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Adaptation and forage productivity of cool-season grasses in the central USA

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Abstract

Cool-season grass species (18) and cultivars (85) were evaluated for use in seeded grasslands in the tallgrass prairie and shortgrass steppe ecoregions of the central United States at the test locations of Ithaca and Sidney, NE, respectively. Both native and introduced grasses were evaluated in sward trails. Significant differences existed among species and cultivars for all traits evaluated except for in vitro dry matter digestibility (IVDMD) among cultivars within species at Sidney. The grasses that had the best establishment, persistence, and forage yields in the Ithaca trial were introduced wheatgrass (*Thinopyrum*) and bromegrass (*Bromus*) species. At the Sidney location, the best species using the same criteria were wheatgrasses (*Thinopyrum*, *Agropryon*, *Pascopyrum*, and *Elymus* spp.) and wildryes (*Psathyrostachys*). The only native grasses that were marginally competitive with the introduced grasses were western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Löve] and thickspike wheatgrass [*Elymus macrourus* (Turcz.) Tzvelev] at the Sidney location and western wheatgrass at Ithaca. The study was the largest cool-season forage grass multispecies and cultivar sward evaluation to date in these two major land areas. The superior species and cultivars that were identified represent the best cool-season grasses available for restoring marginal croplands to grazed grasslands in these two major land areas.

1 | INTRODUCTION

Millions of hectares of grasslands have been converted to cropland throughout the central and northern Great Plains in the past two decades (Baker et al., 2020; Wright & Wimberly, 2013). This conversion of both native and planted grasslands occurred because of high grain commodity prices as a result of mandated government efforts to increase the production of biofuels (Lark et al., 2015; Wright et al., 2017). As a result, grain crops like maize (*Zea mays* L.) have been used for ethanol production and oilseed crops like soybeans [*Glycine max* (L.) Merr.] have been used for biodiesel production. Much of this grassland conversion occurred on land that was in seeded grasslands in expiring Conservation Reserve Program contracts, pasture, or rangeland. Landowners believed they could make greater profits from grain crops on these lands than using them for livestock production systems. Fluctuation in grain commodity prices poses a risk to farmers. Currently, profits on the marginal lands taken out of grasslands and converted to cropland are lacking or limited.

There was and continues to be an effort to produce biofuels from grasses such as switchgrass (*Panicum virgatum* L.). Although significant research progress has been made on the production of biomass grasses (Langholtz et al., 2016), the biorefinery processes to convert biomass into liquid fuels still have some deficiencies, but technological progress is being made (Cantero et al., 2019). To date, commercial scale biorefineries using grass biomass as a primary feedstock are not in production. Currently, if marginal cropland is to be converted back to grasslands, its primary agricultural use will

Abbreviation: CP, crude protein; IVDMD, in vitro dry matter digestibility be for livestock production on grazed grasslands. Regardless of use, a long-term potential benefit of returning perennial grasses to marginally productive cropland is increased soil carbon sequestration and improved soil health.

The focus and purpose of this study was to evaluate cool-season grass species, cultivars, and experimental strains for the use in grazed grasslands in two major ecological regions of the central United States. In these regions, cool-season grasses (C_3 photosynthesis system) are primarily used for spring, autumn, and early winter grazing, whereas warm-season (C_4) grasses are used during summer. Species and cultivars that were not previously tested in sward trials in these regions were compared with grasses previously used in the central United States. Two field test sites representative of the east–west climatic gradient of the regions were used in the study. The Ithaca site is in the Prairie Parkland Temperate ecoregion, which is also known as the tallgrass prairie region, whereas the Sidney site is in the Great Plains Palouse Dry Steppe or the shortgrass steppe region (Bailey, 1995; Stubbendieck et al., 2017). The primary crops in the ecoregion represented by Ithaca are maize and soybeans, whereas the primary grain crop in the ecoregion of Sidney is winter wheat (*Triticum aestivum* L.). Many of the cultivars and experimental strains that were evaluated were developed by the USDA-ARS grass breeding programs at Lincoln, NE; Mandan, ND; and Logan, UT. The traits evaluated were establishment, persistence, forage yield, and forage nutritive value as measured by in vitro dry matter digestibility (IVDMD) and crude protein (CP) concentrations of harvested forage. Initial stand data from the two sites used in this study were reported in a multiple location report that included many other locations (Robins et al., 2013), but forage yield and quality, weed infestations, and disease incidence were not reported in that study. Robins et al. (2020) reported on the productivity and resilience of cool-season grasses across multiple locations that included Ithaca and Sidney, NE. Their report lacked the cultivar-specific detailed evaluation for these ecoregions, did not report on any forage quality data, and included fewer species and experimental strains than reported in the current study.

Core Ideas

- Grasses used in seeded grasslands in the central United States need several essential traits.
- Essential traits are establishment, persistence, forage yield, and quality.
- Grasses from similar ecoregions of Eurasia were superior to native species for these traits.
- The best species and cultivars differed between the two tested ecoregions.

2 | MATERIALS AND METHODS

Released cultivars and experimental strains of 18 different species were evaluated in trials planted at two locations in Nebraska (Table 1). All plots were planted using a seeding rate of 430 pure live seeds (PLS) m^{-2}. The eastern trial was conducted at the University of Nebraska's Eastern Nebraska Research and Extension Center (ENREC) near Ithaca, NE (41.22° N, 96.48° W; elevation 364 m). The soil was a Sharpsburg silt loam (fine, montmorillonitic, mesic Typic Argiudolls). The other site was located at the University of Nebraska High Plains Agricultural Laboratory at Sidney, NE (41.38° N, 103.00° W; elevation 1,310 m) and the soil was a Duroc loam (fine-silty, mixed, superactive, mesic, Pachic Haplustolls). The Ithaca trial was planted on 21 and 22 Sept. 1999, and the Sidney trial was planted on 27 Sept. 1999. All trials were planted into clean, tilled seedbeds. Seeded plots were 4.5 m in length and 1.5 m wide and were separated on the ends by a 1.5-m-wide alley seeded to either tall fescue (*Festuca arundinacea* Schreb., Ithaca) or crested wheatgrass [*Agropyron* cristatum (L) Gaertner, Sidney]. The plot planter had seven double disk openers spaced 0.15 m apart. The field experimental design was a randomized complete block with four replicates.

