

Dietary Options for Hydration and Health in Dry Climate Conditions

Dr. A. Rossi¹, Dr. L. Svensson², Dr. M. Chen^{3*}

¹ Department of Internal Medicine, University of Milan, Milan, Italy

² Department of Public Health, Karolinska Institutet, Stockholm, Sweden

³ Division of Clinical Biochemistry, National University of Singapore, Singapore

ABSTRACT

Rotating summer fallow with wheat (*Triticum* spp.) is done in dryland grain farming at upper latitudes to stabilize yields over time and to prevent crop failure. However, summer fallow is costly since weeds must be controlled and crops are not grown. Replacing summer fallow with grain crops can generate low economic returns. Previous research indicated that annual cool-season forages can be substituted for summer fallow in dryland cropping systems. Our objective was to determine if annual warm-season species were suited for forage production in monocultures and polycultures in the U.S. northern Great Plains. Dry matter (DM) production by 20 warm- and cool-season crop monocultures and 4 polycultures was determined across six environments during 2016, and by 25 warm- and cool-season crop monocultures and polycultures across four environments from 2016 through 2018. Maize (*Zea mays* L.) monoculture produced forage DM in amounts equal to, or greater than, those produced by other warm- and cool-season crop treatments ($P < 0.05$). Maize DM production averaged 2.5 to 5.7 Mg ha⁻¹, depending on the study and environment. Sorghum (*Sorghum bicolor* L.), foxtail millet [*Setaria italica* (L.) P. Beauv.] and sunflower (*Helianthus annuus* L.) also produced relatively large amounts of forage DM. Polycultures failed to produce more DM than monocultures consistently ($P > 0.40$). These results indicate that maize and other warm-season crops are adapted for dryland forage production in cool regions at upper latitudes. Additional research is needed to determine the impacts of annual warm-season forages on grain yield in a forage-wheat crop sequence.

Abbreviations

DM, dry matter; USNGP, U.S. northern Great Plains

Core Ideas:

- Warm-season, annual crops can be grown for forage in dryland regions at upper latitudes.
- Forage yields produced by crop monocultures can equal or exceed those produced by polycultures.
- Warm-season, annual forage crops may be a suitable replacement for summer fallow.

INTRODUCTION

The U.S. northern Great Plains (USNGP) is a major wheat producing region in North America. This region encompasses North Dakota, most of South Dakota and Montana, northeastern Wyoming, and extreme north central and northwest Nebraska within the United States (Padbury et al., 2002). Over 5.5 million ha of wheat were harvested across these five states during 2017 (USDA NASS, 2017). The majority of wheat grown in Montana and North Dakota is spring wheat, while winter wheat dominates production in Nebraska, South Dakota and Wyoming. Barley (*Hordeum vulgare* L.) is another cool-season, dryland small-grain crop grown across the region, though on a much smaller scale than wheat. Barley production totaled under 500,000 ha in the USNGP in 2017 (USDA NASS, 2017). Other small-grain crops [e.g., oat (*Avena sativa* L.) and triticale (\times *Triticosecale*)] are grown, but on a much smaller scale in the region.

Historically, much of the wheat grown in the USNGP was rotated with summer fallow, where land lays idle for 14 months (followed by winter wheat) to as long as 21 months (followed by spring wheat) between successive wheat crops (Tanaka, Lyon, Miller, Merrill, & McConkey, 2010). In part, summer fallow was done to stabilize grain yields over time and prevent complete crop failure due to severe water stress (Hansen, Allen, Baumhardt, & Lyon, 2012; Nielsen & Calderón, 2011). Precipitation is erratic and unpredictable across the region, with long hot and dry periods common during the summer (Padbury et al., 2002). Summer fallow provided time for recharge of plant-available water reservoirs in the soil prior to growing wheat (Black, Siddoway, & Brown, 1974; Hansen et al., 2012), and an opportunity to control weeds (Anderson, Stymiest, Swan, & Rickertsen, 2007; Derksen, Thomas, Lafond, Loepky, & Swanson, 1994; Lenssen, Johnson, & Carlson, 2007; Peairs, Bean, & Gossen, 2005).

Previous research demonstrated the inefficiencies of summer fallow as a soil-water storage strategy (Hansen et al., 2012; Nielsen, Unger, & Miller, 2005; Peterson, Schlegel, Tanaka, & Jones, 1996). The idling of farmland as a result of summer fallow also raised economic efficiency questions (Aase & Schaefer, 1996; Dhuyvetter, Thompson, Norwood, & Halvorson, 1996). Recognizing this, dryland cropping systems researchers emphasized the need to eliminate summer fallow in dryland cropping systems in the USNGP (Aase & Reitz, 1989; Anderson, Tanaka, & Merrill, 2003; Krupinsky, Tanaka, Merrill, Liebig, & Hanson, 2006; Lenssen et al., 2014; Miller & Holmes, 2005) and elsewhere (Anderson et al., 1999; Farahani, Peterson, & Westfall, 1998; Lyon & Peterson, 2005; Peterson et al., 1996; VandenBygaart, Gregorich, & Angers, 2003; Zentner et al., 2006).

Much of the focus in replacing summer fallow with non-cereal grain crops focused on pulses (Krupinsky et al., 2006; Lenssen et al., 2007; Miller & Holmes, 2005; Miller et al., 2002a; Miller, Gan, McConkey, & McDonald, 2003; Miller, Waddington, McDonald, & Derksen, 2002b) and oilseeds (Johnston et al., 2002; Krupinsky et al., 2006; Lenssen et al., 2007, 2012; Miller and Holmes, 2005) in the USNGP and adjacent Canadian provinces. Pea (*Pisum sativum* L.) showed particular promise as a replacement to summer fallow compared with other grain crops in Montana (Miller & Holmes, 2005; Miller et al., 2002b, 2003). However, there were instances when significant yield reductions resulted when wheat followed pea in rotation (Miller et al., 2002b, 2003). Many pulse and oilseed crops also generated negative economic returns when grown in the USNGP, including canola (*Brassica* spp.) (-41 USD ha⁻¹), lentil (-113 USD ha⁻¹), and pea (-52 USD ha⁻¹) (Swenson, 2018).

Summer fallow continues to be used in much of the USNGP in dryland cropping systems, in spite of shortcomings. For example, over 1 million hectares of cropland was summer fallowed in Montana during 2019 (USDA FSA, 2019). In contrast, summer fallow has largely been abandoned in dryland wheat systems in North Dakota, in part due to relatively cool temperatures coupled with greater precipitation which results in a more favorable balance between precipitation and evapotranspiration than in Montana (Hansen et al., 2012). The widespread adoption of no-till farming in North Dakota also contributed to the decline in summer fallow because of the soil-water conservation that results from eliminating tillage (Hansen et al., 2012).

