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Long-term cover crop effects on biomass, soil nitrate, soil water, and wheat

Perry R. Miller[1] | **Clain A. Jones**[1] | **Catherine A. Zabinski**[1] | **Susan M. Tallman**[1,2] | **Megan L. Housman**[1,3] | **Kristen M. D'Agati**[1] | **Jeffrey A. Holmes**[1,#]

[1]Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT, USA

[2]USDA Natural Resources Conservation Service, Bozeman, Montana, USA

[3]J.R. Simplot, Boise, Idaho, USA

Correspondence
Perry Miller, Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59717-3120, USA.
Email: pmiller@montana.edu

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[#]Jeffrey A. Holmes is retired.

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Abstract

Cover crops during summer fallow have been rarely researched in the semiarid northern Great Plains. This study was conducted during 2012–2019 at four Montana locations and included four functional groups (Brassica family, fibrous-rooted crops, legumes, and tap-rooted crops). Eleven treatments included sole functional groups, a *Full Mix*, the *Full Mix* minus each functional group, pea, and chemical fallow. Wheat (*Triticum aestivum* L.) was grown after each cover crop year with three nitrogen (N) fertilizer rates. Cover crops were terminated with herbicide at first flower stage of pea (*Pisum sativum* L.) 57 to 66 days after planting. Shoot biomass averaged 2.0 Mg ha^{-1} over eight site-years representative of dryland farming in Montana. Using equal overall plant densities, treatments with six species averaged 13% greater biomass than two species. Measured at termination to a 0.9-m depth, *Fallow* held greater soil water than cover crop treatments, with *Fallow* averaging 57 mm greater than the *Full Mix*. Soil nitrate averaged 49 kg N ha^{-1} greater after *Fallow* than the *Full Mix*; the *Legume* treatment averaged 26 kg N ha^{-1} greater than the *Minus Legume* treatment. Wheat yield on *Fallow* averaged 0.85 Mg ha^{-1} greater than the *Full Mix* in 5 of 10 site-years, mainly at the driest site-years. The *Legume* treatment elevated wheat protein over the *Minus Legume* treatment by an average of 15 g kg^{-1}. Cover crops grown during summer fallow reduced soil nitrate-N, soil water, and wheat yields compared with chemical fallow, especially in the major wheat growing region of north central Montana.

1 | INTRODUCTION

North central Montana (USDA-NRCS Major Land Resource Area 52) accounts for 0.91 million ha of dryland wheat (*Triticum aestivum* L.) production, with summerfallow accounting for 37% (0.77 million ha) of all dryland annual cropping area in that region (USDA-FSA, 2021). The long-term average annual precipitation for this region is 250 to 350 mm, notably lower than other parts of the northern Great Plains (Padbury et al., 2002; Figure 1). While summerfallow helps recharge valuable soil water in the northern Great Plains, it also increases erosion (Campbell et al., 1991), soil salinization (Black et al., 1981), and nitrate leaching (John et al., 2017), while decreasing soil

Abbreviations: LSD, least significant difference; MBrassica, Minus Brassica; MFibrous, Minus Fibrous, MLegume, Minus Legume; MTap, Minus Tap Root; SW, spring wheat; WW, winter wheat.

organic matter (Campbell et al., 2000) and biological activity (Acosta-Martinez et al., 2007).

Cover crops, especially compared to fallow, can provide a diverse array of benefits, some of which will increase with either biomass production or the type of cover crop (Blanco-Canqui et al., 2015; Reiss & Drinkwater, 2022). Reducing soil erosion by protecting the soil surface could be a function of both quantity of biomass and plant form (rosette vs graminoid). Similarly, root morphology can influence soil penetration in compacted soils (Chen & Weil, 2010), and tap-rooted species can increase nutrient scavenging and decrease nitrate leaching at depth (Dunbabin et al., 2003). Nitrogen (N) fixation by legumes along with the carbon (C):N ratio of legume versus non-legume biomass will affect quality and N mineralization rates of organic residues left by the cover crop (Lupwayi et al., 2004; Rannells & Wagger, 1996).

For producers in areas that are too dry for economically efficient annual cropping (Zentner & Campbell, 1988), cover crops as a partial summerfallow replacement strategy may be economical (Zentner et al., 2004). Previous cover crop work in Montana has mainly focused on annual legumes as early season partial summerfallow replacement (Burgess et al., 2014; Miller et al., 2011, 2015; O'Dea et al., 2013). Farmers in Montana have recently shown interest in growing annual cover crop mixes, but that management is likely occurring on < 50,000 ha and is grown mainly for alternative forage (Figure 2). Multi-species cover crops show higher biomass production than single species in the western Corn Belt (Wortman et al., 2012), and in Montana, Khan and McVay (2019) showed that multi-species cover crop mixes grown in midsummer increased biomass 14% compared to monocultures.

In subhumid areas, multispecies cover crop mixes can provide soil benefits such as increased biomass inputs, nitrogen retention, and weed suppression but can also reduce soil nitrogen for subsequent crops (Finney et al., 2017). In subhumid Michigan, rye (*Secale cereale* L.)—vetch (*Vicia villosa* Roth.) bicultures produced equal or greater biomass than the component monocultures since fall rye used soil N while hairy vetch relied on dinitrogen fixation (Hayden et al., 2014). While cover crops may contribute multiple ecosystem services (Reiss & Drinkwater, 2022), considerations of cover crops in dryland agricultural systems need to account for negative impacts on the following cash crop via excessive soil water use (Nielsen et al., 2016). In semiarid Montana, Miller et al. (2018) found a barley (*Hordeum vulgare* L.)—pea (*Pisum sativum* L.) biculture significantly out-yielded sole pea and produced the same yield as sole barley but with greater forage N concentration. Research on the role of single species legume covers (mostly pea) in semiarid Montana has shown mixed results. In the relatively moist Gallatin Valley in southwestern Montana, Burgess et al. (2014) and Miller et al. (2015) showed that legume covers could have positive impacts. However, in drier north-central Montana, the economic potential of legume covers has been mixed (Miller et al., 2006; O'Dea et al., 2013) to negative (Miller, unpublished data, 2019). Further exploration of the biomass yield of complex mixes grown during the summerfallow period, and their effects on soil and subsequent grain crops, is required for regions of Montana that receive scant precipitation.

Core Ideas

- Soil improvement via cover crop growth is an uncertain trade-off with soil water and nitrogen use.
- May–June rainfall best predicted cover crop biomass ($Y = 757 + 12.4X$; Adj. $R^2 = 0.72$; $p < 0.01$).
- Cover crop treatments that included six crop species averaged 13% greater biomass than those with only two species.
- An eight-species cover crop mix averaged 57 mm less soil water and 49 kg ha^{-1} less soil N compared with fallow.
- Wheat yield on fallow averaged 0.85 Mg ha^{-1} (22%) greater than cover crops for 5 of 10 site-years.

The objectives of this research were to determine long-term plant functional group effects on: (1) cover crop biomass, (2) soil water and nitrate-N, and (3) subsequent wheat yield and protein. Specifically, we aimed to better understand cover crop production by (1) measuring the relationship between precipitation and previous N fertilizer rate on cover crop biomass, and (2) comparing biomass yield of six-species polycultures with two-species cover crop treatments. We hypothesized that in semi-arid regions, growing season rainfall would be a major driver of cover crop biomass production and that cover crop mixtures with a greater number of species would have higher, and more stable, biomass production. We also hypothesized that wheat yield and protein would be affected negatively by the soil water and N use during cover crop growth, compared with standard practices of chemical summer fallow. Such negative aspects of cover crops would best be fully discussed as trade-offs with potential improvements in soil quality, which will be presented in a second paper from this study.

2 | MATERIALS AND METHODS

2.1 | Sites

This study was conducted at four locations; two in southwestern Montana and two in north central Montana (Figure 1).

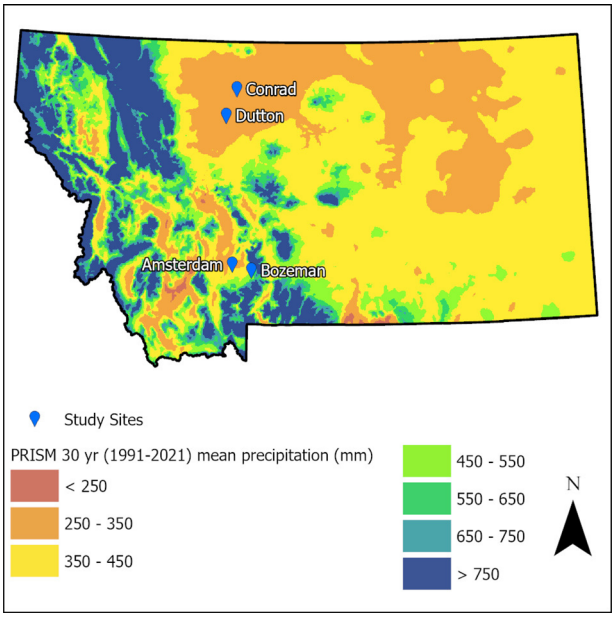

FIGURE 1 Locations of the four mixed cover crop study sites within Montana, including 30-year mean precipitation amounts (PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, US Average Total Precipitation, 1991–2020 [800 m; BIL], data created October 29, 2021, accessed May 23, 2022).

