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Water use in a modified summer fallow system on semiarid northern Great Plains

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Abstract

Wheat (*Triticum aestivum* L.) is the major crop on semiarid northern Great Plains of the USA. Attempts to introduce alternate crops have had limited success. Alternate fallow-spring wheat rotation is the most common cultural practice. Our objective was to investigate water use and water use efficiency and suitability of alternative crops in semiarid northern Great Plains agricultural environment. The study was on glacial till Williams loam (fine-loamy mixed, Typic Argiboroll) 11 km north of Culbertson, MT. Plots, replicated four times in randomized blocks, were 12 m × 15 m. Rotations were: (1) fallow, sunflower (*Helianthus annuus* L.), barley (*Hordeum vulgare* L), winter wheat; (2) fallow, safflower (*Carthamus tinctorious* L.), barley, winter wheat; (3) fallow, buckwheat (*Fagopyrum esculentum* Moench.), annual legume/grain forage crop, spring wheat; (4) fallow, buckwheat, annual legume/grain forage crop, winter wheat; (5) fallow, spring wheat; (6) continuous spring wheat. Soil water to 1.8 m depth was determined near time of seeding and of harvest by neutron attenuation. The soil reached an upper drained limit of 0.20–0.25 $m^3\ m^{-3}$ water in a 1.8 m profile, equating to no more than 450 m water. Safflower and sunflower used ca. 500 mm water, more water than any of the other crops used. The greatest growing season water use efficiency was captured by the annual forage crop. Except following safflower and sunflower, soil water every spring was near the upper drained limit. Deep rooted crops can have a place in rotations on the semiarid northern Great Plains. But one must be prepared for variable yields and potential reduced yields following deep rooted crops, and for an occasional crop failure. Crop and soil management for alternative crops differ from that of small grain management, requiring some adaptation of management practices. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Water use efficiency; Alternate crops; Crop rotations; Spatial variability

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1. Introduction

Wheat is the major crop on the semiarid northern Great Plains of the USA. For example, 76% of 1,045,629 dryland hectares harvested on the eastern plains of Montana is wheat. Barley and oats (*Avena sativa* L.) occupy 82,377 ha (8%). The remaining 16% is occupied by hay and some corn (*Zea mays* L.) (Montana Agricultural Statistics Service, 1995). There have been sporadic attempts to diversify the crop base from essentially a small grains monoculture by including rotations other than fallow and by planting some minor land areas to crops such as deep rooted oil seed crops. Soil water deficiency and instability of weather are the factors that most limit choices of crops available for cultivation on the semiarid northern Great Plains of the USA. Zentner et al. (1990) discussed crops available and recounted benefits of crop rotation on the Canadian portion of the northern Great Plains.

Summer fallow has been- and continues to be -the most common cultural practice. Soil water conservation, necessary for successful crop production in the northern Great Plains, is the main reason for summer fallow. Other benefits to be derived from the summer fallow practice are weed control, and release of plant nutrients. However, there are also drawbacks to summer fallow such as poor soil water storage efficiency and enhanced soil erosion (Tanaka and Aase, 1987; Black and Bauer, 1988; Steiner, 1988). Saline seep development – water, carrying dissolved salts, percolating through the soil profile to an impermeable layer and discharging to the soil surface at a downslope area – is also associated with alternating summer fallow-crop practice (Schneider et al., 1980; Brown et al., 1983). The question is whether other crops, especially deep rooted crops, can be successfully grown in rotation with small grains. Deep rooted crops may extract nutrients and soil water from depths below the nominal 1.2 m rooting depths of small grains.

Our objective was to investigate water use and water use efficiency and suitability of alternative crops in semiarid northern Great Plains agricultural environment.

2. Materials and methods

The study, located 11 km north of Culbertson, MT, was established in 1991 on a 7 ha field that had previously been farmed in a fallow-wheat rotation receiving no fertilizer. The soil, classified as Williams loam (fine-loamy mixed, Typic Argiboroll), formed on glacial till. The plots, replicated four times in a randomized block design, were 12 m × 15 m. There were 19 plots per replicate to accommodate six crop rotations. Each rotation was arranged so every crop was grown every year. The rotations as listed in Table 1, are exemplified by the rotation sequence beginning with fallow in 1991.