Replacing summer fallow with annual forage crops has been considered in the USNGP. Crops use less water when grown for forage than grain since harvest occurs several weeks prior to reaching physiological maturity, and more time is available for soil-water recharge before planting a subsequent wheat crop. Winter wheat yields were not depressed when grown following a winter pea hay crop harvested at flowering in central Montana compared to summer fallow (Chen, Neill, Burgess, & Bekkerman, 2012), and were only 10% lower in southwestern Montana (Miller, Glunk,

Holmes, & Engel, 2018). Impacts on wheat grain yield following a spring pea forage crop were similar to those following a winter pea forage crop in the study by Miller et al. (2018), while spring pea harvested at early flowering had no effect on a subsequent spring wheat crop in a previous study at one of two Montana locations (Miller, Engel, & Holmes, 2006). Interestingly, wheat grain protein concentration generally was comparable or greater following a pea forage crop compared to summer fallow in all three studies (Chen et al., 2012; Miller et al., 2006, 2018).

Cool-season species, in addition to pea, have been considered as a summer fallow replacement in rotations with wheat. Barley is a popular annual forage grown in the USNGP (Meccage, Carr, Bourgault, McVay, & Boss, 2019), and awnleted cultivars have been released for forage production (Hockett et al., 1990). Lenssen, Sainju, Jabro, Allen, & Evans (2015) reported that higher seeding rates (298 vs. 223 live kernels m⁻²) and banded nitrogen fertilizer application in a no-tillage seedbed resulted in greater forage DM production compared to a conventional-tillage system when planting at recommended seeding rates and broadcasting nitrogen fertilizer.

Warm-season annual crops are grown for dryland forage in the USNGP, though not to the extent as are cool-season annual crops (Meccage et al., 2019). Lenssen et al. (2010) concluded that forage DM yield was lower for foxtail millet [*Setaria italica* (L.) P. Beauv.] (4.5 Mg ha⁻¹) than barley (5.0 Mg ha⁻¹) and barley + pea intercrop (5.1 Mg ha⁻¹) averaged over five years in eastern Montana, while sorghum × sudangrass [*Sorghum bicolor* (L.) Moench × *Sorghum sudanese* (Piper) Stapf] produced more forage DM (3.8 Mg ha⁻¹) than foxtail millet (2.8 Mg ha⁻¹) and proso millet [*Panicum americanum* (L.)] (2.3 Mg ha⁻¹) in a separate study (Lenssen & Cash, 2011). Similar research comparing other warm-season grass and broadleaf crop species for forage DM production in the USNGP is lacking. The objective of our research was to identify annual warm-season species adapted as dryland forage crops in regions at upper latitudes. Our hypothesis was that warm-season annual crops produce equal or greater amounts of forage DM compared to cool-season annual forages in Montana and other semiarid regions.

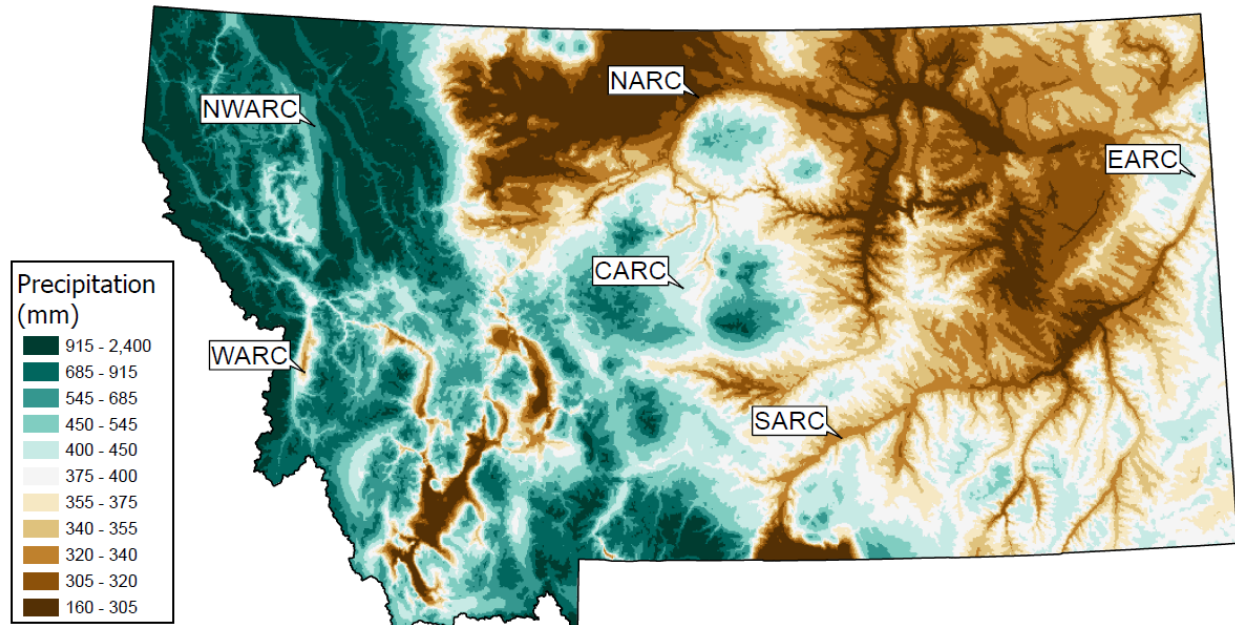
MATERIALS AND METHODS

Study 1

Twenty grass and broadleaf species were evaluated for forage DM yield under dryland management at six locations across Montana during 2016 (Figure 1). Species were grouped as cool-season or warm-season forage crops, depending on the targeted planting date (cool-season = mid-April to mid-May; warm-season = late-May to mid-June). All of these species were grown as monocultures. Several species also were grown together in four different polycultures in response to farmer interest in crop mixtures, ranging from 6 to 10 different crop species, depending on the mixture. The 20 crop species, along with the seeding rate at which each was planted in monoculture, and those planted in polycultures, are listed in Table 1. Monoculture seeding rates reflected local recommendations for the crop species considered [e.g. spring pea: McKay, Burrows, Menalled, Jones, Wanner, & O'Neill, 2013) and varied widely between crops. Polyculture seeding rates were the monoculture seeding rate of each species divided by the number of crops comprising a mixture.

The selection of species included in polycultures was based on a diversity of factors, including the inclusion of (1) legumes that can fix N biologically [e.g., chickpea (*Cicer arietinum* L.)]; (2) crops with different root architectures and rooting depths (shallow tap root [e.g., field pea], deep tap root [e.g., safflower (*Carthamus tinctorius* L.)], and fibrous [e.g., oat, triticale]); (3) inexpensive and locally sourced (e.g., spring pea) and expensive and locally unavailable [e.g.,

radish (*Raphanus sativus* L.) seed; (4) grass or monocotyledonous (e.g., oat) and broadleaf or dicotyledonous [e.g., flax (*Linum usitatissimum* L.)] species; (5) small seeded [(e.g., berseem clover (*Trifolium alexandrinum* L.)) and large seeded (e.g., spring pea) crops; and (6) cool-season or early planted [e.g., Alsike clover (*Trifolium hybridum* L.)] and warm-season or late planted



Data used to generate the precipitation data were retrieved from https://mslservices.mt.gov/Geographic_Information/Data/DataList/datalist_MetadataDetail.aspx?did=%7bAFDC5103-EEAF-4D54-BFB2-1DFB1B532C4B%7d.

