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12. Dynamic cropping systems: Holistic approach for dryland agricultural systems in the Northern Great Plains of North America

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Abstract. Cropping systems development over the past century has increasingly stressed greater crop functionality through better conservation of soil and water and improvement of crop rotational sequencing in an effort to enhance the sustainability of our farming systems. The purpose of this chapter is to discuss the evolution of cropping systems in the northern Great Plains and provide an approach to cropping systems management for more resilient agricultural production systems. Dynamic cropping systems help producers make critical management decisions to remain sustainable in an ever-changing agricultural environment. A key factor associated with dynamic cropping systems is information awareness, particularly the influences of a previous crop and crop residue on factors such as soil water status, nutrient dynamics, crop choices, and pest control. Crop production can be enhanced with appropriate crop sequencing. In general, when the previous crop was a legume (pulse), crop production was increased. When the crop was seeded on its own crop residue, crop production was decreased. Since information awareness is critical for producers to achieve farming sustainability, a user-friendly computer program entitled "Crop Sequence Calculator" was designed and developed to assist producers in determining appropriate crop sequences for the northern Great Plains. Dynamic cropping systems of the future will need to include livestock, perennial forages, and biofeedstocks to meet the ever-changing agricultural environment.

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1. Introduction

Agriculture in the northern Great Plains has been in a continual state of flux. Early agriculture relied on water, nutrients, and energy from the sun to produce the “horsepower” needed for food, fiber, feed and fuel production. The agricultural systems employed during this time had a great deal of crop and animal diversity, employed polyculture, and relied on ecosystem resilience and nutrient cycling (Plieninger 2007). These early agriculturalists operated on the principle that “waste equals food,” (Kirschenmann 2002). Their production systems were designed in such a way waste from one part of the system returns into the system as food for another part of the system.

Agriculture since the post-war era (World War II) has greatly changed. Agriculture has moved away from crop diversity to concentrate on a few species of crops such as corn (*Zea mays* L.), soybean (*Glycine max* L.), and wheat (*Triticum aestivum* L.) transforming agricultural production systems to a large-scale, specialized, energy-intensive system (Brummer 1998). In the process, we have moved almost entirely away from agriculture dependent on energy from the sun to an agriculture that uses stored energy (fossil fuel) and now requires more than a calorie of fossil fuel to produce a calorie of food (Plieninger 2007). We have also made several assumptions: (1) production is more efficient through specialization, simplification, and concentration; (2) production challenges can be overcome with technology; (3) production results are best achieved through controlled management; and (4) cheap unlimited energy will be available (Kirschenmann 2007). These assumptions have transformed agriculture into large-scale, specialized, energy intensive agricultural systems. Because of the major energy transformation the world is experiencing, agricultural systems need to change to be competitive. Therefore, the objectives of this chapter are to discuss past, present, and future cropping systems and provide an approach that uses crop sequencing as a key component for designing and implementing energy-use efficient cropping systems. These future cropping systems improve crop production through synergistic and antagonistic biological processes to develop agricultural production systems that are resilient.

2. Past and present cropping systems

Many of the early settlers to the northern Great Plains came from regions that had longer growing seasons and greater frequency and distribution of precipitation. These settlers came during the wet cycle for the northern Great Plains and therefore, their cropping systems and tillage tools emulated the wetter regions they came from (Gray 1967). These early cropping systems were not resilient and were prone to crop failure during drought periods.

One of the early strategies, developed in Canada, was the crop-fallow system. Fallow was one of the first strategies producers used to help stabilize crop yields during drought periods in the Great Plains (Black et al. 1974). During fallow, neither crops nor weeds are allowed to grow since the goal of fallow is storing precipitation in the soil. Early fallow techniques used inversion implements to create a condition known as “dust mulch” fallow. As fallow techniques improved from dust mulch to no-till, where all crop residues remain on the soil surface, precipitation storage efficiency increased from 20 to 40 % (Greb 1983). While significant progress has been made toward increased soil water storage during fallow, fallow efficiencies seldom exceed 40% (Greb 1983; Tanaka and Aase 1987). This means at least 60% of the precipitation received during fallow is lost to evaporation. Increased residue levels on the soil surface with no-till or minimum-till fallow practices have helped reduce evaporation and control soil erosion, but residue levels in the Great Plains seldom exceed 6000 kg ha^{-1} (Greb 1983; Jones et al. 1997; Tanaka and Anderson 1997). At the present, soil and water conservation practices for soil water storage during fallow are at their practical limits. Therefore, it is obvious that a new approach is needed to more efficiently use precipitation.

Cropping systems that reduced the frequency of fallow were needed to use the increased soil water more efficiently. Cropping systems that use the same sequence of crop year after year have been referred to as fixed-cropping systems (Black et al. 1974). Many of these fixed-cropping systems were designed to use precipitation more efficiently, but lacked sufficient crop diversity. The lack of sufficient crop diversity enhanced subtle weaknesses that dominated the systems and mimicked monoculture systems rather than diverse-cropping systems. To help producers make decisions as to whether to plant a crop or fallow based on soil water status at planting, flexible cropping systems were developed (Brown et al. 1981; Zentner et al. 1993). These systems allowed producers to decide between planting a crop annually or fallowing the land.

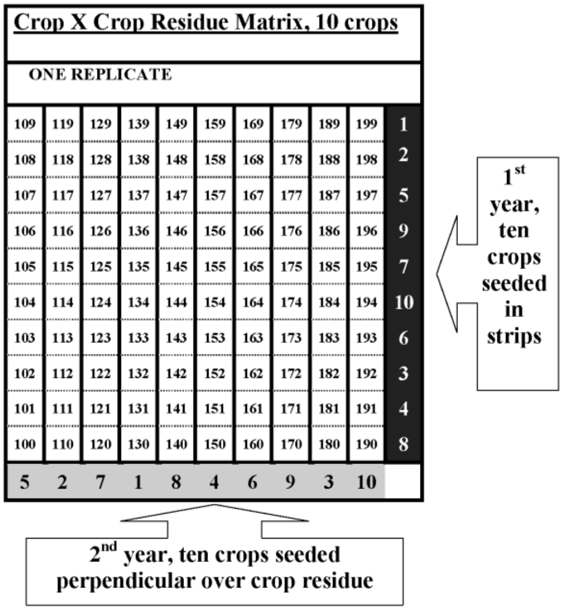
Due to economic outcomes, government programs, and a perceived need among producers and researchers for additional cropping options, the number and diversity of crops in Great Plains cropping systems has increased (Peterson et al. 1996). Annual cropping, which includes diverse crops such as oilseeds, pulses, and forages, has become a viable option for producers. Improved technology (plant and residue management technology, herbicides, techniques to improve soil-water management, improved germplasm, etc.) produced advances in management practices for cropping systems. Cropping systems currently include a multitude of crop species, thereby allowing producers to increase their cropping options and potentially reduce the risk over a monoculture system (Helmers et al. 2001). Dynamic cropping systems have been developed to take advantage of the multitude of crop species, through crop sequencing, to optimize crop and soil management options and to attain production, economic, and resource conservation goals (Tanaka et al. 2002).

3. Dynamic cropping systems: Concept

Resilience is a critically important trait for dryland cropping systems in the North American Great Plains, as this region is known for periods of instability due to extreme variability in precipitation and seasonal temperatures (Peterson 1996). As documented in the previous section, the evolution of dryland cropping systems in the Great Plains has generally followed a trajectory of increased system resilience over time. Transitioning from crop-fallow to cropping practices where the frequency of fallow has been reduced or eliminated has increased the resilience of dryland cropping systems through improvements in precipitation use efficiency and soil quality (Farahani et al. 1998; Wienhold et al. 2006).

Though resilience has been increased in current dryland cropping systems, their long-term viability is linked to the selection and sequencing of crops over time (Tanaka et al. 2002). Crop selection and sequencing order within a cropping system can take multiple forms. Monoculture, fixed-sequence, and opportunity/flex cropping systems represent approaches to crop sequencing that are increasingly responsive to external stressors (e.g., weather) and market conditions (Liebig et al. 2007). Additional flexibility in annual crop sequencing can be realized through the application of a dynamic cropping systems concept, where crop sequencing decisions are made annually based on externalities as well as management goals. Formally defined, a dynamic cropping system represents a long-term strategy of annual crop sequencing that optimizes crop and soil use options to attain production, economic, and resource conservation goals by using sound ecological management principles (Tanaka et al. 2002). A dynamic approach to crop sequencing possesses an inherent flexibility to adapt to high-risk conditions, and has been purported to be more economically and environmentally sustainable than other approaches to crop sequencing (Hanson et al. 2007).

