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Forage sorghum grown in a conventional wheat–grain sorghum–fallow rotation increased cropping system productivity and profitability

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Abstract

Intensifying winter wheat (*Triticum aestivum*)–grain sorghum [*Sorghum bicolor* (L.) Moench]–fallow (W–GS–FL) crop rotation with annual forages can increase productivity and resource use efficiency. The objective of this research was to quantify the impact of increasing crop intensity by growing forages in a traditional W–GS–FL rotation on cropping system productivity, water use, precipitation use efficiency, and net income. The study was conducted at the Southwest Research-Extension Center near Garden City, Kansas, from 2013 through 2020. Winter wheat (W), grain sorghum (GS), forage sorghum (FS), and forage oats (FO, *Avena sativa* L.) were used to generate six crop rotation treatments. These rotation treatments interspersed with fallow periods (FL) were W–GS–FL, W–FS–FL, W/FS–GS–FO, W/FS–FS–FO, W/FS–GS–FL, and W/FS–FS–FL. A W/FS indicates winter wheat double crop FS planted in the same year. The yield of FS was 45%–56% more with W/FS–FS–FO and W/FS–FS–FL compared with W–FS–FL. Available soil water at GS planting was 23%–30% less, and GS yield was 52%–60% smaller with W/FS–GS–FL compared to W–GS–FL. Water productivity and pre-season soil water storage were greatest with W/FS–FS–FL and W/FS–FS–FO. Inclusion of W/FS increased cost of production compared with W–GS(FS)–FL rotations. Gross return was greatest with W/FS–FS–FO and W/FS–FS–FL. The W/FS–FS–FO increased cropping intensity, productivity, resource use, and gross margin relative to other rotations in the semi-arid Great Plains. Producers should consider double-cropping of FS after wheat harvest, followed by a second year of FS in dryland cropping systems if there is sufficient forage demand.

Key words: dryland cropping systems, grain sorghum, forage oat, forage sorghum, double-crop, relay-crop

Introduction

A winter wheat (*Triticum aestivum*) rotation with a 15 month fallow (W–FL) was the predominant cropping system in the semi-arid US Great Plains and surrounding regions before 1970s but was inefficient in water use (Larney and Lindwall 1994; Tarkalson et al. 2006; Hansen et al. 2012). With adoption of no-tillage practices, W–grain sorghum [*Sorghum bicolor* (L.) Moench]–fallow (W–GS–FL) rotation has become the dominant cropping system in the southern and central Great Plains (Nielsen et al. 2002; Assefa et al. 2014). The W–corn (*Zea mays* L.)–FL has replaced W–GS–F in higher rainfall areas where crop insurance is available (Norwood and Currie 1998; Schlegel et al. 2016). However, GS remains more competitive with corn in regions prone to heat stress and limited soil water availability.

The W–GS–FL rotation has greater annualized grain yield, water use, improved soil quality, and reduced fallow period compared with W–FL (Baumhardt et al. 2015). Still, W–GS–FL has 23 of 36 of months cropping cycle without a crop (Baumhardt et al. 2011, 2015). Intensification with additional crops in the rotation or replacing existing crops with forages could increase productivity, profitability, and resource use of the W–GS–FL system. However, information is limited on the overall impact of these options on the cropping system.

The 11 months between wheat harvest and GS planting in a W–GS–FL includes July to November fallow where double crop production is possible before a killing freeze. The March through May period before GS planting is very short for grain or forage crop production and more likely to reduce soil water at GS planting and crop yield compared to growing a crop after wheat harvest. Another option is to replace FL with a spring forage crop when soil water is adequate (Holman et al. 2021b). Therefore, the fallow period just after wheat harvest may be a better window that supports production of a crop. Little is reported on double cropping after wheat in W–GS–FL rotation, but the similarity in W and winter triticale growth cycle suggests double cropping after wheat is also a possibility (Heggenstaller et al. 2008; Lyons et al. 2019; Holman et al. 2020). Compared with grain crops, forage crops require less water and have a shorter growing period as they are harvested at the soft dough stage or earlier for better forage nutritive value. Among annual forages, FS is drought and heat tolerant that uses significantly less water and fertilizer, and it is well-adapted in the Great Plains region (Nielsen et al. 2006; Newman et al. 2013; Alix et al. 2019; Bhattarai et al. 2019; Holman et al. 2021b). Therefore, double cropping FS after wheat, by modifying the W–GS–FL system to W/FS–GS–FL could intensify the cropping system and increase overall productivity.

The second fallow period of about 12 months between GS harvest and wheat planting, in a W–GS–FL system, includes a winter (November–February) just following sorghum harvest that cannot support grain or forage production due to dry soils and cold weather. The fallow period from March through August before W planting, on the other hand, could support additional crop production (Holman et al. 2018, 2022). Further intensification of the W–GS–FL rotation with inclusion of crops in the fallow period between GS harvest and W planting is possible. Previous research showed replacing portions of the fallow after sorghum harvest in a W–GS–FL rotation with spring forages increased overall system productivity (Holman et al. 2021*a*, 2022). Since fallow periods are mainly designed to store soil water for the next crop and reduce the risk of main crop failure (Holman et al. 2021*a*). Inclusion of a flexible cover crop only when soil water is sufficient and seasonal precipitation outlook is favorable can reduce the risk of decreasing grain yield of the subsequent crop and improve system profitability (Holman et al. 2021*a*).

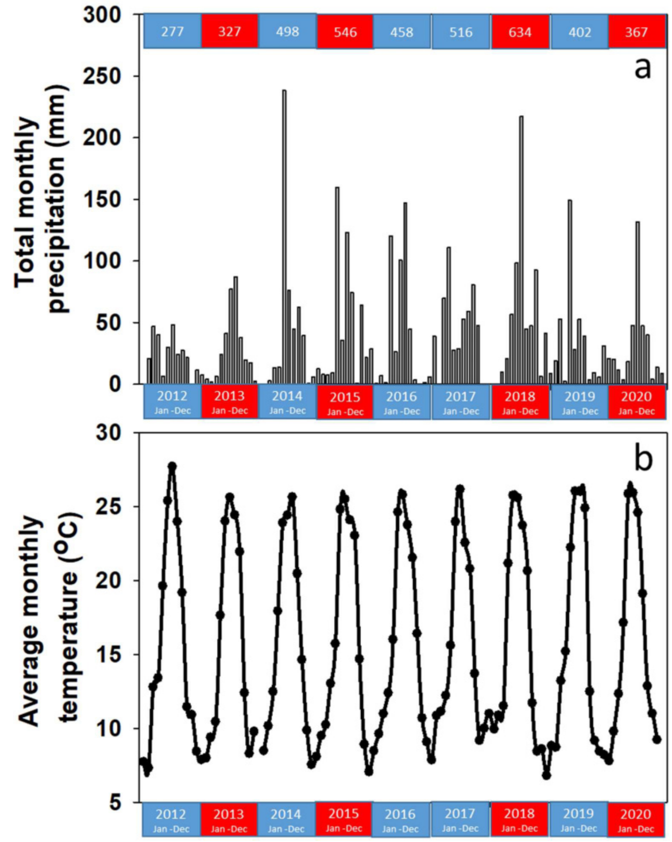
Previous research in water-limited regions of the Great Plains concluded that cropping systems that include forages have more efficient precipitation use compared with grain only cropping systems (Nielsen et al. 2005, 2006). Net income was also greatest in an all forage crop rotation followed by a mixed (grain and forage) crop rotation compared with grain only system (Nielsen et al. 2016). Therefore, in addition to intensifying W–GS–FL with inclusion of forages during fallow periods, a predominantly forage rotation system could improve productivity, precipitation use efficiency, and net income. The objective of this research was to quantify the impact of cropping intensification through fallow replacement with annual forages on individual crop productivity, system productivity, water use, water productivity, net income, and precipitation storage and use efficiencies in dryland W–GS–FL cropping system in the central Great Plains. Our hypothesis was that intensifying dryland crop production with FS and oat will improve productivity and gross margin of the conventional W–GS–FL rotation system.