FIGURE 1. Locations of an annual forage study and 30-yr average precipitation totals (1980-2020) in Montana.

[black bean (*Phaseolus vulgaris* L.)] species. The four polycultures were planted when both the cool-season and warm-season crop monocultures were planted. Two of the broadleaf species planted in a monoculture, radish and turnip (*Brassica rapa* L. subsp. *rapa*), also were planted on early and late planting dates because of farmer interest in these crops. The crop treatments were planted with small-plot research seeders in rows spaced 15 to 30 cm apart in 5.6 to 9.3 m² plots, depending on the location. Two of the seeders were custom fabricated while others were purchased commercially from Fabro, Ltd. (Swift Current, SK, Canada) and Hege-Wintersteiger (United States office located in Salt Lake City, UT). Planting was done directly into a no-tillage seedbed at some locations and into a conventional-tillage seedbed at other locations. Further details regarding the locations and agronomic practices used to establish and manage the field experiments are provided in Table 2.

TABLE 1. Cool- and warm-season crop monocultures and polycultures and planting rates in six dryland environments across Montana during 2016.			
Crop	Scientific name	Cultivar	Planting rate ----- live seed m ² -----
Monocultures			
Cool-season treatments			
Alsike clover ^a	<i>Trifolium hybridum</i> L.	VNS ^b	1134
Canola	<i>Brassica napus</i> L.	DKL 30-42	200
Flax	<i>Linum usitatissimum</i> L.	Omega	650
Hairy vetch	<i>Vicia villosa</i> Roth	VNS ^b	121
Oat	<i>Avena sativa</i> L.	Otana	303
Radish	<i>Raphanus sativus</i> L.	Ground Hog	72
Safflower	<i>Carthamus tinctorius</i> L.	Baldy	79
Spring pea	<i>Pisum sativum</i> L. subsp. <i>sativum</i>	Arvika	67
Triticale	<i>x Triticosecale</i> Wittmack	VNS ^b	213
Turnip	<i>Brassica rapa</i> L. subsp. <i>rapa</i>	Purple Top	495
Warm-season treatments			
Berseem clover	<i>Trifolium alexandrinum</i> L.	VNS ^b	381
Black bean	<i>Phaseolus vulgaris</i> L.	Loreto	42
Chickpea	<i>Cicer arietinum</i> L.	Frontier	28
Fababean	<i>Vicia faba</i> L.	SSNS – 1	43
Foxtail millet	<i>Setaria italica</i> (L.) P. Beauv.	Golden German	778
Maize	<i>Zea mays</i> L.	Indian	8
Sorghum	<i>Sorghum bicolor</i> (L.) Moench	VNS ^b	594
Soybean	<i>Glycine max</i> L.	Sheyenne	26
Sunflower	<i>Helianthus annuus</i> L.	Peredovik	3
Teff	<i>Eragrostis tef</i>	VNS ^b	2072
Polycultures			
Cool-season mix			
Canola			33
Oat			50
Safflower			13
Spring pea			11
Radish			12
Turnip			83
4-species warm-season mix			
Chickpea			5
Fababean			7
Sorghum			99
Sunflower			1
Radish			12
Turnip			83
5-species warm-season mix			
Black bean			6
Fababean			6
Maize			1
Sorghum			86

Teff			301
Radish			11
Turnip			75
<i>8-species mix</i>			
Canola			22
Chickpea			3
Fababean			4
Oat			32
Safflower			11
Sorghum			65
Spring pea			11
Sunflower			<1
Radish			8
Turnip			54

^aLegume seed was inoculated immediately before planting with the appropriate bacterium for biological N₂ fixation.

^bVNS = variety not stated

Plots were arranged in a randomized complete block with crop treatments replicated four times at each of the six locations. Above-ground crop vegetative growth from a 0.3 to 9.3 m² area within each plot was clipped within 7 cm of the soil surface when grasses in small-grain monocultures and polycultures were near or at heading (e.g., triticale at Zadoks Growth Stages 49 to 59; Zadoks, Chang, and Konzak, 1974). Broadleaf crops were clipped near or at flowering (BBCH Growth stage 49 to 59; Lancashire et al., 1991) in plots not containing grasses, with one exception. At the Central Agricultural Research Center (CARC; Figure 1), plants in plots containing grasses were clipped only at the later stages of heading (Zadoks Growth Stage 56 to 59) or at the silk growth stage (R1) in maize plots (Ritchie, Hanway, & Benson, 1996), at 10% flowering (BBCH Growth stage 61) in plots only containing broadleaf crops, or on 13 July for treatments planted early, and 10 August if planted late and reproductive growth had not begun. A vegetative growth subsample was dried down until a constant weight and used to determine dry matter production on a kilogram per hectare basis. Forage quality (crude protein, acid-detergent and total digestible nutrient concentrations) were determined but are discussed elsewhere (Meccage et al., 2019).

TABLE 2. Selected soil and crop management background for annual forage field experiments at six locations in Montana during 2016.

	Location					
	CARC	EARC	NARC	NWARC	SARC	WARC
Latitude	47.0569°	47.1813 °	48°4948	48.1875	45°9166	46.3293
<u>Soil</u>						
texture	clay loam	clay loam	clay loam	silt loam	clay loam	sandy loam
Great group classification	Calciustolls	Argiustolls	Argiustolls	Haploborolls	Haplustalfs	Haplustolls
organic matter	g kg ⁻¹					
	40	20	15	52	19	11
nitrate (0 to 60 cm)	kg ha ⁻¹					
phosphorus	67	29	49	130	----	----
potassium	20	40	60	25	----	----
Fertilizer applied (N-P-K)	607	----	654	280	----	----
Previous crop	None	None	22-10-19	56-12-56	None	None
Preplant herbicide	winter wheat	spring wheat	canola	barley	barley	winter wheat
Tillage	glyphosate	glyphosate	glyphosate	glyphosate	glyphosate	glyphosate
Planting (early)	conventional-tillage	no-tillage	conventional tillage	no-tillage	no-tillage	conventional-tillage
Planting (late)	05 May	14 April	23 April	27 April	12 April	5 May
Harvest (early) ^a	26 May	19 June	4 May	23 June	15 June	13 June
Harvest (late) ^a	05 & 13 July	07 June	28 June	03 June	14 June	01 July
	22 July & 10 August	01 August	28 July	03 August	Not harvested	05 August

^aCereals were harvested when small-grain plants were at the early milk to soft dough kernel stages or around silking in maize. Plots were clipped between 7 and 21 d after plants flowered in broadleaf monoculture plots, or from late August through mid-September if flowering did not occur.

