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Sequence effects among crops on alluvial-derived soil compared with those on glacial till-derived soil in the northern Great Plains, USA ☆

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ABSTRACT

The dynamic cropping systems concept proposes a long-term strategy of crop sequencing to achieve production, economic and soil care goals through sound ecological management. This requires that agriculturalists have comprehensive information about how crop species affect following years' crops. Little research exists about how differences in soil type and properties change crop sequence effects. Sandy loam, alluvial-derived soil in south central North Dakota, USA (400 mm/yr precipitation) was the site of a crop sequence experiment in which four species – maize (*Zea mays* L.), dry pea (*Pisum sativum* L.), spring wheat (*Triticum aestivum* L.), and soybean (*Glycine max* (L.) Merr.) – were grown in strips one year and in perpendicular strips the following, with spring wheat planted a third year. No-till management was used with three replications in land and two in time. Results were compared with those from two 10 × 10 sequence experiments on silt loam, glacial till-derived soil. Soil water depletion (SWD) and root growth were deeper in sandy loam soil than in silt loam. During a year of above average precipitation, prior year soybean enhanced spring wheat yield on sandy loam soil by 14% above average, but prior year spring wheat reduced it by 14%. During a year of deficient precipitation, prior crop effects on spring wheat yield ranked in order of expected springtime soil water storage: dry pea, 11%; spring wheat, 4%; soybean, −5%; maize, −10%. Prior crops' SWD largely determined spring soil water, with maize having greatest depletion. Excluding results from a year of low precipitation, prior crops' effects on spring wheat yield on sandy loam soil were similar to results found at two sequence experiments on silt loam soil: dry pea – generally positive effect (N-production, water conservation); spring wheat – negative (disease); soybean – positive (N-production); maize – generally negative (heavier water use). Same year comparison of three crops (nine sequences) on sandy loam soil vs. silt loam showed average dry pea and spring wheat yields being equivalent ($P < 0.10$). However, average maize yield was 37% lower on silt loam, with maize-after-maize yielding 54% less. The site with sandy loam land had topsoil with lower soil quality indicators (organic C, water holding capacity) than silt loam. However, no-till management and previous grass rendered productivity of the soils equivalent, and superior capacity of the sandy loam site subsoil to conduct water and be conducive to root growth lessened negative, water-generated crop sequence effects.

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1. Introduction

To conserve energy and expand production without expanding land base, agriculture must reestablish balanced ecological functioning. Farmers will have to be paid for re-establishment and increase of ecosystem services on agricultural lands through new economic and governmental policies (Miller, 2008). Industrialized agriculture is characterized by simplification, concentration, and massive substitution of manufactured inputs for natural ones. Thus it needs to be re-diversified, and current wastes of one mode of production used as inputs for another, thereby closing open loops, especially the widespread decoupling of crop and animal agriculture (Kirschenmann, 2007).

Abbreviations: ARS, Agricultural Research Service [of the US Department of Agriculture]; ASL, Alternate Soil Location; CSD, Cool season [species] dominant; LTA, Long-term [precipitation] average; NGPRL, Northern Great Plains Research Laboratory [of the USDA–ARS]; NOAA, National Oceanic and Atmospheric Administration [of the US Department of Interior]; RLD, Root length density; SMAF, Soil Management Assessment Framework; SWD, Soil water depletion; USDA, US Department of Agriculture; WSD, Warm season [species] dominant.

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To help meet challenges of population increase, globalization, energy usage, and climate change in a manner that advances reestablishment of an ecological balance in agriculture, application of the dynamic cropping systems concept has been proposed (Tanaka et al., 2002; Hanson et al., 2007). A dynamic cropping system approach is defined as a long-term strategy of crop sequences for economically and environmentally sustainable soil-crop management that is implemented by agriculturalists through annual decisions that respond to changing environmental, economic, and agronomic conditions (Tanaka et al., 2002). Monoculture and fixed crop rotations are replaced by diverse cropping systems, and individual crops are inserted annually to meet changing circumstances and overall needs of the agroecosystem.

To understand how to manage a dynamic cropping system, knowledge of how one crop species influences the following year's crop is essential. Several large-scale crop sequence experiments have been conducted at the US Dept. of Agriculture, Agricultural Research Service (USDA–ARS), Northern Great Plains Research Laboratory (NGPRL) at Mandan, North Dakota, USA. The experiments utilized a crop matrix design, in which 10 crop species were seeded in strips the first year, and the same 10 species were seeded perpendicular to the original strips the following year, thereby creating 100 crop sequences. Spring wheat (*Triticum aestivum* L.) was seeded over the crop matrices a third year to examine sequence effects on this regionally dominant species. No-tillage management was used for these studies. Sequence effects among ten predominantly cool-season species were examined beginning in 1998 (Krupinsky et al., 2006). Another 10×10 experiment was started in 2002 featuring four of the same species present in the first, plus six predominantly warm-seasoned species (Tanaka et al., 2007).

The statistical design of experiments enabled crop sequence interactions to be more clearly distinguished from complex interactions of other factors at field plot scale. For example, results indicated generally positive effects of pulse crops (i.e., dry pea, *Pisum sativum* L.; lentil, *Lens culinaris* Medik) and often negative effects of higher soil water-using crops (i.e., sunflower, *Helianthus annuus* L.; maize, *Zea mays* L.) (Liebig et al., 2008). However, as pointed out in Merrill et al. (2007a), negative crop sequence effects observed at field plot scale, such as sunflower leaving less soil water for the next crop (up to 10 cm less than dry pea), can have positive effects at a larger spatial scale, such as less water accumulating in lower landscape positions, which can increase the amount of machine-trafficable farmland in early spring. Research addressing multiscalar effects of crop sequence must consider that soil characteristics vary across landscapes.

While information on crop sequence effects *per se* is currently limited, research on influences of soil type on sequence effects is even more so. In Saskatchewan, Miller et al. (2003) reported that yield-enhancing effects of dry pea on spring wheat were greater on clay soil compared with silt loam; the clay soil held more water and had greater amounts of symbiotic nitrogen. In contrast, Miller and Holmes (2005) did not report any general effects of soil type on yield-enhancing influences of dry pea on various small grain species in Montana.

Previous crop sequence studies (Krupinsky et al., 2006; Tanaka et al., 2007) have been conducted on silt loam, glacial till-derived soil. In order to determine the influence of soil type and characteristics on crop sequence effects, we established a new study on a sandy loam, alluvial-derived site using four principal crop species and the same agronomic management, including no-tillage, as used in the previous experiments. The purposes of this report are to detail results of this new 4×4 crop sequence experiment on sandy loam soil, and to compare observations with previous studies conducted on silt loam soil, assessing the role of differences in soil characteristics on the results.

2. Research methods

2.1. Crop sequence experiments and soil/land sites

Table 1 displays complete comparative information about two previously published 10×10 crop sequence experiments as well on the newer 4×4 experiment that is the focus of this paper. The common pattern by which the experiments were conducted featured (a) growth of spring wheat or other small grain crop in the year before start of the experiments; (b) seeding of either 10 (or 4) crop species in 9-m-wide strips one year – the *residue crops*; (c) seeding of the same suite of crop species in 9-m-wide strips perpendicular to the first set during the second year of the experiment – the *matrix crops* – thereby creating a crop matrix whereby the results of 100 (or 16) different crop sequences could be observed; (d) seeding of spring wheat over the crop matrix in the third year of the experiment – the spring wheat *follow-on crop*. Each experiment was replicated once in time, the second series starting one year after the first.

