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Cover Crop Biomass Production and Water Use in the Central Great Plains

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ABSTRACT

The water-limited environment of the semiarid Central Great Plains may not produce enough cover crop biomass to generate benefits associated with cover crop use in more humid regions. There have been reports that cover crops grown in mixtures produce more biomass with greater water use efficiency than single-species plantings. This study was conducted to determine differences in cover crop biomass production, water use efficiency, and residue cover between a mixture and single-species plantings. The study was conducted at Akron, CO, and Sidney, NE, during the 2012 and 2013 growing seasons under both rainfed and irrigated conditions. Water use, biomass, and residue cover were measured and water use efficiency was calculated for four single-species cover crops (flax [*Linum usitatissimum* L.], oat [*Avena sativa* L.], pea [*Pisum sativum* ssp. *arvense* L. Poir], rapeseed [*Brassica napus* L.]) and a 10-species mixture. The mixture did not produce greater biomass nor exhibit greater water use efficiency than the single-species plantings. The slope of the water-limited yield relationship was not significantly greater for the mixture than for single-species plantings. Water-limited yield relationship slopes were in the order of rapeseed < flax < pea < mixture < oat, which was the expected order based on previously published biomass productivity values generated from values of glucose conversion into carbohydrates, protein, or lipids. Residue cover was not generally greater from the mixture than from single-species plantings. The greater expense associated with a mixture is not justified unless a certain cover crop forage quality is required for grazing or haying.

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Use of cover crops in cropping systems is promoted based on several beneficial consequences that follow their use, including reduced erosion, increased soil organic matter, increased infiltration rates and precipitation storage, increased nutrient availability, reduced nutrient loss, and weed suppression (Snapp et al., 2005; Petrosino et al., 2015). Both wind and water erosion are sources of concern for dryland production systems in the Central Great Plains (Skidmore and Siddoway, 1978; Skidmore et al., 1979; Blanco-Canqui et al., 2013). Replacing fallow in a winter wheat–fallow system in southwestern Kansas with a variety of single-species or legume–triticale cover crop mixtures was found to reduce the soil's susceptibility to wind erosion and to reduce runoff loss of sediment, total P, and NO_3–N (Blanco-Canqui et al., 2013). However, this study also reported that these benefits of cover crops diminished rapidly with time after cover crop termination. In that study cover crops had been part of the cropping system for 5 yr, but after only 9 mo of no longer including cover crops in the system there were no discernible effects on the measured soil properties.

The historical, conventional definition of cover crops stated that the crop is not taken for a profitable purpose (Lal et al., 1991). However, more recent definitions of cover cropping allow for the use of the cover crop for animal feed (Franzluebbers and Stuedemann, 2008) so that there can be some direct profitability from growing the cover crop. For such profitability to occur there must be enough biomass produced by the cover crop such that a portion can be grazed or taken for forage while maintaining enough residual mass and surface cover to prevent soil erosion. Under the water-limited conditions of the semiarid Central Great Plains, producing enough

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biomass from cover crops to sufficiently meet both of these needs (i.e., wind erosion control and profitable forage production) may be a challenge.

Some reports of cover crop biomass production from the Northern Great Plains (Aase and Pikul, 2000; Carr et al., 2004; Chen et al., 2004, Miller et al., 2006) would suggest that cover crop production is sufficient to produce both profitable forage production and wind erosion protection. But Briggs and Shantz (1917) provided data that demonstrated that the amount of water required to produce a unit of plant biomass increased significantly as one moved from north to south across the Great Plains of the United States. For example, they reported 518 g of water to produce a gram of alfalfa (*Medicago sativa* L.) in Williston, ND, and 1005 g of water to produce a gram of alfalfa in Dalhart, TX. This difference is due to the evaporative demand differences that exist across the region as quantified by the strong north to south gradient of pan evaporation across the Great Plains (Tanner and Sinclair, 1983; Robinson and Nielsen, 2015; Farnsworth et al., 1982; Stewart and Peterson, 2014; Sinclair and Weiss, 2010). Tanner and Sinclair (1983) indicated that dry matter production was inversely related to pan evaporation. That observation is supported by comparing the water use efficiency data that can be extracted from Nielsen (2001) in the Central Great Plains and Miller et al. (2002) in the Northern Great Plains for pea, chickpea (*Cicer arietinum* L.), and lentil (*Lens culinaris* L.) (Table 1). For all three crops, water use efficiencies were greater in the Northern Great Plains (lesser pan evaporation) than in the Central Great Plains (greater pan evaporation). Likewise Robinson and Nielsen (2015) showed increasing intercepts and decreasing slopes of water use/yield production functions (indicating decreasing water use efficiency) of wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) as location changed from Northern to Southern Great Plains with concomitant increasing pan evaporation (relationships from Brown, 1971; Nielsen et al., 2011; C. Robinson, personal communication, 15 Dec. 2014). Therefore, transferring cover crop production results from the nNorthern Great Plains to the higher evaporative demand environment of the Central and Southern Great Plains should be done with some caution.

Treadwell et al. (2010) stated that cover crop species mixtures are planted to optimize C/N balance, obtain multiple benefits, or more fully achieve a particular objective such as organic matter production or weed suppression. They also stated that planting a mixture of cover crops can reduce risk of crop failure, although dealing with mixtures can require additional planning and labor. In addition, they noted that mixtures can be used to enhance alleopathic effects to control weeds and to either attract beneficial insects or deter pest insects. However, they did not provide any information relative to increased biomass production by mixtures compared with monocultures.

Others have observed that mixtures of species can produce more biomass than monocultures. Tilman et al. (2001) presented data from east-central Minnesota documenting the observation that mixtures of perennial grasses, legumes, nonlegume forbes, and woody species produced greater amounts of aboveground biomass as number of species in the mixtures increased from 1 to 16 species. Cardinale et al. (2007) analyzed data from 44 independent experiments from temperate grasslands, tundra, estuaries, or temperate bryophyte assemblages and concluded that species mixtures produced an average of 1.7 times more biomass than monocultures.

