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Dynamic Cropping Systems for Sustainable Crop Production in the Northern Great Plains

D. L. Tanaka,* J. M. Krupinsky, S. D. Merrill, M. A. Liebig, and J. D. Hanson

ABSTRACT

Producers need to know how to sequence crops to develop sustainable dynamic cropping systems that take advantage of inherent internal resources, such as crop synergism, nutrient cycling, and soil water, and capitalize on external resources, such as weather, markets, and government programs. The objective of our research was to determine influences of previous crop and crop residues (crop sequence) on relative seed and residue yield and precipitation-use efficiency (PUE) for the no-till production of 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.), lentil (*Lens culinaris* Medik.), proso millet (*Panicum miliaceum* L.), sunflower (*Helianthus annus* L.), and spring wheat (*Triticum aestivum* L.) grown in the northern Great Plains. Relative seed yield in 2003 for eight of the 10 crops resulted in synergistic effects when the previous crop was dry pea or lentil, compared with each crop grown on its own residue. Buckwheat, corn, and sunflower residues were antagonistic to chickpea relative seed yield. In 2004, highest relative seed yield for eight of the 10 crops occurred when dry pea was the previous crop. Relative residue yield followed a pattern similar to relative seed yield. The PUE overall means fluctuated for seven of the 10 crops both years, but those of dry pea, sunflower, and spring wheat remained somewhat constant, suggesting these crops may have mechanisms for consistent PUE and were not as dependent on growing season precipitation distribution as the other seven crops. Sustainable cropping systems in the northern Great Plains will approach an optimal scheme of crop sequencing by taking advantage of synergisms and avoiding antagonisms that occur among crops and previous crop residues.

Water is a limiting factor for sustainable crop production in the semiarid Great Plains of North America. Crop–fallow systems were one of the first strategies producers used to help stabilize crop yields during drought periods (Black et al., 1974; Greb, 1979). Over time, agricultural producers and researchers developed management practices that retained greater quantities of surface residues during the fallow period to increase soil water storage and control soil erosion. Improved residue management techniques to store soil water during the fallow period increased wheat yields 2.5-fold in the central Great Plains (Greb, 1983), but had no significant effect on soil water storage or wheat yields in the northern Great Plains (Tanaka and Aase, 1987). The proportion of precipitation received during the fallow period that is stored as soil water appears to have peaked for the present at 40% across all climatic zones (Peterson et al., 1996). Therefore, about 60% of the precipitation received during fallow is lost to evaporation (Greb, 1983; Unger, 1984; Dao, 1993). Currently, soil and water conservation practices for soil water storage during fallow are at their practical limits and new approaches are needed to more efficiently use precipitation.

Fallow efficiencies in the central Great Plains can be improved to 47% by diversifying a wheat–fallow system to include summer annual crops in the system (Farahani et al., 1998b). Farahani et al. (1998a) noted that precipitation use of a cropping system, that is, percentage of precipitation received during the crop period in contrast to the noncrop period, could approach 75% for continuous annual cropping systems compared with <45% for winter wheat–fallow systems. No-till dryland cropping systems with more diverse crops and less fallow per unit of time is one strategy to make more efficient use of precipitation (Peterson et al., 1996). Diverse crops in cropping systems favor the *rotation effect* (synergism), where rotating crops generally increase production compared with monoculture (Porter et al., 1997; Miller and Holmes, 2005).

Inclusion of diverse crops in cropping systems creates a crop production environment that is constantly changing. Greater systems diversity required a dynamic cropping system philosophy to promote the advancement of agricultural systems research and determine information about causal relationships for solving producer problems (Tanaka et al., 2002). Tanaka et al. (2002) define a dynamic cropping system as "a long-term strategy of annual crop sequencing that optimizes cropping options and the outcome of crop production, economics, and resource conservation goals by using sound ecological management principles." Dynamic cropping systems take advantage of crop sequencing and synergism (Tanaka et al., 2005). To optimize the benefits of cropping systems on crop parameters, it is important to understand the effects of previous crops on current crop production. Meager research has been published in the northern Great Plains on the effect of crop sequencing on crop productivity parameters, and research that has been published is inconsistent in terms of positive or negative benefits of crop sequencing (Miller et al., 2002, 2003a, 2003b; Arshad et al., 2002; Gan et al., 2003). Krupinsky et al. (2006) conducted research to evaluate some of the soil and crop ecological interactions that influence crop production of 10 crops grown under similar soil and environmental conditions, but physical restraints did not permit evaluation of several of the major crops grown in the northern Great Plains. They found crop sequence did influence crop production, soil water depletion, and plant disease. Therefore, additional

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

Abbreviations: PUE, precipitation-use efficiency.

Table 1. Crop cultivars, viable seeds planted ha^{-1}, seeding date, and harvest date for crop sequence research at Mandan, ND.