The 4×4 experiment was conducted on alluvial-derived sandy loam soils at a site (designated here as the Alternative Soil Location – ASL), located about 1 km from USDA–ARS Northern Great Plains Research Laboratory (NGPRL) headquarters. Soils at the ASL site are classified (NRCS, 2009) as Lihen-Parshall complex (sandy, mixed, frigid Entic Haplustolls and coarse-loamy, mixed, superactive, frigid Pachic Haplustolls). The four crop species grown in this experiment were dry pea, spring wheat, soybean, and maize.

The first of the two published 10×10 experiments (Krupinsky et al., 2006), labeled here as cool season dominant (CSD) because of the predominance of such species, was carried out on a glacial till-derived silt loam site located at Area IV Soil Conservation Districts Cooperative Research Farm (46°46′N, 100°56′W), which is located approximately 5 km from NGPRL headquarters. Soil at the site is classified (NRCS, 2009) as Temvik-Wilton silt loams (fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls). The second 10×10 experiment (Tanaka et al., 2007) was carried out at sites 1–2 km from the first at the Research Farm on soil of the same type and classification as the first, and is labeled here as warm season dominant (WSD).

A comprehensive summary of properties and characteristics of the two soil/land sites is given in Table 2. Organic C and available water capacity of topsoil was higher on the silt loam soil. The silt loam site was relatively open and had been in crop production for decades before start of the experiments. In contrast, the sandy loam site had tree shelterbelts or trees on three sides and had been in perennial grass for several decades before seeding of a preliminary spring wheat crop in 2001. Both sites consisted of gently rolling land with slopes no greater than approximately 2–3°.

The climate pattern of the area is continental, semi-arid to subhumid, mean annual temperature is 4 °C, and daily averages range from 21 °C in summer to −11 °C in winter. Long term average (LTA) precipitation is 412 mm per year, and greatest monthly precipitation generally occurs in June (84 mm average).

2.2. Crop sequence experiment at ASL sandy loam site

The 4×4 ASL experiment closely followed the design and agronomic management of the two earlier 10×10 experiments, but had three replications vs. four for the latter experiments (Table 1). With the exception of soybean in the CSD experiment, crop cultivars used in the ASL experiment were the same as those used in the two others (Table 3). Spring wheat and winter wheat were seeded in the two years, 2001 and 2002, respectively, prior to the first residue crop year, 2003. Spring wheat was seeded during 2003 in those blocks that were seeded to residue crops during 2004.

Table 1
Comparison of crop sequence experiments.

Crop sequence experiment	ASL alternative soil location	WSD warm season dominant	CSD cool season dominant
Crop matrix size	4 × 4	10 × 10	10 × 10
Soil type	*Sandy loam*, alluvial-derived	*Silt loam*, glacial till-derived	*Silt loam*, glacial till-derived
Location of experiment	1 km south of NGPRL[a] headquarters	Research Farm[b] 6–7 km SW of headquarters	Research Farm 5 km SW of headquarters
Crops prior to residue crops and years	Winter wheat, 2002; spring wheat, 2003	Spring wheat, 2001 and 2002	Barley, 1997; winter wheat, 1998
Residue crop years	2003, 2004	2002, 2003	1998, 1999
Matrix crop years	2004, 2005	2003, 2004	1999, 2000
Spring wheat *follow-on* crop years	2005, 2006	2004, 2005	2000, 2001
Common crops	Dry pea	Dry pea	Dry pea
	Maize	Maize	–
	Spring wheat	Spring wheat	Spring wheat
	Soybean	–	Soybean
Agronomic management	No-tillage	No-tillage	No-tillage
Block (replication) number	3	4	4
Block, subplot size (m)	36.6, 9.1	91.4, 9.1	91.4, 9.1
Average separation distance of blocks, midpoint-to-midpoint (m)	118	125	1998–2000: 118 1999–2001: 125
Where published	This paper	Tanaka et al. (2007)	Krupinsky et al. (2006)

[a] US Dept. Agriculture, Agricultural Research Service (USDA–ARS), Northern Great Plains Research Laboratory (NGPRL), located near southern boundary of city of Mandan, North Dakota, USA.
[b] Area IV Soil Conservation Districts Cooperative Research Farm, operated in cooperation with USDA–ARS.

Table 2
Properties and conditions of two soil/land sites at which crop sequence experiments were conducted.

Property/condition	Alluvial-derived soil/land site	Glacial till-derived soil/land site
Texture	Sandy loam	Loam/silt loam
Sand[a], g kg^{-1}	640	260
Silt, g kg^{-1}	220	480
Clay, g kg^{-1}	140	260
Total organic carbon, g kg^{-1}	11.3	19.2
Available water capacity, cm^3 cm^{-3}	0.15	0.22
Profile structure	Alluvial-derived material throughout	Aeolian-derived upper zone over glacial-till subsoil
Management history	Approx. 40 years in grass before 2000	In crop production for approx. 90 yr
Shelterbelt presence	Tree shelterbelts on both sides	No shelterbelts

[a] Soil property values refer to 0–20 cm depth.

Table 3
Agronomic characteristics of crop species grown at the ASL crop sequence experiment, with listing of crop cultivars for ASL and earlier WSD and CSD crop sequence experiments.

Crop, common	Crop, scientific	ASL experiment			Crop sequence experiment		
		Avg. seeding date	Avg. harvest date	Avg. season length (d)	ASL Crop cultivar	WSD	CSD
Dry pea	*Pisum sativum* L.	April 28	August 8	102	Profi and DS Admiral	DS Admiral	Profi
Spring wheat	*Triticum aestivum* L.	May 1	August 23	114	Amidon	Amidon	Amidon
Soybean	*Glycine max* (L.) Merr.	June 4	October 6	124	TF6042RR[a,b] & TF6052RR	–	Jim
Maize	*Zea mays* L.	May 19	November 3	168	TF2183	TF2183	–

[a] Refers to Roundup Ready® (glyphosate resistant) proprietary genetic modification characteristic of Monsanto Co.
[b] Reference to product or trade names is for the benefit of the reader and should not be interpreted as implying any endorsement, preference, or guarantee on the part of the USDA–Agricultural Research Service.

In all of the experiments, crop species strips were randomized each year. No-till management included pre-seeding application of broad-spectrum herbicide glyphosate (N-[phosphonyl-methyl] glycine), with additional use of post-emergent herbicides. Dry pea and spring wheat were seeded with a no-till drill (John Deere model 750) in 19 cm rows. Seeding of maize and sunflower was accomplished with a no-till row-crop seeder in 75 cm rows. Granular inorganic fertilizer was applied through the seeder implement at rates of 78 kg N ha^{-1} and 11 kg P ha^{-1}. Dry pea and soybean did not receive N fertilizer but did receive *Rhizobium* inoculant at seeding.

Seed yield was determined at maturity from 11.6 m^2 areas with a research combine. Maize forage yield was determined at the end of August from 2.3 m^2 areas. Weed biomass was determined by hand clipping 0.6 m^2 areas in maize plots in mid-August, 2005.

