Introducing cover crops as a fallow replacement in the Northern Great Plains: I. Evaluation of cover crop mixes as a forage source for grazing cattle

Samuel A. Wyffels, Maryse Bourgault*, Julia M. Dafoe, Peggy F. Lamb and Darrin L. Boss

Northern Agricultural Research Center, Montana State University, 3710 Assiniboine Road, Havre, MT 59501, USA

Abstract

Crop-livestock integration has demonstrated that cover crops can be terminated using livestock grazing with minimal negative impacts on soil health, however, provides little information on system-level approaches that mutually benefit soil health and both crop and livestock production. Therefore, the objective of this research was to examine the effects of cover crop mixtures on biomass production, quality and the potential for nitrate toxicity on a dryland wheat-cover crop rotation. This research was conducted at the Montana State University-Northern Agricultural Research Center near Havre, MT (48°29′N, -109°48′W) from 2012 to 2019. This experiment was conducted as a randomized-complete-block design, where 29 individual species were utilized in 15 different cover crop mixtures in a wheat-cover crop rotation. Cover crop mixtures were classified into four treatment groups, including (1) cool-season species, (2) warm-season species dominant, (3) cool and warm-season species mixture (mid-season), and (4) a barley (Hordeum vulgare) control. All cover crop mixtures were terminated at anthesis of cool-season cereal species to avoid volunteer cereal grains in the following wheat crop. At the time of cover crop termination, dry matter forage production was estimated and analyzed for crude protein, total digestible nutrients and nitrates as indicators of forage quality. All mixtures containing oats (Avena sativa) had greater (P ≤ 0.03) biomass production than other mixtures within their respective treatment groups (cool- and mid-season). Forage biomass was influenced by cover crop treatment group, with the barley producing the greatest (P < 0.01) amount of forage biomass when compared to cool-, mid- and warm-season cover crop treatments. Total digestible nutrients were greater (P < 0.01) in the barley control compared to the cool- and mid-season treatment groups. Crude protein was greatest in the warm-season treatment group (P < 0.01) compared to the barley control, cool- and mid-season treatment groups. The barley control produced fewer nitrates (P ≤ 0.05) than the cool-, mid- and warm-season treatment groups; however, all cover crop mixtures produced nitrates at levels unsafe for livestock consumption at least one year of the study. The relatively high and variable nitrate levels of all cover crop mixtures across years in this study suggest that forage should be tested for nitrates before grazing. In conclusion, our research suggests that in a dryland wheat-cover crop rotation that requires early-July termination, cool-season cover crop mixtures are the most suitable forage source for livestock grazing most years.

Introduction

Dryland cereal grain production in the Northern Great Plains typically includes a crop-fallow rotation to allow for soil water recharge and nitrogen mineralization before the following crop year (Lenssen et al., 2007; Gan et al., 2015). However, it has been well documented that in semiarid systems, only 25–40% of precipitation is effectively stored in the soil on fallow years, leading to increased concerns related to soil erosion and sustainability (Hatfield et al., 2001). Diversifying cropping systems, such as incorporating a cover crop in a wheat-fallow system, has been shown to reduce erosion, and improve soil organic carbon and nitrogen, which leads to retention of organically bound nutrients and improved soil hydrology (Franzluebbers and Stuedemann, 2008b; Blanco-Canqui et al., 2015). In addition, cover crops can effectively suppress weeds in various production systems (Teasdale and Abdul-Raki, 1998; Kruidhof et al., 2008; Hodgdon et al., 2016). Therefore, the introduction of cover crop systems can reduce off-farm inputs while producing similar profits to more conventional systems (Davis et al., 2012).

In a wheat-cover crop rotation, cover crops must be terminated prior to the planting of wheat. Conventional cover crop termination typically includes tillage, herbicide, crimper roller or a combination of methods, all of which represents a cost with no immediate return, potentially limiting producer adoption. However, cover crops including annual grasses, small grains
and forage legumes following grain or fiber crops could provide a source of high-quality forage for livestock (Franzluebbers and Stuedemann, 2007, 2008b). In addition, manure deposited from grazing cattle has been demonstrated to increase soil organic carbon accumulation compared to a legume-grain crop rotation and a conventional fertilizer-based system, presumably due to manure taking longer to decompose than plant residue (Hassink, 1992; Paustian et al., 1992; Drinkwater et al., 1998). Therefore, an integrated crop-livestock system that utilizes livestock grazing as a mechanism to terminate cover crops is proposed to better pair nutrient demand and availability compared to other termination methods, mutually benefiting both livestock and crop producers (Russelle et al., 2007; Franzluebbers and Stuedemann, 2008a; Liebig et al., 2012). Although cover crops offer an opportunity for a high-quality forage source for livestock grazing, previous research evaluating the integration of livestock grazing on cover crops focuses solely on the following crop production and soil attributes and evaluates little if any metric of the effects of cover crop mixtures on animal nutrition with the exception that grazing cover crops could expose livestock to toxic levels of nitrates (Brummer et al., 2018; Farney et al., 2018; Lenz et al., 2019b).

Season-long cover crops, planted in the spring, are most often used by producers who intend to graze or harvest the cover crop as forage (Brummer et al., 2015). Conventional wisdom suggests that the greater biomass a cover crop adds to a system, the greater the soil organic C accumulation and available forage for livestock grazing. Therefore, increasing species and functional group diversity of cover crop mixtures has been promoted as a method to increase soil organic C by producing greater above and belowground biomass compared to a single-species mixture (Faé et al., 2009; Wortman et al., 2012; Blanco-Canqui et al., 2015). The use of diverse cover crop mixtures has been demonstrated to have less nutrient leaching than single species cover crops due to the complementarity of root systems in a mixture (Blanco-Canqui et al., 2015). However, the advantage of mixtures over monocultures in biomass production appears dependent on timely precipitation following cover crop seeding (Liebig et al., 2015).

