were consistently present throughout the growing season. *Drechslera tritici-repentis* was the most common fungus identified overall. The types of fungi identified are consistent with leaf spot diseases reported on wheat in the northern Great Plains region (Fernandez et al., 1998a, 1998b; Gilbert and Woods, 2001; Krupinsky et al. (2004) and 2007a; Krupinsky and Tanaka, 2001; McMullen, 2003; and Wang et al., 2002). The frequency of isolation following alternative crops was lower compared with continuous wheat (Fig. 2A and 2B). This demonstrates a benefit of having alternative crops before wheat. This is consistent with lower disease severity following alternative crops discussed below.

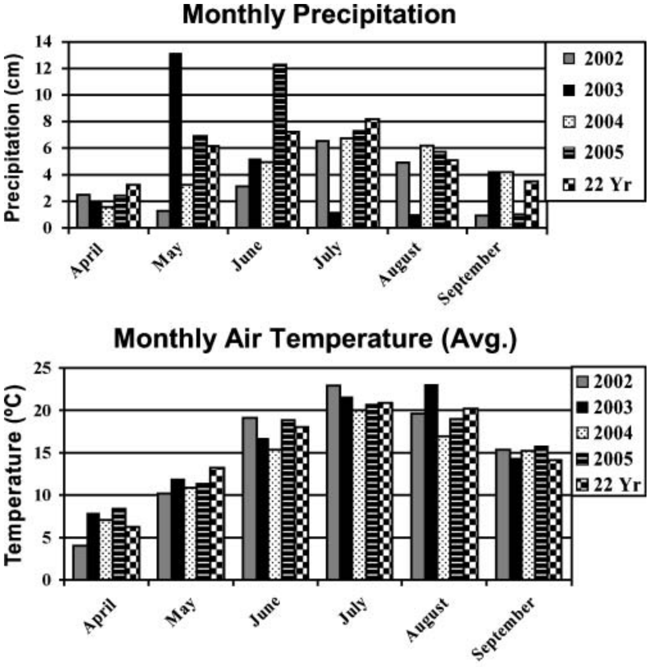

Fig. 1. Growing season precipitation and average air temperature on a monthly basis over the course of the crop sequence project compared to the 22-yr average.

The frequency of isolation for *S. nodorum* was less from spring wheat following 2 yr of alternative crops compared with spring wheat following 1 yr of an alternative crop (Fig. 2C). Three to nine treatments had less isolation of *S. nodorum* following 2 yr of an alternative crop than continuous spring wheat compared with one to three treatments following 1 yr of an alternative crop (Fig. 2C). Since inoculum of *S. nodorum* carries over on wheat residue (Wiese, 1987), one can speculate that, with less wheat straw left in the plots after 2 yr of an alternative crop compared with 1 yr (Krupinsky et al., 2004), there would be less inoculum carryover. Considering that asexual spores of *S. nodorum* are dispersed with splashing water (Wiese,

