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Evaluating Potential Dryland Cropping Systems Adapted to Climate Change in the Central Great Plains

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ABSTRACT

Climate in the semiarid central Great Plains is expected to become warmer and drier in coming decades, with potentially greater variability in precipitation and temperature. Cropping systems that include forages and allow flexibility for determining if a crop should be planted and which crop to plant (based on available soil water at planting) may provide the opportunity to maintain economic viability in a changing climate environment. The objective of this study was to compare cropping system productivity and profitability of flexible rotations that incorporate forages against grain-based cropping systems that are set rotational sequences. Yield and net returns for five set rotations and three flexible rotations were compared at Akron, CO, over 5 yr. Winter wheat (*Triticum aestivum* L.) yields were reduced by 57% when the fallow period prior to wheat production was replaced with crop production. Average net income was greatest for the continuously cropped all-forage set 3-yr rotation followed by the flexible 3-yr rotations that included wheat and forage phases. The lowest net returns were seen for the set grain-based rotations and the flexible wheat–grain crop rotation. Incorporating forage production as a phase in dryland wheat rotational systems can add profitability and sustainability to the production system in the face of climate variability.

Core Ideas

- Including forages in semi-arid dryland cropping systems increases profitability.
- Using flexible rotations based on soil water at planting can reduce fallow frequency.
- Continuously cropping with an all-forage rotation maximizes net returns.
- Flexible rotations with forages may mitigate negative effects of climate variability.

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The central Great Plains is part of the principle winter wheat production region of the United States (Fig. 1). Wheat production in this semiarid environment occurs mainly under dryland conditions. Dryland farming is a special case of rainfed agriculture practiced in arid and semiarid regions in which irrigation is not used, and in which water conservation becomes the primary focus of all management decisions because growing season precipitation is seldom sufficient to fully meet evapotranspiration demand, conditions of moderate to severe moisture stress occur during a substantial part of the year, and storage of water during fallow for use by a subsequent crop is often emphasized (Clay Robinson, personal communication, 2016). The Food and Agriculture Organization of the United Nations (FAO) defines semiarid dryland regions as those in which the ratio of precipitation to potential evapotranspiration is in the range of 0.20 to 0.50. The FAO further states that high variability in both rainfall amounts and intensities are characteristics of dryland regions, as are the occurrence of prolonged periods of drought (Koohafkan and Stewart, 2008).

The dryland production area of central North America is characterized by a high level of temporal and spatial climate variability with recurring periods of severe drought. In 1941 renowned climatologist C.W. Thornthwaite wrote, "In a semiarid climate like that of the Great Plains, wide climatic fluctuations are to be expected. Although it is not yet possible to forecast a specific drought year, it is possible to determine drought frequency and the probability of its occurrence. A stable economy can be achieved only if agriculture is adapted to the entire range of climatic conditions." (Thornthwaite, 1941)

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Abbreviations: FAO, Food and Agriculture Organization of the United Nations; FM–FT–FS, forage millet–forage triticale–forage sorghum; W–C–F, wheat–corn–fallow; W–F, wheat–summer fallow; W–Flex1–Flex2, wheat–flexible crop–flexible crop; W–FS–Flex, wheat–forage sorghum–flexible crop; W–GC, wheat–grain crop; W–M–F, wheat–millet–fallow; W–S–F, wheat–sorghum–fallow.

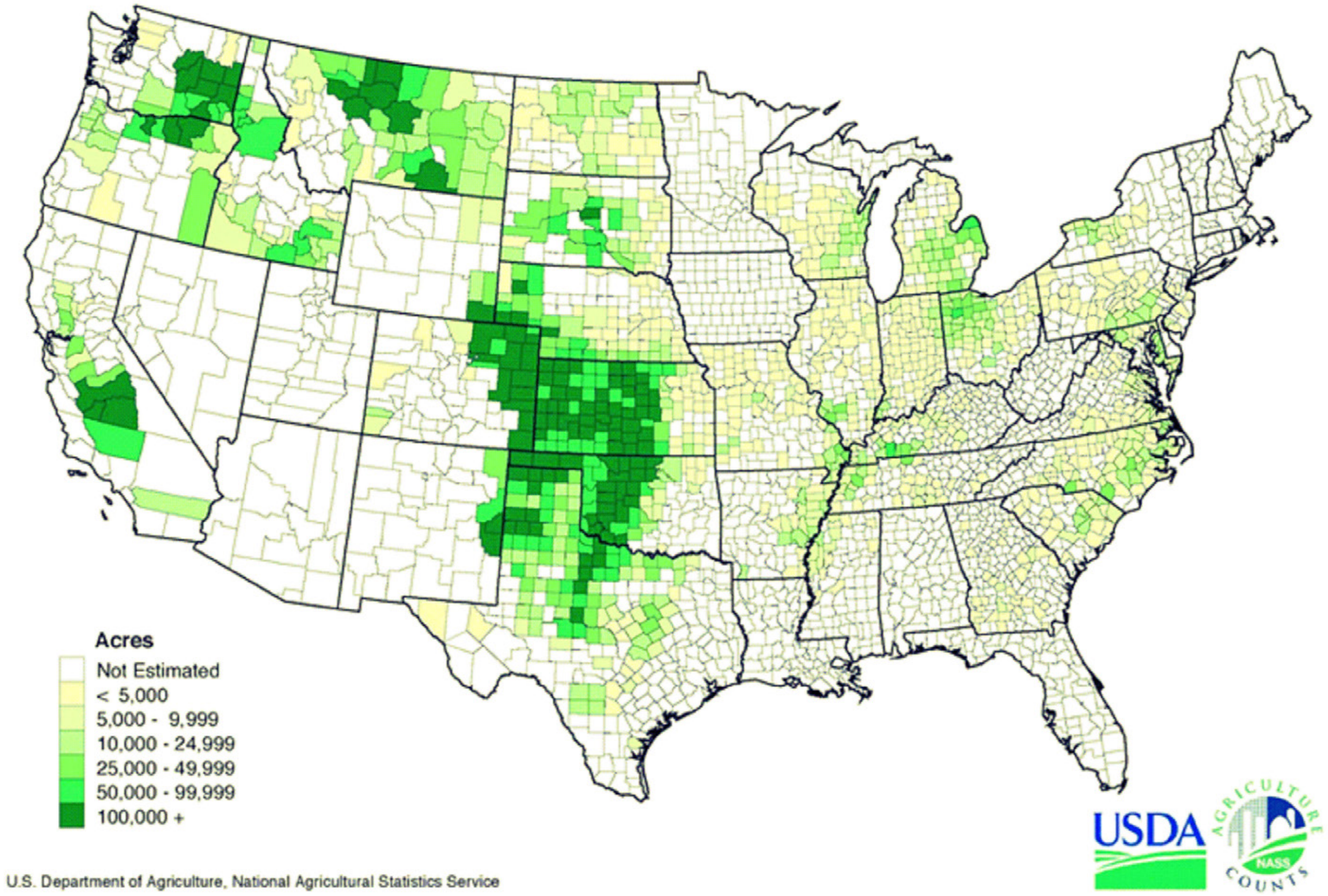
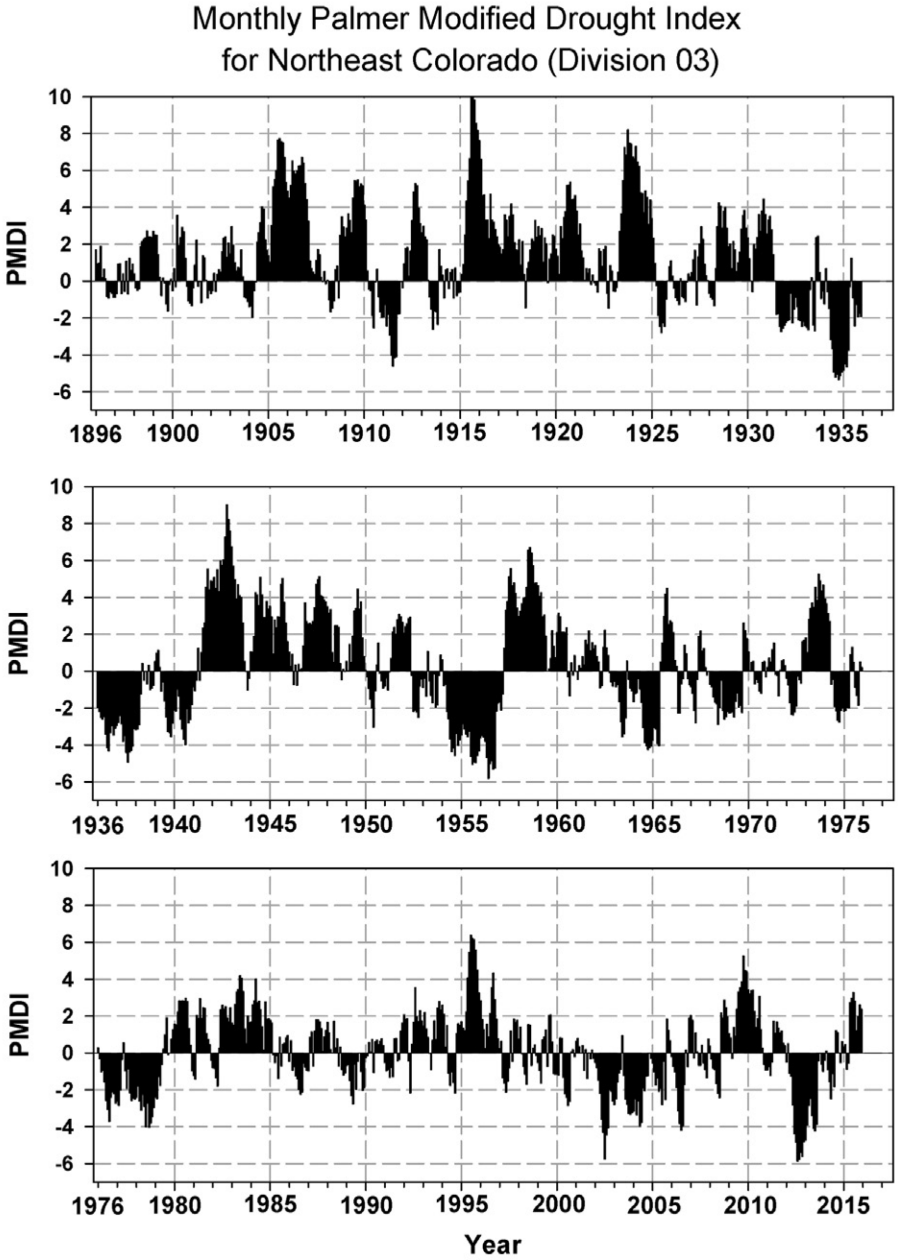