Study 2

Monocultures of 17 warm-season crop species were compared for forage DM yield at the CARC location in central Montana (Figure 1) during 2016, 2017 and 2018. These species included 10 grass and seven broadleaf crops evaluated under dryland management. Two cultivars of foxtail millet, and two cultivars of cowpea [*Vigna unguiculata* (L.) Walp.], were included as separate treatments. In addition, some of the warm-season species were grown in polycultures: two different binary mixtures and one, four-species mixture. Spring wheat and spring pea monocultures were included as cool-season checks in the study, along with a four-species, cool-season polyculture. The 21 crop monoculture and four crop polyculture treatments along with their seeding rates are listed in Table 3.

The study was established in one field during 2016 and 2018, and in two fields during 2017. In 2017, fields were 1.6 km apart and differed in soil nutrient status, previous crop, and other factors prior to field trial establishment (Table 4). Crop treatments were established in plots that were 4.6 by 7.6 m arranged in a randomized complete block with treatment blocks replicated four times. A custom-built, small-plot research seeder was used to plant kernels or seed in 30-cm rows except in maize and sunflower monoculture plots, and in maize + pinto bean polyculture plots, where a 76-cm row spacing was used. Spring-planted winter wheat alleys separated adjacent plots within each block and a 9-m, winter wheat alley separated adjacent blocks. Cool-season crop treatments were planted 40 d prior to planting warm-season treatments in 2016. Persistent and untimely precipitation delayed early seeding of cool-season crop treatments in 2017 and 2018, compressing the time between planting the cool- and warm-season crop treatments to < 10 days (Table 4).

TABLE 3. Cool- and warm-season crop monocultures and polycultures, cultivars, and planting rates in a dryland field study at the Central Agricultural Research Center in Montana.

Crop treatment	Scientific name	Cultivar	Planting rate seed m ⁻²
----- Monocultures -----			
Browntop millet	<i>Urochloa ramosa</i> (L.) Nguyen	VNS	1119
Buckwheat	<i>Fagopyrum esculentum</i> Moench	Koma	181
Cowpea ^a	<i>Vigna unguiculata</i> (L.) Walp.	Chinese Red	22
		Iron and Clay	22
Forage sorghum	<i>Sorghum bicolor</i> (L.) Moench	Canex	146
Foxtail millet	<i>Setaria italica</i> (L.) P. Beauv.	Golden German	807
		Manta	807
Grain Sorghum	<i>Sorghum bicolor</i> (L.) Moench	DK 28E	40
Maize	<i>Zea mays</i> L.	Hybrid ^b	4
Mung bean	<i>Vigna radiata</i> (L.) Wilcz.	OK 2000	36
Navy bean	<i>Phaseolus vulgaris</i> L.	Melvin	23
Pearl millet	<i>Pennisetum americanum</i> (L.) Leeke	VNS ^c	280
Pinto bean	<i>Phaseolus vulgaris</i> L.	Othello	18
Proso millet	<i>Panicum miliaceum</i> L.	Plateau	355
Sorghum x Sudangrass	<i>S. bicolor</i> X <i>S. sudanese</i>	Grazex BMR 801	187
Soybean	<i>Glycine max</i> L.	VNS ^c	39
Spring pea	<i>Pisum sativum</i> L. subsp. <i>sativum</i>	MONT 4152	81
Spring wheat	<i>Triticum aestivum</i>	Vida	247
Sudangrass	<i>Sorghum sudanese</i> (Piper) Stapf	Trudan 8	226
Sunflower	<i>Helianthus annuus</i> L.	NuSun – 3080	3
Teff	<i>Eragrostis tef</i>	VNS	3734
----- Polycultures -----			
<i>Binary mix 1</i>			
Maize		----- ^d	2
Pinto bean		----- ^d	9
<i>Binary mix 2</i>			
Proso millet		----- ^d	404
Pinto bean		----- ^d	9
<i>4-Species, cool-season polyculture</i>			
Barley	<i>Hordeum vulgare</i> L.	Hockett	62
Spring pea		----- ^d	20
Lentil	<i>Lens culinaris</i> Medik.	Richlea	35
Spring wheat			62
<i>4-Species, warm-season polyculture</i>			
Maize		----- ^d	1
Sorghum x Sudangrass		----- ^d	47
Pinto bean		----- ^d	9
Cowpea		Iron and Clay	5

^a Legume seed was inoculated immediately before planting with the appropriate bacterium for biological N₂ fixation.

^b Experimental hybrid

^c VNS = variety not stated

^d Cultivar was the same as that used in the monoculture

TABLE 4. Selected soil and crop management factors for annual forage field experiments comparing cool- and warm-season annual crops at four locations in central Montana during 2016 (SW1), 2017 (SW5 & NT1), and 2018 (SW2).

	Location			
	SW1	SW5	NT1	SW2
Soil Series	----- Danvers-Judith clay loams -----			
Soil Classification	----- Fine-loamy, carbonatic, frigid Typic Calciustolls-----			
Organic matter content (g kg ⁻¹)	40	41	36	43
pH	7.6	7.4	7.2	7.2
Nutrient concentration (kg ha ⁻¹)				
NO ₃ ⁻	67	17	22	18
P	20	38	25	20
K	607	598	650	--
Fertilizer applied	None	None	None	None
Previous crop	winter wheat	barley	spring pea	flax
Pre-plant herbicide treatment	----- glyphosate (4.1 kg a.e. ha ⁻¹) -----			
Seedbed	conventional-tillage	no-tillage	no-tillage	no-tillage
Planting date (cool-season)	21 April	18 May	20 May	21 May
Planting date (warm-season)	01 June	27 May	28 May	29 May
Harvest date (cool-season) ^a	01 through 05 July	-----28 July -----		23 through 30 July
Harvest date (warm-season) ^a	10 to 30 August	28 August to 03 September		31 July to 11 September

^aCereals were harvested when small-grain plants were at the early milk to soft dough kernel stages or around silking in maize. Plots were clipped between 7 and 21 d after plants flowered in broadleaf monoculture plots, or from late August through mid-September if flowering did not occur.

Above-ground crop vegetative growth from a 0.5-m² area within each plot was clipped within 7 cm of the soil surface when cereal crop plants were at the early milk to soft dough stages of kernel development (Zadoks growth stages 73 to 83) for small-grain species, or around the silk growth stage (R1) in maize plots. Plots were clipped between 7 and 21 d after the first flower opened (BBCH 60) in broadleaf monoculture plots, or in early September if flowering did not occur. Crop vegetative growth subsamples were dried until a constant weight and reported on a kilogram per hectare basis.