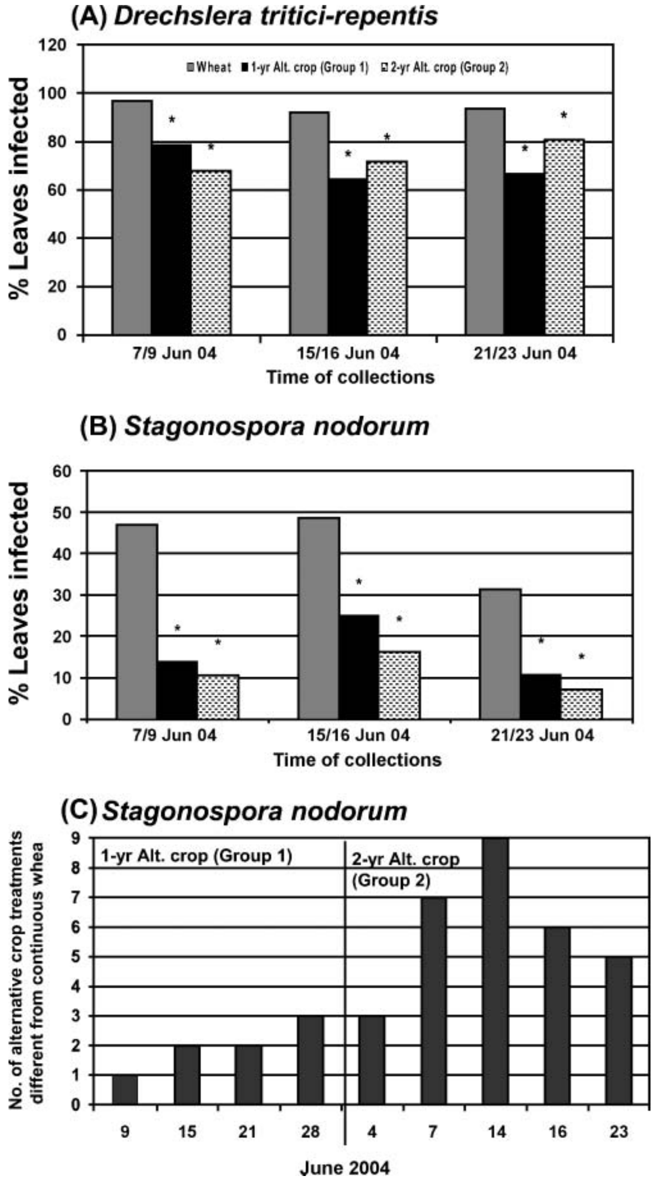

Fig. 2. Isolation of (A) *D. tritici-repentis* and (B) *S. nodorum* from wheat following 1 yr of alternative crops, 2 yr of alternative crops, and continuous spring wheat. * Indicates that wheat following alternative crops, as a group, are significantly different from the continuous spring wheat treatment. (C) When spring wheat followed alternative crops, the number of individual alternative crop treatments with significantly less isolation of *S. nodorum* compared with continuous spring wheat. The continuous spring wheat treatment was used as the control in Dunnett's one-tailed test ($P < 0.05$).

1987), spores would be transported shorter distances than the asexual spores of *D. tritici-repentis*, which are airborne. Consistent differences from wheat following 1 or 2 yr of alternative crops were not evident for the frequency of isolation for *D. tritici-repentis.* Other diseases such as Septoria tritici blotch, powdery mildew (*Erysiphe graminis* DC. f. sp. *tritici* E. Marchal), stem rust (*Puccinia graminis* Pers. f. sp. *tritici* Ericks. & E. Henn.), or leaf rust (*Puccinia recondita* Rob. ex Desm. f. sp. *tritici*) were present at very low levels or not evident.