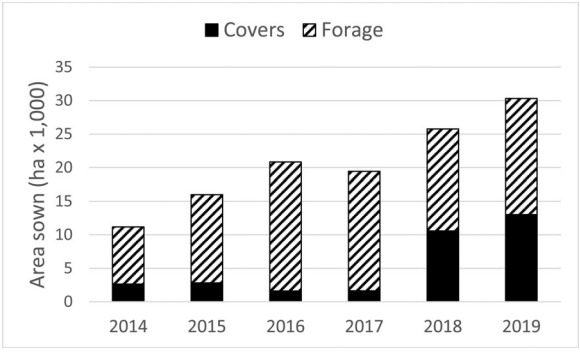

FIGURE 2 Non-irrigated area sown to annual crop mixtures including two or more crop types in Montana, 2014–2019. "Covers" included annual crop mixtures designated as "Cover," "Green Manure," or "Left Standing." Forage includes annual crop mixtures designated as "Forage" or "Grazing." In Montana, records of "Cover only" began within the "Mixed Forage" category in 2014, and assumed a separate "Cover Crop" category in 2018, which was discontinued in 2020 (USDA-NASS, https://www.fsa.usda.gov/state-offices/Montana/resources/index).

Our general intent was to compare cover crop responses in "wet" versus "dry" semiarid locations. The 1981–2010 average annual precipitation totals at Amsterdam and Bozeman were 358 mm (Belgrade—Western Regional Climate Center Station 240622) and 501 mm (Bozeman—WRCC Station 241044), respectively, and 303 mm for Conrad and Dutton (Conrad—WRCC Station 241974). Typical of the spring-centric precipitation pattern for this region, an average of 32%–37% of the annual precipitation at each site is received in the May–June period. Mean annual temperature for the same 30-year period was 7.4°C at Amsterdam, 7.0°C at Bozeman, and 6.2°C at Conrad/Dutton. To better sample "environment" with the cover crop and wheat alternate-year phases of this study, we used a staggered start, with Amsterdam and Conrad in 2012, and Bozeman and Dutton in 2013. Soil properties (top 15 cm) were characterized for each field site (Table 1). All sites, except Bozeman, had a lengthy history of wheat-fallow rotation. Available potassium (K) levels were well above the Montana critical level of 250 mg kg^{-1}, and available phosphorus (P) levels were all above Montana's critical level of 16 mg kg^{-1} except at Amsterdam (13 mg kg^{-1}). The northern sites had higher clay content, but notably the Bozeman site had approximately double the soil organic carbon of the remaining sites, owing to greater annual precipitation and a lengthy prior field history of perennial hay production. The Amsterdam field site was located on an eroded knoll landscape position, chosen presumably to be a highly responsive field site for soil improvement by cover crops. Due to limited funding, the Bozeman and Dutton sites were maintained only through two cover crop/fallow–wheat cycles (4 years), while the Amsterdam and Conrad sites were maintained for four cycles (8 years).

2.2 | Cover crop species

Cover crop species were chosen to represent four plant functional groups: (1) *Brassica family* for the unique biochemistry associated with that plant family, (2) *Fibrous root* to contribute greatest to soil organic carbon, (3) *Legume* for soil nitrogen cycling, and (4) *Tap root* to increase soil water infiltration and to reduce compaction, and due to particular farmer collaborator interest in this category. We included two species in each functional group for planned redundancy of that function, but in some groups, they varied over time as we discovered the most suitable representatives for each group (Table 2). For the *Brassica* family, daikon radish [*Raphanus sativus* var. *longipinnatus* (L.) G. Beck] was familiar to us due to preliminary research and on-farm observations where it grew vigorously in cover crop mixes. Camelina [*Camelina sativa* spp. *sativa* (L.) Crantz] was initially included in the *Brassica* treatment due to low seed cost and its reputation for being easy to grow; however, when sown at a 2-cm depth with other species, establishment rates were very low at both sites in 2012. Further, it posed a volunteer crop (i.e., weed) problem in winter wheat on a farm-scale research site near Conrad, MT (P.R. Miller, personal observation, May 9, 2014). Thus, camelina was replaced with winter rapeseed (*Brassica napus* L.), which maintained a basal rosette growth habit

TABLE 1 Pre-study site characteristics of four cover crop study sites in Montana.

	Amsterdam	Conrad	Bozeman	Dutton
Sample date	Mar 26, 2012	Apr 11, 2012	Apr 12, 2013	Apr 10, 2013
Location	45.72° N, 111.37° W	48.21° N, 111.36° W	45.67° N, 110.98° W	47.83° N, 111.57° W
Elevation (m)	1446	1039	1486	1050
Soil classification	frigid Typic Calciustoll	frigid Aridic Argiustoll	frigid, Typic Argiustoll	frigid, Aridic Argiustoll
Texture[a]	Silt loam	Clay loam	Silt loam	Clay loam
pH	8.2	6.5	7.0	6.7
Organic carbon (g kg^{-1})	14	14	33	19
Nitrate-N (mg kg^{-1})	6.0	8.5	7.3	7.5
Olsen P (mg kg^{-1})	13	28	32	43
Extractable K (mg kg^{-1})	359	498	346	595

[a]Soil properties measured at 0-to-15-cm depth.

TABLE 2 Species used in cover crop treatments and targeted plant density, 2012–2018.

Functional group	Species	Variety	2012	2013	2014–2018
			plants m^{-2}		
Brassica	Camelina	*SO-02*	200	–	–
Brassica	Radish	vns	60	120	120
Brassica	Winter rapeseed	*Dwarf Essex*	–	120	120
Fibrous root	Canary seed	*CDC Maria*	–	–	120
Fibrous root	Italian ryegrass	*Tetila*	240	–	–
Fibrous root	Oat	*Oatana*	160	120	120
Fibrous root	Proso millet	*Dawn*	–	120	–
Legume	Common Vetch	vns	80	–	–
Legume	Lentil	*Indianhead*	–	120	120
Legume	Pea	*Arvika*	80	120	120
Tap root	Safflower	*MonDak*	50	120	120
Tap root	Turnip	vns	60	120	120

Abbreviation: vns, variety not specified.

when sown in spring. Our goal with the *Fibrous* treatment was to choose monocot species not widely grown in Montana to engender diversity relative to wheat and barley. Oat (*Avena sativa* L.) was chosen because it is fatally toxic to wheat stem sawfly larvae (*Cephus cinctus* Norton), an important and persistent insect problem in Montana (Criddle, 1923). Perennial ryegrass (*Lolium multiflorum* L.) was chosen for its vegetative growth for ground cover, but without potential seed production in an annual crop environment. However, in 2012, a small percentage of ryegrass cover crop plants produced reproductive stems, raising concern about potentially introducing a new weed problem to host farms. Proso millet (*Panicum miliaceum* L.) replaced ryegrass but despite being a relatively warm growing season, 2013 proved too cool for any significant growth of that C_4 crop during our spring growth period. Thus, for the remainder of the study, canaryseed (*Phalaris canariensis* L.) was grown as the redundant partner to oat. Pea has been commonly researched in the northern Plains, both as a grain crop and as a N-fixing cover crop, and so it was included in the *Legume* group, given the already existing knowledge. Our desire was to find another legume species where seed was inexpensive and would increase diversity within the *Legume* group. Common vetch (*Vicia sativa* L.) was sown in 2012. However, it proved very tolerant to glyphosate application, which did not kill common vetch, allowing transpiration to continue for more than one month after application. Thus, for 2013 onward, we replaced vetch with black lentil (*Lens culinaris* Medik.; PI 320952), promoted by the University of Saskatchewan for its green manure purpose in 1986 (Anderst, 1992). Safflower (*Carthamus tinctorius* L.) is a commonly grown crop in Montana, and because of its deep root system (Miller & Holmes, 2012), it was

TABLE 3 Cover crop treatments and functional group composition.

	Treatment	Functional group composition
1	Fallow	–
2	Pea	Pea
3	Full Mix	Brassica, fibrous root, legume, tap root
4	Brassica	Brassica
5	Fibrous Root	Fibrous root
6	Legume	Legume
7	Tap Root	Tap root
8	Minus Brassica	Fibrous root, legume, safflower[a]
9	Minus Fibrous	Brassica, legume, tap root
10	Minus Legume	Brassica, fibrous root, tap root
11	Minus Tap Root	Brassica, fibrous root, legume

[a]Turnip excluded from treatment to avoid confounding result, since turnip is also a Brassica.

TABLE 4 Seeding, termination, and soil sampling dates for all sites, 2013–2018.

Year	Site	Seed date	Term. date	Sample date
2013	Bozeman	2 May	5 July	16 July
	Dutton	5 May	10 July	11 July
2014	Amsterdam	8 May	9 July	16 July
	Conrad	9 May	7 July	8 July
2015	Bozeman	30 Apr.	30 June	1 July
	Dutton	27 Apr.	1 July	8 July
2016	Amsterdam	3 May	1 July	8 July
	Conrad	4 May	30 June	5 July
2018	Amsterdam	3 May	6 July	12 July
	Conrad	14 May	11 July	18 July

included in the *Tap root* functional group. Turnip (*Brassica rapa* L.) was also chosen for the Tap root group. Even though turnip is also in the Brassica family, it is a species commonly used in cover crop mixes for its tap root function, and it has obligate formation of the root bulb, unlike the case for daikon radish where root bulb formation is conditioned by day length (and so that root bulb character was absent from the *Brassica family* group in this study). As such, the *Tap root* group was a mix of one basal (turnip) and one vertical species (safflower), similar to the *Brassica family* group. Various combinations of these functional groups were used to form nine cover crop treatments, including all species in one mix, each functional group separately, and the *Full Mix* minus each functional group (i.e., six species mixes) following the example of Liebig et al. (2015) with post-harvest covers at Mandan, ND. Additionally, chemical fallow and sole pea controls were included for a total of 11 treatments (Table 3).