A set of four blocks of the WSD and CSD experiments used for a replication in time were placed in a square pattern. All six blocks of the ASL experiment (two replications in time, three in land) were arranged in a north–south linear pattern, with blocks belonging to the two time replications interspersed. Wildlife depredation was prevalent in 2003, thus, in spring 2004, the ASL site was enclosed in an electrified fence with wire mesh in the lower portion designed to exclude both white-tailed deer (*Odocoileus virginianus*) and smaller mammalian species.

Almost all details of agronomic management of the CSD (Krupinsky et al., 2006) and WSD (Tanaka et al., 2007) experiments were identical to those outlined here for the ASL experiment, including fertilization, herbicidal weed management, seeding equipment and rates, and harvesting techniques. The exception was that

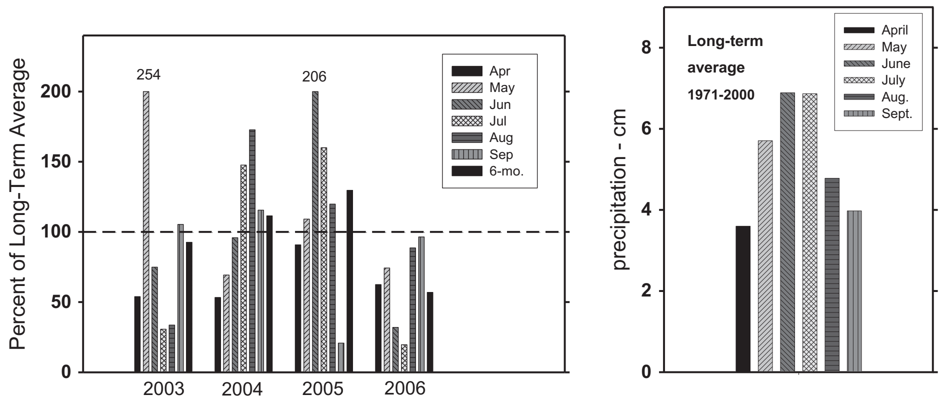


Fig. 1. Precipitation at the location of the ASL (sandy loam site) crop sequence experiment.

legume crops in the CSD experiment received N-fertilization while none was given to these crops in the other two experiments.

2.3. Soil properties, precipitation, water use, and root growth measurements

Soil samples were collected manually with a 7.6 cm diameter probe in mid-June 2005 in four increments of 0–5, 5–10, 10–20, and 20–30 cm depth. Samples were air-dried and passed through a 2 mm sieve. Soil texture was determined by hydrometer technique (Day, 1965). Organic carbon was determined by dry combustion with assumption of negligible carbonates. Available soil water, defined as that between −1.5 and −0.01 MPa matric potential, was calculated from textural parameters, organic matter percentage, and bulk density according to Gupta and Larson (1979).

Precipitation was measured with tipping bucket rainguages connected to dataloggers. Rainguage measurements were made at the ASL site during 2005. Regression of individual storms at the ASL site on storms at a NOAA-supervised site 1 km to the north at NGPRL headquarters revealed that seasonal precipitation at the tree shelterbelt-protected ASL site was about 7% lower than at the less tree-protected NOAA site. Precipitation information for the ASL site (Fig. 1) was prepared from the NOAA long-term record adjusted for differences with the ASL site. Precipitation data for WSD and CSD experiments came from raingauges near the sites.

Soil water content measurements were taken with a neutron moisture meter (CPN International Inc., model DR503) in plots in which spring wheat had been grown during the previous year. Readings were taken weekly or biweekly from April through October to a depth of 2.1 m at 0.3-m intervals in steel access tubes installed in the center of each plot.

Soil samples for root growth analyses were collected at early reproductive stages depending upon species. Samples were taken to a depth of 1.2 m with a tractor-mounted hydraulic 8-cm diameter soil probe in depth increments of 0.15 m. Root material was separated from soil through use of hydropneumatic elutriator apparatus (Smucker et al., 1982). After cleaning of samples by handpicking, root length was determined manually by the method of Newman (1966). Root material was placed in a shallow depth of water spread over a glass tray, which was placed on an overhead projector, and measurements were taken from images projected on a screen.

2.4. Comparison of results among crop sequence experiments

A direct comparison was made in 2004 between yields of matrix crops at the ASL (sandy loam) and the WSD (silt loam) experiments. All three experiments were compared for crop sequence effects on spring wheat follow-on crops. This was accomplished by calculating values of a crop sequence effect (SE) as the percentage increase or decrease in spring wheat yield (Y_i) for a given year that was associated with a particular crop species (i) grown in the previous year relative to the average yield of spring wheat (Y_{avg}) following all four of the crop species grown the previous year:

$$SE = 100 * (Y_i - Y_{avg})/Y_{avg}$$

To get a valid comparison of sequence effects among experiments, the average yield must be based on the same suite of the previous year's crop species. However, out of the four common species, the WSD experiment lacked soybean and the CSD experiment lacked maize. Thus, spring wheat yields for these cases were predicted by (a) calculating the average ratio of yields following the "missing" crop (Y_m) in the two experiments (for two years) where it was present to yields following spring wheat and dry pea ($Y_{(sw+dp)}$): average($Y_m/Y_{(sw+dp)/2}$); (b) the yield of spring wheat in an experiment following the "missing" crop in a particular year (p) was then predicted from the yields of spring wheat-following-spring wheat and spring wheat-following-dry pea, $Y_{((sw+dp)/2),p}$, as:

$$Y_{m,p} = Y_{((sw+dp)/2),p} / \text{average}\left(Y_m / Y_{(sw+dp)/2}\right)$$

Crop sequence effect values for matrix crops showed inadequate statistical significance among the majority of non-predicted data entries to warrant further pursuit here.

2.5. Statistical analyses

Crop yield data from the ASL (sandy loam) site experiment and crop sequence effect data comparing three experiments was subjected to analysis of variance using SAS (SAS Institute, Cary, North Carolina, USA). Because of the low number of treatments, means separation was analyzed by LSD test.

3. Results and discussion

3.1. Crop sequence results at the ASL sandy loam site

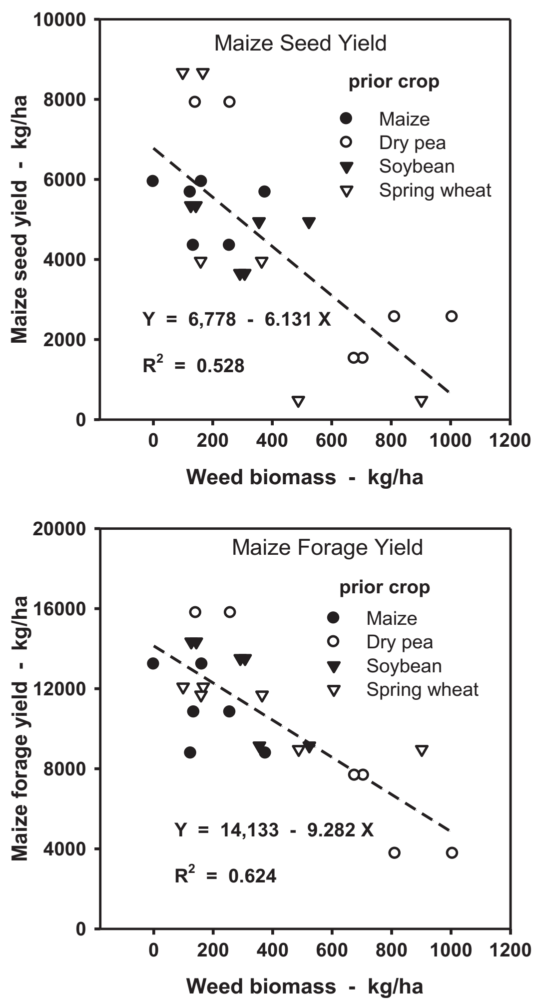
Precipitation at the ASL experiment on sandy loam, alluvial-derived soil (Fig. 1) varied considerably among years. In 2003, April through September precipitation was 97% of LTA, but July and August were only about 30% of average. Seasonal precipitation in 2004 was above average, but April and May values were about half of average. Seasonal precipitation in 2005 was well-distributed and 30% above average, but precipitation in 2006 was about 60% of average with June and July being particularly dry.