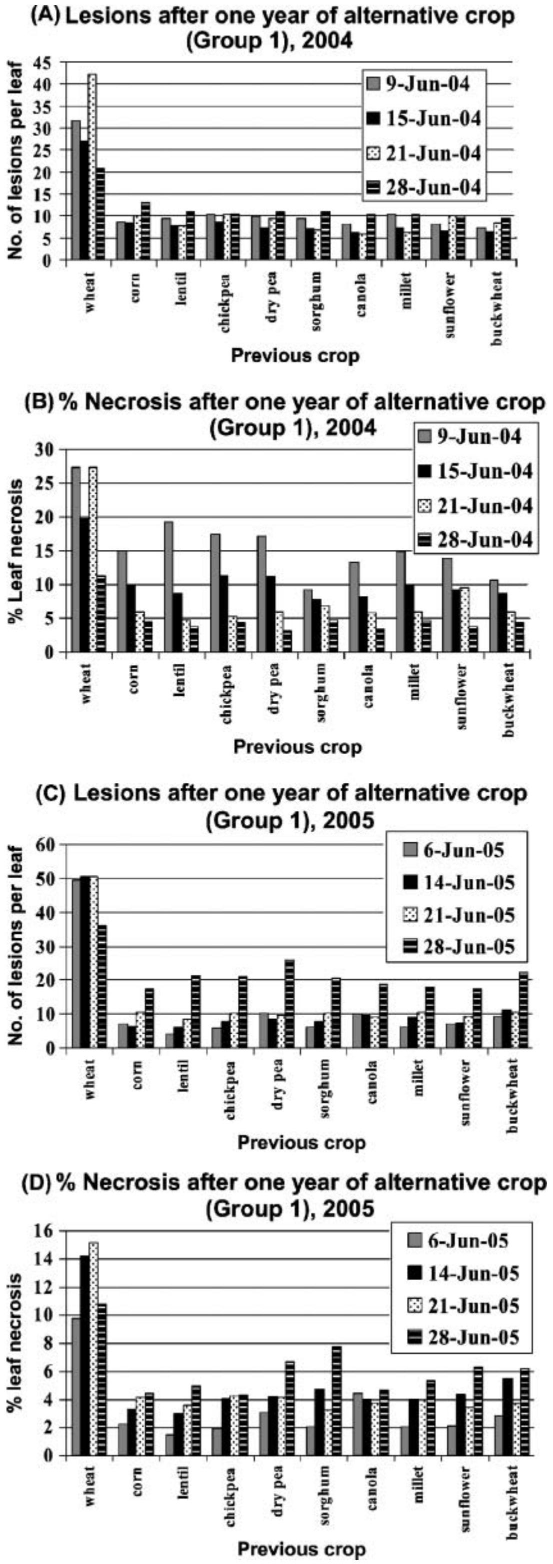

Fig. 3. Number of lesions and percentage necrosis on spring wheat leaves following 1 yr of an alternative crop (Group 1) in 2004 and 2005. In (A), (C), and (D), treatments following alternative crops are significantly less than the continuous spring wheat treatment. In (B), treatments following alternative crops are significantly less than the continuous spring wheat treatment, except for the treatment with lentil as the previous crop on 9 June 2004. The continuous spring wheat treatment was used as the control in Dunnett's one-tailed test ($P \leq 0.05$).

Leaf Spot Disease Severity Following an Alternative Crop (Group 1, Spring Wheat /Alternative Crop/Spring Wheat)

Spring wheat following alternative crops (Group 1, 1 yr of alternative crop) had significantly lower disease severities based on lesion number when compared with the continuous spring wheat treatment for four evaluations in 2004 and four evaluations in 2005 (Fig. 3A and 3C). For example, with the first three evaluations in 2005, leaves following alternative crops had <10 lesions compared with leaves from the continuous spring wheat treatment with ≈50 lesions (Fig. 3C), at least a five-fold difference. These evaluations provide insight on early disease development. Lower lesion numbers following alternative crops illustrate the benefit of having an alternative crop as a preceding crop.

On the basis of percentage necrosis for the same evaluations, differences were evident among treatments for all evaluations. Disease severities following alternative crops were significantly less than the continuous spring wheat treatment with all evaluations in 2005 and with three of four evaluations in 2004 (Fig. 3D and 3B). With the 9 June 2004 evaluation for percentage necrosis, the one exception in 2004, only one treatment with lentil as the previous crop was statistically similar to the continuous spring wheat treatment (Fig. 3B). With this exception, crop sequence treatments with 1 yr of alternative crops had lower disease severities than the continuous wheat treatment for multiple evaluations across two seasons.

These evaluations provided insights on early disease development. A possible weakness of these early evaluations was that disease severity in the continuous wheat plots may have been underestimated because leaves with coalesced lesions were avoided in favor of those with distinct lesions in order to quantify lesions. In contrast, the disease severity in wheat plots following alternative crop treatments may have been overestimated because leaves without lesions were avoided in order to obtain leaves with distinct lesions from each treatment for fungal isolations. Even though the sampling approach was rather conservative because disease severity was underestimated following wheat and overestimated following alternative crops, the difference between following wheat and other alternative crops was significant.

Leaf Spot Disease Severity Following Alternative Crops (Group 2, Alternative Crop/Alternative Crop/Spring Wheat)

On the basis of lesion number, spring wheat following 2 yr of the same alternative crop (Group 2) had lower disease severities than the continuous spring wheat treatment for six evaluations in 2004 and for four evaluations in 2005 (Fig. 4A and 4C). Lower lesion numbers following 2 yr of alternative crops is consistent with results presented above for 1 yr of an alternative crop, again exemplifying the benefit of alternative crops preceding wheat.