In spite of the potential benefits associated with dynamic cropping systems, challenges associated with providing science-based information for their development are daunting. First, dynamic cropping systems, by their nature, are region-specific. Differences in climate and soils impose constraints on which crops can be grown. Consequently, different regions will possess unique crop portfolios (i.e., adaptable crop species), thereby creating numerous combinations of crops within and across regions. Second, for each crop portfolio, a thorough understanding of short-term (1 to 3 yr) crop sequencing effects on relevant agronomic and environmental parameters is needed. Evaluating all possible crop sequencing combinations for a given crop portfolio is a significant challenge to agricultural research, requiring novel methodologies. At the USDA-ARS Northern Great Plains Research Laboratory, a crop by crop residue matrix was used to evaluate crop sequence impacts on agronomic and environmental attributes for a crop portfolio with 10 crops (Figure 1). The matrix was designed so that 10 crops were seeded perpendicular over the residue of the same 10 crops, resulting in 100 different crop sequence combinations. Such short-term research efforts like this can help identify crop sequence ‘synergisms’ and ‘antagonisms’ through evaluations of crop productivity, plant diseases, and soil water use (Krupinsky et al. 2006), and can provide a basis for developing strategies to sequence crops over a longer period of time (Liebig et al. 2006).



109	119	129	139	149	159	169	179	189	199	1
108	118	128	138	148	158	168	178	188	198	2
107	117	127	137	147	157	167	177	187	197	5
106	116	126	136	146	156	166	176	186	196	9
105	115	125	135	145	155	165	175	185	195	7
104	114	124	134	144	154	164	174	184	194	10
103	113	123	133	143	153	163	173	183	193	6
102	112	122	132	142	152	162	172	182	192	3
101	111	121	131	141	151	161	171	181	191	4
100	110	120	130	140	150	160	170	180	190	8
5	2	7	1	8	4	6	9	3	10	

Figure 1. A crop x crop residue matrix used to evaluate the influences of crop sequences on agronomic and environmental attributes (after Tanaka et al., 2007). 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.

4. Dynamic cropping systems: Research and applications

4.1. Introduction to crop sequence research

Research at the USDA-Agricultural Research Service's Northern Great Plains Research Laboratory that most directly supports the dynamic cropping system concept has been conducted over an approximately 10-year period at the Area IV Soil Conservation Districts - Agricultural Research Service Cooperative Research Farm located about 7 km southwest of Mandan, ND. The climate of this area is semiarid-subhumid with approximately 400 mm mean annual precipitation distributed in a continental pattern with June as the peak precipitation month. The frost-free growing season is 130 to 140 days duration. Soils at the Research Farm are predominantly classified as Temvik-Wilton silt loam (Fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls).

The foremost goal of the research program has been to discover the fundamental principles of crop species ecology as they apply to soil-crop management systems. To this end, a series of field research projects (Phase I, II and III) have been conducted examining the basic agronomic and soil management characteristics of diverse crop species with emphasis on the interactive effects among species as they are cultivated in sequence.

The initial experiment in the program was a study of the agronomic characteristics and comparative water use of seven broadleaf crop species under no-till and conservation-till management (Phase I). This 3-yr Alternative Crops project, described in Anderson et al. (2003), was carried out in 1995-1997 and included the following species: canola (*Brassica rapa* L.), crambe (*Crambe abysinnica Hochst ex R.E. Fr.*), dry bean (*Phaseolus vulgarius* L.), dry pea (*Pisum sativum* L.), safflower (*Carthamus tintorius* L.), soybean (*Glycine max* (L.) Merr.), and sunflower (*Helianthus annuus* L.).

The principal part of the program was the execution of two crop sequence projects (CSP) (Phase II and III) which consisted of the systematic observation of all possible sequences of 10 different crop species. The agro-ecological and crop-soil hydrologic characteristics of these crop sequential interactions was determined, including crop production characteristics, differential soil water depletion and recharge, plant disease interactions, soil surface crop residue dynamics, short-term soil quality attributes, and weed spectrum and dynamics. No-till management is considered to be the overall best management practice (BMP) for dryland cropping systems, and so no-till was used exclusively throughout the CSP's.

The CSP's were carried out by planting the 10 crops in strips in one year, and then by planting the same crops in strips perpendicular to the first set the following year as illustrated by Figure 1. The first set of crops is referred to as the "residue crops", and the following years' crops planted perpendicular are referred to as the "matrix crops". Field-size agricultural equipment was used to plant the 9-m wide crop strips. Crop order was randomized within the 10 x 10 crop matrix blocks, which were replicated 4 times. Crop matrices in each of the two CSP's were repeated one year apart for two years.

Complete agronomic and other details of the first CSP (Phase II, crop matrices in 1999 and 2000) are found in Krupinsky et al. (2006). Details of the second CSP (Phase III, crop matrices in 2003 and 2004) are found in Tanaka et al. (2007) and associated papers cited in this publication (Table 1).

The experiments were set up by planting a small grain crop (winter wheat or barley for Phase II, spring wheat for Phase III CSP's) prior to the residue crops. The matrix

Table 1. Summary of crop species used in Phase II and Phase III Crop Sequence Projects (CSP's) at Mandan, ND, U.S.A.

Six crop species unique to Phase II CSP		
Crop	Latin name	Cultivar
Barley	*Hordeum vulgare* L	Stander
Crambe	*Crambe abysinnica* Hochst ex R. E. Fr.	Meyer
Dry bean	*Phaseolus vulgarius* L.	Black Turtle and Shadow
Flax	*Linum usitatissimum* L.	Omega
Safflower	*Carthamus tintorius* L.	Montola 2000
Soybean	*Glycine max* (L.) Merr.	Jim
Four crop species common to both Phase II and Phase III CSP's		
Crop	Latin name	Cultivar
Canola	*Brassica napus* L.	Dynamite and 357RR
Dry pea	*Pisum sativum* L.	Profi and DS Admiral
Spring wheat	*Triticum aestivum* L.	Amidon
Sunflower	*Helianthus annuus* L.	Cenex 803 and 63M91
Six crop species unique to Phase III CSP		
Crop	Latin name	Cultivar
Buckwheat	*Fagopyrum esculentum* Moench	Koto
Chickpea	*Cicer arietinum* L.	Amit
Corn	*Zea mays* L.	TF2183
Grain sorghum	*Sorghum bicolor* (L.) Moench	DK28E
Lentil	*Lens culinaris* Medik	CDC Richlea
Millet	*Panicum miliaceum* L.	Earlybird

crops were followed at each site with spring wheat then with sunflower to observe residual crop sequential after-effects. This 5-year crop sequence was repeated at each site of each project, offset by one year, giving replication in time.

All crops in Phase II CSP and all crops except sunflower and corn in Phase III CSP were seeded using a no-till single disc drill. Sunflower and corn were seeded using a no-till row crop drill. Crops in Phase II CSP were fertilized with N and P at seeding. All Phase III CSP crops were fertilized with P and all crops except chickpea, dry pea, and lentil received N fertilizer.

4.2. Crop sequence research results

Weather and crop yield

The most important environmental control on soil-crop productivity in a semiarid-subhumid region is precipitation. Frequency and distribution of precipitation received during the growing seasons of the two CSP's differed considerably (Figure 2). Precipitation during growing season (May through August) of the first matrix crops year of the Phase II CSP, 1999, was 181% of the long-term average (LTA). During the second matrix crops growing season in 2000, precipitation was about average (104% of LTA). In contrast,

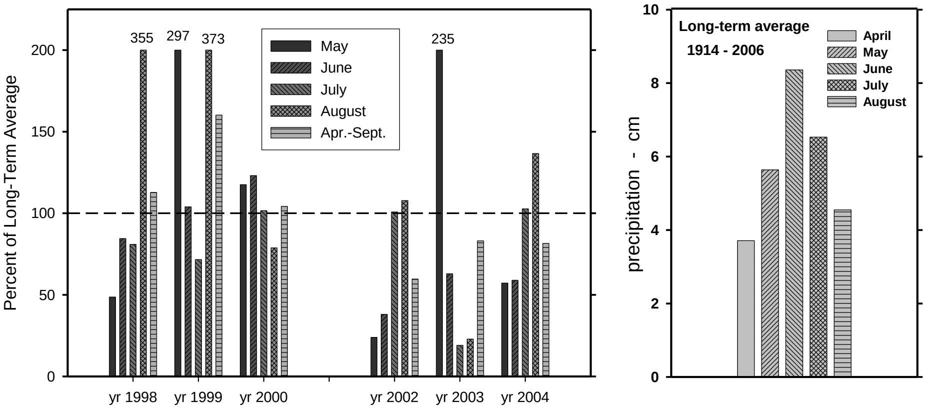


Figure 2. Precipitation at site of the crop sequence projects.