No herbicide or fertilizer was applied the establishment year (1999). Excellent stands were obtained at Ithaca and the trial was harvested in 2000. Good stands were obtained for most plots at Sidney, but harvests were delayed at Sidney until 2001 to enable stands of some plots to improve. Stand frequency measurements were taken in the spring of the first harvest year or after the first harvest using a frequency grid (Vogel & Masters, 2001) and in 2003. Multiplying frequency grid stand percentages by 0.4 gives a conservative estimate of plants per square meter. Disease, lodging, and weed estimates were taken prior to harvest by K. Vogel. Disease percentages are the estimated percentage of the plant tissue in a plot that was infested with a foliar disease. Weed percentage was visually estimated as the percentage of the total harvested biomass that was from a non-seeded species.

At Ithaca, NE, the plots were fertilized in late April or early May with NH_4NO_3 each postestablishment year at a rate of 112 kg N ha^{-1}. At Sidney, a single application of NH_4NO_3 at a rate of 130 kg N ha^{-1} was made in May 2001. Herbicides were used for weed control the first postestablishment year (2000) at Ithaca and Sidney. At Sidney 1.1 kg a.i. ha^{-1} of 2,4-D [(2,4-dichlorophenoxy) acetic acid] low volatile ester was applied in spring while at Ithaca 1.1 kg a.i. ha^{-1} of metalchlor [Dual; 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide] was applied in spring for annual warm-season grass weed

TABLE 1 Cool-season grass species evaluated at Ithaca and Sidney, NE, for establishment, persistence, forage yield and nutritive value

Species Latin binomial	Common name	Native/introduced
Leymus angustus (Trin.) Pilger	Altai wildrye	Introduced
Pseudoroegneria spicata (Pursh) A. Löve	Bluebunch wheatgrass	Native
Leymus cinereus (Scribn. & Merr.) A. Löve	Basin wildrye	Native
Bromus spp. *Bromus inermis* Leyss*Bromus riparius* Rehm.	Smooth bromegrassMeadow bromegrass	Introduced
Agropyron spp. *A.* cristatum (L) Gaertner *A. desertorum* (Fischer ex. Link) Schultes *A. fragile* (Rothe) P. Candargy]	Crested wheatgrass	Introduced
Elymus canadensis L.	Canada wildrye	Native
Thinopyrum intermedium (Host) Barkworth & D.R. Dewey	Intermediate wheatgrass	Introduced
Interspecific hybrid[a]	R-S hybrid	Introduced x native
Psathyrostachys juncea (Fisch.) Nevski	Russian wildrye	Introduced
Elymus wawawaiensis J. Carlson & Barkworth	Snake River wheatgrass	Native
Elymus macrourus (Turcz.) Tzvelev	Thickspike wheatgrass	Native
Thinopyrum ponticum (Podp.) Z.-W. Liu & R.-C. Wang	Tall wheatgrass	Introduced
Achnatherum robustum (Vasey) Barkworth	Robust needlegrass	Native
Elymus submuticus (Hook.) Smyth & Smyth	Virginia wildrye	Native
Pascopyrum smithii (Rydb.) A. Löve	Western wheatgrass	Native

[a]*Elytriga repens* var. *repens* (L.) Desv. Ex B.D. Jackson × *Pseudoroegneria spicata* (Pursh).

control and in late July 2.2 kg a.i. ha^{-1} metolachlor and triasulfuron {Amber; 3-(6-methoxy-4-methyl-1,3,5-trazin-2-yl)−1-[2-chloroethoxy)-phenysulfonyl]-urea (25 g a.i. ha^{-1})} was applied for control of fall germinating annual grasses and broadleaf weeds.

At Ithaca, plots were harvested the first or second week of July after all grasses were fully headed (Stage R3; Moore et al., 1991), which varied with year. There was a wide range in maturity among the species. Early-flowering species were at the seed ripe stage of maturity when the latest maturing species were heading. For this reason, forage quality comparisons should be made only among species with similar heading dates. Regrowth harvests were made at Ithaca, NE, in 2001 and 2002 in mid-November after the end of the growing season. Regrowth harvests were not made in 2000 and 2003 because of insufficient regrowth to warrant a harvest. Lack of rainfall was the primary factor limiting regrowth. If regrowth was not harvested, the accumulated growth was removed the following spring by mowing. All harvests at Sidney were made in early August after plants were fully headed (2001 and 2003) or in mid-October in 2002 after the end of the growing season (2002). The harvest was delayed in 2002 due to the effects of drought (Table 2). There was insufficient regrowth at Sidney to warrant harvesting during the years of this trial.

Prior to harvest, plots were cut to a uniform plot length of 3 m. A flail type forage harvester (Carter Manufacturing) was used to harvest a 0.91-m-wide swath lengthwise down the center of each plot (harvested area was 3 m × 0.91 m or 2.7 m^2) using a 10-cm cutting height. Subsamples were collected by sampling tillers throughout each plot with hand sickles using the same cutting height prior to harvest. Collected samples were dried in a forced-air oven at 50 ˚C to a constant weight, and dry weight was determined. Plot yields were adjusted to a dry weight basis and included sample weights.