Developing cover crop mixtures that include species from different functional groups can also provide multiple system benefits (Sanderson et al., 2018). For example, legumes can provide both nitrogen fixation and pollinator benefits (USDA-SARE, 2015), while brassicas have been shown to suppress weeds, reduce fungal diseases and nematode populations due to the decomposition of glucosinolate compounds and an early rapid canopy development (Weil and Kremen, 2007; Kruidhof et al., 2008; Lawley et al., 2012). Additionally, cereal grain species typically increase biomass and residue that protects against soil erosion (Weil and Kremen, 2007), while species with deep taproot, such as radish (Raphanus sativus), turnip (Brassica rapa), safflower (Carthamus tinctorius) and sunflower (Helianthus annuus) can reduce soil compaction, break the plow pan and increase rainfall infiltration (Merrill et al., 2002; Weil and Kremen, 2007). Thus, the use of complex cover crop mixtures of functionally diverse species offers the potential to improve ecosystem services in various cropping systems (USDA-SARE, 2015; Hodgdon et al., 2016; Sanderson et al., 2018).

Although several cover crop species can be incorporated into a mixture, most are categorized as either cool-season and warm-season species. The fundamental difference between these two categories of cover crop species is the optimal temperature for growth. Cool-season forages including most cereal grains, brassicas and legumes can germinate at temperatures as low as 4°C with optimal temperature for growth near 20°C (Cooper and Taiton, 1968; Nelson and Moser, 1994). Alternatively, warm-season species such as millet (Setaria italica), sorghum-sudangrass (Sorghum × drumondii), sunflower (H. annuus), soybean (Glycine max) and chickpea (Cicer arietinum) do not initiate growth until soil temperature nears 10°C with the optimal temperature for growth occurring between 30 and 35°C (Cooper and Taiton, 1968; Nelson and Moser, 1994). Due to the differences in optimal growth, cool-season crops are often planted earlier in the spring compared to warm-season crops. Including both cool- and warm-season species in a cover crop mixture has been suggested to provide effective ground cover for soil erosion benefits (Sanderson et al., 2018). However, early establishment of cool-season species could limit the potential for warm-season plants to contribute to forage biomass, thus, may require a later planting date to facilitate warm-season plant growth. Therefore, cover crop mixture and planting date can directly impact the timing of forage availability and quality for livestock grazing.

In general, cover crops are promoted worldwide due to the conservation benefits including reduced soil erosion, greater water infiltration and enhanced soil biological abundance and activity (Snapp et al., 2005; Myers and Watts, 2015; Sanderson et al., 2018). Nevertheless, the benefits of incorporating a cover crop rotation in a semi-arid cereal-based system are highly variable compared to the humid environments that the bulk of cover crop research has been performed (Blanco-Canqui et al., 2015). Although livestock grazing of cover crops could provide a low input alternative for beef cattle nutrition requirements while delivering a low-input cover crop termination method, previous research evaluating the integration of livestock grazing on cover crops focuses solely on the following crop production and soil attributes and evaluates little if any metric of the effects of cover crop mixtures on animal nutrition with the exception that grazing cover crops could expose livestock to toxic levels of nitrates (Brummer et al., 2018; Farney et al., 2018; Lenz et al., 2019b). The lack of information on the effect of cover crop mixtures on both cover crop biomass and forage quality for livestock grazing limits our understanding of the long-term sustainability of integrated crop-livestock systems involving cover crop grazing in dryland cereal grain production in the Northern Great Plains. Therefore, the objective of this research was to examine the effects of cover crop mixtures (cool-season, warm-season, a mixture of both cool- and warm-season) on cover crop biomass production, quality and the potential for nitrate toxicity on a dryland wheat-cover crop rotation.

**Methods**

This research was part of a long-term study evaluating cover crops in a semi-arid region of the Northern Great Plains. Research was conducted at the Montana State University-Northern Agricultural Research Center near Havre, MT (48°29′N, −109°48′W) from 2012 to 2019. The research site is approximately 815 m above sea level, with an average annual precipitation of 305 mm. Soil is characterized as clay loam and classified as a Telstad-Joplin complex. The site is characterized as having 129 frost-free days and an average annual temperature of 5.94°C with an average high of 13.6°C and average low of 0.0°C. Weather data were collected onsite with official National Weather Service (NOAA) meteorological instruments. Recorded monthly mean, maximum and minimum temperatures and precipitation for April, May,
June and July 2012 through 2019 and long-term averages (1916–2018) are presented in Table 1.

This experiment was conducted as a randomized-complete-block design, where 29 individual species were utilized in 15 different cover crop mixtures in a wheat-cover crop rotation (Table 2). Cover crop mixtures were classified into three treatment groups, including (1) cool-season species, (2) warm-season species and (3) cool- and warm-season species mixture (mid-season). Both the commodity crop (spring and winter wheat) and each of the 15 cover crop mixtures were present in each of two adjacent fields (three replications per field) for each year of the study (2012–2019). The cover crop mixtures were randomly allotted to plots (7.3 by 40.2 m) within each field the first year of the study and each treatment was planted in the same plot for the remainder of the trial in a wheat-cover crop rotation. Each block was separated by a barley (*Hordeum vulgare*) half-plot (3.6 by 40.2 m), which was later deemed an additional control of interest (barley control), as barley is the second most common grain crop in this region (USDA-FSA, 2020) and continuous cropping with a barley rotation is a common practice in the region (Carr et al., 2021). All seeds for each species used in this trial were locally sourced and tested for germination prior to planting. Only seed sources with \( \geq 95\% \) germination rates were utilized in the cover crop mixtures. Seed sources that failed to meet a 95% germination rate were then re-sourced and tested before mixing. Seeds were then mixed to cover crop specifications by research technicians at the Northern Agricultural Research Center in Havre, MT. Cover crop mixtures including legumes were inoculated with their respective Rhizobium/Bradyrhizobium strains during seeding.

Following a glyphosate application, cover crop mixtures were planted according to their treatment groups using a 12-row ConservaPak hoe-type air seeder with 30 cm row spacing at a depth of 2.54 cm. Seeding rates were based on Montana Natural Resources Conservation Service recommendations adjusted for pure live seed, germination rate and the number of species in each cover crop mixture (Table 2; USDA-NRCS, 2021a). Cool-season mixtures were planted in the spring as soon as conditions allowed, mid-season 10–14 days later, and the warm-season 10–14 days after mid-season planting (Table 3). Cover crop planting dates were also based on Montana Natural Resources Conservation Service recommendations to ensure each cover crop was planted in the respective planting window (cool-season, early-April to mid-May; warm-season, mid-May to mid-June; mid-season, May), mimicking general planting dates of the region for each cover crop treatment group.