			Seeding date		Harvest date		Crop category		
Crop	Cultivar	Viable seeds ha^{-1}	2003	2004	2003	2004	Season length	Seeding time	Harvest time
Buckwheat	Koto	2.5 million	11 June	08 June	23 Oct.	07 Sept.	short	late	late
Canola	357RR	2.5 million	21 May	15 Apr.	15 Aug.	19 Aug.	short	early	early
Chickpea	B-90	500 000	21 May	28 Apr.	28 Aug.	24 Aug.	short	early	early
Corn	TF2183	62 000	30 May	14 May	22 Oct.	16 Nov.	long	early	late
Dry pea	DS Admiral	864 000	16 May	14 Apr.	11 Aug.	29 July	short	early	early
Grain sorghum	DK28E	500 000	11 June	10 June	23 Oct.	17 Nov.	long	late	late
Lentil	Richlea	1.7 million	20 May	28 Apr.	22 Aug.	12 Aug.	short	early	early
Proso millet	Earlybird	3.7 million	11 June	09 June	02 Oct.	21 Sept.	short	late	late
Sunflower	63M91	69 000	17 June	10 June	21 Oct.	09 Nov.	long	late	late
Spring wheat	Amidon	3.2 million	21 May	14 Apr.	19 Aug.	29 July	short	early	early

research was conducted using four of the crops from Krupinsky et al. (2006) (canola, dry pea, sunflower, and spring wheat) and six crops that had not been previously evaluated.

The objective of this component of the research was to determine the influences of buckwheat, canola, chickpea, corn, dry pea, grain sorghum, lentil, proso millet, sunflower, and spring wheat previous crop and crop residues on relative seed and residue yield and PUE for the no-till production of these 10 crops grown in the northern Great Plains.

MATERIALS AND METHODS

Research was conducted on the Area IV Soil Conservation District/Agricultural Research Service Cooperative Research Farm located about 7 km southwest of Mandan, ND. Two sites (6.1 ha each) were chosen about 2 km apart on a Temvik–Wilton silt loam (fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls) soil. At Site 1, initial soil NO_3–N was 99 kg ha^{-1} to a depth of 1.5 m with 16 kg ha^{-1} $NaHCO_3$ extractable P to a depth of 0.15 m. At Site 2, initial soil NO_3–N was 142 kg ha^{-1} to a depth of 1.5 m with 30 kg ha^{-1} $NaHCO_3$ extractable P to a depth of 0.15 m. A 3-yr sunflower–spring wheat–spring wheat crop sequence preceded initiation of the research at both sites, beginning with sunflower. Sunflower was seeded using minimum-till techniques (one pass with an undercutter to apply and incorporate residual herbicide) while spring wheat was seeded using no-till techniques.

Research began in 2002 by seeding 10 crops (buckwheat, canola, chickpea, corn, dry pea, grain sorghum, lentil, proso millet, sunflower, and spring wheat) in adjacent strips to produce their respective crop residues. The following year, the same 10 crops were seeded perpendicular to the previous year, creating a 10-by-10 crop × crop residue matrix with 100 different crop sequences (Tanaka et al., 2002, 2005; Krupinsky et al., 2006). In 2003, a second site was initiated so that the crop sequences would be present for 2 yr, 2003 (Site 1) and 2004 (Site 2) (Table 1 and Fig. 1). Using this crop matrix technique as a research tool allows evaluation of multiple crop sequences in the same experiment under similar weather and soil conditions. Thus, each crop is seeded over the crop residue of all crops included in the matrix. Crops were arranged each year using a randomized-complete block experimental design with a strip-block treatment arrangement and four replicates. The smallest experimental unit was 9 by 9 m. All crops, except corn and sunflower, were seeded using a no-till drill (model 750, John Deere, Moline, IL)[1] with a 19-cm row spacing. At seeding, N fertilizer (ammonium nitrate, 78 kg N ha^{-1}) was banded between every other crop row in 38-cm spacing for all crops except dry pea, chickpea, and lentil. Phosphorus fertilizer was applied to all crops as triple superphosphate (11 kg P ha^{-1}) with the seed at planting. Dry pea and lentil seed were inoculated with *Rhizobium leguminosarium* while chickpea seed was inoculated with *Rhizobium ciceri* before seeding. For canola, 11 kg S ha^{-1} was applied as ammonium sulfate and N source adjusted to provide 78 kg N ha^{-1}. Seeding of corn and sunflower was accomplished with a no-till row-crop planter in 76-cm rows. Nitrogen and P fertilizer was applied with the John Deere model 750 drill just before planting corn and sunflower. Crop cultivar, viable seeds ha^{-1}, seeding date, harvest date, and crop category are shown in Table 1. Weed control for all crop sequences was accomplished using no-till techniques appropriate for each crop. Before, or shortly after seeding each crop, weed control was accomplished using nonselective herbicides for no-till. Crops such as sunflower,

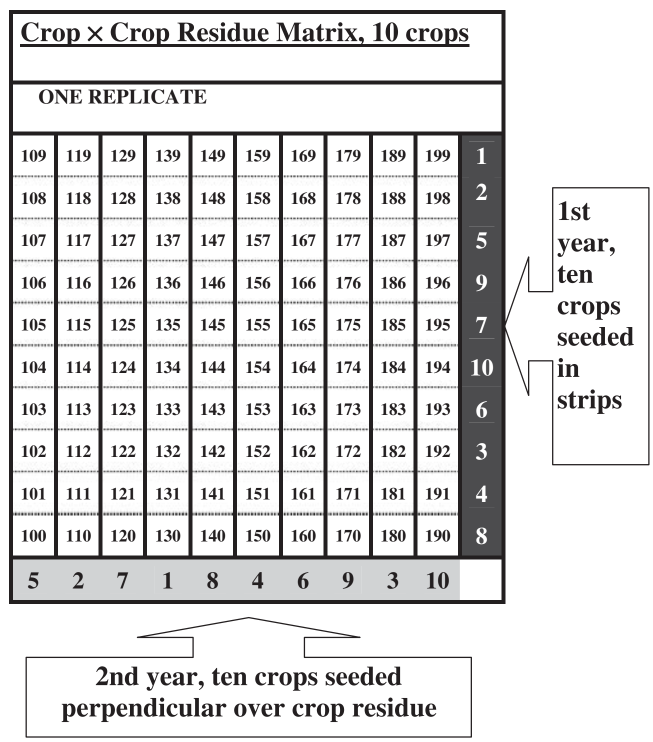

Fig. 1. A crop × crop residue matrix used to evaluate the influences of crop sequence on crop production. During the first year, 10 crops (numbered 1 through 10) were no-till seeded into a uniform crop residue. During the second year, the same 10 crops were no-till seeded perpendicular over the residue of the previous year's crops. Individual plot numbers are assigned for each experimental unit in the replication.