We seeded spring wheat, winter wheat, and barley at between 2 and 2.5 million seeds ha^{-1}, annual forage for hay production at ca. 131 kg ha^{-1}, buckwheat at ca. 46 kg ha^{-1}, and safflower at ca. 29 kg ha^{-1}. Sunflower was seeded at ca. 53,500 seeds ha^{-1} in 1991, 1992, and 1993 and at ca. 58,000 plants ha^{-1} in 1995. In 1994, we seeded miniature sunflower at ca. 200,000 seeds ha^{-1}. Seedbed preparation was generally done with sweeps and rod attached to a toolbar. When necessary, because of hard soil-crusts, a disk

Table 1
Crop rotations exemplified by rotation sequences starting with fallow in 1991

Rotation	Crop				
	1991	1992	1993	1994	1995
1	fallow	sunflower	barley	winter wheat	fallow
2	fallow	safflower	barley	winter wheat	fallow
3	fallow	buckwheat	forage[a]	spring wheat	buckwheat[b]
4	fallow	buckwheat	forage[a]	winter wheat	buckwheat[b]
5	fallow	spring heat	fallow	spring wheat	fallow
6	fallow	spring wheat	spring wheat	spring wheat	spring wheat

[a] Ratio of six to five by weight Austrian winter pea (*Pisum sativum* subsp. *Arvense* (L.) Poir) and oats (*Avena sativa* L.) in 1991 and 1992; field pea (*Pisum sativum* L. and triticale (X *Triticosecale* Whittm.) in 1993; field pea and oats in 1994 and 1995.

[b] Because of problems with volunteer buckwheat in succeeding forage crop, rotation was altered in 1994 so buckwheat would precede fallow.

was used prior to using sweeps. Fallow operations were also performed with sweeps and rod, with disk treatments as necessary.

Phosphorus requirements (Halvorson and Black, 1985a, b), and nitrogen requirements for the first 3 years, were satisfied by the application of 250 kg ha^{-1} of diammonium phosphate (18–46–0) to all plots in 1991, and to all plots except fallow in 1992. In 1993 plots that were in fallow in 1992 received 250 kg ha^{-1} of 18-46-0. In 1994 and 1995, all cropped plots received 34 kg ha^{-1} of ammonium nitrate (34–0–0). Additionally, in 1995, forage and buckwheat received 50 kg ha^{-1} of monoammonium phosphate (11–55–0) with the seed.

As needed, we used appropriate herbicides to control grassy and broad-leaved weeds.

Details of yield sampling for each crop are listed in Table 2. Yield samples were cut near the soil surface except for sunflower heads, and threshed (except for forage) for grain and seed yield determination. Because of a wet and cool season in 1993, safflower did not mature and, therefore, was not harvested. Two meter deep neutron probe access tubes were located in the middle of each plot. Soil water at 0.3 m increments to a depth of 1.8 m was determined by neutron attenuation as a minimum near time of seeding and at harvest. The neutron probe was calibrated according to procedure outlined by Pikul and Aase (1998). Precipitation was monitored at a nearby automated weather station. Soil water holding capacity was determined from field measured estimates of upper and lower drained soil water limits based on wettest and driest soil water content profiles.

At the onset of the study, prior to imposition of any treatments, and starting with the southwest corner, soil cores were taken from every other plot to a depth of 1.8 m. The cores were cut into eight segments: 0–0.075, 0.075–0.15, 0.15–0.30, 0.30–0.60, 0.60–0.90, 0.90–1.20, 1.20–1.50, and 1.50–1.80 m for water content determination, textural and other analyses.

Water use, defined as beginning soil water content minus ending soil water content plus precipitation, and water use efficiency (WUE), defined as crop yield divided by water use, were calculated and comparisons made for growing season and for yearly

Table 2
Yield sampling procedures for each crop from each plot

Year	Crop						
	Spring wheat	Winter wheat	Barley	Safflower	Buckwheat	Sunflower	Forage
1991	six samples at 1 m^2	six samples at 1 m^2	six samples at 1 m^2	six samples at 1 m^2	six samples at 1 m^2	five samples at 2 rows × 2.4 m	–[a]
1992	six samples at 1 m^2	six samples at 1 m^2	six samples at 1 m^2	six samples at 1 m^2	combine 2 strips at 1.2 × 10 m	six samples at 2 rows × 2.4 m	six samples at 5 rows × 1 m
1993	six samples at 1 m^2	six samples at 1 m^2	six samples at 1 m^2	–[b]	combine 2 strips at 1.2 × 10 m	six samples at 2 rows × 2.4 m	1 m samples from 4 swaths at 2.9 m wide
1994	six samples at 1 m^2	six samples at 1 m^2	six samples at 1 m^2	six samples at 1 m^2	combine 2 strips at 1.2 × 10 m	combine 3.6 × 10 m	1 m samples from 4 swaths at 2.9 m wide
1995[c]	–	–	–	–	–	–	–

[a] Missing.

