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ABSTRACT

No-till dryland winter wheat (*Triticum aestivum* L.)-fallow systems in the central Great Plains have more water available for crop production than the traditional conventionally tilled winter wheat-fallow systems because of greater precipitation storage efficiency. That additional water is used most efficiently when a crop is present to transpire the water, and crop yields respond positively to increases in available soil water. The objective of this study was to evaluate yield, water use efficiency (WUE), precipitation use efficiency (PUE), and net returns of cropping systems where crop choice was based on established crop responses to water use while incorporating a grass/broadleaf rotation. Available soil water at planting was measured at several decision points each year and combined with three levels of expected growing season precipitation (70, 100, 130% of average) to provide input data for water use/yield production functions for seven grain crops and three forage crops. The predicted yields from those production functions were compared against established yield thresholds for each crop, and crops were retained for further consideration if the threshold yield was exceeded. Crop choice was then narrowed by following a rule which rotated summer crops (crops planted in the spring with most of their growth occurring during summer months) with winter crops (crops planted in the fall with most of their growth occurring during the next spring) and also rotating grasses with broadleaf crops. Yields, WUE, PUE, value-basis precipitation use efficiency ($PUE), gross receipts, and net returns from the four opportunity cropping (OC) selection schemes were compared with the same quantities from four set rotations [wheat-fallow (conventional till), (WF (CT)); wheat-fallow (no-till), (WF (NT)); wheat–corn (*Zea mays* L.)-fallow (no-till), (WCF); wheat–millet (*Panicum miliaceum* L.) (no-till), (WM)]. Water use efficiency was greater for three of the OC selection schemes than for any of the four set rotations. Precipitation was used more efficiently using two of the OC selection schemes than using any of the four set rotations. Of the four OC cropping decision methods, net returns were greatest for the method that assumed average growing season precipitation and allowed selection from all possible crop choices. The net returns from this system were not different from net returns from WF (CT) and WF (NT). Cropping frequency can be effectively increased in dryland cropping systems by use of crop selection rules based on water use/yield production functions, measured available soil water, and expected precipitation.

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1. Introduction

Dryland cropping systems in the Great Plains are subject to wide variations in productivity and profitability (Dhuyvetter et al., 1996) due to the highly variable nature of the limited precipitation across the region (Nielsen et al., 2010). The traditional wheat-fallow production system of the region was developed in the 1930s as a strategy to minimize incidence of crop failures resulting from erratic precipitation (Hinze and Smika, 1983). The use of herbicides for weed control in this system reduced or eliminated tillage, and led to greater precipitation storage efficiencies (Farahani et al., 1998; Nielsen et al., 2005; Nielsen and Vigil, 2009), such that more frequent cropping could occur (Halvorson and Reule, 1994; Peterson et al., 1993; Anderson et al., 1999; Norwood et al., 1990; Smika, 1990). In particular, both Farahani et al. (1998) and Nielsen and Vigil (2009) pointed out the extremely inefficient precipitation storage that occurred during the second summer fallow period (May through September) during the last 5 months of the 14-month fallow period of the wheat-fallow system. In many instances precipitation storage efficiency during these hot and windy months which can have many days and sometimes weeks between precipitation events was negative, indicating evaporative loss of all of the precipitation occurring during those 5 months plus evaporative loss of some soil water stored earlier in the fallow period.

Abbreviations: OC, opportunity cropping; PUE, precipitation use efficiency; $PUE, value-basis precipitation use efficiency; WUE, water use efficiency; WF (CT), wheat-fallow (conventional till); WF (NT), wheat-fallow (no till); WCF (NT), wheat–corn-fallow (no till); WM (NT), wheat–millet (no till).

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Table 1
Planting, harvesting, and fertilizing details for opportunity cropping system and fixed rotation crops, Akron, CO, 2001–2005.