On the basis of percentage necrosis for the same evaluations, differences among Group 2 treatments

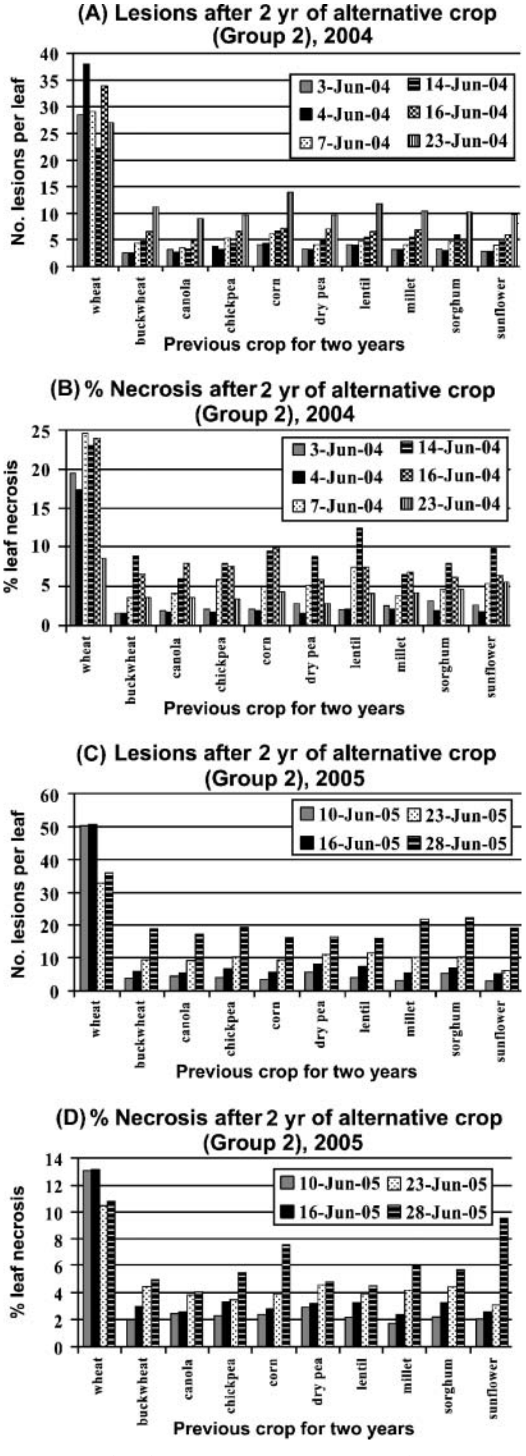

Fig. 4. Number of lesions and percentage necrosis on spring wheat leaves following 2 yr of an alternative crop (Group 2) in 2004 and 2005. (A) Treatments following alternative crops are significantly less than the continuous spring wheat treatment. (B) Treatments following alternative crops are significantly less than the continuous spring wheat treatment, except for the treatment with sunflower as the previous crop for the 23 June 2004 evaluation. (C) Disease severities following alternative crops are significantly less than the continuous spring wheat treatment. (D) Disease severities following alternative crops are significantly less than the continuous spring wheat treatment, except for the treatment with corn and sunflower as the previous crop for the 28 June 2005 evaluation. The continuous spring wheat treatment was used as the control in Dunnett's one-tailed test ($P \leq 0.05$).

were evident. All treatments following alternative crops had significantly lower disease severities than the continuous spring wheat treatment for five of six evaluations in 2004 and for three of four evaluations in 2005 (Fig. 4B and 4D). With the 23 June 2004 evaluation, the one exception in 2004, the treatment with sunflower as the previous crop was similar to the continuous spring wheat treatment. With the 28 June 2005 evaluation, the one exception in 2005, treatments following corn and sunflower were similar to the continuous spring wheat treatment. With these exceptions, treatments with 2 yr of alternative crops had lower disease severities than the continuous wheat treatment for multiple evaluations across two seasons.