Fig. 1. Winter wheat planted acres (1 hectare = 2.47 acres), 2010, by county in the United States. (http://schillerinstitute.org/strategic/2011/us_food_crisis/Original%20Files/e1-Fig. 2-winter_wheat_2010_usda.jpg, accessed 5 May 2016).

The extreme temporal variability of precipitation in the central Great Plains is illustrated by the Palmer Modified Drought Index for eastern Colorado (Fig. 2). Dryland wheat producers in the west-central Great Plains have adapted cropping practices to the limited and highly variable precipitation received (300–500 mm yr^{-1}) and to recurring periods of drought. The principle adaptation is the traditional winter wheat–summer fallow (W–F) cropping system. While producing one crop every 2 yr is an adaptation that stabilizes wheat grain production under the widely varying precipitation conditions that occur from year to year in the Great Plains, summer fallowing has major limitations for long-term sustainability (Nielsen and Calderón, 2011). Frequent tillage and low productivity of the conventionally tilled W–F system have resulted in soil structural degradation and loss of organic matter on millions of acres (Liebig et al., 2009; Nielsen and Calderón, 2011; Westfall et al., 2009). Associated with these negative effects is soil erosion by wind and water, with wind being the primary concern (Unger et al., 2006). Since the Dust Bowl era, conservation tillage adoption has reduced erosion and improved productivity by maintaining crop residues on the soil surface, but the predominant W–F system is still economically and ecologically fragile (Peterson and Westfall, 2004). Cropping systems adaptations other than summer fallow are necessary for sustainable wheat production in the Great Plains.

One alternative is to reduce summer fallow frequency through adoption of no-till cropping systems (Peterson and Westfall, 2004). No-till systems increase the efficiency of precipitation capture and storage allowing for more intensive crop rotations (Farahani et al., 1998; Nielsen and Vigil, 2010). However, the precipitation storage efficiency in northeastern Colorado, even under no-till management is still quite low during the second summer fallow period (1 May–20 September). Farahani et al. (1998) reported a 7-yr average precipitation storage efficiency of −4% and Nielsen and Vigil (2010) reported a 6-yr average value of 12% during the second summer fallow period.

Among the many alternative crop rotations evaluated (Lyon et al., 2007; Saseendran et al., 2010), a system of W–summer crop–F {with corn [*Zea mays* L.], grain sorghum [*Sorghum bicolor* (L.) Moench], or proso millet [*Panicum miliaceum* L.] as summer annual crops} is promising under contemporary climate conditions. Inclusion of a summer crop in the rotation improves precipitation use efficiency because a crop is present during the summer months when rainfall is greatest (Nielsen et al., 2005). Long-term field studies conducted in the central Great Plains have shown that continuous no-till systems increased annualized grain yield by as much as 75% compared with W–F (Peterson and Westfall, 2004) and increased net economic returns by as much as 30% (Kaan et al., 2002; DeVuyst and Halvorson, 2004). In addition, no-till systems with reduced fallow frequency increase crop residues returned to the soil (Cantero-Martinez et al., 2006) and soil carbon content in the 0- to 20-cm soil depth (Sherrod et al., 2005). Increased soil C improves soil physical properties resulting in improved soil water relations (Shaver et al., 2002; Blanco-Canqui et al., 2009). Outreach and extension efforts have led to adoption



http://www1.ncdc.noaa.gov/pub/data/cirs/climdiv/

Fig. 2. Palmer modified drought index for northeastern Colorado (Division 03).

of these practices by innovative producers throughout the Great Plains, although W–F continues to be a prevalent practice.

Two major barriers to adoption of intensified no-till crop rotations (reduced fallow frequency) are reduced wheat yields due to elimination of fallow and previous crop water use, and increased annual risk of crop failure due to widely varying and unpredictable summer drought. Eliminating the fallow period prior to wheat planting has been shown to reduce subsequent wheat yields by 4.0 kg ha^{-1} for every millimeter of soil water that the previous crop used that was not replenished by precipitation prior to planting the wheat crop when wheat growing conditions were dry, and by 14.1 kg ha^{-1} per millimeter when wheat growing conditions were wet (Nielsen et al., 2002). Nielsen and Vigil (2005) presented data that showed that the 6-yr average rate of wheat yield reduction due to previous crop water use was 15.7 kg ha^{-1} per mm of soil water use that was not replenished prior to wheat planting. Aiken et al. (2013) found that replacing the fallow period prior to wheat with oilseed production reduced available soil water at wheat emergence by 145 mm in northwestern Kansas, leading to a 35% reduction in wheat grain yield and a US\$308 ha^{-1} reduction in the net return for wheat production. A cropping systems study over 20 yr in eastern Colorado showed that intensified crop rotations have greater long-term yield than W–F. However, crop failure occurred less than 10% of the time for W–F and more than 30% of the time for the more intensive rotations (Hansen et al., 2006).

Projections of climate change for the central Great Plains by Ray et al. (2008) are for average temperatures to warm by 1.4°C by 2025, relative to the 1950 to 1999 baseline, and 2.2°C by 2050. Additionally, they reported that there are no consistent long-term trends in mean annual precipitation for the central Great Plains in Colorado. However, a seasonal shift in precipitation amounts was projected with a decrease in late spring and summer precipitation, and an increase in fall and winter precipitation.

Changes in both the magnitude and timing of temperature and precipitation will affect crop production (Easterling et al., 2001; Guereña et al., 2001), but the temperature and precipitation effects must be considered together with the effects of elevated CO_2 concentrations. The potential doubling of atmospheric CO_2 and associated warming within the next century will affect agricultural production through changes in evapotranspiration, plant growth rates, plant litter composition, and N–C cycling (Long et al., 2006).

