Crop Residue Coverage of Soil Influenced by Crop Sequence in a No-Till System

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ABSTRACT

Field research was conducted to determine the influence of crop and crop sequencing on crop residue coverage of soil with 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 (*Triticum aestivum* L.)]. Crop residue production was obtained. Crop residue coverage of the soil surface was measured with a transect technique at the time of seeding spring wheat. Crop residue coverage varied and was more clearly associated with the second-year crop than with the first-year crop of a 2-yr crop sequence. Crop sequences composed of spring wheat, proso millet, and grain sorghum had higher crop residue coverage compared with sequences composed of the other crops. When these three crops and three crops that provide lower crop residue coverage of soil the subsequent year (lentil, chickpea, and sunflower) were analyzed as a subset to compare various sequences of crops providing a range of residue coverage, for example, lower (first yr)/lower (second yr), the surface residue coverage ranged from 65% for the lower/lower combination to 93% for the higher/higher combination in 2004 and from 56 to 94% in 2005, respectively. A producer operating on more fragile soil and concerned about reducing soil erosion hazards would be advised to grow crops that provide higher residue coverage in the year before crops that provide lower residue coverage.

THE USE OF CROP RESIDUE–CONSERVING management practices, such as reduced tillage, no tillage, and chemical weed control, has allowed dryland cropping systems in the Great Plains to diversify. Crop diversification has increased the use of crop species that leave considerably less residue cover on the soil than do cereal grains. In an earlier crop sequence project, Merrill et al. (2006) reported a range of 35 to 98% crop residue coverage of soil depending on how two crops were sequenced. Residue coverage was high (89–98%) with crop sequences that included small cereal grains [spring wheat and barley (*Hordeum vulgare* L.)], intermediate (34–86%) with a small cereal grain and a dicotyledonous species combination, and low (35–48%) with only dicotyledonous species. Differences in crop residue coverage of soil among crops can be related to the amount of residue produced by a particular crop, residue position (standing vs. flat), decomposition, and management practices. The rate of residue decomposition varies; for example, wheat residue decomposes more slowly than red clover (*Trifolium pratense* L.), canola, or dry pea residue (Lupwayi et al., 2004; Soon and Arshad, 2002). Residue decomposition is usually less under no-till management compared with conventional tillage (Lupwayi et al., 2004), due to cooler soils and more limited residue contact with soil microorganisms (Larney et al., 2003). Although other factors (row spacing, field slope and orientation, and type of combine threshing mechanism and residue spreader) can affect the decomposition of residue, the amount of precipitation received during the winter months was the primary factor contributing to soybean residue [*Glycine max* (L.) Merr.] cover reduction in Nebraska (Burr and Shelton, 2001).

Crop residue coverage protects soil and land resources from erosion, conserves soil water, maintains soil quality, and influences the soil surface environment. Retention of crop residues on the soil surface has a significant effect on soil quality. Crop residues left on the soil surface result in increased soil organic C (Liebig et al., 2005), improved soil physical properties (Arshad et al., 1999; Pikul and Aase, 1995), and enhanced microbial activity and biomass (Liebig et al., 2006). Such changes in near-surface soil condition improve the functioning of cropping systems through increased water storage (Deibert et al., 1986; Tanaka and Anderson, 1997), reduced soil erosion (Merrill et al., 1999), and improved nutrient conservation (Follett and Schimel, 1989). Collectively, improvements in soil condition through the retention of crop residues on the soil surface increase the resilience of Great Plains cropping systems to droughts, wet periods, intense precipitation events, and extreme temperatures, all of which are common to the region (Peterson, 1996).

Moisture retention is improved with crop residue coverage because of reduced evaporation, increased snow trapping, and reduced surface runoff due to better water infiltration (Cook and Veseth, 1991; Lal, 1995). By promoting water infiltration and by insulating the soil surface, moderating the soil temperature and limiting evaporation, crop residue coverage modifies the microenvironment (Dormaar and Carefoot, 1996). By modifying the microenvironment, residue may influence the development of the subsequent crop. Although results varied with site and year, wheat residue reduced plant establishment, plant biomass, and yield of canola in

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Abbreviations: RUSLE, revised universal soil loss equation; RWEQ, revised wind erosion equation; SLR, soil loss ratio.

New South Wales (Bruce et al., 2005). Similarly, wheat residue influenced the stage of development and height of corn (*Zea mays* L.) in 2 out of 3 yr in Michigan (Kravchenko and Thelen, 2005). Residue management practices can contribute to the suppression of some soilborne plant diseases, but understanding the mechanisms involved is limited (Bailey and Lazarovits, 2003). Crop residue contributes to increasing soil microbial activity and so increases the likelihood of competition among organisms in the soil (Bailey and Lazarovits, 2003). Reduced tillage practices may also favor some plant pathogens by lowering soil temperature, increasing soil moisture, and leaving the residue and soil undistributed (Bockus and Shroyer, 1998). Another possible concern with crop residues is allelopathy, as chemicals released by residue may have deleterious affects on crop growth. In a review of wheat yield responses to conservation practices, Kirkegaard (1995) summarized that allelopathic effects of residue are poorly understood.

Rainfall simulation and wind tunnel technology have shown a relationship between residue coverage of soil and water and wind erosion (Bilbro and Fryrear, 1994; Laflen and Colvin, 1981; Foster et al., 1982). Information on the impact of crop residue on erosion is embedded in USDA-ARS empirical, user-oriented models, such as the revised universal soil loss equation (RUSLE) model (Renard et al., 1997) for water erosion and the revised wind erosion equation (RWEQ) model (Fryrear et al., 1998) for wind erosion. Another model providing information on the interaction of crop residues with other erosion-affecting factors is the wind erosion prediction system (WEPS) model (Hagen, 1991). Much of the information about crop residue coverage effects on erosion and associated residue decay in these models derives from southern or mid-U.S. sources.

Merrill et al. (2006) have reported on the effects of different crop species on crop residue coverage of soil in an earlier crop sequence project. More testing with new and emerging crops and crop sequences, and environmental conditions will help further the understanding of crop sequence effects on crop residue coverage of soil. The objective of this project was to determine the influence of additional crops and crop sequencing on crop residue coverage of soil 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. During the research project, monthly precipitation and air temperature varied during the growing season (Fig. 1).