**Table 1.** Monthly mean, maximum, and minimum temperature and precipitation for April, May, June and July 2012–2019 with long-term averages at Montana State University, Northern Agricultural Research Center

|            | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | Long-term average* |
|------------|------|------|------|------|------|------|------|------|-------------------|
| **April**  |      |      |      |      |      |      |      |      |                   |
| Temperature, C |      |      |      |      |      |      |      |      |                   |
| Mean       | 8.12 | 4.00 | 6.74 | 7.37 | 8.00 | 6.89 | 2.20 | 7.02 | 6.44              |
| Max        | 15.70| 11.10| 14.40| 15.30| 15.20| 13.70| 8.50 | 13.50| 14.80             |
| Min        | 0.60 | –3.10| –0.90| –0.60| 0.80 | 0.10 | –4.10| 0.50 | –0.90             |
| Precipitation, mm | 55.40| 15.50| 23.40| 8.60 | 99.60| 6.40 | 6.10 | 23.40| 24.40             |
| **May**    |      |      |      |      |      |      |      |      |                   |
| Temperature, C |      |      |      |      |      |      |      |      |                   |
| Mean       | 11.12| 12.65| 11.64| 10.79| 11.51| 12.41| 14.93| 9.66 | 12.22            |
| Max        | 18.10| 19.90| 18.90| 18.30| 18.10| 20.20| 22.40| 16.30| 20.70            |
| Min        | 4.10 | 5.40 | 4.40 | 3.30 | 4.90 | 4.60 | 7.40 | 3.00 | 4.70              |
| Precipitation, mm | 75.70| 124.70| 20.10| 64.30| 104.10| 11.40| 27.90| 38.90| 48.30            |
| **June**   |      |      |      |      |      |      |      |      |                   |
| Temperature, C |      |      |      |      |      |      |      |      |                   |
| Mean       | 16.81| 15.93| 14.85| 18.62| 17.20| 17.80| 17.41| 16.34| 16.56           |
| Max        | 23.90| 22.10| 21.40| 27.10| 25.00| 25.80| 24.20| 23.70| 25.30            |
| Min        | 9.80 | 9.70 | 8.30 | 10.10| 9.40 | 9.80 | 10.60| 9.00 | 9.20             |
| Precipitation, mm | 36.30| 129.50| 75.20| 20.10| 42.90| 39.90| 63.50| 82.30| 67.30            |
| **July**   |      |      |      |      |      |      |      |      |                   |
| Temperature, C |      |      |      |      |      |      |      |      |                   |
| Mean       | 22.63| 20.27| 21.10| 20.44| 20.08| 23.14| 20.83| 19.67| 20.72           |
| Max        | 31.50| 28.10| 29.60| 28.50| 27.70| 32.70| 29.50| 28.00| 30.70            |
| Min        | 13.80| 12.50| 12.60| 12.30| 12.50| 13.60| 12.20| 11.30| 12.10            |
| Precipitation, mm | 18.80| 67.60| 5.10 | 98.00| 64.30| 3.60 | 4.60 | 16.30| 39.60            |

*Long-term average (1916–2018).*
All cover crop mixtures were fertilized at their respective planting dates (20-20-20; N-P-K) at a rate of 112 kg ha\(^{-1}\) to ensure cover crop establishment. Cover crop emergence was also measured via stand counts, with all cover crops successfully germinating at predicted rates with cool-season mixtures averaging 97 plants per m\(^2\) while mid- and warm-season cover crop treatment groups and the barley control averaging 75 plants per m\(^2\). All crop fields in this study have been managed as no-till for over 25 years.

Cover crop mixtures were typically terminated from late June to early July at anthesis of cool-season cereal species to avoid volunteer cereal grains in the following wheat crop. At the time of crop termination cool-season broadleaf species were typically vegetative and flowering while warm-season species were vegetative and budding. Cover crops were divided into three termination plots (7.3 × 13.4 m); herbicide, swathing and bailing, and grazing as part of a larger project evaluating the effects of cover crop and termination method on subsequent wheat yield and soil bacterial...
Table 4. Biomass production, crude protein (CP), total digestible nutrients (TDN), nitrate levels on a dry matter basis for cover crop treatment groups and barley control grown for livestock grazing at Montana State University, Northern Agricultural Research Center between 2012 and 2019.

| Year | Cool-season Biomass, kg ha⁻¹ | Mid-season Biomass, kg ha⁻¹ | Warm-season Biomass, kg ha⁻¹ | Barley Biomass, kg ha⁻¹ |
|------|-----------------------------|-----------------------------|-----------------------------|------------------------|
| 2012 | 4138 ± 474                  | 1770 ± 224                  | 26 ± 26                     | 7549 ± 472             |
| 2013 | 1846 ± 123                  | 1038 ± 117                  | 406 ± 70                    | 4724 ± 264             |
| 2014 | 1437 ± 121                  | 1139 ± 107                  | 449 ± 58                    | 2925 ± 157             |
| 2015 | 1624 ± 166                  | 787 ± 157                   | 455 ± 68                    | 3913 ± 167             |
| 2016 | 2761 ± 208                  | 1290 ± 162                  | 424 ± 43                    | 4501 ± 266             |
| 2017 | 558 ± 100                   | 114 ± 36                    | 35 ± 16                     | 999 ± 90               |
| 2018 | 1616 ± 146                  | 1059 ± 115                  | 529 ± 38                    | 2211 ± 89              |
| 2019 | 2692 ± 95                   | 1577 ± 170                  | 359 ± 50                    | 1885 ± 10              |