[b] Did not mature, no harvest.

[c] Hail damaged/destroyed, no reliable data.

cycle from spring seeding to following spring seeding; as well as for complete 4-year-cycle of each rotation. Although some runoff was observed from all plots, runoff along with deep percolation were considered negligible for water balance calculations.

Analysis of variance with least significant difference and Duncan's multiple range test to separate means were used in data analyses.

3. Results and discussion

3.1. Precipitation

The study area has a summer precipitation pattern that varies greatly around monthly averages. June has the greatest average monthly precipitation with 75 mm. In 4 of the 5 years of study, yearly total precipitation was more than the 361 mm average (Fig. 1). The exception was 1994 with 84% of average. However, during May and June 1994 (critical months for wheat growth and development), rain was average and above average, respectively.

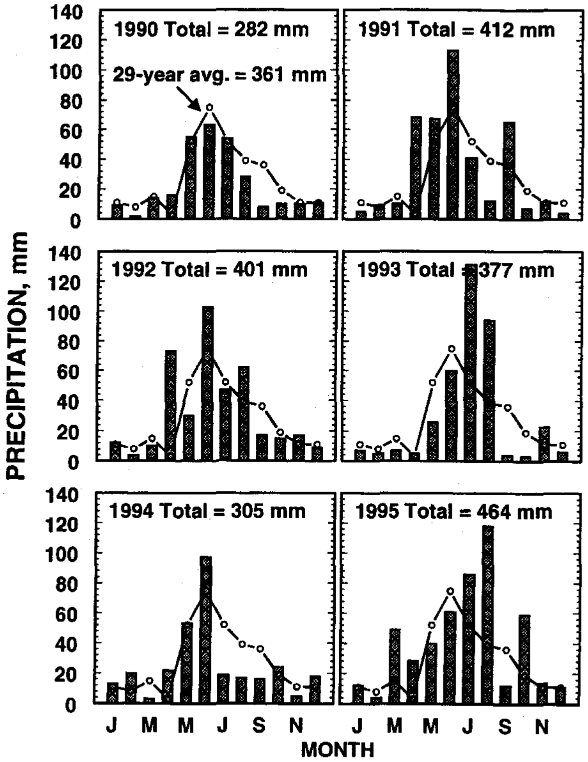

Fig. 1. Monthly and yearly total precipitation for years of study, plus long-term average monthly and average yearly precipitation (shown as solid line).

Precipitation data for 1990 are included in Fig. 1 to illustrate the potential for soil water recharge for the 1991 establishment year of the study. Because fall rains in 1990 were below average and precipitation during the 1990–1991 winter about average, the potential for filling the soil water profile to capacity between wheat harvest in 1990 and early crop seeding in 1991 was marginal. However, rains during April of 1991 made for favorable planting conditions. Average water content in the 1.8 m soil profile was 399 mm at spring planting in 1991.

April rains during 1992 were similar to those of 1991 and created favorable conditions for planting. The rest of 1992 had a near average distribution of precipitation and a favorable growing season. In 1993 there was a paucity of rain during early spring and summer, but because of abundant rains during July and August yearly total precipitation was above average.

3.2. Soil water holding capacity

Yearly soil water content cycles in the 1.8 m soil profile of this glacial till soil indicate that soil water holding capacity may limit crop production (Fig. 2, and Table 3). Because of the large number of soil water content profiles generated, only plots with crop sequences that started with fallow in 1991 are presented in Fig. 2and in Table 3 to represent each rotation.

The first winter of the typical 21-month fallow period for fallow-spring wheat rotation is generally the most important for soil water storage, contributed from winter precipitation and snowmelt. The soil profile may reach maximum, or near-maximum, water holding capacity prior to the second winter of fallow, resulting in little if any gain during that period (Staple and Lehane, 1952; Black and Siddoway, 1976; Tanaka, 1985; Tanaka and Aase, 1987).