[1] Inclusion of branded product information is for the benefit of the reader and does not imply preference nor endorsement by the USDA-Agricultural Research Service.

buckwheat, and lentil have very limited postemergence broadleaf weed control, while proso millet had limited grassy weed control options. Buckwheat and proso millet compete with weeds, so weed control problems were minimal, while less competitive crops such as lentil, sunflower, chickpea, and in some cases, corn presented a more challenging weed control problem. Volunteer crop was not a weed control problem, except for buckwheat.

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, seed cleaned and weighed, and seed was subtracted from the total biomass to get residue production. Seed yield was measured using a plot combine to harvest 11.6 m^2. Previous research suggested the lowest crop seed and residue yields occurred when a crop was seeded on its own residue (Tanaka et al., 2005). We used actual seed and residue yield of the 10 crops seeded on their own residue as the denominator to divide all values of that crop grown on the remaining nine crop residues in calculating relative seed and residue yield. Hence, the crop seeded on its own residue has a relative value of 1.00. Precipitation-use efficiency, a measure of how well crop sequences use precipitation, was calculated by determining the quantity of precipitation that occurred from the harvest of one crop to the harvest of the following crop divided into the actual crop yield of each experimental unit [PUE = crop yield/precipitation (harvest to harvest)]. Precipitation received from harvest of one crop to the harvest of the following crop was crop-sequence dependent. Statistical analysis (F test) indicated a year (site) × treatment interaction, therefore, each year (site) was analyzed separately (statistical analyses for year × treatment not shown). Also, a crop × crop residue interaction was evident and each crop was analyzed separately. Year (site), and treatments (crop and crop residue) were considered fixed variables while the remainder (replicate and interaction terms with replicate) were random. Since we were interested in the synergisms or antagonisms that occur among crop residues preceding a particular crop, differences were determined on each crop by using PROC MIXED and LSD at the 0.05 probability level (Littell et al., 1996).

RESULTS AND DISCUSSION

Average residue production for 2002 before matrix crop production in 2003 (Site 1) was the greatest for corn, grain sorghum, and proso millet (Fig. 2). Chickpea, dry pea, lentil, sunflower, and spring wheat produced the least amount of residue in 2002. Grain sorghum and proso millet produced more crop residue than chickpea, buckwheat, canola, dry pea, and lentil in 2003 (Site 2). Soil water deficit and below-average growing season rainfall (Fig. 3) in 2003 may be the reason for reduced residue production, especially for some of the later harvested crops, such as corn (Merrill et al., 2007).

Growing Season Weather

Precipitation during the 2003 growing season was 86% of the long-term average of 28.9 cm (Fig. 3). May accounted for >50% of the 2003 growing season precipitation of 24.9 cm. Precipitation for June, July, and August was only 38% of the long-term average for these months (19.5 cm). May and June were 58% of the long-term average growing season precipitation in 2004.

Average monthly temperatures for the 2003 growing season were about average (Fig. 4). Only August had a