Photosynthesis and water use become more efficient for crops with the C3 photosynthetic pathway (e.g., wheat) under elevated CO_2 (Easterling et al 2001). This greater efficiency may result in increased crop yields (Ainsworth and Long, 2005; Kimball et al., 2002), but in water-limited regions such as the central Great Plains, the concurrent increase in temperatures and change in precipitation timing may result in yield declines due to increased water stress, which counteract the positive effects of increased CO_2 concentration. Crops with the C4 photosynthetic pathway (corn, sorghum) do not have as high a photosynthetic advantage with elevated CO_2 as seen with C3 species. If yields of these crops are reduced while in rotation with winter wheat, reduced residues and C return to the soil will, in the long term, also negatively affect wheat yields. These climate change projections suggest that more intensive rotations could have even higher yield uncertainty and potentially greater rates of crop failure. Ko et al. (2012) modeled dryland wheat, corn, and millet yields in W–F, W–C–F, and W–C–M systems in a semiarid environment under the increasing CO_2 and temperature conditions expected to occur to the year 2100 and found declining yields of all three crops over the period.

While coping with highly variable climatic conditions is not new for wheat producers in the Great Plains, existing adaptation strategies may not be sufficient to cope with the projected changes in climate. There is a need to identify sustainable wheat-based cropping systems in the central Great Plains that are adapted to climate change or increased climate variability without the pitfalls of extensive summer fallow. Some researchers have suggested that decision tools could be developed to help farmers reduce production risk and make better planting decisions based on measured soil water at planting and weather forecasts (Felter et al., 2006; Lyon et al., 2007; Nielsen et al., 2011). Another adaptation to the current production practices that could help in developing resilience to changing climate may be greater use of forages in cropping systems. Inclusion of forages in rotations would likely stabilize yields under increasingly variable precipitation because of the relatively lesser effect that water stress has on plant biomass productivity during vegetative development compared with effects on grain production from water stress during reproductive and grain-filling developmental stages (Denmead and Shaw, 1960; Nielsen et al., 2010; Robins and Domingo, 1956). The objective of this experiment was to compare cropping system productivity and profitability of set and flexible rotations that incorporate forages vs. grain-based cropping systems that are set rotational sequences.

MATERIALS AND METHODS

This study consisted of a subset of data collected from a long-term cropping systems experiment previously described by Anderson et al. (1999), Bowman and Halvorson (1997), and Nielsen and Vigil (2010). The long-term study was established in September 1990 at the USDA-ARS Central Great Plains Research Station, 6.4 km east of Akron, CO (40°09′ N, 103°09′ W, 1384 m above mean sea level). The soil type was a Weld silt loam (fine, smectitic, mesic Aridic Argiustoll). The main purpose of the study was to investigate the possibility of cropping more frequently than every other year, as done with the traditional W–F system. 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 by 30.5 m, with East–West row direction.

All rotations in the current study were managed under no tillage conditions with weed control during both cropped and non-crop periods consisting of contact and residual herbicide applications applied at recommended rates. Herbicides used were glyphosate [*N*-phosphonomethyl)glycine]; paraquat (1,1¢-dimethyl-4,4¢-bipyridinium dichloride); atrazine (1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine); 2,4-D (2,4-dichlorophenoxyacetic acid); dicamba (3,6-dichloro-2-methoxybenzoic acid); fluroxypyr {[4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy] acetic acid}; imazamox {2-[4,5-dihydro-4-methyl-4-(1-methyethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid}; and carfentrazone {ethyl-a-2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-,2,4-triazol-1-yl]-4-fluorobenzenepropanoate}.

Four of the set rotations were W–F, wheat–corn–fallow (W–C–F), wheat–millet–fallow (W–M–F), and wheat–sorghum–fallow (W–S–F). The W–F, W–C–F, and W–M–F rotations had been in place from the beginning of the long-term experiment (1990). The W–S–F rotation was added in 2006, and had sorghum planted in a skip row planting geometry (Abunyewa et al., 2010; Lyon et al., 2009) with two planted rows 0.76 m apart and a non-planted skip of 2.28 m between pairs of planted rows. Row spacing for corn was 0.76 and 0.19 m for all other crops.

In 2011 several existing rotations in the long-term experiment were converted to forage and flexible cropping rotations in such a way that the previous crop to the one planted in 2011 was what would have been in place had the new rotation existed in 2010. Those new rotations were:

- forage millet (*Setaria italica* L. Beauv.)–forage triticale (X *Triticosecale* Wittmack)–forage sorghum (*S. bicolor* or *S. bicolor* × *S. sudanense*) (FM–FT–FS)
- wheat–grain crop (W–GC)
- wheat–forage sorghum–flexible crop (W–FS–Flex)
- wheat–flexible crop–flexible crop (W–Flex1–Flex2)

Cropping choices for the GC, Flex, Flex1, and Flex2 phases in the above rotations were made following the method described by Nielsen et al. (2011) in which available soil water (0- to 180-cm soil profile) was measured at several decision points during the year (generally early and late spring). Those measurements were made with a TDR system in the 0- to 30-cm surface layer and with a neutron probe at 45, 75, 105, 135, and 165 cm below the soil surface. The available soil water was added to average growing season precipitation to estimate a water use value that was then entered into previously determined water use/yield production functions to determine predicted yields for a variety of grain and forage crops (Nielsen et al., 2006, 2011; Nielsen, 2010). The predicted yield was compared against break-even threshold values to determine potential crops from which a crop selection was made. The W–GC

Table 1. Variety, planting, harvesting, and fertilizing details for set rotations and flexible rotations, Akron, CO, 2011 to 2015.

Crop	Variety	Planting date	Swath date	Harvest date	Seeding rate	Harvest area	Fertilizer	
						m^2	kg N ha^{-1}	kg P_2O_5 ha^{-1}
				2011				
Wheat	Snowmass	24 Sept. 2010		19 July 2011	67.2 kg ha^{-1}	42.0	44.8	16.8
Corn	NuTech 1H797	10 May 2011		12 Oct. 2011	29,650 seeds ha^{-1}	37.2	67.2	0.0
Proso millet	Huntsman	9 June 2011		22 Aug. 2011	16.8 kg ha^{-1}	31.6	39.2	0.0
Sorghum	DKS 29-28	2 June 2011		24 Oct. 2011	74,130 seeds ha^{-1}	83.0	67.2	0.0
Pea	Admiral	4 Apr. 2011		19 July 2011	202 kg ha^{-1}	42.0	inoculated	16.8
Forage millet	Golden German	9 June 2011	15 Aug. 2011	20 Aug. 2011	13.4 kg ha^{-1}	2.9	39.2	0.0
Forage triticale	Merlin	7 Apr. 2011	24 June 2011	26 June 2011	67.2 kg ha^{-1}	2.9	0.0	0.0
Forage sorghum	Super Sugar	8 June 2011	15 Aug. 2011	20 Aug. 2011	16.8 kg ha^{-1}	2.9	39.2	0.0
Forage pea	Arvika	5 Apr. 2011	18 July 2011	23 July 2011	134 kg ha^{-1}	2.9	inoculated	16.8
Corn silage	Not planted							
				2012				
Wheat	Snowmass	26 Sept. 2011		13 June 2012	67.2 kg ha^{-1}	42.0	56.0	16.8
Corn	PH 500	10 May 2012		23 Oct. 2012	29,650 seeds ha^{-1}	37.2	67.2	0.0
Proso millet	Huntsman	30 May 2012		No harvest	16.8 kg ha^{-1}		39.2	16.8
Sorghum	DKS 29-28	21 May 2012		23 Oct. 2012	74,520 seeds ha^{-1}	94.8	67.2	0.0
Pea	Not planted							
Forage millet	Golden German	30 May 2012		17 June 2012	13.4 kg ha^{-1}	2.9	39.2	16.8
Forage triticale	Bobcat	30 Sept. 2011		No harvest	67.2 kg ha^{-1}	2.9	39.2	16.8
Forage sorghum	Super Sugar	29 May 2012	11 Sept. 2012	15 Sept. 2012	16.8 kg ha^{-1}	2.9	39.2	16.8
Forage pea	Arvika	10 Apr. 2012	28 June 2012	3 July 2012	134 kg ha^{-1}	5.8	inoculated	16.8
Corn silage	PH 500	10 May 2012		20 Aug. 2012	29,650 seeds ha^{-1}	4.0	67.2	0.0

Continued next page

Table 1. (continued).