Soil water profile curves from fall of 1991 (first row in Fig. 2) and from spring of 1992 (second row) represent a second overwinter fallow period. Since there was adequate rain during 1991 and over-winter precipitation was near normal (Fig. 1), one would expect that soil water should have remained reasonably constant during the second overwinter period. The first two depths in rotation 1 through 5 did in fact gain water (only 4.0 and

Table 3
Soil water content to 1.8 m depth near spring seeding time of each year and at completion (Spring 1995) of six rotation sequences beginning with fallow in 1991

Rotation sequence	Spring soil water content (mm)				
	1991	1992	1993	1994	1995
Fal.–Sunfl.–Barley–W. wh.	327	342	250	305	344[a]
Fal.–Saffl.–Barley–W. wh.	407	413	321	381	413
Fal.–Buckwh.–Forage–Sp. wh.	400	413	370	413	395
Fal.–Buckwh.–Forage–W. wh.	445	442	419	436	445
Fal.–S. wh.–Fal.–Sp. wh.	385	411	376	450	390
Fal.–Sp. wh.–Sp. wh.–Sp. wh.	427	409	371	432	429

[a] Statistically significant ($P \leq 0.05$) from spring 1991 value.

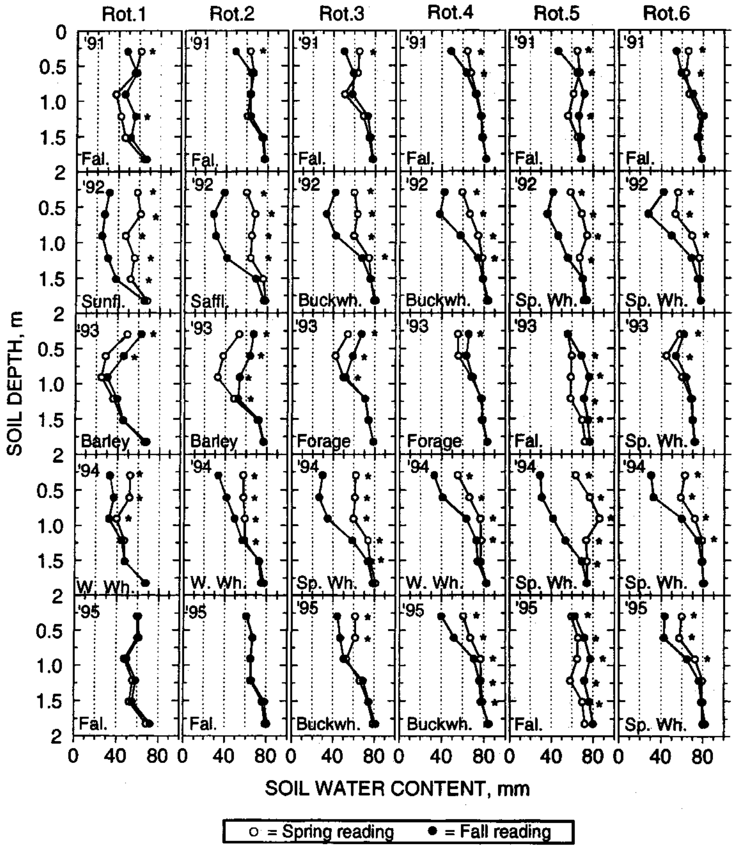

Fig. 2. Sample soil water profiles from each of six crop rotations. Asterisks denote significant differences at given depths at $P \leq 0.05$.

5.8%) during the second winter ($P \leq 0.05$). Soil water in the 1.8 m profiles averaged 363 mm in the fall of 1991 and 405 mm in the spring of 1992. Nevertheless, the fall 1991 and spring 1992 soil water profiles (first and second rows in Fig. 2) look much alike. Rotation 6 lost a nonsignificant 2.6%.

This soil water replenishment pattern is illustrated with the even-year fallow-spring wheat rotation as depicted in Fig. 2, and with both even and odd year rotations as represented in Table 4. An exception to the replenishment pattern occurred during the fall 1993 to spring 1995 fallow period. The soil water profile was nearly filled by the more than twice average rain that fell during July and August 1993 (Fig. 1), prior to the first winter period. There was essentially no change in soil water content during the first winter (1993–1994) and only a small gain occurred during the second overwinter period from 1994 to 1995 (Table 4).