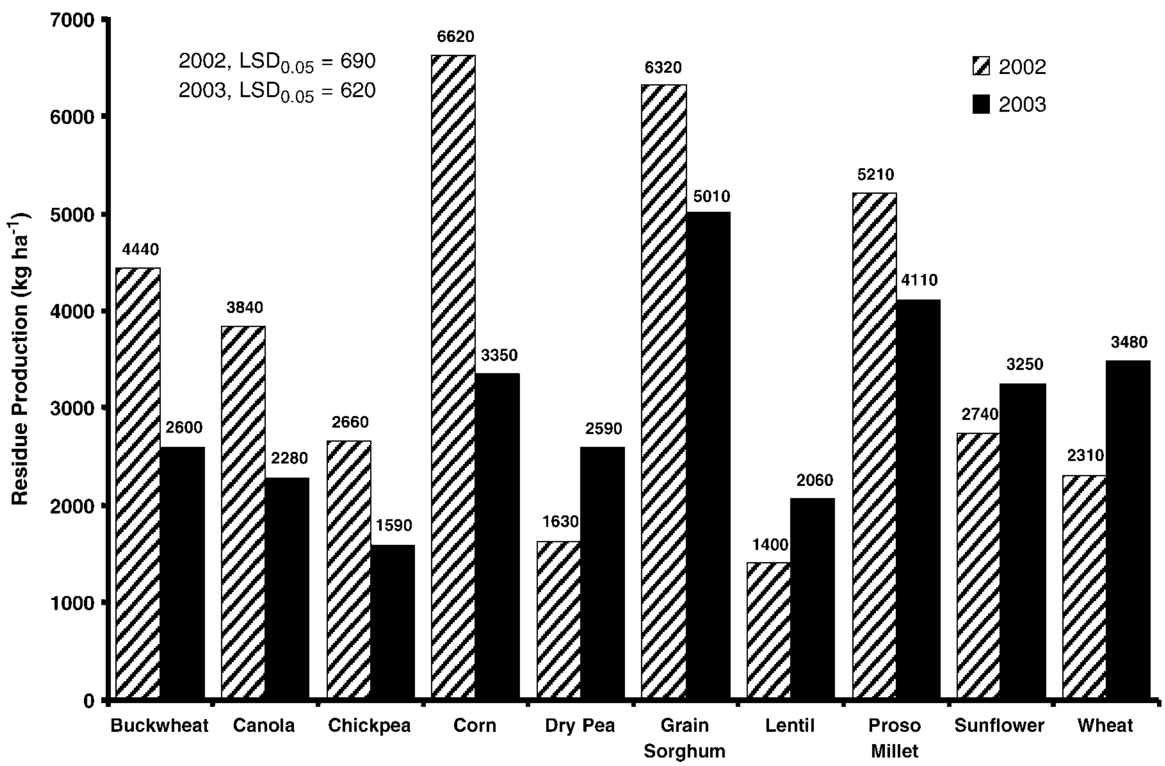

Fig. 2. Residue production in 2002 before matrix crop production in 2003 (Site 1) and residue production in 2003 before matrix crop production in 2004 (Site 2) at Mandan, ND.

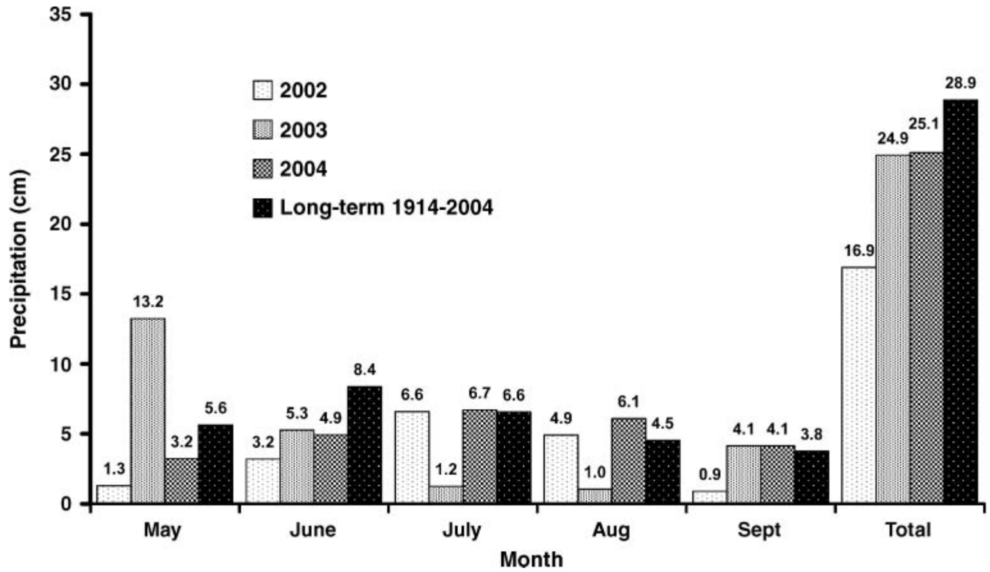

Fig. 3. Monthly growing season precipitation in 2002, 2003, 2004, and 1914 to 2004 at Mandan, ND.

mean temperature (23.1°C) that was greater than the long-term average temperature (20.4°C) for the month. For 2004, average monthly temperatures for the growing season were all below average except for September. The growing season mean temperature was 1.7°C below the long-term mean temperature. Growing degree units (using 0°C as a base) in 2004 for May through September were 2450 compared with the long-term average of 2700 (data not shown). The 2004 growing season was one of the five coolest growing seasons on record.

Relative Seed Yield

Comparative relative seed yield for 2003 (Site 1) and 2004 (Site 2) varied among previous crop residues, affirming that crop sequencing influences seed yield (Tables 2 and 3) and that crop diversity in agricultural systems mitigates production risks (Miller and Holmes, 2005). In 2003 (Site 1), pulse crop residues (chickpea, dry pea, and lentil) resulted in significantly greater relative seed yield (synergism) for six of the 10 crops (buckwheat, corn, dry pea, grain sorghum, proso millet, and sunflower) when compared with the crop seeded on its own residue. Only canola, chickpea, lentil, and spring wheat did not have significantly greater relative seed yield on pulse crop residue. Relative seed yield was equal to the greatest relative yield for five crops on buckwheat residue, six crops on canola residue, nine crops on chickpea residue, three crops on corn residue, eight crops on dry pea residue, five crops on grain sorghum residue, eight crops on lentil residue, seven crops on proso millet residue, two crops on sunflower residue, and eight crops on wheat residue. Specific crop and crop