Dried samples were ground to pass a 2-mm screen in a Wiley mill and a 1-mm screen in a cyclone mill and scanned on a near-infrared reflectance spectrophotometer (NIRS; Model 6500). Calibration samples to develop NIRS prediction equations were chosen by cluster analysis of the reflectance data (Shenk & Westerhaus, 1991). Calibration samples were analyzed in triplicate for IVDMD with the ANKOM Rumen Fermenter (ANKOM Technology Corporation) using the procedures described by Vogel et al. (1999). Nitrogen (N) concentration was determined by the LECO combustion method (Model FP 428 and FP 2000, LECO Corporation) (Bremner, 1996; Watson & Isaac, 1990). Laboratory means were used to develop NIRS prediction by partial least squares (Shenk & Westerhaus, 1991). These prediction equations were used to predict IVDMD and N of all samples for both locations. Crude protein concentration was calculated as grams of N per kilogram x 6.25.

Analysis of variance (ANOVA) was conducted by location for individual years and for plot means averaged over years using SAS (SAS Institute, 1999) software. The main effects in the ANOVA were replicates (r), species (s), r × s, cultivars

TABLE 2 Monthly precipitation at Ithaca and Sidney, NE, during the period 1999–2003

Site	Year	Monthly precipitation Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
		mm												
Ithaca	1999	8	21	33	142	156	129	72	92	81	0	25	17	777
	2000	2	20	41	58	58	143	97	30	20	54	45	19	587
	2001	29	32	26	55	225	46	22	64	74	61	56	6	695
	2002	9	17	22	84	84	13	64	210	34	103	7	0	646
	2003	11	25	19	73	131	103	24	43	91	44	72	15	651
	30-yr mean	13	14	47	69	101	99	82	89	74	53	39	16	696
Sidney	1999	2	3	11	101	60	85	39	97	51	0	7	6	460
	2000	13	9	59	54	49	29	22	14	46	37	12	1	347
	2001	13	13	13	85	102	38	99	66	71	24	23	0	548
	2002	2	1	12	8	25	30	20	134	5	29	4	0	270
	2003	1	14	65	55	57	34	29	50	24	6	14	9	356
	30-yr mean	7	9	26	38	73	66	56	51	32	21	14	5	400

Note. Data from National Climate Center.

(s) [cultivars nested within species], and error. Cultivars and species were fixed effects. The r × s mean square was used as the error term for species, and the error term for cultivars (s) was the error mean square. Stands are reported for the initial year of harvest and for the last year of harvest. Average mean forage yield over years is the most important forage yield trait for perennial grasses. For this reason, forage yields and nutritive value are reported as means averaged over years.

3 | RESULTS AND DISCUSSION

The plots at both locations were planted the latter third of September 1999. Both locations received no measurable precipitation in October 1999 (Table 2), which slowed establishment. Because of adequate later precipitation, the Ithaca plots were well established by the late spring of 2000, and forage yields were harvested from those plots in the summer of 2000. At Sidney, which receives less annual precipitation and has a shorter grower season because of its elevation compared with Ithaca, it was necessary to delay harvests until 2001 to allow the plots to become better established before harvests were initiated. The annual precipitation at Ithaca was below the 30-yr average only for 2000 (Table 2). There was severe drought at Sidney for most of 2002 except for the month of August.

3.1 | Species comparisons

Establishment capability and persistence under management are essential traits of forage grasses. Both can be measured using a frequency grid (Vogel & Masters, 2001). Frequency grid stand percentages of 50% or greater (20 plants m^2) are considered fully successful, stands 25–50% are considered marginal to adequate, whereas stands <25% are considered unsuccessful in the Great Plains (Vogel & Masters, 2001). The initial stand percentages for all grass species was >90% for all species at Ithaca in 2000 except for Snake River wheatgrass (*Elymus wawawaiensis* J. Carlson & Barkworth), which had a species mean stand percentage of 82% (Table 3). All grass species had fully successful initial stands at Ithaca. At Sidney, the only grass species that had first harvest year (2001) stands >85% were intermediate [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey], tall [*Thinopyrum ponticum* (Podp.) Z.-W. Liu & R.-C. Wang], and western wheatgrass[*Pascopyrum smithii* (Rydb.) A. Löve] (Table 4). Basin wildrye [*Leymus* cinereus (Scribn. & Merr.) A. Löve], robust needlegrass [*Achnatherum robustum* (Vasey) Barkworth], and Snake River wheatgrass had marginal initial stands of <50% at Sidney, whereas the remaining species had stands >50% and were considered fully successful stands.

By 2003, there were highly significant changes in the stands of species at both locations. At Ithaca, the bromegrasses, intermediate, tall, and western wheatgrasses, R-S hybrid[a cross between *Elytriga repens* var. *repens* (L.) Desv. Ex B.D. Jackson × *Pseudoroegneria spicata* (Pursh); Jensen et al., 2003), and Russian wildryes [*Psathyrostachys juncea* (Fisch.) Nevski] all had stands >90% (Table 3). The crested wheatgrasses except for the cultivars Douglas and experimental strain Pub Siberian also had excellent stands (Table 5). By 2003, stands of bluebunch [*Pseudoroegneria spicata* (Pursh) A. Löve], Snake River, and thickspike wheatgrasses [*Elymus macrourus* (Turcz.) Tzvelev], robust needlegrass, and Virginia wildrye [*Elymus* submuticus (Hook.) Smyth & Smyth] were below acceptable levels and the forage harvested from their plots was primarily weeds (Table 4). Altai wildrye [*Leymus angustus* (Trin.) Pilger] stands were marginal and the harvested biomass was mostly weeds. Bluebunch wheatgrass and thickspike wheatgrass are native to the intermountain and

TABLE 3 Means for forage yield, forage nutritive value as measured by in vitro dry matter digestibility (IVDMD) and crude protein (CP), stand percentages, disease ratings, and plot weeds percentages for the species evaluated in the cool-season grass evaluation trial conducted near Ithaca, NE, during the period 1999–2003