Year	Crop	Variety	Planting date	Harvest date	Seeding rate	Fertilizer	
						kg N ha^{-1}	kg P_2O_5 ha^{-1}
2001	Wheat	Akron	26 September 2000	9 July	67 kg ha^{-1}	67	22
	Corn	NK4242BT	16 May 2001	23 October	41,020 s ha^{-1}	90	22
	Proso Millet	Huntsman	25 June 2001	12 September	17 kg ha^{-1}	45	17
	Foxtail Millet	Golden German	25 June 2001	29 August	11 kg ha^{-1}	67	17
	Pea	Profi	10 April 2001	10 July	202 kg ha^{-1}	Inoculated	22
	Canola	Hyola	6 April 2001	3 July	10 kg ha^{-1}	0	0
2002	Wheat	Akron	20 September 2001	1 July	67 kg ha^{-1}	67	22
	Corn	NK4242BT	5 May 2002	No harvest	41,000 s ha^{-1}	67	22
	Proso Millet	Sunup	12 June 2002	No harvest	17 kg ha^{-1}	90	22
	Foxtail Millet	Golden German	18 June 2002	No harvest	13 kg ha^{-1}	45	22
	Sunflower	Triumph 665	3 June 2002	No harvest	41,000 s ha^{-1}	0	21
2003	Wheat	Akron	25 September 2002	15 July	67 kg ha^{-1}	67	22
	Corn	NK4242BT	21 May 2003	7 October	34,590 s ha^{-1}	67	22
	Proso Millet	Sunup	20 June 2003	21 August	17 kg ha^{-1}	56	22
	Sunflower	Triumph 665	10 June 2003	21 October	40,350 s ha^{-1}	0	22
2004	Wheat	Akron	19 September 2003	13 July	67 kg s ha^{-1}	56	22
	Corn	N42B7	3 June 2004	26 October	29,640 s ha^{-1}	67	22
	Proso Millet	Sunup	7 June 2004	17 September	17 kg ha^{-1}	50	17
	Forage Pea	Arvika	28 April 2004	26 July	157 kg ha^{-1}	Inoculated	22
2005	Wheat	Akron	27 September 2004	7 July	67 kg ha^{-1}	56	34
	Corn	N42B7	18 May 2005	3 November	29,640 s ha^{-1}	67	0
	Proso millet	Sunup	10 June 2005	2 September	17 kg ha^{-1}	56	22
	Foxtail millet	Golden German	10 June 2005	8 September	13 kg ha^{-1}	56	22
	Pea	Profi	8 April 2005	14 July	213 kg ha^{-1}	Inoculated	22

Farahani et al. (1998) and Peterson and Westfall (2004) suggested that intensifying Great Plains dryland cropping systems by reducing or eliminating the occurrence of fallow as much as possible was the key to improving water use efficiency (WUE). Peterson and Westfall (2004) reported a 37% increase in grain WUE when the cropping system was intensified from one crop in 2 years to three crops in 4 years. Silburn et al. (2007) noted that continuing to fallow after filling the soil profile to 80% available water capacity was highly inefficient because of losses to evaporation, runoff, and drainage below the root zone. They suggested that those water losses could be reduced using stored soil water and growing season precipitation more efficiently through OC rather than using a fixed rotation with set periods of fallow.

With OC (sometimes called flexible cropping) cropping frequency is increased by basing the decision on whether or not to fallow on the amount of soil water at planting time. Young and van Kooten (1989) noted that OC attempts to minimize the risks associated with continuous cropping in dryland regions. They stated that by opting to fallow in the driest springs, OC is able to remove some of the downside risk associated with a fixed rotation. Weisensel et al. (1991) used Monte Carlo simulation to demonstrate that OC based on available soil moisture at planting time resulted in more profitable cropping systems than traditional fixed rotations in Saskatchewan.

Unger (2001) evaluated dryland OC in the Texas panhandle with a variety of alternative crops for grain and forage. His strategy was to intensify cropping from the traditional wheat–sorghum [*Sorghum bicolor* (L). Moench]-fallow system to cropping as often as possible based on the available soil water (at least 0.60 m of wetted soil; wetted soil was not defined more specifically). He also stated that potential growing season precipitation should be favorable ("favorable" was likewise not defined), and alternative crop potential yield was not estimated in order to make a crop choice. He concluded that OC provided for more intensive cropping than that achieved with fixed cropping systems, thereby making more efficient use of precipitation than achieved by cropping systems that included long fallow periods. Nielsen et al. (2005) showed that the $PUE of the three opportunity cropping systems of Unger (2001) based on the average price received for the product was relatively high, ranging from \$0.45 ha^{-1} mm^{-1} to \$1.21 ha^{-1} mm^{-1}. All three of those systems included a high percentage of forage crops.

Researchers in Montana and North Dakota promoted OC in the 1970s to use precipitation more effectively to increase yields and to help prevent and control saline seeps (Brown et al., 1981). They recommended an available soil water content of at least 76 mm at planting to produce spring barley (*Hordeum vulgare* L.) or spring wheat. Other researchers reported winter wheat, proso millet, pinto bean (*Phaseolus vulgaris* L.), and grain sorghum grain yields to be highly correlated with amount of stored soil water at planting (Unger, 1978; Musick et al., 1994; Lyon et al., 1995, 2007; Nielsen et al., 1999, 2002; Stone and Schlegel, 2006). Similarly, dry matter yields of spring triticale (x*Triticlsecale* Wittmack) and foxtail millet (*Setaria italica* L. Beauv.) are well correlated with available soil water at planting (Felter et al., 2006).

In order to provide farmers with yield estimates for OC, Brown and Carlson (1990) published regression equations relating yield of winter wheat, spring wheat, barley, oat (*Avena sativa* L.), and safflower (*Carthamus tinctorius* L.) to the sum of plant available stored soil water at planting and growing season precipitation. Similar linear production functions (yield vs. water use) for corn, winter wheat, proso millet, pea (*Pisum sativum* L.), canola, (*Brassica napus* L.) sunflower (*Helianthus annuus* L.), soybean (*Glycine max* L.), winter triticale, and foxtail millet have been published for the central Great Plains (Nielsen, 1990, 1995, 1998, 1999, 2001, 2006a,b; Nielsen et al., 2006) and could be used to predict yields and guide crop selection in an OC system.