Materials and methods

Study site and experimental design

The study was conducted at the Southwest Research-Extension Center near Garden City, KS (37°99′07″N, 100°82′47″W, 865 m asl) from 2013 through 2020. The soil in the study area is characterized as Ulysses silt loam (fine-silty, mixed, superactive, mesic Aridic Haplustolls). Normal annual precipitation is 505 mm at Garden City (Kansas State University weather data library). Annual precipitation during the 8-year study ranged from 327 mm in 2013 to 634 mm in 2018 (Fig. 1).

Fig. 1. Study area (*a*) total monthly precipitation and (*b*) average monthly temperature from 2012 (January 12) to 2021 (January 21).



The crops used in this study included wheat (W), grain sorghum (GS), forage sorghum (FS), and forage oats (FO), which were arranged to generate six crop rotation treatments. These rotation treatments interspersed with FL periods were W–GS–FL, W–FS–FL, W/FS–GS–FO, W/FS–FS–FO, W/FS–GS–FL, and W/FS–FS–FL, where the dash sign (–) indicates sequential cropping and the slash sign (/) indicates double cropping systems. FO was planted when a minimum of 30 cm of plant available soil water was determined in the 180-cm soil profile at spring planting using a Paul Brown soil water probe (Brown 1960; Obour et al. 2022), and when the National Weather Service Seasonal Outlook for the fallow period was neutral or favorable (NOAA 2021). Since FO planting was dependent on plant available water near planting, it was designated as flexible oat. These treatments were left to FL when the above conditions were not met. The experimental design of the study was a randomized complete block, and all crop rotation phases [W–GS–FL, GS-FL-W, and FL-W-GS] for each treatment were present each year. The study area was managed as a no-till W–GS–FL rotation by block, with all crop phases present every year 2 years prior to this study. This arrangement allowed all treatments to be "in phase" at the beginning of the study in 2013. Individ-

Table 1. Crop and soil management for different crops in the study for the years from 2013 to 2020 at Garden City, KS.

Management	Winter wheat	Double crop forage sorghum	Grain sorghum	Single crop forage sorghum	Forage oats
Planting date	Late September–early October	Early July	Late May–Early June	Late May–Early June	Late February–mid-March
Seeding rate	27–32 kg	5–7 kg	52 000–57 000 seed ha^{-1}	5–7 kg	29 kg
Row spacing	20 cm	20 cm	76 cm	20 cm	20 cm
Variety/hybrid[1]	TAM 111 (2013–2015), T158 (2016–2017), Colby (2018), T158 (2019), Tanka (2020)	Canex	DKS 28-05 (2013), DKS 29-28 (2014–2015) , 86P20 (2016–2017), 84P68 (2018), SP68M57 (2019), DKS36-07 (2020)	Canex	Jerry
N fertilizer rate	45 kg ha^{-1}	—	45 kg ha^{-1}	45 kg ha^{-1}	45 kg ha^{-1}
Herbicide[2]					
Pre-emerg.	—	0.45 kg atrazine, 0.63 L metolachlor	0.45 kg atrazine, 0.63 L metolachlor	0.45 kg atrazine, 0.63 L metolachlor	0.14 kg mesotrione
Post-emerg.	0.001 kg Ally, XP 0.06 kg dicamba	0.45 kg Huskie, 0.11 kg atrazine	0.45 kg Huskie, 0.11 kg atrazine	0.45 kg Huskie, 0.11 kg atrazine	0.03 kg Thifensulfuron methyl SG, 0.12 L dicamba
Chemical fallow	1.42 L Gramoxone, 0.06 L Sharpen, 0.24 L dicamba, 0.94 L glyphosate				
Harvesting date	Early June	Late August–Early September	Octpber–November	Late August–Early September	Early June

[1]Variety/hybrid varied over years for winter wheat and grain sorghum.
[2]Herbicide chemical names or active ingredient: atrazine, 1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine; dicamba, 3,6-dichloro-2-methoxybenzoic acid; glyphosate, isopropylamine salt of *N*-(phosphonomethyl) glycine; Gramoxone, 1,1"-Dimethyl-4,4"-bipyridinium dichloride; Huskie, Pyrasulfotole and bromoxynil; mesotrione, 2-(4-methylsulphonyl-2-nitrobenzoyl)-1,3-cyclohexanedione; metolachlor, (RS)-2-chloro-*N*-(2-ethyl-6-methyl-phenyl)-*N*-(1-methoxypropan-2-yl) acetamide; Sharpen, Saflufenacil.

Table 2. Grain and forage yield of winter wheat, forage sorghum, grain sorghum, and forage oats by rotation at Garden City, KS, from 2013 to 2020.

Treatment	Winter wheat Grain yield (kg ha^{-1})	Double crop forage sorghum Forage yield (kg ha^{-1})	Grain sorghum Grain yield (kg ha^{-1})	Single crop forage sorghum Forage yield (kg ha^{-1})	Forage oats Forage yield (kg ha^{-1})	Treatment Annualized forage yield (kg ha^{-1})
W–GS–FL[1]	1605	—	4311a	—	—	0
W–FS–FL	1522	—	—	6755	—	2252bc
W/FS–FS–FO	1397	3408	—	6615	514	3512a
W/FS–GS–FO	1625	3560	2856b	—	580	1380 cd
W/FS–FS–FL	1354	3339	—	6489	—	3276ab
W/FS–GS–FL	1506	3767	2708b	—	—	1256d
HSD[2]	NS	NS	653	NS	NS	1088
P-value	0.375	0.828	<0.001	0.825	0.903	<0.001

Note: Mean values within a column followed by the same letter or with no letter are not significantly different ($P < 0.05$).
[1]Winter wheat (W), grain sorghum (GS), forage sorghum (FS), forage oats (FO), and fallow period (FL). The dash sign (–) indicates sequential cropping, and the slash sign (/) indicates a double cropping system. [2]HSD is the minimum difference between two treatments used to declare they are significantly different using Tukey's honest significant difference test at $P < 0.05$. NS = non-significant.

ual plot size was 9 m × 36 m, and each treatment had four replications.