	Harvest 1			Harvest 2			2000	2003	2003	2001	2002
Species	Yield	IVDMD	CP	Yield	IVDMD	CP	Stand	Stand	Weeds	Disease	Disease
	Mg ha^{-1}	—g kg^{-1}—		Mg ha^{-1}	—g kg^{-1}—		%				
Altai wildrye	5.58	685	133	1.06	727	99	94	38	61	20	11
Bluebunch wheatgrass	2.69	593	107	0.90	766	136	93	13	88	21	>90
Basin wildrye	5.10	665	116	0.61	745	139	94	42	58	38	15
Bromegrasses	6.96	671	100	0.49	709	92	100	100	0	17	10
Crested wheatgrasses	7.05	605	89	0.49	730	109	97	88	12	27	15
Canada wildrye	9.62	618	87	0.41	753	97	98	74	25	15	22
Intermediate wheatgrass	9.35	652	93	0.93	748	92	100	100	0	21	9
R-S hybrid[a]	7.07	652	105	0.64	733	97	99	99	0	11	8
Russian wildrye	4.09	712	132	0.91	738	92	97	97	3	26	13
Snake River wheatgrass	4.26	557	88	0.85	746	151	82	20	80	22	26
Thickspike wheatgrass	3.92	594	99	0.62	728	129	93	20	80	34	16
Tall wheatgrass	9.95	645	85	1.06	784	89	99	100	0	14	12
Robust needlegrass	5.81	583	115	1.04	562	76	95	13	87	5	0
Virginia wildrye	6.76	646	106	0.58	709	103	98	8	88	48	70
Western wheatgrass	7.36	634	101	0.89	680	105	100	98	4	36	11
F test	**	**	**	**	**	**	**	**	**	**	**
SE	0.23	5	29	0.14	10	6	5	9	9	3	5
LSD .05	0.66	16	83	0.41	28	18	14	25	25	10	13

Notes. Harvest 1 means are multiple year averages for 2001, 2002, and 2003; Harvest 2 means are averages for 2001 and 2002. Grass stand percentages determined by frequency grid (Vogel & Masters, 2001). Disease (%) is the percentage of plant tissue that was visibly infested with disease before harvest. Bromegrasses include both smooth bromegrass and meadow bromegrass. Crested wheatgrasses include crested wheatgrass, Siberian wheatgrass, and desert wheatgrass.

[a]*Elytriga repens* var. *repens* (L.) Desv. Ex B.D. Jackson × *Pseudoroegneria spicata* (Pursh).

**Significant at the .01 probability level.

northern Great Plains of the United States, whereas Snake River wheatgrass is native to the northwestern United States (USDA-NRCS, 2020). As demonstrated by these results, these grass species do not have the persistence necessary to be used in the tallgrass prairie ecoregion of the central United States for in forage production systems. Based on our observations, we believe that the stand loss of these species was due to crown and root diseases. Virginia wildrye is native to the ecoregion but was a short-lived perennial in this study.

In 2003 at Sidney, the grass species that still had fully successful stands were intermediate, crested, western, tall, thickspike, and bluebunch wheatgrass, the bromegrasses, and Russian wildryes (Table 4). Basin wildrye, Canada wildrye (*Elymus canadensis* L.), Virginia wildrye, robust needlegrass, and Snake River wheatgrass had unacceptable to poor stands. Altai wildrye had marginal stands. We believe the stand losses at Sidney were primarily due to drought conditions that existed from December 2001 through January 2003 (Table 2). At Sidney in 2003, the only species with stands >90% was intermediate wheatgrass. Species with stands >70% were the bromegrasses, tall and western wheatgrass, R-S hybrid, and Russian wildrye. The crested wheatgrasses had stands >60%.

There was weed invasions in plots where the seeded species failed to persist (Tables 3 and 4). The plots with the poorest stands in 2003 had the most weeds. At Ithaca and Sidney in 2003, the main weed in plots with poor stands were annual *Bromus* species. At Ithaca, some of plots with poor stands were also invaded by perennial grasses invading from adjacent plots.

Forage production and nutritive value are essential traits for grasses used in livestock production systems. The grass species that had the greatest three year mean forage yields at the Ithaca site were the grasses that maintained the best stands over the three harvest years with the exception of Russian wildrye (Table 3). These were intermediate, tall, and western wheatgrass, the bromegrasses that included both smooth (Bromus inermis Leyss) and meadow bromegrasses (*Bromus riparius* Rehm.), and the R-S hybrids. Although they maintained good stands at Ithaca, the Russian wildryes had significantly lower yields than the other grasses that maintained good stands at Ithaca. Canada wildrye had high mean forage yields at Ithaca, but >25% of its yield was estimated to be weeds and its stands had significantly diminished over the production years. The forage production results were similar for

TABLE 4 Means for forage yield, forage nutritive value as measured by in vitro dry matter digestibility (IVDMD) and crude protein (CP), stand percentages, and plot weeds percentages for the species evaluated in the cool-season grass evaluation trial conducted near Sidney, NE, during the period 1999–2003

Species	Harvest 1 Yield	Harvest 1 IVDMD	Harvest 1 CP	2001 Stand	2003 Stand	2001 Weeds	2003 Weeds
	Mg ha^{-1}	g kg^{-1}		%			
Altai wildrye	1.78	723	124	64	44	35	34
Bluebunch wheatgrass	2.00	673	101	75	55	23	33
Basin wildrye	1.61	692	101	39	31	41	54
Bromegrass	2.42	704	123	74	70	9	14
Crested wheatgrass	2.41	695	115	61	65	23	12
Canada wildrye	2.78	735	137	72	29	17	67
Intermediate wheatgrass	3.34	722	110	94	93	1	2
R-S hybrid[a]	2.77	688	110	76	73	9	8
Russian wildrye	3.32	672	104	72	77	14	3
Snake River wheatgrass	1.82	672	110	49	42	47	46
Thickspike wheatgrass	2.60	652	84	75	66	25	22
Tall wheatgrass	2.71	715	113	91	73	1	17
Robust needlegrass	0.44	704	130	34	21	71	60
Virginia wildrye	2.79	707	117	72	9	18	75
Western wheatgrass	2.56	706	116	89	88	10	12
F test (species)	**	**	**	**	**	**	**
SE	0.30	12	11	13	13	13	14
LSD .05	0.86	35	32	37	37	36	39

Notes. Harvest 1 Means are multiple year averages for 2001, 2002, and 2003. Grass stand percentages determined by frequency grid (Vogel & Masters, 2001). Weeds percentage is the visual estimated of the total harvested biomass that was from nonseeded species. Bromegrasses include both smooth bromegrass and meadow bromegrass. Crested wheatgrasses include crested wheatgrass, Siberian wheatgrass, and desert wheatgrass.