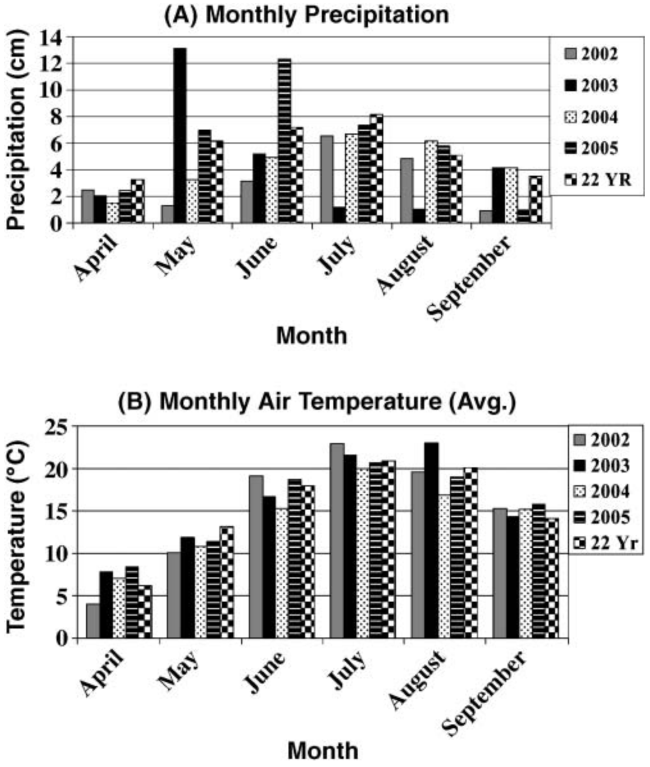


Fig. 1. Growing season precipitation and average air temperature on a monthly basis over the course of the crop sequence project and 22 yr average. (A) Monthly precipitation. (B) Monthly average air temperature.

An experimental crop × crop residue matrix design was used to allow the simultaneous evaluation of numerous crop sequences under similar weather and soil conditions (Krupinsky et al., 2006). To prepare the research sites and provide a similar residue background, oil seed sunflower was grown for 1 yr and hard red spring wheat was grown for 2 yr under no-till management (Table 1). Another 2 yr were required to form a crop × crop residue matrix (referred to hereafter as crop matrix) in which 10 crops were direct-seeded into the crop residue of the same 10 crops (Fig. 1 in Tanaka et al., 2007). 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. 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. In Project Year 3 (Table 1), spring wheat was uniformly seeded over the crop matrix.

Nitrogen was applied as a mid-row (between every other row) band application of NH_4NO_3 at 78 N kg ha^{-1} during seeding except for chickpea, dry pea, or lentil. Phosphorus was

Table 1. Project years with crops and sites used to evaluate the influence of crops and crop sequence on crop residue production and surface residue coverage (crop residue coverage of soil).

		Site 1†			Site 2†		
Project year	**Crop**	**Season**	**Surface residue coverage measured**	**Crop residue production determined**	**Season**	**Surface residue coverage measured**	**Crop residue production determined**
0	Sunflower	1999	–	–	2000	–	–
0	Spring wheat‡	2000	–	–	2001	–	–
0	Spring wheat‡	2001	–	–	2002	–	–
1	Crop strips§ (10 crops)	2002	After seeding spring wheat (26 April)¶	–	2003	After seeding spring wheat (21 May)	–
2	Crop matrix# (10 crops, 100 crop sequences)	2003	After seeding spring wheat (21 May)	At maturity of individual crops	2004	After seeding spring wheat (14 April)	At maturity of individual crops
3	Spring wheat††	2004	After seeding spring wheat (13 April)	–	2005	After seeding spring wheat (20–21 April)	–

† Two locations to provide two site years.

‡ Spring wheat grown for 2 yr to provide a uniform residue background.

§ During Project Year 1, 10 crops were direct-seeded into spring wheat residue. These crop strips provide the crop residue into which the same 10 crops were seeded during Project Year 2. This is the first of 2 yr required to establish a crop matrix.

¶ Date of spring wheat seeding.

During Project Year 2, 10 crops were seeded perpendicular over the crop residue from crop strips seeded during Project Year 1 to form a crop matrix with 100 crop sequences.

†† During Project Year 3, only spring wheat was seeded on the previous crop matrix.

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 inoculants were applied to dry pea, lentil, and chickpea seed before seeding. Weed control was accomplished using no-till techniques appropriate for each crop.

Crop Residue Production

Crop residue production data from Project Year 2 (Table 1) were obtained to show the amount of crop residue produced. Crop residue production was determined at physiological maturity by hand clipping all aboveground biomass from 0.35 m^2 (0.57 by 0.61 m). Samples were air dried for about 1 mo, oven dried at 60°C for 48 h, and weighed to determine total biomass. Samples were threshed, grain was cleaned and weighed, and grain was subtracted from the total biomass to get residue production. Crop residue production data from Project Year 1 was reported (Tanaka et al., 2007).

Crop Residue Coverage of Soil (Surface Residue Coverage)

All measurements of crop residue coverage of soil were done after spring wheat was direct-seeded into crop residue from the previous growing season. Crop residue coverage of soil was measured with a transect technique (Tanaka and Hofman, 1994). Counts of residue presence on the soil surface were taken at 25 points equally spaced along a 7.6-m cable, which was stretched across a plot to count the number of residue contacts. On each plot, a double-transect diagonal sampling pattern (V) was used, which pointed in the same direction of seeding. When residue intersected with a point on the cable, it was counted as a contact. The total number of residue contacts was recorded. During Project Years 1 and 2, two double transect V patterns (for 100 points) were used for each plot. Because of the number of plots (100 plots × 4 replicates) for all crop sequence combinations evaluated during Project Year 3, one double transect V pattern (for 50 points) was used. When 50-count and 100-count data were compared at Site 1 in 2004, similar results were obtained for the 100 plots evaluated. Plots were evaluated after seeding and before crop emergence.

In Project Year 1 (Table 1), surface residue coverage from the previous 2 yr of spring wheat was measured after spring wheat was seeded to obtain an overall estimate of background crop residue coverage for the project. Surface residue coverage was measured in every other plot, (five plots per rep, total of 20 plots) at the time of seeding spring wheat.