Statistical Analyses

Linear mixed-effects modeling was performed using R version 1.2.5001 (R Core Team, 2017) with the *lmer* function of the *lme4* package version 1.1-15 (Bates et al., 2013), which provides functions for fitting of linear and generalized linear mixed-effects models. Model parameter estimates were determined by restricted maximum likelihood. Differences in crop DM yield were assessed across locations and field-years in studies 1 and 2, respectively. In study 1, replicate was nested within location as a random effect, while in study 2 replicate was nested within field-year, also as a random effect. Crop treatment was designated as the sole fixed effect term and replicate was included as a second random effect term in both models. Crop DM yield in both models was log transformed to satisfy assumptions of normality and homogeneity of residuals in the analyses, but was back-transformed and reported on a Mg ha⁻¹ basis. To minimize noise caused by logistical and non-defined (e.g., pests) management issues, DM yields below 0.4 and 0.7 Mg ha⁻¹ were excluded from the raw datasets in studies 1 and 2, respectively. Within-crop DM yields adjusted for random effects terms (i.e., estimated marginal means or least-square means) were calculated using the *emmeans* function from the R package *emmeans* version 1.1.2 (Lenth, 2018) with the model parameters estimated with *lmer* described above.. Contrasts of selected forage DM means were performed using Scheffe adjustment for multiple comparisons in the contrast function of the *emmeans* package (Lenth, 2018).

RESULTS

Weather

Annual precipitation (September 2015 through August 2016) ranged from 244 to 484 mm (Figure 2), depending on the location (Figure 1). These amounts were greater than long-term averages at two locations, near the long-term average at one location, and less than the long-term average at three locations. Precipitation received during the growing season (April through August) ranged from 114 to 347 mm (data not presented), with the driest conditions at the Western Agricultural Research Center (WARC) in southwestern Montana (Figure 1). This location was irrigated (330 mm) to prevent abandonment of the field experiment because of persistent drought, particularly during April, June, and August when < 20 mm of precipitation was received. Field experiments were not irrigated at other locations.

Average annual temperature ranged from almost 13 to 17°C during the growing season (Figure 2) across locations (Figure 1). The warmest month was July at most locations, when the average temperature ranged from nearly 18°C at CARC in central Montana, to almost 22°C at the Southern Agricultural Research Center (SARC) in south central Montana. Coolest temperatures during the growing season occurred in April, ranging from almost 5.5°C at CARC to near 10°C at the Northwestern Agricultural Research Center (NWARC) and Western Agricultural Research Center (WARC), both in western Montana (Figure 1).

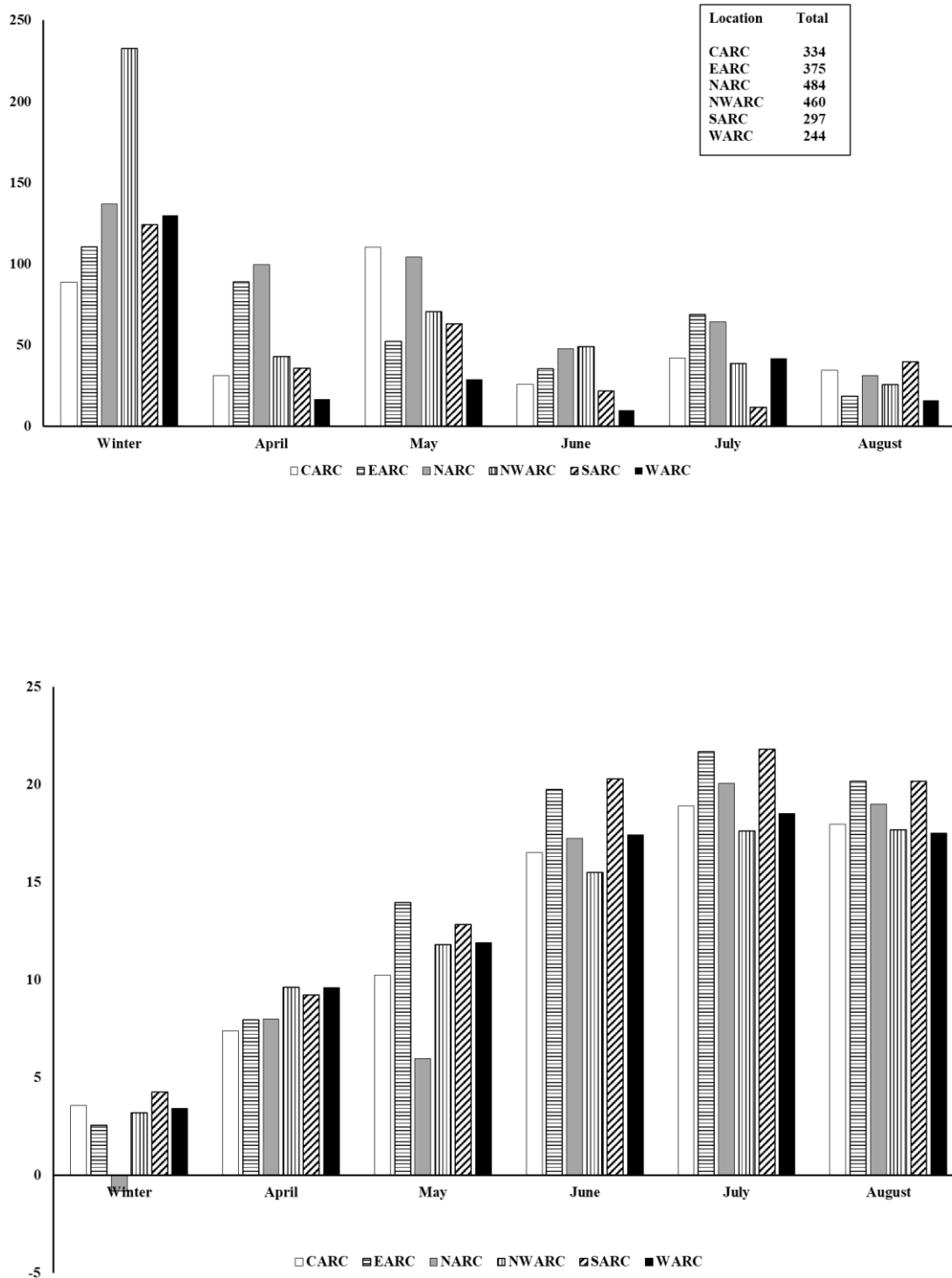


FIGURE 2. Precipitation (mm; top) and temperature (°C: bottom) for six locations in Montana.