Another factor to consider in OC is the rotation effect (Pierce and Rice, 1988; Porter et al., 1997). Anderson (1998) suggested that in order to minimize negative weed, insect, and pathogen effects on yield, cropping systems should rotate broadleaf crops with grasses, and also rotate summer crops (crops planted in the spring with most of their growth occurring during summer months) with winter crops (crops planted in the fall with most of their growth occurring during the next spring) or spring crops (crops planted in the spring with most of their growth occurring during the spring). The objective of this experiment was to evaluate yield, WUE, PUE, and net returns of four OC systems where crop choice was based on several crop selection rules using crop responses to

Table 2
Water use/yield production functions (kg ha^{-1} = a × [mm-b]) and yield reporting moisture content for dryland crops in the central Great Plains.

Crop	Production function slope a (kg ha^{-1} mm^{-1})	Production function intercept b (mm)	Source for production function	Grain or dry matter yield reporting moisture content (kg kg^{-1})
Corn	25.67	232	Nielsen (1995)	0.155
Winter wheat	12.49	132	Nielsen (2006b)	0.125
Proso millet	10.44	88	Nielsen (2006b)	0.120
Pea	8.00	22	Nielsen (2001)	0.125
Canola	7.73	158	Nielsen (1998)	0.080
Sunflower	6.64	175	Nielsen (1999)	0.100
Soybean	6.53	17	Nielsen (1990)	0.130
Forage triticale	33.00	86	Nielsen et al. (2006)	0.000
Foxtail millet	29.30	78	Nielsen et al. (2006)	0.000
Forage pea	24.77	32	Nielsen (2006a)	0.000

anticipated water use while incorporating a grass/broadleaf, summer crop/winter crop rotation scheme.

2. Materials and methods

This study was conducted at the USDA Central Great Plains Research Station, 6.4 km east of Akron, CO (40°09′ N, 103°09′ W, 1384 m). The soil type was a Weld silt loam (fine, smectitic, mesic Aridic Argiustoll). Average annual precipitation at this location is 417 mm. In 1990, several rotations were established to investigate the possibility of cropping more frequently than every other year, as done with the traditional winter wheat-fallow system. A description of the plot area, tillage systems, and experimental design are given in Bowman and Halvorson (1997) and Anderson et al. (1999). Briefly, rotation treatments were established in a randomized complete block design with three replications. All phases of each rotation were present every year. Individual plot size was 9.1 m by 30.5 m, with east–west row direction. The current study analyzes data from the 2001 through 2005 time period. Crop varieties and planting, harvesting, and fertilizing dates and rates are given in Table 1. Nitrogen fertilizer rates varied slightly from year to year as those rates were based on typical application rates for dryland production in this region, adjusted occasionally for expected residual N amounts. Seed yield sample size was generally between 35 and 42 m^2, and biomass (seed and forage) sample size was between 2.9 and 3.8 m^2. Grain and dry matter yields are reported with the moisture contents shown in Table 2.

Four OC systems were evaluated, with the decision to plant a crop based on predicted yield exceeding an established threshold (Table 3) which was established in consultation with local producers. The predicted yield was calculated using a spreadsheet yield calculator (available at http://www.ars.usda.gov/Services/docs.htm?docid=19206, verified 4/1/2010) which employed water use/yield production functions (Table 2) established at Akron, CO. Water use was assumed to be the sum of measured available soil water just prior to planting and expected growing season precipitation, where expected growing season precipitation ranged from 70% of average to 130% of average (Table 3). The OC1 system was considered to be a conservative system, where only 70% of average growing season precipitation was expected, and only the traditional dryland crops of winter wheat, corn, proso millet, and foxtail millet for forage were allowed as crop choices. The other three OC systems allowed for all possible crop choices that we had established production functions for, but expected growing season precipitation was 100% (OC2), 70% (OC3), or 130% (OC4) of average.

Soil water was measured to a depth of 1.65 m in 0.30-m intervals using a neutron probe for all depths except the 0.0–0.3-m layer. Soil water in this surface layer was determined using time-domain reflectometry with 0.3 m waveguides installed vertically to average the water content over the entire layer. The neutron probe was calibrated against gravimetric soil water samples taken in the plot area. Gravimetric soil water was converted to volumetric water by multiplying by the soil bulk density for each depth. Two measurement sites were located near the center of each plot and data from the two sites were averaged to give one reading of soil water content for each plot. Available water per plot was calculated as

$$(\text{Volumetric water} - \text{lower limit}) \times \text{layer thickness}$$

where volumetric water = m^3 water m^{-3} soil from neutron probe or time-domain reflectometry measurements, lower limit = lowest volumetric water observed under these crops in the plot area (Ritchie, 1981; Ratliff et al., 1983), and layer thickness = 0.3 m. The lower limits used to calculate available water are given in Table 4. Available water for each plot was calculated as the sum of available water from all six measurement depths. The soil water measurements were made at several decision points during the year (mid-September for winter wheat and forage triticale decision; end of March for canola, pea, and forage pea decision; end

Table 3
Crop choice decision rules, available crop choices, and yield thresholds.