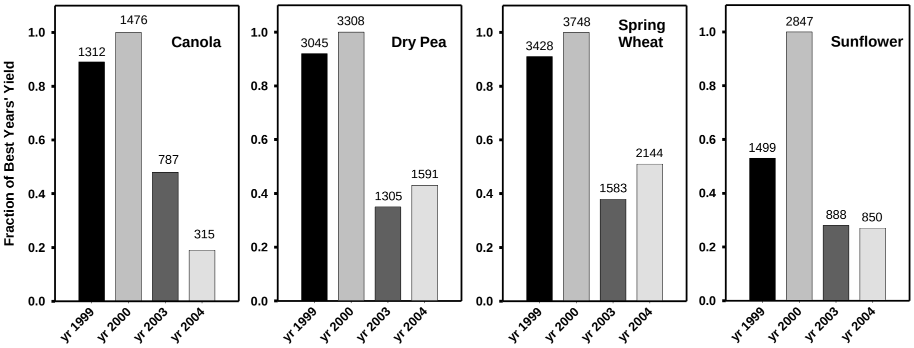


Figure 3. Seed yields of four crop species present in both Phase II (1999, 2000) and Phase III (2003, 2004) crop sequence projects. Yield values shown by bars are relative to value for each crop in year of highest yields, 2000. Values above each bar are actual yields in kg ha^{-1}.

growing season precipitation during years of the Phase III CSP matrix crops was below the LTA, 83% of LTA in 2003 and 72% of LTA in 2004, and maldistributed through the season, particularly in 2003.

Precipitation patterns impacted relative annual yields of the four crops (canola, dry pea, spring wheat, and sunflower) common to both CSP's (Figure 3). Seasonal precipitation in year 2000 was associated with the highest relative seed yields for all four crops. Yields of three of the crops were down from 2000 by approximately 10% in significantly wetter than average 1999, and sunflower yield was down from 2000 by about 50%. For years of Phase III matrix crops, 2003 and 2004, yields were about 20% to 50% of yields in 2000. Of the four crops, spring wheat seed yields were affected the least by low precipitation, while sunflower yields were affected the most.

Soil water, depletion, and recharge

In dryland agriculture, evapotranspiration exceeds precipitation during the growing season resulting in soil water depletion (SWD). Seasonal soil water use (evapotranspiration, ET) can be approximated by determining soil water depletion and assuming water use as the sum of SWD + seasonal precipitation. Overwinter soil water recharge (SWR) among crops for a given site and year are highly useful for understanding one of the most important factors underlying crop sequence effects; crop differences in spring soil water content.

Extensive soil water measurements were taken during the course of the CSP's to determine comparative water use, SWD, and SWR associated with the various crop species used (Merrill et al. 2004; 2007). Using a neutron moisture meter permits repeated, non-destructive determinations of soil water content. To achieve valid comparison among crop species, measurements were made in plots of a given crop type that had supported a spring wheat crop in the prior year. Also, a common accounting period of mid-May to mid-September was used for SWD determinations, and a period of mid-September to mid-April of the following calendar year was used for SWR determination.

Results of the principal SWD determinations of the CSP's are displayed in Figure 4. Within a CSP, the crops are arranged in order of average SWD, from highest to lowest. Sunflower had the highest SWD in both CSP's and dry pea the lowest. In the Phase II CSP, safflower and soybean had the 2nd and 3rd highest SWD, and barley and crambe had the 2nd and 3rd lowest. In the Phase III CSP, corn and grain sorghum had 2nd and 3rd highest SWD and lentil and chickpea being the 2nd and 3rd lowest.

The average amount of SWD varies significantly from year to year (Figure 4) as does the range of SWD values within a year. During the Phase II CSP, average SWD was lower and the range in SWD values was narrower for 1999 a wet year, compared to 2000,

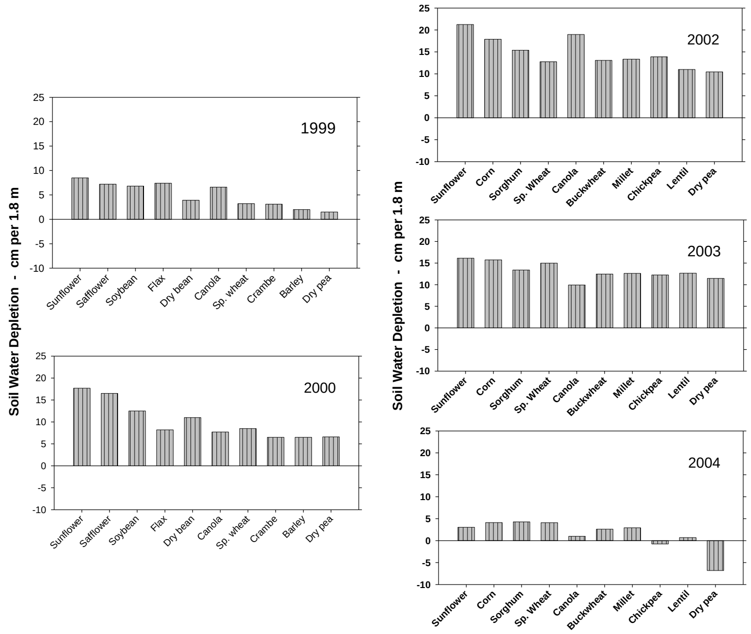


Figure 4. Seasonal (mid-May to mid-September) soil water depletion (SWD) values for Phase II (left side) and Phase III (right side) crop sequence projects measured by neutron moisture meter to soil depth of 1.8 m. Measurements were conducted in crops following a prior spring wheat crop. Species are arranged in decreasing order of average SWD values. Data from Merrill et al. (2004a) and Merrill et al. (2007).

an average year. In 1999, a greater percentage of seasonal water use (ET) came from seasonal precipitation. During the drier-than-average years of the Phase III CSP, spring soil water contents started out in 2002 at average to somewhat less than average levels, and then became progressively lower in spring 2003 and 2004. Soil water depletion along with subsequent soil water recharge during dry years can influence succeeding crop SWD. In 2002 when the residue crop was grown, SWD was greater than in 2003 for most crops (Figure 4). As a result, average SWD in 2004 was rather low, and dry pea actually had negative SWD for the 4-mo seasonal accounting period, meaning that mid-season precipitation was greater than the relatively low SWD of this water-thrifty crop species in a low precipitation year.

During the Alternative Crops project (Phase I, above), extensive measurements of root length growth were made on the seven species plus two others using minirhizotron methodology (Merrill et al. 2002). Combining this information with that from soil water measurements during Phase II CSP, Merrill et al. (2004a) used various regression analyses to determine that the length of active growing season for a crop species were stronger determinants of relative SWD than root length or depth of rooting.

The relative amount of soil water found in the soil profile in spring at seeding time may be said to be “the farmer’s bottom line.” This amount is determined by the relative amount of SWD by the prior season’s crop and the amount of SWR, which is comprised of fall-to-early spring precipitation, snow capture and retention by crop residue, and snowmelt. From Phase III CSP measurements in Figure 5 (Merrill et al. 2007), we can see that average amount of mid-April soil water is negatively correlated with SWD among the crop species. A crop with a high rank for SWD has a low rank for spring soil water content. With the exception of two crops, spring wheat and chickpea, the other 8 crop species have a spring soil water content rank that is e within 1 value of the expected rank. SWD is greatly affected by crop species, whereas SWR, while it may be significantly affected by crop residue, is predominantly determined by abiotic landscape and physical factors occurring overwinter.