Study 1

Forage yield by maize monoculture was equal to, or greater than, yields produced by other warm- or cool-season monoculture and polyculture crop treatments across the six locations in 2016. Dry Matter production by maize averaged 2.5 Mg ha⁻¹ (Figure 3). Sorghum (2.2 Mg ha⁻¹), ‘Golden German’ foxtail millet (1.9 Mg ha⁻¹), and sunflower (1.6 Mg ha⁻¹) were other warm-season crops treatments that produced relatively large amounts of forage DM in monoculture treatments. Two cool-season grasses, oat and triticale, produced comparable amounts of forage DM as maize, averaging 2.0 Mg ha⁻¹ and 1.7 Mg ha⁻¹. Overall, there was no forage DM advantage when comparing across cool-season grass species (oat and triticale) and warm-season grass species {foxtail millet, maize, sorghum, and teff [*Eragrostis tel (Zucc.) Trotter*]} (Table 5).

Collectively, warm-season grasses produced more forage DM than warm-season broadleaf monocultures in this study (Table 5). Forage DM averaged 2.0 Mg ha⁻¹ across the four warm-season grass monocultures (foxtail millet, maize, sorghum and teff) compared with 1.2 Mg ha⁻¹ across the six warm-season broadleaf monocultures [berseem clover (*Trifolium alexandrinum* L.), black bean, chickpea, faba bean (*Vicia faba* L.), soybean (*Glycine max* L.) and sunflower]. The cool-season broadleaf crop species [alsike clover, spring pea, canola, flax, radish, safflower, and turnip] also were relatively low yielding, producing an average of only 1.0 Mg ha⁻¹ of forage DM across the six locations (Figure 3).

No advantage existed in forage DM yield for polycultures compared to monocultures of several high yielding warm-season and cool-season crop species in this study, whether considered singly (Figure 3) or collectively (Table 5). Similarly, planting the cool-season polyculture in mid-April to mid-May (early) failed to affect DM production compared with delaying planting until late-May to mid-June (late) (Figure 3). However, the 4- and 5-species, warm-season polycultures

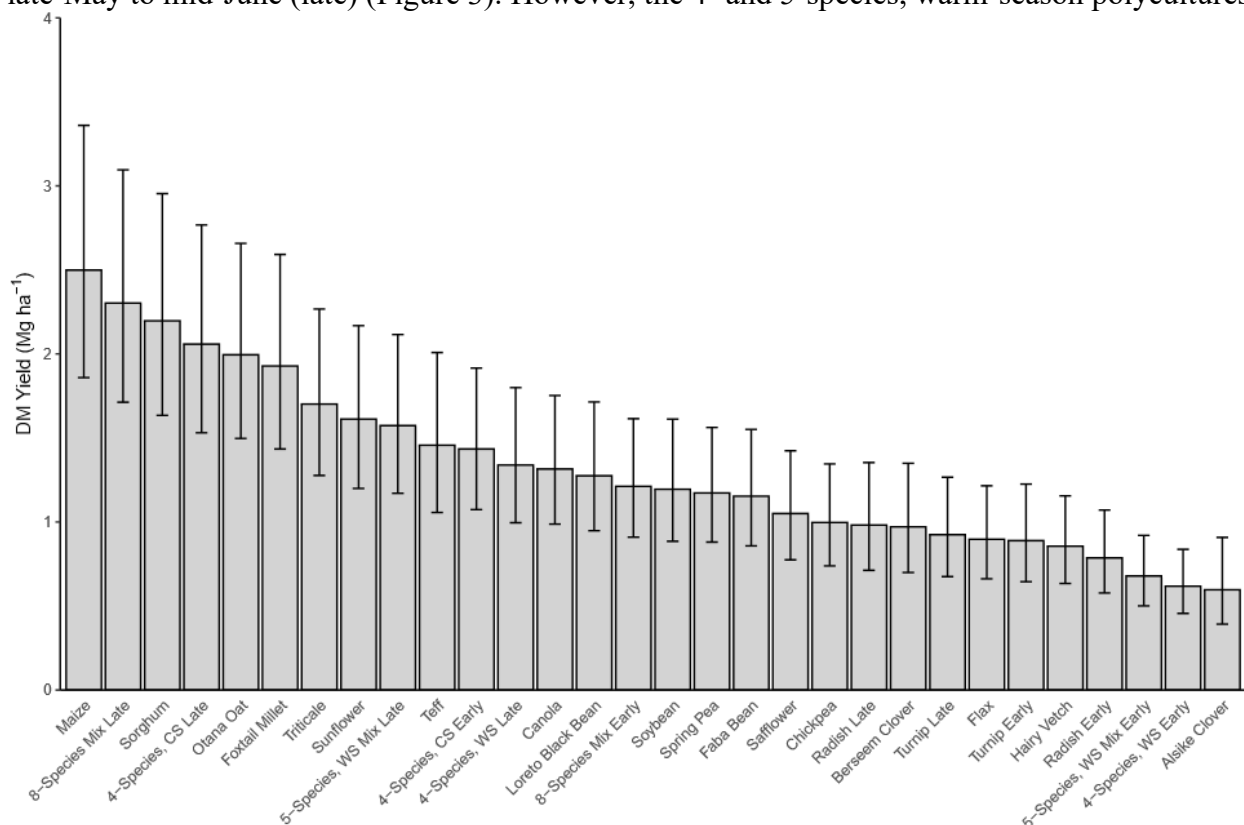


FIGURE 3. Mean forage yields and 95% confidence intervals for annual forage monocultures and polycultures across six locations in Montana during 2016.

both produced more forage DM when planted earlier than later (Figure 3). Likewise, more forage was produced by the 8-species polyculture when planted earlier than later (Figure 3; Table 5). These results suggest that there were forage yield advantages when warm-season species were planted by early May under the environmental conditions that occurred across the six locations in this study (Table 2).

Study 2

Maize monoculture produced more DM than other warm- or cool-season crop treatments across four environments, with the exception of sunflower. Forage DM production averaged 5.7 Mg ha⁻¹ for maize and 4.6 Mg ha⁻¹ for sunflower (Figure 4). When comparing warm-season crops, the maize + pinto bean (*P. vulgaris* L.) mixture produced comparable amounts of forage DM (3.4

TABLE 5. Selected contrasts of forage dry matter production by annual crop monocultures and polycultures at six locations across Montana during 2016.