Clark (2012) stated that cover crop mixtures will improve biomass production compared with single species, and specifically that oat can improve the productivity of legumes when planted in mixtures, although no data were presented. Published studies with annual cover crop species have shown mixed results. Robinson (1960) presented data from a southern Minnesota study that showed greater forage yield for an oat–pea mixture compared with oat alone on a sandy soil, but not on a silt loam or clay loam soil. In that same study there was no yield advantage for an oat–vetch (*Vicia sativa* L.) mixture compared with oat alone. Dunavin (1987) found in a Florida study that two- and three-species mixtures of turnip–Chinese cabbage hybrid [*Brassica campestris* var. rapa L. X *B. pekinensis* (Lour.) Rupr.], rape (*B. napus* L.), rye (*Secale cereale* L.), ryegrass (*Lolium multiflorum* Lam.), and crimson clover (*Trifolium incarnatum* L.) produced more dry matter than all of the separate species grown as monocultures, except ryegrass (ryegrass was a component of all of the mixtures). LaChance and Bradley (2014) reported on 2 yr of biomass data collected in central Pennsylvania with cover crop monocultures and mixtures (three-, four-, six-, and seven-species mixtures) planted following winter wheat harvest. The fall growth of the mixtures was generally greater than that of the single-species plantings of rye, canola (*B. napus* L.), radish (*Raphanus sativus* L.), and red clover (*T. pratense* L.), but not of pea and oat. Carr et al. (2004) found the dry matter yields of oat–pea and barley (*Hordeum vulgare* L.)–pea mixtures were greater than single-species plantings of oat and barley when planted in a low-soil-N environment in southwestern North Dakota. In that same study the dry matter production of pea was greater than oat–pea and barley–pea in the low-N environment. Carr et al. (1998) reported that dry matter yield was not increased and may be reduced when pea was intercropped with cereals under high-soil-N conditions. Lenssen et al. (2010) evaluated 5 yr of forage production in northeastern Montana and found the dry matter yields of barley and a barley–pea mixture to be equal in each year. Working in the semiarid environment of Cyprus, Droushiotis (1989) found that average dry matter yields of single-species plantings of oat and triticale were the same as mixtures of those species with pea, and that total dry

Table 1. Water use efficiency (kg ha^{-1} mm^{-1}) of seed production for pea, chickpea, and lentil in the Central Great Plains (Nielsen, 2001) and Northern Great Plains (Miller et al., 2002).

	Central Great Plains		Northern Great Plains	
Species	Average	Range (No. of observations)	Average	Range (No. of observations)
Pea	7.3	3.9–11.1 (32)	8.5	4.1–16.3 (29)
Chickpea	5.3	2.7–8.2 (36)	6.2	2.5–13.6 (24)
Lentil	3.0	1.8–4.5 (31)	4.8	0.5–11.7 (30)

matter production decreased linearly as the seed proportion of the legume component in the mixture increased.

Brown (2011) presented some unreplicated, on-farm data collected from central North Dakota documenting nearly three times greater dry matter production (5115 vs. 1770 kg ha^{-1}) for cover crops grown in a six-species mixture compared with monocultures grown during 1 yr (2006) on 38 mm of growing season precipitation (Table 2). Differences were attributed to differences in rooting depth (no measurements were made to confirm this hypothesis) and how the soil functions with a diversity of plant species present (unspecified functioning mechanism).

Several factors can affect the relationship between dry matter production and crop water use, including photosynthetic efficiency (e.g., C_3 vs. C_4 carboxylation pathway; Kramer, 1983), energy requirements to produce different plant compositions (e.g., starch, protein, oil; Tanner and Sinclair, 1983), timing of precipitation and level of water stress at particular phenological stages of development (Nielsen et al., 2009), pest (weed, insect, disease) problems, shattering losses, limited soil fertility, soil physical limitations, hail, frost, limited plant populations, etc. (Angus and van Herwaarden, 2001; Passioura and Angus, 2010). French and Schultz (1984) demonstrated the usefulness of plotting dry matter or seed yield against growing season water use and then fitting a "frontier" line to the plotted data that defined the water-limited yield. The slope of this line quantified the target water use efficiency that farmers should be trying to attain through proper management. This data analysis method provides an opportunity to assess whether water use efficiency of cover crop dry matter production of mixtures is different from dry matter production for single-species plantings.

We have not been able to find data comparing productivity of cover crop species grown in mixtures vs. single-species plantings under the semiarid climate conditions of the Central Great Plains that would support the finding of enhanced productivity of mixtures compared with single species plantings reported by Tilman et al. (2001) using perennial species or Brown (2011) using annual species. Therefore, the objectives of this study were to (i) determine whether a 10-species cover crop mixture produced more biomass than single-species plantings; (ii) determine whether a 10-species cover crop mixture exhibited greater water use efficiency of dry matter production than single-species plantings; and (iii) quantify residue cover differences on the soil surface between a 10-species cover crop mixture and single-species plantings at cover crop termination and subsequent winter wheat planting.

MATERIALS AND METHODS

The study was conducted during the 2012 and 2013 growing seasons at the USDA-ARS Central Great Plains Research Station, 6.4 km east of Akron, CO, (40°09′ N, 103°09′ W, 1384 m elevation above sea level) and at the University of Nebraska High Plains Ag Lab, 9.7 km northwest of Sidney, NE, (41°12′ N, 103°0′ W, 1315 m elevation above sea level). The soil type at both locations was silt loam (Akron: Weld silt loam (fine, smectitic, mesic Aridic Argiustoll); Sidney: Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustoll).

The cropping system being investigated was a no-till proso millet (*Panicum miliaceum* L.)–spring cover crop–winter wheat rotation. In this system proso millet was harvested in mid-September and a cover crop was planted in early April. The cover crop was terminated in mid-June and winter wheat was planted in late September. The experiment was laid out as a split plot design with four replications at both locations. The main plot factor was irrigation treatment (rainfed or irrigated) and the split plot factor was cover crop species (four single-species cover crop plantings [flax, oat, pea, rapeseed] and one 10-species cover crop mixture). Additionally, a no-till fallow treatment (no crop between millet harvest and wheat planting) was included to evaluate changes in soil surface residue cover that occurred over time. Main plots were 6.1 by 54.6 m (2012) and 12.2 by 36.6 m (2013) at Akron and 4.6 by 54.6 m (both years) at Sidney. Individual split plot dimensions were 6.1 by 9.1 m (2012) and 6.1 by 12.2 m (2013) at Akron, and 4.6 by 9.1 m (both years) at Sidney. Planting dates, seeding rates, and mixture composition are given in Table 3. Seeding rates were recommended by Green Cover Seed, Bladen, NE. Planting date at Sidney in 2013 was delayed until 30 April because of wet conditions.