In Project Year 2 (Table 1), surface residue coverage was measured in all plots seeded to spring wheat. This was done to determine the amount of crop residue coverage of soil provided by each of the 10 crops after only 1 yr.

In Project Year 3 (Table 1), at the time spring wheat was seeded over the crop matrix, surface residue coverage was measured for all plots to determine crop residue coverage of soil following the 100 crop sequences present in the crop matrix (four replicates).

Three subsets of Project Year 3 data were selected and analyzed for additional insights: (i) The first subset included nine treatments with an alternative crop for 1 yr (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. These treatments were measured after seeding spring wheat to determine the amount of surface residue coverage provided by each of the 10 crops after only 1 yr, similar to the Project Year 2 data. (ii) The second subset included nine treatments with the same alternative crop for 2 yr (alternative crop, Project Year 1/same alternative crop, Project Year 2/spring wheat, Project Year 3; e.g., canola/canola/spring wheat) plus the continuous spring wheat treatment. These treatments provided a more homogeneous crop residue by reducing the carryover of residue from another crop species. They were measured to determine the amount of residue coverage provided by each of the 10 crops after 2 yr of the same crop. (iii) The third subset included 36 crop sequence combinations of six crops, three crops that provided higher surface residue coverage the subsequent year (proso millet, grain sorghum, and spring wheat), and three crops that provided lower surface residue coverage the subsequent year (lentil, chickpea, and sunflower). This subset was analyzed to compare sequence combinations of crops that provide a range of surface residue coverage [lower (first year of crop sequence)/lower (second year of crop sequence), lower/higher, higher/lower, and higher/higher, e.g., nine crop sequence combinations of lentil, chickpea, and sunflower, nine crop sequence combinations of proso millet, grain sorghum, and spring wheat.]

Residue Coverage and Erosion

The soil erosion hazards of the lowest residue coverage values measured can be evaluated by applying algorithms dealing with flat residue coverage that are contained in empirical erosion models: the RWEQ model (Fryrear et al., 1998) and the RUSLE model (Renard et al., 1997). Equations in the models predict soil loss ratio (SLR) values directly from residue coverage values. The SLR is defined as the ratio of soil loss with residue present to soil loss that would occur without residue under conditions in which other soil factors are in a state of relatively high soil erodibility, such as a dry, smooth soil surface with low soil aggregation. Thus, SLR = 1 with no residue present, and SLR = 0 with complete residue coverage. Wind-erodible soils have smooth surfaces with low slope, while water-erodible soils are sloped.

Statistical Analysis

Data for crop residue production and crop residue coverage of soil were analyzed using the general linear model procedure (SAS Institute, 2003). Statistical comparisons for each evaluation were made with Student-Newman-Keuls' test and Dunnett's one-tailed test. Dunnett's one-tailed test was used to make comparisons between crop sequence treatments and the continuous spring wheat treatment, which was used as a control. Statistical differences were evaluated at the probability level of $P < 0.05$. Probability level of $P < 0.01$ was also used to compare surface residue coverage after 99 crop sequences to the continuous spring wheat treatment.

RESULTS AND DISCUSSION

Background Surface Residue Coverage

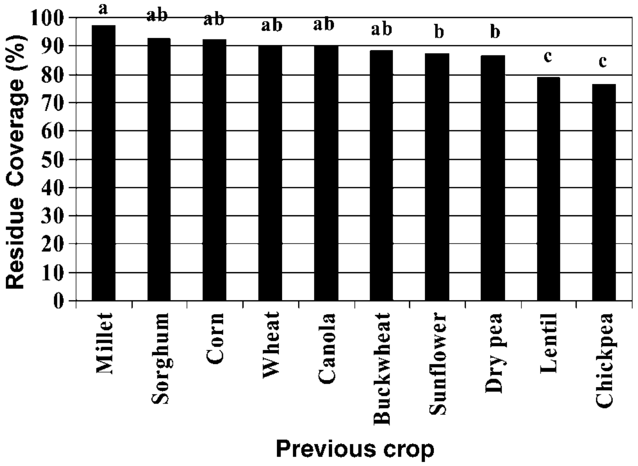
During Project Year 1 (Table 1), strips of all crops were seeded into spring wheat residue, which provided the background surface residue coverage for the project. Surface residue coverage measured at the time of seeding spring wheat ranged from 90 to 98% at Site 1 (2002) and 70 to 87% at Site 2 (2003).

Surface Residue Coverage after Alternative Crop for One Year (Spring Wheat/Alternative Crop)

During the establishment of each crop matrix (Project Year 2), crop residue coverage was evaluated soon after seeding spring wheat. The crop residue coverage after seeding spring wheat averaged 88% at Site 1 and 72% at Site 2. At Site 1, higher residue coverage followed proso millet, grain sorghum, spring wheat, corn, canola, and buckwheat and lower crop residue coverage followed chickpea and lentils (Fig. 2A). At Site 2, higher residue coverage followed spring wheat and proso millet (Fig. 2B) and lower residue coverage followed sunflower and corn. Thus, surface residue coverage was differentially impacted by the previous alternative crop. One can speculate that the plant biomass production and carryover of crop residues varied among alternative crops impacting the surface residue coverage the following spring.

Residue coverage following corn showed the greatest difference between sites (years). The lower residue coverage after corn in spring of 2004 (Site 2) was influenced by lower corn residue production in 2003 (Tanaka et al., 2007). This was probably due to the precipitation pattern during the 2003 growing season. Precipitation for May, June, July, and August was 13.2, 5.3, 1.2, 1.0 cm (5.21, 2.07, 0.49, and 0.41 in.), respectively, for 2003 compared with 1.3, 3.2, 6.6, and 4.9 cm (0.53, 1.25, 2.59, and 1.93 in.), respectively, for 2002 (Fig. 1). Although 4-mo precipitation in both 2002 and 2003 was below average (16 and 21 cm, respectively, vs. long-term avg. of 25.1 cm), the precipitation pattern during 2003 (Site 2) apparently did not favor corn residue production.