Crop management and data collected

Herbicide application was determined based on weed population and local control recommendations. Winter wheat was planted in the fall (late September to the first week of October) and harvested in June (Table 1). Double crop FS was planted in early July after wheat harvest and harvested late August or early September of the same year. In the next year after W harvest, GS was planted in late May or early June and harvested in October—November. Single crop FS was planted also in the next year after W harvest, in late May or early June, and harvested in late August or early September. Flexible FO was planted in the spring (late February through the middle of March) and harvested for hay in early June. Volumetric soil water content was measured at planting and harvest time for all plots by 30-cm increments to 180-cm soil depth. Volumetric soil water samples were converted to available soil water as described by Black (1965). Winter wheat and GS were har-

Fig. 2. Total (*a*) grain, (*b*) forage biomass, and (*c*) yield produced with one cycle of rotation (3 years) of each treatment at Garden City, KS.

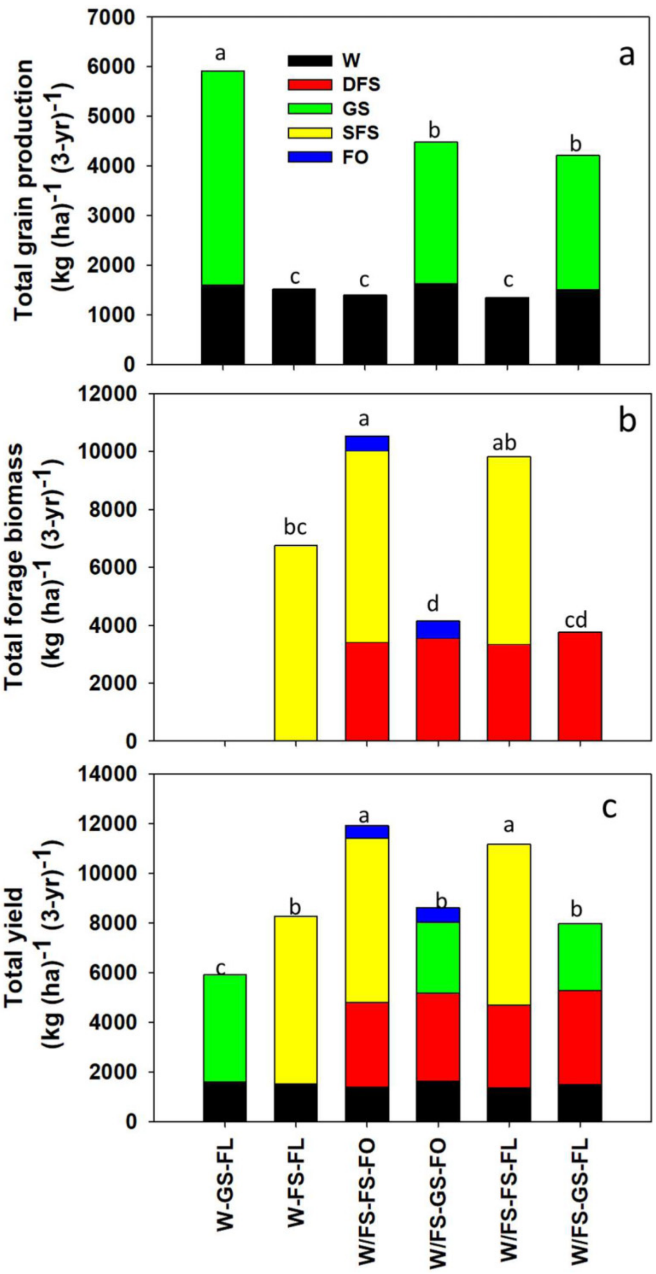
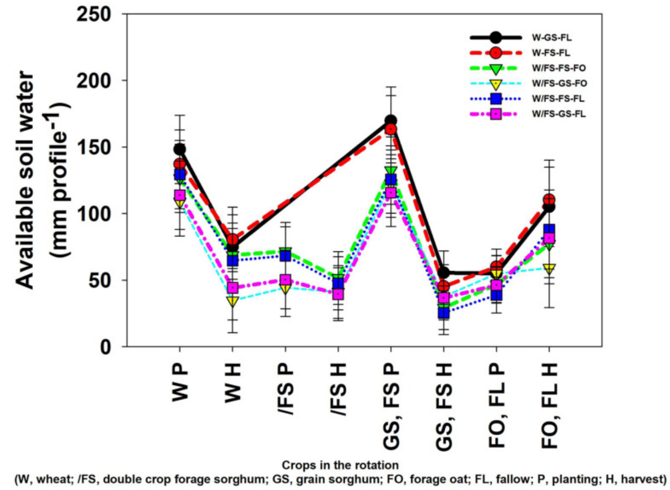


Fig. 3. Available soil water at planting and harvest of wheat, double crop forage sorghum, grain sorghum, single crop forage sorghum, forage oat, and at the start and end of fallow of one cycle of rotation for each treatment at Garden City, KS.



vested with a small plot combine (Wintersteiger model delta) to measure grain yield. Winter wheat was harvested with a 2.5 m Shelbourne stripper header, and GS was harvested with a two-row 76 cm John Deere row crop header. Grain subsamples were collected at harvest and analyzed with a Dicky–John grain analyzer (model GAC2100, Dickey John) for moisture and test weight. Grain yield was adjusted to 13.5% water content. Forages were mechanically harvested with a Carter harvester (Carter Manufacturing Company, Brookston, IN) at approximately 15 cm above the soil surface. Forage samples from the harvested area were dried in a forced-air dryer at 65 °C until constant weight, and dry weight was determined.

Cost of production for W, GS, and FS was collected from Kansas Farm Management Association State-wide Enterprise Summaries including seed, herbicide, fertilizer, and crop value (AgManager 2021*a*). For drilling, swathing, raking, baling, and stacking, costs represent state-wide values from the survey rates paid by Kansas Farmers for Custom Work published biannually in 2016, 2018, and 2020 by the Kansas State University Land Use Survey Program and the Kansas Department of Agriculture (AgManager 2021*b*). Forage oat and grain oat seed prices were assumed the same and obtained from the United States Department of Agriculture (USDA NASS 2021). Oat hay feed values for year 2016 through 2020 were from Economic Research Services reported for hay other than alfalfa (USDA ERS 2021).