Fall and overwinter precipitation (77 mm) from 1992 to 1993 appeared not to be adequate to recharge any of the soil profiles (Fig. 2, and Table 3). The abundant rains

Table 4
Soil water gain, measured to 1.8 m depth, for three fallow segments during 21 month fallow between spring wheat crops

Fallow period	Fallow segments		
	Fall to spring (first winter), mm	Spring to fall (summer), mm	Fall to spring (second winter), mm
Fall 1990 to Spring 1992	–	3	23
Fall 1991 to Spring 1993	52	67	−2
Fall 1992 to Spring 1994	50	49	24
Fall 1993 to Spring 1995	−7	7	17
Fall 1994 to Spring 1996	90	50	–

during July and August 1993 caused the soil profiles to either fill or remain static for all plots except safflower, sunflower, and buckwheat.

The soil apparently reached an upper drained limit, which varied some depending on location in the field. Water content at 1.8 m depth varied some among plots but remained constant within plots, suggesting that soil water at 1.8 m depth remained at the upper drained limit.

Soil developed from glacial till has an inherent soil textural variability which in turn causes available soil water variability. To illustrate, as shown in Fig. 3, we selected the 0.6–0.9 m depth, typical of all depth increments, to represent the textural and soil water variability of the soil profile. Depending on the location in the field, it therefore appears that the amount of water that can be stored in this soil varies from about 0.20–0.25 $m^3 m^{-3}$ in a 1.8 m profile, or no more than about 450 mm (Table 3).

Water draining past the root zone has implications for development of saline seeps and also the potential for leaching of any excess nutrients and other chemicals that may have been applied to the soil surface (Brown et al., 1983). Therefore, it becomes of interest to investigate the potential of reducing the use of summer fallow and of growing deep rooted crops such as sunflower and safflower in an attempt to tap the deep water and compare their water use to traditional crops.

3.3. *Water use*

Growing season soil water change reflects crop water requirements, as is illustrated in Fig. 2. For example, both sunflower and safflower, based on a 1-year-cycle, used 499 mm water compared to an average 442 mm for buckwheat and spring wheat (Fig. 2 second row, and Table 5). Similar to Fig. 2, for reason of simplicity, only rotation sequences that started with fallow during the first year of the study are reported in Table 5. Because of late maturity, sunflower and safflower take advantage of late season rains. This contrasts with other crops for which early season rains are most important because of earlier maturity and earlier harvest. Buckwheat was next to sunflower and safflower in water use, followed by spring wheat seeded on fallowed soil.

Although differences in water use existed among individual crops during the 4 year rotation cycle, total water use at the end of the cycle differed only slightly among the six

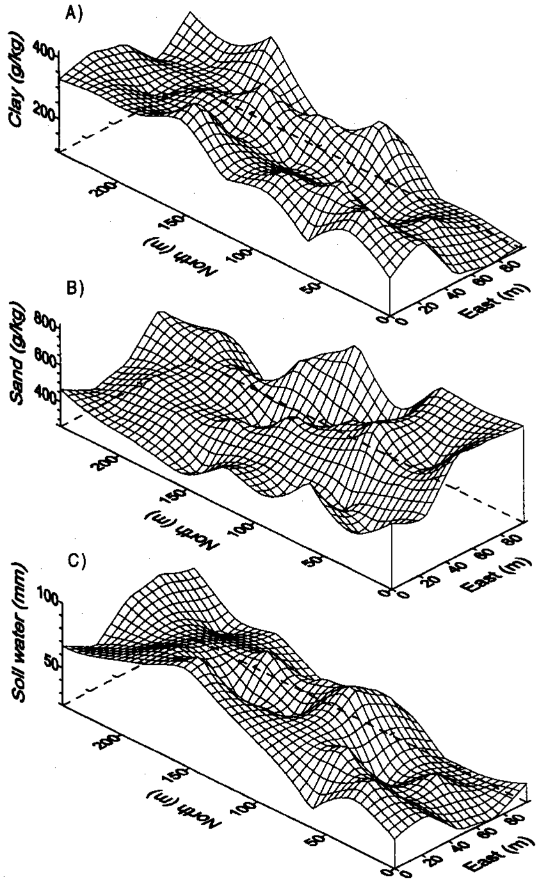

Fig. 3. Spatial variability of clay (A), sand (B), and soil water content (C) at the 0.6–0.9 m depth of the experimental site. Variability at this depth was typical of all depths. Spatial patterns plotted using kriging interpolation methods ('SURFER' v. 6.04; Golden Software; Golden, Colorado).