At both Akron and Sidney all cover crop treatments were no-till seeded into proso millet residue left following proso millet harvest the previous September. Row spacing was 0.20 m at Akron and 0.25 m at Sidney. The plot area was sprayed with glyphosate [N-(phosphonomethyl)glycine] before planting and fertilized with 34 kg N ha^{-1} (32–0–0) at Akron so that there would be no N-fertility limitations to cover crop growth and water use efficiency of biomass production could be accurately assessed. Soil testing at Sidney determined that no fertilizer was required. Hand-weeding was performed periodically at Akron and Sidney during the growing season, with most of that performed during the last week of April.

At Akron the irrigated plots were irrigated bi-weekly to simulate average precipitation at Blue Hill, NE, (south-central Nebraska, near the site of the study by Berns and Berns (2009)) to determine if cover crop water use/yield differences or similarities between single-species plantings and the mixture remained the same in a higher rainfall regime but with similar evaporative demand (about 1830 mm per year; Kohler et al., 1959). The irrigated plots at Sidney were irrigated bi-weekly to simulate the 30-yr average precipitation at Sidney. Because of the severe drought conditions experienced at Akron in 2012, the dryland plots received enough supplemental irrigation to keep them at 80% of the long-term average precipitation received at Akron. Observed and average monthly precipitation and irrigation amounts are shown in Table 4. Irrigations at both locations were applied through linear move irrigation systems, and 13 to 19 mm of water was applied with each irrigation.

Table 2. Dry matter production of cover crops grown as single-species and in a six-species mixture in Central North Dakota in 2006 (Brown, 2011).

Cover crop species	Dry matter
	kg/ha^{-1}
Oilseed radish (*Raphanus sativus* L.)	1410
Purple top turnip (*Brassica rapa* L.)	1695
Pasja turnip [*B. rapa* (L.); syn. *B. campestris*]	2320
Soybean [*Glycine max* (L.) Merr.]	1675
Cowpea [*Vigna unguiculata* (L.) Walp.]	2145
Lupin (*Lupinus angustifolius* L.)	1380
Six-species mixture (one-half seeding rate)†	5359
Six-species mixture (full seeding rate)	4870

† Millet (*Panicum miliaceum* L.), cowpea, sunflower (*Helianthus annuus* L.), soybean (*Glycine max* L. Merrill), turnip, oilseed radish.

Table 3. Cover crop planting and termination dates, seeding rates, and mixture composition at Akron, CO, and Sidney, NE.

Planting date	Termination date	Crop†	Seeding rate
			kg ha^{-1}
	Akron		
27 Mar. 2012	16 June 2012	Rapeseed	7.4
4 Apr. 2013	27 June 2013	Flax	39.2
		Oat	94.0
		Pea	114.5
		Mixture	59.7
		Rapeseed	2.3
		Flax	4.7
		Oat	13.7
		Pea	8.9
		Lentil	5.9
		Common Vetch	4.7
		Berseem Clover	1.2
		Barley	12.5
		Phacelia	2.3
		Safflower	3.5
	Sidney		
4 Apr. 2012	15 June 2012	Rapeseed	6.7
30 Apr. 2013	18 July 2013	Flax	39.2
		Oat	100.8
		Pea	112.0
		Mixture	57.1
		Rapeseed	2.2
		Flax	4.5
		Oat	13.1
		Pea	8.5
		Lentil	5.7
		Common Vetch	4.5
		Berseem Clover	1.1
		Barley	11.9
		Phacelia	2.2
		Safflower	3.4

† Rapeseed (*Brassica napus* L.), Flax (*Linum usitatissimum* L.), Oat (*Avena sativa* L.), Pea (*Pisum sativa* L.), Lentil (*Lens culinaris* L.), Common Vetch (*Vicia sativa* L.), Berseem Clover (*Trifolium alexandrinum* L.), Barley (*Hordeum vulgare* L.), Phacelia (*Phacelia tanacetifolia* L.), Safflower (*Carthamus tinctorius* L.).

Soil water was measured at the center of each plot in 0.3-m intervals using a neutron probe (Model 503 Hydroprobe, CPN International, Martinez, CA) at all locations. At Akron the depth intervals were 0.3 to 0.6 m, 0.6 to 0.9 m, 0.9 to 1.2 m, 1.2 to 1.5 m, and 1.5 to 1.8 m. Soil water in the 0.0 to 0.3 m surface layer was determined using time-domain reflectometry (Trase System I, Soil Moisture Equipment Corp., Santa Barbara, CA) with 0.3-m waveguides installed vertically to average the water content over the entire layer. At Sidney all soil water measurements were made only with the neutron probe and the lowest layer measured was 1.2 to 1.5 m (2012) and 0.9 to 1.2 m (2013) due to the presence of a restricting calcium carbonate layer that limited access tube insertion depth. The neutron probe was calibrated against gravimetric soil water samples taken in the plot area. Gravimetric soil water was converted to volumetric water by multiplying by the soil bulk density for each depth. Bulk density was determined from the dry weight of the soil cores (38 mm diam. by 300 mm length) taken from each depth at the time of neutron probe access tube installation.

Full-season water use was calculated from the water balance as the difference between soil water readings at planting and cover crop termination plus growing season precipitation. Precipitation was manually measured daily at all locations at weather observing sites approximately 300 m from the plot areas. Runoff and deep percolation were assumed to be negligible. This was considered a reasonable assumption as the slopes in the plot areas were <1% and visual observations in the plot areas following heavy rains did not show evidence of runoff. However, there may have been some deep percolation unaccounted for at Akron in 2013, especially under the irrigated condition (Nielsen et al., 2015).

Plant biomass samples were collected on the dates and from the areas shown in Table 5. Samples were oven-dried to 0 g kg^{-1} moisture content. In 2012 at both Akron and Sidney and in 2013 at Sidney the biomass samples from the cover crop mixture treatment at termination had each species separately weighed to determine the fractional composition of the mixture by weight. The late harvest date at Sidney in 2013 (17 July) was a consequence of the late planting date (30 April). Water use efficiency of biomass production was calculated as biomass dry weight divided by growing season water use.

Plant population was measured at Akron on 1 May 2012 and 29 May 2013 with number of plants counted in 1 m of row in each single-species plot and 2 m of row in each mixture plot. Plant population was measured for the mixture treatment only at Sidney on 15 June 2012 and 17 July 2013 at Sidney.