Calculated response variables

Water use (WU), water productivity, fallow accumulation, PSEpre, and total precipitation storage and use efficiencies were calculated from soil water measurements in the field and weather data. Water use of each crop was calculated (eq. 1) as a summation of the difference between available soil water at planting (ASWP) and available soil water at harvest (ASWH), and in-season precipitation (ISP). Water productivity (WP) was calculated as a quotient of grain yield to seasonal WU. Fallow accumulation (FA) for each crop was calculated as a difference between ASWP and available soil water at previous harvest (ASWPH). The sum of all FA prior to each crop in rotation resulted in the FA of the rotation.

$$\text{(1)} \qquad \text{WU} = (\text{ASWP} - \text{ASWH}) + \text{ISP}$$

Preseason precipitation storage efficiency (PSEpre) was defined here as the sum of the fraction of the precipitation that is stored in the soil in a fallow season prior to planting of each crop in the rotation. The PSEpre was calculated (eq. 2) as the sum of the ratio of FA (the difference between ASWP

Table 3. Water use (mm) by winter wheat, forage sorghum, grain sorghum, and forage oats in rotation experiments at Garden City, KS.

Treatment	Winter wheat	Double crop forage sorghum	Grain sorghum	Single crop forage sorghum	Forage oats	Treatment total
W–GS–FL[1]	378	—	422a	—	—	800bc
W–FS–FL	361	—	—	348	—	781c
W/FS–FS–FO	368	254	—	333	72	1037a
W/FS–GS–FO	365	237	391b	—	83	993a
W/FS–FS–FL	364	253	—	330	—	948ab
W/FS–GS–FL	375	244	385b	—	—	1004a
HSD[2]	NS	NS	23	NS	NS	169
P-value	0.831	0.247	0.004	0.229	0.096	<0.001

Note: Mean values within a column followed by the same letter or with no letter are not significantly different ($P < 0.05$). NS = non-significant.
[1]Winter wheat (W), grain sorghum (GS), forage sorghum (FS), forage oats (FO), and fallow period (FL). The dash sign (–) indicates sequential cropping, and the slash sign (/) indicates a double cropping system. [2]HSD is the minimum difference between two treatments used to declare they are significantly different using Tukey's honest significant difference test at $P < 0.05$.

Table 4. Water productivity (kg ha^{-1} mm^{-1}) by winter wheat, forage sorghum, grain sorghum, and forage oats in rotation experiments at Garden City, KS.

Treatment	Winter wheat	Double crop forage sorghum	Grain sorghum	Single crop forage sorghum	Forage oats	Treatment annualized average
W–GS–FL[1]	3.51	—	10.23a	—	—	3.74c
W–FS–FL	3.17	—	—	18.83	—	7.18bc
W/FS–FS–FO	2.88	13.11	—	19.30	3.66	13.25a
W/FS–GS–FO	3.36	14.17	7.33b	—	3.47	8.46b
W/FS–FS–FL	2.71	12.82	—	19.11	—	9.65ab
W/FS–GS–FL	3.15	7.08	7.01b	—	—	7.64b
HSD[2]	NS	NS	1.53	NS	NS	3.60
P-value	0.344	0.574	<0.001	0.941	0.777	<0.001

Note: Mean values within a column followed by the same letter or with no letter are not significantly different ($P < 0.05$). NS = non-significant.
[1]Winter wheat (W), grain sorghum (GS), forage sorghum (FS), forage oats (FO), and fallow period (FL). The dash sign (–) indicates sequential cropping, and the slash sign (/) indicates a double cropping system. [2]HSD is minimum difference between two treatments used to declare they are significantly different using Tukey's honest significant difference test at $P < 0.05$.

and ASWPH) and total fallow period precipitation (precipitation from previous crop harvest to current crop planting, PreSP) of each crop in the rotation.

$$\text{(2)}\qquad \text{PSE}_{\text{pre}} = \sum_{x=1}^{n} \frac{\text{FA}_x}{\text{PreSP}_x} = \sum_{1}^{n} \frac{\text{ASWP}_x - \text{ASWPH}_x}{\text{PreSP}_x}$$

where x is a crop, first crop (crop 1) to last crop (crop n), in one cycle of rotation. One cycle of rotation is a period between the beginning seasons for planting the first crop in all phases of the rotation through the end seasons after harvesting of the last crop in the crop sequence of all phases of the rotation.

Precipitation storage and use efficiency (PSUE) was defined here as the sum of the fraction of the precipitation that is stored in the soil (ASWH minus ASWPH) and used by crop (WU) in the period between the fallow prior to crop planting to crop harvest. Total precipitation storage and use efficiency (TPSUE) was calculated (eq. 3) as the sum of PSUE (total water used by each crop (WU) in the rotation and the soil water stored) divided by total annual precipitation in one cycle of rotation.

$$\text{(3)}\qquad \text{TPSUE} = \sum_{x=1}^{n} \frac{\text{PSUE}_x}{\text{PreSP}_x + \text{ISP}_x} = \sum_{x=1}^{n} \frac{\text{WU}_x + (\text{ASWH} - \text{ASWPH})_x}{\text{PreSP}_x + \text{ISP}_x}$$

Total variable cost was calculated as a summation of the costs of seed and drilling, fertilizer application, herbicide and herbicide application, and total forage or grain harvesting expense. Gross return was calculated as the product-of the price and yield of the crop. Gross margin was calculated as the difference between gross return and total expense. Government payments, crop insurance, interest, management, and land rent were excluded from the economic analysis.

Average yield, forage accumulation, water use, water productivity, cost, and gross margin calculated for flexible oat were in consideration of the frequency of planting. In years when oat was not planted had zero yields resulting in a reduced average overall yield across years than the average yield realized in years oat was planted. Those years when oat

Table 5. Total fallow accumulation (FA), pre-season precipitation storage efficiency (PrePSE), and total precipitation storage and use efficiency (TPSUE) by rotation at Garden City, KS, from 2013 to 2020.

Treatment	FA (mm)	PrePSE	TPSUE
W–GS–FL[1]	147	−1.53ab	0.41b
W–FS–FL	141	4.29a	0.45b
W/FS–FS–FO	143	3.66a	0.81a
W/FS–GS–FO	143	−0.83ab	0.74a
W/FS–FS–FL	139	4.30a	0.76a
W/FS–GS–FL	125	−4.93b	0.67a
HSD[2]	NS	7.48	0.22
P-value	0.963	0.001	<0.001

Note: Mean values within a column followed by the same letter or with no letter are not significantly different ($P < 0.05$). NS = non-significant.
[1]Winter wheat (W), grain sorghum (GS), forage sorghum (FS), forage oats (FO), and fallow period (FL). The dash sign (–) indicates sequential cropping, and the slash sign (/) indicates a double cropping system. [2]HSD is minimum difference between two treatments used to declare they are significantly different using Tukey's honest significant difference test at $P < 0.05$.

was not planted the cost of fallow was used in the economic analysis.