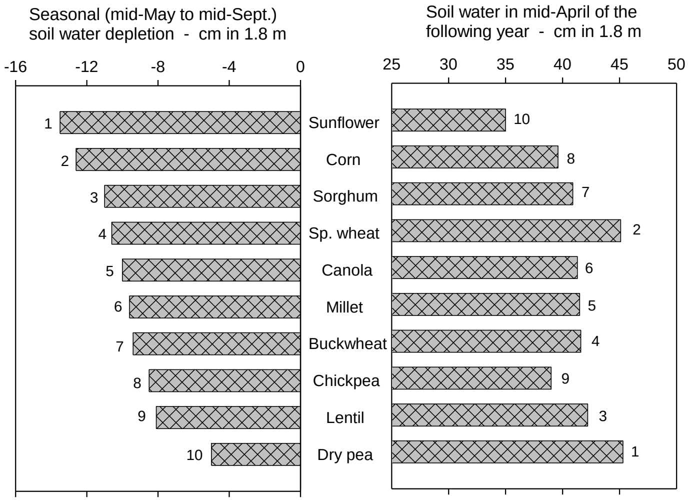


Figure 5. Ranked values of average soil water depletion (SWD) and of following year mid-April soil water contents (to depth of 1.8 m) for Phase III crop sequence project. Shown are 3 year averages. Data from Merrill et al. (2007).

Increased average mid-April soil water for spring wheat appears to be the result of superior snow capture by this crop (Merrill et al. 2007). Snow depth measurements made in the winter of 2004 indicate that sunflower and the pulse legume crops, dry pea, lentil, and chickpea, are relatively poor at snow capture and retention.

The average difference in spring soil water (0-1.8m) between dry pea and sunflower, 10.3 cm, determined in Phase III CSP is similar to a dry pea – sunflower difference of 8.6 cm measured in Phase II CSP for 2000-2001 (Merrill et al. 2004a). Furthermore, sunflower has been shown to deplete 2 times as much total soil water from subsoil below 0.9 m when compared to shallower rooted crops such as dry pea and lentil (Merrill et al. 2007).

It is well known that crop yields following sunflower (and other crops with high water demands, e.g. sorghum) are reduced in limited precipitation years. Merrill et al. (2004) used spring wheat critical yield vs. water data of Bauer and Black (1991: 130 kg ha^{-1} cm^{-1}) to estimate that sunflower land having 7 cm less spring soil water than dry pea land could lower gross return from spring wheat under critical precipitation years by (US dollars) \$150 ha^{-1} for a spring wheat price of \$0.165 kg^{-1} (\$3.50 bu^{-1} to \$4.50 bu^{-1}). For wheat priced at \$0.30 kg^{-1} (\$10 bu^{-1}), this would amount to a theoretical loss of \$272 kg^{-1}.

Plant disease interactions

Leaf spot disease evaluations were made on spring wheat during the third year, when spring wheat was seeded over the crop matrix in Phase II and Phase III. Common leaf spot diseases on spring wheat were tan spot (*Drechslera tritici–repentis* [Died.] Shoemaker (teleomorph = *P. tritici-repentis*)) and stagonospora nodorum blotch (*Stagonospora nodorum* [Berk] Cast. et Germ. (teleomorph = *Phaeosphaeria nodorum*) [E. Müller] Hedjaroude) (Krupinsky et al. 2004). Spring wheat disease severity was influenced by crop sequence treatments. Crop sequence treatments where spring wheat had not been grown for two years could not be distinguished from crop sequence treatments where spring wheat had not been grown for one year. The most favorable disease development occurred where spring wheat was seeded after spring wheat (Krupinsky et al. 2007). In the northern Great Plains, new crops used in cropping systems as an alternative to spring wheat reduced the levels of spring wheat leaf spot diseases.

Crop sequence and crop productivity

In considering the effects of crop sequence on productivity in general, one of the most important considerations is the relative sensitivity of a given crop species' productivity to the prior crop (Tanaka et al. 2007). This production sensitivity to prior crop species can vary greatly, as overall data from our CSP's indicate. For the Phase II CSP, the 2-year average coefficient of variation (CV) of seed yield due to prior species ranged from 6.7% to 29.4%. The ranking of Phase II crops from least yield sensitivity to prior crop to most sensitive were as follows: 1 - spring wheat; 2 – barley; 3 – dry pea; 4 – canola; 5 – soybean; 6 – sunflower; 7 – dry bean; 8 – safflower; 9 – crambe; 10 – flax. For the Phase III CSP, 2-year average CV's of seed yield due to prior crop ranged from 10.5% to 48.0%. The ranking of Phase III crops from least yield sensitivity to prior crop to most sensitive were as follows: 1 - spring wheat; 2 – proso millet; 3 – dry pea; 4 – buckwheat; 5 – canola; 6 – chickpea; 7 – lentil; 8 – sunflower; 9 – corn; 10 – grain sorghum.

As previously noted, the Phase III CSP was conducted under considerably greater water limitation compared to the Phase II CSP, and thus crops yields were lower and the magnitude of crop sequence effects were considerably greater in the Phase III CSP, as reflected in the overall range of CV values for the two projects. In general, SWD is an indicator of crop water use and appears to be associated with the prior crop. For the Phase II CSP, the three crop species exhibiting the least sensitivity to the prior crop (spring wheat, barley, and dry pea) were the 4th, 2nd, and lowest water-using crops, respectively, and the 3rd most prior-crop sensitive species, safflower, had the next to highest water use. For the Phase III CSP, the 2nd and 3rd least prior-crop sensitive species (proso millet and dry pea) were the 4th least and the least water-using crops, respectively, while the most, next to most, and 3rd most prior-crop sensitive species, grain sorghum, corn, and sunflower, respectively, were the 3rd greatest, next to greatest, and greatest water-using crops.

The complete results of crop sequential effects of both CSP's are displayed in Table 2 with residue crops on left margins and matrix crops across the top. Both residues and matrix crops are ordered by average SWD rank (shades of grey and white show negative and positive crop sequential effects, respectively).

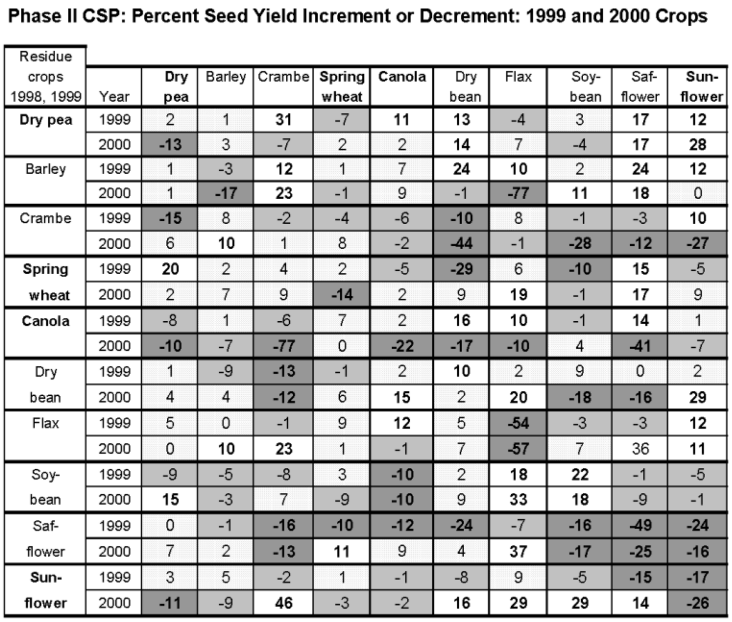
Absolute values of crop sequential effects are typically higher for Phase III CSP compared with Phase II CSP because under the precipitation-limiting conditions of the Phase III project yields were lower and both positive and negative effects were generally more related to water use effects than in the Phase II project. The upper right quarter of the Phase III chart (Table 2) had many positive effects from lower water using legumes as residue crops acting on heavier water using matrix crops. The lower rows of the Phase III chart show predominantly negative effects from heavy water using sunflower and sorghum acting as residue crops.

While the diagonals of both CSP's charts (Table 2), representing crop-on-own residue sequences, show predominately negative crop sequential effects, the lower right corners of the charts show an especially great density of negative effects, representing heavier water using residue crops acting on heavier water-using matrix crops. The non-endomycorrhizal mustard family crops canola and crambe, acting as residue crops in significantly wetter-than-average 1999, showed a number of negative crop sequential effects on matrix crops in 2000, apparently representing negative soil biological and/or plant pathological interactions under relatively higher soil water. The wetter than average 1999 to produce the residue crop also resulted in above average incidences of sclerotinia which increased inoculum present during the matrix crop year of 2000. Increased inoculum enhanced the potential for plant disease on susceptible crops. Canola and crambe have also been referred to as non-endomycorrhizal crops and do not form a symbiotic relationship with mycorrhiza (Harley and Smith 1983). Without the symbiotic relationship during the production of crop residue, succeeding crops would not have the benefit of mycorrhiza, especially for mycorrhiza dependent crops such as sunflower, dry pea, flax and dry bean. The result is lower crop production because of antagonistic factors.