Crop	Variety	Planting date	Swath date	Harvest date	Seeding rate	Harvest area	Fertilizer	
						m^2	kg N ha^{-1}	kg P_2O_5 ha^{-1}
				2013				
Wheat	Brawl CL Plus	2 Oct. 2012		8 July 2013	67.2 kg ha^{-1}	40.0	16.8	16.8
Corn	PH 5140	16 May 2013		8 Oct. 2013	29,650 seeds ha^{-1}	37.2	67.2	0.0
Proso millet	Huntsman	3 June 2013	21 Aug. 2013	3 Sept. 2013	16.8 kg ha^{-1}	30.8	39.2	16.8
Sorghum	DKS 29-28	30 May 2013		14 Nov. 2013	74,520 seeds ha^{-1}	73.7	67.2	0.0
Pea	Not planted							
Forage millet	Golden German	3 June 2013	21 Aug. 2013	25 Aug. 2013	13.4 kg ha^{-1}	2.9	39.2	16.8
Forage triticale	Bobcat	11 Oct 2012	17 June 2013	21 June 2013	67.2 kg ha^{-1}	5.8	56.0	16.8
Forage sorghum	Super Sugar	31 May 2013	21 Aug. 2013	25 Aug. 2013	16.8 kg ha^{-1}	2.9	39.2	0.0
Forage pea	Not planted							
Corn silage	PH 5140	16 May 2013		4 Sept. 2013	29,650 seeds ha^{-1}	4.0	67.2	4.5
				2014				
Wheat	Brawl CL Plus	2 Oct. 2013		23 July 2014	67.2 kg ha^{-1}	41.1	56.0	16.8
Corn	PH 5140	16 May 2014		22 Oct. 2014	29,650 seeds ha^{-1}	33.7	67.2	0.0
Proso millet	Huntsman	12 June 2014	10 Sept. 2014	15 Sept. 2014	16.8 kg ha^{-1}	37.2	39.2	16.8
Sorghum	DKS 29-28	30 May 2014		20 Nov. 2014	74,520 seeds ha^{-1}	80.5	67.2	16.8
Pea	Not planted							
Forage millet	Golden German	18 June 2014	19 Aug. 2014	26 Aug. 2014	13.4 kg ha^{-1}	2.9	39.2	16.8
Forage triticale	Bobcat	9 Oct. 2013	18 June 2014	22 June 2014	56.0 kg ha^{-1}	8.7	56.0	16.8
Forage sorghum	High Plains 200 BMR	18 June 2014	4 Sept. 2014	14 Sept. 2014	16.8 kg ha^{-1}	2.9	39.2	0.0
Forage pea	4010	21 Apr. 2014	8 July 2014	13 July 2014	134 kg ha^{-1}	2.9	inoculated	16.8
Corn silage	Not planted							
				2015				
Wheat	Brawl CL Plus	29 Sept. 2014		20 July 2015	67.2 kg ha^{-1}	43.5	56.0	16.8
Corn	PH 5140	3 June 2015		19 Oct. 2015	29,650 seeds ha^{-1}	32.2	67.2	0.0
Proso millet	Huntsman	18 June 2015	10 Sept. 2015	1 Sept. 2015	16.8 kg ha^{-1}	37.2	39.2	16.8
Sorghum	DKS 29-28	3 June 2015		2 Nov. 2015	74,520 seeds ha^{-1}	80.2	67.2	0.0
Pea	Admiral	8 Apr. 2015		21 July 2015	202 kg ha^{-1}	44.9	inoculated	16.8
Forage millet	Golden German	18 June 2015	4 Sept. 2015	9 Sept. 2015	13.4 kg ha^{-1}	2.9	39.2	16.8
Forage triticale	Trical 718	10 Oct. 2014	17 June 2015	22 June 2015	56.0 kg ha^{-1}	2.9	56.2	16.8
Forage sorghum	Super Sugar	19 June 2015	4 Sept. 2015	9 Sept. 2015	16.8 kg ha^{-1}	8.7	39.2	0.0
Forage pea	4010	8 Apr. 2015	1 July 2015	8 July 2015	134 kg ha^{-1}	2.9	inoculated	16.8
Corn silage	Not planted							

Table 2. Prices received for grain or forage produced at Akron, CO (from USDA-NASS†).

Commodity	2011	2012	2013	2014	2015
	\$ kg^{-1}				
Wheat	0.244	0.285	0.257	0.216	0.164
Corn	0.242	0.270	0.181	0.156	0.146
Millet	0.260	0.723	0.190	0.146	0.127
Sorghum	0.236	0.276	0.169	0.153	0.125
Pea	0.337	0.351	0.326	0.269	0.254
Forage millet	0.177	0.239	0.251	0.222	0.201
Forage triticale	0.177	0.239	0.251	0.222	0.201
Forage sorghum	0.177	0.239	0.251	0.222	0.201
Corn silage	0.069	0.078	0.066	0.058	0.052
Forage pea	0.230	0.263	0.261	0.228	0.201

† Prices obtained from http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1050 (accessed 13 Apr. 2016); prices are for those reported for Colorado, except for pea where North Dakota prices were used because no prices were reported for Colorado; prices for forage millet, forage triticale, and forage sorghum were taken from the All Other Hay prices; prices for forage pea were taken from Alfalfa Hay prices; prices for corn silage were calculated as the average of the corn-based and alfalfa-hay-based prices using the relationships given in Berger (2013), for corn silage at 65% moisture content.

Table 3. Costs used in net returns economic analysis of cropping systems at Akron, CO (2011–2015).

Cropping system†	Crop	Operation	2011	2012	2013	2014	2015
			\$ ha^{-1}				
W–F	Wheat	Planting/seed	41.51	61.28	60.54	60.54	53.13
		N fertilizer	43.69	67.95	21.50	79.07	63.01
		P fertilizer	14.05	20.39	20.76	16.31	18.16
		Herbicides/spraying	0.00	0.00	0.00	54.36	54.36
		Harvesting	71.31	58.16	49.42	78.63	75.28
	Fallow	Herbicides/spraying	122.02	150.71	130.69	337.89	248.64
W–C–F	Wheat	Planting/seed	41.51	61.28	60.54	60.54	53.13
		N fertilizer	43.69	67.95	21.50	79.07	63.01
		P fertilizer	14.05	20.39	20.76	16.31	18.16
		Herbicides/spraying	0.00	0.00	0.00	54.36	54.36
		Harvesting	67.83	54.07	49.42	70.09	78.26
	Corn	Planting/seed	106.26	116.63	118.86	134.97	112.43
		N fertilizer	70.77	86.78	91.23	100.13	80.85
		P fertilizer	0.00	0.00	0.00	0.00	0.00
		Herbicides/spraying	81.94	157.85	129.16	189.73	173.79
		Harvesting	97.28	39.31	87.71	79.01	61.47
	Fallow	Herbicides/spraying	117.89	117.89	175.32	219.95	175.32
W–M–F	Wheat	Planting/seed	41.51	61.28	60.54	60.54	53.13
		N fertilizer	43.69	67.95	21.50	79.07	63.01
		P fertilizer	14.05	20.39	0.00	16.31	18.16
		Herbicides/spraying	62.12	35.95	125.21	153.92	125.23
		Harvesting	72.78	57.00	49.42	75.24	78.19
	Millet	Planting/seed	43.91	54.17	46.43	48.16	47.84
		N fertilizer	38.23	47.57	50.16	55.35	44.11
		P fertilizer	0.00	20.39	20.76	16.31	18.16
		Herbicides/spraying	57.38	124.39	66.87	117.94	126.22
		Harvesting	94.90	0.00	94.19	98.68	86.49
	Fallow	Herbicides/spraying	168.87	166.08	149.97	204.01	255.56
W–S–F	Wheat	Planting/seed	41.51	61.28	60.54	60.54	53.13
		N fertilizer	43.69	67.95	21.50	79.07	63.01
		P fertilizer	14.05	20.39	20.76	16.31	18.16
		Herbicides/spraying	62.12	35.95	148.81	153.92	80.61
		Harvesting	72.78	56.42	49.42	72.18	79.30
	Sorghum	Planting/seed	45.89	53.30	49.59	52.07	52.07
		N fertilizer	70.77	86.78	91.23	100.13	80.85
		P fertilizer	0.00	0.00	0.00	16.31	0.00
		Herbicides/spraying	64.17	116.49	33.43	242.81	154.59
		Harvesting	64.62	49.42	56.45	77.77	71.31
	Fallow	Herbicides/spraying	168.87	202.03	149.97	264.58	226.87

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Table 3. (continued).

