Replacing Fallow with Continuous Cropping Reduces Crop Water Productivity of Semiarid Wheat

R. M. Aiken,* D. M. O'Brien, B. L. Olson, and L. Murray

ABSTRACT

Water supply frequently limits crop yield in semiarid cropping systems; water deficits can restrict yields in drought-affected subhumid regions. In semiarid wheat (*Triticum aestivum* L.)-based cropping systems, replacing an uncropped fallow period with a crop can increase precipitation use efficiency but reduce wheat productivity. Our objective was to analyze crop sequence and environmental effects on water use, components of water productivity, and net returns of winter wheat (WW) in a semiarid region. A field study was established to evaluate eight 3-yr crop sequences, including a wheat phase followed by a feed grain phase (corn [*Zea mays* L.] or grain sorghum [*Sorghum bicolor* (L.) Moench]) and an oilseed phase (OS; spring canola [*Brassica napus* L.], soybean [*Glycine max* (L.) Merr.], sunflower [*Helianthus annuus* L.], or none [fallow]). Standard measurements included crop water use (WU), canopy leaf area index at anthesis, biomass, grain yield, and yield components. Net return (NR) was calculated as the difference between crop revenue and total operating costs. Replacing an uncropped fallow period with an OS crop reduced water productivity responses of WW (biomass, grain yield, and NR) by 18, 31, and 56%, respectively, relative to that of WW grown after fallow. These responses to continuous cropping corresponded to reductions in all components of a water-limiting yield production function. The modest water productivity observed (0.28–0.62 kg m^{-3}), relative to a reported global range of 0.6 to 1.7 kg m^{-3}, indicates opportunity to improve wheat water productivity through management and genetic gain.

Water supply frequently limits crop productivity in semiarid cropping systems; drought-related water deficits can reduce crop yields in normally water-sufficient regions such as the U.S. Corn Belt (Stambaugh et al., 2011). Increasing crop water productivity (the ratio of marketable crop yield to actual evapotranspiration [ET]) can help ensure food security in the face of declining global freshwater supplies (Zwart and Bastiaanssen, 2004).

Dryland crop production in the U.S. central High Plains (CHP) is frequently limited by precipitation relative to evaporation potential (Farahani et al., 1998). A fallow period, i.e., leaving the land idle during a cropping season, increased soil water recharge by 111 mm for sweep-till soil management and 188 mm for no-till (Nielsen and Vigil, 2010); Norwood (1994) reported similar results. Nielsen and Vigil (2010) reported, however, that precipitation storage efficiency (the fraction of precipitation stored in soil during a time period) averaged 20% for sweep-till and 35% for no-till during a 14-mo fallow period before planting winter wheat. Substantial evaporative losses during fallow indicate the potential for increasing precipitation use efficiency (PUE) (Farahani et al., 1998). Nielsen et al. (2005) reported that PUE increased with cropping intensity (the number of potential crop harvests in the duration of a crop sequence), on a biomass basis, and increased with latitude in the Great Plains for crop systems with similar combinations of cereal, legume, and oilseed crops. Increasing the cropping intensity can increase land productivity without limiting wheat productivity when wheat is grown after a fallow period (Nielsen et al., 2002); net economic returns can also increase with cropping intensity, provided that a fallow period precedes winter wheat production (Norwood and Dhuyvetter, 1993; Dhuyvetter et al., 1996). Intensified crop sequences reduce the fallow fraction of the cropping sequence, increase the fraction of precipitation available to crop systems, increase biomass productivity, and can increase net economic returns in semiarid regions.

Continuous cropping systems in semiarid regions replace fallow with crops, providing protective cover or green manure or producing cereal, oilseed, legume grain, or forage, thereby substituting crop transpiration for a fraction of the evaporative losses associated with fallow. Fallow replacement cover crops, however, can reduce the soil water available to a subsequent wheat crop by 55 to 104 mm (Nielsen and Vigil, 2005); green manure crops can reduce wheat productivity by 400 to 1050 kg ha^{-1}

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Published in Agron. J. 105:199–207 (2013)
doi:10.2134/agronj2012.0165
Available freely online through the author-supported open access option.

Abbreviations: ASW_E, available soil water at emergence; ASW_{FL}, available soil water at flowering; ASW_S, available soil water at spring end of dormancy; CHP, central High Plains; FFC, fraction of culms that were fertile; FG, feed grain; HI, harvest index; LAI, leaf area index; NR, net return; OS, oilseed; PNW, Pacific Northwest; RD, relative soil water deficits at emergence; TF, transpiration fraction; WU_F, water use from emergence to spring end of dormancy; WU_{GF}, water use from anthesis to maturity; WU_S, water use from spring end of dormancy to anthesis; WU_{TOT}, water use from emergence to maturity; WW_C, winter wheat in sequences containing corn; WW_{CC}, winter wheat in continuous cropping sequences; WW_F, winter wheat following fallow; WW_{SB}, winter wheat following soybean; WW_{SC}, winter wheat following spring canola; WW_{SF}, winter wheat following sunflower; Y, year or growing season.

(Vigil and Nielsen, 1998) in the CHP. Lyon et al. (2007), also in the CHP, found that the available soil water and crop water use of a subsequent wheat crop decreased with summer fallow replacement crops compared with spring fallow replacement crops. In the Pacific Northwest (PNW), replacing fallow with a spring broadleaf crop resulted in modest (0–16%) yield reductions in normal years but greater yield reductions (21–41%) under drought conditions (Miller and Holmes, 2005). Juergens et al. (2004) reported positive net returns for continuous spring wheat, in the PNW, that were similar to the annualized net returns of a winter wheat–fallow system in that region. Eliminating fallow in semiarid cropping systems can reduce the water available to subsequent wheat crops, thereby reducing crop productivity in the CHP, and, to a lesser extent, in the PNW.