Crop sequential effects are summarized in Table 3 for the major crop species in both CSP's. The data confirms that the value of the effects were often two or more times greater for the Phase III CSP compared with the Phase II CSP. The most consistent and general results were that legume crops had positive effects as residue crops and crops on their own residue showed negative effects.

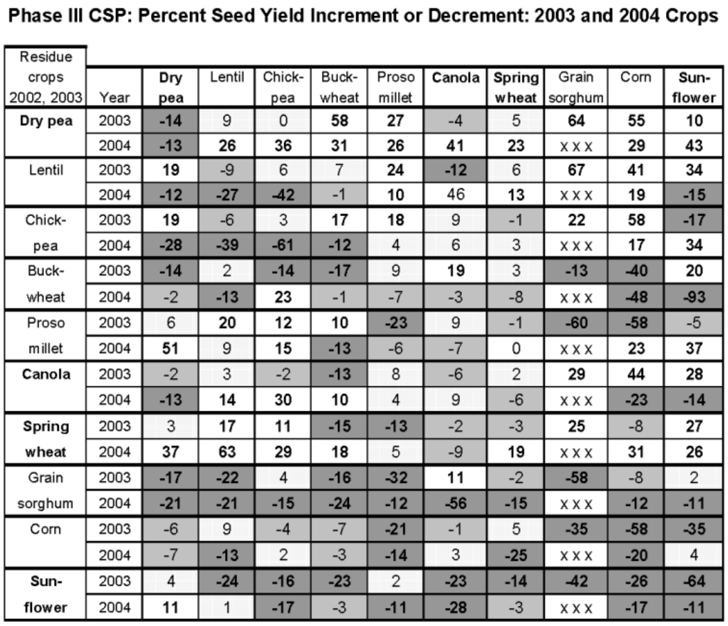
The legume dry pea showed approximately a three-fold greater positive crop sequential effect in precipitation-limited Phase III CSP compared with Phase II CSP, undoubtedly due to less water use by this species. The positive spring wheat effect was many time greater in Phase III than in Phase II, reflecting its superiority at snow capture

Table 2. Crop sequence effects as percent increases or decreases of seed yields relative to matrix crop annual means. Crop species are arranged from left to right and top to bottom in ascending order of average soil water depletion.



Phase II CSP: Percent Seed Yield Increment or Decrement: 1999 and 2000 Crops

Residue crops 1998, 1999	Year	**Dry pea**	Barley	Crambe	**Spring wheat**	**Canola**	Dry bean	Flax	Soy-bean	Saf-flower	**Sun-flower**
Dry pea	1999	2	1	31	-7	11	13	-4	3	17	12
	2000	-13	3	-7	2	2	14	7	-4	17	28
Barley	1999	1	-3	12	1	7	24	10	2	24	12
	2000	1	-17	23	-1	9	-1	-77	11	18	0
Crambe	1999	-15	8	-2	-4	-6	-10	8	-1	-3	10
	2000	6	10	1	8	-2	-44	-1	-28	-12	-27
Spring wheat	1999	20	2	4	2	-5	-29	6	-10	15	-5
	2000	2	7	9	-14	2	9	19	-1	17	9
Canola	1999	-8	1	-6	7	2	16	10	-1	14	1
	2000	-10	-7	-77	0	-22	-17	-10	4	-41	-7
Dry bean	1999	1	-9	-13	-1	2	10	2	9	0	2
	2000	4	4	-12	6	15	2	20	-18	-16	29
Flax	1999	5	0	-1	9	12	5	-54	-3	-3	12
	2000	0	10	23	1	-1	7	-57	7	36	11
Soy-bean	1999	-9	-5	-8	3	-10	2	18	22	-1	-5
	2000	15	-3	7	-9	-10	9	33	18	-9	-1
Saf-flower	1999	0	-1	-16	-10	-12	-24	-7	-16	-49	-24
	2000	7	2	-13	11	9	4	37	-17	-25	-16
Sun-flower	1999	3	5	-2	1	-1	-8	9	-5	-15	-17
	2000	-11	-9	46	-3	-2	16	29	29	14	-26

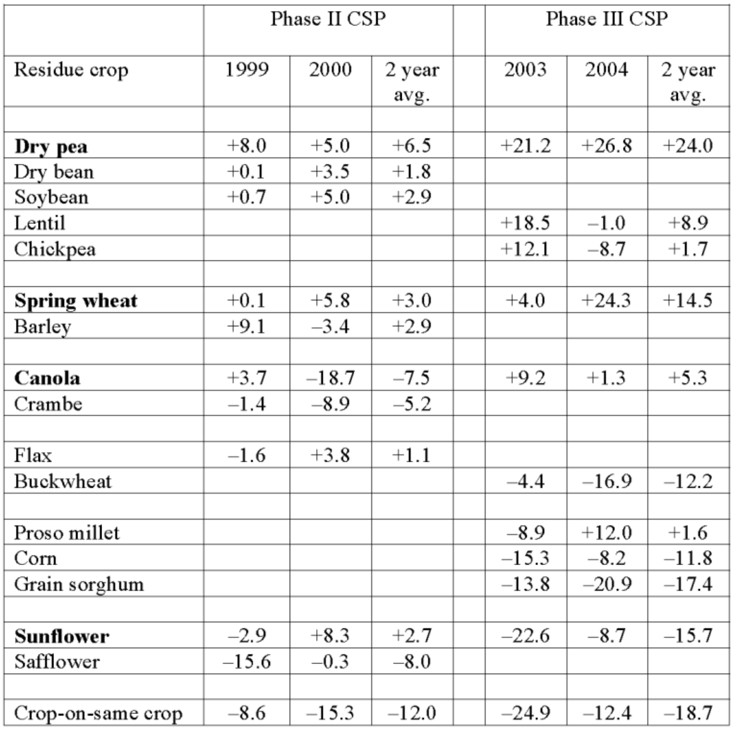


Phase III CSP: Percent Seed Yield Increment or Decrement: 2003 and 2004 Crops

Residue crops 2002, 2003	Year	**Dry pea**	Lentil	Chick-pea	Buck-wheat	Proso millet	**Canola**	**Spring wheat**	Grain sorghum	Corn	**Sun-flower**
Dry pea	2003	-14	9	0	58	27	-4	5	64	55	10
	2004	-13	26	36	31	26	41	23	x x x	29	43
Lentil	2003	19	-9	6	7	24	-12	6	67	41	34
	2004	-12	-27	-42	-1	10	46	13	x x x	19	-15
Chick-pea	2003	19	-6	3	17	18	9	-1	22	58	-17
	2004	-28	-39	-61	-12	4	6	3	x x x	17	34
Buck-wheat	2003	-14	2	-14	-17	9	19	3	-13	-40	20
	2004	-2	-13	23	-1	-7	-3	-8	x x x	-48	-93
Proso millet	2003	6	20	12	10	-23	9	-1	-60	-58	-5
	2004	51	9	15	-13	-6	-7	0	x x x	23	37
Canola	2003	-2	3	-2	-13	8	-6	2	29	44	28
	2004	-13	14	30	10	4	9	-6	x x x	-23	-14
Spring wheat	2003	3	17	11	-15	-13	-2	-3	25	-8	27
	2004	37	63	29	18	5	-9	19	x x x	31	26
Grain sorghum	2003	-17	-22	4	-16	-32	11	-2	-58	-8	2
	2004	-21	-21	-15	-24	-12	-56	-15	x x x	-12	-11
Corn	2003	-6	9	-4	-7	-21	-1	5	-35	-58	-35
	2004	-7	-13	2	-3	-14	3	-25	x x x	-20	4
Sun-flower	2003	4	-24	-16	-23	2	-23	-14	-42	-26	-64
	2004	11	1	-17	-3	-11	-28	-3	x x x	-17	-11