None of the effects of residue crops on seed yields of ASL matrix crops (Table 4) were significant beyond the $P = 0.13$ level. The relatively low significance of prior crop effect may be attributed to block (replication) effects being greater than crop effects and low (replication = observation = 3) number. The largest crop sequence effect was in soybean-following-soybean, with increases of 27% and 18% above average in 2004 and 2005, respectively. Positive soybean-following-soybean effects were also observed in the CSD experiment on silt loam soil in 1999 and 2000 (Krupinsky et al., 2006). Soils at sites of the experiments had been soybean-free, and the positive soybean-following-soybean effect could have been a case of soil microfloral self-conditioning associated with this legume.

Weed biomass in maize in 2005 was negatively and significantly correlated with both maize seed yield ($P < 0.001$; Fig. 2) and maize forage yield ($P < 0.001$). Some of lowest maize yields were in plots of maize-following-dry pea and maize-following-spring wheat, which had greater weed growth. Weed control in the shorter season crops, dry pea and spring wheat, was not as good as in maize and soybean. Dry pea has sparser and more fragile

Table 4
Seed yields of 2004 and 2005 crop matrices in the ASL (sandy loam site) crop sequence experiment. Replication and sample number = 3. Maximum and average values are bolded. Six month (April through September) precipitation at the site was 35.5 in 2004 and 40.4 cm in 2005, with a long term average of 30.3 cm.

2003 Residue crop	2004 Matrix crop				2004 Residue crop	2005 Matrix crop			
	Dry pea (kg ha^{-1})	Spring wheat (kg ha^{-1})	Soybean (kg ha^{-1})	Maize (kg ha^{-1})		Dry pea (kg ha^{-1})	Spring wheat (kg ha^{-1})	Soybean (kg ha^{-1})	Maize (kg ha^{-1})
Dry pea	1292	2290	1558	5162	Dry pea	1563	**1963**	2085	4001
Spring wheat	1368	2346	1799	**5435**	Spring wheat	1603	1525	1850	4372
Soybean	1305	**2806**	**2293**	5353	Soybean	**1824**	1912	**2366**	4650
Maize	**1406**	2463	1558	5261	Maize	1757	1645	1720	**5322**
Average	**1343**	**2476**	**1802**	**5298**	Average	**1687**	**1761**	**2005**	**4586**
$P > F$ (residue crop)	0.36	0.44	0.16	0.94	$P > F$ (residue crop)	0.88	0.15	0.13	0.84
$P > F$ (block)	<0.001	0.14	0.80	0.21	$P > F$ (block)	0.33	<0.001	0.01	0.04



Prior crop	Weed biomass
	kg ha^{-1}
Dry pea	600[a]
Spring wheat	363[b]
Soybean	291[bc]
Maize	176[c]
Average	357
$LSD_{.05}$	163
Block (rep), location	
5 (north)	470[x]
3 (middle)	465[x]
1 (south)	137[y]
Average	357
$LSD_{.05}$	141

Fig. 2. Maize seed and forage yields vs. weed biomass for the ASL sandy loam site experiment in 2005. Also weed biomass as related to prior crop treatment and block. Values with the same letter for a given treatment or block are not significantly different at $P < 0.05$ by LSD test.

Table 5
Seed yields of 2005 and 2006 spring wheat *follow-on* crops in the ASL (sandy loam site) crop sequence experiment. Sample number = 12. Six month (April through September) precipitation at the site was 40.5 cm in 2005 and 18.4 cm in 2006, with a long term average of 30.3 cm.

2005 Spring wheat *follow-on* crop seed yields						2006 Spring wheat *follow-on* crop seed yields					
2003 Crops	2004 Crops					2004 Crops	2005 Crops				
	Dry pea ($kg\ ha^{-1}$)	Spring wheat ($kg\ ha^{-1}$)	Soybean ($kg\ ha^{-1}$)	Maize ($kg\ ha^{-1}$)	Avg. $P > F = 0.50$		Dry pea ($kg\ ha^{-1}$)	Spring wheat ($kg\ ha^{-1}$)	Soybean ($kg\ ha^{-1}$)	Maize ($kg\ ha^{-1}$)	Avg. $P > F = 0.77$
Dry pea	2106	1969	2340	2180	2149	Dry pea	1001	1061	875	871	952
Spring wheat	2289	2048	2413	2342	2273	Spring wheat	1098	968	1013	924	1001
Soybean	992	1660	2670	2247	2142	Soybean	1164	1035	928	883	1002
Maize	2254	1892	2586	2154	2222	Maize	1104	996	913	846	965
Average ($P > F < 0.0001$)	2160[bA]	1892[c]	2502[a]	2231[b]	2196	Average ($P > F = 0.006$)	1092[a]	1015[ab]	932[bc]	881[c]	980
Difference from grand avg.[B]	No diff.	<Avg.	>Avg.	No diff.		Difference from grand avg.	>Avg.	No diff.	No diff.	<Avg.	
Sequence effect[C]	−1.3	−13.9	13.8	1.5		Sequence effect	11.4	3.6	−4.9	−10.1	
Block (rep)	$P > F < 0.0001$					Block (rep)	$P > F < 0.0001$				

[A] Values in a row or a column with the same lower-case letter are not different according to a LSD means separation test at $P < 0.05$.
[B] According to *t*-test at $P < 0.10$.
[C] Percentage difference from grand average.

residues (Merrill et al., 2006), and later-season growth of weeds in this crop was quite evident.

Seed yield results for spring wheat follow-on crops (Table 5) planted after the matrix crops were greatly affected by seasonal precipitation: precipitation was 30% above LTA in 2005, but in 2006 it was 40% below LTA (Fig. 1). Crops in the first year of the sequences (the original residue crops) had no significant effects on yields of spring wheat follow-on crops, but given greater statistical power ($n = 12$ for follow-on crops vs. 3 for matrix crops), immediately prior matrix crops did have significant effects. Spring wheat-following-spring wheat had negative crop sequence effect in 2005, a result that has been shown to be associated with disease in the CSD (silt loam) experiment, which was conducted under average to above average precipitation (Krupinsky et al., 2006). Soybean had a positive effect on following spring wheat in 2005, but dry pea had no effect. It is possible that positive crop sequence effects expected of dry pea under adequate soil water availability (Miller and Holmes, 2005; Miller et al., 2006) may had been negated by post-harvest weed growth. As was shown above, greater weed growth was found in maize-following-dry pea than in maize following the other crops (Fig. 2). The heaviest water-using crop of the four, maize (Merrill et al., 2007a), had no significant crop sequence effect on spring wheat under the higher than average precipitation conditions of 2005.