Notes:
- Mixture of cool- and warm-season species.
- CP: %
- TDN: %
- Nitrate, ppm

| Year | CP, % | TDN, % | Nitrate, ppm |
|------|-------|--------|--------------|
| 2012 | 7.4 ± 0.3 | 54.4 ± 1.2 | 950 ± 171    |
| 2013 | 10.6 ± 0.3 | 57.9 ± 0.7 | 677 ± 133    |
| 2016 | 14.7 ± 0.7 | 50.0 ± 0.6 | 3600 ± 503   |
| 2017 | 23.3 ± 1.7 | 58.0 ± 0.6 | 9120 ± 2231  |

Results

Cover crop mixture nested within treatment had an influence (P < 0.01) on biomass production (Table 5), where all mixtures containing oats (Avena sativa) had greater (P ≤ 0.03) biomass production than the mixtures excluding oats within their respective treatment groups (cool- and mid-season). Additionally, cool-season cover crops including turnip, radish, vetch (Vicia villosa), oat and sweet clover (Melilotus sp.) produced on average 670 kg ha⁻¹ more biomass (P = 0.02) than a similar mixture that replaced sweet clover with a combination of pea (Pisum sativum arvense), lentil (Lens culinaris) and safflower. There was no effect (P > 0.88) of cover crop mixture on biomass production within the warm-season treatment group, averaging 335 kg ha⁻¹. However, the barley control on average produced a minimum of 949 kg ha⁻¹ more biomass than any other cover crop mixture regardless of treatment group (P < 0.01). When evaluating the effect of cover crop treatment group on forage biomass, the barley control produced the greatest (P < 0.01) amount of forage biomass when compared to cool-, mid- and warm-season cover crop treatment groups (3588 ± 253, 2084 ± 214, 1097 ± 214, 335 ± 214 kg ha⁻¹, respectively; Fig. 1). Additionally, the cool-season treatment group produced on average 987 and 1749 kg ha⁻¹ greater (P < 0.01) forage biomass than mid- and warm-season treatment groups.
Furthermore, the mid-season treatment group had 702 kg ha$^{-1}$ greater ($P < 0.01$) forage production than the warm-season treatment group.

Cover crop mixture nested within treatment group also had an effect ($P = 0.02$) on crude protein content of the forage (Table 5). However, this effect was limited to cool-season cover crop mixtures that excluded oats having 3.4% greater crude protein on a dry matter basis than five-species cool-season cover crop mixtures including oats (14.9 vs 11.5% CP). There was no effect of cover crop mixture within mid- ($P \geq 0.32$) and warm-season ($P \geq 0.82$) treatment groups averaging 16.9 and 20.0% CP, respectively. The crude protein content of the barley control did not differ ($P = 0.99$) from other cool-season mixtures that included oats. However, the barley control averaged 3.8% less crude protein content on a dry matter basis than all other cover crop mixtures ($P \leq 0.05$). When evaluating the effect of cover crop treatment group on crude protein content, the warm-season treatment group had greater ($P < 0.01$) crude protein compared to the barley control, cool- and mid-season treatment groups (20.0 $\pm$ 4.0, 11.5 $\pm$ 2.3, 12.5 $\pm$ 2.5 and 16.8 $\pm$ 3.3%, respectively; Fig. 2). Additionally, the mid-season treatment group had on average 4.8% greater ($P < 0.01$) crude protein content on a dry matter basis than the cool-season treatment group and the barley control. The crude protein content of the barley control and cool-season treatment group did not differ ($P = 0.48$), averaging 12% crude protein.

There were no meaningful effects ($P = 0.08$) of cover crop mixture nested within treatment group on total digestible nutrients, therefore total digestible nutrient data are displayed only as treatment group main effects. Total digestible nutrients were greater ($P < 0.01$) in the barley control compared to the cool- and mid-season treatment groups (20.0 $\pm$ 4.0, 11.5 $\pm$ 2.3, 12.5 $\pm$ 2.5 and 16.8 $\pm$ 3.3%, respectively; Fig. 3). However, total digestible nutrients did not differ ($P = 0.13$) between the barley control and the warm-season treatment group, averaging 65.5%. In addition, the warm-season

![Fig. 1. Influence of cover crop treatment group grown for livestock forage on biomass production ($P < 0.01$; mean $\pm$ SE; kg ha$^{-1}$) at Montana State University, Northern Agricultural Research Center between 2012 and 2019. Data points without a common letter differ ($P < 0.05$).](https://www.cambridge.org/core)
The cover crop treatment groups in our study were planted at different dates and, therefore, harvested at different stages of maturity. Thus, the results of cover crop treatment groups on forage quality of this study are likely attributed to the stage of maturity at the time of termination. However, all cover crop mixtures were planted within the Natural Resources Conservation Service recommended planting windows for the region and are representative of general cover crop management of the Northern Great Plains. Thus, although influenced by planting date, the effects of cover crop mixture and treatment group on forage quality presented in this study are representative of the general cover crop management of the Northern Great Plains when cover crops are terminated by early July.

Our study results suggest that the addition of oat in a cool- or mid-season cover crop mixture can increase overall biomass production, however, can reduce crude protein content in cool-season mixtures. However, we found that cover crop mixture within treatment group had no effect on crude protein for mid- and warm-season cover crop mixtures or biomass production in warm-season mixtures. In addition, cover crop mixture within treatment group had no effect on total digestible nutrients or nitrate content of the forage. In general, we found that
warm- and mid-season cover crop mixtures produce greater crude protein and total digestible nutrients than cool-season mixtures; however, produce less biomass at the time of termination. Although warm-season forage species typically contain lower crude protein levels and are less digestible than cool-season species when at similar stages of maturity, it is important to note that forage digestibility and crude protein decrease as plants reach reproductive maturity and dormancy (Minson, 1981; Coleman et al., 2004). The reduction of forage quality is related to increased fiber and lignification, which is negatively correlated to both total digestible nutrients and crude protein (Ely et al., 1953). Considering the optimal temperature for growth is near 20°C for cool-season forages, with reproductive maturity occurring in late-June to early-July, and 30–35°C for warm-season forages, with maturity not occurring until August to September, suggests that cover crop termination occurred when cool-season forages were mature and warm-season forages were not (Cooper and Taiton, 1968; Nelson and Moser, 1994). Additionally, the temperature can have a considerable effect on forage quality as higher ambient temperatures are typically associated with lower dry matter digestibility (Ford et al., 1979; Fick et al., 1988). When forage is grown at the lower end of their optimal temperature, forages tend to be more digestible (Akin et al., 1987). Due to weather conditions at the study site never reaching the optimal temperature for warm-season forages before termination and the different stages of maturity between cool- and warm-season species may explain greater crude protein and digestibility of the warm-season mixtures. Furthermore, the addition of oat in the cover crop mixture likely increased biomass production and decreased protein due to cover crop termination being based on anthesis of cool-season cereal species.

