SW11-099 Final Report

General Information: (project title, participants, funding amount, etc.)

Title: *Using cover crop mixtures to improve soil health in low rainfall areas of the northern plains*

Participants: *Perry Miller*, Professor - Cropping Systems – MSU, *Clain Jones*, Associate Professor - Soil Fertility Extension – MSU; *Cathy Zabinski*, Professor – Rhizosphere Ecology – MSU, *Jane Holzer*, Montana Salinity Control Association; *Jay Norton* – Extension Soil Fertility Specialist, University of Wyoming; *Susan Tallman* and *Meg Housman*, M.Sc. Students in Land Resources and Environmental Sciences Dept – MSU, *Carl Vandermolen*, farmer; *Herb Oehlke*, farmer; *Chad Doheny*, farmer; *Will Roehm*, farmer; *Roger Benjamin*, farmer; *Jim Bjelland*, farmer.

Funding amount: $354,405

Summary: (100 words maximum – it seems Word may be counting this differently than SARE website)

We measured effects of cover crop mixes (CCMs) grown during the fallow period on soil properties, water use, and wheat yield. CCMs included plant groups that 1) fix nitrogen, 2) provide ground cover, 3) have deep tap roots, or 4) have fibrous roots. Farmer-conducted field studies showed important soil water and nitrogen use, and reduced wheat yields compared with fallow. Water use and yield loss was less in plot-scale studies due to earlier termination. Compared with chem fallow we documented soil cooling, enhanced soil biological activity, and generally better wheat response with legume vs. non-legume cover crop mixes.

Objectives/Performance Targets: (as in Proposal)

1. Position this project for maximal success by gaining familiarity with growth characteristics of targeted candidate species for CCM's by growing crops locally in 2011 prior to potential award of this grant.

    a. We will produce seed of 8 – 12 crop species at Bozeman to gain greater familiarity with plant growth habit and obtain seed of known quality for research project.

    b. To ensure success of our field research, we will monitor nearby farm fields of CCM's, as time and budget permits, to gain familiarity with sampling CCM's and with practical field challenges.

2. Quantify the effects of CCM's (compared with fallow) on grain yield, quality, and economic return compared with fallow

    a. We will determine differences (with 90% confidence) in yield and quality of grain following each CCM compared to fallow for 4 plot studies and 6 field scale studies following the 2nd year of the study.

    b. Based on grain yield, quality, seed costs, equipment costs, NRCS payments, etc. we will determine if the net economic return is different among the treatments. Our performance target is to identify soil-building CCM's that produce similar or more profit in a CCM-wheat system than fallow-wheat, because otherwise adoption is relatively unlikely.

3. Determine the effects of CCM's on soil quality using fallow as a control

    a. Soil quality indicators that we will measure include biological (potentially mineralizable N (PMN), microbial biomass, enzyme activities, mycorrhizal colonization levels and infectivity potential, and earthworm density), physical (wet aggregate stability, temperature, compaction), and chemical (available nitrogen and phosphorus).

    b. Comparing CCM's with single functional groups to those with subsets or the entire set of functional groups, we will identify the functional group(s) that most contributed to any soil quality change detected.

    c. Indicators that are different between each CCM and fallow after the third year of the study will be identified. Our performance target is to identify which CCM's most improve different aspects of soil quality, allowing farmers to customize a CCM depending on their soil needs.

4. Introduce growers and agricultural professionals ("audience") to the potential sustainable aspects of CCM's

    a. We will conduct one Field Day and two workshops during the first year of the project, focusing on general CC principles, and any regional research results (for example from ND). Our first performance target is to directly reach 200 people with these events, and indirectly reach another 800 by asking our audience to take handouts to neighbors, friends, and colleagues, and by producing a video of the Field Days that will be accessed online.

    b. Our second performance objective will be to increase the audience awareness and understanding of potential benefits of CCM's. We will assess this with audience evaluations.

5. Educate audience about effects of CCM's on subsequent crop and economics

    a. In the winter after the wheat phase of this study, we will conduct three to four more workshops to share yield, quality, and economic results, have one radio interview with a PI, and produce a CCM webpage to share our findings. Our first performance target is to directly reach 300 people with these events and reach another 2000 indirectly.

    b. Our second performance target will be to increase our audience's understanding of the agronomic and economic effects of CCM's in our region. This will be assessed with evaluations.