The pattern of spring wheat yields (Table 5) under significant soil water limitation in 2006 was different from that of 2005. The order of spring wheat yields following various prior crops was: prior dry pea > prior spring wheat > prior soybean > prior maize. Differences in water use (approximately, soil water depletion (SWD) plus precipitation) among crop species can be substantial. In a semiarid/subhumid area where there is typically greater seasonal water use (evapotranspiration) than precipitation, SWD is the principal determinant of differences in amounts of springtime soil water. The ranking of prior crops' effects on spring wheat yields in 2006, from positive to negative, is the exact inverse of the ranking of the crops' relative SWD observed in the CSD (Merrill et al., 2004) and WSD (Merrill et al., 2007a) experiments.

These results from the ASL sandy loam experiment clearly support a prime principle for understanding crop sequence interactions in semiarid crop ecology: under significant precipitation limitation, differentials in soil water use by crops will tend to dominate crop sequence effects. Under average to above average precipitation, crop sequence effects involving disease interactions, weed growth, positive legume effects, and other factors will become more evident. These results and the crop ecological principles they illuminate, have been supported by a more complex pattern of prior results from the CSD (Krupinsky et al., 2006) and WSD (Tanaka et al., 2007) experiments on silt loam soil.

Block, or replication, intended to statistically remove land variance interactions with plant-soil effects, is often not discussed in reportage of agronomic experiments. However, soil water storage and weed intensity can vary significantly over landscape at scales comparable to those in the current experiments, and will interact with crop sequence effects. Weed biomass varied more than 3-fold over blocks in maize at the ASL experiment in 2005 (Fig. 2). For matrix crops in the ASL experiment (Table 4), block effects were greater than prior crop effects for 7 out of 8 crop-year cases. Although none of the prior crop treatments showed significance at $P < 0.10$, dry pea yield was affected by block with $P < 0.001$ in 2004 and block was significant at $P = 0.04$ or better for three out of four crop species in 2005. For spring wheat follow-on crops (Table 5), block effects were significant at $P < 0.001$ in both 2005 and 2006, while prior crop effects were significant at $P < 0.001$ and $P = 0.006$ for those years, respectively.

3.2. Soil water depletion and root growth

Soil water depletion (SWD) is important for understanding crop sequence effects in a semiarid area, because it is the principal determinant of the relative amounts of soil water accumulated in the springtime following various species planted the prior year. The effects of SWD on springtime soil water can be modified by differences in crop species' relative abilities to capture and hold snow overwinter (Merrill et al., 2007a). Studies of crop sequence effects in the Great Plains have shown that heavier water-using crops such as sunflower, maize, and soybean often have negative effect on yields of following crops in years of limited precipitation (Krupinsky et al., 2006; Nielsen et al., 1999; Norwood, 2000; Tanaka et al., 2007). Differences in SWD (the variable component of seasonal water use) among crops under dryland conditions can be large. For example, Black et al. (1981) noted that in eastern Montana, USA, safflower SWD was 70% greater than that of barley. Such differences in SWD have been positively linked to depth of root growth (Black et al., 1981; Merrill et al., 2002), and linked to both root growth depth and length of a crop's growing season (Merrill et al., 2004).

Seasonal (mid-May to mid-September) SWD during the ASL experiment varied considerably among years (Fig. 3). Soil water

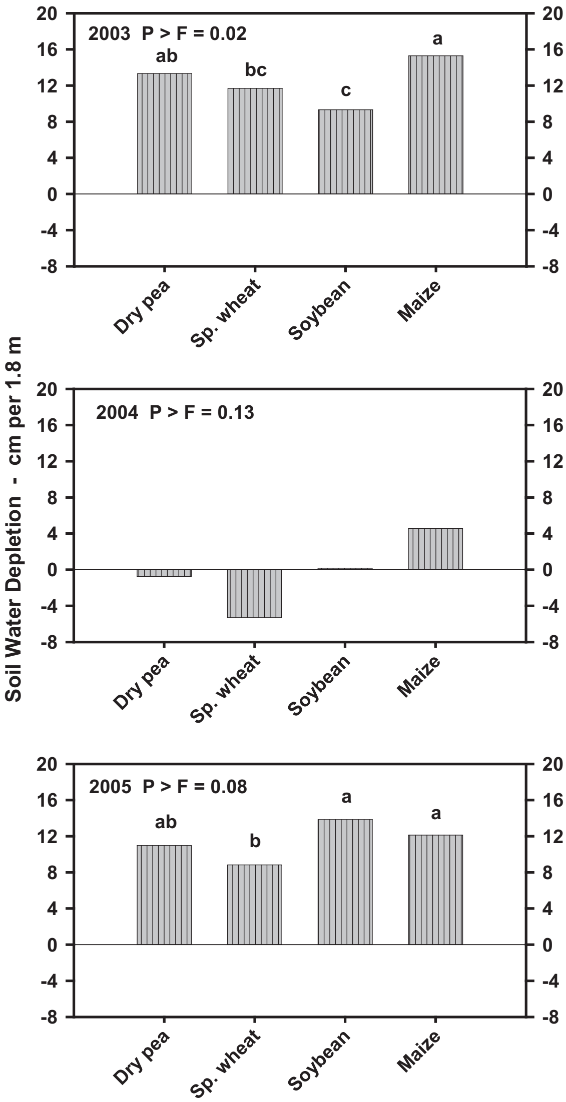


Fig. 3. Soil water depletion (SWD) from mid-May to mid-September measured to a soil depth of 1.8 m at the location of the ASL (sandy loam site) crop sequence experiment. April through September (6 mo) precipitation for years 2003, 2004, and 2005 was 29.5, 35.5, and 40.4 cm, respectively, compared with 30-yr mean precipitation of 30.3 cm. Values with the same letter for a given year are not significantly different at $P < 0.10$ by LSD test.

depletion values were lower in 2004 because summer 2003 and spring 2004 were relatively dry (Fig. 1). Wildlife depredation problems affected SWD results in 2003, especially the relatively low value for soybean. The average SWD during 2004 and 2005 in the ASL experiment for maize, soybean, spring wheat, and dry pea was 8.3, 7.0, 1.8 and 5.1 cm, respectively. Soil water depletion values for maize, soybean, and spring wheat were in the expected order, from highest to lowest, based on reported results from the CSD (Merrill et al., 2004) and WSD (Merrill et al., 2007a) experiments. But dry pea SWD would be expected to be lower than that of spring wheat based on this previous research.

Average SWD for maize, spring wheat, and dry pea in the WSD experiment (2002–2004; Merrill et al., 2007a) was 12.6, 10.6, and 5.0 cm, respectively, which compares with 2-yr average SWD for the same crops in the ASL experiment of 8.3, 1.8, and 5.1 cm, respectively. For the CSD experiment, average SWD (1999–2000; Merrill et al., 2004) for soybean, spring wheat, and dry pea was 9.7, 5.9, and 4.1 cm, respectively, compared with 7.0, 1.8, and 5.1 cm for the ASL experiment. Soil water depletion for the heavier water-using crops maize and soybean was greater for the two silt loam site experiments than for the ASL sandy loam site experiment. Maize SWD was greater in the WSD experiment than in the ASL, 12.6 cm vs. 8.3 cm, respectively, and soybean SWD was greater in the CSD experiment than in the ASL, 9.7 cm vs. 7.0 cm, respectively. These differences are believed due to soil property differences, including finer textured soil at the WSD site, and possibly due to somewhat less precipitation at this site compared with the ASL site.