Water-limiting effects on crop yield can be analyzed in relation to the harvest index (HI, the ratio of grain mass to aboveground biomass), transpiration efficiency (TE, the ratio of aboveground biomass to transpiration), transpiration fraction (TF) of ET, and crop water use (WU) (Passioura, 1977): $Y = \text{HI} \times \text{TE} \times \text{TF} \times \text{WU}$, assuming that ET is the principle component of WU. Increasing cropping intensity by eliminating summer fallow before a winter wheat crop can reduce the soil water available for use by the wheat crop, thereby increasing crop susceptibility to soil water deficits when precipitation is untimely or inadequate (Lyon and Peterson, 2005), with the potential to decrease the harvest index (Fan et al., 2008). Reduced wheat yield response to available water at planting during dry years, relative to that observed in average and wet years (Nielsen et al., 2002), could then result from reduced primary productivity, reduced harvest index, or both. Knowledge of factors affecting water use, grain yield, and water productivity of winter wheat in semiarid regions can contribute to increased water productivity of semiarid crop systems and drought-affected crops in subhumid regions, thus enhancing food security. Our objective was to analyze the effects of crop sequence and environmental variation on available soil water, wheat water use, the components of wheat water productivity, and net returns from winter wheat in a semiarid region.

MATERIALS AND METHODS

A long-term field study was established in 2000 at Colby, KS (39.413° N, 101.078° W, 975 m asl) on a Keith silt loam soil (a fine-silty, mixed, superactive, mesic Aridic Argiustoll). Crop sequence effects were represented by eight 3-yr crop sequences including a wheat phase followed by a feed-grain phase (FG; corn or grain sorghum) and an OS phase (spring canola, soybean, sunflower, or none, i.e., fallow), each phase corresponding with a harvest period. Crop sequences that include an oilseed crop (winter wheat following spring canola [WW_{SC}], soybean [WW_{SB}], or sunflower [WW_{SF}]) represent continuous cropping (WW_{CC}), with a range of soil water depletion and recharge opportunities following a given oilseed crop. Winter wheat preceded by an 11-mo fallow period, without cropping, is indicated by WW_F. Three sets (replicate blocks) of experimental units were contained in nine 36.6- by 36.6-m cropped areas. A single set of three cropped areas, comprising wheat, feed-grain, and oilseed phases, was composed of (i) a 36- by 36-m winter wheat area, planted east–west; (ii) a feed-grain area, consisting of two 36.6- by 18.3-m subareas, planted and oriented (lengthwise) east–west; and (iii) an oilseed area, consisting of four 36.6- by 9.14-m subareas, planted and oriented (lengthwise) north–south. An experimental unit had dimensions of 18.3 by 9.14 m and represented a particular phase of a crop sequence; detailed descriptions of the eight crop sequences are provided in Table 1. Once crop sequences were assigned to experimental units, the same cropping sequence was maintained for each experimental unit at the site; with time, crop sequence effects represent cumulative, ongoing effects. Standard measurements, described below, included crop water use at different development stages, from emergence to the spring end of dormancy, anthesis, and physiological maturity. The canopy leaf area index (LAI) was quantified at anthesis; aboveground biomass and grain yield were quantified at physiological maturity.

Table 1. Crop sequences used to evaluate previous crop effects on water use and productivity of winter wheat at Colby, KS, 2002 to 2008.

Crop sequence†	Feed grain phase	Oilseed phase	Wheat phase
C-SC-WW	corn	spring canola	winter wheat
C-SB-WW	corn	soybean	winter wheat
C-SF-WW	corn	sunflower	winter wheat
C-F-WW	corn	none	winter wheat
GS-SC-WW	grain sorghum	spring canola	winter wheat
GS-SB-WW	grain sorghum	soybean	winter wheat
GS-SF-WW	grain sorghum	sunflower	winter wheat
GS-F-WW	grain sorghum	none	winter wheat

† C, corn; SC, spring canola; WW, winter wheat; SB, soybean; SF, sunflower; F, fallow; GS, grain sorghum. Each annual phase of the 3-yr sequence was present every year at the study site.

Crop Culture

Wheat (TAM 107 in 2002–2004, 67.3 kg ha^{-1} seeding rate; Jagger in 2005–2008, 100.8 kg ha^{-1} seeding rate) was seeded using a no-till drill (Model 1006, 0.19-m row spacing, Great Plains Manufacturing) in late September. Standard nutrient supplementation was applied at seeding (Nielsen and Halverson, 1991). Nitrogen (78.4 kg ha^{-1} as 28–0–0 or 32–0–0, as well as 8–32–0) and P (33.6 kg ha^{-1} as 8–32–0 as P_2O_5) were applied at seeding. Competitive commercial hybrids and cultivars were selected for the FG and OS crops, updated at 3-yr intervals and planted following recommended practices for the region. Combinations of pre-emergent and contact herbicides were utilized to minimize weed growth. For wheat, thifensulfuron (3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl] amino]sulfonyl]-2-thiophenecarboxylic acid, 7.3 × 10^{-3} L ha^{-1}) and tribenuron (2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) methylamino]carbonyl]amino]sulfonyl]benzoic acid, 3.7 × 10^{-3} L ha^{-1}) were applied in 2005 and 2006 to control winter broadleaf species.

Soil Water and Crop Water Use

Soil water was measured by neutron thermalization using a Hydroprobe 503DR (Instro Tek). Access tubes 3.6 m in length were installed in the field plots and soil water was measured at 0.3-m increments to a depth of 2.4 m; ratios of observed counts to standard counts were related to soil water using calibration factors established on-site. Available soil water was calculated as the difference between the measured soil water and the lower limit to water extraction by wheat, determined for each soil depth, by observation on-site under persistent drought conditions (316 mm in the 0–2.4-m profile). The volumetric soil water content was measured, for each experimental unit, at emergence, the spring end of dormancy, anthesis, and physiological maturity. Crop water use between soil water measurement intervals was calculated as the sum of soil water depletion and precipitation recorded at a National Weather Service weather observation station located within 1 km of the study site. Water use was calculated for intervals from emergence to the spring end of dormancy (WU_F), from the spring end of dormancy to anthesis (WU_S), and from anthesis to physiological maturity (WU_{GF}). Total water use (WU_{TOT}) was the sum of WU_F, WU_S, and WU_{GF}.