2.3 | Experimental design and plot management

The experiment was set up in a randomized complete block design in a split-plot arrangement, with each block containing the 11 cover crop treatments, with four replicate blocks per site. Main plots (7.3 × 14.6 m) were cover crop treatments while the split plot (7.3 × 4.9 m) was N application during the wheat cropping phase. The cover crop treatments were sown directly into wheat stubble on commercial farm fields, targeting the summer fallow period, and repeated in place over years. In north central Montana, wheat is typically sown after a year of summerfallow, during which time the soil is kept plant-free with non-selective herbicides to prevent soil water and nutrient use. Thus, one harvestable grain crop is grown every 2 years. Winter wheat is typically sown in late September of the fallow year and harvested in mid- to late July, or spring wheat is sown the following spring, usually in April, and harvested late July to mid-August. This study's purpose was to explore the role of cover crops providing biological inputs to soil during the normal summer fallow period, by growing a crop which is terminated at an immature stage before it has fully exhausted stored soil water accumulated over the previous winter. Then, wheat, winter or spring, as best suited to the local field situation (primarily for weed management concerns or to provide suitable soil sampling windows in the fall and/or spring) was sown following the cover crop treatments. All sites had no-till farming histories greater than 4 years except for the Bozeman location, which had been tilled annually for at least 4 years. A low disturbance, 1.8-m wide no-till disk drill was used with 23-cm row spacing and mid-row disk-banders for urea-N fertilization application during wheat years (*Fabro Ltd*., Swift Current, Canada). Seed depth was 2 cm for both the cover crop and wheat phases. Glyphosate was applied pre-seeding at 630-840 g a.e. ha^{-1}, by collaborating farmers at Conrad and Dutton, with various adjuvants (most commonly ammonium sulfate at ~2% of spray solution by weight) to enhance herbicide efficacy. In 2012, cover crops were sown in early April, but in all years after that, seeding occurred late April to early May to be more consistent with grower practice in Montana (Table 4) and to allow pre-seeding glyphosate application to be more effective. In 2012 at Conrad, a pre-seeding glyphosate application of 780 g a.e. ha^{-1} failed to control downy brome (*Bromus tectorum* L.), which caused us to abandon data for that site-year. Fortunately, downy brome did not pose a weed problem in the ensuing 7 years at that site. Reasoning that cover crop seed and the seeding operation were already significant expenses, no fertilizer was applied during the cover crop year.

In 2012, plant densities were based on "recommended" densities for optimal grain or vegetable yield (Table 2). However, this approach biased biomass in favor of species

with higher recommended plant densities, despite cover crop purpose being independent of grain or vegetable yield. For example, at Amsterdam in 2012, the *Fibrous* treatment was sown at the highest plant density and yielded the greatest biomass (1.05 Mg ha^{-1}), while the *Tap root* treatment used low recommended densities for turnip and safflower, resulting in much lower biomass (0.41 Mg ha^{-1}). Thus, in subsequent years, all treatments were sown at a common target density of 120 plants m^{-2} to avoid plant density bias, and only results from 2013 onward were considered in this report. After that seeding change, actual plant density averaged 114 plants m^{-2} for 10 site years × 10 cover crop treatments, but varied among site-years, ranging from overall treatment averages of 70 to 161 plants m^{-2} (data not shown). Overall plant density averages varied much less among treatments, from 100 (*Brassica*) to 123 (*Fibrous root*) plants m^{-2} (data not shown).

Cover crops were terminated with glyphosate from June 30 to July 11 after approximately 60 days of growth (Table 4), using the same range of application rates as stated above. First bloom of the pea treatment was used as a biological marker for termination of all treatments, when ≥50% of the plants had at least one open flower. Occasionally, termination occurred 1–3 days early when, for example, weather dictated early termination, but never late. Following cover crop treatments, sawfly-resistant spring (cv. *Duclair* except cv. *Vida* in 2015 at Amsterdam) or winter wheat (cv. *Warhorse*) were grown in the subsequent year to assess the cash crop response to cover crop treatments. Wheat was sown at a target density of 200 plants m^{-2} (59–78 kg ha^{-1}) perpendicular to the cover crop rows in split-strip plots at three nitrogen fertilizer rates, (0, 67, and 134 kg N ha^{-1}), banded mid-row, in a split plot design with fertilizer rates as the subplot level in the same four replicate blocks. No phosphate fertilizer was applied since three of four sites tested very high in available phosphorus, and the other site, Amsterdam, was not considered strongly deficient (Table 1).

2.4 | Data collection and analysis

Crop species density was measured for each plot 4 weeks after seeding by counting 4 m of row length, which was flagged for subsequent biomass measurement at termination. Aboveground cover crop and corresponding weed biomass were sampled by hand either immediately prior to glyphosate application or within 72 h after glyphosate application. Plants were cut at the soil surface (for turnip, the root bulb portion above soil surface was included), separated by functional group or weeds, dried for >72 h at 50°C and weighed directly out of the oven. Wheat was harvested with a plot combine, grain moisture measured with a hand-held grain moisture meter (Dickey-John) on a 375-g subsample to calculate dry weight, and protein content estimated via NIR spectroscopy on a 500-g subsubsample with an *Infratec 225* instrument (FOSS Analytical A/S) and calculated to zero grain moisture.

Within one to 11 days after cover crop termination, soil was sampled in all medium N rate treatments, and at all N rates for Fallow, Pea, and Full treatments. A hydraulic probe (diam. = 3.0 cm) was used to sample soil to 90 cm in 30-cm sections at two locations within each subplot, and the subsamples were composited. Soil was weighed wet, dried at 50°C for at least 5 days, and then weighed dry to calculate soil water content and bulk density. Soil was ground (<2.0 mm), extracted with 1 M KCl, and analyzed for nitrate with cadmium reduction on a Lachat autoanalyzer (HACH).

Cover crop and wheat data were combined across site-years for initial analyses but strong heterogeneity of error variance occurred, and 'site-year' dominated ANOVA model variance. Thus, data were analyzed and reported by individual site-year using the standard least squares linear regression model, suitable to fully balanced experimental designs (*JMP 8*, SAS Institute, 2008). For analyses of cover crop biomass, the fallow treatment was excluded since it contained zero cover crop biomass. Weed biomass was measured for all treatments but generally did not constitute an important proportion of biomass (except for Conrad in 2018). Blocks were considered random effects and cover crop treatments and N fertilizer rates were considered fixed effects. The interaction of cover crop x fertilizer N rate (i.e., legacy effect from previous wheat for 2nd to 4th cover crop cycles) was unimportant for cover crop biomass but was occasionally significant ($p < 0.05$) during the wheat phase. This interaction was caused by the *Legume* and *Pea* treatments increasing wheat yield and grain protein at the zero N rate, compared with other treatments. However, the interaction never accounted for an important proportion of model variance. Since cover crops were sown in early May and the majority of cover crop growth occurred during the month of June in our trials, mean cover crop biomass for each site-year was regressed against three precipitation periods including June to determine which precipitation period was most predictive of cover crop biomass; (1) September–June, (2) May–June, and (3) June. To test whether species richness affected cover crop biomass, linear orthogonal contrasts were estimated to measure biomass response in the four single treatments (two species each) versus four "minus" treatments which contained three functional groups treatments (five or six species each).

3 | RESULTS AND DISCUSSION

3.1 | Cover crop biomass

Cover crop biomass was grown in alternate years with wheat, four times in 8 years, with treatments conserved exactly in place over time. It is unlikely that Montana farmers would

TABLE 5 Precipitation in the pre-crop Aug.–Apr. and crop growth periods (May–June for cover crops, May–July for wheat) at four sites in Montana, 2013–2019.

	LLTA[a]	2013	2014	2015	2016	2017	2018	2019
	Amsterdam							
Aug.–Apr.	*205*	124	191	279	172	227	260	221
May–June	*125*	–	191	–	69	–	160	–
May–July	*153*	164	–	148	–	107	–	166
	Conrad							
Aug.–Apr.	160	98	229	179	184	244	190	178
May–June	114	–	113	–	116	–	119	–
May–July	149	177	–	102	–	68	–	122
	Bozeman							
Aug.–Apr.	305	173	373	300	330	–	–	–
May–June	159	187	–	95	–	–	–	–
May–July	197	–	158	–	113	–	–	–
	Dutton							
Aug.–Apr.	160	135	163	112	237	–	–	–
May–June	114	151	–	25	–	–	–	–
May–July	149	–	121	–	99	–	–	–

Note: Growing season precipitation collected on-site with Hobo data logger Onset Computer Corp., except Bozeman which was taken directly from WRCC Station 241044.
[a]Long-term average (1981–2010) for Amsterdam calculated from Belgrade (Station 240622) which was 20 km from field site, Bozeman (Station 241044) which was 7 km from the Bozeman field site, and Conrad (Station 241974) which was 34 km from both the Conrad and Dutton field sites (Western Regional Climate Center, 2022).

TABLE 6 Year-1 mean cover crop (CC) and weed biomass values for cover crop treatments at Bozeman and Dutton, MT, 2013.