Opportunity cropping system	Estimated water use used to calculate crop choice yield	Available crop choices[a]
OC1	Measured available soil water + 70% of average growing season precipitation	Wheat, corn, proso millet, foxtail millet
OC2	Measured available soil water + 100% of average growing season precipitation	Wheat, corn, proso millet, foxtail millet, sunflower, soybean, canola, pea, forage pea, forage triticale
OC3	Measured available soil water + 70% of average growing season precipitation	Wheat, corn, proso millet, foxtail millet, sunflower, soybean, canola, pea, forage pea, forage triticale
OC4	Measured available soil water + 130% of average growing season precipitation	Wheat, corn, proso millet, foxtail millet, sunflower, soybean, canola, pea, forage pea, forage triticale

[a] Yield thresholds needed to determine crop selection in opportunity cropping system: wheat (2688 kg ha^{-1}), corn (3763 kg ha^{-1}), proso millet (2016 kg ha^{-1}), foxtail millet (4256 kg ha^{-1}), sunflower (1232 kg ha^{-1}), soybean (2352 kg ha^{-1}), canola (1120 kg ha^{-1}), pea (1568 kg ha^{-1}), forage pea (4256 kg ha^{-1}), forage triticale (4256 kg ha^{-1}).

Table 4
Lower limits of volumetric soil water used to calculate available soil water for corn, winter wheat, winter triticale, soybean, canola, pea, foxtail millet, proso millet, forage pea, and sunflower on a Weld silt loam, Akron, CO.

Soil depth (m)	Corn	Winter wheat, winter triticale, soybean, canola	Pea, foxtail millet, proso millet, forage pea	Sunflower
	$m^3\ m^{-3}$			
0.0–0.3	0.110	0.090	0.100	0.120
0.3–0.6	0.135	0.120	0.129	0.126
0.6–0.9	0.087	0.072	0.087	0.071
0.9–1.2	0.074	0.061	0.067	0.054
1.2–1.5	0.079	0.082	0.086	0.049
1.5–1.8	0.101	0.111	0.119	0.064

of April for corn and soybean decision; end of May for proso millet, foxtail millet, and sunflower decision). Total seasonal water use was calculated from the water balance as the difference between beginning and ending soil water readings plus growing season pr ecipitation (runoff and deep percolation were assumed to be negligible, considered a reasonable assumption as the slope in the plot area was <1% and visual observation in the plot area following heavy rains did not show evidence of runoff).

The yield, water use, WUE, and PUE of these four OC systems were compared against observations from four set rotations: wheat-fallow (conventional till) [WF (CT)], wheat-fallow (no till) [WF (NT)], wheat–corn-fallow (no till) [WCF (NT)], and wheat–millet (no till) [WM (NT)]. The WUE was calculated as grain yield (or dry matter yield for forage crops) divided by the total water use. The PUE was calculated as the grain yield (or dry matter yield for forage crops) divided by the total precipitation received over the entire period of the cropping system (2001–2005 for the cropping systems in this experiment).

Due to the different photosynthetic costs of producing oil, protein, and starch, the PUE changes with proportion of crop types in a cropping system. These differences in PUE do not necessarily reflect inherent rotation water wastage or crop physiological inefficiencies. The principle of supply and demand generally takes this into account so that the photosynthetically costly plant products (oil, protein) are worth more than the less costly plant products (starch). Using gross dollars produced per unit of precipitation received, as suggested by Nielsen et al. (2005), can be a more useful way of determining the efficiency with which a given cropping system or rotation makes use of water when comparing across crop types. We calculated the value-basis precipitation use efficiency ($PUE) as the dollars received for the total grain or dry matter produced divided by the total precipitation received over the entire period of the cropping system (2001–2005 for the cropping systems in this experiment). The precipitation amounts are not the same for all cropping systems over this period because the sums are computed from the planting of the first crop to the harvest of the last crop, and those starting and ending dates vary depending on the crops selected to begin and end the cropping system. The 10-year average market values (1992–2001) used were the same as given in Nielsen et al. (2005), shown in Table 5. Net returns were calculated using the expenses shown in Table 6.

Prior to the beginning of the current study the plots were cropped with a somewhat similar decision strategy. The crops planted in the 3 years previous to the beginning of the current study were wheat, wheat, corn (OC1); corn, proso millet, pea (OC2); wheat, corn, sunflower (OC3); and wheat, sunflower, and oats for forage (OC4).

Table 5
Average prices received (1992–2001) for crops.

Crop	Price[a] (US$ kg^{-1})
Winter wheat	0.1179
Corn	0.0941
Sunflower	0.2147
Pea	0.0780
Proso millet	0.1270
Canola	0.2147
Foxtail millet	0.0937
Forage pea	0.0937

[a] All prices obtained from http://www.nass.usda.gov (verified 1 March 2010).