Peak nutrient requirements for a 544.31 kg cow weaning a 7-month-old calf weighing 224.98 kg is approximately 56.2% total digestible nutrients and 8.8% crude protein (National Research Council, 1996, 2016). Additionally, requirements for 272.16 kg growing cattle with an anticipated finishing/mature weight of 544.31 kg are 56.6% total digestible nutrients and 8.7% crude protein for expected 0.68 kg average daily gain, or 60.7% total digestible nutrients and 9.8% crude protein for 0.91 kg average daily gain (National Research Council, 1996, 2016). In general, the forage produced by the cover crops met the nutritional requirements of beef cattle for most stages of production at the time of crop termination (National Research Council, 1996, 2016). However, it should be noted that the barley control and cool-season cover crop mixture did not fully meet the crude protein nutritional requirements for cattle one of the 4 years that forage quality data were recorded (2012), likely related to below-average precipitation for June (Table 4).

Although nutrient quality sets the upper limit of individual animal performance, forage quantity determines the proportion of the performance that is attained (Duble et al., 1971; Sollenberger and Vanzant, 2011). Thus, forage quality interacts with forage quantity in determining animal performance, where forages with greater nutrient quality require less forage quantity to reach maximum potential. Past research has suggested that cover crop mixtures can produce greater biomass than single-species cover crops (Khan and McVay, 2019). However, our results contradict these findings as the barley control consistently produced a minimum of 949 kg ha⁻¹ more biomass than all cover crop mixtures used in the trial. Differences in results between our research and the previous study are likely related to differences in annual precipitation (283.46 vs 349.76 mm), annual temperatures (6.36 vs 7.92°C), cover crop termination dates (late-June to early-July vs late-July to early-August) and species combination within the mixtures used. Additionally, it’s likely that certain single species crops, such as barley, can produce higher biomass than mixtures; however, it’s challenging to predict a single species’ crop success in any given season or location (Khan and McVay, 2019). Mid- and warm-season cover crops used in this trial had substantially lower biomass production than the cool-season cover crop mixture and the barley control. These findings are likely due to the differences in optimum growing temperatures and stage of maturity between warm and cool-season species at the time of crop termination.

Previous research suggests that moderate to high-quality forages require 750–1000 kg ha⁻¹ of forage biomass to achieve optimum animal performance while grazing (Duble et al., 1971; Sollenberger and Vanzant, 2011). In general, the barley control, cool-season and mid-season cover crop treatment groups produced adequate forage biomass to achieve optimum animal performance. However, the warm-season treatment group never produced over 528.46 ± 37.61 kg ha⁻¹. The barley control produced over 1000 kg ha⁻¹ consistently across all years of the study, and cool- and mid-season mixtures produced over 1000 kg ha⁻¹ for 7 and 6 years of the 8 years, respectively. However, the year cool-season cover crops did not produce over 1000 kg ha⁻¹, and one of the 2 years mid-season cover crops did not produce adequate forage biomass (2017) was a severe drought, with precipitation during the growing season 118.3 mm below average. Although severe drought can reduce overall biomass production, forage quality is often greater under drought stress compared to normal conditions (Grant et al., 2014), as seen in our study. When not limited by the nutritive quality of forage, cattle typically consume 1–3% of their body weight daily (Cordova et al., 1978). Thus, assuming an animal consumes 3% of its body weight per day, a 544.31 kg cow will consume approximately 16.32 kg d⁻¹. Furthermore, grazing efficiency (the proportion of forage consumed by livestock compared to the total that disappears due to all other activities) for moderately stocked pastures is estimated at 50% (Allison et al., 1982; Smart et al., 2010). Therefore, based on these assumptions, the cover crop mixtures used in this trial could support approximately 2.13 animal unit months (AUM) per ha for cool-season mixtures, 1.12 AUM ha⁻¹ for mid-season mixtures, 0.34 AUM ha⁻¹ for warm-season mixtures, and 3.66 AUM ha⁻¹ if the barley control were grazed.

This study also found that species composition of the mixtures used did not influence nitrate contents. Both mid- and warm-season cover crop mixtures contained greater levels of nitrates than cool-season cover crop mixtures and the barley control. These results are likely due to the stage of maturity as nitrate levels are negatively associated with plant maturity (Khorasani et al., 1997; Lenz et al., 2019a). Thus, succulent, actively growing tissue is typically higher in nitrates than mature plants. Additionally, many species grown as crops can accumulate nitrates under stress conditions such as drought, shading, injury, frost or an improper balance of soil nutrients (Wilson, 1943; Crawford et al., 1961; Undersander et al., 1999). Our results support previous work as nitrates of all cover crop treatment groups were substantially elevated during the drought conditions of 2017. Considering weather conditions at the study site never reached the optimal temperature for warm-season forages before termination may further explain elevated levels of nitrates. Additionally, nitrogen fertilizer application is one of the most common causes of elevated nitrate levels in plant tissue (Bolan and Kemp, 2003). Although the rate of
nitrogen fertilizer application was likely too low to affect plant nitrate levels in our study (22.4 kg ha⁻¹), additional nitrogen fertilizer application could potentially further elevate plant nitrate concentrations and increase the likelihood of nitrate toxicity of grazing livestock.