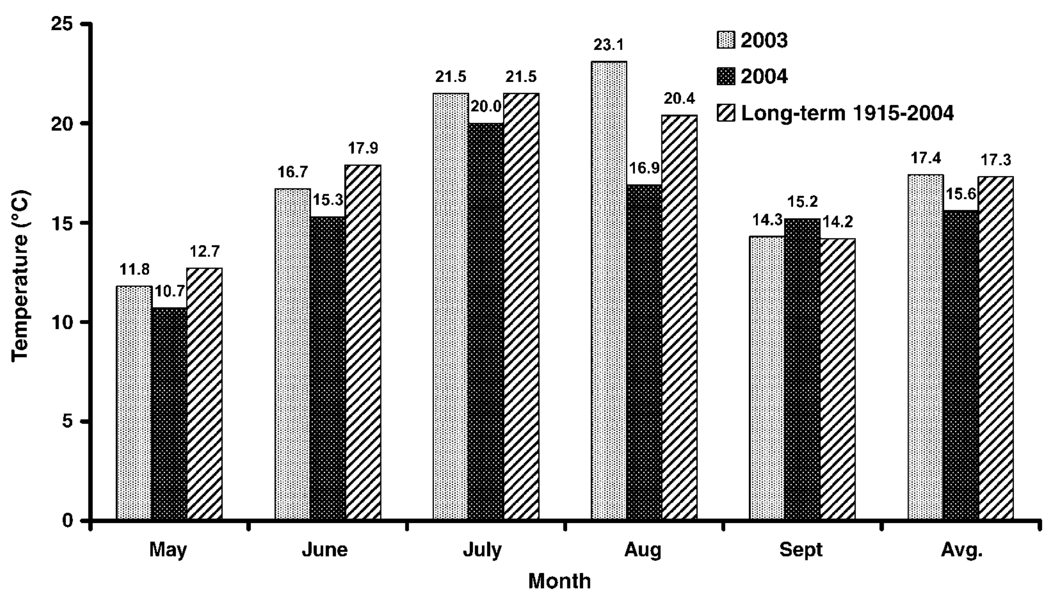

Fig. 4. Mean monthly growing season temperatures in 2003, 2004, and 1915–2004 at Mandan, ND.

Table 2. Relative seed yield of 10 crops grown in 2003 (Site 1) as influenced by previous crop residue at Mandan, ND.

	2003 crop									
Previous crop	Buckwheat	Canola	Chickpea	Corn	Dry pea	Grain sorghum	Lentil	Proso millet	Sunflower	Wheat
Buckwheat	1.00b†	1.27a	0.83d	1.42c	1.00bc	2.05bc	1.12abc	1.42abc	3.37ab	1.07a
Canola	1.05b	1.00bcd	0.95bcd	3.44ab	1.14bc	3.04ab	1.13abc	1.41abc	3.59a	1.05a
Chickpea	1.41ab	1.16ab	1.00abc	3.78a	1.38a	2.86ab	1.03bcd	1.53ab	2.31ab	1.02a
Corn	1.12b	1.05bc	0.93cd	1.00c	1.09bc	1.52bc	1.20abc	1.03bc	1.82ab	1.09a
Dry pea	1.90a	1.02bcd	0.97abc	3.70a	1.00bc	3.87a	1.20abc	1.66a	3.09ab	1.09a
Grain sorghum	1.01b	1.18ab	1.01abc	2.19abc	0.96c	1.00c	0.86cd	0.89c	2.84ab	1.01ab
Lentil	1.29ab	0.94bcd	1.03abc	3.36ab	1.38a	3.94a	1.00d	1.62a	3.74a	1.10a
Proso millet	1.32ab	1.16ab	1.09a	1.00c	1.23ab	0.95c	1.32a	1.00bc	2.67ab	1.02ab
Sunflower	0.93b	0.82bcd	0.81d	1.77bc	1.21ab	1.36bc	0.83d	1.33abc	1.00b	0.89b
Wheat	1.02b	1.04bc	1.08ab	2.20abc	1.19abc	2.94ab	1.28ab	1.13abc	3.54a	1.00ab
LSD (0.05)	0.65	0.20	0.14	1.84	0.24	1.69	0.26	0.54	2.43	0.65

† Means followed by different letters within a column are significantly different at $P \leq 0.05$ by least significant difference test.

residues can synergize relative crop yield and result in more sustainable cropping systems for the northern Great Plains. In most cases, a crop seeded on its own residue was antagonistic to relative seed yield. Miller et al. (2002) suggests that pulse crops have an associated N effect that is important for explaining crop sequence effects on seed yield in semiarid regions. Probably just as important, and one of the most limiting factors, is soil water. Miller et al. (2002) found postharvest soil water status differed among pulse crops for a loam soil in the following manner: dry pea > lentil > chickpea > wheat. By the following spring, differences in soil water status had disappeared because of ample winter snow and the superior snow trapping ability of wheat stubble compared with sparse broadleaf crop stubble. Merrill et al. (2007) recorded the greatest amount of soil water the year following dry pea and lentil among a group of 10 crops during years when winter precipitation was not average or above average. In their research, greater soil water after dry pea and lentil, along with their associated N effect, may be why these crops had greater relative seed yield. Relative seed yield was generally the lowest when a crop was seeded on its own residue or the previous crop was late-harvested, such as sunflower, grain sorghum, or corn. Perhaps this is because these crops are long-growing-season types (Table 1) that are generally high water users. Also, corn and grain sorghum generally produced considerable quantities of crop residue (Fig. 2), which the drill may not have been able to effectively seed through. This is in contrast to years of above-average precipitation, when late-harvested crops such as sunflower used excess soil water and created a more conducive crop environment (Krupinsky et al., 2006).