Cropping system†	Crop	Operation	2011	2012	2013	2014	2015
			$\$$ ha^{-1}				
FM–FT–FS	Forage millet	Planting/seed	41.02	43.49	44.73	44.73	44.73
		N fertilizer	38.23	47.57	50.16	55.35	44.11
		P fertilizer	0.00	20.39	20.76	16.31	18.16
		Herbicides/spraying	93.33	93.33	117.94	207.20	128.10
		Harvesting	56.83	0.00	63.01	61.78	61.78
	Forage triticale	Planting/seed	59.31	64.25	65.48	65.48	65.48
		N fertilizer	0.00	47.57	71.66	79.07	63.01
		P fertilizer	0.00	20.39	20.76	16.31	18.16
		Herbicides/spraying	102.00	88.24	73.32	146.63	102.00
		Harvesting	56.83	56.83	63.01	61.78	61.78
	Forage sorghum	Planting/seed	49.42	53.13	54.36	54.36	54.36
		N fertilizer	38.23	47.57	50.16	55.35	44.11
		P fertilizer	0.00	0.00	0.00	0.00	0.00
		Herbicides/spraying	57.38	170.23	96.91	191.26	277.70
		Harvesting	56.83	0.00	63.01	61.78	61.78
W–GC	Wheat	Planting/seed	41.51	61.28	60.54	60.54	53.13
		N fertilizer	43.69	67.95	21.50	79.07	63.01
		P fertilizer	14.05	20.39	20.76	16.31	18.16
		Herbicides/spraying	57.38	57.38	96.91	153.92	79.84
		Harvesting	62.07	41.22	49.42	75.24	69.23
	GC–Millet: 2011, 2012, 2013, 2015	Planting/seed	43.91	54.17	46.43	54.61	47.84
	-Sorghum: 2014	N fertilizer	38.23	47.57	50.16	94.89	44.11
		P fertilizer	0.00	20.39	20.76	0.00	0.00
		Herbicides/spraying	86.07	130.69	52.29	229.68	194.15
		Harvesting	93.88	0.00	49.42	63.69	86.49
W–FS–Flex	Wheat	Planting/seed	41.51	61.28	60.54	60.54	53.13
		N fertilizer	43.69	67.95	21.50	79.07	63.01
		P fertilizer	14.05	20.39	20.76	16.31	18.16
		Herbicides/spraying	93.33	93.33	117.94	98.99	98.99
		Harvesting	59.37	41.27	49.42	65.42	68.99
	Forage sorghum	Planting/seed	49.42	53.13	54.36	54.36	54.36
		N fertilizer	38.23	47.57	50.16	55.35	44.11
		P fertilizer	0.00	0.00	0.00	0.00	0.00
		Herbicides/spraying	57.38	130.69	125.60	235.89	235.89
		Harvesting	56.83	56.83	63.01	61.78	61.78
	Flex–forage millet: 2011	Planting/seed	41.02	129.48	118.86	133.68	169.27
	-Forage pea: 2012, 2014	N fertilizer	38.23	0.00	85.99	0.00	0.00
	-Corn silage: 2013	P fertilizer	0.00	20.39	5.54	16.31	18.16
	-Pea: 2015	Herbicides/spraying	86.07	130.69	129.16	157.48	157.48
		Harvesting	56.83	56.83	135.91	61.78	67.82
W–Flex1–Flex2	Wheat	Planting/seed	41.51	61.28	60.54	60.54	53.13
		N fertilizer	43.69	67.95	21.50	79.07	63.01
		P fertilizer	14.05	20.39	20.76	16.31	18.16
		Herbicides/spraying	36.47	34.67	117.94	54.36	54.36
		Harvesting	58.96	44.67	39.25	63.88	64.10
	Flex1–forage pea: 2011, 2015	Planting/seed	124.05	116.63	44.73	52.07	127.79
	-Corn silage: 2012	N fertilizer	0.00	81.54	50.16	94.89	0.00
	-Forage millet: 2013	P fertilizer	14.05	0.00	20.76	16.31	18.16
	-Sorghum: 2014	Herbicides/spraying	63.81	100.47	102.00	175.32	166.65
	Flex2–Pea: 2011	Planting/seed	170.01	43.49	118.86	133.68	127.79
	-Forage millet: 2012	N fertilizer	0.00	47.57	85.99	0.00	0.00
	-Corn silage: 2013	P fertilizer	14.05	20.39	5.54	16.31	18.16
	-Forage pea: 2014, 2015	Herbicides/spraying	101.01	146.63	129.16	162.57	137.96
		Harvesting	61.14	0.00	135.91	61.78	61.78

† W, wheat; C, corn; M, millet; S, sorghum; F, fallow; GC, grain crop; FM, forage millet; FT, forage triticale; FS, forage sorghum; Flex, flexible crop choice; Flex1, flexible crop choice immediately after wheat; Flex2, flexible crop choice immediately after a previous flexible crop choice.

rotation was a continuously cropped system in which the flexible GC choice was either corn, millet, or grain sorghum. The Flex crop in the W–FS–Flex rotation could be summer fallow or a short-season crop such as millet, forage millet, pea (*Pisum sativum* L.), forage pea, or corn silage. For the W–Flex1–Flex2 rotation, the Flex1 crop could be summer fallow or any grain or forage crop, and the Flex2 crop could be summer fallow or a short season crop that would provide the opportunity to be followed by winter wheat. The dates of planting, swathing, and harvest are shown in Table 1 along with the crop varieties planted, seeding rates, harvest areas, and fertilizer amounts applied.

The seed and forage yield data are reported as yearly values for each crop in each rotation and as 5-yr means for each crop in each rotation. However it is not possible to compare rotation productivity based on the mass of seed or forage produced since five of the rotations are seed-based, one is forage-based, and two consist of seed crops and forages. Therefore, we compared the productivity of rotations based on their net economic returns. In the economic analysis, the gross income generated by each rotation was computed using prices obtained (Table 2) from the USDA National Agricultural Statistics Service (NASS) website (http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1050, accessed 13 Apr. 2016) for prices received in Colorado for each of the 5 yr (2011–2015). The only two exceptions were for the price received for:

1. Dry pea. Since there were no price data for dry pea in Colorado, the price given for pea sold in North Dakota was used.
2. Corn silage. The NASS website gave no value for corn silage, so the valuation method described by Berger (2013) was used in which the value of corn silage is estimated based on relationships to the corn grain selling price and the alfalfa selling price.

The costs of production used in the economic analysis are given in Table 3. The custom rates for planting, swathing, baling, combining, silage chopping, and spraying operations were obtained from publications found at the Colorado State University Agriculture and Business Management website (http://www.coopext.colostate.edu/ABM/, accessed 13 Apr. 2016). Herbicide, fertilizer, and seed costs were those actually paid by the Central Great Plains Research Station to local vendors in Washington and Yuma counties in northeastern Colorado for each year. The exception was the fertilizer cost in 2012, which was estimated from Table 7 of the National Agricultural Statistics Service [Agricultural Prices, National Agricultural Statistics Service (http://usda.mannlibcornell.edu/MannUsda/viewDocumentInfo.do?documentID=1002)]. We used the average price of urea ammonium nitrate solution UAN (32–0–0) as our N source. For P we used the average price of mono-ammonium phosphate (MAP) (11–52–0). Zinc prices were based on zinc sulfate prices. Net income was computed as the difference between gross income and expenses.