	Bozeman		Dutton	
	CC	Weed	CC	Weed
	Mg ha^{-1}			
Fallow	NA	**1.30 a**	NA	0.13
Pea	3.85 a	0.29 bc	2.66	0.01
Full	**3.94 a**	0.36 bc	2.91	0.01
Brassica	3.47 ab	0.26 c	2.89	0.04
MBrassica	3.79 ab	0.57 bc	2.51	0.08
Fibrous	3.62 ab	0.71 b	2.26	0.04
MFibrous	3.73 ab	0.36 bc	3.18	0.04
Legume	3.13 bc	0.31 bc	2.38	0.02
MLegume	3.88 a	0.32 bc	2.70	0.03
Tap	2.68 c	0.21 c	2.78	0.05
MTap	3.67 ab	0.27 bc	2.78	0.03
$LSD_{0.05}$[a]	0.70	0.45	NS	NS
	Linear contrast			
2 vs 6 species	$p < 0.01$	$p = 0.94$	$p = 0.32$	$p = 0.97$
2 species	3.22	0.37	2.58	0.04
6 species	3.77	0.38	2.79	0.05

Note: Bold indicates the largest value in the column; underlining indicates the smallest value.
Abbreviation: M indicates minus treatment.
[a]Fisher's protected LSD ($p = 0.05$).

ever grow cover crops with this frequency, but our goal was to accelerate possible treatment responses. Thus, cover crop biomass is presented by "cycle" in Tables 6–8 to gauge treatment responses over time. To estimate average cover crop biomass for typical dryland cropping areas in Montana, the wettest Bozeman site with the highest soil organic carbon was excluded, resulting in an overall average above-ground cover crop biomass of 2.0 Mg ha^{-1} for the remaining eight site-years, with individual site-years averaging from 1.1 to 2.9 Mg ha^{-1} (Tables 6–8). This overall average was very similar to the 2.1 Mg ha^{-1} average biomass measured in cool-season cover crop mixes grown in Havre, also in north central MT, during the same years, despite cover crops there being fertilized with 22.4 kg N ha^{-1}, 9.8 kg P ha^{-1}, and 18.4 kg K ha^{-1}, and grown for 2 weeks longer than in our study (Wyffels et al., 2022). However, the range in variability among years was slightly larger in the Wyffels et al. (2022) study, 0.6–2.8 Mg ha^{-1}, excluding the startup year when covers were grown on fallow.

3.2 | Precipitation effects

As is typical of this semiarid region, precipitation amounts and timing varied greatly among site-years, such that Amsterdam was notably wetter than Conrad during the May–June cover crop growth period in 2014 and 2018, but notably drier during the same period in 2016 (Table 5). As expected, Bozeman was wetter than the Dutton site in both 2013 and 2015

TABLE 7 Mean cover crop (CC) and weed biomass values for cover crop treatments from the 2nd rotation cycle at Amsterdam and Conrad, MT, 2014, and Bozeman and Dutton, MT, 2015.

	Amsterdam		Bozeman		Conrad		Dutton	
	CC	Weed	CC	Weed	CC	Weed	CC	Weed
Zero N	2.78 B	0.26	2.30 A	0.02	2.39	0.02	1.52	0.22
High N	2.98 A	0.38	2.14 B	0.05	2.28	0.03	1.56	0.23
	Mean values for cover crop treatments averaged for N rates							
Fallow	NA	**1.22 a**	NA	0.03	NA	NA[a]	NA	**1.42** a
Pea	3.18 ab	0.17 b	2.38 b	0.04	2.38	0.02	1.51 bc	0.12 b
Full	**3.23 a**	0.15 b	2.35 bc	0.01	2.44	0.03	1.38 cd	0.09 b
Brassica	2.75 c	0.36 b	2.05 de	0.06	1.92	0.02	1.15 d	0.02 b
MBrassica	2.81 bc	0.28 b	2.08 c–e	0.02	2.40	0.03	1.74 b	0.20 b
Fibrous	2.78 c	0.23 b	2.25 b–d	0.04	2.61	0.02	**2.14 a**	0.14 b
MFibrous	2.89 a–c	0.13 b	2.39 ab	0.03	2.51	0.02	1.62 bc	0.06 b
Legume	2.70 c	0.16 b	2.00 de	0.03	1.96	0.02	1.41 cd	0.20 b
MLegume	3.21 a	0.17 b	2.24 b–d	0.01	2.43	0.06	1.42 b–d	0.02 b
Tap	2.24 d	0.37 b	1.81 e	0.07	2.33	0.01	1.53 bc	0.12 b
MTap	3.05 a–c	0.26 b	**2.68 a**	0.04	2.40	0.03	1.50 bc	0.08 b
$LSD_{0.05}$[b]	0.38	0.31	0.30	NS	NS	NS	0.33	0.36
	Linear contrasts							
2 vs. 6 species	$p < 0.01$	$p = 0.02$	$p < 0.01$	$p = 0.04$	$p = 0.13$	$p = 0.07$	$p = 0.88$	$p = 0.72$
2 species	2.62	0.28	2.03	0.05	2.21	0.02	1.56	0.12
6 species	2.99	0.21	2.35	0.02	2.44	0.03	1.57	0.09

Note: Bold indicates the largest value in the column; underlining indicates the smallest value. Mean values for N legacy within a column differ by $p < 0.05$ if denoted with different letters.

Abbreviation: M indicates minus treatment.

[a]Fallow had herbicide applied inadvertently, preventing biomass measurement.

[b]Fisher's protected LSD ($p = 0.05$).

[†]NS, not significant.

during the only 2 years that cover crops were grown at those sites. Cover crop biomass (Tables 6–8) regression over 10 site-year was correlated to monthly precipitation (Table 5) during June (Adjusted $R^2 = 0.20$; $p = 0.11$), and was improved by considering the bimonthly period of May–June (Adjusted $R^2 = 0.45$; $p = 0.02$), but not by considering the longer September–June period (Adjusted $R^2 = 0.03$; $P = 0.29$). In 2018 at Amsterdam, precipitation did not relate closely to biomass production (Table 8), likely due to much greater than average precipitation during September–April (256 mm) plus greater than average May–June precipitation (160 mm). Whatever residual soil nitrate remained from the 2017 wheat crop likely was thoroughly leached from that low organic matter silt loam soil such that water was not the chief limiting factor to cover crop growth in 2018. As further evidence, the *Pea* and *Legume* treatments had much greater biomass than the remaining treatments for that site-year, likely attributable to their ability to fix atmospheric N_2 via rhizobial nodulation. If mean biomass from these two legume treatments was considered exclusively for Amsterdam-2018, then that X–Y coordinate falls very near the estimated linear regression lines for all other site-years. When that site-year was removed from the data set, the correlation between all precipitation periods and cover crop biomass improved notably with adjusted regression coefficients of 0.42 ($p = 0.04$), 0.72 ($p < 0.01$), and 0.33 ($p = 0.06$), respectively. The linear regression of cover crop biomass on May-June precipitation estimated a precipitation-use-efficiency rate of 12.4 kg ha mm^{-1} with a *y*-intercept of 757 kg ha^{-1} (Figure 3). This is lower than the water-use-efficiency values for a 10-species mix reported by Nielsen et al. (2015), which averaged 19.1 kg ha mm^{-1} over four site-years in the high plains of Colorado. Their reported values may be greater because cover crops there were grown for 10 weeks, compared with 8 weeks in our study, and their cover crop mix received fertilizer at a rate of 34 kg N ha^{-1} to ensure that water was the main limiting factor to plant growth.

3.3 | Fertilizer effects

The legacy N rate from the previous wheat crop did not influence cover crop growth importantly in any site-year until the 4th cycle of cover crops in 2018, indicating that the intervening wheat year generally extracted applied fertilizer N nearly

TABLE 8 Mean cover crop (CC) and weed biomass values for cover crop treatments from the 3rd and 4th rotational cycles at Amsterdam and Conrad, MT, 2016 and 2018.

	Amsterdam				Conrad			
	2016		2018		2016		2018	
	CC	Weed	CC	Weed	CC	Weed	CC	Weed
Zero N	1.10	0.07	1.31 B	0.04	1.61 B	0.01	1.60 B	0.35
Medium N	NA	NA	1.52 A	0.08	NS	NA	2.34 A	0.31
High N	1.15	0.13	1.52 A	0.04	1.79 A	0.02	NA[a]	NA
	Mean values for cover crop treatments averaged for N rates							
Fallow	NA	NA[b]	NA	**0.31 a**	NA	**0.09 a**	NA	**1.08 a**
Pea	**1.56 a**	0.10	**2.75 a**	0.01 b	**2.13 a**	0.01 b	**2.69 a**	0.32 bc
Full	1.17 bc	0.05	1.39 de	0.03 b	1.68 c–e	0.01 b	1.94 bc	0.19 bc
Brassica	0.99 cd	0.17	0.67 g	0.04 b	1.52 de	0.00 b	1.07 de	0.30 bc
MBrassica	1.17 b	0.05	1.64 c	0.02 b	1.67 c–e	0.01 b	2.54 a	0.20 bc
Fibrous	0.86 de	0.06	1.27 e	0.03 b	2.04 ab	0.01 b	2.35 ab	0.23 bc
MFibrous	1.28 b	0.08	1.34 de	0.02 b	1.76 cd	0.01 b	1.87 c	0.23 bc
Legume	1.23 b	0.14	2.14 b	0.01 b	1.72 c–e	0.01 b	2.46 a	0.50 b
MLegume	0.98 d	0.05	0.95 f	0.02 b	1.50 e	0.00 b	1.52 cd	0.15 c
Tap	0.72 e	0.08	0.81 fg	0.07 b	1.15 f	0.01 b	0.78 e[c]	0.31 bc
MTap	1.30 b	0.23	1.53 cd	0.05 b	1.83 bc	0.01 b	2.50 a	0.15 c
$LSD_{0.05}$[d]	0.19	NS	0.24	0.08	0.26	0.04	0.46	0.35
	Linear contrasts							
2 vs. 6 species	$p < 0.01$	$p = 0.87$	$p < 0.01$	$p = 0.92$	$p = 0.20$	$p = 0.64$	$p < 0.01$	$p = 0.09$
2 species	0.95	0.11	1.22	0.03	1.61	0.01	1.67	0.34
6 species	1.18	0.10	1.37	0.03	1.69	0.01	2.11	0.18

Note: Bold indicates the largest value in the column; underlining indicates the smallest value. Mean values for N legacy within a column differ by $p < 0.05$ if denoted by different letters.