rotations (Table 5). The statistical difference ($P = 0.05$) between rotations 1 and 3, may in view of the small differences among all rotations and particularly between rotations 3 and 6, in practicality be ignored. Soil water used by the prior crop was replenished or exceeded during the fallow season (Table 4) and soil water available in the spring of every year for crops following fallow was near the upper drained limit (Fig. 2). In the spring of 1995 soil water had in most instances recovered to, or exceeded, the 1991 beginning soil water content (Table 3).

3.4. Crop water use efficiency

Based on water use/loss from spring seeding in 1 year to spring seeding in the following year and on economic yield, WUE was calculated for each year for each

Table 5
Water use, and water use efficiency (WUE) from each rotation represented by crop sequence that started with fallow in 1991 followed in each subsequent year by indicated crop. Water use and WUE are based on water use from spring in 1 year to spring the following year

Rotation[a]	Year				
	1991–1992[b]	1992–1993	1993–1994	1994–1995	4-year-cycle 1991–1995
	Water use (mm)				
Fa–Su–Ba–Ww	266 bc[c]	499 a	365 a	304 d	1433 b
Fa–Sa–Ba–Ww	275 bc	499 a	359 a	311 d	1444 ab
Fa–Bu–Fo–Sw	268 bc	450 b	376 a	361 ab	1454 a
Fa–Bu–Fo–Ww	284 ab	430 c	402 b	335 c	1451 ab
Fa–Sw–Fa–Sw	255 c	443 bc	375 a[b]	376 a	1449 ab
Fa–Sw–Sw–Sw	302 a	445 bc	358 a	348 bc	1453 ab
			WUE (kg ha^{-1} mm^{-1})		
Fa–Su–Ba–Ww	–	3.70 d	5.58 a	6.17 b	4.01 b
Fa–Sa–Ba–Ww	–	5.42 c	6.23 a	5.58 bc	4.62 a
Fa–Bu–Fo–Sw	–	2.71 b	4.56 b	7.78 a	3.94 b
Fa–Bu–Fo–Ww	–	2.45 b	4.46 b	7.31 a	3.65 b
Fa–Sw–Fa–Sw	–	9.00 a	–	7.82 a	4.78 a
Fa–Sw–Sw–Sw	–	8.58 a	4.74 b	5.30 c	5.06 a

[a] Fa: fallow; Su: sunflower; Ba: barley; Ww: winter wheat; Sa: safflower; Bu: buckwheat; Fo: forage; Sw: spring wheat

[b] Second over-winter period of fallow.

[c] Within years, means followed by same letter are not significantly different ($P \leq 0.05$).

rotation and for the complete rotation cycle (Table 5). For reference, average yearly yield data are listed in Table 6. Spring wheat following summer fallow in rotations 5 and 6 had the largest WUE of any crop during the 1992 season at 9.00 for rotation 5 and 8.58 kg ha^{-1} mm^{-1} for rotation 6. In 1994, spring wheat and winter wheat following forage in rotations 3 and 4, respectively, had WUE similar to that of spring wheat following fallow (rotation 5). Safflower had a larger WUE than sunflower. Including the first fallow year, rotations 2 and 5 exhibited the largest WUE for the complete 4-year-cycle (Table 5). Although the largest WUE for the 4-year-cycle is shown for 'continuous wheat' (rotation 6) in Table 5, it must be discounted because the first year in that rotation had wheat following fallow. If we approximate first year yield of rotation 6 at 65% of wheat grown following summer fallow (based on yield comparisons from the other years), WUE of continuous wheat approaches 4 kg ha^{-1} mm^{-1}.