Analysis of variance for the calculated net economic return values was performed with Statistix 10 software (Analytical Software, Tallahassee, FL) using the General AOV option with year as a random effect and rotation as a fixed effect. Rotation treatment effects were considered significant when the probability of achieving a greater value of *F* in the analysis of variance was ≤0.05.

RESULTS

Precipitation

Annual precipitation during the 5-yr study period (Table 4) was near the long-term average in 2011 and 2014, extremely below average in 2012, 12% above average in 2015, and 50% above average in 2014. The precipitation most influential to pea production (April–June) was much below average in 2012 and 2013 (36 and

Table 4. Precipitation at Akron, CO.

Month	2010	2011	2012	2013	2014	2015	2011–2015	1908–2015
	mm							
January		10	3	3	25	8	10	8
February		5	39	10	10	10	15	9
March		12	4	18	17	9	12	21
April		34	44	37	40	49	41	42
May		165	16	41	95	130	89	74
June		37	4	46	114	57	52	62
July		99	62	53	62	58	67	67
August		3	2	66	129	77	55	55
September		30	24	88	83	4	46	32
October	17	28	16	27	30	24	25	23
November	7	10	4	8	7	28	11	14
December	8	6	10	3	17	14	10	11
Year		439	228	400	629	468	433	418
April–June		236	64	124	249	236	182	178
June–September		169	92	253	388	196	220	216
Oct. –June		295	154	185	339	290	253	264
		% of long-term average						
Year		105	55	96	150	112		
April–June		133	36	70	140	133		
June–September		78	43	117	180	91		
Oct.–June		112	58	70	128	110		

70% of average, respectively) and 33 to 40% above average in 2011, 2014, and 2015. The June through September precipitation influencing corn, sorghum, and millet production was 43% of normal in 2012, 78% of normal in 2011, 91% of normal in 2015, 17% above normal in 2013, and 80% above normal in 2014. The October through June precipitation that affected wheat grain and triticale biomass yields was likewise extremely low in 2012 (58% of normal) and 70% of normal in 2013, but 10 to 12% above normal in 2015 and 2011 and 28% above normal in 2014.

The average (2011–2015) annual precipitation for the study (433 mm) was only 4% above the long-term (1908–2015) average annual precipitation (418 mm). Additionally, the cumulative probability exceedance graph for precipitation (Fig. 3) shows that annual precipitation over the 2011 to 2015 period occurred with relatively the same probability distribution as seen in the long-term precipitation record. Therefore, the 5-yr results from this study should be fairly indicative of what could be expected from a longer-term study.

Grain and Forage Yields

The 5-yr average wheat yields (Table 5) were not significantly different for all of the rotations with a fallow period ahead of wheat production (average 2631 kg ha^{-1}, ranging from 2406 kg ha^{-1} for W–C–F to 2774 kg ha^{-1} for W–F[NT]). However, the wheat yields for the more intense rotations without a fallow period (W–GC, W–FS–Flex, W–Flex1–Flex2) were significantly lower ($P < 0.01$), but not different from one another (average 1361 kg ha^{-1}).

Corn, millet, and sorghum yields in the W–C–F, W–M–F, and W–S–F rotations were highly variable from year to year. Corn yields ranged from 87 to 3242 kg ha^{-1} and averaged 1974 kg ha^{-1}; millet yields ranged from 0 to 2550 kg ha^{-1} and averaged 1517 kg ha^{-1}; sorghum yields ranged from 728 to 3510 kg ha^{-1} and averaged 2293 kg ha^{-1}. The average yields for these three crops were not statistically different from one another ($P = 0.15$). The year by rotation interaction was not significant when comparing the yields of these three crops ($P = 0.34$).

The forage yields in the set rotation (FM–FT–FS) were also highly variable from year to year. The forage millet yields ranged from 0 to 8532 kg ha^{-1} and averaged 5117 kg ha^{-1}; forage triticale yields ranged from 2513 to 12,965 kg ha^{-1} and averaged 6835 kg ha^{-1}; the forage sorghum yields ranged from 0 to 6878 kg ha^{-1} and averaged 4056 kg ha^{-1}. The 5-yr average forage yield was significantly greater (69%) for the forage triticale than for the forage sorghum ($P < 0.05$). This was primarily the result of no forage sorghum yield in 2012 and extremely high forage triticale yield in 2015 (a consequence of the precipitation timing and amounts in those 2 yr, see Table 4). The 5-yr average forage millet yield was not significantly different from either of the other two forage crops ($P > 0.05$). Nielsen et al. (2006) similarly reported 7-yr average dry matter yields of corn, forage millet, and forage winter triticale that were not statistically different from one another in northeastern Colorado.

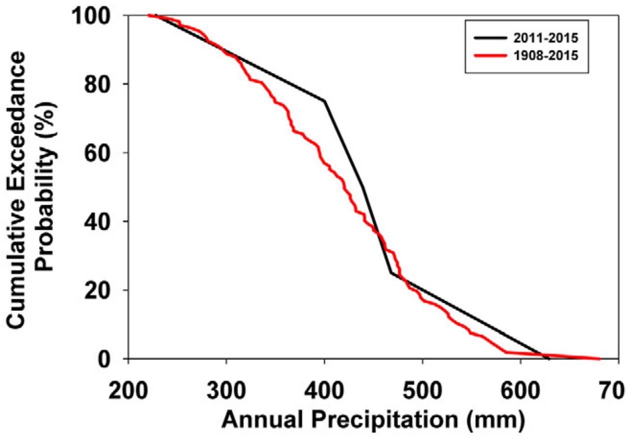

Fig. 3. Cumulative exceedance probability for annual precipitation at Akron, CO, for the study period (2011–2015) and for the long-term precipitation record (1908–2015).

The flexible crop selection logic used in this experiment (Nielsen et al., 2011) did not call for a fallow phase in any of the flexible rotations in any year. Hence, all three of those rotations (W–GC, W–FS–Flex, W–Flex1–Flex2) were continuously cropped. The crop selection logic resulted in four forage crops and one grain crop in the Flex phase of the W–FS–Flex rotation, and similarly for both Flex1 and Flex2 phases of the W–Flex1–Flex2 rotation. There were two complete flexible crop failures during the experiment, both occurring in the severe drought year of 2012. In that year the millet crop (GC phase of the W–GC rotation) failed to produce any grain and the forage millet crop (Flex2 phase of the W–Flex1–Flex2 rotation) failed to produce any forage. In contrast, the forage pea crop in 2012 (Flex phase of W–FS–Flex rotation) produced 2450 kg ha^{-1} of forage. The forage sorghum phase of the W–FS–Flex rotation produced a 5-yr average forage yield of 5320 kg ha^{-1}, and a very good forage yield of 5161 kg ha^{-1} in the severe drought year of 2012 compared with the corn silage yield of 2227 kg ha^{-1} in 2012 (both of these forage crops followed wheat). The forage sorghum in the W–FS–Flex rotation was the most consistent producing crop of all of the crops grown over the 5-yr

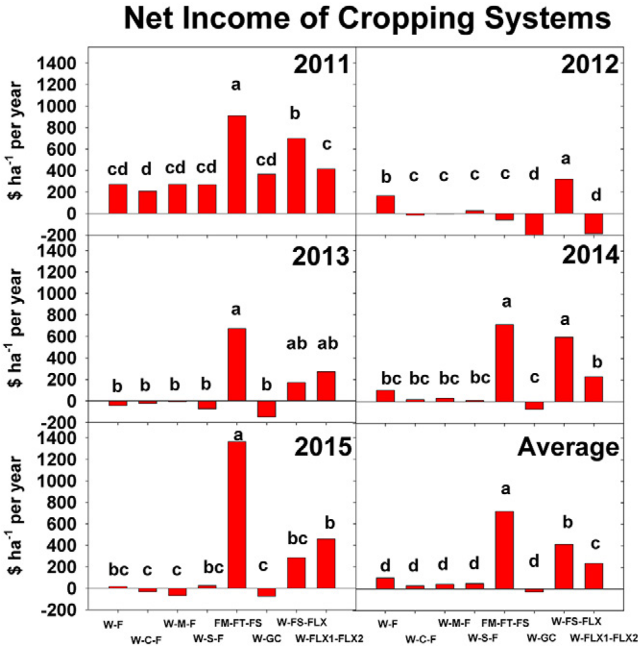

Fig. 4. Net income of cropping systems from 2011 to 2015 at Akron, CO. Within an individual panel, different letters indicate statistically significant differences ($P < 0.05$) as tested by the Tukey HSD comparison method. W, wheat; C, corn; M, millet; S, sorghum; F, fallow; GC, grain crop; FM, forage millet; FT, forage triticale; FS, forage sorghum; Flex, flexible crop choice; Flex1, flexible crop choice immediately after wheat; Flex2, flexible crop choice immediately after a previous flexible crop choice.