In 2004, the pattern of monthly precipitation for the growing season was opposite of the 2003 growing season precipitation (Fig. 3). Relative seed yield was equal to the greatest relative yield for two crops on buckwheat residue, five crops on canola residue, four crops on chickpea residue, three crops on corn residue, eight crops on dry pea residue, two crops on grain sorghum residue, six crops on lentil residue, six crops on proso millet residue, four crops on sunflower residue, and eight crops on spring wheat residue (Table 3). Lack of precipitation in May and June (Fig. 3) stressed crops where the previous crop was long season (corn, grain sorghum, and sunflower). The lowest relative seed yield for seven of the 10 crops (buckwheat, canola, corn, dry pea, lentil, proso millet, and spring wheat) occurred when grain sorghum was the previous crop (Table 3). Unusually cool temperatures in July and August (Fig. 4) caused poor pollination and seed set for grain sorghum (Table 3), and resulted in no seed yield. Grain sorghum is a crop that is marginally adapted to the northern Great Plains because of growing degree unit requirements. Also, late season crops such as sunflower and corn, which were planted in rows, were not able to compete with volunteer buckwheat from the previous year and had low seed yield. Volunteer buckwheat was part of the crop sequence impacts on sunflower and corn that were produced with no tillage. Even under tillage management, cultivation with conventional equipment would not have been an option because of the crop height when volunteer plants became a problem late in the growing season.

Table 3. Relative seed yield of 10 crops grown in 2004 (Site 2) as influenced by previous crop residue at Mandan, ND.

	2004 crop									
Previous crop	Buckwheat	Canola	Chickpea	Corn	Dry pea	Grain sorghum	Lentil	Proso millet	Sunflower	Wheat
Buckwheat	1.00bcd†	0.89abc	3.18ab	0.65e	1.13bc	–	1.19bcd	0.99bcd	0.08b	0.77bcd
Canola	1.12abc	1.00abc	3.35ab	0.96de	1.00c	–	1.56bc	1.11bc	0.97a	0.79abcd
Chickpea	0.89cd	0.97abc	1.00b	1.46abcd	0.83c	–	0.83d	1.11bc	1.50a	0.86abcd
Corn	0.98bcd	0.94abc	2.64ab	1.00cde	1.07c	–	1.19bcd	0.91d	1.17a	0.63d
Dry pea	1.33a	1.29ab	3.50a	1.61ab	1.00c	–	1.73ab	1.34a	1.61a	1.03a
Grain sorghum	0.77d	0.40c	2.19ab	1.10bcde	0.91c	–	1.08cd	0.94cd	1.00a	0.71cd
Lentil	1.00bcd	1.34a	1.50ab	1.49abcd	1.02c	–	1.00cd	1.17ab	0.95a	0.95abc
Proso millet	0.88cd	0.85abc	2.97ab	1.53abc	1.74a	–	1.49bc	1.00bcd	1.54a	0.84abcd
Sunflower	0.98bcd	0.66bc	2.14ab	1.04cde	1.28abc	–	1.38bcd	0.95cd	1.00a	0.81abcd
Wheat	1.20ab	0.83abc	3.32ab	1.64a	1.58ab	–	2.23a	1.12bc	1.41a	1.00ab
LSD (0.05)	0.29	0.64	2.35	0.54	0.50	–	0.60	0.20	0.71	0.25

† Means followed by different letters within a column are significantly different at $P \leq 0.05$ by least significant difference test.

Table 4. Relative residue yield of 10 crops grown in 2003 (Site 1) as influenced by previous crop residue at Mandan, ND.

	2003 crop									
Previous crop	Buckwheat	Canola	Chickpea	Corn	Dry pea	Grain sorghum	Lentil	Proso millet	Sunflower	Wheat
Buckwheat	1.00abc†	1.11ab	0.93de	1.14c	1.03a	1.41bc	1.01ab	1.31abc	1.91ab	1.09bcd
Canola	0.99abc	1.00ab	0.93de	1.59a	1.07a	1.74ab	1.05a	1.46a	1.50bcd	1.26abcd
Chickpea	1.15ab	1.06ab	1.00bcde	1.48ab	1.09a	1.59abc	0.97ab	1.47a	1.01cd	1.31abc
Corn	0.95bc	1.07ab	1.15abc	1.00c	1.00ab	1.00d	0.82ab	1.17abc	1.57abcd	1.36ab
Dry pea	1.17a	1.12ab	1.28a	1.55a	1.00ab	1.82a	1.00ab	1.35abc	1.61abcd	1.43a
Grain sorghum	0.87c	1.20ab	1.16ab	1.12c	0.80b	1.00d	0.94ab	0.95c	1.72abc	1.12abcd
Lentil	0.97abc	0.92b	1.10abcd	1.56a	0.94b	1.40c	1.00ab	1.55a	2.24a	1.27abcd
Proso millet	0.89c	0.94b	1.09abcd	0.90c	0.86b	1.38cd	0.95ab	1.00bc	1.55abcd	1.29abcd
Sunflower	0.91c	1.07ab	0.85e	0.94c	0.96b	1.29cd	0.73b	1.37ab	1.00d	0.98d
Wheat	1.12ab	1.27a	1.13abcd	1.17bc	0.95ab	1.40bc	1.11a	1.18abc	1.93ab	1.00cd
LSD (0.05)	0.20	0.30	0.22	0.33	0.23	0.38	0.31	0.40	0.71	0.32

† Means followed by different letters within a column are significantly different at $P \leq 0.05$ by least significant difference test.