Abbreviation: M indicates minus treatment.

[a]Field site became infested with glyphosate-resistant tumbleweed, *Kochia scoparia*, becoming common in that region. The high N legacy had fourfold the weed biomass of the lower N rates and was the majority fraction in some of the biomass samples. Thus, high N was excluded from the analysis.

[b]Fallow had herbicide applied inadvertently, preventing biomass measurement.

[c]Safflower was preferentially and severely grazed by antelope at this site, especially reducing biomass in the tap root treatment.

[d]Fisher's protected LSD ($p = 0.05$).

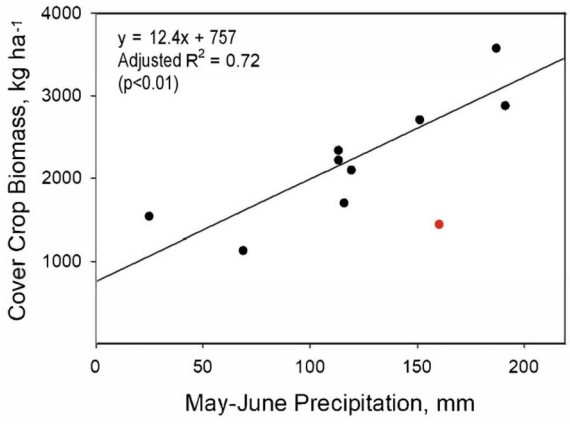

FIGURE 3 Cover crop biomass versus precipitation received during May–June for 10 site-years in Montana. Amsterdam 2018 was excluded (red) due to anomalously high overwinter and spring precipitation that likely made soil nitrogen the growth-limiting factor.

completely (Tables 6–8). Even then, the legacy effect of the medium N rate did not differ from the high N rate at Amsterdam, which both had 16% greater average cover crop biomass than the zero N legacy (Table 8). However, at Conrad in 2018, the legacy N effect of the medium N rate produced 46% greater cover crop biomass than following the zero N legacy. Unlike at Amsterdam, wheat at Conrad experienced strong drought in 2017 (68 mm total precipitation during May–July), which likely left unusually large amounts of residual nitrate-N. However, since it was evident that generally N fertilizer from the previous wheat crop did not have an important effect on cover crop biomass, the remaining discussion pertains to cover crop biomass averaged across legacy N rates.

3.4 | Functional group treatments

On average, biomass did not vary greatly among the ten cover crop treatments, ranging from 2.2 to 2.7 Mg ha^{-1} (Tables 6–8

TABLE 9 Total soil nitrate-N in the top 0.9 m of soil measured after cover crop termination in early July at Amsterdam (Amst), Bozeman (Boze), Conrad (Conr), and Dutton (Dutt), MT, 2013–2018, and in spring prior to wheat planting at Amsterdam and Conrad, 2019. Measured in medium N rate subplots.

Treatment	2013		2014		2015		2016		2018		2019	
	Boze	Dutt	Amst	Conr	Boze	Dutt	Amst	Conr	Amst	Conr	Amst	Conr
	kg of nitrate-N ha^{-1}											
Fallow	**249 a**	**87 a**	**37 a**	**63 a**	**103 a**	40 a–c	**60 a**	**87 a**	**53 a**	31	59 ab	50 b–d
Full mix	113 c	24 b	15 b–d	10 b–d	34 cd	24 cd	25 d	11 e	24 b	37	50 a–c	41 cd
Pea	177 b	47 b	26 ab	19 b–d	44 bc	51 ab	45 b	60 b	26 b	15	60 ab	**114** a
Brassica	–	–	14 b–d	11 b–d	16 e	21 d	25 d	14 e	–	–	54 ab	43 cd
MBrassica	–	–	26 ab	15 b–d	36 cd	27 cd	37 bc	38 c	–	–	50 a–c	68 b–d
Fibrous	–	–	12 cd	19 bc	36 cd	33 b–d	26 d	28 cd	–	–	40 c	34 cd
MFibrous	–	–	19 b–d	9 cd	28 de	23 cd	28 cd	16 de	–	–	49 bc	73 a–c
Legume	–	–	23 bc	20 b	54 b	**53 a**	43 b	60 b	–	–	**61 a**	90 ab
MLegume	–	–	8 d	9 cd	23 de	17 d	24 d	15 e	–	–	50 a–c	26 d
Tap	–	–	14 b–d	8 d	23 de	24 cd	24 d	23 de	–	–	42 c	43 cd
MTap	–	–	10 d	10 b–d	25 de	28 cd	22 d	19 de	–	–	56 ab	40 cd
LSD$_{0.05}$[a]	54	31	13	11	15	19	10	13	7	NS	12	43
	***p*-Values and means for linear contrasts of 2- vs. 6-species**											
p-Value	–	–	0.99	0.22	0.26	0.07	0.44	0.13	–	–	0.54	0.94
2 species	–	–	16	14	32	33	30	31	–	–	49	52
6 species	–	–	16	11	28	24	28	22	–	–	51	52

Note: Bold indicates the largest value in the column; underlining indicates the smallest value.

Abbreviation: M indicates minus treatment.

[a]Fisher's protected LSD ($p = 0.05$).

and here including the two Bozeman site-years). During the first two cover-crop cycles (Tables 6 and 7), biomass in the *Full Mix* did not differ from *Pea* for those six site-years. However, in the 3rd and 4th cycles (Table 8), *Pea* biomass was greater than the *Full Mix* in all four site-years, with *Full* biomass averaging only 68% of *Pea*. At Amsterdam, the coarse-textured soil was conducive to soil nitrate leaching, especially in 2018 when precipitation was unusually high prior to cover crop growth, favoring the growth of N_2-fixing legume cover crop treatments. However, on the finer textured soil at Conrad, soil N-enrichment by multiple cycles of legumes over the course of this study likely favored growth of wheat following the legume treatments (Table 9). Similar soil N enrichment over multiple cycles of pea cover cropping was reported in a previous long-term study at Bozeman, MT, (Miller et al., 2015) and observed also in an 8-year study at Big Sandy, MT (Miller, unpublished data, 2019). The *Tap root* group biomass appeared in the lowest statistical grouping for 7 of 10 site-years, while the *Brassica* treatment biomass was in the lowest statistical grouping for 4 of 10 site-years. Thus, it was not surprising that average biomass from single functional groups (i.e., two species only) yielded less than that from the six-species 'Minus' mixes in 6 of 10 site-years, and trended similarly for two more site-years (Tables 6–8). On average, the six-species mixes had 13% greater biomass than two-species single functional groups, and had notably less variance amongst treatments. A study in Nebraska found that increased cover crop diversity (all mixes containing 50% legumes) increased biomass in two of three study years, with six-species mixes producing 2.1 times more biomass than two-species treatments, and that more diverse cover crop mixes stabilized cover crop biomass (Wortman et al., 2012). The study authors attributed the greater biomass for six-species treatments due to superior plant recovery after a hail storm, compared with two-species treatments. Similar to our study, Khan and McVay (2019) at Huntley, MT, compared four cover crop mixes with six sole cover crops in a 2-year study and reported 14% greater average biomass yield ($p = 0.04$) from the mixes than the sole species treatments. However, in contrast, they found yield to be less stable for the mixes than the sole species treatments. While biomass in our study did not increase nearly as much from more diverse mixes, biomass production was similarly stabilized. For the two-species single functional groups, the average difference between the greatest and least biomass within site-years was 0.88 Mg ha^{-1}, equal to 40% of the average total biomass of 1.96 Mg ha^{-1}. In contrast, for the six-species treatments, the average difference between the greatest and least biomass was 0.47 Mg ha^{-1}, equal to 24% of the average total biomass of 2.11 Mg ha^{-1}. Weed biomass was greater on the chemical

fallow control than all cover crop treatments for six of eight site-years where this comparison could be made (Tables 6–8). Weed biomass on fallow averaged 0.70 Mg ha^{-1} (range 0.03 to 1.42 Mg ha^{-1}) which equated to 31% of the average cover crop biomass for those same eight site-years. Otherwise overall average weed biomass for cover crop treatments was 0.13 Mg ha^{-1} and ranged from 0.03 to 0.37 Mg ha^{-1}. On average, weeds accounted for 5% of total plant biomass for cover crop treatments, and volunteer wheat was the most common 'weed' observed except at Conrad in 2018, where kochia (*Bassia scoparia* (L.) A. J. Scott) dominated weed biomass.