6. Educate audience about the effects of CCM's on soil quality, including functional group benefits, based on our study

    a. In the year of the 2nd CCM crop, we will host another Field Day, conduct two to three more workshops to discuss our soil quality results, and prepare an Extension fact sheet on our findings. Our first performance target will be to directly reach 300 people with these events and 1200 indirectly.

    b. Our second performance target will be to increase the understanding of plant functional groups, and to assess this with our educational evaluation plan.

7. Enhance adoption, if study results warrant, of CCM’s.

Accomplishments:

All proposed research is complete for this 3-yr project. We used a planned no-cost extension to accomplish 4th-yr wheat harvest (i.e. After two CCM sequences with all treatments kept in place) at two of four sites for plot-scale research, and independent funding from the *Montana Fertilizer Advisory Committee* to complete soil sampling and wheat harvest at the final two sites (external to WSARE proposal but will be reported here after the 2016 harvest, if possible to edit 'final' reports). It is important to continue these cover crop treatments for two more sequences to fully explore cover crop effects on soil change and since our project was not renewed by WSARE in our 2015 application we will attempt to secure funding from other sources to fully accomplish this long-term project at two locations in accordance with the wishes of collaborating growers at Amsterdam and Conrad, MT.

Objective 1) This research, conducted preliminarily to this proposal, was used to refine our choice of plant entries for the cover crop treatments.

a. It was possible to produce seed of nearly all cover crop species in Montana growing environments. Note that turnip is biennial but it has successfully overwintered on a grower field near Bozeman, MT. Clover species such as red and berseem are not commonly grown for seed in Montana
b. Preliminary on-farm investigation of cover crop effects was folded into Objective 2a. and reported as the '2010' site in Tables 1 and 2.

Objective 2) Agronomic assessment was conducted at both field and plot scales (ongoing pending funding availability). **Soil water and nitrate-N response is included here together with cereal crop yield and protein rather than separately under Obj. 3a. below.** Unless cereal yield (or protein for wheat) is improved by cover crops, short-term economic comparison is obviously negative due to added costs for managing a cover crop (disregarding USDA-NRCS incentive payments). However, until cover crop effects on soil improvement are understood mechanistically, allowing optimization, it may be preliminary to consider economic outcomes. Short-term agronomic comparison of cover crops with chem fallow, at both field and plot scale, is reported below and the short-term economic outcomes would be decidedly negative, without any need for elaboration.

2a. Field scale soil water and nitrogen and subsequent crop response.

Seeding and spray-termination operations for this cover crop study were conducted by the participating farmers, as advised by personnel independent of MSU [i.e. USDA-NRCS and Montana Salinity Control Association advised farmers on seed mixtures and planting/ termination dates]. Our role was to objectively measure soil water and nitrate-N, and subsequent crop yield and protein following cover crops, compared to an adjacent chem fallow control (Table 2-1). We collected GPS-referenced crop and soil samples systematically along the length of the cover crop – fallow interface (usually every 80 - 100 ft) and at randomly assigned distances from the interface (from 50 to 250 ft), avoiding potential seeder overlap areas near field edges. This usually resulted in 12 samples from both the cover crop and fallow field areas. We committed to monitoring six total farm field sites in our proposal, but ultimately seven were attempted (two were completely hailed out during the test crop phase). In this report we also include one farm field site that provided preliminary data to support this proposal, for a total of eight.