[a]*Elytriga repens* var. *repens* (L.) Desv. Ex B.D. Jackson × *Pseudoroegneria spicata* (Pursh).

**Significant at the .01 probability level.

Sidney. The grasses with the best 2-yr forage mean yields were intermediate, crested, western, and thickspike wheatgrasses, the R-S hybrid, and Russian wildryes (Table 4). The yields at Sidney were ~50% of those at Ithaca due to annual precipitation differences.

Forage nutritive value or forage quality has economic value for grasses used for livestock production. The two traits that we used to measure forage quality in this study was IVDMD and CP concentration. In a comprehensive review of pasture trials, Casler and Vogel (1999) reported that averaged across species, a 1% increase in IVDMD generally leads to a 3.2% increase in average daily gains of beef cattle (*Bos taurus*). They also reported that increased IVDMD generally does not decrease forage yield per se and sometimes occurs with increased forage yield depending on cultivar. These increased gains result in increased beef production per hectare (Casler & Vogel, 1999). Adequate levels of CP are needed in forages to optimize animal performance. As a general rule, the greater the protein concentration of a forage, the higher its economic value. There were significant differences among grass species at Ithaca for IVDMD and CP for both Harvest 1 and Harvest 2 (Table 3) and for Harvest 1 at Sidney. Some of these species differences in IVDMD and CP are due to differences in maturity since as grasses mature both IVDMD and CP concentrations decrease (Jung & Vogel, 1986). The species that had the greatest forage yield at Ithaca, such as bromegrasses and the intermediate and tall wheatgrasses, were later in maturity than some of the other species and also had greater IVDMD and CP concentrations in their harvested forage (Table 3). In general, the species at Sidney that maintained good stands had good to excellent forage yields and had acceptable to excellent IVDMD and CP concentrations in their harvested forage. Intermediate wheatgrass had both the large forage yields and excellent IVDMD and CP concentrations.

There were significant differences among species for incidence of leaf diseases before the first forage harvests at Ithaca. The percentage of disease was larger in 2001 than in 2002 (Table 3), probably due to the very wet conditions that existed at the site during May of 2001 (Table 2). The grass species that maintained the best stands and had the greatest 3-yr average yields tended to have the smaller disease percentages at Ithaca. Disease data were not taken at Sidney because the incidence of leaf and stem diseases were minimal on all species at that site.

TABLE 5 Means for forage yield, forage nutritive value as measured by in vitro dry matter digestibility (IVDMD) and crude protein (CP), stand percentages, disease ratings, and plot weeds percentages for the cultivars and experimental strains evaluated in the cool-season grass evaluation trial conducted near Ithaca, NE, during the period 1999–2003

	Harvest 1			Harvest 2			2000	2003		2001	2002
Cultivar or strain	Yield	IVDMD	CP	Yield	IVDMD	CP	Stand	Stand	Weeds	Disease	Disease
	Mg ha^{-1}	—g kg^{-1}—		Mg ha^{-1}	—g kg^{-1}—		—%				
Altai wildrye											
Angustus_hybrid	4.8	682	136	1.0	742	108	74	38	63	10	2
Arthur_Dahurian	6.3	658	101	0.3	715	87	100	34	66	18	33
M5	6.3	681	133	1.5	725	95	100	58	38	20	6
Pearl	6.1	691	136	1.2	711	91	96	38	60	33	5
Prairieland	6.3	681	133	1.2	730	101	99	21	79	20	8
Bluebunch wheatgrass											
Acc 238 2x	4.4	566	98	.	.	.	89	5	95	23	>90
Goldar	1.1	612	114	0.4	827	136	96	5	95	16	>90
P5 2x	4.6	597	106	1.2	699	129	96	18	83	23	>90
P7 2x	4.0	619	93	.	.	.	89	9	91	18	>90
Shrublab BBWG1	3.7	621	111	1.2	774	141	97	26	74	23	>90
Basin wildrye											
L4PX 3	5.4	659	116	0.3	743	147	99	39	59	35	29
Magnar	6.9	683	114	0.5	759	136	90	53	55	35	6
TC hybrid	5.2	649	110	0.7	734	134	100	30	68	40	13
Trailhead	5.2	668	113	0.6	735	123	88	48	50	40	14
Bromegrasses											
Lincoln	7.9	673	103	0.5	690	106	100	100	0	10	5
Lincoln HDMD C4	7.6	665	95	0.4	682	95	100	100	0	15	3
Newell	7.8	681	97	0.5	702	93	100	100	0	15	5
Manchar	5.7	664	120	0.3	699	98	100	100	0	25	8
NE BI 1 C2	6.6	697	104	0.5	710	83	100	100	0	15	5
NE BI 2 C0	7.3	663	98	0.4	708	92	100	100	0	15	5
NE BI 4 C2	7.3	665	99	0.4	674	98	100	100	0	10	6
Fleet (MB)[a]	6.3	660	94	0.6	754	90	100	100	0	23	23
Regar (MB)[a]	6.3	683	97	0.7	737	81	100	100	0	30	16
Cache (MB)[a]	6.7	662	93	0.5	735	81	100	100	0	15	21
Crested wheatgrasses											
CD 2	7.8	625	91	0.6	761	98	100	99	1	20	13
Douglas	5.3	589	103	0.9	763	136	92	35	64	33	28
Fairway	6.5	614	93	0.5	671	99	93	100	0	28	8
HXB28	7.5	614	91	0.3	740	114	100	98	3	18	11
Hycrest	7.8	633	87	0.4	728	92	98	100	1	25	18
I 28	7.8	627	85	0.4	738	93	98	100	0	23	18
NE AC1	6.8	605	91	0.4	680	95	98	97	4	33	10
NU ARS AC2	7.4	600	85	1.0	703	102	98	100	0	30	6
Nordan	7.3	628	90	0.4	743	118	100	96	3	25	19
Nordan HYLD-DMD C1	8.1	613	85	0.4	742	107	99	100	0	25	16
P 27	7.4	589	86	0.4	735	119	99	80	20	25	11
Pub siberian	4.8	563	81	0.5	742	139	95	35	65	35	23
Ruff HYLD -DMD C1	7.5	605	90	0.4	699	92	97	100	0	33	13