Crop Canopy Development and Yield Determination

Stand establishment was quantified by visual ratings in the fall. Crop LAI was measured at anthesis, nondestructively, using an Li-2000 Plant Canopy Analyzer (LiCor, Lincoln, NE). Three sets of four measurements of diffuse light transmission through the canopy—parallel, perpendicular, and diagonal to the row orientation—comprised input to the manufacturer's algorithm, solving for LAI ($m^2\ m^{-2}$). Crop aboveground biomass and grain yield were measured by clipping stems in a 0.76- by 0.76-m sample at physiological maturity. Dry mass was determined after drying for a minimum of 7 d at 50°C. Grain was threshed, weighed, and the final moisture content determined by drying at 60°C for a minimum of 48 h. The seed weight of 100 seeds was also recorded. Plots were also mechanically harvested; grain moisture and test weights were determined by a seed analyzer (GAC 2000, Dickey-John Corp) and adjusted to a standard moisture content of 13%. Yield components were assessed by dissection of a single representative plant to determine the number of culms, number of spikes, and seed number, from which the fraction of culms with spikes (FFC, fraction of fertile culms) and number of seeds per spike was calculated. Yield analysis was based on hand-harvested samples. Crop water productivity was analyzed as biomass or grain production in relation to crop water use from emergence through maturity.

Statistical Analysis

The field study was designed as a randomized complete block, with three replicates and each annual phase of the crop sequence present each year. Experimental treatments consisted of eight crop sequences of 3-yr duration (Table 1). Statistical analysis included replicate (REP) as blocking criteria, harvest year (Y) as a whole-plot effect (tested by REP × Y), feed grain (FG, 2 yr before wheat harvest) as a split-plot effect (tested by REP × FG and REP × Y × FG terms), and oilseed as a split-split-plot effect (tested by the residual error term); REP and Y were considered random effects. Fixed and random effects were distinguished using PROC GLM (SAS version. 9.1, SAS Institute); *F* values were constructed from Type III mean squares. Preplanned contrasts (WW_F vs. WW_{CC}, WW_{SC} vs. WW_{SB} and WW_{SF}, and WW_{SB} vs. WW_{SF}) were identified to separate means for OS main effects. Oilseed effects interacting with FG were evaluated using the preplanned contrasts; OS and FG effects interacting with Y were evaluated by contrasts suggested by the experimental results. Linear associations between response variables were evaluated by Pearson correlation coefficients. Crop water productivity was evaluated by analysis of covariance, with crop water use (WU_{TOT}) as the covariate for biomass, grain productivity, and net economic return responses.

Economic Analysis

An economic analysis of the relative profitability of the wheat phase of these cropping systems was performed following the experimental and treatment design described above. Crop input cost estimates were developed using the procedures described in Dumler et al. (2011). A common set of per-unit cost estimates for seed, fertilizer, and herbicides were used throughout the analysis. Current estimates of field operation costs were taken from Kansas Agricultural Statistics (www.nass.usda.gov/Statistics_by_State/Kansas/). Field operation costs used in this analysis included those for seeding, application of fertilizer and herbicide, and harvesting and hauling of grain. Wheat grain prices (northwest Kansas, annual) for the 2002–2003 through 2008–2009 marketing years were taken from the National Agricultural Statistics Service (www.nass.usda.gov). Decisions on whether to include harvest costs in net returns for a particular year were made in the following manner. If the revenue from the crop (yield times grain price) was greater than or equal to the total harvesting and hauling cost of the grain, then harvest costs were included in the total operating costs. Conversely, if crop revenue was less than total harvesting costs, then crop enterprise financial losses were minimized by assuming that the crop was not harvested and the total operating costs included the costs of materials and field application. Net returns to land and management were calculated as the difference between crop revenue and total operating costs. Response variables analyzed were the proportion of years when wheat production was considered worth harvesting and net economic returns.

RESULTS

Growing-season environmental conditions are presented in Table 2. Fall to winter precipitation was less than normal in 2004, 2006, and 2008 and greater than normal in the 2005 and 2007 harvest years (*t*-test, 0.05 probability level); spring precipitation was less than normal in 2002, 2004, 2006, 2007, and 2008 and greater than normal in 2003 and 2005; evaporative demand was greater than normal in 2002, 2005, and 2006; late freezes occurred in 2004 and 2008; heat stress occurred with the greatest frequency in 2002 and 2006.

All response variables differed with respect to growing season (Y) and oilseed phase (OS) effects; also, interacting effects (Y × OS) were detected for all response variables (Tables 3–6) with the exception of WU_F. Consistently, available soil water, crop water use, LAI, biomass, grain yield, HI, components of yield, and NR were greater for WW_F than for WW_{CC}. Our analysis examined the interacting effects of Y × OS, Y × FG, and FG × OS before analysis of main effects.

The interacting effects of year and oilseed phase were evaluated by contrasts. Available soil water at emergence (ASW_E) has been identified as a factor related to water-limited wheat productivity (Nielsen and Vigil, 2005). An examination of annual ASW_E values for WW_F and WW_{CC} (Table 3) revealed substantially less ASW_E for WW_{CC} in the harvest years of 2004, 2006, and 2008 relative to WW_F (15–28% of ASW_E measured for WW_F); in-season precipitation was also less in those years relative to normal (63–75% of normal September–June precipitation). In contrast, for harvest years 2003, 2005, and 2007, ASW_E for WW_{CC} was 38 to 78% of the ASW_E measured for WW_F, and in-season precipitation was 109 to 130% of normal; in 2002, ASW_E for WW_{CC} was 61% of that for WW_F, winter precipitation was near normal, but spring

Table 2. Growing-season environmental conditions for winter wheat in the crop sequence study, 2002 to 2008, Colby, KS.

Year	Precipitation Sept.–Feb.	Precipitation Mar.–June	Evaporation† Apr.–June	Planting	Last freeze‡	Heat stress§
	mm	mm	mm			d
2002	133	87	882	24 Sept. 2001	2 May 2002	18
2003	124	268	663	11 Oct. 2002	10 Apr. 2003	4
2004	32	194	706	25 Sept. 2003	14 May 2004	7
2005	172	268	722	17 Sept. 2004	3 May 2005	8
2006	90	178	901	3 Oct. 2005	26 Apr. 2006	11
2007	268	198	716	20 Oct. 2006	14 Apr. 2007	3
2008	88	172	704	4 Oct. 2007	11 May 2008	4
1981–2010	131 (55)¶	227 (74)	677 (93)			

† Class A Pan evaporation.
‡ Minimum daily temperature < –1.7°C.
§ Calculated as maximum daily temperature ≥35°C.
¶ Mean and standard deviation (in parentheses) calculated for 1981–2010 normal conditions.