The experiment at Akron included no-till fallow plots in which no cover crop was planted so that residue cover provided by the cover crop treatments could be evaluated against the residue cover provided by the existing proso millet residue. Residue cover was evaluated at Akron by the method described by Nielsen et al. (2012) in which four photographs in each plot were taken with a digital camera held level with the horizon and at arm's length to the South of the photographer at midday to minimize shadows. Each digital image was subsequently analyzed using SamplePoint Measurement Software v. 1.53 (Booth et al., 2006; USDA-ARS, 2012). The SamplePoint software was set to select 64 randomly located points in each image. The software operator classified each of the 64 points as either crop residue or soil. The residue cover percentage was calculated as the fraction of 64 sample points that overlaid crop residue. The results from the four areas photographed in each plot were averaged to give a single value of residue cover for each plot at each sampling time. Residue cover was evaluated following cover crop planting (only millet residue was present at this time), following cover crop termination, and following wheat planting in 2012 and 2013. An additional measurement of residue cover was made in 2012 just before wheat planting. No residue cover measurements were made at Sidney.

Two methods of quantifying cover crop water use efficiency were used: (i) dividing biomass dry weight at termination by cover crop water use from planting to termination, and (ii) plotting biomass dry weight against water use for all plot-level data and eye-fitting a water-limited yield "frontier line" (French and Schultz, 1984; Angus and van Herwaarden, 2001; Sadras and Angus, 2006; Kirkegaard and Hunt, 2010). The frontier line was then moved to the right, parallel to itself,

Table 4. Monthly precipitation (P) at Akron CO, and Sidney NE, during the experimental period and long-term averages (Pavg). Also shown are irrigation amounts applied at each site. Growing season amounts are only those amounts accumulated between crop emergence and termination.

Year	Month	Akron P	Akron Pavg†	Akron Irrigation	Sidney P	Sidney Pavg‡	Sidney Irrigation
		mm					
2012	April	42	42	51	57	41	0
	May	41	73	87	22	73	38
	June	67	62	16	28	80	51
	Growing season	85		155	71		44
2013	April	57	42	8	–§	–	–
	May	40	73	82	81	73	25
	June	72	62	87	74	80	28
	July	–	–	–	100	66	0
	Growing season	178		177	109		41

† 1908 to 2013.
‡ 1946 to 2013.
§ "–" indicates a time when the cover crop was not present.

Table 5. Cover crop biomass sampling dates and area at Akron, CO, and Sidney, NE.

Location	Year	Sampling date	Sample area	Method
			m^2	
Akron	2012	15 May	0.203	Hand harvest
		1 June	0.203	Hand harvest
		13 June	0.203 (single species) 0.406 (mixture)	Hand harvest
	2013	26 June	8.13	Machine harvest
Sidney	2012	1 June	0.254	Hand harvest
		15 June	0.508	Hand harvest
	2013	17 July	0.254	Hand harvest

Table 6. Cover crop plant populations and fractional composition of mixture total weight at termination Akron, CO, and Sidney, NE.

Cover crop	Akron 2012 Dryland	Akron 2012 Irrigated	Akron 2013 Dryland	Akron 2013 Irrigated	Sidney 2012 Dryland	Sidney 2012 Irrigated	Sidney 2013 Dryland	Sidney 2013 Irrigated
	Plant population, 1000 plants ha^{-1}							
Rapeseed	1316	1107	897	676				
Flax	3296	3308	1254	984				
Oat	2583	2841	2201	1992				
Pea	885	922	381	418				
Mixture	2792	3468	403	323	1175	1468	3365	3060
	Fractional composition of mixture total weight, %							
Rapeseed	1.5	1.2			0.0	0.0	3.3	0.2
Flax	1.8	1.9			2.3	1.9	0.1	0.3
Oat	33.4	36.6			32.2	37.7	53.5	57.7
Pea	3.9	1.4			4.4	6.4	0.4	1.8
Lentil	1.6	0.7			1.7	1.6	0.5	4.2
Common vetch	2.2	0.6			1.1	0.9	1.7	1.5
Berseem clover	0.1	0.1			0.0	0.3	0.0	0.0
Barley	36.3	35.1			50.8	40.5	38.1	26.3
Phacelia	4.8	5.9			1.0	3.7	0.1	0.8
Safflower	4.8	8.8			6.5	6.9	0.0	0.1
Pigweed	0.0	0.1			0.0	0.0	0.1	1.2
Kochia	4.3	2.1			0.0	0.0	0.1	2.8
Russian thistle	4.9	5.1			0.0	0.0	0.0	0.0
Proso millet	0.4	0.4			0.0	0.0	1.9	3.1
Wheat	0.0	0.0			0.0	0.0	0.2	0.0

Table 7. Cover crop water use, biomass dry weight, and water use efficiency at termination at Akron, CO, and Sidney, NE.

Water treatment	Crop	Water use	Dry weight	Water use efficiency
		mm	kg ha^{-1}	kg ha^{-1} mm^{-1}
		Akron, CO, 2012		
Dryland	Flax	136a	3040ab	22.4a
	Oat	136a	3460ab	25.4a
	Pea	127a	3300ab	26.0a
	Rapeseed	135a	2920b	21.6a
	Mixture	147a	4190a	28.5a
	P	0.58	0.04	0.22
Irrigated	Flax	258a	5210a	20.2a
	Oat	250a	5880a	23.5a
	Pea	239a	5420a	22.7a
	Rapeseed	257a	4590a	17.9a
	Mixture	256a	5670a	22.1a
	P	0.19	0.25	0.24
		Akron, CO, 2013		
Dryland	Flax	171b	1630b	9.5ab
	Oat	252a	3540a	14.0a
	Pea	188ab	2400ab	12.8ab
	Rapeseed	221ab	1920b	8.7b
	Mixture	178b	2020b	11.3ab
	P	0.02	<0.01	0.02
Irrigated	Flax	277abc	3090b	11.2a
	Oat	332a	5630a	17.0a
	Pea	313ab	3230b	10.3a
	Rapeseed	258bc	2780b	10.8a
	Mixture	230c	2630b	11.4a
	P	<0.01	<0.01	0.05
		Sidney, NE, 2012		
Dryland	Flax	99b	1940ab	19.7a
	Oat	140ab	2560a	18.3a
	Pea	122ab	2510a	20.6a
	Rapeseed	134ab	1370b	10.2b
	Mixture	143a	2540a	17.8a
	P	0.04	<0.01	<0.01
Irrigated	Flax	165ab	2860b	17.3b
	Oat	185a	4230ab	22.9ab
	Pea	158b	4400a	27.8a
	Rapeseed	163ab	3070ab	18.8ab
	Mixture	164ab	3770ab	23.0ab
	P	0.04	0.02	0.03
		Sidney, NE, 2013		
Dryland	Flax	204b	3010c	14.8a
	Oat	252ab	5160a	20.5a
	Pea	245ab	4990a	21.4a
	Rapeseed	271a	3170bc	11.7a
	Mixture	258a	4790ab	18.6a
	P	0.01	>0.01	0.05
Irrigated	Flax	233b	2920b	12.5a
	Oat	287ab	4840ab	16.9a
	Pea	274ab	5130ab	18.7a
	Rapeseed	312a	4400ab	14.1a
	Mixture	278ab	5590a	20.1a
	P	0.02	0.03	0.17