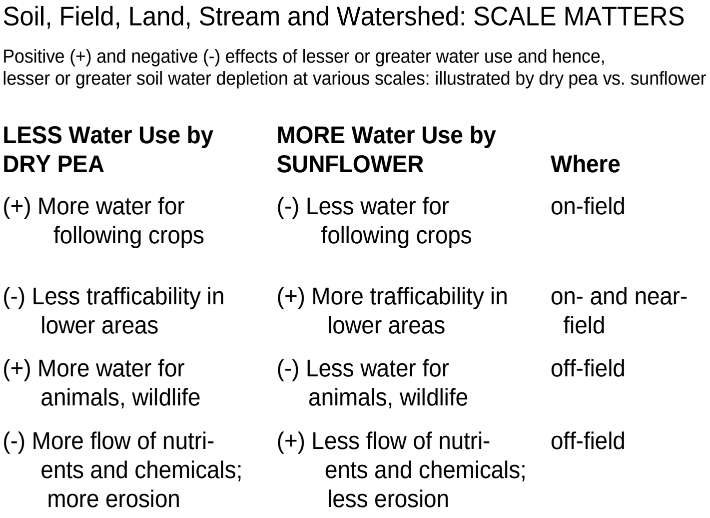
□	░	▒	▓
> 10% effect	< 10%, > 0%	< 0%, > -10%	< -10%

Table 3. Crop sequential effects as average percent seed yield increment or decrement that a residue crop causes matrix crops to exhibit for Phase II and Phase III crop sequence projects (CSP's).



	Phase II CSP				Phase III CSP		
Residue crop	1999	2000	2 year avg.		2003	2004	2 year avg.
Dry pea	+8.0	+5.0	+6.5		+21.2	+26.8	+24.0
Dry bean	+0.1	+3.5	+1.8				
Soybean	+0.7	+5.0	+2.9				
Lentil					+18.5	–1.0	+8.9
Chickpea					+12.1	–8.7	+1.7
Spring wheat	+0.1	+5.8	+3.0		+4.0	+24.3	+14.5
Barley	+9.1	–3.4	+2.9				
Canola	+3.7	–18.7	–7.5		+9.2	+1.3	+5.3
Crambe	–1.4	–8.9	–5.2				
Flax	–1.6	+3.8	+1.1				
Buckwheat					–4.4	–16.9	–12.2
Proso millet					–8.9	+12.0	+1.6
Corn					–15.3	–8.2	–11.8
Grain sorghum					–13.8	–20.9	–17.4
Sunflower	–2.9	+8.3	+2.7		–22.6	–8.7	–15.7
Safflower	–15.6	–0.3	–8.0				
Crop-on-same crop	–8.6	–15.3	–12.0		–24.9	–12.4	–18.7

Table 4. Scale matters: a consideration of the agronomic, hydrological, and environmental consequences of greater or lesser water use by different crop species acting at multiple soil and land scales illustrated by the example of dry peas vs. sunflower.



Soil, Field, Land, Stream and Watershed: SCALE MATTERS

Positive (+) and negative (-) effects of lesser or greater water use and hence,
lesser or greater soil water depletion at various scales: illustrated by dry pea vs. sunflower

LESS Water Use by DRY PEA	**MORE Water Use by SUNFLOWER**	**Where**
(+) More water for following crops	(-) Less water for following crops	on-field
(-) Less trafficability in lower areas	(+) More trafficability in lower areas	on- and near-field
(+) More water for animals, wildlife	(-) Less water for animals, wildlife	off-field
(-) More flow of nutrients and chemicals; more erosion	(+) Less flow of nutrients and chemicals; less erosion	off-field

which resulted in spring wheat having relatively high average spring soil water content that nearly matching the soil water content of dry pea. Dry pea is inferior to spring wheat in snow capture and uses less soil water; therefore, spring soil water contents were similar.

Relatively heavy water-using corn and sunflower both exhibited negative average crop sequential effects in Phase III CSP, –12% and –16%, respectively (Table 3). However, sunflower acting as residue crop in wetter-than-average 1999 in Phase II CSP had a positive effect on matrix crops in 2000 (+8%). This can possibly be explained if it is hypothesized that the higher water-use of sunflower encouraged a healthier, less disease-prone soil environment under higher-than-average soil water conditions.

Precipitation and water-use efficiency

Water-use efficiency (WUE) is an agro-ecological parameter allowing for comparison of production efficiency among alternatives in a water-limited system. Seed, residue, and total WUE was calculated based on average yields of matrix crops following the four species common to both CSP's (Figure 6). For the Phase II CSP, which was conducted during above-average precipitation years, there was a negative trend evident between total WUE and water use; lower water-using species dry pea, barley and spring wheat had the three largest total WUE values.

For the Phase III CSP, there was no immediately obvious relationship between total WUE and water use. Furthermore, there was less consistency between the results for the two matrix crop years in the Phase III CSP compared with the Phase II CSP. The heavier water-using warm season grass crops corn and sorghum had 1st or 2nd highest total WUE in one or another of the years of the CSP, and the agro-botanically related proso millet was 1st in total WUE in 2004 and 2nd in 2003. Proso millet and corn were 1st and 2nd, respectively, for seed WUE in 2004. Dry pea showed relatively high total WUE under the especially water-limited conditions of 2004, a result attributable to its notably low water use that year.

Soil quality, soil coverage by residue, and soil conservation

The percentage of soil surface covered with crop residue was determined during both CSP's by recording observations using the cable transect method (Merrill et al. 2006; Krupinsky et al. 2007). Most of the measurements were made at a point in the crop management calendar when soil coverage was at a minimum – soon after passage of a seeding implement in the spring. Passage of a seeder is the most soil-disturbing agronomic operation in a no-till management system. The majority of the measurements were made in plots seeded to spring wheat after passage of the seeder but before any crop emergence occurred.

Results were grouped into three categories (Figure 7): (a) following crop sequences having the highest coverage percentages; (b) following crop sequences with spring wheat in the first year and one of the relatively lowest residue-producing species in the second and (c) following sequences having the lowest coverage percentages. For Phase II CSP, sequences with spring wheat and barley produced residue coverage >90%. In Phase III CSP, grain sorghum and proso millet as well as spring wheat in sequences also produced high coverage levels >90%. Crop sequences with sunflower and dry pea in various combinations, or sunflower with itself and other crops produced the lowest coverage levels in Phase II CSP, about 40 to 50%. Phase III CSP sequences with dry pea had coverage levels at least 58% or greater, which raises the probability that post harvest weed growth raised coverage levels, especially in the case of shorter-season crops like dry pea.

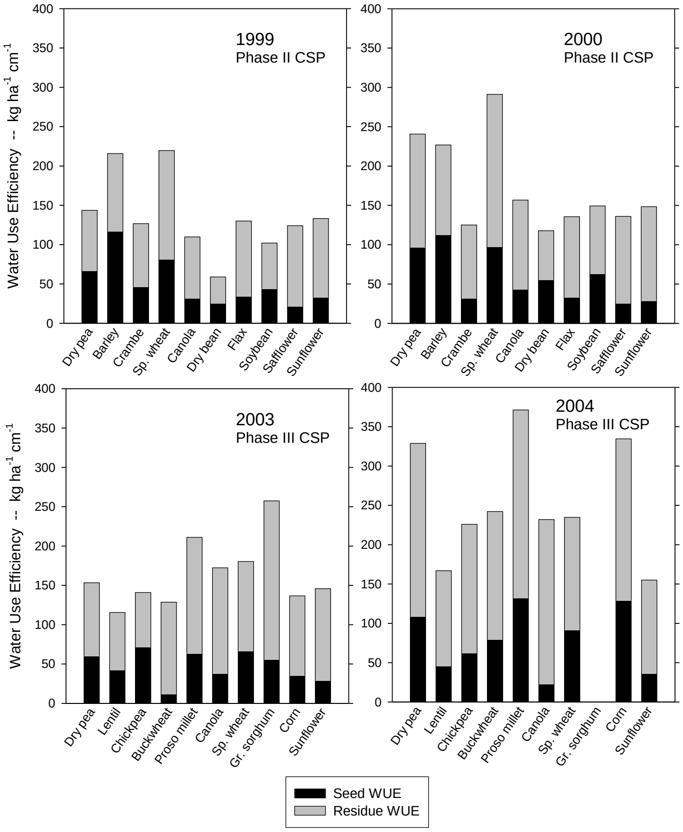


Figure 6. Water use efficiency (yield/seasonal water use) of seed and residue yields of matrix crops in crop sequence projects (CSP's). Crop species are arranged left to right in order of increasing 2-yr average SWD. The SWD accounting period was approximately mid-May to mid-September.