Table 3. Crop sequence effects on available soil water for water use of winter wheat following fallow (F) or in continuous cropping (CC) from fall emergence (ASW_E), early spring (ASW_S), flowering (ASW_{FL}), and maturity (ASW_M). Crop sequences consisted of wheat, feed-grain, and oilseed phases; each phase was present in each year. Values for ANOVA *F* tests and contrasts are Type III observed significance levels. Main effect values are means.

Effect	ASW_E F	ASW_E CC	ASW_S F	ASW_S CC	ASW_{FL} F	ASW_{FL} CC	ASW_M F	ASW_M CC
	mm							
Year means								
2002	284	174	259	156	137	49	124	56
2003	88	69	120	78	82	72	100	68
2004	194	29	181	25	160	27	105	29
2005	151	64	137	51	35	25	75	76
2006	280	78	257	68	98	47	47	49
2007	136	52	218	141	107	48	72	31
2008	341	95	294	88	188	85	85	58
Oilseed means								
Spring canola	–	113	–	108	–	60	–	56
Soybean	–	81	–	89	–	60	–	61
Sunflower	–	52	–	63	–	32	–	40
Fallow	227	–	209	–	115	–	87	–
ANOVA *F* tests								
Year (Y)	<0.0001		<0.0001		0.0005		0.0284	
Feed grain (FG)	ns†		ns		ns		ns	
Y × FG	ns		ns		0.0334		ns	
Oilseed (OS)	<0.0001		<0.0001		<0.0001		<0.0001	
Y × OS	<0.0001		<0.0001		<0.0001		0.0016	
FG × OS	0.0156		ns		ns		ns	
Y × FG × OS	ns		ns		ns		0.0514	
Contrasts								
RD vs. no RD‡	ns§		0.0040		0.0002		0.0113	
F vs. CC	<0.0001§		<0.0001		<0.0001		<0.0001	
SC vs. SB + SF¶	<0.0001§		0.0002		0.0130		ns	
SB vs. SF¶	0.0001§		0.0066		<0.0001		0.0017	
RD & F vs. CC#	<0.0001§		<0.0001		<0.0001		ns	
RD & SC vs. SB + SF#	ns§		ns		ns		ns	
RD & SB vs. SF#	ns§		ns		ns		ns	

† ns, not significant at $P < 0.05$.
‡ Effects of years with relative ASW_E soil water deficits (RD) (2004, 2006, and 2008) against years with no relative deficit (2002, 2003, 2005, and 2007).
§ Contrasts exclude the year 2003, for which data were incomplete.
¶ Oilseed-phase effects of spring canola (SC) against combined effects of soybean (SB) and sunflower (SF) or SB effects against SF effects.
# Interacting effects of relative water deficit vs. no-deficit years against F vs. CC, SC vs. SB and SF, or SB vs. SF.

precipitation was 38% of normal. Thus, contrasts were established for relative ASW_E deficit (RD) years (RD years: 2004, 2006, and 2008) against non-RD years (2002, 2003, 2005, 2007). With regard to oilseed effects, preplanned contrasts consisted of WW_F vs. WW_{CC}, WW_{SC} vs. WW_{SB} and WW_{SF}, and WW_{SB} vs. WW_{SF}. Orthogonal contrasts were created for interacting effects of Y and OS from contrasts constructed for main effects. The results are included in Tables 3 through 6.

The available soil water (ASW_E, at the spring end of dormancy [ASW_S], and at flowering [ASW_{FL}]) was significantly less for

Table 4. Crop sequence effects on water use of winter wheat following fallowing (F) or in continuous cropping (CC) from emergence to early spring (WU_F), from early spring to flowering (WU_S), from flowering to maturity (WU_{GF}), and from emergence through maturity (WU_{TOT}). Crop sequences consisted of wheat, feed-grain, and oilseed phases; each phase was present in each year. Values for ANOVA *F* tests and contrasts are Type III observed significance levels. Main effect values are means.

Effect	WU_F		WU_S		WU_{GF}		WU_{TOT}	
	F	CC	F	CC	F	CC	F	CC
	mm							
Year means								
2002	94	82	169	153	71	38	334	272
2003	57	60	154	127	119	124	330	311
2004	63	55	107	84	144	86	314	225
2005	128	127	216	140	118	107	462	374
2006	114	101	186	48	132	78	432	227
2007	107	95	242	225	90	72	440	392
2008	103	63	235	132	124	48	463	244
Oilseed means								
Spring canola	–	91	–	142	–	86	–	319
Soybean	–	80	–	123	–	78	–	281
Sunflower	–	78	–	124	–	74	–	277
Fallow	95	–	187	–	114	–	396	–
ANOVA *F* tests								
Year (Y)	<0.0001		<0.0001		<0.0001		<0.0001	
Feed grain (FG)	ns†		ns		ns		ns	
Y × FG	0.0064		ns		0.0048		ns	
Oilseed (OS)	<0.0001		<0.0001		<0.0001		<0.0001	
Y × OS	ns		<0.0001		<0.0001		<0.0001	
FG × OS	ns		ns		0.0239		0.0438	
Y × FG × OS	ns		ns		ns		ns	
Contrasts								
RD vs. no RD‡	<0.0001		<0.0001		ns		<0.0001	
F vs. CC	0.0006		<0.0001		<0.0001		<0.0001	
SC vs. SB + SF§	0.0011		0.0002		0.0032		<0.0001	
SB vs. SF§	ns		ns		ns		ns	
RD & F vs. CC¶	0.0306		<0.0001		<0.0001		<0.0001	
RD & SC vs. SB + SF¶	ns		ns		ns		ns	
RD & SB vs. SF¶	ns		ns		ns		ns	

† ns, not significant at $P < 0.05$.

‡ Effects of years with relative ASW_E soil water deficits (RD) (2004, 2006, and 2008) against years with no relative deficit (2002, 2003, 2005, and 2007).

§ Oilseed-phase effects of spring canola (SC) against combined effects of soybean (SB) and sunflower (SF) or SB effects against SF effects.