Table 6
Production costs used to calculate expenses in calculating net returns for cropping systems analysis.

Operation	Crop/herbicide	Operation cost ($ ha^{-1})	Seed cost	Herbicide cost ($ ha^{-1})	Fertilizer cost ($ kg^{-1})	Hauling
Planting	Corn, sunflower	$24.70	$1.375 1000 $seed^{-1}$			
	Wheat	$22.23	$0.265 ha			
	Pea, forage pea	$22.23	$0.260 ha			
	Foxtail, proso millet	$22.23	$0.260 ha			
	Canola	$22.23	$5.620 ha			
Spraying	Glyphosate	$12.97		$12.35		
	Paraquat	$12.97		$27.00		
	Sethoxydim	$12.97		$42.56		
	2,4-D	$12.97		$2.30		
Tillage-sweep plow		$14.82				
Tillage-rod weeder		$19.76				
Tillage-deep chisel		$21.00				
Fertilizing N		Applied with planter			$0.82	
Fertilizing P_2O_5		Applied with planter			$0.42	
Swathing small grain		$19.76				
Harvesting and hauling	Small grains, corn	$32.11 + $3.69 m^{-3} for >567 m^3				$3.69 m^{-3}
	Oilseeds	$39.52 ha^{-1}				$5.51 T^{-1}
	Peas	$44.46 ha^{-1}				$5.51 T^{-1}
Swathing hay		$24.70				
Baling hay		$14.70 T^{-1}				$3.23 T^{-1}

Swathing and baling charges assume hay at 12% moisture. Hay hauling charges (Edwards, 2007) calculated assuming 20-mile loaded distance. All other operation costs (except hay hauling) come from Tranel et al. (2006).

Table 7
Measured grain and dry matter yields for four opportunity cropping systems and four set rotations at Akron, CO.

Year	OC1	OC2	OC3	OC4	WF (CT)	WF (NT)	WCF		WM	
	Crop and Yield (kg ha^{-1})									
2001	Foxtail millet	Wheat	Pea	Canola	Wheat	Wheat	Wheat	Corn	Wheat	Millet
	4545	2813	1191	169	3494	3926	3661	4527	2472	2415
2002	Wheat	Sunflower	Foxtail Millet	Proso Millet	Wheat	Wheat	Wheat	Corn	Wheat	Millet
	1034	0	0	0	1628	2062	2005	0	594	0
2003	Corn	Corn	Fallow	Sunflower	Wheat	Wheat	Wheat	Corn	Wheat	Millet
	2915	3138	0	352	3872	4406	4789	3073	4365	2563
2004	Fallow	Forage Pea	Forage Pea	Proso Millet	Wheat	Wheat	Wheat	Corn	Wheat	Millet
	0	3862	3502	390	896	2116	1807	3096	310	2647
2005	Wheat	Foxtail Millet	Foxtail Millet	Pea	Wheat	Wheat	Wheat	Corn	Wheat	Millet
	2302	4717	2611	564	2163	2819	2256	2278	599	562

OC1–OC4 refer to opportunity cropping systems 1 through 4 as designated in Table 1.
WF (CT) is wheat-fallow, conventional tillage; WF (NT) is wheat-fallow, no-till; WCF (NT) is wheat–corn-fallow, no-till; WM (NT) is wheat–proso millet, no-till.