When comparing the disease severity of spring wheat following 2 yr of an alternative crop (Group 2) with spring wheat following 1 yr of an alternative crop (Group 1), differences were not consistent for all comparisons across both years. Even though having 2 yr without a susceptible crop would allow more time for pathogen populations to decline while unrelated crops are being grown (Cook and Veseth, 1991), without consistent statistical differences, 2 yr of an alternative crop could not be clearly distinguished from 1 yr of an alternative crop in reducing disease severity under our conditions.

Early evaluations of disease severity demonstrate and confirm the benefit of alternative crops preceding wheat. Considering all Group 1 and Group 2 evaluations (spring wheat after 1 yr of an alternative crop and spring wheat after 2 yr of alternative crops), lesion numbers were reduced about 30% overall and percentage necrosis was reduced about 60% overall when spring wheat followed alternative crops. This benefit is more obvious and evident earlier in the season than results of late-season sampling obtained previously (Krupinsky et al., 2004, 2006). This may be due to in part to interplot interference. With relatively small plots (9 by 9 m), there probably was movement of spores among plots (particularly for tan spot), which could help explain the relatively greater rotation effect seen in earlier samplings compared with later sample times when higher levels of fungal spores would be present (Morrall and Howard, 1975).

Leaf Spot Disease Severity Following Different Crop Residue Levels (Group 3)

When lesion numbers were quantified, differences among treatments were obvious for two evaluations in 2004 and one evaluation in 2005 (Table 2). Compared with the continuous spring wheat treatment, spring wheat had significantly lower lesion numbers following all 25 alternative crop sequence treatments, which provided a range of crop residue coverage on the soil early in the season (Fig. 5A and 5C). Compared with the continuous spring wheat treatment, spring wheat also had lower percentage necrosis following the alternative crop sequence treatments (Fig. 5B and 5D) for four evaluations, two each in 2004 and 2005 (Table 2). In one (23 June 2004) out the four evaluations, two treatments