Statistical data analysis

Data were analyzed in SAS 9.4 (SAS Institute Inc., Cary, NC). The effects of treatments on grain yield, WU, water productivity, PSEpre, available soil water (ASW), variable cost, and returns were analyzed using the PROC MIXED procedure. For the type three test of fixed effects, treatment was the fixed effect variable and replication, and year were random effect variables. Once a significant fixed effect ($P < 0.05$) was identified, mean separation tests were conducted using Tukey's honest significant difference test.

In addition, correlation and regression analysis were conducted using the PROC CORR and PROC REG procedures of SAS. The correlation of yield of crops following one another in the same rotation from the same plot was studied using plot level data ($n = 168$) to understand impact of performance of prior crops in a crop rotation sequence. The water use—yield regression analysis was conducted for each of the crops in the study.

Results

Grain and forage yield

Grain yield of W did not differ significantly ($P > 0.05$) across treatments (Table 2). Precipitation during the W growing season was erratic and low (Fig. 1), resulting in a below average wheat yield of 1500 kg ha^{-1}. Like W yield, double cropped FS yield did not differ across treatments (Table 2). Average double crop FS yield across years and treatments for the study was 3518 kg ha^{-1}.

Grain sorghum yield was significantly different across treatments (Table 2). Yield of GS with W–GS–FL was 50%–60% greater than W/FS–GS–FO and W/FS–GS–FL treatments. Unlike GS, single cropped FS yield was not different across treatments (Table 2). Averaged across treatments and years, single crop FS yield was 88% (6620 kg ha^{-1}) more than double crop FS. Flexible forage oat yields were not different across the two treatments (Table 2). Oat was planted in 2013 and 2016, and average forage oat yield across those 2 years and treatments was 547 kg ha^{-1}.

Overall, for one cycle of the crop rotation, W–GS–FL produced greatest total grain yield (from W and GS combined) compared with all other treatments (Fig. 2). The W/FS–GS–FL and W/FS–GS–FO treatments had similar total grain yield that was less than W–GS–FL, but greater than the other treatments. The W/FS–FS–FO(FL) produced greatest forage compared with all other treatments (Table 2; Fig. 2). Total yield (grain + forage) was also greatest for W/FS–FS–FO which was on par with W/FS–FS–FL treatment. Annual yields from the study varied significantly over the 8 years for each crop and precipitation during the 8 years of this study occurred mostly during the summer growing season (Fig. 1).

Available soil water at planting and harvest

Averaged ASW at wheat planting was 127 mm with no rotation treatment effects (Fig. 3). Mean ASW at W harvest was 61 mm, and it was not affected by rotations except W/FS–GS–FO had less ASW compared with W–GS–FL or W–FS–FL. This decrease in ASW corresponded with increased cropping intensity. Average ASWP of double crop FS was 59 mm, and mean ASWH of double crop FS was 45 mm with no rotation treatment effects (Fig. 3).

At GS planting, ASW ranged between 116 and 170 mm averaged across years (Fig. 3) and there was a difference among rotation treatments. ASWP of GS for the W–GS–FL was greater than both W/FS–GS–FL or W/FS–GS–FO treatments. At GS harvest, average ASW was 38 mm and there was no difference among rotation treatments.

ASWP of single crop FS planting ranged from 126 to 163 mm averaged across years (Fig. 3) and differed among rotation treatments. ASWP of single crop FS for the W–FS–FL treatment was greater than both W/FS–FS–FL or W/FS–FS–FO treatments (Fig. 3). At FS harvest, average ASW was 38 mm and there was no difference among treatments. ASWP and harvest of FO varied but did not differ among treatments.

Water use

Water use was not affected by rotation treatment for W, single and double cropped FS, and FO. Grain sorghum water use, however, was significantly different across treatments (Table 3). Average GS water use in W–GS–FL was 422 mm, significantly greater than W/FS–GS–FO (391 mm) or W/FS–GS–FL (385 mm).

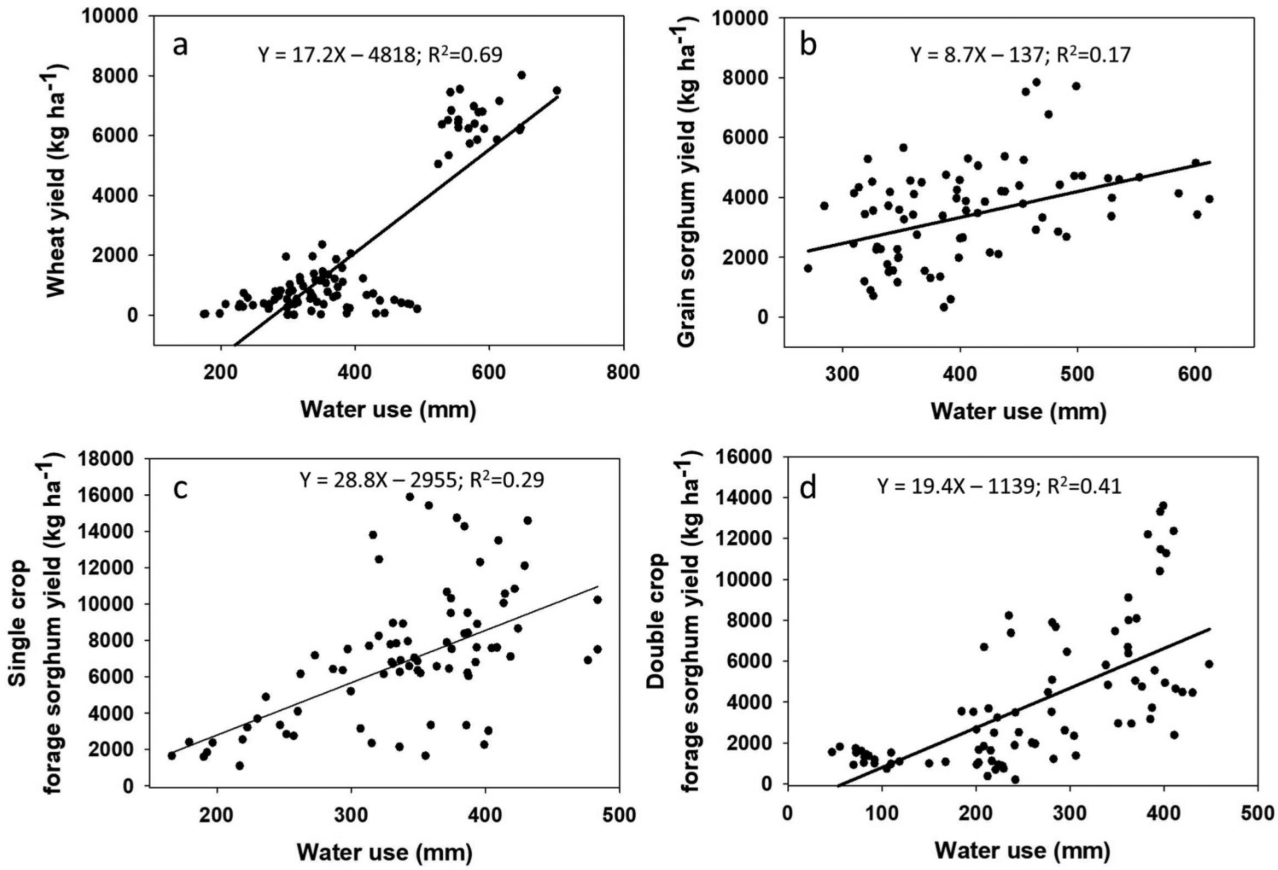
During a cycle of the rotation, W–GS–FL and W–FS–FL treatments had the least amount of water use compared with the remaining treatments that had double crop FS (Table 3). Overall, a 25%–33% increase in water use of W/FS–GS(FS)–FL(FO) rotations was recorded compared with W–GS(FS)–FL rotations.