The distributions of seasonal SWD over soil depth for 2003 are shown in Fig. 4 for the three crops common to the ASL (sandy loam) and WSD (silt loam) experiments. Soil water depletion occurred significantly and consistently deeper in the soil profile at the ASL experiment site than at the WSD experiment site. For the ASL site, median depths of mid-June to early September SWD for dry pea, spring wheat, and maize were 80.4, 84.6, and 89.8 cm, respectively, compared to 45.1, 54.1, and 51.7 cm, respectively, for the WSD site. Low soil water in spring 2004 resulted in net soil water accumulation earlier in the season and interfered with calculation of SWD soil depth distributions for that year. However, median depths of mid-July to mid-August SWD under maize in 2004 were 42.4 and 26.1 cm for the ASL and WSD sites, respectively.

The considerably deeper SWD at the ASL (sandy loam) site was reflected by deeper root growth compared with that at the WSD (silt loam) site (Fig. 5); profiles of root length density (RLD) showed a greater attenuation of growth with depth at the WSD site. For maize and spring wheat at the ASL site, median depths of root length growth were 45.6 cm and 41.8 cm, respectively; median depths for maize and spring wheat at the WSD site were 21.0 cm and 24.1 cm, respectively. Dry pea RLD profiles at the two sites were more similar, with median depths of root length growth being 28.3 cm and 24.5 cm for the ASL and WSD sites, respectively. Additional spring wheat and maize root growth probably occurred at the ASL site below 1.2 m, the greatest depth of observation.

3.3. Comparison of crop sequence results among experiments

A direct comparison between matrix crop yields at the ASL sandy loam and the WSD silt loam experiments could be made for the year 2004 for the three crops common to both (Table 6). There were no significant differences at $P < 0.10$ between the experiments in dry pea and spring wheat seed yields averaged over the three preceding residue crops. However, spring wheat-following-maize was 37% lower ($P < 0.20$) in the WSD experiment compared with the ASL. Following dry pea, spring wheat, and maize residue crops, maize seed yields at the WSD experiment were 28% ($P < 0.10$), 30% ($P < 0.20$), and 54% ($P < 0.001$) lower, respectively, and average maize yield was 37% lower ($P < 0.01$) at the WSD experiment. Maize forage yield was not as sensitive as seed yield to a prior maize crop on silt loam soil. Yields following dry pea and spring wheat were not significantly different, but maize forage-following-maize was 32% lower ($P < 0.10$) at the WSD experiment.

While the glacial till-derived silt loam soil at the WSD experiment has larger available water capacity than the sandy loam, alluvial-derived soil at the ASL experiment (Table 2), water moves relatively slowly into the finer-textured subsoil of the glacial-till soil, which has been shown to have low hydraulic conductivity (Trooien and Reichman, 1990). Furthermore, a lesser percentage of water depletion occurred at lower depths in the silt loam soil (Fig. 4), and root growth of spring wheat and maize occurred at shallower depths in the profile of this soil (Fig. 5). Thus, when a heavier water-using crop, such as maize, depletes water from the soil profile during a year of limited precipitation, the potential for negative crop sequence effects is increased on the silt loam soil. Crops with shorter growing seasons, such as spring wheat and dry pea, are less dependent on stored soil water, and are less subject to

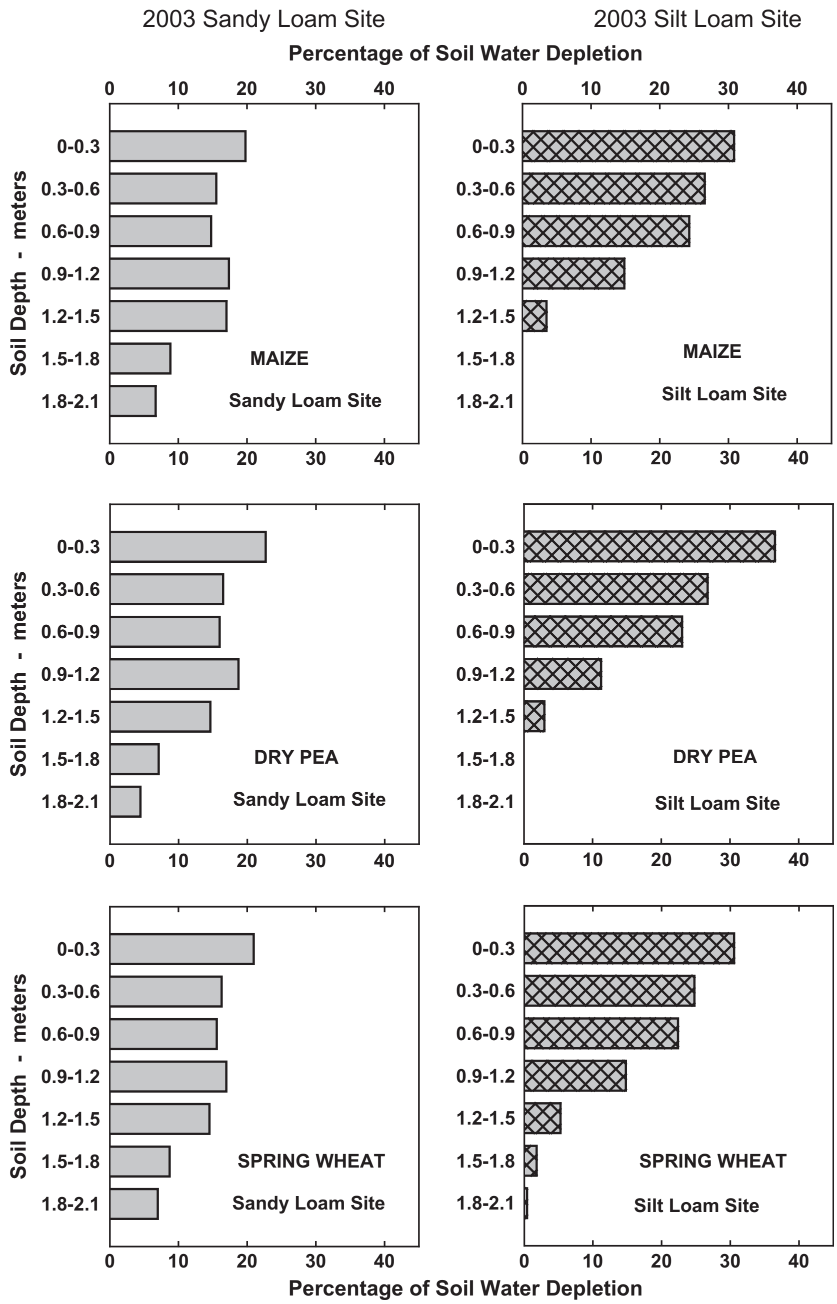


Fig. 4. Profiles of soil water depletion (SWD) measured in 2003 to a soil depth of 2.1 m at the ASL sandy loam soil site and at the WSD silt loam soil site.

negative effects of water depletion by maize in the prior season. The growth of longer-season crops at the WSD silt loam site might have been somewhat reduced by the fact that 2004 seasonal (6 mo) precipitation was somewhat lower than precipitation at the ASL site, 31.2 vs. 35.5 cm, respectively (LTA at the ASL site = 30.3 cm). However, this difference largely occurred in July, and August precipitation was actually higher at the silt loam site.