Table 5. Measured grain and forage yields for five set rotations and three flexible rotations at Akron, CO.

	Set rotations									
	W–F†	W–C–F		W–M–-F		W–S–F		FM–FT–FS		
Year	Wheat	Wheat	Corn	Wheat	Millet	Wheat	Sorghum	Forage millet	Forage triticale	Forage sorghum
	kg ha^{-1}									
2011	3438‡	3008	2214	3718	2113	3621	2438	8532	8006	4696
2012	2425	2286	87	2280	0	2209	728	0	2513	0
2013	764	466	3106	688	2550	441	2065	3273	5281	3574
2014	3890	2601	3242	3378	1995	2916	3510	5361	5408	5133
2015	3351	3675	1219	3667	927	3788	2724	8418	12965	6878
Average	2774	2407	1974	2746	1517	2595	2293	5117	6835	4056
CV	42.9	48.4	73.0	46.2	68.2	50.2	52.7	72.4	61.3	63.0

	Flexible rotations							
	W–GC		W–FS–Flex			W–Flex1–Flex2		
Year	Wheat	Grain crop	Wheat	Forage sorghum	Flex crop	Wheat	Flex1 crop	Flex2 crop
	kg ha^{-1}							
2011	2297	2518 (millet)	1963	4739	9682 (forage millet)	1912	4523 (forage pea)	1818 (pea)
2012	330	0 (millet)	336	5161	2450 (forage pea)	757	2227 (corn silage)	0 (forage millet)
2013	34	849 (millet)	45	4894	5882 (corn silage)	86	6956 (forage millet)	2785 (corn silage)
2014	1598	1525(sorghum)	1895	6427	5546 (forage pea)	1662	1381 (sorghum)	5567(forage pea)
2015	2692	500 (millet)	2667	5377	2116 (pea)	2135	6270 (forage pea)	4465 (forage pea)
Average	1390	1078	1381	5320	na§	1310	na	na
CV	80.3	62.0	76.9	31.2	na	66.7	na	na

† W, wheat; C, corn; M, millet; S, sorghum; F, fallow; GC, grain crop; FM, forage millet; FT, forage triticale; FS, forage sorghum; Flex, flexible crop choice; Flex1, flexible crop choice immediately after wheat; Flex2, flexible crop choice immediately after a previous flexible crop choice.

‡ Reporting moisture contents: wheat, pea (12.5%); corn, sorghum (15.5%); millet (12.0); forages (15.0%); corn silage (65.0%)

§ na = average and CV not applicable because of a mix of seed crops and forage crops period, with a CV for yield of 31.2% (Table 5). As expected, the CVs for wheat yield were much lower for wheat following fallow in the four set rotations (42.9–50.2%) than for the wheat in the continuously cropped flexible rotations (66.7–80.3%).

Net Income of Cropping Systems

Figure 4 shows the net income of the various cropping systems in each year and the 5-yr average net income calculated using the commodity prices shown in Table 2, the operations and input costs shown in Table 3, and the yields shown in Table 5. The most productive year for the set rotations with grain production was 2011, a result of relatively high grain yields, third highest grain prices, and generally lower production costs. The net income for the W–F, W–C–F, W–M–F, W–S–F, and W–GC systems were not different from one another and averaged US\$278 ha^{-1}. The all-forage set rotation of FM–FT–FS had the highest net income in 2011 (\$910 ha^{-1}), followed by the W–FS–Flex rotation (with forage millet as the Flex crop) with a net income of \$698 ha^{-1}. The next highest net income was seen in the W–Flex1–Flex2 rotation (\$416 ha^{-1}), but this was not statistically different from the net income for the W–F, W–M–F, W–S–F, and W–GC rotations.

Net income in the severe drought year of 2012 showed an average net loss of \$13 ha^{-1} for the W–C–F, W–M–F, W–S–F, and FM–FT–FS rotations. The W–F rotation had a positive net income of \$166 ha^{-1}, while the W–FS–Flex rotation (with forage pea as the Flex crop) netted the most income (\$321 ha^{-1}). The W–GC and W–Flex1–Flex2 rotations lost an average of \$196 ha^{-1}. This year had the highest average grain prices and the highest or second highest forage prices, but yields for most commodities except wheat were low or extremely low and costs of production were on average 16% greater than in 2011 (Table 6).

In 2013, when precipitation was below average for the wheat and spring crop growing seasons, but above average for the summer crop growing season, net income averaged a loss of \$59 ha^{-1} for the W–F, W–C–F, W–M–F, W–S–F, and the W–GC rotations. The highest net income was recorded for the FM–FT–FS rotation (\$674 ha^{-1}) which was not significantly different from the net income of the W–FS–Flex and W–Flex1–Flex2 rotations (average \$222 ha^{-1}). However, the positive net income of two flexible rotations was not statistically different from set and flexible grain-based rotations which showed negative net returns.

All rotations in 2014 showed positive net income except the W–GC rotation (–\$70 ha^{-1}). The average net income for the W–F, W–C–F, W–M–F, and W–S–F rotations was \$43 ha^{-1}. The net income for the W–Flex1–Flex2 rotation was \$233 ha^{-1}, but this was not significantly different from the set grain-based rotations. The two highest net incomes were recorded for the FM–FT–FS and W–FS–Flex rotations (average \$659 ha^{-1}).

Very good forage yields were recorded in 2015, especially for triticale, leading to a very high net income for the FM–FT–FS rotation of \$1366 ha^{-1}, the highest net income recorded in this 5-yr study. The next highest net income was seen for the W–FS–Flex and W–Flex1–Flex2 rotations (average \$371 ha^{-1}). Forage pea was being grown in the non-wheat phases of the W–Flex1–Flex2 rotation and grain pea was being grown in the Flex phase of the W–FS–Flex rotation. The average net income for the W–F, W–C–F, W–M–F, W–S–F, and W–GC rotations was –\$26 ha^{-1}, but the net incomes from these five rotations were not significantly different from the net income from the W–FS–Flex rotation (\$284 ha^{-1}).

Averaged over the 5 yr of the study, the greatest net income was recorded for the all-forage FM–FT–FS rotation (\$721 ha^{-1} yr^{-1}), followed by the W–FS–Flex rotation (\$415 ha^{-1} yr^{-1}) and the W–Flex–Flex rotation (\$239 ha^{-1} yr^{-1}). The remaining rotations showed average net income values that were not statistically different from one another and averaged \$41 ha^{-1} yr^{-1}. The flexible systems incorporating forages (W–FS–Flex, W–Flex1–Flex2) were clearly more productive than the flexible grain-based system (W–GC) which produced a 5-yr net income of –\$26 ha^{-1} yr^{-1}.