(A) Site 1 after seeding wheat, 21 May 2003



(B) Site 2 after seeding wheat, 14 Apr. 2004

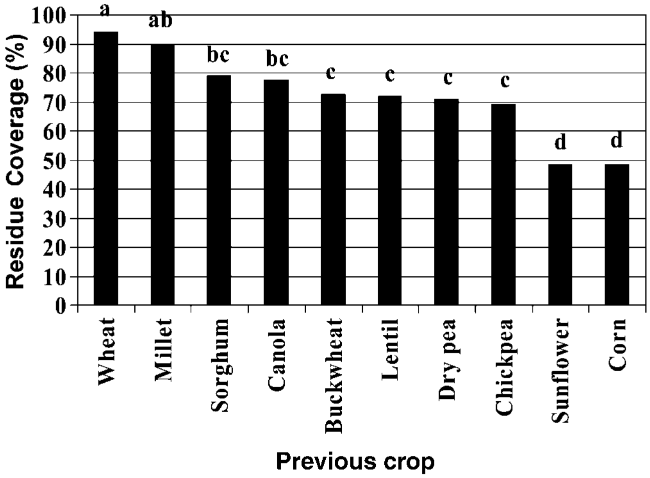


Fig. 2. Crop residue coverage of soil surface (Project Year 2) measured after seeding spring wheat into the residue of 10 crops during the establishment of the crop matrix at two sites. Bars with the same letter do not differ significantly at $P \leq 0.05$.

Crop Residue Production

Crop residue production data from Project Year 2 (Table 1) were obtained for all 100 crop sequence treatments in the crop matrix. Overall, the amount of crop residue returned to the soil surface varied among second-year crops of the crop sequences (Tables 2 and 3, bottom row). At Site 1 (2003), the highest average crop residue production was measured after grain sorghum, followed by proso millet, sunflower, and spring wheat (Table 2, bottom row). At Site 2 (2004), the highest average crop residue production was measured after corn and sunflower (Table 3, bottom row). When evaluating the overall carryover effect of the first-year crop of the sequence (Table 2 and 3, right column) differences were not evi-

Table 2. Residue yields (kg ha^{-1}) of 10 crops grown in Project Year 2 (Site 1, 2003) as influenced by previous crop and crop residue at Mandan, ND.

2002 crop, first year of sequence	2003 crop, second year of crop sequence†										
	Corn†	Chickpea	Sunflower	Dry pea	Lentil	Canola	Buckwheat	Proso millet	Sorghum	Spring wheat	Avg.‡
Corn	2287b	1813ab	3398ab	2156a	1526a	2774a	2597a	3114a	3360c	3554a	2658yz
Chickpea	3214a	1663ab	2376b	2377a	1856a	2794a	3128a	4160a	5185abc	3396a	3015wx
Sunflower	1972b	1335b	2294b	2077a	1345a	2792a	2508a	3778a	4059bc	2567a	2473z
Dry pea	3308a	2042a	3570ab	2198a	1864a	2902a	3178a	3597a	5967a	3687a	3231w
Lentil	3317a	1771ab	4406a	2015a	1896a	2420a	2603a	4115a	4528abc	3156a	3023wx
Canola	3378a	1525ab	3359ab	2365a	1981a	2726a	2687a	3933a	5744ab	3361a	3106wx
Buckwheat	2378b	1463ab	3921ab	2237a	1886a	2939a	2747a	3451a	4501abc	2794a	2832xy
Proso millet	1936b	1766ab	3291ab	1843a	1775a	2528a	2385a	2850a	4255abc	3342a	2597yz
Sorghum	2509ab	1897ab	3581ab	1716a	1701a	3087a	2343a	2717a	3439c	2858a	2585yz
Spring wheat	2589ab	1819ab	3862ab	2071a	2069a	3318a	3047a	3179a	4677abc	2665a	2930wxy
Average§	2689x	1710z	3406v	2106y	1790z	2828x	2722x	3489v	4571u	3138w	

† Crop residue yield from 2003 crops (second-year crop of sequence); data for each 2003 crop were analyzed separately; when comparing the 10 first-year crops for each second-year crop, numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

‡ 2002 crop (first-year crop of sequence) averaged across all second-year crops; all data analyzed together; average numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

§ 2003 crop (second-year crop of sequence) averaged across all first-year crops; all data analyzed together; average numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

dent at both sites. At Site 1 (2003), the highest average crop residue production was measured after dry pea, followed by canola, lentil, chickpea, and spring wheat (Table 2, right column). This may be related to soil water available to the second-year crop in the sequence. For example, dry pea, when present as a first-year crop in the sequence, would use the least soil water of the crops grown, leaving more available for the second-year crop in the sequence, whereas sunflower, when used as a first-year crop in the sequence, a higher soil water user of the crops grown, would leave less soil water available for the second-year crop in the sequence (Merrill et al., 2007). At Site 2 (2004), no carryover effect from the crop used in the first year of the sequence was evident (Table 3, right column).

The carryover effects of the 10 first-year crops were also compared when data for each second-year crop were analyzed individually. At Site 1, crop residue production of four crops (corn, chickpea, sunflower, and grain sorghum) was influenced by the first-year crop in the sequence (Table 2, individual crop columns, excluding the bottom row), with the lowest crop residue production for three of the four crops following sunflower, a high water user (Merrill et al., 2007). At Site 2, no differences were evident (Table 3, individual crop columns, excluding the bottom row).

Surface Residue Coverage after Crop Matrix

In Project Year 3 (Table 1), at the time of spring wheat seeding, crop residue coverage of soil was obtained for all 100 crop sequence treatments in the crop matrix. Differences in surface residue coverage were evident among second-year crops of the crop sequences (Tables 4 and 5, bottom row). The highest average residue coverage was measured following spring wheat, proso millet and grain sorghum at both sites. At Site 1, the lowest residue coverage was measured after sunflower and corn, followed by chickpea, lentil, and dry pea (Table 4, bottom row). At Site 2, the lowest residue coverage was measured after sunflower, followed by lentil, chickpea, dry pea, and then corn (Table 5, bottom row).

When evaluating the overall carryover effect of crop residue by the first-year crop of the sequence (Tables 4

Table 3. Residue yields (kg ha^{-1}) of 10 crops grown in Project Year 2 (Site 2, 2004) as influenced by previous crop and crop residue at Mandan, ND.