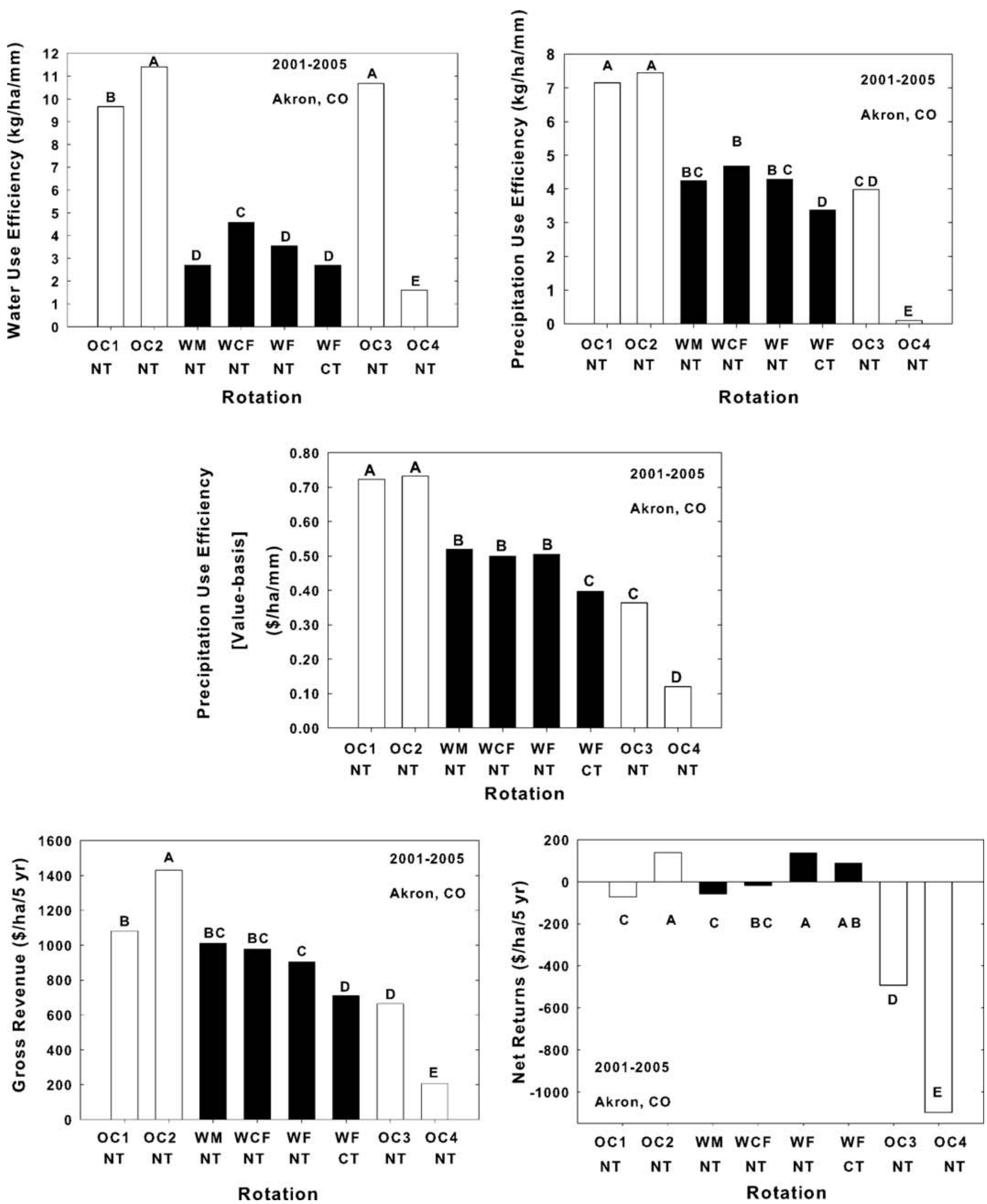

Fig. 1. Water use efficiency, precipitation use efficiency, value-basis precipitation use efficiency, gross revenue, and net returns for four opportunity cropping (OC) systems (defined in Table 2) and four set rotations at Akron, CO. W = winter wheat, M = proso millet, C = corn, F = fallow, NT = no till, CT = conventional till.

3. Results

3.1. Sequences and yields

The 5-year cropping sequence (and measured yields) generated by following the decision rules for OC1 (Table 7) were foxtail millet (dry matter yield of 4545 kg ha^{-1}), wheat (1034 kg ha^{-1}), corn (2915 kg ha^{-1}), fallow, and wheat (2302 kg ha^{-1}). Following the decision rules for OC2 (which assumed average growing season precipitation) resulted in a cropping sequence (and measured yields) of wheat (2813 kg ha^{-1}), sunflower (0 kg ha^{-1} due to severe drought), corn (3138 kg ha^{-1}), forage pea (dry matter yield of 3862 kg ha^{-1}), and foxtail millet (dry matter yield of 4717 kg ha^{-1}). The OC3 decision rules (which assumed 70% of average growing season precipitation) called for growing four crops in 5 years in a sequence of pea (1191 kg ha^{-1}), foxtail millet (dry matter yield of 0 kg ha^{-1} due to severe drought), fallow, forage pea (dry matter yield of 3502 kg ha^{-1}), and foxtail millet (dry matter yield of 2611 kg ha^{-1}). The OC4 decision rules called for the most intensive cropping due to the assumption of 130% of normal growing season precipitation. This method resulted in a cropping sequence which produced very low yields: canola (169 kg ha^{-1}), proso millet (0 kg ha^{-1} due to severe drought), sunflower (352 kg ha^{-1}), proso millet (390 kg ha^{-1}), and pea (563 kg ha^{-1}). The average wheat yields for the four set rotations were 2411 kg ha^{-1} (WF (CT)), 3066 kg ha^{-1} (WF (NT)), 2904 kg ha^{-1} (WCF (NT)), and 1668 kg ha^{-1} (WM (NT)). Average corn yield in the WCF (NT)) system was 2595 kg ha^{-1} and average proso millet yield in the WM (NT)) system was 1637 kg ha^{-1}.

3.2. Water use efficiency and precipitation use efficiency

Water use efficiency (Fig. 1, top left panel) was greatest following the OC2 and OC3 decision rules (both systems having two forage crops in 5 years) followed by the OC1 strategy (one forage crop in 5 years) with values between 9.66 and 11.40 kg ha^{-1} mm^{-1}. The OC4 decision rule resulted in the lowest WUE of 1.61 kg ha^{-1} mm^{-1} because of the very low seed yields obtained in all 5 years. The WUE for the WCF system (4.59 kg ha^{-1} mm^{-1}) was the greatest of the set rotations, but less than half of that obtained by OC1, OC2, and OC3, because of the system producing only seed and no forage.