Relative Residue Yield

Residue production is important for soil erosion control, soil water conservation, and efficient use of soil water (Miller and Holmes, 2005). Relative residue yield for 2003 was equal to the greatest residue yield for six crops on buckwheat residue, eight crops on canola residue, eight crops on chickpea residue, seven crops on corn residue, all crops on dry pea residue, five crops on grain sorghum residue, seven crops on lentil residue, four crops on proso millet residue, two crops on sunflower residue, and seven crops on spring wheat residue (Table 4). Crops that produced the greatest relative residue yield were grown when previous crops had an early harvest time (Table 1). Harvesting early in the growing season allowed a wider window of opportunity to store soil water for the next crop, and crops harvested early do not deplete as much soil water as sunflower (Merrill et al., 2007). The greater availability of soil water following a crop harvested early, along with above-average precipitation in May, resulted in greater relative residue yield. Low relative residue yield for all crops occurred when the previous crops were grain sorghum, proso millet, or sunflower.

Previous crop did not influence relative residue yield for dry pea and grain sorghum in 2004 (Table 5). Relative residue in 2004 for the remaining crops was equal to the greatest residue yield for four crops on buckwheat residue, six crops on canola residue, four crops on chickpea residue, five crops on corn residue, eight crops on dry pea residue, four crops on grain sorghum residue, five crops on lentil residue, six crops on proso millet residue, four crops on sunflower residue, and seven crops on spring wheat residue. Soil water amounts in mid-April were greatest for dry pea and spring wheat residues (Merrill et al., 2007). Dry pea and spring wheat residues may have suppressed evaporation and modified the microclimate to promote early vegetative crop growth (Miller et al., 2003b). Lowest relative residue yield for eight of the 10 crops occurred when the previous crops were chickpea or sunflower. It is understandable that when the previous crop was sunflower, relative residue yields would be low because of reduced soil water amounts, but no explanation can be given for chickpea, which had soil water amounts similar to corn and buckwheat (Merrill et al., 2007).

Precipitation-Use Efficiency

We used PUE as a system integrator to evaluate the interaction of the previous crop and crop residue on how well the crop sequence uses precipitation for seed yield. In 2003, the overall means for each crop suggest that spring wheat and chickpea use precipitation effectively on all crop residues for seed production, whereas crops such as buckwheat, sunflower, or corn were not able to effectively use the precipitation for seed production (Table 6). Precipitation patterns in 2003 (Fig. 3) favored early-season crops like spring wheat and chickpea, while it was detrimental to late-season crops like buckwheat, sunflower, and corn. This was true for the early matur-

Table 5. Relative residue yield of 10 crops grown in 2004 (Site 2) as influenced by previous crop residue at Mandan, ND.

	2004 crop									
Previous crop	Buckwheat	Canola	Chickpea	Corn	Dry pea	Grain sorghum	Lentil	Proso millet	Sunflower	Wheat
Buckwheat	1.00ab†	0.95c	1.80ab	1.09bc	1.08a	0.97a	0.89b	0.82c	2.85a	0.95ab
Canola	0.91abc	1.00c	1.85ab	1.35ab	1.04a	1.15a	1.04b	1.08ab	1.68abc	0.90ab
Chickpea	0.82c	1.01bc	1.00b	1.36ab	0.92a	1.07a	0.92b	0.98abc	1.74abc	0.95ab
Corn	0.90abc	1.07bc	1.81ab	1.00c	1.08a	1.02a	1.10ab	0.91bc	1.55abc	0.95ab
Dry pea	1.01ab	1.50a	2.22a	1.33ab	1.00a	1.21a	1.24ab	1.10ab	1.79abc	1.21a
Grain sorghum	0.96abc	0.94c	1.15b	1.27abc	0.96a	1.00a	0.84b	0.93abc	1.91abc	0.71b
Lentil	0.88abc	1.04c	1.45ab	1.17bc	0.93a	0.89a	1.00b	1.00abc	1.68abc	1.02ab
Proso millet	0.84bc	1.38ab	1.81ab	1.52a	1.08a	1.05a	1.09ab	1.00abc	1.34bc	1.04ab
Sunflower	0.85bc	0.87c	1.58ab	1.27abc	1.16a	1.23a	1.45a	0.88bc	1.00c	0.99ab
Wheat	1.04a	0.95c	1.95ab	1.50a	1.14a	1.03a	1.48a	1.15a	2.43ab	1.00ab
LSD (0.05)	0.18	0.33	1.02	0.32	NS‡	NS	0.41	0.23	1.34	0.35

† Means followed by different letters within a column are significantly different at $P \leq 0.05$ by least significant difference test.
‡ NS = no significance at $P < 0.05$.

Table 6. Precipitation-use efficiency for seed yield of 10 crops grown in 2003 (Site 1) as influenced by previous crop residue at Mandan, ND.

	2003 crop									
Previous crop	Buckwheat	Canola	Chickpea	Corn	Dry pea	Grain sorghum	Lentil	Proso millet	Sunflower	Wheat
	kg ha^{-1} cm^{-1}									
Buckwheat	8.0a†	38.5a	52.5cd	15.2c	43.3cd	33.5bcde	36.9ab	47.3a	28.5a	67.6bc
Canola	7.6a	30.4bc	60.1bc	34.7a	51.2abc	43.0abc	37.9ab	47.4a	29.9a	66.1bcd
Chickpea	8.8a	31.1bc	56.7bcd	32.9a	54.2ab	45.4ab	30.7b	46.6a	20.0ab	58.0de
Corn	8.3a	35.0ab	65.1ab	16.4bc	53.5ab	22.7e	44.3a	38.9a	23.3ab	76.6a
Dry pea	10.1a	25.5c	50.7d	33.7a	37.2d	46.7ab	32.4b	47.9a	21.6ab	57.2e
Grain sorghum	8.1a	39.8a	69.9a	27.8ab	46.7bcd	28.8cde	30.9b	38.7a	23.6ab	71.2ab
Lentil	9.3a	25.5c	57.9bcd	32.3a	53.7ab	52.0a	30.2b	49.4a	29.0a	62.8cde
Proso millet	9.4a	35.7ab	70.2a	15.8bc	53.6ab	18.7e	44.5a	38.3a	24.1ab	66.0bcd
Sunflower	7.4a	27.6c	56.7cd	19.8bc	58.8a	27.0de	30.7b	48.1a	12.7b	62.2cde
Wheat	7.2a	28.1c	60.6bc	23.0abc	46.6bcd	42.7abcd	37.6ab	36.4a	27.3a	56.5e
Crop overall mean	8.4	31.7	60.0	25.2	49.9	39.9	35.6	43.9	24.0	66.3
LSD (0.05)	NS‡	6.1	8.4	12.3	10.1	15.9	8.6	NS	14.4	8.1