In the 3rd and 4th cycles, cover crop treatments differed more strongly than during the first two cycles, ranging from 0.9 Mg ha^{-1} (*Tap root*) to 2.3 Mg ha^{-1} (*Pea*) (Table 8). *Pea* appeared in the highest statistical grouping and ranked highest in all four site-years, while the *Fibrous root* treatment appeared in the highest statistical grouping in both site-years at Conrad, but not at Amsterdam. The *Tap root* treatment ranked lowest overall for three of four site-years. This result was expected since turnip biomass was mainly below ground. Safflower was also preferentially grazed by pronghorn (*Antilocapra americana* Ord.) in both these years at Conrad, especially in 2018, limiting biomass of the *Tap root* treatment. At Conrad in 2018, turnip appeared N-deficient, especially in the 0 N legacy wheat stubble, and this may have helped explain the low biomass for the *Tap root* treatment.

3.5 | Soil response

3.5.1 | Water use

When measured shortly after cover crop termination, *Fallow* averaged 59 mm more soil water to a 0.9-m depth than the *Full Mix* and *Pea* treatments, clearly quantifying soil water depletion by cover crops (Table 10). This is in agreement with previous studies in the NGP that have reported soil water depletion by cover crops at termination; mainly legumes (Biederbeck & Bouman, 1994; Burgess et al., 2014; Miller et al., 2006, 2011, 2018; O'Dea et al., 2013). At Swift Current, SK, Biederbeck and Bouman (1994) found four annual legume cover crop species depleted soil water by 63 mm to a 1.2-m soil depth compared with minimum tillage fallow. Under no-till management, Miller et al. (2006) reported mean soil water depletion of 32 mm by a pea cover crop at three Montana locations with measurable soil depths ranging from 0.6 to 1.2 m. Under organic management at Big Sandy, MT, soil water was 35 mm less to a 0.9-m soil depth after mustard and spring pea cover crops than tilled fallow (Miller et al., 2011). Soil water depletion by legume (pea or lentil) cover crops on five farms in north central Montana was 43 mm more than chemical fallow to a 0.9-m soil depth (O'Dea et al., 2013). Similarly, lentil and pea cover crops depleted soil water by 56 mm to a 0.9-m soil depth at Amsterdam, MT (Burgess et al., 2014). Also at Amsterdam, MT, pea and barley hay treatments terminated with similar timings as for cover crop termination depleted soil water by 65 mm to a 0.9-m soil depth compared with chemical fallow (Miller et al., 2018). We re-measured soil water the following spring only in two instances at the end of the study. In 2018 after termination, soil water averaged 48 mm more under *Fallow* than the *Full Mix* and *Pea* treatments at Amsterdam, and 34 mm more under *Fallow* at Conrad. However, when measured again in 2019 prior to spring wheat seeding, *Fallow* no longer differed from cover crops at Amsterdam but soil water under *Fallow* remained 32 mm greater than cover crops ($p = 0.065$) at Conrad. Despite average 2018/19 overwinter soil water recharge in the *Full Mix* and *Pea* treatments of 97 mm at Amsterdam and 88 mm at Conrad (Table 10), the *Fallow* versus cover crop difference persisted at the drier location in north central Montana. Water use by the *Full Mix* was less than *Pea* in two of 10 site-years, at Amsterdam in 2014 and 2018, and never greater.

Although differences in soil water use among the remaining cover crop treatments generally were not large, there were a few notable patterns. After cover crop termination, soil water under the *Brassica* treatment averaged 25 mm greater than the *Minus Brassica* treatment in four of 10 site-years (Table 10). Three of these differences occurred at Amsterdam (2014, 2016, 2018) but corresponded with differences in biomass only in 2018 when *Brassica* biomass was about half of the *Minus Brassica* biomass (Tables 6–8). Very similar biomass differences occurred at Conrad in 2018, when Brassica species appeared visibly N-deficient, and yet no soil water difference was observed. Also, the *Fibrous root* treatment held an average of 22 mm greater soil water than *Minus Fibrous* after termination in four of 10 site-years, all occurring in the wetter environment of southwest Montana, including the same 3 years at Amsterdam noted above, and at Bozeman in 2013. Biomass for the *Fibrous* treatment was equal to that of the *Minus Fibrous* treatment in three of those four site-years, illustrating weak correspondence of plant biomass with soil water use for any particular site-year. The *Fibrous* treatment produced a visibly denser cover pattern which may have reduced soil evaporative losses. Differences in soil water measured after termination between the *Legume* and *Minus Legume* treatments were highly inconsistent and did not relate clearly to biomass differences except at Amsterdam in 2018. There, the *Minus Legume* treatment had only 44% of the *Legume* biomass, consequently holding 34 mm greater soil water at termination and still trending greater (19 mm, $p = 0.07$) when measured after overwinter soil water recharge and prior to spring wheat seeding. Soil water at termination averaged for the five or six-species "*Minus*" treatments was less than under two-species treatments in only two of 10 site-years despite greater "*Minus*" biomass in six of those site-years. Thus,

TABLE 10 Total soil water in the top 0.9 m of soil measured after cover crop termination in early July at Amsterdam (Amst), Bozeman (Boze), Conrad (Conr), and Dutton (Dutt), MT, 2013–2018, and in spring prior to wheat planting at Amsterdam and Conrad, 2019.

	2013		2014		2015		2016		2018		2019	
Treatment	**Boze**	**Dutt**	**Amst**	**Conr**	**Boze**	**Dutt**	**Amst**	**Conr**	**Amst**	**Conr**	**Amst**	**Conr**
	mm of rainfall equivalent											
Fallow	241 a	277 a	**190 a**	**240 a**	**267 a**	209	**204 a**	**238 a**	**232 a**	173 a	279	258
Full	194 bc	216 c	142 c	169 b	190 b–d	175	139 d	139 bc	198 de	142 b	278	229
Pea	192 c	214 c	126 e	154 bc	200 b	186	130 d	146 bc	170 f	136 bc	283	224
Brassica	203 bc	225 c	155 b	168 b	178 d	172	152 c	139 bc	217 b	**175 a**	281	233
MBrassica	198 bc	231 c	139 c	163 b	180 cd	180	139 d	128 c	190 e	133 bc	276	232
Fibrous	**244 a**	271 ab	152 b	166 b	190 b–d	197	166 b	156 b	209 bc	138 bc	285	244
MFibrous	214 bc	**284 a**	139 c	156 bc	176 d	212	139 d	143 bc	190 e	130 bc	280	220
Legume	206 bc	283 a	128 de	141 c	201 b	217	133 d	134 c	173 f	113 c	272	211
MLegume	204 bc	219 c	151 b	162 bc	184 b–d	168	153 c	140 bc	207 cd	137 bc	291	214
Tap	209 bc	232 c	140 c	152 bc	186 b–d	189	150 c	146 bc	201 c–e	141 b	281	241
MTap	206 bc	236 bc	135 cd	169 b	197 bc	190	137 d	140 bc	191 e	131 bc	284	240
$LSD_{0.05}$[a]	22	37	8	22	19	NS	10	20	10	26	NS	NS
	***p*-Values and means for linear contrasts comparing 2- vs. 6-species**											
p-Value	0.07	0.26	0.14	0.31	0.34	0.55	<0.01	0.23	0.03	0.18	0.28	0.55
2 species	216	253	144	157	189	194	150	144	200	142	280	232
6 species	206	242	141	163	184	187	141	138	195	133	283	226

Note: Bold indicates the largest value in the column; underlining indicates the smallest value.

Abbreviation: M indicates minus treatment.

[a]Fisher's protected LSD ($p = 0.05$).

in this study, there did not appear to be a strong relationship between biomass and soil water at termination among different cover crop treatments within site-years.

3.5.2 | Nitrate-N

When measured at cover crop termination, soil nitrate-N (0–0.9 m) was greater after *Fallow* than the *Full Mix* and *Pea* in eight and seven site-years, respectively, out of the 10 site-years (Table 9). For those site-years with differences, nitrate-N averaged 60 kg ha^{-1} greater under *Fallow* than under the *Full Mix*, and 33 kg ha^{-1} greater than under *Pea*. This is unsurprising given that covers take up nitrate, whereas N mineralization would have been higher under *Fallow* due to higher water content (Table 10). Previous cover crop studies from Montana have not shown as large of differences in soil nitrate-N at cover crop termination, but those studies were focused on legume species (Burgess et al., 2014; Miller et al., 2006, 2018; O'Dea et al., 2013). Under no-till soil management, a pea cover crop depleted soil nitrate-N at only one of three Montana locations, by 20 kg ha^{-1} less nitrate-N to a 0.6-m soil depth ($p < 0.10$) than chemical fallow (Miller et al., 2006). Legume (pea or lentil) cover crops depleted soil nitrate-N by an average of 16 kg ha^{-1} to a 0.9-m soil depth less than chemical fallow on five farms in north central Montana (O'Dea et al., 2013). Similarly, at Amsterdam, lentil and pea cover crops depleted soil nitrate-N by an average of 13 kg ha^{-1} to a 0.9-m soil depth less than chemical fallow (Burgess et al., 2014). Also at Amsterdam, MT, pea and barley hay treatments depleted soil nitrate by an average of 29 kg ha^{-1} to a 0.9-m soil depth compared with chemical fallow (Miller et al., 2018). Haying occurred with similar timing as for cover crop termination in the current study.