¶ Interacting effects of relative water deficit vs. no-deficit years against F vs. CC, SC vs. SB and SF, or SB vs. SF.

WW_{CC} in RD years than in non-RD years relative to that of WW_F; correspondingly, crop water use (WU_F, WU_S, WU_{GF}, and WU_{TOT}) was also less for WW_{CC} in RD years than in non-RD years relative to that of WW_F. As for ASW and WU, indicators of crop productivity (LAI, biomass, yield, HI, and seed mass) and NR were less for WW_{CC} in RD years than in non-RD years relative to that of WW_F. In addition, grain yield, HI, seed mass, and NR of WW_{SF} was less than that of WW_{SB} in RD years; the FFC and seed mass for WW_{SB} and WW_{SF} were less than that of WW_{SC} in RD years. Years with below-normal (≤75%) in-season precipitation and substantially less (≤28%) ASW_E for WW_{CC} relative to WW_F also had greater reductions in ASW, WU, crop productivity, and NR relative to years with above-normal precipitation (≥109%) or ASW_E for WW_{CC} that was >60% of that for WW_F. These interacting effects of Y and cropping intensity were further analyzed by correlation and regression; direct effects of Y per se were not further addressed.

The FG used in a crop sequence (corn or grain sorghum) affected ASW, wheat WU, and wheat productivity in some years. Interacting effects of Y × FG were tested for specific years against all others. The variables WU_{GF}, LAI, yield, HI, and NR were greater for crop sequences including corn as the FG (WW_C) relative to crop sequences including grain sorghum as the FG (WW_{GS}) in 2005; in 2008, ASW_{FL}, WU_{GF}, yield, HI, and NR were less for WW_C relative to WW_{GS}; WU_F was less for WW_C relative to WW_{GS} in 2007, and seed mass was greater for WW_C relative to WW_{GS} in 2006. Interacting effects of FG and OS occurred for ASW_E, WU_{GF}, and WU_{TOT}. Available soil water (ASW_E) was greater for WW_F when grown in a sequence that included corn relative to one that included grain sorghum; however, no effects of FG response were detected among WW_{CC} responses for ASW_E. Among WW_{CC} responses to FG, WU_{GF} and WU_{TOT} of WW_{SC} increased for crop sequences that included grain sorghum rather than corn effects, but no differences were detected in WU_{GF} or WU_{TOT} responses of WW_{SB} and WW_{SF}.

All response variables differed with respect to OS effects. Averaged across FG and Y effects, all measures of ASW and WU were greater for WW_F than for WW_{CC}. Within WW_{CC}, ASW (ASW_E, ASW_S, and ASW_{FL}) and WU (WU_F, WU_S, WU_{GF}, and WU_{TOT}) were greater for WW_{SC} than combined effects for WW_{SB} and WW_{SF}. Crop water use was similar for WW_{SB} and WW_{SF} although ASW (ASW_E, ASW_S, ASW_{FL}, and ASW at maturity [ASW_M]) was greater for WW_{SB} than WW_{SF}. Crop productivity (LAI, biomass, grain yield, and HI) and NR were also greater for WW_F than for WW_{CC} and greater for WW_{SC} than WW_{SB} and WW_{SF}, with the exception of HI, which was similar for all WW_{CC} conditions. All yield components were greater for WW_F than WW_{CC}, with no

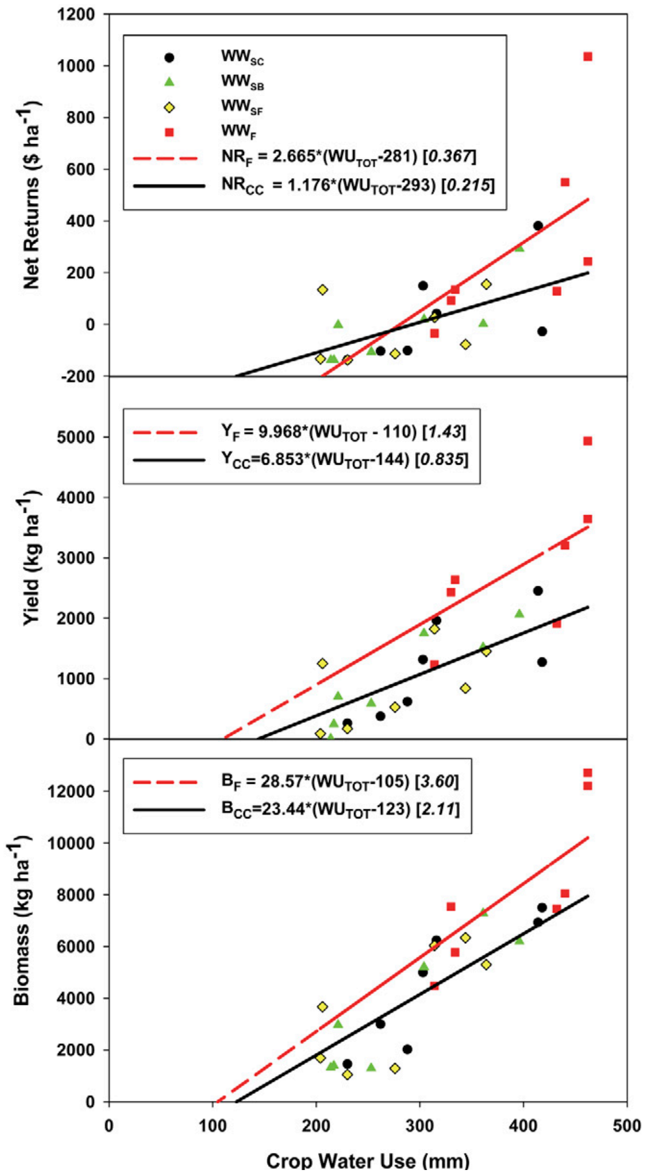

Fig. 1. The linear relationships between seasonal crop water use (WU_{TOT}, emergence to maturity) under fallow or continuous cropping and net returns (NR_F or NR_{CC}), grain yield (Y_F or Y_{CC}), and biomass (B_F or B_{CC}) in wheat grown in eight cropping sequences. Winter wheat was preceded by spring canola (WW_{SC}), soybean (WW_{SB}), sunflower (WW_{SF}), or fallow (WW_F). Standard errors of the slope are indicated in brackets following each linear relationship. Coefficients of determination for biomass, grain yield, and net return relationships with crop water use, derived by analysis of covariance, were 0.688, 0.659 and 0.505, respectively.

differences detected among WW_{CC} conditions. The responses of NR to crop sequences corresponded to those of grain yield, exhibiting similar Y, OS and interacting effects (Table 5).