Table 2-1. Location, planting, termination, sampling dates, and species composition for farmer-run field scale cover crop sites in Montana

Location	Farmer	Seed	Terminate	Sample	Cover crop mixture
Amsterdam – 1 45.72N,111.37W	Carl Vandermolen	6/15/10	9/01/10	9/24/10	pea, sudangrass, sunflower, turnip
Amsterdam – 2 45.72N,111.37W	“ “	5/29/12	7/29/12	8/01/12	Millet (foxtail), pea, turnip
Conrad 48.22N,111.48W	Herb Oelhke	4/7/12	7/1/12	7/04/12	camelina, clover (crimson), oat, pea, turnip, weeds
Conrad – 2 48.21N,111.51W	Jim Bjelland	6/11/13	8/15/13	8/20/13	camelina, flax, oat, pea, radish, turnip, vetch
Dutton – 1 47.95N,111.40W	Chad & Eric Doheny	4/22/12	7/20/12	7/25/12	camelina, clover (crimson), flax, oat, pea, radish, turnip
Dutton – 2 47.95N,111.40W	“ “	5/21/13	6/27/13	7/01/13	barley, camelina, lentil, millet, mustard, oat, pea, radish, sunflower, turnip
Fort Benton 47.93N,110.85W	Roger Benjamin	5/23/13	7/24/13	7/29/13	chickpea, corn, clover (red), millet (foxtail), pea, radish, sorghum, sunflower, turnip
Great Falls 47.52N,111.14W	Will Roehm	5/03/13	7/09/13	7/12/13	buckwheat, camelina, clover (berseem), pea, safflower, turnip

At all farm sites, cover crop biomass was unevenly distributed among species and typically dominated by pea, turnip, and/or oat (Figs. 1-8). Biomass at termination totaled from 900 to 2600 lb/ac (dry weight) among fields and years (Table 2-2). Note that weeds contributed trivially to biomass at most sites. Compared with a chem fallow control, cover crop mixtures depleted soil water to a depth of 3 ft by an average of 2.9 inches (range = 0.7 to 5.3) and soil nitrate-N by an average of 54 lb/ac (range = 22 to 86) (Table 2-2). Except for one site (Great Falls), subsequent cereal crop yield and/or protein was depressed following cover crops (*P*<0.10), consistent with soil water and nitrogen measurements.

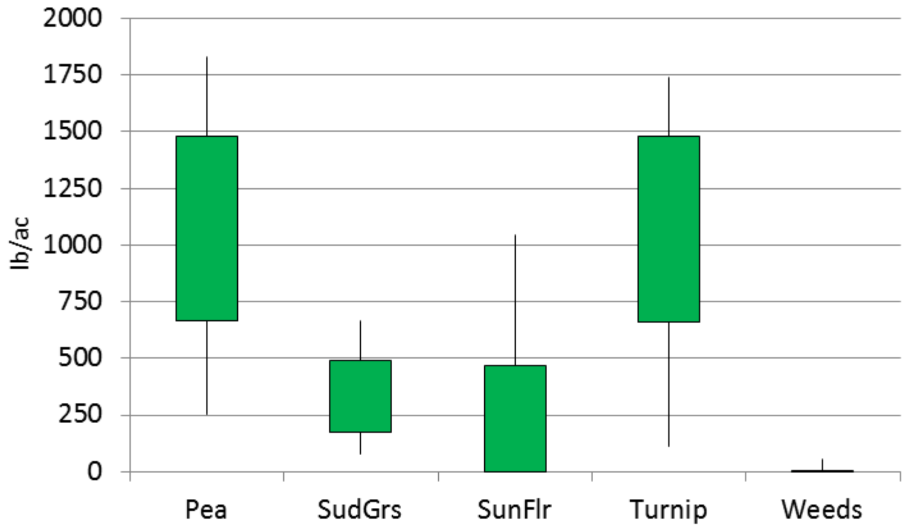

Figure 1. Above-ground biomass by crop species and weeds, **Amsterdam, 2010**. Boxes represent the average '+' and '–' one standard deviation. Whiskers (or box ends) represent maximum and minimum values observed across 20 field samples. Note: biomass for turnips includes root bulb at this site only.