When consumed by cattle, nitrates are reduced to nitrates in the rumen, and when absorbed, they interfere with the blood's ability to carry oxygen (Emerick, 1988). Chronic symptoms of nitrate poisoning in ruminants include depressed intake, weight loss, abortion, reduced fertility and reduced milk production (Davison et al., 1964; Bennett et al., 1968; Thompson, 2014). Therefore, it is not recommended for pregnant cattle to graze forages with greater than 1500 ppm nitrates on a dry matter basis; however, 1500–5000 ppm on a dry matter basis is generally considered safe for non-pregnant livestock (Cash et al., 2002). Nitrate levels between 5000 and 10,000 ppm on a dry matter basis are not suitable for livestock grazing but could be harvested and fed as hay to non-pregnant livestock, as long as feeding is limited to 25–50% of the ration (Cash et al., 2002). All cover crop mixtures used in this study contained between 1500 and 3500 ppm nitrates on a dry matter basis on average. When evaluating nitrate levels of cover crop mixtures within year of our research, the cool-season mixtures and barley control were below 1500 ppm nitrates 2 years and mid-season mixtures for 1 year of forage quality data (2012 and 2013). Warm-season mixtures were never below 1500 ppm throughout the study. Each cover crop mixture produced nitrates at unsafe levels for livestock grazing for one of the 4 years of quality data (2017), likely related to drought conditions. High nitrate levels could be mitigated by altering species composition of the mix, as brassica species (present in all mixtures in this study) are known to be nitrate accumulators, waiting to graze until the crop is more mature, limiting grazing time, providing low nitrate supplemental feed and providing concentrate supplements (Burrows et al., 1987; Bolan and Kemp, 2003; Lenz et al., 2019a). However, forage quality decreases with plant maturity and could result in a forage base that doesn’t meet animal requirements. Intensifying grazing management, providing supplementary feed, and concentrate supplements increase livestock production costs and do not eliminate the risk of nitrate toxicity. Additionally, environmental conditions that elicit plant stress, such as drought, further elevate plant nitrate levels (as seen in 2017). Thus, when evaluating the potential for nitrate toxicity associated with grazing cover crops, forages should be tested prior to grazing, especially during drought conditions. If nitrate levels of a cover crop are beyond the limits for livestock grazing, producers should consider postponing grazing till nitrate levels drop to a safe level or harvest the cover crop as hay.

Conclusion

Although cover crop mixtures containing warm-season species had greater crude protein levels and total digestible nutrients than cool-season mixtures and the barley control, warm-season species produced the least amount of biomass with the highest levels of nitrates. An integrated crop-livestock system approach that is mutually beneficial for livestock and crop producers necessitates a cover crop that produces an abundant source of forage that meets livestock nutrient requirements. The barley forage-wheat grain rotation consistently produced the greatest biomass at an acceptable forage quality for grazing livestock during the barley phase. However, this cereal rotation is more susceptible to carry-over diseases and will not likely provide the benefits of mixed-species cover crops (Faé et al., 2009; Blanco-Canqui et al., 2015; Khan and McVay, 2019). Therefore, in a dryland cover crop-wheat rotation that requires early-July termination to prevent volunteer cereal grains in the following wheat crop, cool-season cover crop mixtures should provide a suitable forage source for livestock grazing most years. However, the relatively high and variable nitrate levels of all cover crop mixtures across years in this study suggests that forage should be tested for nitrates before grazing. Additional research is needed that focuses on season-long cover crop biomass production, forage quality and nitrate levels when cover crop harvesting occurs later in the year (August–September).

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1742170521000417.

Acknowledgements. The Montana Natural Resource and Conservation Service CIP grant was the initial funding source for the project. Montana Wheat and Barley Committee funding was also instrumental to the initiation and early years of this long-term project. The Montana Research and Economic Development Initiative supported this project from 2015 to 2017, and the United States Department of Agriculture (USDA) National Institute of Food and Agriculture supported the project from 2018 to 2020. The authors would like to acknowledge the contributions of various Northern Agricultural Research Center staff who helped with various aspects of data collection over the years. Particularly, sincere thanks are due to Roger Hybner for all aspects of the technical work related to this project, Tom Allen for planting and spraying operations, and Cory Parsons and the livestock crew for putting up electrical fences and bringing cows and bulls in for grazing. Numerous short-term employees and student interns have also helped with soil sample collection, residue counts, infiltration measurements, and sample processing and cleaning and are also acknowledged.

Conflict of interest. None.

References

Akin D, Fales S, Rigsby L and Snook M (1987) Temperature effects on leaf anatomy, phenolic acids, and tissue digestibility in tall fescue 1. Agronomy Journal 79, 271–275.

Allison CD, Kothmann M and Rittenhouse L (1982) Efficiency of forage harvest by grazing cattle. Rangel and Ecology & Management 55, 351–354.

Bates D, Maechler M, Bolker B and Walker S (2015) Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67, 1–48.

Bennett RC, Olds D and Seath DM (1968) The relationship between nitrate content of forages and dairy herd fertility. Journal of Dairy Science 51, 629.

Bolan-Canqui H, Shaver TM, Lindquist JL, Shapiro CA, Elmore RW, Francis CA and Hergert GW (2015) Cover crops and ecosystem services: insights from studies in temperate soils. Agronomy Journal 107, 2449–2474.

Bolan NS and Kemp P (2003) A review of factors affecting and prevention of pasture-induced nitrate toxicity in grazing animals. Proceedings of the New Zealand Grassland Association 65, 171–178. doi: 10.3358/jnag.2003.65.2492.

Brummer F, Sedevic K, Nester P, Gaugler E and Schauman C (2015) Annual cover crop options for grazing and haying in the northern plains. North Dakota State Univ. Ext Bull. R1759, Fargo, ND.

Brummer J, Johson S, Obour A, Caswell K, Moore A, Holman J, Schipanski M and Harmonky K (2018) Managing spring planted cover crops for livestock grazing under dryland conditions in the high plains region. Colorado State University Extension Fact Sheet No. 0309, Fort Collins, CO.

Burrows G, Horn G, McNew R, Croy L, Keeton R and Kyle J (1987) The prophylactic effect of corn supplementation on experimental nitrate intoxication in cattle. Journal of Animal Science 64, 1682–1689.