Table 6. Pearson correlation coefficient (*r*) and probability of significance ($p > |r|$) among sequence of crop yields in each of the rotations studied at Garden City, KS.

Treatment	First crop vs. second (W vs. GS, FS, or /FS)		First crop vs. third (W vs. GS or FS)		Second crop vs. third (/FS vs. GS or FS)	
	r	$p > \|r\|$	*r*	$p > \|r\|$	*r*	$p > \|r\|$
W–GS–FL[1]	−0.52*	0.004	—	—	—	—
W–FS–FL	−0.48*	0.008	—	—	—	—
W/FS–FS–FO	−0.24	0.202	−0.44*	0.017	0.19	0.324
W/FS–GS–FO	−0.28	0.146	−0.34	0.073	0.39*	0.042
W/FS–FS–FL	−0.20	0.338	−0.47*	0.011	0.10	0.641
W/FS–GS–FL	−0.25	0.199	−0.31	0.102	0.37	0.053

Note: If $P > |r|$ is less than 0.05, then correlation is significant (*). [1]Winter wheat (W), grain sorghum (GS), forage sorghum (FS), forage oats (FO), and fallow period (FL). The dash sign (–) indicates sequential cropping, and the slash sign (/) indicates a double cropping system.

Fig. 4. Linear relationship between water use and yield in (*a*) wheat, (*b*) grain sorghum, (*c*) single crop forage sorghum, and (*c*) double crop forage sorghum for years from 2013 to 2020 at Garden City, KS.



Crop water productivity

The water productivity of W was not different among the various rotation treatments (Table 4). Averaged across treatments, water productivity of W was about 3.13 kg ha^{-1} mm^{-1}. The water productivity of double-cropped FS did not differ among treatments (Table 4). The water productivity of GS differs among treatments (Table 4). Water productivity in W–GS–FL (10.2 kg ha^{-1} mm^{-1}) was significantly greater than W/FS–GS–FO (7.3 kg ha^{-1} mm^{-1}) or W/FS–GS–FL (7.0 kg ha^{-1} mm^{-1}). There was no difference in the water productivity of GS between W/FS–GS–FO and W/FS–GS–FL treatments.

The water productivity of single cropped FS averaged 19.1 kg ha^{-1} mm^{-1} across treatments, and it was unaffected by crop rotation treatment (Table 4). Water productivity of FO was not different between the two rotation treatments (Table 3). Average FO water productivity was about 3.56 kg ha^{-1} mm^{-1} across treatments and years. Water productivity was greater whenever growing conditions (ISP and ASWP) were more favorable.

Fallow accumulation, precipitation storage, and water use efficiency

Total fallow water accumulation (fallow periods combined for a complete crop rotation cycle) was not different among treatments (Table 5). When data were combined for all crops,

Table 7. Input prices and crop values for the last 5 years of the study (2016–2020). The average of the 5 years is used to estimate cost of production and return for each year, each crop, and treatments.

Input	Unit	Year 2020	2019	2018	2017	2016	Average
Winter wheat							
Seed[1]	\$ ha^{-1}	36.3	32.7	27.5	26.0	32.9	31.1
Planting[2]	\$ ha^{-1}	43.1	—	39.6	—	38.3	40.3
Fertilizer[1]	\$ ha^{-1}	114.4	111.8	97.4	91.4	112.8	105.6
Herbicide[1]	\$ ha^{-1}	48.2	54.1	43.4	52.6	74.1	54.5
Harvest[2]	\$ ha^{-1}	56.9	—	56.0	—	57.3	56.7
Trucking	\$ kg^{-1}	0.007	—	0.007	—	0.008	0.007
Grain sorghum							
Seed[1]	\$ ha^{-1}	34.6	34.8	31.4	32.7	33.1	33.3
Planting[2]	\$ ha^{-1}	42.9	—	41.1	—	41.0	41.7
Fertilizer[1]	\$ ha^{-1}	120.7	115.3	96.0	91.0	101.9	105.0
Herbicide[1]	\$ ha^{-1}	107.2	108.9	102.9	100.1	126.4	109.1
Harvest[2]	\$ ha^{-1}	58.5	—	58.2	—	60.3	59.0
Trucking	\$ kg^{-1}	0.007	—	0.008	—	0.008	0.008
Forage sorghum and Oat							
Forage sorghum seed[1]	\$ ha^{-1}	43.2	54.4	45.2	36.1	34.6	42.7
Oat seed price[3]	\$ ha^{-1}	45.2	46.5	47.2	48.4	48.2	46.9
Drilling[2]	\$ ha^{-1}	43.0	—	40.8	—	41.0	41.5
Herbicide[1]	\$ ha^{-1}	41.0	64.5	41.0	40.8	35.8	44.7
Fertilizer[1]	\$ ha^{-1}	80.1	63.0	47.4	50.2	42.0	56.6
Swath[2]	\$ ha^{-1}	37.6	—	35.8	—	38.3	37.3
Bale[2]	\$ kg^{-1}	0.019	—	0.015	—	0.016	0.016
Stack & other[2]	\$ kg^{-1}	0.004	—	0.009	—	0.011	0.008
Crop value							
Forage Oat[4]	\$ kg^{-1}	0.10	0.11	0.11	0.09	0.08	0.10
Forage sorghum[1]	\$ kg^{-1}	0.08	0.08	0.09	0.06	0.05	0.07
Grain sorghum[1]	\$ kg^{-1}	0.18	0.12	0.12	0.12	0.10	0.13
Winter wheat[1]	\$ kg^{-1}	0.16	0.15	0.18	0.14	0.12	0.15