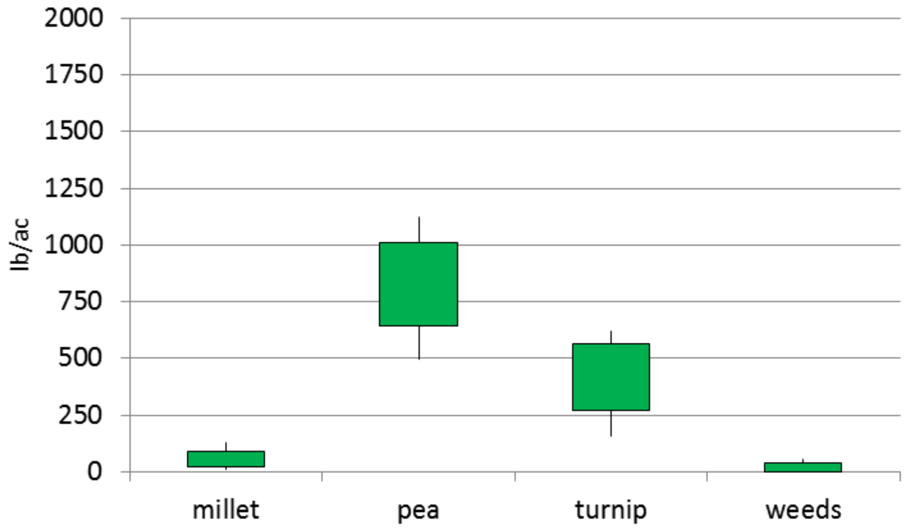

Figure 2. Above-ground biomass by crop species and weeds, **Amsterdam, 2012**. Boxes represent the average '+' and '–' one standard deviation. Whiskers (or box ends) represent maximum and minimum values observed across 12 field samples. Note: above-ground portion of turnip bulb harvested.

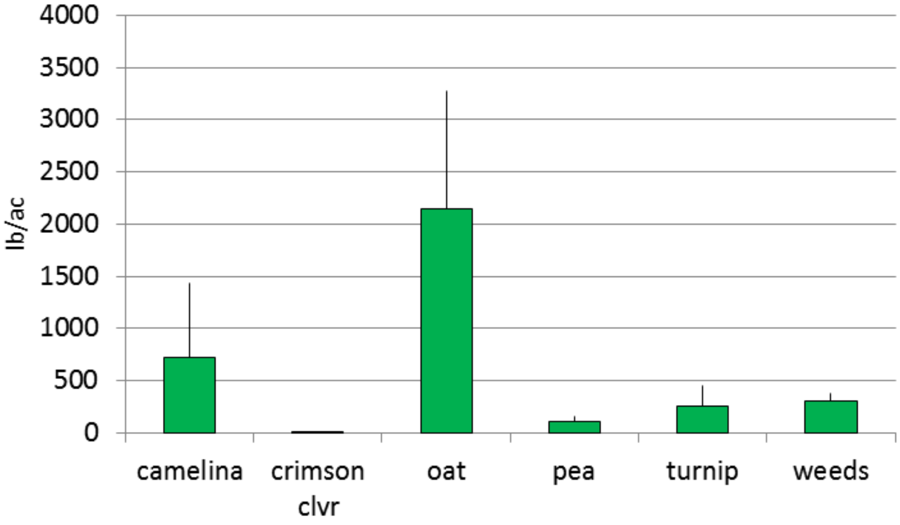

Figure 3. Above-ground biomass by crop species and weeds, **Conrad, 2012**. Boxes represent the average '+' and '–' one standard deviation. Whiskers (or box ends) represent maximum and minimum values observed across 12 field samples. Note: above-ground portion of all roots harvested (i.e. turnip).