Soil nitrate after *Pea* was greater than after the *Full Mix* in 4 of 10 site-years, with an average difference of 51 kg N ha^{-1} in those four site-years. Although the *Full Mix* consisted of two N-fixing species which would have met their N needs through N fixation when soil nitrate was low, the other six species apparently extracted a substantial amount of nitrate. Although pea did not fix much N during the vegetative stage when nitrate was more than 48 kg N ha^{-1} in a field study in France (Voisin et al., 2002), the largest differences in soil nitrate between *Full Mix* and *Pea* occurred when nitrate after *Pea* was the highest (Bozeman 2013: 177 kg N ha^{-1}; Conrad 2016: 60 kg N ha^{-1}). This strongly suggests that pea fixed substantial N at high soil nitrate, especially given that the *Full Mix* did not accumulate more biomass than *Pea* (Tables 6 and 8). Pea had increased protein with rhizobial inoculation at fertilizer rates as great as 250 kg N ha^{-1} in southern Manitoba, suggesting N fixation can occur at high available N levels (Igbasan et al., 1996). Similarly, under controlled growth conditions, N fixation was observed at N rates exceeding 700 kg N ha^{-1} under enriched CO_2 atmosphere (Butterly et al., 2016).

Soil sampling occurred within 1 to 11 days after termination, in dry summer conditions, preventing any meaningful N mineralization of cover residue. It is important to note, however, that soil nitrate status at termination does not necessarily reflect the soil condition the following spring. For example, the two sites which were studied for 8 years were resampled in 2019 just prior to seeding spring wheat and the soil nitrate-N status had changed markedly overwinter at both sites (Table 9). At Amsterdam, the difference in nitrate-N (28 kg ha^{-1}) between *Fallow* and the *Full Mix* or *Pea* in the previous summer disappeared, with *Fallow* remaining near its post-termination value, but the *Full Mix* and *Pea* increasing over winter. At Conrad, the overwinter change in nitrate-N was even more interesting, where *Fallow* nitrate increased by 19 kg N ha^{-1}, *Full Mix* registered no important nitrate increase, and *Pea* increased by 99 N kg ha^{-1}. A notably larger effect on soil-available N by legumes in drier north central versus wetter southwest Montana was observed in another study by the same researchers (Jones and Miller, unpublished data, 2019), but we can offer no good explanation for this response. Similar overwinter recovery of soil nitrate-N status from legume cover crop depletion has been found previously in Montana (Burgess et al., 2014; Miller et al., 2006, 2011, 2018; O'Dea et al., 2013).

After cover crop termination, soil nitrate under *Legume* was greater than under *Minus Legume* by an average of 27 kg N ha^{-1} in the six site-years where this comparison was possible (Table 9). Further, when measured in spring 2019 just prior to wheat seeding at the two sites which were studied for 8 years, there was a trend ($p = 0.06$) of 11 kg ha^{-1} greater nitrate-N for *Legume* at Amsterdam, and a large *Legume* benefit (64 kg ha^{-1}) noted at Conrad. The largest differences were again in the site-years with the highest soil nitrate levels, strongly indicating that legumes fixed N when nitrate-N was greater than a previously identified nitrate inhibition cutoff of 48 kg N ha^{-1} (Voisin et al., 2002). *Brassica* had less nitrate than *Minus Brassica* in three of six site-years, and trended similarly at a 4th site-year (Amsterdam 2014; $p = 0.055$) where differences in those four site-years averaged 17 kg N ha^{-1}. Biomass, and hence likely N uptake did not differ between those treatment pairs (Tables 6 and 7), suggesting perhaps that the legumes in the five-species *Minus Brassica* mix fixed a substantial amount of N. Interestingly, the percentage legume of the total biomass was numerically larger for the *Minus Brassica* treatment (34%–51%) than in either the *Minus Fibrous* or *Minus Tap* treatments, and approximately twice as large for three of these four site-years (data not shown). Others have found that legumes need to represent more than 25% of a cover mix to produce substantial plant available N for the next crop (Sullivan et al., 2020). Linear contrasts comparing two- versus six-species treatments found no differences in soil nitrate, despite higher biomass in six-species covers than two-species mixes in five of eight site-years, which could be expected to lower nitrate in six-species mixes. It is likely

TABLE 11 Mean wheat (SW = spring wheat, WW = winter wheat) yields grown at three N fertilizer rates following cover crop treatments at Bozeman, Dutton, Amsterdam, and Conrad, MT, 2014–2019.

	Bozeman		Dutton		Amsterdam			Conrad		
	2014	2016	2014	2016	2015	2017	2019	2015	2017	2019
Nitrogen	**WW**	**WW**	**WW**	**WW**	**SW**	**WW**	**SW**	**SW**	**WW**	**SW**
kg ha^{-1}										
0	3.25	4.70 c	2.07 b	3.27 a	1.69 b	1.80 c	2.03 c	1.03 a	1.66 a	1.73 c
67	3.42	5.48 a	2.61 a	3.29 a	1.96 a	2.15 b	2.92 b	0.93 b	1.49 b	2.22 a
134	3.27	5.15 b	2.60 a	2.93 b	2.04 a	2.26 a	3.12 a	0.91 b	1.24 c	1.99 b
$LSD_{0.05}$[a]	NS	0.29	0.26	0.18	0.09	0.08	0.12	0.06	0.08	0.12
Treatment	**Mean yield values for wheat following cover crop treatments**									
Fallow	3.54 a	**5.86 a**	**2.97 a**	3.73[b]	1.86	1.96 de	2.78 ab	**1.69 a**	**2.12 a**	1.93 b
Pea	3.30 a–c	4.85 c	2.57 bc	3.39	1.88	2.07 a–e	2.74 ab	0.75 e	1.66 b	2.12 ab
Full	3.68 a	4.83 c	2.31 d	2.56	1.86	2.15 ab	2.73 ab	0.98 bc	1.45 b–d	2.04 b–d
Brassica	3.43 a	5.01 bc	2.36 d	3.05	2.01	**2.19 a**	**2.82 a**	0.87 b–e	1.61 bc	1.82 de
MBrassica	3.21 a–c	5.24 bc	2.29 d	3.40	1.83	1.99 c–e	2.65 a–c	1.03 b	1.34 cd	2.07 bc
Fibrous	2.94 a–c	5.19 bc	2.27 d	2.42	1.84	1.95 e	2.45 c	0.98 bc	0.97 e	1.92 b–d
MFibrous	**3.70 a**	5.41 ab	2.46 b–d	3.32	1.83	2.12 a–c	2.70 ab	0.83 c–e	1.30 d	2.02 b–d
Legume	3.39 a–c	5.12 bc	2.62 b	3.48	1.89	2.03 b–e	2.56 bc	0.77 de	1.49 b–d	**2.30 a**
MLegume	3.16 a–c	4.92 bc	2.30 d	3.14	1.87	2.09 a–e	2.63 a–c	0.92 b–e	1.26 d	1.63 e
Tap	2.66 c	4.81 c	2.21 d	2.77	1.94	2.14 ab	2.73 ab	0.76 e	1.48 b–d	2.03 b–d
MTap	3.44 a	4.94 bc	2.44 bc	3.48	2.04	2.10 a–d	2.79 a	0.95 b–d	1.43 b–d	1.88 cd
$LSD_{0.05}$	0.77	0.55	0.26	NS	NS	0.15	0.22	0.19	0.28	0.23
	***p*-Values and means for linear contrasts comparing 2- vs. 6-species treatments**									
2 vs. 6 species	**0.02**	0.49	0.99	0.07	0.51	0.97	0.35	**0.05**	0.13	**0.05**
2 species	3.11	5.03	2.37	2.93	1.92	2.08	2.64	0.84	1.39	2.02
6 species	3.38	5.13	2.37	3.34	1.89	2.08	2.69	0.93	1.33	1.90

Note: Bold indicates the largest value in the column; underlining indicates the smallest value.

Abbreviation: M indicates minus treatment.

[a]Fisher's protected LSD ($p = 0.05$).

[b]Single degree of freedom contrast for Fallow versus Full mix was significant ($p < 0.01$).

that the presence of legumes in three of the four six-species mixes helped counter the greater N uptake from the greater biomass.

3.6 | Wheat response

3.6.1 | Yield

Overall average wheat grain yield for the 10 site-years was 2.5 Mg ha^{-1}, but yield varied widely from a low of 0.96 Mg ha^{-1} (spring wheat) during summer drought at Conrad in 2015 to 5.11 Mg ha^{-1} (winter wheat) at Bozeman in 2016 (Table 11). These wheat yields occurred in a similar range as that reported by Bourgault et al. (2022) at Havre, MT, during the same years as our study, for a cover crop trial focused on forage value of covers grown during the summerfallow period. Wheat yield differed among the three N rates in 9 of 10 site-years, with 67 kg N ha^{-1} increasing yield for six site-years relative to the zero-N control, and decreasing yield for two site-years. With 134 kg N ha^{-1}, yield was greater than at 67 kg N ha^{-1} for two site-years, but less for four site-years. Overall, the medium N rate increased wheat yield by 14% over the zero-N control, and the highest rate of 134 kg N ha^{-1} decreased yield by an average of 4% from the medium N rate. It is important to note that fertilized wheat production under the drought conditions common to Montana is often susceptible to "haying off," whereby vigorous early wheat biomass production is too water consumptive to be maintained through the grain fill period, reducing harvest index and grain mass (van Herwaarden et al., 1998). However, for the purpose of this study, the range of N rates were intended only to assess cover crop effects on wheat yield across different background amounts of applied soil N fertility, rather than assess wheat yield response to applied fertilizer N. Nitrogen fertilizer rate x cover crop interactions were generally not important, except legume

TABLE 12 Mean wheat (SW, spring wheat; WW, winter wheat) protein (dry weight basis) grown at three N fertilizer rates following cover crop treatments at Bozeman, Dutton, Amsterdam, and Conrad, MT, 2014–2019.