(Continues)

TABLE 5 (Continued)

	Harvest 1			Harvest 2			2000	2003		2001	2002
Cultivar or strain	**Yield**	**IVDMD**	**CP**	**Yield**	**IVDMD**	**CP**	**Stand**	**Stand**	**Weeds**	**Disease**	**Disease**
Vavilov	7.6	590	89	0.4	737	109	100	94	6	25	18
Canada wildrye											
Homestead	9.4	627	88	0.3	747	91	98	68	33	13	18
NE5	9.8	610	83	0.4	735	85	98	81	18	18	26
Virginia wildrye											
Omaha	6.9	648	101	0.7	702	99	98	8	88	48	70
Intermediate wheatgrass											
AI	8.9	667	101	1.0	762	102	100	100	0	23	9
Amur RMFS C4	8.8	650	91	0.8	747	87	100	100	0	15	6
Greenar	9.1	646	94	0.9	738	88	100	100	0	18	9
Luna	8.6	629	85	1.6	769	106	100	100	0	40	26
Mandan I1821	9.2	646	90	0.6	727	79	100	100	0	15	6
Manifest	11.0	651	91	0.8	735	82	99	100	0	18	5
Mandan I1891	9.7	651	94	1.3	744	93	98	100	0	18	6
Manska	8.6	663	97	1.0	746	92	99	100	0	20	8
Beefmaker	9.2	665	93	0.6	761	90	100	100	0	20	10
NE50 RMFS C4	9.0	660	91	0.6	741	84	100	100	0	15	8
Haymaker	10.1	651	94	0.9	734	87	100	100	0	23	6
Oahe	9.5	641	89	0.8	748	93	100	100	0	25	10
Reliant	9.7	660	95	1.0	755	99	100	100	0	18	5
Rush	9.3	649	92	1.0	759	103	100	100	0	30	11
R-S hybrid[b]											
Newhy	6.8	657	111	0.5	733	92	100	100	0	13	9
RL	8.0	643	95	0.7	736	88	99	100	0	10	8
RSH	6.4	656	109	0.6	729	110	99	98	0	10	6
Russian wildrye											
Bozetet	3.9	748	137	0.8	753	87	100	100	0	33	11
Bozoisky	4.1	684	119	1.2	722	80	100	98	3	15	10
Mandan R1831 2x	4.5	702	134	1.2	720	100	100	100	0	23	15
Mandan R1981 2x	4.3	694	133	0.9	708	84	100	100	0	20	15
Mandan R1983 4x	4.0	719	135	0.8	765	95	100	100	0	35	13
Mankota	4.1	695	135	0.9	723	98	100	100	0	25	15
Syn A	4.4	717	134	0.9	726	98	99	100	0	20	9
Tetra1	3.9	746	133	0.9	769	87	99	100	0	25	13
Tetracan	3.6	710	129	0.7	758	95	75	78	23	37	15
Snake River wheatgrass											
E 21	4.6	578	93	1.1	765	174	87	13	88	20	25
E 25	4.6	552	80	0.8	782	141	75	14	86	19	33
E 29	4.6	565	83	0.6	699	118	94	19	81	25	26
Secar	5.7	569	81	0.6	804	171	73	34	66	23	19
Thickspike wheatgrass											
Bannock	4.4	582	93	0.7	782	123	98	20	80	20	3
Critana	4.1	617	97	0.6	722	114	76	13	88	38	23
Critana X Bannock	4.9	576	82	0.6	719	130	98	33	68	40	20
Sodar	3.1	629	100	0.6	670	115	100	16	84	40	19

(Continues)

TABLE 5 (Continued)

Cultivar or strain	Harvest 1 Yield	Harvest 1 IVDMD	Harvest 1 CP	Harvest 2 Yield	Harvest 2 IVDMD	Harvest 2 CP	2000 Stand	2003 Stand	2003 Weeds	2001 Disease	2002 Disease
Tall wheatgrass											
Alkar	9.7	637	85	0.9	779	86	100	100	0	15	15
Jose	10.2	642	82	1.1	780	87	98	100	0	15	8
NE TP HYLD HDMD C2	9.9	652	89	1.1	786	92	100	99	1	15	13
Platte	9.9	648	87	1.0	791	90	98	100	0	10	13
Robust needlegrass											
T953	6.5	589	101	1.1	571	83	91	5	95	3	0
T961	5.4	581	115	1.0	553	70	100	21	79	8	0
Western wheatgrass											
Arriba	8.0	616	91	1.0	656	117	100	99	5	48	15
Flintlock	7.0	625	103	0.9	684	94	100	100	0	35	6
NE Exp 1 C1	8.2	626	100	1.0	707	93	100	99	1	28	10
Rodan	6.7	654	111	0.8	677	107	100	100	0	33	13
Rosana	6.5	650	101	0.7	676	116	100	90	11	38	10
F test (cultivars)	**	**	**	**	**	**	**	**	**	**	**
SE	0.2	3	2	0.1	9	4	5	6	6	3	3
LSD .05	0.5	9	5	0.3	24	12	14	16	15	9	9

Note. Harvest 1 Means are multiple year averages for 2001, 2002, and 2003; Harvest 2 means are for 2001 and 2002. Grass stand percentages determined by frequency grid (Vogel & Masters, 2001). Disease (%) is the percentage of plant tissue that was visibly infested with disease before harvest. Bromegrasses include both smooth bromegrass and meadow bromegrass. Crested wheatgrasses include crested wheatgrass, Siberian wheatgrass, and desert wheatgrass.