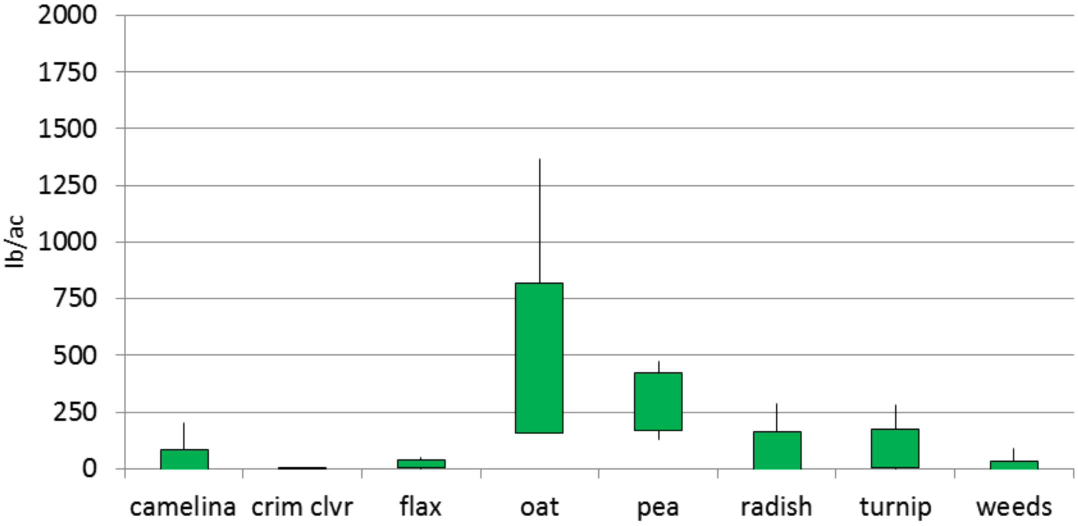

Figure 4. Above-ground biomass by crop species and weeds, **Dutton, 2012**. Boxes represent the average '+' and '–' one standard deviation. Whiskers (or box ends) represent maximum and minimum values observed across 12 field samples. Note: above-ground portion of all roots harvested (i.e. turnip, radish).

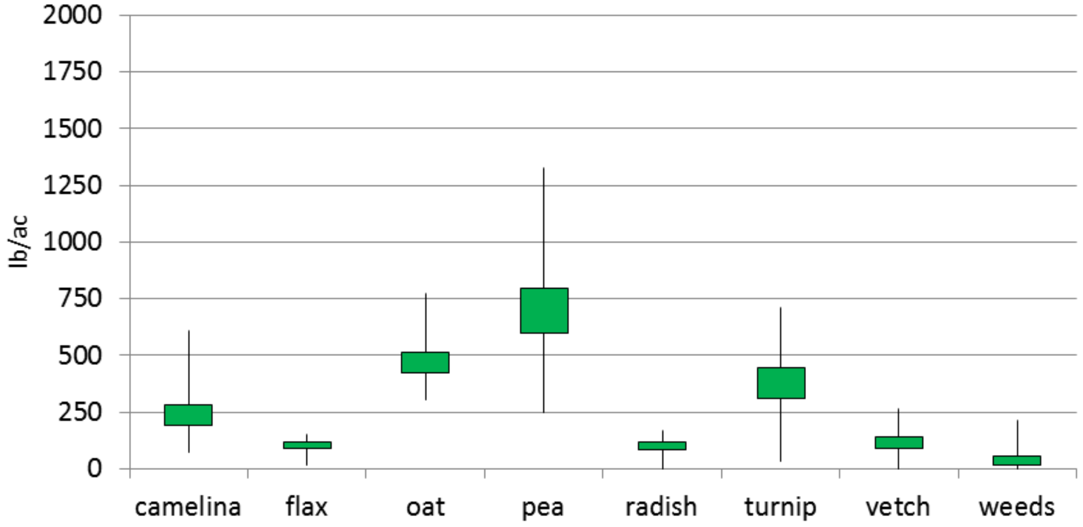

Figure 5. Above-ground biomass by crop species and weeds, **Conrad, 2013**. Boxes represent the average '+' and '–' one standard deviation. Whiskers (or box ends) represent maximum and minimum values observed across 10 field samples. Note: above-ground portion of all roots harvested (i.e. turnip, radish).