Several reports are available discussing water use efficiencies, especially for small grains, along with some of the specialty crops, grown on the Great Plains. Our results generally agree with reported results for similar crops on a complete rotation basis as well as on a growing season basis (e.g., Aase and Siddoway, 1982; Brown et al., 1983; Deibert et al., 1986; Tanaka, 1989, 1990; Aase and Pikul, 1995; Walley et al., 1999). Peterson et al. (1996) summarized results from several studies across the Great Plains. In our study, growing season WUEs (from seeding to harvest) were similar to the yearly WUEs shown

Table 6
Yield data from rotation study. All crops in 1991 followed winter wheat harvested in 1990

Crop	Rotation	Year			
		1991 Yield (kg ha^{-1})	1992	1993	1994
Sp. wheat	3	1179	1969	1472	2801
	5	1133	3986	2634	2939
	6	–[a]	3814[d]	1699	1838
Wh. wheat	1	1138[b]	2991	2220	1868
	2	1194[b]	2530	2067	1734
	4	1242[b]	2703	2373	2448
Barley	1	2131	3122	2029	2711
	2	1791	2818	2229	3313
Buckwheat	3	356	1214	972	25
	4	320	1062	996	37
Forage	3	–[c]	5679	1717	4689
	4	–[c]	5534	1790	4761
Sunflower	1	1461	1854	1936	312
Safflower	2	1206	2719	0	1263

[a] Fallow.
[b] Spring wheat.
[c] No data.
[d] Following fallow.

in Table 5, except for forage which had a growing season WUE of 20.5 Mg ha^{-1} mm^{-1}. Forage was harvested while actively growing (grain in soft dough stage), accounting for the high growing season WUE. On a yearly basis, forage had no better WUE efficiency than any other crop.

Results of correlations of crop yields on growing season water use rendered results such as those shown in Fig. 4. Although the units of the slopes of each line are in common WUE units, the slopes, unless the intercept equals 0, are not equivalent to WUE as described in Table 5. Rather, the slopes describe the response of each crop to additions of increments of water during the growing season. Forage and spring wheat yields responded the best of any of the crops to each increment of water added during the growing season with respective slopes of 33.7 and 24.5 Mg ha^{-1} mm^{-1} water. Of the oil seed crops, safflower was slightly more efficient that sunflower. The only statistically non-significant correlation was for barley. Our results are similar to results shown by Hatfield et al. (1988) for both grain yield and total phytomass of winter wheat across a wide range of latitudes on the Great Plains.

Water conservation measures are important for successful annual cropping on the semiarid northern Great Plains and, with such measures, continuous annual small grain production in the semiarid northern Great Plains can be successful (Aase and Pikul, 1995; Aase and Schaefer, 1996). Based on variable cost and net return calculations and in spite of fluctuating year-to-year yields of safflower, Aase and Reitz (1989) concluded that safflower appeared to be a viable economic crop option for the semiarid northern Great Plains.

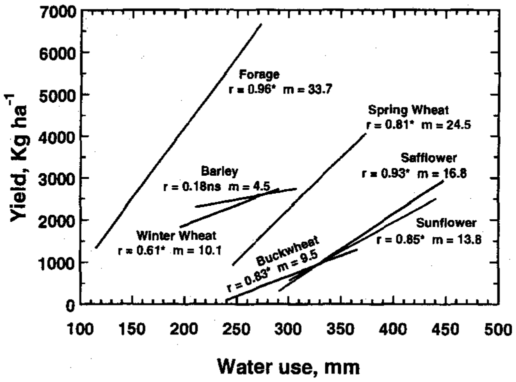

Fig. 4. Yield-water use relationships for each crop in six rotations. Same crops from each rotation are combined. Water use is from seeding to harvest, including rain.

4. Conclusions

The greatest growing season water use efficiency was garnered by the annual legume/grain-forage hay crop. However, on a yearly basis, and in rotation with low WUE buckwheat, it was least. Nevertheless, the legume/grain forage mix, in addition to aiding in potential soil improvement, also yields a high quality forage and seems to fit in a rotation with the typical spring wheat grown on the northern Great Plains. In addition, it appears that deep rooted crops, such as safflower and sunflower, can have a place in crop rotations on the semiarid northern Great Plains. But one must be prepared for variable yields and accept possible reduced yields for the following crop and also for an occasional crop failure not associated with drought, such as happened with safflower in 1993. Crop selection along with crop sequence is important in a rotation. It may be worthwhile to look at other rotation sequences, such as seeding winter wheat, rather than spring wheat, following forage or placing the most important crop (e.g., wheat) following fallow and deep rooted crops last in a 4-year sequence so that a fallow period follows to replenish soil water. Another possibility is to carefully observe soil water conditions and rainfall probabilities and follow a flexible crop rotation strategy. Crop and soil management for non-traditional crops differ from that of small grain management, so some adaptation by growers of management practices is necessary.

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