	Bozeman		Dutton		Amsterdam			Conrad		
	2014	2016	2014	2016	2015	2017	2019	2015	2017	2019
Nitrogen	**WW**	**WW**	**WW**	**WW**	**SW**	**WW**	**SW**	**SW**	**WW**	**SW**
kg ha^{-1}										
0	139 b	110 c	144 c	118 c	126 c	123 c	122 c	147 c	117 c	118 c
66	148 a	123 b	160 b	139 b	157 b	156 b	145 b	191 b	164 b	159 b
134	151 a	142 a	167 a	162 a	163 a	164 a	164 a	204 a	180 a	186 a
LSD$_{0.05}$[a]	6	4	4	4	3	2	2	5	3	6
Treatment	**Cover crop treatment means**									
Fallow	**158 a**	**134 a**	163 ab	136	150 ab	**155 a**	143 bc	176 cd	146 de	151 d
Pea	150 ab	131 ab	**165 a**	149	**154 a**	153 ab	155 a	197 a	168 ab	**167 a**
Full	157 a	124 bc	155 c	143	150 ab	145 de	142 cd	173 de	151 de	147 d
Brassica	146 a–c	121 c	153 c	142	146 b–d	144 ef	140 de	175 c–e	145 e	149 d
MBrassica	139 b–d	123 c	157 bc	137	149 a–c	150 bc	145 b	183 bc	154 cd	152 cd
Fibrous	135 cd	123 c	154 c	140	144 cd	146 de	139 ef	167 e	146 de	156 b–d
MFibrous	154 a	126 bc	153 c	134	152 a	146 de	143 bc	186 b	160 bc	161 a–c
Legume	156 a	125 bc	163 ab	148	**154 a**	153 ab	**156 a**	**200 a**	**173 a**	163 ab
MLegume	135 cd	123 c	154 c	133	143 d	141 f	137 fg	173 de	148 de	149 d
Tap	131 d	120 c	153 c	140	146 b–d	145 de	136 g	180 b–d	150 de	152 cd
MTap	145 a–d	124 bc	157 b	134	146 b–d	148 cd	145 b	176 cd	150 de	149 d
LSD$_{0.05}$	14	8	7	NS	6	4	3	9	9	10

Note: Bold indicates the largest value in the column; underlining indicates the smallest value.

Abbreviation: M indicates minus treatment.

[a]Fisher's protected LSD ($p = 0.05$).

covers at the zero N rate increased wheat yields relative to other cover crops more than when fertilizer N was applied. This was expected due to the commonly known soil N benefits afforded by legume crops.

With some exceptions, cover crop treatment effects on subsequent wheat yield did not cause important differences, and yields were most often greatest on *Fallow*. Compared to *Fallow*, the *Full Mix* treatment decreased wheat yield in 5 of 10 site-years (average = 0.85 Mg ha^{-1} or 29% of fallow yield; range = 0.66–1.17 Mg ha^{-1} or 18% to 42%), and increased yield in one site-year by 0.19 Mg ha^{-1} (10% greater than fallow yield). Wheat yield suppression occurred most commonly in the drier climate of north central Montana (Conrad and Dutton) and in average to drier than average growing seasons. This drought-induced yield loss highlights an important cost to cover crops that may not commonly occur in wetter regions. Further, a major purpose of cover crops is to increase plant C inputs to soil but the partially offsetting loss in crop residues associated with wheat yield reduction must be considered carefully relative to net 2-year plant C inputs to soil from cover crops. As such, these results were similar to those of Nielsen et al. (2016) in the central Great Plains.

Otherwise relatively few differences occurred consistently between specific cover crop functional groups and their "minus" contrast treatments. The *Fibrous root* treatment yielded less than *Minus Fibrous* in 4 of 10 site-years, with an overall average of 89% of the *Minus Fibrous* treatment. This response was expected, based on commonly reported yield advantages in wheat due to diverse cropping sequences (Kirkegaard et al., 2008). Wheat following the *Legume* treatment yielded statistically greater than the *Minus Legume* treatment in 2 of 10-site-years, and trended similarly in four other site-years, for an overall average yield of 107% of the *Minus Legume* treatment. These two significant responses occurred at the drier northern sites, somewhat surprising given water was expected to be much more limiting than N for wheat production there. The *Tap Root* treatment yielded statistically less than the *Minus Tap* treatment in only one site-year, but trended similarly in three other site-years, for an overall average of 93% of the *Minus Tap root* treatment. It is notable that this yield trend occurred for the *Tap Root* treatment where cover crop biomass was generally lowest compared with all other cover crop treatments, and so presumably used the least soil water. Six-species cover crop treatments increased wheat yield in 3 of 10 site-years, and decreased yield in one site-year. However, observed differences between two and six-species biomass did not correspond closely with site-years where subsequent differences in wheat yield occurred, suggesting wheat yield was not closely related to biomass differences.

3.6.2 | Protein

Unlike the case with wheat yield, N fertilizer affected wheat grain protein consistently, differing progressively with increasing N application rates for all site-years (Table 12). Overall averages of grain protein concentration were 126, 154, and 168 g kg^{-1} for the 0, 67, and 134 kg N ha^{-1} rates, respectively. Engel et al. (1999, 2006) published grain protein–yield threshold concentrations (dry matter basis) of 147 g kg^{-1} for spring wheat and 140 g kg^{-1} for winter wheat that correspond with N sufficiency to meet environmental wheat yield potential. By that measure, 3 of 10 site-years (Bozeman & Dutton, 2014; Conrad, 2015) required no fertilizer N to meet the yield potential for those production environments, while six other site-years (all but Bozeman 2016) required only the medium N rate to meet full environmental yield potential. Once yield potential has been met, then additional N increases wheat grain protein, explaining the generally high average grain protein values measured in this study.

Wheat grain protein was less following *Full Mix* than *Fallow* for 3 of 10 site-years, averaging 2.5 g kg^{-1} less overall. In contrast, wheat protein after the *Pea* cover crop treatment was greater than after *Fallow* for 4 of 10 site-years, averaging 7.7 g kg^{-1} greater overall, and 10.2 g kg^{-1} greater than *Full Mix*. When considering specific contrasts of single functional groups and their "minus" partner, only two of the four functional groups responded consistently. The *Legume* treatment had greater wheat grain protein than *Minus Legume* for 8 of 10 site-years, with an overall difference of 15.5 g kg^{-1}. Conversely, the *Fibrous root* treatment had lower wheat grain protein than *Minus Fibrous* for 5 of 10 site-years, with an overall average deficit of 6.5 g kg^{-1}. Contrasts between two- and six-species showed no differences in wheat grain protein (data not shown).

4 | CONCLUSIONS

Cover crop above-ground biomass averaged 2.0 Mg ha^{-1} over eight site-years representative of dryland farming in Montana when terminated 57 to 66 days after planting. Using equal overall plant densities, treatments with three functional groups averaged 13% greater biomass than single functional groups. Measured at cover cop termination, *Fallow* held greater soil water than most cover crop treatments, but otherwise no consistent differences among cover crop treatments occurred. Soil water averaged 57 mm greater after *Fallow* than the *Full Mix*. Soil nitrate averaged 49 kg N ha^{-1} greater after *Fallow* than the *Full Mix* and 30 kg N ha^{-1} greater than after *Pea*. The *Legume* treatment averaged 26 kg N ha^{-1} greater than the *Minus Legume* treatment, with no nitrate differences among other cover crop treatments. Wheat yield on *Fallow* averaged 0.85 Mg ha^{-1} (22%) greater than the *Full Mix* for 5 of 10 site-years, mainly at sites in drier north central Montana. Otherwise, yield on N-fertilized wheat was not consistently different among previous cover crop treatments. The *Legume* treatment consistently elevated wheat protein over the *Minus Legume* treatment by an average of 15 g kg^{-1}. Cover crops grown during the summer fallow period reduced soil nitrate-N, soil water, and subsequent wheat yields compared with fallow, especially in the major wheat growing region of north central Montana. With the exception of legumes, functional groups and number of species mattered little for subsequent wheat yield and protein. Cover crops should be considered cautiously by farmers in low rainfall areas of the northern Great Plains.

AUTHOR CONTRIBUTIONS

Perry Miller: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing. **Clain Jones**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing. **Cathy Zabinski**: Conceptualization; methodology; resources; supervision; visualization; writing—original draft; writing—review and editing. **Susan Tallman**: Data curation; formal analysis; investigation; methodology; project administration; writing—original draft. **Megan Housman**: Data curation; formal analysis; investigation; project administration; writing—original draft. **Kristen D'Agati**: Data curation; formal analysis; investigation; project administration; writing—original draft. **Jeffrey Holmes**: Conceptualization; data curation; investigation; methodology; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Perry R. Miller https://orcid.org/0000-0003-4719-2137

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