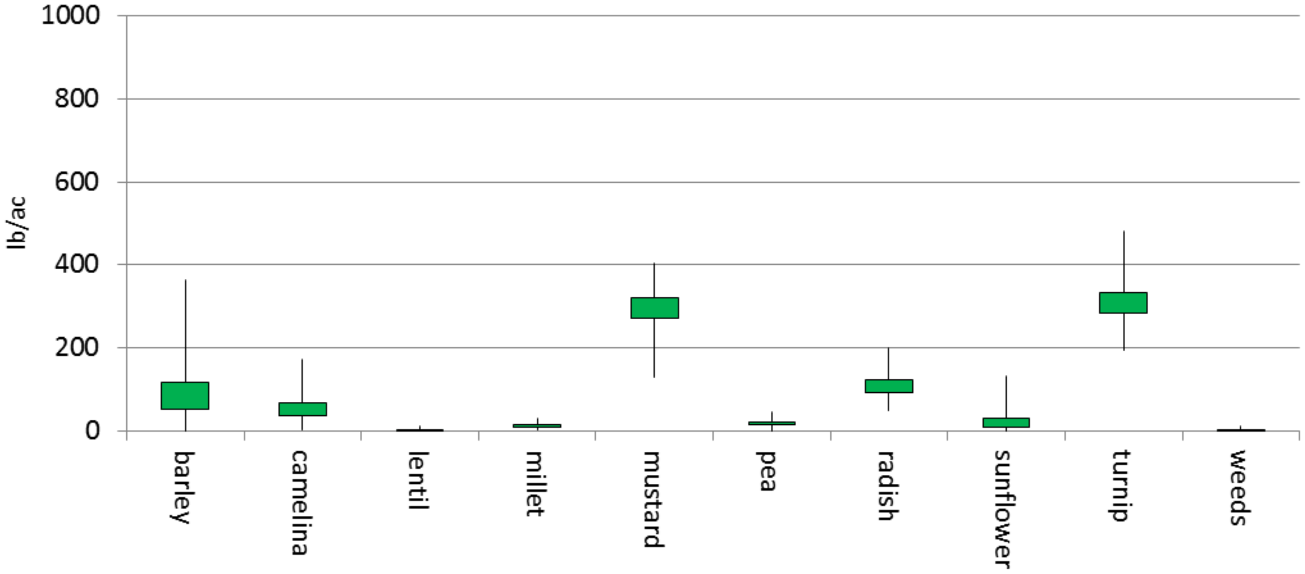

Figure 6. Above-ground biomass by crop species and weeds, **Dutton, 2013**. Boxes represent the average '+' and '–' one standard deviation. Whiskers (or box ends) represent maximum and minimum values observed across 12 field samples. Note: above-ground portion of all roots harvested (i.e. turnip, radish).

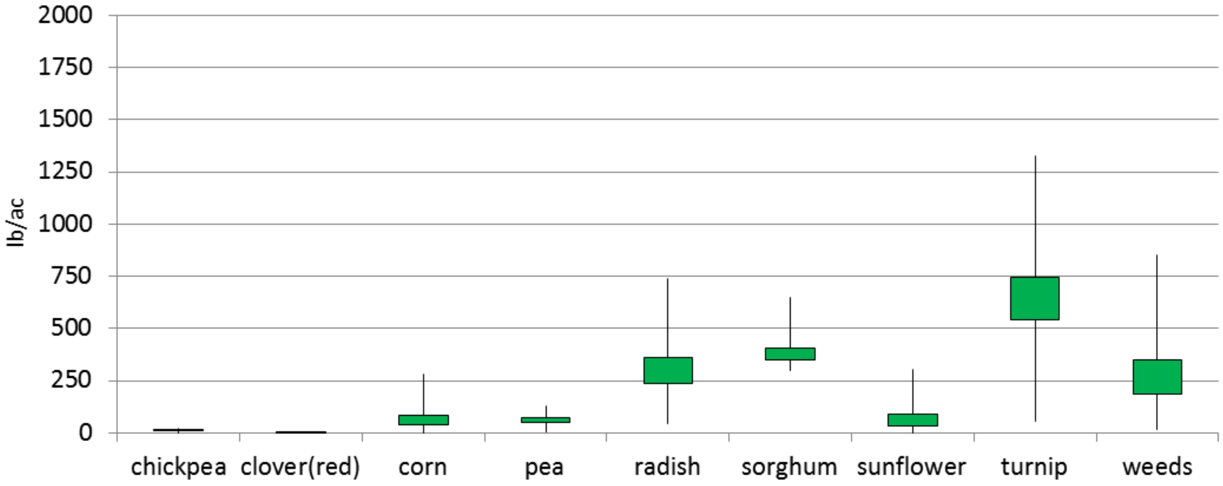

Figure 7. Above-ground biomass by crop species and weeds, **Fort Benton, 2013**. Boxes represent the average '+' and '–' one standard deviation. Whiskers (or box ends) represent maximum and minimum values observed across 12 field samples. Note: above-ground portion of all roots harvested (i.e. turnip, radish). *Note: foxtail millet and sorghum inadvertently mixed at biomass sampling and all classed as sorghum.*