The correlation structure of crop water use terms with respect to available water, crop productivity, and yield components are presented in Table 7; correlations were computed separately for WW_F and WW_{CC}. The variables ASW_S, LAI, biomass, grain yield, and NR were consistently positively correlated with WU_S and WU_{TOT} for both WW_F and WW_{CC}, as was HI, with WU_S (positive) and WU_{GF} (negative), and seed mass, with WU_S (positive). In contrast, for WW_F, WU_F was positively related to grain yield, seed mass, and NR, but for WW_{CC}, WU_F was negatively related to HI, FFC, and seeds per spike and positively related to culms per plant. The variable WU_S was positively related to spikes per plant, FFC, and seeds per spike for WW_{CC} but not related to these yield formation factors for WW_F. Positive correlations of WU_{GF} with LAI, biomass, grain, culms per plant, and spikes per plant were observed for WW_{CC} but not WW_F. Although WW_F and WW_{CC} shared correlation of WU_S and WU_{TOT} with crop productivity, the correlation structure of WU terms with the components of yield differed substantially for WW_F and WW_{CC}.

Recognizing the divergent responses of WW_F and WW_{CC} yield responses to components of ASW and WU (described above), analysis of covariance models were fitted using WU_{TOT} as a covariate. Significant differences in both slopes and intercepts for WW_F and WW_{CC} were detected among relationships of biomass, yield, and NR to increments of WU_{TOT} (Fig. 1). The expected biomass growth response to an increment of WU_{TOT} was 18% less for WW_{CC} than for WW_F; the expected grain yield response of WW_{CC} to an increment of WU_{TOT} was 31% less than for WW_F; the slope, for WW_{CC}, of the linear relationship of NR to WU_{TOT} was 56% less than for WW_F. Threshold values (e.g., intercepts) for biomass, yield, and NR relationships with WU_{TOT} were greater for WW_{CC} than for WW_F. Interpreting the threshold value of the biomass relationship with WU_{TOT} (Fig. 1) as an indication of average growing-season evaporation and considering the average WU_{TOT} for WW_{CC} and WW_F, the corresponding average TF values for WW_{CC} and WW_F were 0.58 and 0.73, respectively.

Considering the practical significance of the HI to water-limited grain productivity (Passioura, 1977) and the complex interactions (Tables 4, 5, and 6) and correlations (Table 7) of water and crop productivity parameters, a stochastic model for HI was investigated. Significant terms among all ASW and WU parameters were identified using PROC STEPWISE (backward elimination, $P < 0.05$) for each OS condition (WW_{SC}, WW_{SB}, WW_{SF}, and WW_F). Considering the value of utility and simplification, analysis of covariance models were used to quantify distinctive effects and effects of terms common to two or more OS conditions (Table 8). Statistically significant terms of HI models for WW_{SC}, WW_{SB}, and WW_{SF} were WU_F (negative effect) and WU_S (positive effect); the HI models for WW_{SB}, WW_{SF}, and WW_F indicated sensitivity to ASW_E (positive effect); the HI model for WW_F indicated a negative influence of WU_{GF}.

DISCUSSION

Continuous cropping reduced the amount of water available to the winter wheat crop and subsequent biomass, grain, and crop water productivity of WW_{CC} relative to that of WW_F. Thus, all components of the water-limiting yield formation function (HI, TE, TF, and WU; Passioura, 1977) were reduced when fallow was eliminated in continuous cropping systems. These results are consistent with those of Lyon et al. (2004, 2007), Nielsen and Vigil (2005), Saseendran et al. (2004), Vigil and Nielsen (1998), Miller et al. (2006), and Nielsen et al. (2002). Our results also support prior findings that reductions in ASW and crop productivity increase with the duration of the fallow replacement crop (Vigil and Nielsen, 1998; Nielsen and Vigil, 2005; Lyon et al., 2004) and that these effects were exacerbated under drought conditions in the CHP (Nielsen et al., 2002; Nielsen and Vigil, 2005; Lyon et al., 2007), PNW (Miller and Holmes, 2005), and Mediterranean (López-Bellido et al., 1996). Despite decreased wheat productivity

Table 5. Crop sequence effects on leaf area index at anthesis (LAI), biomass, grain yield, and harvest index of winter wheat following fallow (F) or in continuous cropping (CC). Crop sequences consisted of wheat, feed-grain, and oilseed phases; each phase was present in each year. Values for ANOVA *F* tests and contrasts are Type III observed significance levels. Main effect values are means.

Effect	LAI		Biomass		Grain yield		Harvest index		Net returns	
	F	CC	F	CC	F	CC	F	CC	F	CC
	$m^2\ m^{-2}$		kg ha^{-1}				kg kg^{-1}		US\$ ha^{-1}	
Year means										
2002	1.90	0.63	5,775	1535	2638	576	0.40	0.35	134	–107
2003	2.58	1.98	7,543	5827	2429	1844	0.28	0.28	92	29
2004	2.02	0.81	4,477	1300	1234	225	0.24	0.15	–34	–137
2005	3.15	2.28	12,720	7041	3643	1209	0.25	0.14	243	–34
2006	2.14	0.63	7,457	2003	1914	156	0.22	0.04	128	–124
2007	2.83	3.11	8,049	6143	3206	1988	0.35	0.28	549	276
2008	4.17	1.93	12,210	3878	4935	1088	0.35	0.24	1036	93
Oilseed means										
Spring canola	–	1.94	–	4591	–	1178	–	0.210	–	28.90
Soybean	–	1.48	–	3667	–	981	–	0.216	–	–10.11
Sunflower	–	1.46	–	3625	–	878	–	0.204	–	–20.93
Fallow	2.68	–	8319	–	2857	–	0.299	–	307.00	–
ANOVA *F* tests										
Year (Y)	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
Feed grain (FG)	ns†		ns		ns		ns		ns	
Y × FG	0.0355		ns		0.0262		0.0175		0.0530	
Oilseed (OS)	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
Y × OS	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
FG × OS	ns		ns		ns		ns		ns	
Y × FG × OS	ns		ns		ns		ns		ns	
Contrasts										
RD vs. no RD‡	<0.0001		<0.0001		<0.0001		<0.0001		0.0003	
F vs. CC	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
SC vs. SB + SF§	<0.0001		<0.0001		0.0013		ns		0.0015	
SB vs. SF§	ns		ns		ns		ns		ns	
RD & F vs. CC¶	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
RD & SC vs. SB + SF¶	ns		ns		ns		ns		ns	
RD & SB vs. SF¶	ns		ns		0.0049		<0.0001		0.0020	

† ns, not significant at $P < 0.05$.