[a]MB indicates the cultivar is a Meadow bromegrass.

[b]*Elytriga repens* var. *repens* (L.) Desv. Ex B.D. Jackson × *Pseudoroegneria spicata* (Pursh).

**Significant at the .01 probability level.

The species comparisons that were made at both locations were based on 2–14 cultivars and experimental strains for each species other than using a single cultivar to represent a species in contrast to some species comparisons. The persistence of intermediate and western wheatgrass, Russian wildrye, and smooth bromegrass under heavy grazing was evaluated by Harmony (2007) at Hays, KS, on both a lowland and upland site. Hays is located in the mid-grass prairie region of the central United States. All grasses maintained stands of >90% following 2 yr of heavy grazing in 2003 and 2004 except for smooth bromegrass, which had stands of 98% on the lowland site and 86% on the upland site, which is still a fully acceptable stand. The tolerance of the crested wheatgrasses to grazing has been known for decades. These grazing results substantiate the persistence results that we determined in harvested sward trials. It should be noted that only two of the better performing species, western wheatgrass and thickspike wheatgrass, are native species. The others are grasses that have been introduced into the United States from Eurasia. The introduced grasses originated from similar ecoregions in Eurasia.

3.2 | Cultivar within species comparisons

Within the best species, there were significant differences among cultivars for both forage yield and forage quality as measured by IVDMD and CP at the Ithaca site (Table 5) and for the same traits except for IVDMD at Sidney (Table 6). The cultivars with the best combinations of desirable traits for the tallgrass prairie ecoregion based on the results of the Ithaca trial (Table 5) are summarized as follows for best grass species for the ecoregion. For smooth bromegrass, the two best cultivars were the older, reliable cultivar 'Lincoln' and the newer cultivar 'Newell'. The best meadow bromegrasses were 'Regar' and 'Cache'. Superior intermediate wheatgrass cultivars were 'Manifest', 'Beefmaker', and 'Haymaker', whereas the best tall wheatgrass cultivars were 'Platte' and 'Jose'. 'Arriba' and 'Flintlock' were the two best western wheatgrass, although an experimental strain NE Exp 1 C1, which is unreleased to date, also had superior test results. The best R-S hybrid cultivars were 'Newhy' and 'RL'. In the tallgrass prairie ecoregion, we recommend a mixture of smooth bromegrass, meadow bromegrass, and intermediate wheatgrasses to be used in pasture plantings.

The cultivars with the best combinations of desirable traits for the shortgrass prairie ecoregion based on the results of the Sidney trial (Table 6) are summarized for the best species which were intermediate, crested, western, and thickspike wheatgrasses, Russian wildryes, and the RS hybrids. Superior intermediate wheatgrass cultivars were 'Manifest', 'Beefmaker', 'Oahe', and 'Reliant'. The best crested

TABLE 6 Means for forage yield, forage nutritive value as measured by in vitro dry matter digestibility (IVDMD) and crude protein (CP), stand percentages, disease ratings, and plot weeds percentages for the cultivars and experimental strains evaluated in the cool-season grass evaluation trial conducted near Sidney, NE, during the period 1999–2003

Cultivar or strain	Yield	IVDMD	CP	2001 Stand	2003 Stand	2001 Weeds	2003 Weeds
	Mg ha^{-1}	——g kg^{-1}——		——%——			
Altai wildrye							
Angustus hybrid	1.71	734	122	45	39	56	44
Arthur Dahurian	1.61	752	156	72	15	39	55
M5	3.03	694	105	87	81	2	9
Pearl	1.91	688	96	54	40	45	45
Bluebunch wheatgrass							
Acc 238 2x	2.04	652	89	64	60	30	28
Goldar	2.74	658	103	80	28	38	59
P 5 2x	2.59	650	94	88	75	4	16
P 7 2x	2.33	668	93	69	33	35	55
Shrublab BBWG1	2.22	648	91	75	80	6	9
Basin wildrye							
Magnar	2.07	706	101	47	39	35	48
Trailhead	2.12	679	101	31	23	46	61
Bromegrass							
Lincoln	2.81	685	114	73	75	8	4
Lincoln HDMD C4	2.76	692	109	72	73	19	4
Newell	2.56	696	113	69	73	7	11
Manchar	2.27	698	128	43	38	45	41
NE BI 1 C2	2.68	697	114	82	83	0	5
NE BI 2 C0	2.91	685	115	74	76	6	9
NE BI 4 C2	3.07	702	117	84	88	3	1
Fleet MB[a]	2.37	684	109	80	69	1	21
Regar MB[a]	2.81	697	120	79	78	2	2
Cache M[a]	3.06	690	117	87	46	4	39
Crested wheatgrass							
CD 2	2.85	684	109	65	65	13	14
Douglas	2.56	671	104	55	28	38	53
Fairway	2.09	699	125	28	35	53	25
HXB28	2.91	681	105	74	68	10	3
Hycrest	3.05	702	111	61	69	30	8
I 28	2.84	670	98	70	73	18	5
NE AC1	2.66	678	111	53	71	28	3
NU ARS AC2	3.15	684	114	62	79	8	4
Nordan	2.72	673	98	55	65	18	8
Nordan HYLD HDMD C1	2.66	690	104	75	70	3	6
P 27	2.77	664	108	60	57	35	26
Pub siberian	1.74	679	114	69	73	43	8
Ruff HYLD HDMD C1	2.71	688	114	54	76	28	8
Vavilov	3.03	671	99	77	83	5	1
Canada wildrye							
Homestead	3.08	721	132	73	31	21	70

(Continues)

TABLE 6 (Continued)