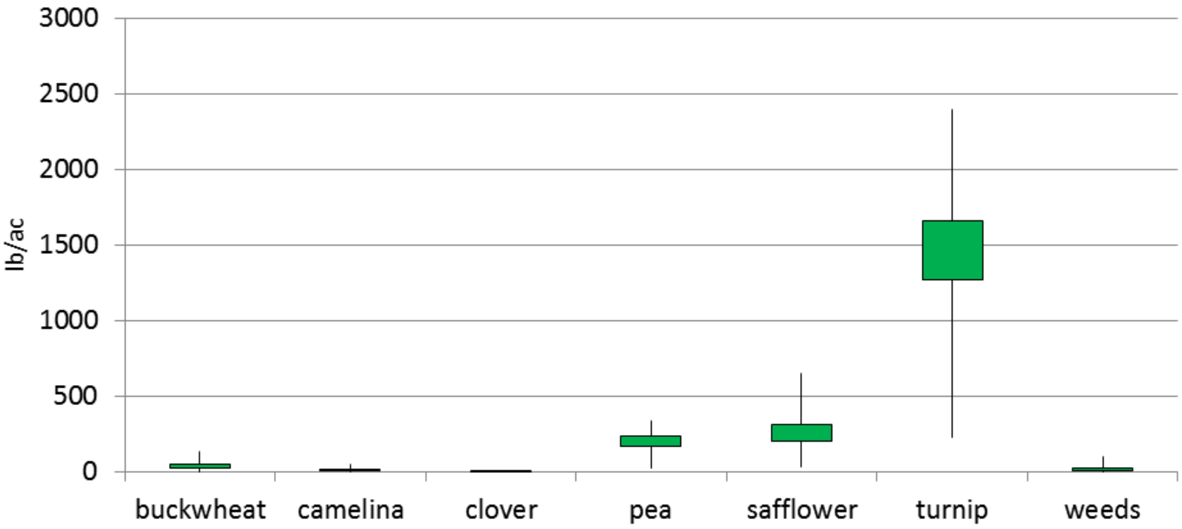

Figure 8. Above-ground biomass by crop species and weeds, **Great Falls, 2013**. Boxes represent the average '+' and '–' one standard deviation. Whiskers (or box ends) represent maximum and minimum values observed across 12 field samples. Note: above-ground portion of all roots harvested (i.e. turnip).

Table 2-2. Total cover crop biomass, soil water and nitrate-N to 3-ft depth at termination, and subsequent cereal crop yield and protein for cover crop mixture (CCM) vs chem fallow management.

Location	CCM vs Fallow	Total Biomass	Soil water	Soil N	Yield	Protein
		lb/ac	inches	lb/ac	bu/ac	%
Amsterdam					Winter wheat	
2010/11	CCM	2600†	7.1	not	53.6	11.4
	Fallow		7.8	measured	60.4	12.6
	*P-value**		*<0.01*		*0.14*	*0.02*
Amsterdam‡					Winter wheat	
2012/13	CCM	1320	4.4	8	Hailed out 100%	
	Fallow	-	6.7	56		
	P-value		*<0.01*	*<0.01*		
Conrad					Barley	
2012/13	CCM	2000	5.8	32	64.6	9.5
	Fallow	-	7.8	81	82.9	12.1
	P-value		*<0.01*	*<0.01*	*<0.01*	*<0.01*
Dutton					Spring wheat	
2012/13	CCM	1000	9.3	43	37.7	14.0
	Fallow	-	11.7	65	45.7	14.5
	P-value		*<0.01*	*<0.01*	*<0.10*	*NS*
Conrad					Spring/Winter wheat§	
2013/14	CCM	2140	7.1	10	22.0	14.6
	Fallow	-	10.9	64	52.3	12.3
	P-value		*<0.01*	*<0.01*	*<0.01*	*<0.01*
Dutton					Spring wheat	
2013/14	CCM	900	8.4	21	48.2	13.9
	Fallow	-	13.7	89	74.4	13.3
	P-value		*<0.01*	*<0.01*	*<0.01*	*NS*
Fort Benton					Winter wheat	
2013/14	CCM	1780	2.7	46	Hailed out 100%	
	Fallow	-	6.3	132	Crop much weaker on CC	
	P-value		*<0.01*	*<0.01*	See Figure 9 below	
Great Falls					Winter wheat	
2013/14	CCM	1990	9.9	51	75.9	12.0
	Fallow	-	12.2	101	78.3	12.4
	P-value		<0.05	*<0.01*	*0.53*	*0.38*