† Means followed by different letters within a column are significantly different at $P \leq 0.05$ by least significant difference test.
‡ NS = no significance at $P < 0.05$.

ing chickpea cultivar we used, but late-maturing cultivars may not have the same response (N.R. Riveland, 2006, personal communication). Previous crop influenced PUE for eight of the 10 crops; only buckwheat and proso millet were not influenced by previous crop (Table 6). No single previous crop consistently resulted in higher PUE; however, eight of the 10 crops with the lowest PUE occurred where the previous crop was dry pea or sunflower.

In 2004, precipitation for the growing season was distributed differently than in 2003, and PUE overall means fluctuated considerably for seven of the 10 crops (Tables 6 and 7). Only dry pea, sunflower, and spring wheat remained somewhat constant for both years (2003 and 2004), suggesting these crops have mechanisms for consistent PUE and were not dependent on growing season precipitation distribution. The mechanisms for each crop are different; for sunflower, a possible explanation may be its ability to use soil water from deeper in the soil profile than wheat (Merrill et al., 2002), which provides a buffer against short-term dry periods. A plausible explanation for spring wheat and dry pea may be their early seeded, short-season growth habits (Table 1) that use the cool spring weather as a buffer against dry periods. Dry pea, sunflower, or spring wheat would need to be strongly considered to develop sustainable dynamic cropping systems for the northern Great Plains. For 2004, PUE was the greatest for six out of 10 crops when the previous crop was dry pea (Table 7). Lowest PUE for five out of 10 crops occurred when the previous crop was chickpea.

CONCLUSIONS

Crop production occurs in a systems environment that is constantly changing. Cropping systems that are not flexible to change will be unsustainable. Crop producers can initiate more sustainable cropping systems (dynamic cropping systems) by considering a more optimal sequencing of crops that will take advantage of inherent internal resources (synergisms, nutrient cycling, and soil water) while also capitalizing on external resources such as weather, markets, government programs, and new technology. Our research suggests crop sequence does influence relative seed and residue yield and PUE. Seeding crops on their own residue generally resulted in the lowest seed and residue relative yields. For sustainable dynamic cropping systems in the northern Great Plains, dry pea, sunflower, or spring wheat need to be included since they are consistent in their PUE, when compared with the remaining seven crops, no matter what the growing season precipitation distribution may be. During extreme dry periods, caution should be taken in crop selection when growing crops after sunflower.

Table 7. Precipitation-use efficiency for seed yield of 10 crops grown in 2004 (Site 2) as influenced by previous crop residue at Mandan, ND.

	2004 crop									
Previous crop	Buckwheat	Canola	Chickpea	Corn	Dry pea	Grain sorghum	Lentil	Proso millet	Sunflower	Wheat
	kg ha^{-1} cm^{-1}									
Buckwheat	48.8ab†	16.9ab	33.1ab	43.8d	46.5bc	–	24.3b	82.7ab	1.5c	70.9ab
Canola	46.1ab	14.3abc	34.2ab	57.6cd	33.0c	–	22.9bc	79.7b	16.2ab	60.2ab
Chickpea	37.1b	11.7abc	23.5b	86.1abc	32.4c	–	13.7c	79.2b	25.5ab	66.8ab
Corn	47.8ab	17.4a	29.4ab	69.1bcd	48.6abc	–	21.1bc	75.8b	22.7ab	57.8b
Dry pea	54.8a	17.1a	40.0a	91.5ab	38.4bc	–	26.6ab	95.2a	27.0ab	77.4a
Grain sorghum	37.4ab	8.1c	24.6b	79.4abc	42.9bc	–	20.7bc	78.9b	20.3ab	63.0ab
Lentil	41.8ab	14.3abc	30.8ab	87.8ab	41.6bc	–	20.3bc	83.8ab	16.5ab	71.5ab
Proso millet	41.7ab	11.1abc	36.3ab	101.2a	69.4a	–	30.5ab	82.2ab	28.4a	72.7ab
Sunflower	46.8ab	13.4abc	36.2ab	68.4bcd	59.2ab	–	29.2ab	78.1b	14.8b	70.7ab
Wheat	49.7ab	10.5bc	35.4ab	94.3ab	57.0ab	–	36.8a	79.5b	23.5ab	75.7ab
Crop overall mean	45.2	13.5	32.4	77.9	46.9	–	24.6	81.5	19.6	68.7
LSD (0.05)	13.1	6.5	13.3	30.0	21.6	–	10.3	14.4	12.5	19.5

† Means followed by different letters within a column are significantly different at $P \leq 0.05$ by least significant difference test.

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