until 10 points in each plot of dry matter vs. water use were intercepted and those 10 points were used to determine linear regression equations that defined the water-limited yield relationship. The regressions were performed with Statistix 10 software (Analytical Software, Tallahassee, FL) and the same software was used to compare regression lines for significant differences between slopes and intercepts as indicators of differences in water use efficiency.

Analysis of variance for cover crop water use, biomass dry weight, water use efficiency, and residue cover was performed with Statistix 10 software. Statistically significant differences in cover crop water use, biomass dry weight, and water use efficiency were determined by the Tukey HSD mean separation test ($\alpha = 0.05$) when the analysis of variance indicated significant treatment effects.

RESULTS

Precipitation

The precipitation received during the growing seasons at the various locations during the 2 yr of the study ranged from 71 mm at Sidney in 2012 to 178 mm at Akron in 2013 (Table 4). The sum of growing season precipitation plus irrigation ranged from 115 mm at Sidney in 2012 to 355 mm at Akron in 2013. These conditions provided a broad range of water availability for quantifying cover crop dry matter production and water use efficiency and comparing these quantities for the four single-species plantings against the 10-species mixture.

Plant Populations

Plant populations at Akron in 2012 were greatest for flax and the mixture (Table 6) and least for pea. Much lower plant stands were observed at Akron in 2013 than in 2012 due to cold conditions in April following planting that delayed beginning plant emergence for 21 d as noted by Nielsen et al. (2015), likely resulting in seed depredation. Plant population of oat in 2013 at Akron was least affected by these cool temperatures and delayed emergence. Irrigation did not consistently improve plant stands across cover crop species in either year.

Plant populations were only available for the mixture treatment at Sidney. In 2012 the population of the mixture was less than half of the population observed at Akron. The 2013 Sidney population was more than twice the population obtained in 2012.

Biomass, Water Use, and Water Use Efficiency

Akron (2012)

The cover crop biomass, water use, and water use efficiency results (Table 7) are presented as individual analyses by location and year and water treatment due to significant interactions (Table 8). The water use of all five cover crop treatments were statistically the same (average 136 mm) for the dryland treatment at Akron in 2012, but ranged from 127 mm for pea to 147 mm for the mixture. Biomass dry weight ranged from 2920 kg ha^{-1} for rapeseed to 4190 kg ha^{-1} for the mixture. The mixture biomass was significantly greater than rapeseed, but statistically the same as for the other single-species plantings.

Both water use and biomass were greater under irrigation at Akron in 2012. Water use was not different among the cover crop treatments and averaged 252 mm. Biomass under irrigation ranged from 4590 kg ha^{-1} for rapeseed to 5880 kg ha^{-1} for

Table 8. Analysis of variance tables for cover crop water use, biomass dry weight, and water use efficiency. The main effect, Environment, was the classification of data as coming from a specific combination of location (Akron, CO or Sidney, NE), year (2012 or 2013), and water availability treatment (dryland or irrigated). Environment was treated as a random variable and cover crop was treated as a fixed variable.

Source	df	SS	MS	*F*	*P*
		Water use			
Environment	7	437,672	62,524.6	12.11	<0.001
Environment × Rep	24	123,919	5,163.3		
Cover crop	4	24,067	6,016.8	3.15	0.029
Environment × Crop	28	53,468	1,909.6	4.07	<0.001
Environment × Rep × Crop	96	45,046	469.2		
Total	159	684,173			
		Biomass dry weight			
Environment	7	1.352×10^8	1.932×10^7	9.32	<0.001
Environment × Rep	24	4.976×10^7	2.073×10^6		
Cover crop	4	5.050×10^7	1.262×10^7	9.45	<0.001
Environment × Crop	28	3.742×10^7	1.336×10^6	2.69	<0.001
Environment × Rep × Crop	96	4.768×10^7	4.966×10^5		
Total	159	3.206×10^8			
		Water use efficiency			
Environment	7	3,098.9	442.7	12.80	<0.001
Environment × Rep	24	830.1	34.6		
Cover crop	4	885.6	221.4	10.01	<0.001
Environment × Crop	28	619.2	22.1	2.21	0.002
Environment × Rep × Crop	96	1,305.0	13.6		
Total	159	6,738.8			

oat, but was statistically the same for all cover crop treatments. Averaged over all cover crop treatments, the additional 155 mm of water added as irrigation to simulate the average precipitation condition of south-central Nebraska increased water use by 85% and biomass by 58%. Water use efficiency under both water treatments was not different among the cover crop treatments, averaging 24.8 kg ha^{-1} mm^{-1} for the dryland treatment and 21.3 kg ha^{-1} mm^{-1} for the irrigated treatment.

The fractional composition (by weight) of the mixture in 2012 was dominated by the two grasses (Table 6). Oat and barley comprised 69.7% of the dryland mixture biomass and 71.7% of the irrigated biomass. The legumes (pea, lentil, vetch, and clover) comprised 7.8% of the dryland mixture biomass, but only 2.8% of the irrigated mixture biomass.

Akron (2013)

Average cover crop water use at Akron in 2013 for the dryland treatment was greater (202 mm) than in 2012 (136 mm) due to the doubling of growing season precipitation (85 mm in 2012, 178 mm in 2013). The lowest water use was observed for flax and the mixture (about 175 mm) and the highest for oat (252 mm). Dryland biomass production was greatest for oat (3540 kg ha^{-1}) and least for flax (1630 hg ha^{-1}). The biomass production of the mixture (2020 kg ha^{-1}) was only significantly different from the biomass of oat. Even though growing season precipitation and water use were greater in 2013 than in 2012, average 2013 dryland biomass production was only 68% of the average 2012 production due to the reduced plant stands mentioned earlier.