2003 crop, first year of sequence	2004 crop, second year of crop sequence†										
	Corn†	Chickpea	Sunflower	Dry pea	Lentil	Canola	Buckwheat	Proso millet	Sorghum	Spring wheat	Avg.‡
Corn	43642a	3092a	31719a	5474a	2115a	4081a	3442a	4843a	4983a	3158a	10655z
Chickpea	58965a	2148a	38311a	4990a	1777a	4160a	3180a	5250a	3384a	3249a	12541z
Sunflower	54861a	2854a	26112a	4304a	2700a	3284a	3255a	4527a	5362a	3293a	11055z
Dry pea	54916a	2804a	44864a	4206a	2269a	4061a	3610a	5221a	5088a	3009a	13005z
Lentil	51025a	2965a	34388a	5949a	2086a	4002a	3338a	5243a	4805a	3390a	11719z
Canola	58312a	2963a	40293a	4986a	1931a	3913a	3463a	5644a	5805a	2953a	13026z
Buckwheat	47838a	2878a	60105a	4873a	1805a	3669a	3862a	4185a	5752a	3157a	13812z
Proso millet	66164a	3184a	30554a	4481a	2042a	5397a	3256a	5378a	7185a	3437a	13108z
Sorghum	57960a	2761a	43751a	5630a	1822a	5260a	3900a	5239a	5477a	3423a	13522z
Spring wheat	65301a	3284a	52969a	4688a	2907a	3686a	4038a	5907a	4708a	3354a	15084z
Average§	55898x	2893z	40306y	4958z	2145z	4151z	3534z	5144z	5255z	3242z	

† Crop residue yield from 2004 crops (second-year crop of sequence); data for each 2004 crop were analyzed separately; when comparing the 10 first-year crops for each second-year crop, numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

‡ 2003 crop (first-year crop of sequence) averaged across all second-year crops; all data analyzed together; average numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

§ 2004 crop (second-year crop of sequence) averaged across all first-year crops; all data analyzed together; average numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

Table 4. Crop residue coverage of soil surface (percentage) associated with 100 crop sequences measured after spring wheat was seeded in Project Year 3 following the crop matrix at Site 1, 2004.

2002 crop, first year of sequence	2003 crop, second year of crop sequence†										
	Corn†	Chickpea	Sunflower	Dry pea	Lentil	Canola	Buckwheat	Proso millet	Sorghum	Spring wheat	Avg.‡
Corn	68bc	75ab	68a	78ab	78bc	78abc	85ab	90a	93a	95ab	81xy
Chickpea	51d	61b	66a	73b	74bcd	80abc	79bc	93a	90a	89ab	75yz
Sunflower	55cd	61b	74a	71b	71cd	77abc	77bc	87a	91a	90ab	75yz
Dry pea	55cd	61b	57a	70b	67d	76bc	76bc	89a	91a	91ab	73yz
Lentil	50d	61b	50a	70b	68d	70c	71c	84a	90a	86b	70z
Canola	52d	65b	52a	74ab	71cd	75bc	78bc	92a	88a	95ab	74yz
Buckwheat	58cd	69b	48a	81ab	71cd	81abc	78bc	89a	90a	90ab	75yz
Proso millet	77ab	74ab	71a	82ab	77bc	90a	92a	92a	93a	96a	84x
Sorghum	83a	85a	71a	84a	88a	85ab	91a	92a	98a	94ab	87x
Spring wheat	71b	73ab	60a	72b	80b	85ab	89a	93a	91a	92ab	80xy
Average§	62z	68y	61z	75x	74x	80w	81w	90v	91v	92v	

† Crop residue coverage of the soil after 2003 crops (second-year crop of sequence); data for each 2003 crop were analyzed separately; when comparing the 10 first-year crops for each second-year crop, numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

‡ 2002 crop (first-year crop of sequence) averaged across all crops; all data analyzed together; average numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

§ 2003 crop (second-year crop of sequence) averaged across all crops; all data analyzed together; average numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

and 5, right column), the highest average crop residue coverage was numerically associated with proso millet, grain sorghum, and spring wheat for both years. Differences among average residue coverage were more clearly associated with the second-year crop than with the first-year crop of the sequence.

The carryover effects of the 10 first-year crops were also compared when data for each second-year crop were analyzed individually. The carryover effect of the first-year crop in the crop sequence was more evident with crops which provide lower levels of surface residue coverage than with crops which provide higher levels of surface residue coverage (Tables 4 and 5, individual crop columns, excluding the bottom row). For example, almost no differences were detected with spring wheat, proso millet, and grain sorghum (data columns 8, 9, and 10), crops which provide higher levels of surface residue coverage. With these three crops, the amount of surface residue coverage of the second-year crop had an overriding influence on surface residue coverage with almost no obvious carryover effect from the first-year crop in the crop sequence. For second-year crops which provide lesser amounts of surface residue coverage, crop residue coverage of soil tended to be higher following a first-year crop that produces a higher level of surface residue coverage. This is consistent with the recommendation that crops producing higher levels of residue be grown before crops producing lower levels of residue especially on more fragile soils (Merrill et al., 2006). Besides the variation in the amount of residue produced by a particular crop, the rate of residue decomposition may have varied (Soon and Arshad, 2002).

Spring wheat, canola, dry pea, and sunflower were common to the present crop sequence project and an earlier crop sequence project (Krupinsky et al., 2006). The surface residue coverage values observed in the two projects may be compared by aggregating crop sequences and taking 2-yr averages of surface residue coverage values measured following the crop matrix phase (Project Year 3) in 2000 and 2001 (Fig. 3 in Merrill et al., 2006) and in 2004 and 2005 (Table 6). The present crop sequence project was performed during years which had

Table 5. Crop residue coverage of soil surface (percentage) associated with 100 crop sequences measured after spring wheat was seeded in Project Year 3 following the crop matrix at Site 2, 2005.