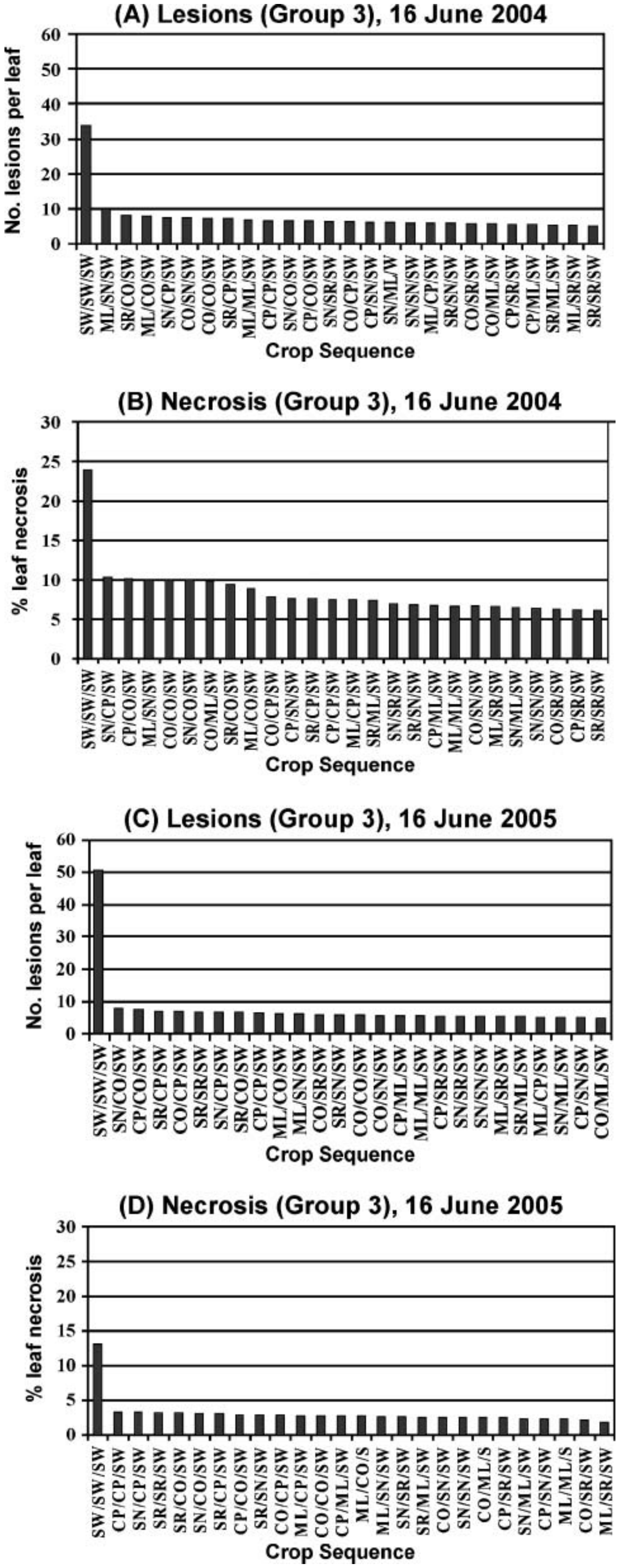

Fig. 5. Number of lesions and percentage necrosis on spring wheat leaves following 2 yr of an alternative crop with different residue levels (Group 3) in 2004 and 2005. (A–D) Disease severity following alternative crop sequences is significantly less than the continuous spring wheat treatment. The continuous spring wheat treatment was used as the control in Dunnett's one-tailed test ($P \leq 0.05$). CO = corn, CP = chickpea, ML = proso millet, SN = sunflower, SR = grain sorghum, and SW = spring wheat.

(sunflower/sunflower/spring wheat and proso millet/corn/spring wheat) were similar to the continuous wheat treatment. With these exceptions, crop sequence treatments with 2 yr of alternative crops with different levels of crop residue on the soil surface (Group 3) had lower disease severities than the continuous wheat treatment for several evaluations early in the season, similar to Group 2.

When the 25 alternative crop sequences were analyzed as a group (without the continuous spring wheat treatment), differences in the crop residue coverage on soil associated with different alternative crop sequences apparently did not impact disease severity. Even though the different levels of alternative crop residue coverage of soil may have influenced the microenvironment of the treatment plots, apparently those differences did not influence disease severity under our conditions.

CONCLUSIONS

Drechslera tritici-repentis and *S. nodorum* were major components of the leaf spot disease complex on hard red spring wheat, with *D. tritici-repentis* being the most common. Both organisms were consistently present throughout the growing season. Percentage of isolation from spring wheat following alternative crops was lower compared with spring wheat following spring wheat. With *S. nodorum*, the frequency of isolation was less from spring wheat following 2 yr of alternative crops compared with spring wheat following 1 yr of an alternative crop. Lower fungal isolations following alternative crops demonstrate a benefit of diverse alternative crops before wheat.

Crop sequencing influenced leaf spot diseases on hard red spring wheat. Spring wheat following crop sequences with alternative crops for 1 or 2 yr (Groups 1, 2, and 3) had lower levels of disease severity compared with a continuous spring wheat treatment early in the growing season. Lesion numbers were reduced about 30% overall and percentage necrosis was reduced about 60% overall when spring wheat followed alternative crops. Disease severity was apparently not associated with the amount of crop residue coverage of soil associated with alternative crop sequences (Group 3) early in the season. These early evaluations of disease severity demonstrate and confirm the benefit of alternative crops preceding wheat. This benefit is more obvious and evident earlier in the season than results obtained previously (Krupinsky et al., 2004, 2006).

Overall, crop sequencing with preceding alternative crops lowers the risk for leaf spot diseases of spring wheat. Even though rotating crop types is a valuable tool for reducing plant diseases in cropping systems, producers should not rely exclusively on a single management practice to minimize disease risk, but rather integrate a combination of practices to develop a sustainable long-term strategy for disease management that is suited to their production system and location (Cook and Veseth, 1991; Holtzer et al., 1996; Krupinsky, 1999; Krupinsky et al., 2002; Turkington et al., 2003).

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