Carr PM, Bell JM, Boss DL, DeLaune P, Eberly JO, Edwards L, Fryer L, H, Graham C, Holman J, Islam MA, Liebig M, Miller PR, Obour A and Xue...
Q (2021) Annual forage impacts on dryland wheat farming in the Great Plains. Agronomy Journal 113, 1–25.

Cash D, Funston R, King M and Wichman D (2002) Nitrate toxicity of Montana forages. Montana State University Extension Service MontGuide 200205. Bozeman, MT.

Coleman SW, Moore JE and Wilson JR (2004) Quality and utilization. In Moser LE, Burson BL and Sollenberger LE (eds), Warm-season (C4) Grasses, Agronomy Monographs 43. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, pp. 267–308. doi: 10.2134/agronmonogr43.c8.

Cooper J and Taitton N (1968) Light and temperature requirements for the growth of tropical and temperate grasses. Herbage Abstracts 38, 167–176.

Cordova F, Wallace JD and Pieper RD (1978) Forage intake by grazing livestock: a review. Journal of Range Management 31, 430–438.

Crawford R, Kennedy W and Johnson W (1961) Some factors that affect nitrate accumulation in forages 1. Agronomy Journal 53, 159–162.

Davis AS, Hill JD, Chase CA, Johanns AM and Liebman M (2012) Increasing cropping system diversity balances productivity, profitability and environmental health. PLoS ONE 7, e47149.

Daveison K, Hansel W, Krook I, McIntere K and Wright M (1964) Nitrate toxicity in dairy heifers. I. Effects on reproduction, growth, lactation, and vitamin A nutrition. Journal of Dairy Science 47, 1065–1073.

Drinkwater LE, Waggoner P and Sarrantino M (1998) Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–265.

Duble R, Lancaster J and Holt E (1971) Forage characteristics limiting animal performance on warm-season perennial grasses 1. Agronomy Journal 63, 795–798.

Ely R, Kane E, Jacobson W and Moore L (1953) A study of the crude fiber and nitrogen-free extract fractions of orchard grass hay and the digestibility of some of the constituents by milking cows. Journal of Dairy Science 36, 334–345.

Emerick R (1988) Nitrate and urea toxicities. In Church DC (ed), The Ruminant Animal: Digestive Physiology and Nutrition. Englewood Cliffs, NJ: Prentice-Hall, pp. 480–484.

Faé GS, Sulc RM, Barker DJ, Dick RP, Eastridge ML and Lorenz N (2009) Integrating winter annual forages into a no-till corn silage system. Agronomy Journal 101, 1286–1296.

Farney J, Shoup D, Betherost D, Blasi D and Holman J (2018) Forage crops: grazing management: toxic plants. Manhattan: Kansas State University Agricultural Experiment Station and Cooperative Extension Service MF3244.

Fick G, Holt D and Lugg D (1988) Environmental physiology and crop growth. In Hanson AA, Barnes DK and Hill RR (eds), Alfalfa and alfalfa improvement, Agronomy Monographs 29. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, pp. 163–194. doi: 10.2134/agronmonogr29.c5.

Ford CW, Morrison JM and Wilson JR (1979) Temperature effects on lignin, hemicellulose and cellulose in tropical and temperate grasses. Australian Journal of Agricultural Research 30, 621–633.

Fox J and Weisberg S (2011) An R Companion to Applied Regression, 2nd Edn. Thousand Oaks, CA: Sage. URL: http://soserv.sossci.mcmaster.ca/ fjfox/Books/Companion.

Franzluebbers A and Stuedemann J (2007) Crop and cattle responses to tillage systems for integrated crop–livestock production in the Southern Piedmont, USA. Renewable Agriculture and Food Systems 22, 168–180.

Franzluebbers AJ and Stuedemann JA (2008a) Early response of soil organic fractions to tillage and integrated crop–livestock production. Soil Science Society of America Journal 72, 613–625.

Franzluebbers AJ and Stuedemann JA (2008b) Soil physical responses to cattle grazing cover crops under conventional and no tillage in the Southern Piedmont USA. Soil and Tillage Research 100, 141–153.

Gan Y, Hamel C, O’Donovan JT, Cutforth H, Zentner RP, Campbell CA, Niu Y and Poppy L (2015) Diversifying crop rotations with pulses enhances system productivity. Scientific Reports 5, 1–14.

Grant K, Kreyling J, Dienstbach LFH, Beierkuhlein C and Jentsch A (2014) Water stress due to increased intra-annual precipitation variability reduced forage yield but raised forage quality of a temperate grassland. Agriculture, Ecosystems & Environment 186, 11–22.

Hassink J (1992) Density fractions of soil microorganic matter and microbial biomass as predictors of C and N mineralization. Soil Biology & Biochemistry 27, 1099–1108.

Hatfield JL, Sauer TJ and Prueger JH (2001) Managing soils to achieve greater water use efficiency: a review. Agronomy Journal 93, 271–280.

Hodgson EA, Warren ND, Smith RG and Sideman RG (2016) In-season and carry-over effects of cover crops on productivity and weed suppression. Agronomy Journal 108, 1624–1635.

Khan QA and McVay KA (2019) Productivity and stability of multi-species cover crop mixtures in the Northern Great Plains. Agronomy Journal 111, 1817–1827.

Khorasani G, Jedel P, Helm J and Kelly J (1997) Influence of stage of maturity on yield components and chemical composition of cereal grain silages. Canadian Journal of Animal Science 77, 259–267.

Kruithof HM, Bastiaans L and Kropf MJ (2008) Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. Weed Research 48, 492–502.

Lawley YE, Teasdale JR and Weil RR (2012) The mechanism for weed suppression by a forage radish cover crop. Agronomy Journal 104, 205–214.

Lensen AW, Johnson G and Carlson G (2007) Cycling sequence and tillage system influences annual crop production and water use in semiarid Montana, USA. Field Crops Research 100, 32–43.

Lenth R, Singmann H, Love J, Buerkner P and Vpve M (2018) Emmeans: estimated marginal means, a R package version 1.3.3, Available at https://CRAN.R-project.org/package=emmeans.