Results from the spring wheat follow-on crops in all three crop sequence experiments may be compared by use of calculated crop sequence effect values (Table 7). Five out of six experiment-year cases showed a common, general pattern: prior dry pea had positive to neutral effects on spring wheat production (N-production, soil water conservation); prior spring wheat had negative effects (disease probable); prior soybean was positive (N-production, possible soil self-conditioning), and prior maize was mostly negative to neutral from heavier SWD. Crop sequence effect values for follow-on spring wheat at the ASL sandy loam site in 2006, a year of low precipitation, ranked from highest to lowest in the same order as the prior crops' probable spring soil water storage amounts, and in inverse order of prior crops' expected SWD: dry pea > spring wheat > soybean > maize.

In the WSD silt loam experiment, prior dry pea boosted spring wheat production 34.6% over prior spring wheat, and 18.3% over prior spring wheat in the CSD silt loam experiment, an average of 26.5% for both (Table 7). This compares with an average prior dry pea vs. prior spring wheat production increase of 11.1% at the ASL sandy loam site. Miller et al. (2003) measured spring wheat production increases from prior dry pea vs. prior spring wheat at two sites in Saskatchewan, one with clay soil, the other with silt loam, and found an average 27.9% dry pea increase from six site-years. At three Montana sites, two with clay loam and one with silty clay loam soil, Miller et al. (2006) reported a one year 28.0% average

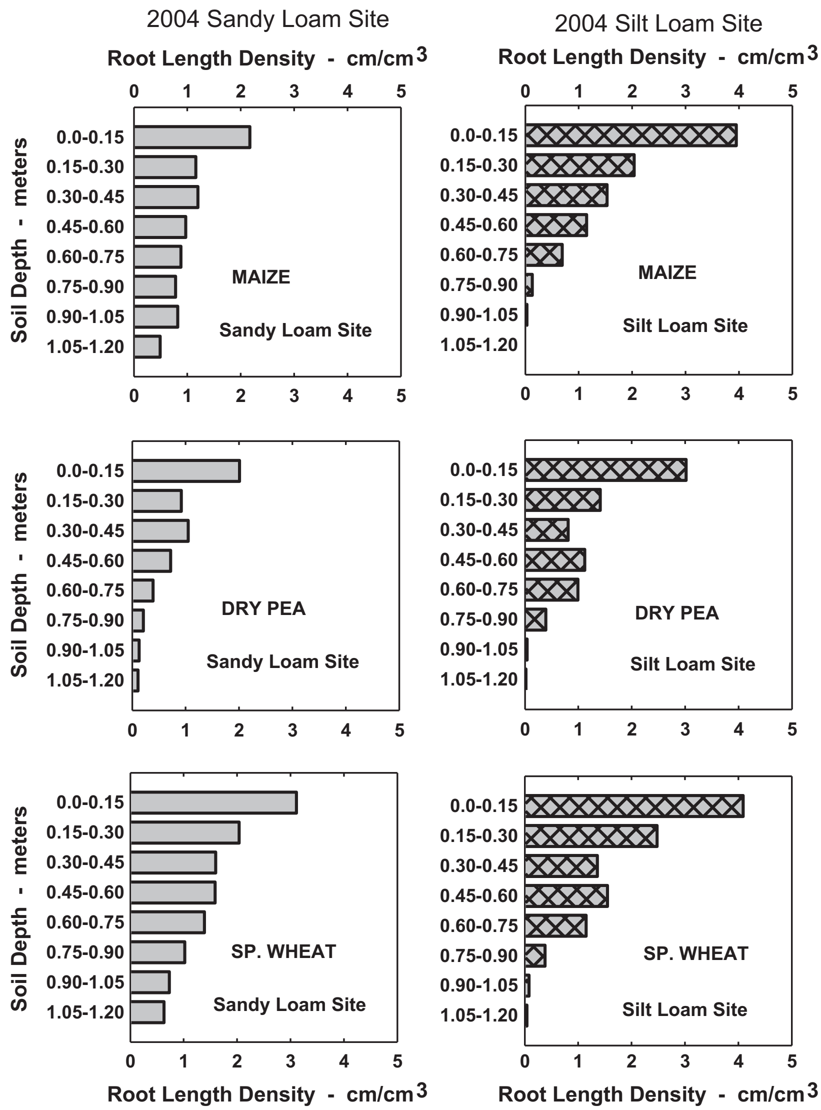


Fig. 5. Profiles of root length density (RLD) measured in 2004 to a soil depth of 1.2 m at the ASL sandy loam soil site and at the WSD silt loam soil site. Note that the soil depth of measurement in this figure is approximately 60% of that in the previous figure which shows profiles of soil water depletion.

increase in spring wheat from prior dry pea vs. prior spring wheat. The prior dry pea increases measured at Montana and Saskatchewan sites are rather close to the four-year average of 26.5% for the CSD and WSD silt loam experiments, and probably reflects similarity of crop cultivars, soils, and production techniques. The lower prior pea increase in spring wheat production (11.1% average) at the ASL sandy loam experiment could have been the result of some combination of factors on this coarser-textured soil, such as less symbiotic N-production, more post-harvest weed growth in dry pea, or relatively less disease in spring wheat-after-spring wheat.

4. Applications and conclusions

4.1. Soil quality and crop sequence

Soil quality is defined as the ability of a soil to function. The alluvial-derived, sandy loam site (ASL experiment) had topsoil with lower-valued soil quality properties (organic C, available water capacity; Table 2) than topsoil at the glacial till-derived, silt loam site (CSD and WSD experiments). Furthermore, soil at the ASL sandy loam site was more wind erodible (NRCS, 2009). Presence of tree shelterbelts, no-till management, and 20 years or more of perennial grass before start of cropping operations in 2001 for the ASL experiment would have raised overall soil quality of the sandy loam site. The Soil Management Assessment Framework (SMAF) is a tool developed by Andrews et al. (2004) for assessing soil quality changes in response to management. Application of SMAF to soil properties measured in the upper 30 cm of soil at the two locations (Merrill et al., 2007b) produced soil quality index values for the ASL sandy loam site that were as high or higher than those for the WSD silt loam site. Comparing crop yields on the two soil sites, the ASL produced generally as well as the WSD for dry pea and spring wheat, but the ASL site outyielded the WSD site in maize (Table 6).

The lower maize yields in 2004 at the WSD silt loam site compared to those at the ASL sandy loam site (Table 6) appears to have been associated with greater sensitivity of crop growth to water use by the prior year's crops. Maize has the greatest SWD of the crops used here, and this negative crop sequence interaction was greatest for maize-following-maize. It has already been reported above that SWD and root growth are deeper in the soil profile for crops at the ASL site compared to those at the WSD. Although soil at the WSD silt loam site could store more soil water (Table 2), hydraulic functioning of subsoils at the two sites was different: the sandy loam soil is known to have considerably higher hydraulic conductivity than the glacial-till subsoil at the silt loam site, and

Table 6
Comparison of 2004 *matrix crop* seed and forage yields for ASL (sandy loam site) and WSD (silt loam site) crop sequence experiments. Replication (equals sample) number = 3 for ASL and = 4 for the WSD experiments. Six-month (April through September) precipitation for 2004 was 35.5 cm at the ASL experiment site and 31.2 at the WSD experiment site, with long term average = 30.3 cm.