2003 crop first year of sequence	2004 crop, second year of crop sequence†										
	Corn†	Chickpea	Sunflower	Dry pea	Lentil	Canola	Buckwheat	Proso millet	Sorghum	Spring wheat	Avg.‡
Corn	59c	61bc	42b	67bc	62bc	75ab	73bc	94a	92a	85ab	71z
Chickpea	77abc	54c	44b	57c	54c	73ab	76bc	97a	95a	80b	70z
Sunflower	69abc	65c	57ab	62bc	59c	66b	73bc	94a	92a	83ab	71z
Dry pea	76abc	65abc	52ab	58c	56c	72ab	75bc	98a	95a	88ab	73yz
Lentil	70abc	65abc	54ab	63bc	65abc	75ab	69c	97a	95a	87ab	74xyz
Canola	65bc	73ab	52ab	73abc	61bc	70ab	77bc	94a	97a	86ab	75xyz
Buckwheat	76abc	72ab	73a	69abc	70abc	78ab	79abc	95a	91a	88ab	79xyz
Proso millet	85a	78a	51ab	76ab	79a	80ab	81ab	95a	95a	90ab	81xy
Sorghum	79ab	74ab	69a	76ab	70abc	80ab	88a	96a	96a	88ab	81xy
Spring wheat	83ab	77a	64ab	83a	77ab	84a	83ab	94a	96a	95a	83x
Average§	74x	67y	56z	68y	65y	75x	77x	95v	94v	87w	

† Crop residue coverage of soil by crop residue after 2004 crops (second-year crop of sequence); data for each 2004 crop were analyzed separately; when comparing the 10 first-year crops for each second-year crop, numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

‡ 2003 crop (first-year crop of sequence) averaged across all second-year crops; all data analyzed together; average numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

§ 2004 crop (second-year crop of sequence) averaged across all first-year crops; all data analyzed together; average numbers followed by the same letter are not significantly different at the $P \leq 0.05$ level according to Student-Newman-Keul's test.

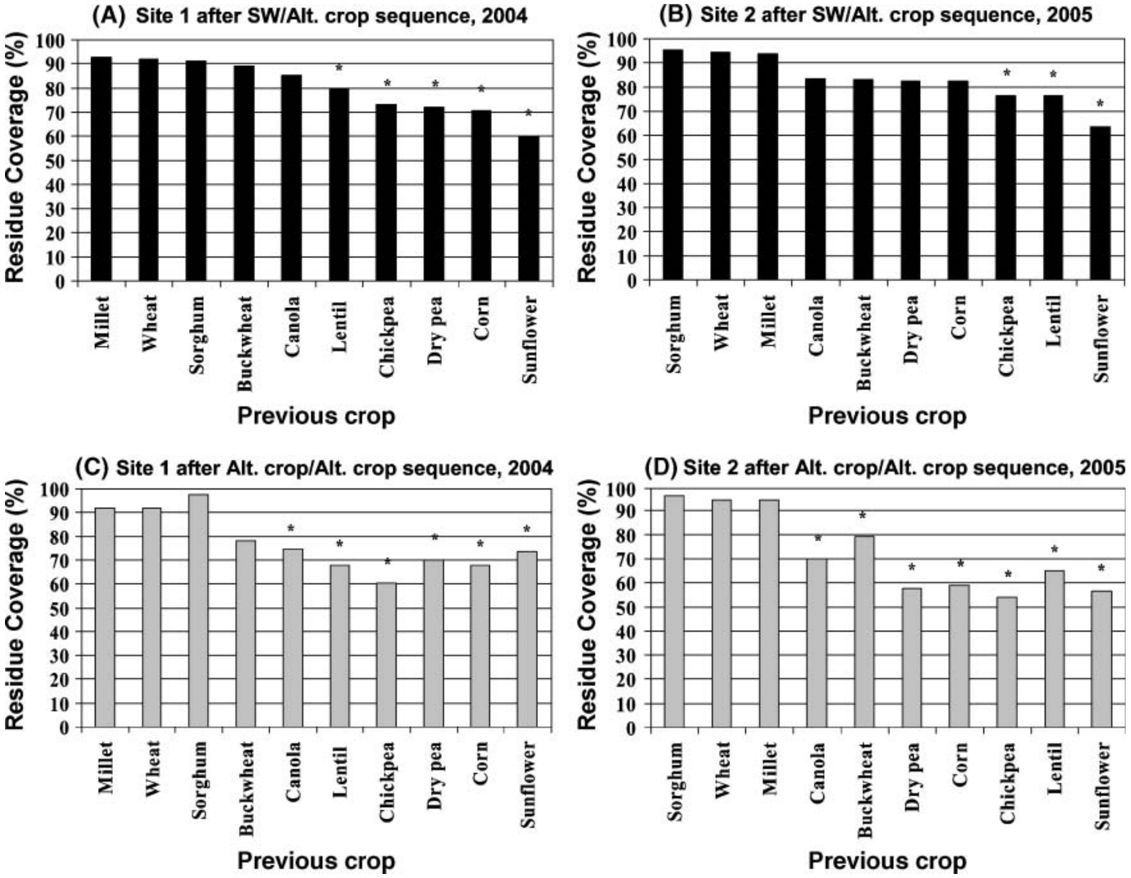


Fig. 3. Crop residue coverage (Project Year 3) of selected groups of crop sequence treatments measured after seeding spring wheat into the residue of the crop matrix. * = crop sequence treatments with statistically less residue coverage than the continuous spring wheat treatment according to Dunnett's one-tailed *t* test ($P < 0.05$).

below-average annual precipitation (Fig. 1), while the earlier crop sequence project was performed in years with above-average precipitation (Fig. 2 in Krupinsky et al., 2006). The greater availability of moisture during the earlier project may have led to greater decay of residues (Stott et al., 1986; Summerell and Burgess, 1989) in crop sequences with dry pea and sunflower and may possibly have been the reason that there was lower average surface residue coverage of the soil for these sequences than in the present project (Table 6). However, surface residue coverage values for sequences with spring wheat in the first year and sunflower or dry pea in the second had similar values in both experiments, and sequences with spring wheat, canola, or both crops had higher surface residue coverage values in the earlier project than in the present project.

Table 6. Combinations of crop sequences and 2-yr averages from the present and previous crop sequence research.

	Crop residue coverage (%), 2-yr avg.	
Crop sequences†	2000 and 2001‡	2004 and 2005§
SN–SN, PE–PE, PE–SN	44	61
SW–SN, SW–PE	71	70
SW–SW, CN–CN, SW–CN	90	84

† CN = Canola, PE = dry pea, SW = Spring wheat, and SN = sunflower.
‡ Earlier Crop Sequence Project carried out during years with above average precipitation (Fig. 3 in Merrill et al., 2006).
§ Present Crop Sequence Project (Tables 4 and 5) carried out during years with below average precipitation.