[1]Kansas Farm Management Association State-wide Enterprise Summaries for wheat, grain sorghum, and Sudan Cane Hay, double crop forage sorghum grow with residual fertilizer from wheat, forage crop values are for hay with ~85% dry matter, therefore adjusted to 100% dry matter. [2]Rates Paid by Kansas Farmers for Custom Work, harvest costs for yield above 610 kg ha^{-1} for grain sorghum and above 1200 kg ha^{-1} for wheat have an additional cost which is \$0.01 for every additional 26 kg ha^{-1} yield above these values. [3]USDA ERS Forage oat and grain oat seed prices are assumed same. [4]USDA NASS hay price other than alfalfa.

pre-season precipitation storage efficiency was significantly less in W/FS–GS–FL than in rotations that did not include GS. TPSUE was greater for treatments with double crop FS compared to W–GS(FS)–FL (Table 5).

Yield correlation and yield-water use relations

There was a negative correlation coefficient between wheat yield and the subsequent crop yield (either double crop FS or second year crop (in the absence of double crop FS; Table 6). There was a significant negative correlation between wheat and GS or single cropped FS yield, but the correlation between W and double crop FS was not significant. There was a negative correlation between W yield and crop yield in the subsequent year (crops following double cropped FS) in all four rotations with double crop FS.

A linear wheat yield–water use relation showed W yield increase of 17 kg ha^{-1} for each millimeter increase in water use (Fig. 4*a*). Similarly, GS yield-water use relation indicated a yield increase of 9 kg ha^{-1} for each millimeter increase in water use (Fig. 4*b*). Single cropped FS yield increased per millimeter of water use was greater than (Fig. 4*c*) double cropped FS yield increased per millimeter water used (Fig. 4*d*).

Economic analysis

A partial budget analysis considered seed, planting, fertilizer, herbicide, and harvesting costs (Table 7). Total variable cost of W, double cropped FS, single cropped FS, and FO did not vary by rotation (Table 8). Grain sorghum cost of production was greater in W–GS–FL rotation compared to the W/FS–GS–FL(FO). Overall, adding double cropped FS increased cost of production, cost of production was greater for

Table 8. Cost of production, gross-, and gross margin of winter wheat, forage sorghum, grain sorghum, and forage oats by rotation at Garden City, KS, average of 2013–2020.

Treatment	Winter wheat	Double crop forage sorghum	Grain sorghum	Single crop forage sorghum	Fallow	Oats	One-cycle of treatment
			Cost of production ($ ha^{-1})				
W–GS–FL[1]	300	—	384a	—	187	—	871b
W–FS–FL	299	—	—	385	187	—	871b
W/FS–FS–FO	298	203	—	382	—	210	1093a
W/FS–GS–FO	300	207	372b	—	—	212	1090a
W/FS–FS–FL	298	202	—	379	187	—	1065a
W/FS–GS–FL	299	212	371b	—	187	—	1068a
HSD[2]	NS	NS	6	NS	NS	NS	107
			Gross return ($ ha^{-1})				
W–GS–FL	241	—	560a	—	0	—	801b
W–FS–FL	228	—	—	554	0	—	782b
W/FS–FS–FO	209	279	—	542	—	60	1092a
W/FS–GS–FO	244	292	371b	—	—	68	975ab
W/FS–FS–FL	203	274	—	532	0	—	1009ab
W/FS–GS–FL	226	309	352b	—	0	—	887ab
HSD	NS	NS	85	NS	NS	NS	290
			Gross margin ($ ha^{-1})				
W–GS–FL	−59	—	176a	—	−187	—	−70ab
W–FS–FL	−71	—	—	169	−187	—	−89ab
W/FS–FS–FO	−89	76	—	161	—	−150	−2a
W/FS–GS–FO	−56	85	−1	—	—	−144	−116ab
W/FS–FS–FL	−95	72	—	154	−187	—	−56ab
W/FS–GS–FL	−73	97	−19	–	−187	—	−182b
HSD	NS	NS	79	NS	NS	NS	180

Note: Mean values within a column followed by the same letter or with no letter are not significantly different ($P < 0.05$). NS = non-significant. [1]Winter wheat (W), grain sorghum (GS), forage sorghum (FS), forage oats (FO), and fallow period (FL). The dash sign (–) indicates sequential cropping, and the slash sign (/) indicates a double cropping system. [2]HSD is minimum difference between two treatments used to declare they are significantly different using Tukey's Honest Significant Difference Test at $P < 0.05$.

W/FS–FS(GS)–FL(FO) rotations compared to W–GS(FS)–FL(FO) (Table 8).

Gross return from W, double cropped FS, single cropped FS, and FO was unaffected by the rotation scheme (Table 8). Grain sorghum gross return was greater in W–GS–FL rotation compared with W/FS–GS–FL(FO). Overall, the W/FS–FS–FO rotation had a greater gross return compared with the W–GS(FS)–FL(FO) rotations (Table 8).

Gross margin from W, double-cropped FS, single cropped FS, and FO was not different among rotations (Table 8). Gross margin was negative for W and FO but was positive for double crop and single cropped FS. Wheat failed to produce any grain in 2016 (data not included in economic analysis) and was near zero in two other years (2013 and 2014) due to erratic and low precipitation and high springtime temperatures causing crop stress during W growing seasons. Most producers would utilize crop insurance to protect against very low yield years, but crop insurance was excluded from this economic analysis. Oat's cost of production was greater than gross revenue. Grain sorghum gross margin was far greater and positive in W–GS–FL rotation compared with negative gross margin from W/FS–GS–FL(FO) rotations. Overall, gross margin was negative but W/FS–FS–FO and W/FS–FS–FL rotations reduced economic losses significantly compared with W/FS–GS–FL rotation (Table 8).

Discussion

To our knowledge, this study is the first to report on productivity and profitability of double cropping FS after wheat in W–GS–FL rotation in the central Great Plains. This is important because the results of our study indicated that inclusion of FS within the conventional W–GS–FL rotation in any of the rotations increased overall economic yield. The more intensified double-cropped FS rotation (W/FS–FS–FL) increased overall forage productivity by 46% compared with W–FS–FL. Likewise, adding FO to replace the fallow period of W/FS–FS–FL to W/FS–FS–FO increased forage yield an additional 7%. Forage crops require shorter growing period and less water which perhaps contributed to the economic benefits observed. This result in our study is in line with results of Nielsen et al. (2017) who reported an increase in system productivity when spring forage triticale was grown in place of fallow in a W–corn–spring forage triticale rotation compared with W–corn–FL. A

5-year study that examined potential dryland cropping systems adapted to climate change for Central Great Plains also showed a significantly greater yield from W–FS–flexible crop compared with W–GS–FL for all 5 years from 2011 to 2015 (Nielsen et al. 2016).