Some readers may be aware that forage prices for the 2011 to 2015 period in the central Great Plains were higher than during the previous 5-yr period. The price data obtained from the NASS website for the 2006 to 2010 period showed hay, forage pea, and corn silage prices that were 60, 53, and 41%, respectively, greater in 2011 to 2015 than in 2006 to 2010. Grain prices (with the exception of millet and dry pea) were generally not so different between the two 5-yr periods. Prices for wheat, corn, sorghum, millet, and pea were 17, 25, 34, 72, and 42%, respectively, greater in 2011 to 2015 than in 2006 to 2010. Using the 2006 to 2010 product prices, but still using the costs of production for 2011 to 2015, we found the average net income was still greatest for the all-forage FM–FT–FS rotation (\$320 ha^{-1} yr^{-1}), followed by the W–FS–Flex rotation (\$167 ha^{-1} yr^{-1}) and the W–Flex1–Flex2 rotation (\$43 ha^{-1} yr^{-1}). The remaining rotations showed

Table 6. Summary of total costs of production for five set rotations and three flexible rotations at Akron, CO (using values from Table 3).

Set or flexible	Rotation†	2011	2012	2013	2014	2015	Average
		\$ ha^{-1} yr^{-1}					
Set	W–F	146	179	141	313	256	207
	W–C–F	214	241	252	335	290	266
	W–M–F	212	218	228	309	305	255
	W–S–F	216	250	227	379	293	273
	FM–FT–FS	216	251	285	372	348	295
Flexible	W–GC	240	251	234	414	328	293
	W–FS–Flex	225	303	346	366	370	322
	W–Flex1–Flex2	267	317	339	350	324	319
Averaged over all rotations		217	251	257	355	314	279

† W, wheat; C, corn; M, millet; S, sorghum; F, fallow; GC, grain crop; FM, forage millet; FT, forage triticale; FS, forage sorghum; Flex, flexible crop choice; Flex1, flexible crop choice immediately after wheat; Flex2, flexible crop choice immediately after a previous flexible crop choice.

average net income values that were, again, not statistically different from one another and averaged –\$7 ha^{-1} yr^{-1}.

DISCUSSION

The results of this study show rather clearly the value of including forages in rotational cropping systems grown under widely varying precipitation conditions. All three systems that regularly included forages (FM–FT–FS, W–FS–Flex, W–Flex1–Flex2) showed positive net returns under the widely ranging precipitation conditions encountered during the 5 yr of the study, except in the severe drought year of 2012. However, even in 2012 the W–FS–Flex rotation had a positive net return (the Flex phase was forage pea in 2012). These overall positive results for the systems with forages occurred despite the fact that the 5-yr average costs of production for the systems with forages were the highest of all of the rotations evaluated (\$295–\$322 ha^{-1} yr^{-1}, Table 6). Possible reasons for why there is no widespread use of forages in current dryland cropping systems despite these rather convincing results regarding the greater economic returns compared with grain-based systems may include greater labor requirements, transportation costs, and marketing challenges for forage production, as well as the necessity to acquire additional forage handling equipment.

Of the four set grain-based rotations, W–F had the greatest average net income (\$104 ha^{-1} yr^{-1}), but it was not significantly different from the other fixed grain-based rotations (W–C–F, W–M–F, W–S–F) that averaged \$43 ha^{-1} yr^{-1}. The total production costs for W–F were the lowest of all of the rotations evaluated in 4 of the 5 yr of the study, averaging \$207 ha^{-1} yr^{-1} (Table 6). The average production costs of the other three set grain-based rotations averaged \$265 ha^{-1} yr^{-1}, or 28% greater than W–F.

The probability of achieving at least a break-even net income was determined by finding where the zero net income line (dotted line in Fig. 5) intersected the cumulative exceedance probability lines for each of the cropping systems. That probability was lowest for the W–GC rotation (21%) followed by W–C–F (37%), W–M–F (46%), W–S–F (78%), W–F (81%), W–Flex1–Flex2 (89%), FM–FT–FS (98%), and W–FS–Flex (100%). The probability of achieving at least a given net income falls off very rapidly as desired net income increases for the four set grain-based rotations and the flexible W–GC rotation and less quickly for the set forage rotation and the two flexible rotations that also include wheat. The probability of achieving at least a \$200 ha^{-1} net income (Fig. 5) was lowest for the W–C–F rotation (2%) followed by W–S–F and W–M–F (both 8%), W–GC (10%), W–F (12%), W–Flex1–Flex2 (77%), FM–FT–FS (91%), and W–FSvFlex (95%).

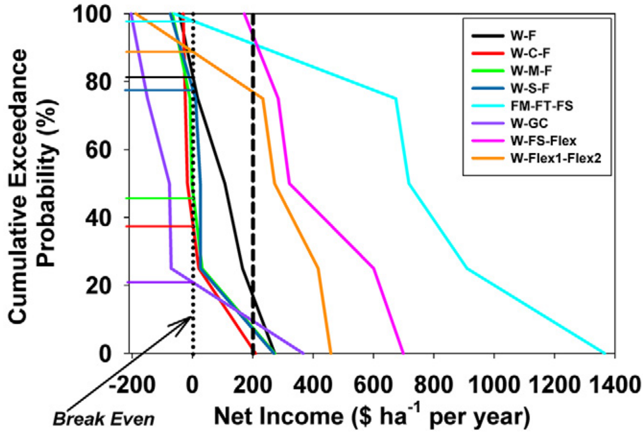

Fig. 5. Cumulative exceedance probability of net income for eight cropping systems at Akron, CO, from 2011 to 2015. W, wheat; C, corn; M, millet; S, sorghum; F, fallow; GC, grain crop; FM, forage millet; FT, forage triticale; FS, forage sorghum; Flex, flexible crop choice; Flex1, flexible crop choice immediately after wheat; Flex2, flexible crop choice immediately after a previous flexible crop choice.

When using the lower product prices from the 2006 to 2010 period in the economic analysis, net income averaged over all eight rotations was reduced to 31% of the average net income produced in the 2011 to 2015 period (\$62 vs. \$198 ha^{-1} yr^{-1}). However, the relative productivity of the rotations remained the same, with the rotations incorporating forages being the more economically productive rotations. The set all-forage rotation (FM–FT–FS) still showed the greatest net income.

If the projected changes in precipitation timing occur in future decades (less spring and summer rainfall) it may be advantageous to have forages as a component of a cropping system as the effects on biomass yield would likely be less than the effects on grain yield. To take greatest advantage of the increases in CO_2 concentration that are projected for the coming decades, triticale (the C3 forage species) should perhaps be given some preferential consideration as a flexible crop over the C4 forage species (corn silage, forage sorghum, forage millet) as triticale is likely to have the greatest yield response to the higher CO_2 levels, although Ward et al. (1999) concluded increasing atmospheric CO_2 would alleviate drought effects on C4 species to a greater degree than on C3 species. Additionally, when evaluating the potential benefits of including forages in future cropping systems grown under different climate conditions, it is important to consider that the relative value of forages may change during that period of time. A current assessment of whether forages will become more valuable or less valuable in the future would be very difficult.

CONCLUSIONS

In contrast to some earlier published data, the results of this study do not provide a convincing argument to encourage a central Great Plains farmer currently using the traditional W–F production system with no-till management to change to a more intensive system of grain crop production in which two crops are grown in 3 yr in a set rotation. While it is true that the 5-yr average grain production for the 3-yr rotations (W–C–F, W–M–F, W–S–F) was greater than for the W–F system (1503 vs. 1387 kg ha^{-1} yr^{-1}), the net returns of the W–F system were more than twice as great as the average of the other three set grain-based rotations; however, the difference was not statistically significant. On the other hand, the results of this study would argue strongly in favor of incorporating forages into the cropping system, whether in a set rotation or in a flexible rotation in which a decision about which crop should be selected for planting is made on the basis of starting available soil water at planting and assuming average growing season precipitation. The results of the study did not support the use of a flexible grain-based cropping system (W–GC) in which the crop choice during the flexible GC phase is made based on starting available soil water at planting and assuming average growing season precipitation. That cropping decision logic apparently called for cropping in some situations in which a fallow period should have been used. As stated at the beginning of this paper, the central Great Plains is a major producer of winter wheat in the United States. Therefore, it is likely that wheat needs to remain as a component of any cropping system developed for the region that would mitigate the effects of a potentially drier, more variable climate in the future. Consequently a good cropping system to consider may be a W–FS–Flex rotation or a W–Flex1–Flex2 rotation in which forage production is a regular consideration for the Flex phase of the system. These systems appear to have the advantages of adequate profitability and elimination of fallow phases.

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