Contrast	P-value
WSG ^a vs WSB ^b	.015
WSG vs CSG ^c	1.000
CSG vs. WSB	0.599
WSB vs. CSB ^d	0.988
WSG, WSB vs. warm-season, 4-species polyculture planted late ^e	1.000
WSG, WSB vs. warm-season, 5-species polyculture planted late ^f	1.000
WSG, WSB vs. 8-species polyculture planted late ^g	0.973
Polycultures planted early ^h vs. polycultures planted late	<0.001
WSG, WSB vs. cool-season, 4 species polyculture ⁱ	1.000
WSG vs. warm-season, 4-species polyculture planted late	0.999
WSB vs. warm-season, 4-species polyculture planted late	1.000
WSB vs. warm-season, 4-species polyculture	0.595
CSG, CSB vs. cool-season, 4-species polyculture	1.000
CSG, CSB vs. warm-season, 4-species polyculture	0.910

^aWSG = warm season grass species (foxtail millet, maize, sorghum, and teff)

^bWSB = warm season broadleaf species (berseem clover, black bean, chickpea, fababean, and sunflower)

^cCSG = cool season grass species (oat and triticale)

^dCSB = cool season broadleaf species (alsike clover, canola, flax, hairy vetch, radish, spring pea, and turnip)

^echickpea, fababean, sorghum and sunflower mixture (along with radish and turnip) planted in late May through mid-June (late), depending on the location

^fblackbean, fababean, maize, sorghum, and teff (along with radish and turnip) planted late, depending on the location

^gcanola, chickpea, fababean, oat, safflower, spring pea, sorghum, and sunflower (along with radish and turnip) planted late, depending on the location

^hearly planting ranged from late-April to mid-May, depending on the location

ⁱcanola, oat, safflower, and spring pea mixture (along with radish and safflower)

Mg ha⁻¹) to the amount produced by the sunflower monoculture, but less than the maize monoculture. Spring pea and spring wheat, the cool-season monoculture checks, produced less forage DM than the three warm-season treatments. Spring pea and spring wheat forage DM

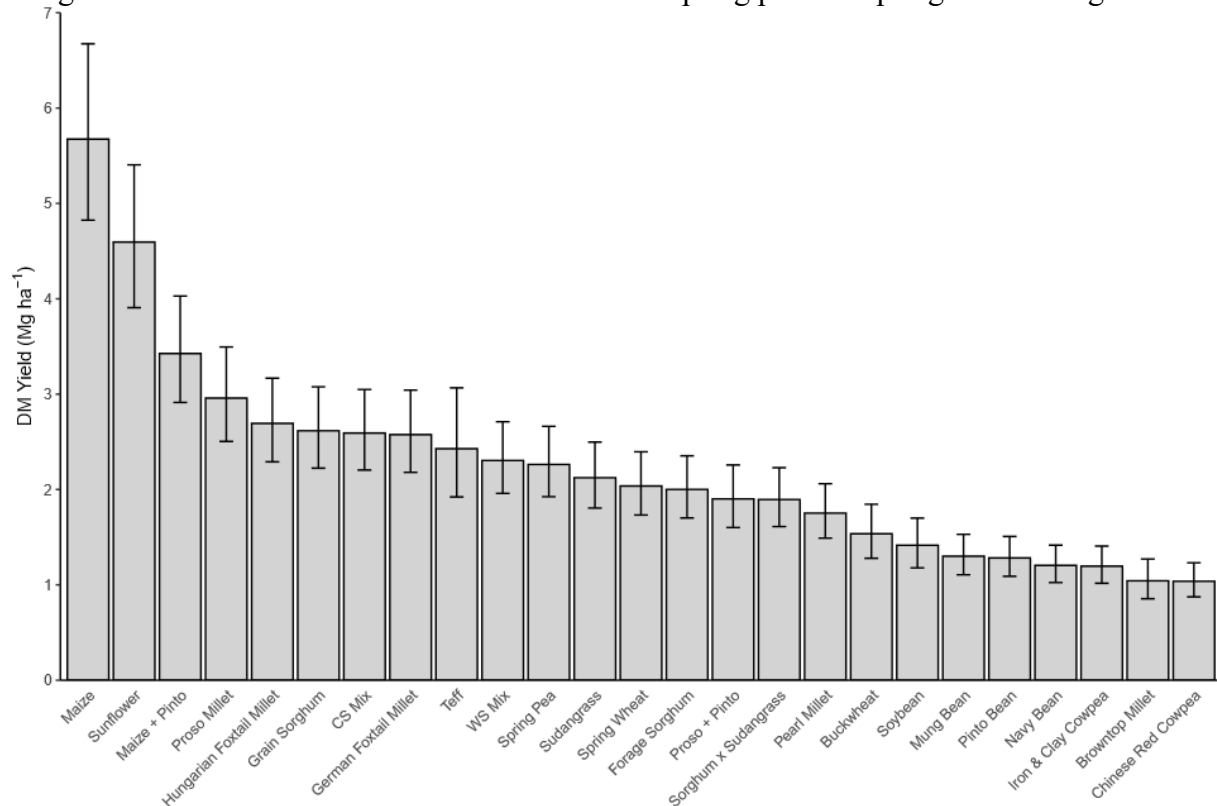


FIGURE 4. Mean forage yields and 95% confidence intervals for annual forage monocultures and polycultures in four central Montana environments from 2016 through 2018.

production averaged 2.3 Mg ha⁻¹ and 2.0 Mg ha⁻¹. Other warm-season monocultures produced comparable forage DM to both cool-season monoculture checks including forage sorghum (2.0 Mg ha⁻¹), German and Hungarian foxtail millet (2.7 and 2.6 Mg ha⁻¹), grain sorghum (2.6 Mg ha⁻¹), proso millet (3.0 Mg ha⁻¹), sudangrass (*Sorghum sudanese* (Piper) Stapf ; 2.1 Mg ha⁻¹), and teff (2.4 Mg ha⁻¹).

Warm-season grasses {browntop millet [*Urochloa ramosa* (L.) Nguyen], forage sorghum, foxtail millet, grain sorghum, maize, pearl millet [*Pennisetum americanum* (L.) Leeke], proso millet, sorghum × sudangrass, sudangrass, and teff} produced more forage DM as a group than the cool-season monoculture check (spring wheat) (Table 6), but that yield advantage was driven largely by the maize and proso millet monoculture treatments (Figure 4). For example, forage DM

TABLE 6. Selected contrasts of forage dry matter production by annual crop monocultures and polycultures at four locations across three years in central Montana.

Contrast	P-value
WSG ^a vs. CSG ^b	<0.001
WSG vs. WSB ^c	<0.001
CSG vs. WSB	0.933
WSB vs. CSB ^d	0.351
Mix1 ^e vs. Mix ^f	<0.001
WSG, WSB vs. Mix1, Mix 2, WSPOLY ^g	0.402
WSG, WSB vs. CSPOLY ^h	0.944
WSG vs. WSPOLY	<0.001
WSB vs. WSPOLY	0.247
Mix 1, Mix 2 vs. WSPOLY	1.000
CSG, CSB vs. CSPOLY	1.000
CSG, CSB vs. WSPOLY	1.000

^aWSG = warm season grass species (browntop millet, forage sorghum, foxtail millet, grain sorghum, maize, pearl millet, proso millet, sorghum X sudangrass, sudangrass, and teff)

^bCSG = cool season grass species (spring wheat)

^cWSB = warm season broadleaf species (buckwheat, cowpea, mung bean, navy bean, pinto bean, soybean, and sunflower)

^dCSB = spring pea

^eMix 1 = maize + pinto bean polyculture

^fMix 2 = proso millet + pinto bean polyculture

^gWSPOLY = maize + sorghum X sudangrass + pinto bean + cowpea polyculture

^hCSPOLY = barley + spring pea + lentil + spring wheat polyculture

production by browntop millet (1.0 Mg ha⁻¹) was among the lowest in the study. Still, average DM yield for warm-season grass monocultures (2.4 Mg ha⁻¹) was greater than for warm-season broadleaf crops {buckwheat (*Fagopyrum esculentum* Moench), soybean, mung bean [*Vigna radiata* (L.) Wilcz.], pinto bean, navy bean, and cowpea}, which averaged only 1.3 Mg ha⁻¹ (Figure 4 and Table 6). Also, three warm-season grass monocultures were among the top five crop treatments for DM forage yield (Figure 4).