Surface Residue Coverage after 99 Crop Sequences Compared with Continuous Spring Wheat

When surface residue coverage for 99 crop sequence treatments (2-yr crop sequence combinations) was compared with the continuous spring wheat treatment after seeding spring wheat in Project Year 3, 51 and 41 of the crop sequence treatments had surface residue coverage similar to the continuous wheat treatment at Sites 1 and 2, respectively, (Table 7). Similar to the analyses presented above, the crop residue coverage from the preceding year (second year of the crop sequence) appeared to have a greater influence on crop residue coverage than residue from the first-year crop in the sequence.

Crop sequences with grain sorghum, spring wheat, and proso millet in the second year of the crop sequence, were all similar to the continuous spring wheat treatment, confirming the higher level of crop residue coverage following these three crops (Table 7). In contrast, crop sequences with corn, chickpea, sunflower, dry pea, and lentil in the second year of the sequence had typically lesser surface residue coverage than the continuous spring wheat treatment, confirming a lower level of surface residue coverage following these five crops. With

Table 7. Crop residue coverage of soil surface (percentage) measured after seeding spring wheat into the residue of the crop matrix (Project Year 3). Italicized treatments have less crop residue coverage than the continuous spring wheat treatment according to Dunnett's one-tailed *t* test.

	Second year of crop sequence									
	Corn	Chickpea	Sunflower	Dry pea	Lentil	Canola	Buckwheat	Millet	Sorghum	Spring wheat
					Site 1, spring wheat seeded 13 Apr. 2004					
2002 crop, first year of crop sequence										
Corn	_68**_	_75*_	_68**_	78	78	78	85	90	93	95
Chickpea	_51**_	_61**_	_66**_	_73**_	_74**_	80	79	93	90	89
Sunflower	_55**_	_61**_	_74**_	_71**_	_71**_	_77*_	_77*_	87	91	90
Dry pea	_55**_	_61**_	_57**_	_70**_	_67**_	_76*_	_77*_	89	91	91
Lentil	_50**_	_61**_	_50**_	_70**_	_68**_	_70**_	_71**_	84	90	86
Canola	_52**_	65**	_52**_	_74**_	_71**_	_75**_	78	92	88	95
Buckwheat	_58**_	69**	_48**_	81	_71**_	81	78	89	90	90
Millet	_77*_	74**	_71**_	82	_77*_	90	92	92	93	96
Sorghum	83	85	_71**_	84	88	85	91	92	98	94
Spring wheat	_71**_	_73**_	_60**_	_72**_	80	85	89	93	91	92
					Site 2, spring wheat seeded 20–21 Apr. 2005					
2003 crop, first year of crop sequence										
Corn	_59**_	_61**_	_42**_	_67**_	_62**_	_75**_	_73**_	94	92	85
Chickpea	_77*_	_54**_	_44**_	_57**_	_54**_	_73**_	_76**_	97	95	80
Sunflower	_69**_	_65**_	_57**_	_62**_	_59**_	_66**_	_73**_	94	92	83
Dry pea	_76**_	_65**_	_52**_	_58**_	_56**_	_72**_	_75**_	98	95	88
Lentil	_70**_	_65**_	_54**_	_63**_	_65**_	_75**_	_69**_	97	95	87
Canola	_65**_	_73**_	_52**_	_73**_	_61**_	_70**_	_77*_	94	97	86
Buckwheat	_76*_	_72**_	_73**_	_69**_	_70**_	_78*_	79	95	91	88
Millet	85	_78*_	_51**_	_76**_	79	80	81	95	95	90
Sorghum	79	_74**_	_69**_	_76*_	_70**_	80	88	96	96	88
Spring wheat	83	_77*_	_64**_	83	_77*_	84	83	94	96	95

* $P \leq 0.05$.

** $P \leq 0.01$.

buckwheat and canola as the second-year crop of a sequence, surface residue coverage was influenced by the first-year crop. Surface residue coverage after buckwheat and canola following crops that provided higher crop residue coverage of soil (proso millet, grain sorghum, and spring wheat), was comparable with the continuous spring wheat treatment at both sites (Table 7). Thus, with buckwheat and canola (second year of the crop sequence), residue coverage was influenced by carryover residue from the first year of the sequence.

Selected Surface Residue Coverage Treatments (Spring Wheat/Alternate Crop) after Crop Matrix

The first subset of Project Year 3 data included nine treatments with an alternative crop for 1 yr (spring wheat/alternative crop/spring wheat) plus the continuous spring wheat treatment. Treatments were analyzed to evaluate the surface residue coverage after an alternative crop for one growing season. Crop residue coverage of soil was similar for both sites, with an average of 80% coverage at Site 1 and 83% at Site 2. Higher levels of crop residue coverage of soil were associated with previous spring wheat, grain sorghum, proso millet, buckwheat, and canola crops at both sites (Fig. 3A and 3B). Lower levels of crop residue coverage of soil were observed after lentil, chickpea, and sunflower at both sites. Thus, crops varied in their impact on surface residue coverage when measured the next spring at the time of seeding a subsequent spring wheat crop. This is consistent with results presented above when the same crop sequence treatments were evaluated soon after seeding spring wheat in Project Year 2 when the crop matrix was established.

Selected Surface Residue Coverage Treatments (Alternate Crop/Same Alternate Crop) after Crop Matrix

The second subset of Project Year 3 data included nine treatments with the same alternative crop for 2 yr (alternative crop/same alternative crop/spring wheat) plus the continuous spring wheat treatment. Treatments were analyzed to evaluate the surface residue coverage after growing the same crop for 2 yr. Crop residue coverage averaged 77% at Site 1 and 73% at Site 2. The crops varied in their impact on crop residue coverage of soil. Higher levels of surface residue coverage were associated with previous spring wheat, grain sorghum, and proso millet crops at both sites (Fig. 3C and 3D). Lower levels of surface residue coverage were observed after sunflower, lentil, chickpea, corn, and canola at both sites. There is a tendency for surface residue coverage following two seasons of crops that provide lower crop residue coverage of soil to be lesser than surface residue coverage following one season of the same crop.