Our study shows an average decline in GS yield following double crop FS. That is result of an overall decline in soil water. Other studies reported that growing forage in place of fallow in W–F or W–GS–FL rotation did not affect the main crop (W or GS) yield in years with either very low or very high precipitation, but did reduce main crop grain yield in average production years (Holman et al. 2018, 2022). Most importantly, averaged across years growing forages in place of fallow tended to improve cropping system profitability even when increased cropping intensity reduced grain yields. In an annual forage cropping system, greater forage productivity from double cropping FS after winter triticale compared with either continuous FS or continuous triticale was also reported (Holman et al. 2020).

ASWP of GS and FS was affected due to double cropping of FS in W–GS–FL or W–FS–FL. The main reason for the 11–12 months fallow periods between W harvest and GS planting and between GS harvest and W planting in W–GS–FL rotation is to store soil water for the next crop and avert the risk of crop failure (Tanaka and Aase 1987; Holman et al. 2018). Inclusion of FS in W–GS–FL rotation in any of the forms mentioned in our study did not decrease soil water at W planting. When double cropped FS was grown after W, there was a 38%–47% decrease in ASWP of GS compared to W–GS–FL and a 23%–30% decrease in ASWP of FS compared to W–FS–FL. This decline in ASWP at planting of GS following double crop FS after W translated into lower water use, yield, and water productivity for GS but did not affect FS water use, yield, or water productivity. A significant negative correlation between W yield and the subsequent GS or FS crops in the presence of double crop FS indicates that water use of both W and double crop FS had significant effects on the following crop.

In our study, soil water at W planting was not affected because the fallow between GS or FS and W was replaced with FO, which was purposefully planted in years when soil water at W planting should have been sufficient. Nielsen et al. (2017) reported an average of 88 mm less available soil water at W planting in three site-years when fallow was replaced with spring forage triticale in W–corn–FL rotation. Similar to the results of this study, Holman et al. (2021) concluded that fallow replacement spring forage crops in W–GS–FL rotation did not affect ASWP of W, but ASWP of W was less with spring grain crops compared to fallow. Water productivity and preseason precipitation storage efficiency were greater for the forage-dominated, W/FS–FS–FL or W/FS–FS–FO, systems compared with the other rotations in this study. Other studies also reported greater precipitation use efficiency for forage cropping systems compared with a grain-based cropping system (Nielsen et al. 2005, 2006).

Rotations that included double crop FS increased the cost of production compared with W–GS(FS)–FL rotations. Gross marginal return was negative for all rotations when crop insurance was excluded, mainly because of small W yields in this study. However, forage-dominated W/FS–FS–FO or W/FS–FS–FL systems significantly increased net revenue compared with W/FS–GS–FL. These forage-dominant systems also tended to increase net profit compared to the conventional W–GS–FL rotation mainly due to positive gross margin from single and double crop forages and reduced no-tillage management cost from FO. Forage oat gross margin was negative like W, but including FO in place of fallow reduced net loss compared with chemical fallow due to revenue from the FO and less herbicide expense. Forage oat yield was lower than expected in this study due to little spring precipitation and high spring temperatures. Oat yield of >2000 kg ha^{-1} would have produced sufficient gross revenue to cover oat production and hay expenses. Grazing forage crops with low forage yield has less production cost and is more profitable compared to haying (Holman et al. 2021*b*). Nielsen et al. (2016) reported that compared with a W only or W and other grain-based crop rotations, net incomes were greater in an all forage crop rotation followed by a mixed grain and forage crop rotation system. In another study, when the fallow phase of a W–corn–FL was replaced with forage spring triticale, net income increased in the years when rainfall was abundant and remained similar in drier years (Nielsen et al. 2017). Holman et al. (2018) reported that growing a cover crop as forage in place of fallow increased gross margins of the fallow phase by 26%–240% when forage yields were sufficiently high (>2000 kg ha^{-1}), seed costs were low, and impact on following grain crop yields was minimal (favorable growing conditions). Forage sorghum grown as a double crop after W and replacing GS with FS W/FS-FS-FL(FO) increased total yield, water productivity, and net income. The only limitation of implementing double cropping FS after W was reduced GS yields and difficulty growing sufficient double crop forage yield in dry years.

Historical trend line of dryland W yield for the study area was 3360 kg ha^{-1} (Holman et al. 2011), which was 124% more than yields reported in the current study. Southwest Kansas average W yield reports for the years 2013 to 2019 from USDA statistics service were 1170, 1137, 1910, 3921, 2845, 2327, and 3786, respectively, was to most part similar to our yearly averages. This region is prone to highly variable wheat yields due to water and temperature variability. During the 8 years of this study, precipitation mostly occurred during the summer growing season, which is the primary precipitation period, and tended to favor summer crop yields compared to W. In 2016, a dry fall limited wheat growth combined with excessive jackrabbit (*Lepus californicus*) feeding resulted in little W yields. Therefore, 2016 wheat yields were excluded from the grain yield and subsequent economic analysis. Although rare, jackrabbit populations in this region can reach levels causing excessive crop damage, particularly after several dry years when predator populations and disease levels are low (Bronson and Tiemeier 1959). Gross margin for the W/FS–FS–FO and W/FS–FS–FL rotations would be positive had crop insurance been included or average wheat yield was near long-term trend line yields of 3360 kg ha^{-1}, with sufficient precipitation and soil water, reported for the study location (Holman et al. 2011).

Conclusion

Forage yield increased by 56% and 46% in the W/FS–FS–FO and W/FS–FS–FL compared to F–FS–FL. Including double crop FS followed by the second year FS (W/FS–FS–FO and W/FS–FS–FL) in the cropping system increased gross margins compared to W–GS–FL. The W/FS–FS–FO or W/FS–FS–FL rotations performed best at increasing cropping intensity, productivity, resource use, and gross margin as an alternative crop rotation to W–GS–F in the Central Great Plains of the United States and similar agro-ecologies. Forage oat yield was low in this study, and grazing rather than mechanical harvest of oat could have further increased profitability. The findings from this study support previous findings that cropping systems intensification could be accomplished successfully by using annual forages, as they require less water use than grain crops. Increased utilization of annual forages in the existing cropping systems may increase forage availability and support animal production in the region. Further research in the integration of forages to replace grain use in beef production should be explored to reduce input expense and water use.

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Data availability

The data that support this study will be shared upon reasonable request to the corresponding author.

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The authors declare no conflicts of interest.

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