Coverage percentages following sequences in which spring wheat is the first year crop and the lower residue-producing species is the second crop were at least 10 percentage points greater and typically 20 percentage points or more greater than coverage percentages for combinations of lower residue crops (Figure 7). The SpW/SpW sequence (>90%) had the highest residue coverage, while Sun/Sun sequence was on average 40% to 50% lower. When spring wheat was the first crop, SpW/Sun sequences had about 35% greater residue coverage compared with Sun/Sun.

Simple, empirical wind and water erosion risk formulas taken from soil erosion models were applied to our results (Merrill et al. 2006; Krupinsky et al. 2007). The lowest coverage levels of about 40% indicated lower to moderate theoretical levels of erosion risk could be present. For non-fragile well-managed land, this should not be a substantial problem. For cropping systems managed with no-till, risk of soil erosion occurs when fragile soils are seeded to low-residue producing crops such as sunflower or dry pea. When drought is constant with tillage and such practices as summer fallow, soil erosion can occur. This was demonstrated in an experiment in which actual wind erosion losses were measured on the same soil and land type as

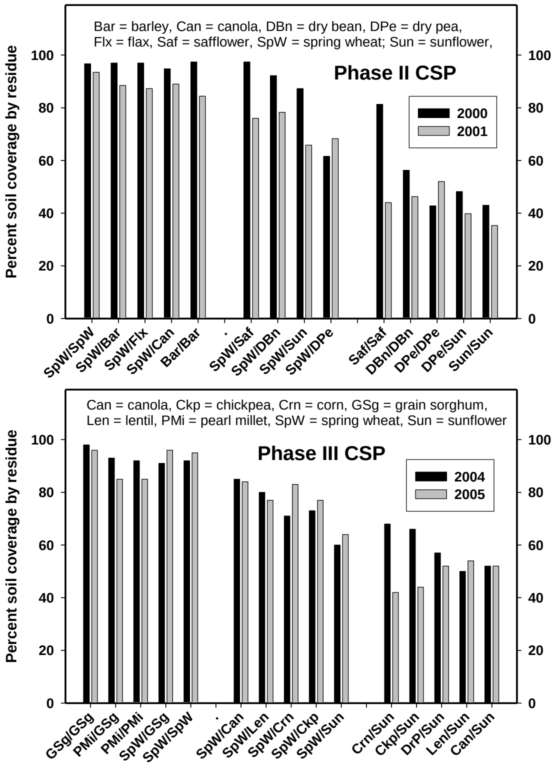


Figure 7. Soil coverage by residue measured in crop sequence projects (CSP's) soon after seeding of spring wheat in early May of the year following the indicated 2-yr. crop sequences.

these CSP's (Merrill et al. 2004b). Sunflower stubble land was subjected to spring tillage levels (no-till, moderate, and heavy tillage) followed by chemical fallowing. During a year of significantly below-average summer precipitation, good weed control on no-till resulted in unacceptable levels of wind erosion control. During a repeat of the experiment in the following year, marginally higher and better distributed precipitation coupled with less effective weed control reduced measured erosion loss ten-fold.

Thus, for the sake of best soil conservation practice, farmers are well advised to precede such crops as sunflower and dry pea with a small grain crop. Flax can also provide a durable preceding crop (Merrill et al. 2006). Depending on the soil susceptibility to erosion, safflower, lentil, and chickpea could be added to the list of crops of concern.

4.3. Trends and conclusions

Soil water depletion and recharge

Crops determined to have the 1st, 2nd, and 3rd highest levels of SWD in the Phase II CSP were sunflower, safflower, and soybean, respectively. Crops determined to have the highest levels of SWD in Phase III CSP were sunflower, corn, and grain sorghum, respectively. Crops depleting the 1st, 2nd, and 3rd least amounts of soil water in the Phase II CSP were dry pea, barley, and crambe. For the Phase III CSP, these three crops were dry pea, lentil, and chickpea, respectively.

The amount of water found in the soil profile at seeding time in the spring affects crop production in a direct manner. In the Phase III CSP, the crop leaving the greatest amount of soil water the following spring, and the crops leaving the 2nd and 3rd greatest amounts of soil water were dry pea, spring wheat, and lentil, respectively. Crops leaving the least, 2nd least, and 3rd least amounts of soil water in the spring were sunflower, chickpea, and corn, respectively.

The greatest determinant of springtime soil water is soil water depletion by the previous season's crop. This can be modified by differing abilities of crop residues to capture snow and subsequent spring snow melt. Also spring soil water can be decremented by post-harvest weed control.

Productivity and crop sequence effects

In the Phase II CSP, flax, crambe, and safflower were the 1st, 2nd, and 3rd crops, respectively, most sensitive to crop sequence as determined by seed yield. In the Phase III CSP, the 1st, 2nd, and 3rd most crop sequence-sensitive crops were grain sorghum, corn, and sunflower. The 1st, 2nd, and 3rd least crop sequence-sensitive crops for the Phase II CSP were spring wheat, barley, and dry pea, respectively, while the three crops for the Phase III CSP were spring wheat, proso millet, and dry pea. In general, higher water-using crops tend to be more sensitive to crop sequences and lower water-using crops less sensitive to crop sequences. The five legume crops in both CSP's all exhibited positive average crop sequence (CS) effects. Crops growing on their own residues exhibited a considerably negative CS effect. Spring wheat (both CSP's) and barley (Phase II) had positive average CS effects. Canola and crambe, both non-endomycorrhizal species, exhibited negative average CS effects in Phase II CSP, but canola, present in Phase III, showed positive average CS effects. Heavier water-using safflower showed negative CS effects in Phase II CSP, but heavier water-using sunflower, which usually have negative CS effects, had positive CS effects following a year of significantly greater than average precipitation. Both heavier water-users corn and grain sorghum exhibited negative average CS effects in the Phase III CSP. In general, crop sequence effects of individual crops were 2 to 3 times greater during years of below-average precipitation (Phase III) when compared to years of average or above-average precipitation (Phase II).

Soil coverage by residue and soil conservation

Crops with the greatest levels of spring soil coverage by crop residue, with values generally 90% or more, were spring wheat, barley, and flax for Phase II CSP, and spring wheat, grain sorghum, and proso millet for the Phase III CSP. For both CSP's, dry pea and sunflower, and combinations of these crops with other non-small grain crops produced the lowest relative coverage values, generally in the range of 35 to 50%.

Seeding a small grain crop (spring and winter wheat, barley) in the year before sunflower or dry pea will raise the level of residue coverage after these crops by roughly 20 to 30%, improving soil erosion control.

Although all residue coverage levels were moderately protective because of no-till management, an active wind erosion measurement experiment demonstrated that sunflower stubble land subjected to chemical fallow and/or tillage can suffer unacceptably high levels of wind-erosive loss under drier climate conditions.

4.4. Application of research results (crop sequence calculator)

The volume of research data obtained from the CSP's and the need for a method to make the data available to users led to the development of the Crop Sequence Calculator (CSC), an interactive computer software program (Fehmi et al. 2001; Krupinsky et al. 2002b) (available at www.mandan.ars.usda.gov). The CSC was designed to help users assess crop options and crop sequencing information in a timely manner. The CSC runs directly from a CD-ROM, eliminating the need for additional disk space or installation procedures. The CSC is designed for computers running Windows® (95/98/ME/2000/ XP) and works best with a screen area of 800 X 600 pixels or greater. The CSC can show the short-term experimental crop production effects of the ten crops grown in any two-year combination, i.e. as grouped in Phase II and III CSP's. Expected crop prices and loan deficiency payments or crop premiums can be entered to provide rapid calculations. Past short-term experimental returns can be modified to provide estimated returns. Once the previous crop (residue producing crop) and the expected crop are entered with a click of the mouse, summary statements appear for crop and forage production, economics, plant diseases, soil water, weeds, soil quality and conservation, and insects. This information aids users in an evaluation of management risks associated with different crop sequences. The CSC also provides an introduction to the dynamic agricultural systems concept (Tanaka et al. 2002) and the crop sequence research project. Informative websites are also listed. Supplemental information, which is usually not readily available in a single resource, is easily accessed. For example, plant disease information includes an introduction to plant diseases, research data, internet resources, and photographs of plant diseases to aid in their identification. The CSC also includes numerous photographs of weeds and insects to aid in identification. Information is generally applicable to the northern Great Plains, where annual precipitation averages less than 43 cm (17 in).