‡ Effects of years with relative ASW_E soil water deficits (RD) (2004, 2006, and 2008) against years with no relative deficit (2002, 2003, 2005, and 2007).

§ Oilseed-phase effects of spring canola (SC) against combined effects of soybean (SB) and sunflower (SF) or SB effects against SF effects.

¶ Interacting effects of relative water deficit vs. no-deficit years against F vs. CC, SC vs. SB and SF, or SB vs. SF.

in continuous cropping systems (Juergens et al., 2004; Lyon et al., 2004) relative to that of WW_F, annualized net returns, calculated across the entire cropping system, indicated that continuous spring wheat was competitive with WW_F in the PNW (Juergens et al., 2004) and an oat (*Avena sativa* L.)–pea (*Pisum sativum* L.) forage or proso millet (*Panicum miliaceum* L. ssp. *miliaceum*) fallow replacement crops were economically competitive with WW_F systems in the CHP (Lyon et al., 2004). Wheat biomass and grain yield were reduced by continuous cropping in relative proportion to the duration and intensity of water extraction by the fallow replacement crop; the effects were amplified under conditions of limited soil water recharge before emergence of the subsequent wheat crop. Decision-support guidelines regarding continuous cropping in semiarid regions will probably take into account the effects of fallow replacement crops on the components of water-limiting wheat yield formation, the threshold WU_{TOT} for a positive NR and subsequent NR response to increments of WU_{TOT}, and compensatory productivity of the fallow replacement crop.

Nielsen et al. (2002) found that the wheat productivity response to WU differed in dry and normal years; Nielsen and Vigil (2005) reported that wheat yields were linearly related to ASW_E, but the apparent yield response to subsequent precipitation differed among growing seasons. In this study, differences in the correlation structure for WW_F and WW_{CC} among WU and crop productivity parameters suggest impacts of preanthesis water deficits on yield formation factors and HI. The increase in culms per plant with WU_F and increased spike formation and seed set with WU_S for WW_{CC} but not WW_F indicates that these can be critical yield formation processes that may be vulnerable to water deficits before anthesis. The smaller HI of WW_{CC} relative to that of WW_F—exacerbated in relative deficit years—indicates the consequences of impaired yield formation. The biomass and grain yield responses of WW_{CC} to an increment of WU_{TOT} were 18 and 31% less, respectively, than the responses of WW_F. Preanthesis water-deficit conditions for WW_{CC} may increase the likelihood of sink limitations to yield potential, compounding the effects of source limitations to yield related to reduced WU.

Wheat water productivity of WW_F and WW_{CC} averaged 0.62 and 0.28 kg m^{-3}, respectively. These values are similar to or less than the minimum of the range reported for wheat (0.6–1.7 kg m^{-3}) in a global survey by Zwart and Bastiaanssen (2004). Results from this study indicate an opportunity to increase the yield potential and crop water productivity of WW_{CC} in water-limited systems by developing adapted germplasm (Araus et al., 2002). Cultivars that favor root formation in the fall may limit WU_F (via reduced canopy expansion) while supporting water extraction in the spring. Fan et al. (2008) reported increased crop water productivity for wheat cultivars with greater root water uptake efficiency. Robust tiller and spike formation under water-deficit conditions would support sink formation and avoid sink limitations to yield potential

Table 6. Crop sequence effects on components of grain yield for winter wheat following fallow (F) or in continuous cropping (CC). Crop sequences consisted of wheat, feed grain and oilseed phases; each phase present in each year. Values for ANOVA F-tests and contrasts are Type III observed significance levels. Main effect values are means.

Effect	Culms		Fertile culms fraction		Spikes		Seeds		Seed mass	
	F	CC	F	CC	F	CC	F	CC	F	CC
	— no. plant^{-1} —		— fraction of total culms —		— no. plant^{-1} —		— no. spike^{-1} —		— g (100 seed)$^{-1}$ —	
Year means										
2002	7.7	3.3	0.94	0.97	7.0	3.2	28.8	17.0	2.30	1.90
2003	5.6	5.1	0.73	0.82	4.0	4.1	19.3	17.8	2.44	2.30
2004	3.5	3.1	0.86	0.76	3.0	2.3	16.8	17.6	1.70	1.40
2005	7.2	5.9	0.94	0.67	6.8	4.0	14.4	9.9	2.78	1.91
2006	6.3	3.7	0.73	0.21	4.5	0.7	18.0	2.4	2.69	1.36
2007	4.3	4.1	0.78	0.65	3.5	2.7	27.0	21.6	1.96	1.71
2008	2.5	2.3	0.94	1.00	2.3	2.3	23.9	13.3	2.72	2.54
Oilseed means										
Spring canola	–	3.79	–	0.751	–	2.76	–	13.9	–	1.95
Soybean	–	4.05	–	0.732	–	2.83	–	14.4	–	1.80
Sunflower	–	3.90	–	0.700	–	2.67	–	14.4	–	1.88
Fallow	5.31	–	0.846	–	4.45	–	21.2	–	2.37	–
ANOVA *F* tests										
Year (Y)	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
Feed grain (FG)	0.0440		ns†		ns		ns		ns	
Y × FG	ns		ns		ns		ns		0.0028	
Oilseed (OS)	<0.0001		0.0020		<0.0001		<0.0001		<0.0001	
Y × OS	0.0480		<0.0001		0.0017		0.0049		<0.0001	
FG × OS	ns		ns		ns		ns		ns	
Y × FG × OS	ns		ns		ns		ns		ns	
Contrasts										
RD vs. no RD‡	<0.0001		0.0013		<0.0001		0.0070		<0.0001	
F vs. CC	<0.0001		0.0003		<0.0001		<0.0001		<0.0001	
SC vs. SB + SF§	ns		ns		ns		ns		ns	
SB vs. SF§	ns		ns		ns		ns		ns	
RD & F vs. CC¶	ns		ns		ns		ns		0.0096	
RD & SC vs. SB + SF¶	ns		0.0020		ns		ns		0.0416	
RD & SB vs. S ¶	ns		ns		ns		ns		<0.0001	

† ns, not significant at $P < 0.05$.