Lenz ME, Farney JK, Kern RJ, Orvis CE and Drewnoski ME (2019a) Nitrate toxicity in annual forages: survey of beef producer perspectives and samples submitted to a commercial testing laboratory in Nebraska. Applied Animal Science 35, 455–463.

Lenz ME, Kern RJ, Orvis CE and Drewnoski ME (2019b) Nitrate concentrations of annual forages grown for grazing in Nebraska. University of Nebraska-Lincoln Nebraska Beef Cattle Reports. 1035. Lincoln, NE. Available at http://digitalcommons.unl.edu/animalscience/1035.

Liebig MA, Tanaka DL, Kronberg SL, Scholljegerdes EJ and Karn JF (2012) Integrated crop and livestock in central North Dakota, USA: agroecosystem management to buffer soil change. Renewable Agriculture and Food Systems 27, 115–124.

Liebig MA, Hendrickson JR, Archer DW, Schmer MA, Nichols KA and Tanaka DL (2015) Short-term soil responses to late-seeded cover crops in a semi-arid environment. Agronomy Journal 107, 2011–2019.

McLean RA, Sanders WL and Stroup WW (1991) A unified approach to mixed linear models. The American Statistician 45, 54–64.

Merrill SD, Tanaka DL and Hanson JD (2002) Root length growth of eight crop species in a haplustoll soil. Soil Science Society of America Journal 66, 913–923.

Minson D (1981) Nutritional differences between tropical and temperate pastures. In Morley FH (ed.), Grazing Animals. Amsterdam: Elsevier, pp. 143–158.

Moore KJ and Dixon PM (2015) Analysis of combined experiments revisited. Agronomy Journal 107, 763–771.

Myers R and Watts C (2015) Progress and perspectives with cover crops: interpreting three years of farmer surveys on cover crops. Journal of Soil and Water Conservation 70, 125A–129A.

National Research Council (1996) Nutrient Requirements of Beef Cattle. Washington, DC: National Academy Press.

National Research Council (2016) Nutrient Requirements of Beef Cattle. Washington, DC: National Academy Press.

Nelson C and Moser LE (1994) Plant factors affecting forage quality. In Fahey G, Collins CJ, Mertens DR and Moser LE (eds), Forage Quality, Evaluation, and Utilization. Madison, WI: American society for Soil Science, pp. 115–154. doi: 10.2134/1994.foragequality.c3.

Pauktan K, Parton WJ and Persson J (1992) Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil Science Society of America Journal 56, 476–488.

R Core Team (2020) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. Available at: http://www.R-project.org/.

Russelle MP, Eitz MH and Franzluebbers AJ (2007) Reconsidering integrated crop–livestock systems in North America. Agronomy Journal 99, 325–334.
Sanderson M, Johnson H and Hendrickson J (2018) Cover crop mixtures grown for annual forage in a semi-arid environment. *Agronomy Journal* **110**, 525–534.

Smart A, Derner J, Hendrickson J, Gillen R, Dunn B, Mousel E, Johnson P, Gates R, Sedivec K, Harmany K, Volesky J and Olson KC (2010) Effects of grazing pressure on efficiency of grazing on North American Great Plains rangelands. *Rangeland Ecology & Management* **63**, 397–406.

Snapp SS, Swinton SM, Labarta R, Mutch D, Black JR, Leep R, Nyiraneza J and O’Neil K (2005) Evaluating cover crops for benefits and costs and performance within cropping system niches. *Agronomy Journal* **97**, 322–332.

Sollenberger LE and Vanzant ES (2011) Interrelationships among forage nutritive value and quantity and individual animal performance. *Crop Science* **51**, 420–432.

Teasdale JR and Abdul-Raki AA (1998) Comparisons of mixtures vs. monocultures of cover crops for fresh-market tomato production with and without herbicide. *HortScience* **33**, 1163–1166.

Thompson L (2014) *Overview of Nitrate and Nitrate Poisoning*, Merck Veterinary Manual. New Jersey: Merck and Co.

Undersander D, Combs D, Shaver R and Thomas D (1999) *Nitrate Poisoning in Cattle, Sheep and Goats*. University of Wisconsin-Madison Extension Cooperative Service. Madison, WI: University of Wisconsin-Madison.

USDA-FSA (2020) Montana Farm Service Agency 2020 reported crops. Bozeman, MT: U.S.A. Farm Services Agency, Montana Office. Retrieved from [https://www.fsa.usda.gov/state-offices/Montana/resources/index](https://www.fsa.usda.gov/state-offices/Montana/resources/index).

USDA-NRCS (2021a) Cover crop (code 340) seed calculator. Electronic Field Office Technical Guide. USDA Natural Resources Conservation Service, Bozeman, Montana. Available at [https://efotg.sc.egov.usda.gov/#/state/MT](https://efotg.sc.egov.usda.gov/#/state/MT) (last accessed: July 26, 2021).

USDA-NRCS (2021b) Cover crop (code 340) practice specification. Electronic Field Office Technical Guide. USDA Natural Resources Conservation Service, Bozeman, Montana. Available at [https://efotg.sc.egov.usda.gov/#/state/MT](https://efotg.sc.egov.usda.gov/#/state/MT) (last accessed: July 26, 2021).

USDA-SARE (2015) Cover cropping for pollinators and beneficial insects. Available at [http://www.sare.org/Learning-Center/Bulletins/Cover-Cropping-for-Pollinators-and-Beneficial-Insects](http://www.sare.org/Learning-Center/Bulletins/Cover-Cropping-for-Pollinators-and-Beneficial-Insects) (accessed 15 July, 2021).

Weil R and Kremen A (2007) Thinking across and beyond disciplines to make cover crops pay. *Journal of the Science of Food and Agriculture* **87**, 551–557.

Wilson J (1943) Nitrate in plants: its relation to fertilizer injury, changes during silage making, and indirect toxicity to animals. *Journal of the American Society of Agronomy* **35**, 279–290.

Wortman SE, Francis CA, Bernards ML, Drijber RA and Lindquist JL (2012) Optimizing crop cover benefits with diverse mixtures and an alternative termination method. *Agronomy Journal* **104**, 1425–1435.