As in 2012, irrigation increased both water use and biomass in 2013. Water use was least for the mixture (230 mm) and greatest for oat (332 mm). This low value for the mixture was a consequence of the very low plant population established (323,000 plants ha^{-1}) which was only 9.3% of the 2012 population (3,468,000 plants ha^{-1}). Biomass was again greatest for oat (5630 kg ha^{-1}) which was significantly greater than all of the other cover crop treatments (averaging 2930 kg ha^{-1}).

Because of these poor plant stands, water use efficiency was much lower in 2013 than in 2012. Greatest water use efficiency under both dryland and irrigated treatments was observed for oat (14.0 kg ha^{-1} mm^{-1} and 17.0 kg ha^{-1} mm^{-1}, respectively). Under both dryland and irrigated treatments the water use efficiency of the mixture was about 11.4 kg ha^{-1} mm^{-1}, which was not different from any of the other single-species cover crops.

Sidney (2012)

Water use for the dryland plots at Sidney in 2012 ranged from 99 mm for flax to 143 mm for the mixture (Table 7). The biomass dry weight was statistically the same for flax, oat, pea, and the mixture, averaging 2390 kg ha^{-1}. Rapeseed produced 1370 kg ha^{-1}. Water use for the irrigated treatment ranged from 158 mm for pea to 185 mm for oat. Biomass ranged from 2860 kg ha^{-1} for flax to 4400 kg ha^{-1} for pea which was not significantly different from the biomass produced by oat, rapeseed, or the mixture. Water use efficiency under the dryland condition was the same for flax, oat, pea, and the mixture (average 19.1 kg ha^{-1} mm^{-1}) which was significantly greater than for rapeseed (10.2 kg ha^{-1} mm^{-1}). Under irrigation the water use efficiency was greatest for pea (27.8 kg ha^{-1} mm^{-1}) and least for flax (17.3 kg ha^{-1} mm^{-1}). The water use efficiency of the mixture was not significantly different from any of the single-species plantings.

As observed at Akron, the fractional composition (by weight) of the mixture in 2012 was dominated by the two grasses (Table 6). Oat and barley comprised 83.0% of the dryland mixture biomass and 78.2% of the irrigated biomass. The legumes (pea, lentil, vetch, and clover) comprised 7.2% of the dryland mixture biomass and 9.2% of the irrigated mixture biomass.

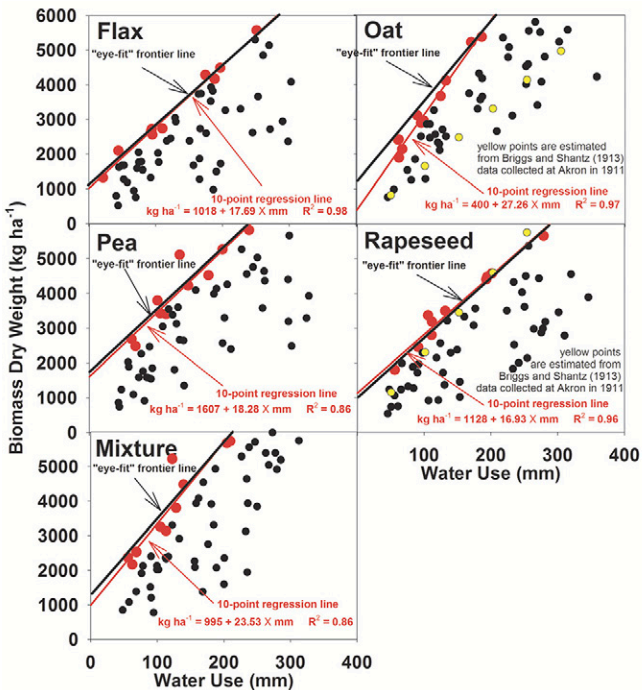

Fig. 1. Water use and biomass dry weight of flax, oat, pea, rapeseed, and a 10-species mixture of cover crops grown at Akron, CO, and Sidney, NE, in 2012 and 2013.

Sidney (2013)

As at Akron, dryland cover crop water use in 2013 was greater than in 2012 due to greater precipitation (54% greater), resulting in greater dryland biomass (Table 7). Water use was least for flax (204 mm) and greatest for rapeseed (271 mm), which was not significantly different from the water use observed for oat, pea, and the mixture. Dryland biomass ranged from 3010 kg ha^{-1} for flax to 5160 kg ha^{-1} for oat, which was not significantly different from pea, rapeseed, or the mixture.

Under the irrigated condition flax was again the lowest water using crop (233 mm) while rapeseed used the most water (312 mm). The least biomass was produced by flax (2920 kg ha^{-1}) while the mixture produced the most biomass (5590 kg ha^{-1}), which was not different from oat, pea, or rapeseed.

Water use efficiency under the dryland treatment ranged from 11.7 kg ha^{-1} mm^{-1} for rapeseed to 20.5 kg ha^{-1} mm^{-1} for oat, but the differences were not significant. Water use efficiency for the irrigated treatment ranged from 12.5 kg ha^{-1} mm^{-1} for flax to 20.1 kg ha^{-1} mm^{-1} for the mixture, but again the differences were not significant.

The fractional composition (by weight) of the mixture in 2013 was even more dominated by the two grasses (Table 6). Oat and barley comprised 91.6% of the dryland mixture biomass and 84.0% of the irrigated biomass. The legumes (pea, lentil, vetch, and clover) comprised 2.6% of the dryland mixture biomass and 7.5% of the irrigated mixture biomass.

Water-Limited Yield Potential

As stated earlier, plots of water use vs. biomass can identify the water-limited yield potential (French and Schultz, 1984). We graphed our individual plot data after this manner and eye-fit a data frontier line (black line, Fig. 1). As is usually the case in crop production, there are factors other than water availability that cause yield to fall below and to the right of the frontier line. The most easily identified factor in the current dataset was the poor plant establishment in 2013 at Akron due to the abnormally cold April temperatures that delayed emergence. Additionally, hailstorms at Akron on 23 and 24 June 2013 also reduced harvestable biomass, particularly of rapeseed (visual observation). The linear regressions (red lines, Fig. 1) fit to the 10 data points nearest to the eye-fit frontier line define the water-limited yield potentials and allow for another comparison of the water use efficiency of the cover crop treatments. The greatest regression slope (27.26 kg ha^{-1} mm^{-1}) and consequently the greatest water use efficiency was observed for oat (Table 9), which was not significantly different from the mixture (23.53 kg ha^{-1} mm^{-1}), but was different from pea (18.28 kg ha^{-1} mm^{-1}), flax (17.69 kg ha^{-1} mm^{-1}), and rapeseed (16.93 kg ha^{-1} mm^{-1}). The flax slope was not significantly different from the pea, rapeseed, and mixture slopes.