The Crop Sequence Calculator can save users money by optimizing net returns for a given crop rotation. For example, a user who grows dry bean after barley can expect an average net loss of \$7.44 ha^{-1} (\$3.00 acre^{-1}). However, if that same user grew dry bean after wheat, the result would be a net gain of \$158.42 ha^{-1} (\$64.00 acre^{-1}). The CSC shows net returns for dry bean varied by as much as \$260.40 ha^{-1} (\$105.00 acre^{-1}) depending on the previous crop. Wheat was much more stable and showed differences of less than \$49.60 ha^{-1} (\$20.00 acre^{-1}) depending on crop sequence. Considering the hundreds of farm acres planted to various crops each year, the CSC provides substantial savings to producers who take advantage of this important technology.

The CSC provides information awareness, one of the key factors of a dynamic cropping system. The number of requests for the CSC clearly indicates that this technology fulfills a substantial need of the agricultural community. Since its release in mid-January, 2001, over 2,300 copies of the CSC, v. 1, and over 9,700 copies of CSC, v. 2 have been distributed, making a total distribution of nearly 12,000 copies. The impact of the CSC has been far reaching. In addition to being requested by hundreds of individual producers, the CSC has been promoted and requested by numerous groups within the agricultural community. For example, the CSC was featured in The Sunflower Magazine (Anon. 2001, 2002), a publication of the National Sunflower Association. The CSC was featured in the Agricultural Research magazine (Comis 2002). Requests have been made to demonstrate the CSC at the board meetings of several commodity groups and at a number of producers meetings in the US and Canada. Seed companies have requested many copies of the CSC for their suppliers and customers. At the request of the USDA—

Natural Resource Conservation Service, the CSC has been placed in all NRCS field offices in North Dakota. Furthermore, scientists of the North Dakota State University Extension Service also have distributed the CSC throughout North Dakota, South Dakota, and eastern Montana. A number of Canadian and U.S. banks have seen utility in the use of the CSC as a spring planning tool and have requested copies for their use and for use by their customers.

The concept of using CSC-type technology to distribute information has been successful. Even producers outside the northern Great Plains region have requested a CSC-like product for their particular regions. As producers become accustomed to new information technologies, they are not as willing to accept a time lag in receiving the latest in research information as they were in the past, particularly with a challenging economic environment. Future challenges to research scientists are to provide user-friendly information that can be readily accessed by producers in a more timely manner.

4.5. Dynamic cropping systems: Future opportunities

Introduction

As we enter the 21st century, agriculture faces challenges unlike any other time in human history. Human population growth this century will increase demand of food, feed, and fiber well above current production levels (Brown 2006; United Nations Population Division 2006), and will require agriculture to become more resource intensive in a world where nonrenewable resources are increasingly scarce and have clear monetary and environmental drawbacks (Diamond 2005). Additionally, these momentous challenges will be addressed when changes to the global climate are accelerating (Flannery 2006), the impacts of which are projected to have overwhelmingly negative effects on agroecosystems (Lobel and Asner 2003; Nearing et al. 2004; Shaobing et al. 2004).

Responses to future challenges in agriculture will include the development of new and innovative production systems that are highly productive, effectively utilize renewable resources, and minimize damage to the environment (Hanson et al. 2007). Meeting these multiple goals will be no small feat, as it will require more complex, diverse, and management-intensive production systems than currently employed (Kirschenmann 2007). Furthermore, future agroecosystems will need to be inherently ‘dynamic’ in order to provide producers with multiple options to adapt to changing socioeconomic and environmental conditions (Hanson et al. 2007). Given this context, dynamic cropping systems appear have an important role to play in the future of agriculture.

Future application of dynamic cropping system concepts may take many forms, depending on the context in which they are applied. However, there are two emerging areas in agriculture with particular relevance to dynamic cropping systems, namely, integration of crops and livestock, and use of agroecosystems for bioenergy production. Both topics will be briefly discussed, with emphasis on potential research opportunities within each.

Integration of dynamic cropping systems with livestock production

Integrating crop and livestock production can improve agroecosystem productivity, environmental quality, operational efficiency, and economic performance relative to specialized, single-enterprise agricultural production systems (Russelle et al. 2007).

Agronomic and environmental benefits from crop/livestock integration stem largely from production synergies brought about by using crops and crop residues for livestock feed while capturing recycled nutrients from livestock manure for crop production (Karn et al. 2005; Tanaka et al. 2005). The extent of these synergies may be increased through the application of dynamic cropping systems, though a number of unknown factors could affect system performance. For dynamic cropping systems utilizing an annual cropping strategy, these factors – phrased as questions – may include:

- What is the forage value of individual crops within a crop portfolio?
- How does forage value of individual crops change over the course of a growing season?
- What is the forage value of crop residue?
- What are the threshold levels of crop residue that permit grazing or haying without compromising subsequent crop productivity or impairing soil function?
- In what ways can cover crops (individually and in mixtures) be used to meet forage needs in dynamic cropping systems?
- How is livestock performance affected by grazing crops or crop residue relative to conventional grazing strategies?
- Are some species of livestock better suited to utilize certain crops?
- Are crops most efficiently utilized by single or multiple livestock species?
- Inclusion of perennial crops in cropping systems can improve yields of annual crops following stand termination, reduce weed infestations, and improve soil quality (Entz et al. 2002). For dynamic cropping systems utilizing perennial crops in a crop sequence, questions in addition to those outlined above can be raised. For instance:
- What is the crop portfolio for perennial species?
- What crops, crop sequences, and associated management practices are most effective at promoting the establishment and subsequent productivity of perennial crops?
- How long should the perennial phase be growing to optimize agronomic performance of and environmental benefits from the forage crop?
- What management practices need to be employed to successfully transition from perennial to annual cropping?
- Which annual crops in a portfolio should be sequenced following the perennial phase in order to maximize agronomic performance while minimizing negative environmental impacts?

Numerous additional research questions can – and should – be addressed, with particular emphasis on economic performance and environmental outcomes of different integration strategies. Moreover, given that crop and livestock integration can occur within or among farms (Russelle et al. 2007), all of the above research questions possess scale dependency.

Capitalizing on production synergies by integrating crops and livestock in a ‘dynamic’ context will undoubtedly increase system complexity considerably over ‘business as usual’ production systems. Understanding biological interactions contributing production synergies, and providing sound management recommendations based on those interactions, will require long-term research commitments by multidisciplinary teams capable of working together. Furthermore, as pointed out by Russelle et al. (2007), management complexities associated with integrated crop/livestock systems may limit their adoption by producers. Consequently, interdisciplinary research teams will need to be closely aligned with effective outreach programs in order to increase the likelihood of producer adoption.

Inclusion of bioenergy crops in dynamic cropping systems

The use of crops as biofeedstocks has received increased interest as a way to reduce dependence on fossil-based energy, more efficiently use plant nutrients, and mitigate negative environmental impacts from agroecosystems (Anex et al. 2007). Understanding rotational benefits and drawbacks of annual and perennial biofeedstocks will be essential in order to maximize cropping system performance and net energy returns (Liebig et al. 2007). Accordingly, many of the questions outlined above for integrating crops and livestock apply to the inclusion biofeedstocks in dynamic cropping systems. Additional questions unique to biofeedstocks may include:

- What are the most effective management approaches to transition between annual crops and perennial biofeedstocks (and vice versa) for achieving maximum net energy returns without impacting food security?
- For annual biofeedstocks, how might dynamic cropping systems be intensified (e.g., intercropping and/or inclusion of cover crops) in order to mitigate potential negative consequences from crop residue removal?
- What are the agronomic, energetic, and environmental benefits and drawbacks of annual vs. biennial harvesting of perennial biofeedstocks?

Cropping systems for bioenergy generation have the potential to concurrently achieve production, energetic, and environmental goals. The degree of success in achieving multiple goals has been proposed to be associated with how well the production and conversion of biofeedstocks are integrated (Anex et al. 2007). In this regard, linkages between biofeedstock and livestock production are certainly conceivable, particularly for perennial forages possessing favorable attributes as lignocellulosic bioenergy sources. Flexibility to use crops in multiple ways (e.g., harvest for feed or fuel, or graze) provides producers with options to most effectively respond to market trends and/or environmental constraints. Such flexibility is the cornerstone of adaptive management (Kirschenmann 2007), which relies on the utilization of biological synergies to meet production goals.

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