Residue crop	Dry pea seed			Spring wheat seed			Maize seed			Maize forage		
	ASL sandy loam (kg ha^{-1})	WSD silt loam (kg ha^{-1})	Prob. of diff.[a]	ASL sandy loam (kg ha^{-1})	WSD silt loam (kg ha^{-1})	Prob. of diff.	ASL sandy loam (kg ha^{-1})	WSD silt loam (kg ha^{-1})	Prob. of diff.	ASL sandy loam (kg ha^{-1})	WSD silt loam (kg ha^{-1})	Prob. of. diff.
Dry pea	1292	1215	ns	2290	2475	ns	5162	3727	<0.10	9483	8221	<0.20
Spring wheat	1368	1782	ns	2346	2401	ns	5435	3818	<0.20	9158	9006	ns
Maize	1406	1253	ns	2463	1518	<0.20	5261	2419	<0.001	9370	6348	<0.10
Average	1355	1417	ns	2366	2131	ns	5286	3321	<0.01	9337	7858	ns

[a] Based upon *t*-tests. No significance at $P > 0.20$ is indicated as "ns".

water would have percolated into subsoil faster. Thus it was more responsive to current season precipitation, and was less subject to negative crop sequence effects generated by heavier water-using crops in the prior season.

4.2. Agronomic application

Trends in crop sequence effects observed in the ASL (sandy loam) experiment had been found in similar forms in the silt loam site experiments: the WSD (Tanaka et al., 2007) and the CSD (Krupinsky et al., 2006). These trends included: (a) generally positive crop sequence effects of prior legumes dry pea and soybean, with the sequence soybean-following-soybean showing consistently strong positive effects; (b) negative crop sequence effects of prior heavier water-using crops such as maize and sunflower, particularly under limited precipitation. In the ASL experiment, this occurred particularly in 2006 with spring wheat-following-maize (Tables 5 and 7). (c) A negative crop sequence effect of spring wheat-following-spring wheat has been attributed to disease (Krupinsky et al., 2006). (d) Due to its relatively short season length and consequent thriftiness in use of soil water, positive crop sequence effects of prior dry pea were increased in experiment-years of reduced precipitation (Tables 5 and 7).

Comparison of the ASL sandy loam, alluvial-derived and WSD silt loam, glacial till-derived experiments reveals an important difference between these soil types with regard to one of the principal kinds of crop sequence effects in semiarid crop ecology: provided precipitation is adequate in the current season, crops on alluvial-derived soil are less subject to negative crop sequence effects of prior heavier water-using crops such as maize (Table 6). Because the alluvial-derived soil absorbs and stores precipitation more efficiently than glacial till-derived soil, it has less "hydraulic memory" of the effect of prior heavier water-using crops provided that current-season precipitation erases that "memory". If early season precipitation has been relatively plentiful following a heavier water-using crop the prior season, farmers can plant a wider range of crops on alluvial-derived soil with relatively higher confidence. On glacial till-derived soil following a deeper-rooted, heavier water-using crop such as sunflower or safflower, farmers should consider planting such earlier- and shorter-season crops such as dry pea or spring wheat.

While the alluvial-derived soil has more hydraulically-responsive subsoil than the glacial till-derived soil, it also stores less water. Due to the finer texture of glacial till subsoils, the difference in profile water storage capacities between the soils is greater than indicated by the figures in Table 2 for the upper 30 cm of soil. This has been shown by neutron moisture meter measurements (data not shown). Thus, under semiarid climatic conditions, farmers encounter greater risk on alluvial-derived soil of soil water becoming overly depleted by longer-season crops such as maize or soybean than on glacial till-derived soil. Deeply rooted, heavier water-using crops such as sunflower and safflower would be higher-risk on alluvial-derived soil. The same properties that make alluvial-derived soil more responsive to current-season precipitation than glacial till-derived soil also make it capable of well-supporting irrigation.

Agriculturalists must be aware of the greater soil conservation risks of managing crops on more fragile and erodible alluvial-derived soils. Even with the use of soil-conserving no-tillage practices, certain sequences of lower residue-producing crops will result in marginal soil coverage at seeding time in the following spring. Of the crop sequences used in the ASL experiment, dry pea-dry pea was shown to result in soil coverage of approximately 50% or less under the no-till management of the CSD experiment (Merrill et al., 2006).

Implementing the dynamic cropping systems concept (Tanaka et al., 2002) for making annual decisions about soil-crop manage-

Table 7
Crop sequence effect[A] of prior year's crop on yields of spring wheat *follow-on* crops. Values in parentheses are predicted. Also given: LSD, probability of greater *F*-value, average spring wheat seed yield, and April through September precipitation (long term mean 6 mo precipitation = 30.3 cm). Crop sequence experiments: ASL, alternative soil location (sandy loam soil); WSD, warm season dominant; CSD, cool season dominant (both on silt loam soil).

Crop sequence experiment	ASL		WSD		CSD	
Soil type	Alluvial-derived, sandy loam		Glacial till-derived, silt loam		Glacial till-derived, silt loam	
Prior crop	Year					
	2005 (percentage)	2006 (percentage)	2004 (percentage)	2005 (percentage)	2000 (percentage)	2001 (percentage)
Dry pea	−1.3[b]	11.4[a][B]	17.0[a]	10.7[a]	9.7[a]	3.2[a]
Spring wheat	−13.9[c]	3.6[ab]	−19.8[c]	−10.2[b]	−13.8[b]	−5.5[b]
Soybean	13.8[a]	−4.9[bc]	(7.0)	(8.8)	10.6[a]	8.0[a]
Maize	1.5[b]	−10.1[c]	−4.1[b]	−9.4[b]	(−6.7)	(−5.7)
$LSD_{0.10}$	7.5	10.0	9.9	4.1	7.3	6.0
P of greater F	<0.0001	0.005	<0.0001	<0.0001	<0.0001	0.004
Avg. yield, kg/ha	2199	980	2653	2519	2655	3924
6 mo precip., cm	40.4	18.4	31.2	39.6	33.9	43.7

[A] See definition in Section 2.
[B] Values in a column followed by the same lower-case letter are not significantly different at the $P = 0.10$ level according to LSD test.

ment requires the integration of annual, field plot-scale research, such as reported here, and longer-term crop ecological study carried out at field or greater scale. Longer-term studies of crop rotations have shown positive synergistic effects of diverse crop species, including increased yields and reduced pest pressure. Anderson (2008) reviewed 8- and 12-yr studies at three sites in Colorado and South Dakota showing that four-year rotations of two cool-season and two warm-season crop species reduced weed populations eightfold compared with two-year rotations of one warm- and one cool-season crop.

4.3. Considerations for dry pea

Dry pea crop sequence effects were generally positive according to results of the CSD and WSD experiments on silt loam soil (Tanaka et al., 2010; Liebig et al., 2008). These positive effects are ascribed to water conservation and symbiotic N-production effects. In the ASL (sandy loam) experiment, dry pea, which had the shortest season of the four crops (Table 3), was associated with greater weed growth in the following maize crop (Fig. 2). Dry pea must be considered to be a partial fallow crop, and the downside to its water conservation and symbiotic N-production is relatively lower carbon inputs to the soil (Sainju et al., 2007). Dry pea has prostrate, quite non-durable residue, and, as noted above, provides relatively thin soil coverage in the following spring, even under no-till management (Merrill et al., 2006). Thus, cover crops or fall-seeded crops should be considered for planting later in the season after dry pea harvest, especially on more erodible soils such as the sandy loam, alluvial-derived soil used for the ASL experiment.

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