Precipitation use efficiency (Fig. 1, top right panel) was greatest for the OC1 and OC2 systems (about 7.29 kg ha^{-1} mm^{-1}). The PUE of the OC3 system was much lower (3.98 kg ha^{-1} mm^{-1}) because of 2 years without crop production (crop failure due to drought in 2002 and a fallow year in 2003, Table 7). The PUE of the OC4 system was extremely low (0.1 kg ha^{-1} mm^{-1}), while PUE for the set rotations ranged between 3.37 kg ha^{-1} mm^{-1} (WF (CT)) and 4.69 kg ha^{-1} mm^{-1} (WCF).

The value-basis PUE (Fig. 1, center panel) allows a fairer comparison of cropping systems that have mixes of forages, seed legumes, and grains. The $PUE was greatest for OC1 and OC2 ($0.73 ha^{-1} mm^{-1}) with $PUE for OC3 being similar to WF (CT) ($0.38 ha^{-1} mm^{-1}). The $PUE for the other three set rotations was intermediate ($0.51 ha^{-1} mm^{-1}) while the lowest $PUE was generated by following the OC4 decision rules ($0.12 ha^{-1} mm^{-1}). The lower PUE and $PUE for OC3 compared with OC1 and OC2 is primarily attributable to the very dry conditions in 2002 which resulted in no foxtail millet yield, followed by a decision rule result to fallow in 2003 due to low soil water content and an assumed growing season precipitation of 70% of average. Had there been sufficient soil water in the fall of 2002 to predict a wheat yield that met or exceeded the wheat yield decision threshold (2688 kg ha^{-1}), a wheat yield of approximately 4200 kg ha^{-1} likely would have been achieved (see wheat yields for 2003 in the set rotations, Table 7) resulting a system $PUE of $0.63 ha^{-1} mm^{-1} (lower than OC1 and OC2, but higher than the set rotations), nearly double what was actually obtained.

3.3. Gross revenues and net returns

The gross revenues (Fig. 1, lower left panel) were greatest when the OC2 decision rules were followed ($1431 ha^{-1} 5 yr^{-1}). Following the OC1 decision rules produced gross revenues similar to those generated by the WM and WCF cropping systems ($978–1081 ha^{-1} 5 yr^{-1}). The OC3 strategy produced gross revenues similar to WF (CT) (about $689 ha^{-1} 5 yr^{-1}). As with the production efficiency measures discussed above, gross revenues were least when the OC4 decision rules were followed ($205 ha^{-1} 5 yr^{-1}) because of the very low yields obtained.

The very low yields with OC4 resulted in the most extreme economic losses (−$1097 ha^{-1} 5 yr^{-1}) among the systems being compared (Fig. 1, lower right panel). The OC3 system also exhibited large economic losses (−$493 ha^{-1} 5 yr^{-1}) because of the 2 years without any crop production. Net returns were negative as well for OC1, WM, and WCF, but to a much lesser degree. Positive net returns were seen for WF (CT) ($89 ha^{-1} 5 yr^{-1}), WF (NT) ($138 ha^{-1} 5 yr^{-1}), and OC2 ($136 ha^{-1} 5 yr^{-1}).

4. Discussion

As pointed out earlier in the case of the low $PUE value for OC3 resulting from no crop planted in 2003, there may be missed opportunities to plant and harvest a crop because of the inability to forecast long-range precipitation. While Steiner et al. (2004) expressed optimism in improved long-range seasonal forecasts in semi-arid regions that might aid farmers in making cropping choice decisions, it is our opinion that improvement in long-range forecasting of growing season precipitation in the central Great Plains, which largely occurs as a result of convective thunderstorm activity that is highly variable in time and space, is not likely to occur. Lyon et al. (2003) also concluded that long-range forecasts of summer precipitation in western Nebraska using the Southern Oscillation Index (Stone and Auliciems, 1992) lacked sufficient skill to be useful in making cropping decisions regarding corn.

The OC1 and OC2 decision rule strategies appear to be more efficient users of water and precipitation than the set rotations, but were not statistically different from the WF (CT) and WF (NT) set rotations in net returns generated. It should be kept in mind, though, that OC1, OC2, and OC3 all had forages in some years and the cost of hauling can be a large factor in increasing or decreasing profitability compared with the set rotations depending on transportation costs (we used a forage hauling cost of $3.23 per ton based on a 20-mile hauling distance).