‡ Effects of years with relative ASW_E soil water deficits (2004, 2006, and 2008) against years with no relative deficit (2002, 2003, 2005, and 2007).

§ Oilseed-phase effects of spring canola (SC) against combined effects of soybean (SB) and sunflower (SF) or SB effects against SF effects.

¶ Interacting effects of relative water deficit vs. no-deficit years against F vs. CC, SC vs. SB and SF, or SB vs. SF.

Table 7. Pearson correlation coefficients for available soil water from fall emergence (ASW_E), early spring (ASW_S), flowering (ASW_{FL}), and maturity (ASW_M); water use from emergence to early spring (WU_F), from early spring to flowering (WU_S), from flowering to maturity (WU_{GF}), and from emergence through maturity (WU_{TOT}), canopy formation, and components of yield for winter wheat grown in eight cropping sequences, 2002 to 2008, at Colby, KS.

Parameter	Wheat after fallow (*n* = 42)				Wheat in continuous cropping (*n* = 126)			
	WU_F	WU_S	WU_{GF}	WU_{TOT}	WU_F	WU_S	WU_{GF}	WU_{TOT}
ASW_E	0.049	0.181	0.201	0.229	0.194*	0.237*	–0.216*	0.162
ASW_S	0.239	0.463**	0.111	0.442**	0.154	0.642***	–0.129	0.479***
ASW_{FL}	–0.182	–0.023	0.187	–0.003	–0.081	0.099	0.152	0.106
ASW_M	–0.251	–0.221	0.034	–0.378*	0.165	–0.053	0.116	0.077
Leaf area index	0.290	0.608***	0.269	0.624***	0.183	0.623***	0.314***	0.669***
Biomass	0.540***	0.699***	0.154	0.743***	0.340***	0.512***	0.501***	0.730***
Grain	0.463**	0.750***	–0.036	0.651***	0.051	0.620***	0.371***	0.639***
Harvest index	0.055	0.321*	–0.502***	–0.021	–0.262**	0.594***	–0.188*	0.252**
Culms plant^{-1}	0.190	–0.022	–0.202	–0.030	0.240**	0.149	0.437***	0.396***
Spikes plant^{-1}	0.228	0.024	–0.226	0.004	–0.025	0.386***	0.253**	0.385***
FFC†	0.048	0.079	–0.037	0.054	–0.286***	0.371***	–0.172	0.085
Seeds spike^{-1}	–0.043	0.140	–0.546***	–0.154	–0.300***	0.519***	–0.019	0.256**
100 seed wt.	0.436**	0.409**	0.118	0.481***	–0.122	0.256**	0.025	0.152
Net return	0.362*	0.704***	–0.000	0.600***	0.041	0.651***	0.115	0.547***

* Statistically significant correlation coefficient at the 0.05 α level.

** Statistically significant correlation coefficient at the 0.01 α level.

*** Statistically significant correlation coefficient at the 0.001 α level.

† Fraction of culms that are fertile.

(Ehdaie, 1995). Cultivars that promote translocation of preanthesis assimilates to grain (Xue et al., 2006; Ehdaie et al., 2006) would augment seed mass and yield formation under post-flowering drought conditions. Advances in pre-flowering and post-flowering drought tolerance traits are probably required to maintain HI and corresponding crop water productivity of wheat in water-limited continuous cropping systems and drought-affected crops in subhumid regions.

Table 8. Relationships of harvest index to available soil water at emergence (ASW_E) and water use from emergence to early spring (WU_F), from early spring to anthesis (WU_S), from anthesis to maturity (WU_{GF}) for winter wheat (WW) following spring canola (SC), soybean (SB), sunflower (SF), and fallow (F) in 3-yr cropping sequences that included a feed-grain (FG) phase. Coefficients were derived from covariance analysis; coefficient of determination for the covariance model: 0.682; RMSE = 0.06.

Cropping sequence	Intercept	ASW_E	WU_F	WU_S	WU_{GF}
WW-FG-SC	0.1179*	0.00018	–0.001201***	0.001215***	0.000057
WW-FG-SB	0.0493	0.00133***	–0.001699***	0.001321***	0.000398
WW-FG-SF	0.1831***	0.00084***	–0.001513***	0.000969***	–0.000330
WW-FG-F	0.3293***	0.00026*	–0.000382	0.000413	–0.001122***

* Statistically significant crop sequence effects testing for deviation from zero at the 0.05 α level.

*** Statistically significant crop sequence effects testing for deviation from zero at the 0.001 α level.

CONCLUSIONS

Replacing an uncropped fallow period with an OS crop reduced biomass, grain yield, and expected NR responses of WW_{CC} to an increment in WU_{TOT} by 18, 31, and 56%, respectively, relative to that of WW_F. These reductions, similar to that reported previously, resulted from the combined effects of continuous cropping, which reduced HI, TE, TF, and WU—all components of a water-limiting yield production function. Under severe water-deficit conditions, further reductions in the water productivity of WW_{CC} resulted from further decreases in HI, indicating sink-limited yield under drought. The modest water productivity observed (0.28 kg m^{-3} for WW_{CC} and 0.62 kg m^{-3} for WW_F) relative to a reported global range of 0.6 to 1.7 kg m^{-3} indicates the potential for improvement in CHP wheat water productivity through management and genetic gain.

ACKNOWLEDGMENTS

We acknowledge the technical contributions of Ralph Wolf, Larry Dible, and Ray Duffey for data collection and plot management efforts.

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