Selected Surface Residue Coverage Treatments (Crops Associated with Low and High Residue Coverage) after Crop Matrix

The third subset of Project Year 3 data included crop residue coverage associated with three crops that provide higher crop residue coverage of the soil the subsequent year (proso millet, grain sorghum, and spring wheat) and three crops that provide lower crop residue coverage of the soil the subsequent year (lentil, chickpea, and sunflower). Treatments were analyzed to compare various combinations of surface residue coverage (lower/lower, lower/higher, high/lower, and higher/

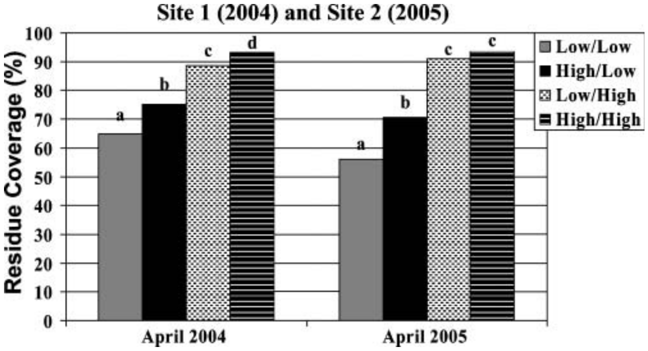


Fig. 4. Summary of crop residue coverage of soil (Project Year 3) for 36 crop sequence combinations of three crops with higher residue coverage the following year (proso millet, grain sorghum, and spring wheat) and three crops with lower residue coverage the following year (lentil, chickpea and sunflower). Bars with the same letter do not differ significantly with Student-Newman-Keuls' test analyses ($P \leq 0.05$). Low = lower crop residue coverage of soil surface, High = higher crop residue coverage of soil surface.

higher). The surface residue coverage ranged from 65% for the lower/lower combination to 93% for the higher/higher combination in 2004, and from 56 to 94% in 2005, respectively (Fig. 4). Consistent with results presented above, two seasons of crops which provide lower crop residue coverage of soil provide significantly less surface residue coverage than other combinations. This supports studies that have shown potentially greater soil erosion when crops which provide lower crop residue coverage of soil are grown in succession (Merrill et al., 2006).

Residue Coverage and Erosion

The lowest average residue coverage value following matrix crops and measured soon after spring wheat seeding in 2004 was 48% (Table 4), yielding $SLR_{water} = 0.186$, and $SLR_{wind} = 0.122$. The lowest average residue coverage value following matrix crops in 2005 was 42% (Table 5), giving $SLR_{water} = 0.230$ and $SLR_{wind} = 0.159$. These theoretically calculated soil loss potentials indicate only a moderate degree of erosion risk, and refer to conditions that are generally more erodible than those occurring in typical well-managed no-till soil-crop systems that are not under drought or on marginal, fragile soils. For comparison, the average residue coverage value for continuous spring wheat was 92% in 2004 (Table 4), yielding $SLR_{water} = 0.040$ and $SLR_{wind} = 0.018$, and 95% in 2005 (Table 5), yielding $SLR_{water} = 0.036$ and $SLR_{wind} = 0.016$; with the highest average residue coverage value being 98% for both years, yielding $SLR_{water} = 0.032$ and $SLR_{wind} = 0.014$.

Even with the practice of no-till, the use of sequences with crops such as sunflower and pulse legumes such as dry pea for two consecutive years can result in lack of adequate residue coverage and heightened soil erosion risks under drought conditions. Lack of precipitation at critical times can result in reduced crop stands and lack of adequate crop growth, and subsequently inadequate surface residue coverage. During drought periods, inadequate crop growth and consequent low residue presence will negatively synergize with soil erodibility factors to increase wind erosion risks (Merrill et al., 1999). Inadequate precipitation and stored soil water can lead to a decision to summer fallow in dryland cropping areas. Most likely the greatest erosion hazard in cropping systems occurs if tillage and/or summer fallowing are practiced after a lower-residue crop. Merrill et al. (2004) measured the wind erosion of a silt loam soil on no-till-managed sunflower stubble land (sunflower following spring wheat), which was subjected to various degrees of spring tillage treatments (no-till, medium-till, and heavy tillage [conventional]) followed by chemical (glyphosate) summer fallowing. The combination of tillage and chemical weed control under relative summer dryness resulted in unacceptably high levels of wind erosion. Even the no-till treatment had moderately elevated measured levels of soil loss under a high-energy windstorm event (Merrill et al., 2004).

CONCLUSIONS

Crop species vary in the amount of crop residue coverage of soil provided in no-till cropping systems. Crop residue production and crop residue coverage of soil for 100 crop sequence combinations in a crop matrix was obtained. Surface residue coverage measured at the time of spring wheat seeding indicated that crop sequences composed of spring wheat, proso millet, or grain sorghum had the highest surface residue coverage, while sequences composed of two alternative species such as chickpea, lentil, dry pea, sunflower, and corn had lower surface residue coverage. When evaluating the 2-yr crop sequence combinations, differences in surface residue coverage were more clearly associated with the second-year crop than with the first-year crop of the sequence. Second-year crops which provide higher amounts of surface residue coverage had an overriding influence on surface residue coverage with almost no obvious carry-over effect from the first-year crop in the crop sequence. With second-year crops which provide lesser amounts of surface residue coverage, crop residue coverage of soil tended to be higher following a first-year crop that produces a higher level of surface residue coverage. Two seasons of crops which provide lower crop residue coverage of soil provide significantly less surface residue coverage than other combinations.

Sustainable management of dynamic cropping systems requires that producers base crop sequencing on the principles of adaptability, diversity, environmental awareness, information awareness, multiple enterprises, and reduced input costs (Tanaka et al., 2002). We have shown that certain crops produce lesser amounts of residue or tend to have less durable residues. Two-year sequences with higher-residue crops like spring wheat in the first year produce greater residue coverage than sequences with 2 yr of lower-residue crops. A first-year crop of spring wheat, proso millet, or grain sorghum can provide sufficient residues in a sequence where the next crop is low-residue (or rapidly decomposable). A producer operating on more fragile soil and concerned about reducing soil erosion hazards would be advised to grow higher-residue crops in the year before such species as dry pea or sunflower.

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