A greater intercept of the water-limited yield regression line could be interpreted as an indication of potentially greater biomass production under low water availability conditions. The regression intercept was greatest for pea (1607 kg ha^{-1}) and least for oat (400 kg ha^{-1}). The intercepts for oat and the mixture were not different from each other. The intercepts for flax and rapeseed were also not different from each other, and neither were the intercepts for the mixture and pea.

When the regression slopes are ordered from smallest to largest they rank as rapeseed, flax, pea, mixture, and oat. This is the order that would be expected based on the energy requirements to produce different plant compositions (e.g., starch, protein, oil; Tanner and Sinclair, 1983). In other words, we would expect greater water use efficiency from a grass (oat) and a grass-dominated mixture than we would from a legume (pea) or from an oilseed (flax, rapeseed).

As a point of comparison with previous research, we have calculated water use and yield points for oat and rapeseed (Fig. 1, yellow points) from the water requirement values published by Briggs and Shantz (1913). Those calculated points indicated that Briggs and Shantz found a lower water use efficiency for oat but a similar water use efficiency for rapeseed.

Residue Cover

Residue cover measurements taken at Akron following cover crop planting showed the proso millet residue provided about 85% cover in 2012 and 73% cover in 2013 (Fig. 2). Following cover crop termination in 2012 the dryland residue cover declined for the proso millet fallow treatment to 73%, which was similar to flax (73%), pea (75%), and the mixture (78%) residue cover. Oat (81%) had maintained the original residue cover percentage, but rapeseed had declined to 65%. Under the irrigated treatment in 2012, residue cover was maintained at more than 80% for rapeseed, oat, pea, and the mixture, but declined to 74% for flax and 68% for the fallow millet residue. Residue cover continued to decline for all treatments with time to wheat planting for both water availability conditions, with the greatest cover seen for oat and the mixture. There was a rapid loss of residue cover following wheat planting in 2012 due to the action of the grain drill, with an average loss across cover crop treatments and water availability conditions of 16 percentage points. The least loss in residue cover due to planting the wheat was seen for oat (74% declining to 71%, averaged over irrigation treatments).

Table 9. Slopes and intercepts of linear regression lines fit to the 10-point data frontier of water use vs. dry matter production for cover crops grown at Akron, CO, and Sidney, NE, in 2012 and 2013, and matrices of regression slope and intercept comparison statistics. Also shown for comparison with the slopes are the biomass productivity (gram seed per gram of photosynthate) values computed by Sinclair and de Wit (1975).

Regression slopes and intercepts				
Species	Slope	Intercept	R^2	Biomass productivity
	kg ha^{-1} mm^{-1}	kg ha^{-1}		g g^{-1}
Flax	17.69	1018	0.98	0.46
Oat	27.26	400	0.96	0.70
Pea	18.28	1607	0.86	0.65
Rapeseed	16.93	1128	0.96	0.43
Mixture	23.53	995	0.93	–

Matrices of regression slope and intercept comparisons. Matrix values are the probability that the null hypothesis (slopes [or intercepts] of the data frontier water-limited yield regression lines are equal) is true.

Regression slope comparison				
	Flax	Oat	Pea	Rapeseed
Oat	<0.01			
Pea	0.82	0.02		
Rapeseed	0.59	<0.01	0.63	
Mixture	0.08	0.37	0.23	0.07

Regression intercept comparison				
	Flax	Oat	Pea	Rapeseed
Oat	<0.01			
Pea	<0.01	0.47		
Rapeseed	0.96	<0.01	<0.01	
Mixture	<0.01	0.37	0.80	<0.01

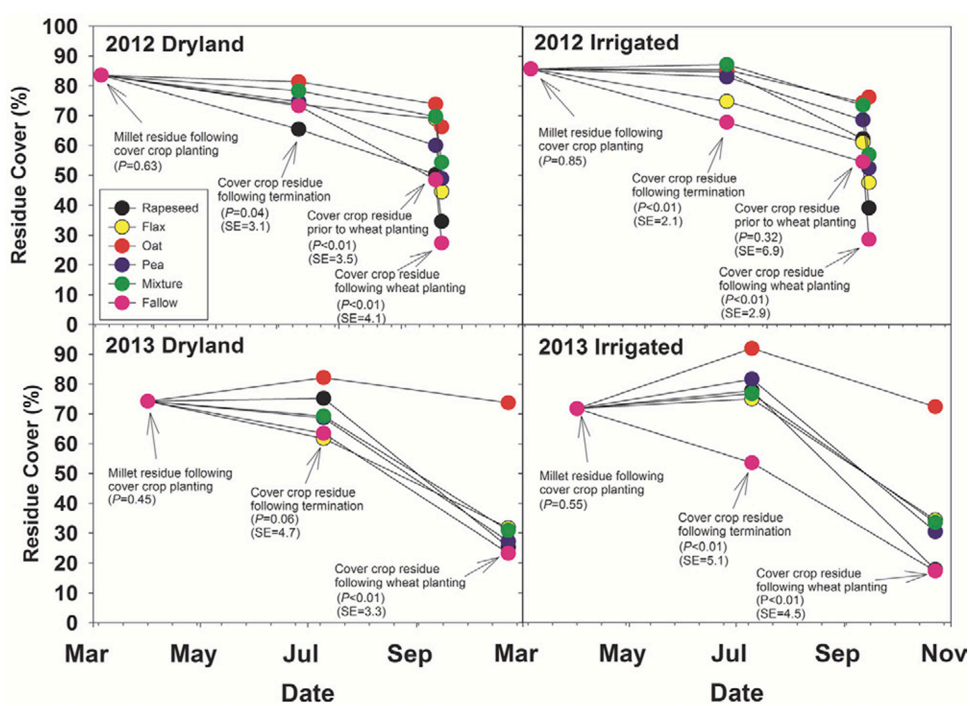

Fig. 2. Residue cover of fallow and cover crops following proso millet fallow at Akron, CO, in 2012 and 2013. Rapeseed, flax, oat, and pea were grown as single-species plantings. The mixture was composed of 10 species.