Additionally, conclusions regarding the profitability differences between systems should be drawn cautiously. From the economic analysis given in this study, a farmer would have been no further ahead using the OC1 strategy than using set rotations of WM or WCF, or using the OC2 strategy instead of set rotations of WF (CT) or WF (NT). Perhaps this conclusion would change in favor of the OC systems if more years of data were available for analysis, as one of the 5 years used in this study was from the most severe drought on record for this location. As evidence that the years selected and the number of years of record can affect the conclusions drawn, we cite another northeastern Colorado cropping systems study (Kaan et al., 2002; Peterson and Westfall, 2004) that used data from 1989 to 1997 (a relatively wetter set of years, in terms of both annual and growing season precipitation compared with the 2001–2005 period used in this study). They concluded that net returns from the WCF system were 25–40% greater than from WF (NT), very different than the much greater net returns for WF (NT) compared with WCF

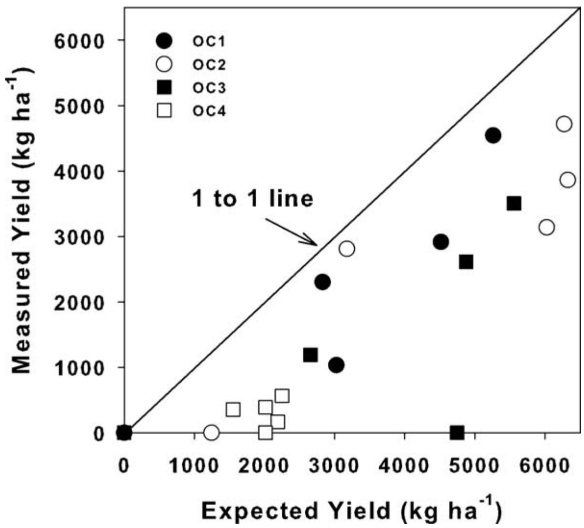

Fig. 2. Comparison of expected crop yield (generated prior to growing season from water use/yield production functions) and measured yields for four opportunity cropping (OC) systems (defined in Table 2).

found in the current study. Lyon et al. (2003) also cautioned that different conclusions regarding profitable dryland corn populations for western Nebraska could be drawn depending on whether studies were conducted during the relatively wetter 1990s period vs. the drier early 2000s.

The OC4 decision rules could be considered a non-viable crop selection strategy as evaluated by any one of the measures shown in Fig. 1. The assumption of 130% of average growing season precipitation was not met even once in the 5 years of the study. The year that came closest to meeting that assumption was 2004 when the millet growing season precipitation was 116% of average. Clearly, basing a cropping decision on a continuing optimistic prediction of above-average growing season rainfall is not wise in this semi-arid climate where annual precipitation records indicate rainfall amounts fluctuating widely about the mean on a nearly annual basis (Nielsen and Vigil, 2009). On the other hand, the OC2 strategy that based crop choice on available soil water at planting and a prediction of average growing season rainfall resulted in continuous cropping (although no crop was produced in 2002 because of severe drought) producing a cropping sequence that was highly efficient in terms of water and precipitation use, more profitable than WM and WCF, and equal in profitability to WF (CT) and WF (NT).

Surprisingly, none of the four OC systems resulted in measured yields greater than the expected yields generated by the production functions combined with the measured available soil water and expected precipitation (Fig. 2). In fact, most of the measured yields were far below the expected yields. In only three instances (two for OC1 and one for OC2) did measured yield fall within 20% of expected yield. This result of always obtaining measured yields lower than expected yields was not expected because measured growing season precipitation was above expected growing season precipitation in 3 years for OC1, 2 years for OC2, and 4 years for OC3. This lack of ever achieving a measured yield greater than expected may indicate that (1) the production functions need to be refined or (2) water stress during critical stages of development are more detrimental to yield than can be accounted for by this simple yield prediction system or (3) all of the available soil water measured at the decision points is not really ultimately available to the crop during the growing season and different lower limits of water availability will need to be established. Two recent analyses of dryland corn yield sensitivity to water deficits during pollination and grain filling explain why the measured corn yields may be lower than expected (Nielsen et al., 2009, 2010).

5. Conclusions

Using estimated crop water use (measured available soil water at several decision points during the year plus 70–100% of average growing season precipitation) with established water use/yield production functions can assist farmers in making a crop choice that can increase cropping frequency, WUE, PUE, and $PUE over that obtained with set rotations. The crop prices and production costs used in the economic analysis of this study did not reveal a net revenue advantage for an OC system over a set WF rotation, but did indicate an advantage over the WM and WCF rotations. Even though none of the OC crop selection methods resulted in a net revenue advantage of the WF systems, producers may want to consider using the OC2 method to increase cropping frequency over the WF systems because of the potential benefits associated with increasing surface soil organic carbon and particulate organic matter levels (Mikha et al., 2010), greater carbon sequestration (Halvorson et al., 2002), reducing exposure to wind erosion (McMaster et al., 2000), reducing surface soil compaction (Blanco-Canqui et al., 2010), and improvement to other physical properties of the soil (Benjamin et al., 2007). An OC decision support system would benefit from combining the method described in this paper with economic factors (estimated costs and revenues) for the various crops for which pre-season yield estimates are made.

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