Forage DM yield of the maize + pinto bean binary mix was relatively high, compared with proso millet + pinto bean mixture and other treatments in this study (Figure 4), likely driven by the maize component in the mixture. Overall, polycultures failed to produce more forage DM than warm-season grass and broadleaf monocultures (Table 6). Similarly, there was no advantage when growing the 4-species, warm-season polyculture compared to the warm-season binary mixtures. Forage DM yields were similar between the 4-species, cool-season polyculture (2.6 Mg ha⁻¹) and the 4-species, warm-season polyculture (2.3 Mg ha⁻¹) (Figure 4).

DISCUSSION

Cool-season, small-grain crops (e.g., barley and oat) are popular annual forages in the USNGP, as mentioned previously (Meccage et al., 2019). Warm-season annuals also are grown for dryland forage, but not to the extent of cool-season species. Two studies were conducted across 10 environments demonstrating that there are several warm-season annual grasses capable of producing as much forage and, in some instances, more DM than cool-season annual species in these environments. Specifically, maize produced the highest mean forage yield in both studies. Several millet and sorghum species also were among the top-ranked forage producers. These results suggest that warm-season cereal crops can be utilized as dryland annual forages in the USNGP and other semi-arid regions at upper latitudes. Future research should explore management strategies that optimize DM production by warm-season annual grasses when grown in cool dryland regions.

Collectively, warm-season grasses produced more forage DM than warm-season broadleaf crops in both studies. However, there were exceptions to this general trend. For example, sunflower monoculture was ranked relatively high in forage yield among crop treatments. This suggests other warm-season, annual broadleaf crops [e.g., sunn hemp (*Crotalaria juncea* L.) and annual lespedeza (*Kummerowia* spp.)], that were not considered in either study, might be suitable if grown for forage in the USNGP, particularly due to rising temperatures attributed to climate change (Wolf van Diepen, 1994). Additional research is needed to determine the potential of warm-season, annual broadleaf species as forage crops in semi-arid regions at upper latitudes.

Dry matter quality (e.g., crude protein concentration and digestibility) is important in determining the potential of crops grown for forage. Dry matter production was the focus of both studies discussed in this paper. Forage quality was determined in Study 1 (Meccage et al., 2019) but not in Study 2. Previous research on annual forages in the USNGP did include quality data (Carr et al., 1998; Chen, Westcott, Neill, Wichman, & Knox. 2004; Lenssen et al., 2010, 2015; Miller et al., 2018), but these studies were limited to cool-season species (Carr et al., 1998; Chen et al., 2004; Lenssen et al., 2015; Miller et al., 2018) or included a single warm-season species in comparisons (Lenssen et al., 2010). Moreover, these studies did not consider anti-nutritional factors, even though high nitrate and prussic acid concentrations are a concern when growing warm-season, annual forages in dryland regions (Meccage et al., 2019). Future research is needed which includes nutritional and anti-nutritional factor analyses of the forage produced by warm- and cool-season annual crops.

Several cool- and warm-season crop monocultures produced as much forage DM as polycultures in both studies discussed in this manuscript. This is consistent with previous research that failed to identify forage DM advantages when comparing polycultures to monocultures in the USNGP (Carr et al., 1998; Sanderson, Johnson, & Hendrickson, 2018), adjacent regions in Canada (Izaurrealde et al., 1990), and the U.S. central Great Plains (Nielsen, Lyon, Hergert, Higgins, & Holman, 2015), in spite of non-research-based claims to the contrary, as cited in Nielsen et al. (2015). Research is needed to determine if soil quality improvements, crop quality enhancements, or other ecosystem services are provided when forage crop polycultures are compared to monocultures. However, there is a growing body of evidence which questions non-scientific claims that annual crop polycultures enhance forage yield compared with high-yielding annual crop monocultures in the Great Plains region of North America and similar dryland environments.

There is an effort to intensify and diversify dryland wheat farming in the USNGP. These twin goals might be met if warm-season, annual crops can be incorporated into wheat-based cropping systems successfully. While grain yield was depressed when wheat was grown following

a warm-season, annual forage crop in previous research (Lenssen et al., 2010), this work was limited to a single warm-season, annual species (foxtail millet). Future research is needed which compares the impact of additional warm-season grass and broadleaf crops grown for forage on wheat yield in 2-yr and more diverse rotations. This research should focus on soil water use by the warm-season forages prior to planting winter as well as spring wheat.

There is a quadratic relationship between crop maturity and forage yield (Khorasani, Jedel, Helm, & Kennelly, 1997). Previous research indicated optimum forage yield and quality resulted when delaying harvest of cool-season, small-grain crops until plants reached late-milk to early soft dough stages of development (Cherney & Martin, 1982; Smith, 1960). Similarly, forage production increased when harvest occurred at pod development in lentil and pea rather than earlier, at flowering (Miller et al., 2018; Pikul, Aase, & Cochran, 1997). Less soil water was available to wheat following annual, cool-season forage crops compared with fallow in some studies (Lenssen et al., 2010), but not in others (Miller et al., 2006; Pikul et al., 1997). The importance of harvest timing is critical when growing warm-season, annual crops for forage in dryland wheat systems, since harvesting earlier provides more time for soil-water recharge before planting a subsequent crop. Work is needed to determine the optimum time for forage harvest of both cool- and warm-season, annual crops while providing a window for soil-water recharge in a forage-wheat sequence in dryland environments.

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- FIGURE 1.** Locations of an annual forage study and 30-yr average precipitation totals (1980-2020) in Montana.
- FIGURE 2.** Precipitation (mm; top) and temperature (°C: bottom) data for six locations in Montana.
- FIGURE 3.** Mean forage yields and 95% confidence intervals for annual crop monocultures and polycultures across six locations in Montana during 2016.
- FIGURE 4.** Mean forage yields and 95% confidence intervals for annual crop monocultures and polycultures in four central Montana environments during 2016 through 2018.