In 2013, where the starting proso millet fallow residue was lower (73%) than in 2012, oat under the dryland treatment increased residue cover to 82% at cover crop termination while over the same period the proso millet fallow residue declined to 63%. The residue covers provided by the other crops were observed to be 75% for rapeseed, 69% for the mixture and pea, and 62% for flax. Following wheat planting the residue cover provided by oat still remained high (74%) while all of the other treatments were reduced by weathering and the action of the grain drill to between 23% (fallow) and 32% (flax). The greater cover crop biomass produced under irrigation in 2013 (Table 7) resulted in increases in residue cover at the time of cover crop termination compared with the cover crop residue following cover crop planting. The greatest cover was again seen for the oat residue (92%), followed by pea (82%), rapeseed (78%), mixture (77%), and flax (75%). The millet residue had declined to 54% by the time of cover crop termination. Following wheat planting, the oat residue covered 72% of the ground while flax, pea, and mixture residues covered about 33% of the ground. The poorest residue cover following wheat planting was noted for flax and fallow (18%).

DISCUSSION

No differences were seen that would indicate consistently greater biomass production or greater water use efficiency by the 10-species mixture than by any of the single-species plantings of cover crops. The water use efficiency values reported in Table 7 vary widely from 8.7 to 28.5 kg ha^{-1} mm^{-1}, likely depending on factors such as timing and amount of precipitation and irrigation, temperature stress, plant stand, hail, photosynthetic carboxylation pathway, and differing energy requirements to make starch, protein, or oil. Therefore a better method for determining differences in water use efficiency that may arise due to synergistic effects of mixing cover crop species is the use of the frontier analysis of French and Schultz (1984). The slopes identified in Table 9 for the water-limited yield lines of the single-species plantings rank in the same order as the biomass productivity (gram of seed per gram of photosynthate) calculated by Sinclair and de Wit (1975), also shown in Table 9, from the values of glucose conversion into carbohydrates, protein, or lipids provided by Penning de Vries (1975). That similarity in ranking (rapeseed < flax < pea < oat) gives us confidence that the slope of the regression line of the mixture (intermediate to the slope of oat and pea) is a true reflection of the mixed photosynthetic productivities of the grasses, legumes, and oilseeds that make up the mixture. We can conclude with certainty that for this study growing the cover crops in a mixture did not change the basic chemistry and physics of the photosynthetic process into a more efficient plant process than occurs with single-species plantings. This conclusion is based on the observation that the slope of the mixture regression line was not greater than the slope of the oat line and was intermediate to the slopes for oat and pea. Because the experiment was established in a new area each year at both sites, the study is not able to address if longer-term use of cover crop mixtures might lead to improvements in water use efficiency.

The fractional composition of the mixture by seeding rate weight was 44% grasses, 35% legumes, and 18% oilseeds (Table 3). At termination the fractional composition of the mixture (by biomass weight) averaged 80% grasses, 6% legumes, and 7% oilseeds (Table 6). There is quite a bit of variability from year to year and between sites as to which of the oilseeds and which of the legumes were dominant in the mixture, but clearly the grasses were more competitive than the legumes and oilseeds. Because water use efficiency of biomass production was not improved with the mixture compared with single-species plantings of grasses, there may be little justification for incorporating legumes and oilseeds into a cover crop planting for the sake of diversity if the primary purpose is to provide biomass for cover and erosion protection. However, if the primary purpose of the cover crop is to provide some forage production for livestock feed, then inclusion of legumes and oilseeds to obtain a specific forage quality may need to be considered.

Previous research (Nielsen and Vigil, 2005) has shown that spring-planted cover crop water use in this semiarid environment will depress yields of subsequent wheat crops planted 70 to 100 d following cover crop termination, with that yield depression ranging from 905 to 1650 kg ha^{-1}. Therefore, most farmers will need to receive some economic benefit from the cover crop to pay for the cover crop seed, planting costs, and the yield depression they are likely to experience because of the cover crop water use. That benefit may come from taking a portion of the cover crop as forage or grazing off a portion of the cover crop. Determining how much of the cover crop can be removed while still maintaining sufficient cover to provide adequate erosion control and soil organic matter levels is a complex problem with highly variable answers depending on soil type, weather, and existing levels of organic matter (Wilhelm et al., 2004; Andrews, 2006). Data from the current study show widely ranging amounts of cover crop biomass produced (1366 to 5880 kg ha^{-1}) depending primarily on available growing season water, cover crop species, and plant stands. Residue cover amounts at Akron following cover crop termination time ranged from 62 to 92% (Fig. 2), which appears to be more than enough to allow for some biomass removal and still maintain enough cover for wind erosion protection (Fryrear, 1985; Williams et al., 1997). However, even without grazing, the residue cover percentages declined over time until wheat planting, and in 2013 when plant stands were poor, the residue cover following wheat planting was far below 60% for all treatments except oat, which should give some concern regarding soil erosion potential. Growing the cover crop helped to maintain residue cover at greater amounts than the constantly weathering and declining millet residue, with oat residue providing the most cover in 2013 because of the better plant stand observed for oat compared with the other treatments. Further studies are likely needed to evaluate changes in residue cover that follow grazing and the economics associated with managed grazing practices.

CONCLUSIONS

Cover crops serve useful purposes in improving both soil structure and organic matter and also in reducing wind and water erosion potential. These beneficial effects are more likely to be seen in more humid regions of the United States where lack of precipitation that limits biomass production does not frequently occur. In contrast, the Central Great Plains region often has dryland biomass production limited by available water and consequently may not produce enough biomass to allow for profitable grazing while still maintaining erosion protection and soil organic matter levels. Growing cover crops in mixtures does not improve the water use efficiency of biomass production. The added expense generally seen for cover crop mixtures compared with single-species plantings (Nielsen et al., 2015) is therefore not likely to be justified. Where previous crop residues are insufficient to provide erosion protection and a cover crop must be employed to provide ground cover, inexpensive monocultures are recommended. Cover crop mixtures may be justified if a portion of the biomass produced is to be grazed and if a certain desired forage quality can be produced by proper mixture selection, but growing a cover crop mixture is not likely to produce greater biomass than a single-species planting.

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