Cultivar or strain	Yield	IVDMD	CP	2001 Stand	2003 Stand	2001 Weeds	2003 Weeds
NE5	2.80	719	122	72	28	13	64
Virginia wildrye							
Omaha	2.79	707	117	72	9	18	75
Intermediate wheatgrass							
AI	3.14	720	109	96	94	1	3
Amur RMFS C4	3.35	714	106	99	98	0	0
Greenar	3.26	721	112	96	93	0	4
Luna	3.19	690	96	91	90	1	1
Mandan I1821	3.29	730	111	99	98	1	0
Manifest	3.61	724	117	97	89	0	3
Mandan I1891	3.54	714	109	85	94	0	0
Manska	3.45	730	106	97	91	0	3
Beefmaker	3.65	739	115	98	94	0	3
NE50 RMFS C4	3.34	741	113	77	89	9	6
Haymaker	3.47	719	109	98	90	0	5
Oahe	3.77	702	92	98	95	0	0
Reliant	3.55	718	111	90	93	3	1
Rush	3.03	726	120	98	90	1	5
R-S hybrid[b]							
Newhy	3.12	661	92	87	81	2	2
RL	3.44	669	101	80	78	5	1
RSH	3.15	683	101	62	61	20	24
Russian wildrye							
Bozetet	3.32	686	111	80	80	15	9
Bozoisky	3.58	645	87	71	83	4	0
Mandan R1831 2x	3.65	654	96	56	70	23	6
Mandan R1981 2x	3.58	656	97	70	80	23	4
Mandan R1983 4x	3.41	682	113	79	79	13	3
Mankota	3.38	688	111	80	78	10	0
Syn A	3.60	671	97	72	74	14	3
Tetra1	2.87	688	113	68	73	11	4
Tetracan	3.04	667	108	75	81	11	1
Snake River wheatgrass							
E 21	2.54	636	92	61	48	38	45
E 25	2.63	628	93	50	33	36	48
E 29	2.71	639	90	39	39	60	53
Secar	2.62	633	85	46	48	55	38
Thickspike wheatgrass							
Bannock	3.13	628	74	87	69	18	28
Critana	2.27	644	84	61	56	34	35
CritanaXBannock	3.22	633	78	75	64	24	23
Sodar	2.34	667	82	76	76	25	4
Tall wheatgrass							

(Continues)

TABLE 6 (Continued)

Cultivar or strain	Yield	IVDMD	CP	2001 Stand	2003 Stand	2001 Weeds	2003 Weeds
Alkar	3.03	705	105	87	75	1	19
Jose	2.62	722	115	97	84	0	3
NE TP HYLD HDMD C2	2.85	719	113	94	65	0	24
Platte	2.29	712	113	85	69	1	24
Robust needlegrass							
T953	2.00	701	118	39	21	64	53
T961	0.21	691	128	29	21	78	68
Western wheatgrass							
Arriba	2.81	675	108	85	73	13	26
Flintlock	3.11	694	112	91	95	8	6
NE Exp 1 C1	3.05	707	113	96	96	9	1
Rodan	2.56	703	113	84	87	11	13
F test (cultivars)	**	ns[†]	*	**	**	**	**
SE	0.22	10	6	8	8	9	9
LSD .05	0.60	ns	17	21	22	25	25

Note. Yield, IVDMD, and CP means are multiple year averages for 2001, 2002, and 2003. Grass stand percentages determined by frequency grid (Vogel & Masters, 2001). Weeds percentage is the visual estimated of the total harvested biomass that was from nonseeded species. Bromegrasses include both smooth bromegrass and meadow bromegrass. Crested wheatgrasses include crested wheatgrass, Siberian wheatgrass, and desert wheatgrass.

[a]MB indicates the cultivar is a meadow bromegrass.

[b]*Elytriga repens* var. *repens* (L.) Desv. Ex B.D. Jackson × *Pseudoroegneria spicata* (Pursh).

*Significant at the .05 probability level. **Significant at the .01 probability level. [†]ns = non-significant.

wheatgrasses were 'Hycrest', 'Vavilov', and NUARS AC2, which currently is not in seed production. Superior Russian wildryes were 'Bozoisky' and 'Mankota', but there were also several promising experimental strains of this species. 'Flintlock' and 'Arriba' were the two best released western wheatgrass cultivars in this trial, whereas 'Bannock' and 'Critana' were the two best thickspike wheatgrass cultivars. The best R-S hybrid cultivars were 'Newhy' and 'RL'. In the shortgrass plains ecoregion, which has periodic drought, we again recommend multispecies mixtures of grasses that should include crested, western, and intermediate wheatgrasses, and one or more of the other three grasses. The new cultivars of Russian wildrye appear to very well adapted to the region.

4 | CONCLUSIONS

Conversion of marginal cropland back to perennial grasslands in the central United States has to be economically viable because most of the land is in private ownership. Grasses have to be easily established and they need to persist. They need to be productive and produce quality forage. More different cool-season grass species and cultivars for use in the central United States were evaluated than what has been evaluated in single trials previously or since. The grass species that met these criteria in the Ithaca trial for the tallgrass prairie ecoregion were intermediate, tall, and western wheatgrass, the bromegrasses that included both smooth and meadow bromegrasses, and the R-S hybrids. At Sidney, the best grasses for the shortgrass prairie ecoregions were intermediate, crested, western, and thickspike wheatgrasses, the R-S hybrid, and Russian wildryes. Only the western and thickspike wheatgrasses are native species which for production agriculture is irrelevant. Because of the breeding work that has been done by the USDA-ARS breeding programs at Lincoln, NE; Mandan, ND; and Logan, UT; there are improved cultivars available for these species. Cultivars of these grass species with best combinations of desired traits were identified for each ecoregion.

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AUTHOR CONTRIBUTIONS

Kenneth P. Vogel: Conceptualization; Data curation; Formal analysis; Methodology; Validation; Writing-original draft; Writing-review & editing. Rob Mitchell: Methodology; Validation; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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