†Includes turnip root as pulled from soil, at this site only. Otherwise root bulbs were cut at the soil line.

* P-value stands for probability value and values less than 0.10 have greater than 90% probability of being caused by the treatments. Values less than 0.01 reflect greater than 99% probability.

‡ This is the exact same CCM-fallow field boundary that was sampled in 2010/11.

§ Winter wheat suffered high mortality and significant weed pressure from volunteer camelina on the cover crop area and was resown to spring wheat. Winter wheat remained on the chem fallow control.

Fig. 9. Hailed out winter wheat at Fort Benton, MT, June 19, 2014. Top image is cover crop area and bottom image is chem fallow. Note strong visual difference in drought stress. Pink blur in bottom right corner of each image is finger of amateur photographer Perry Miller.

2a. **Plot scale** research was conducted at four locations: near **A**msterdam (45.72ºN, 111.37ºW), **B**ozeman, MT (45.67ºN, 110.98ºW), **C**onrad (48.22ºN, 111.48ºW), and **D**utton (48.00ºN, 111.57ºW). The **A** and **B** sites occur in the Gallatin Valley of southwestern Montana while the **C** and **D** sites occur in north-central Montana, aka 'The Golden Triangle'. Plant species that were included in each 'functional group' (FG) and the full mix consisted of all four functional groups (Table 2-3). A single species pea and chem fallow were considered control treatments, and there were four 'minus' treatments that contained all but one FG. In 2012 we sowed the **A** and **C** sites near April 1st with the goal of reaching pea bloom by June 15th, the presumed (incorrect) date for maintenance of summerfallow crop insurance coverage. Peas did not bloom until approx. 1 week after June 15, there was significant frost injury to some of the plant species, and control of downy brome (*Bromus tectorum*) with glyphosate was inadequate at both sites. Thereafter we sowed cover crop treatments near May 1st which was consistent with grower practice (i.e. after spring cash crops). Also in 2013 **we set all treatments to the same plant density (~11 plants/sq. ft.)** after realizing that in 2012 we were biasing our multi-species biomass proportions due to sole crop plant densities that differed by as much as 4X. Plant density targets were generally achieved.

Table 2-3. Cover crop treatments by plant functional groups.

Treatment	Abbrev.	Plant species
Summerfallow	SF	Incidental weeds (mainly volunteer wheat)
Pea	PEA	Forage pea (*Pisum sativum* L. cv. Arvika)
Full Mix	FULL	NF + FR + TR + BC
Nitrogen Fixer	NF†	Forage pea Black lentil (*Lens culinaris* Medik. cv. Indianhead)
Fibrous Root	FR‡	Oat (*Avena sativa* L. cv. Oatana) Canaryseed (*Phalaris canariensis* L. vns)
Taproot	TR	Turnip (*Brassica rapa* L. vns) Safflower *Carthamus tinctorius* L. cv. MonDak)
Brassica	BC§	Radish (*Raphanus sativus* L. var. *longipinnatus* vns) Winter canola (*Brassica napus* L. cv. Dwarf Essex)
Minus Nitrogen Fixers	MNF	FULL minus NF.
Minus Fibrous Roots	MFR	FULL minus FR.
Minus Taproots	MTR	FULL minus TR.
Minus Brassicas	MBC	FULL minus BC and turnip.

†Common vetch was used in 2012 and proved difficult to kill with glyphosate at both sites.

‡Perennial ryegrass was used in 2012 but it was contaminated with annual ryegrass so was discontinued for fear of introducing a new weed problem on farms. Proso millet was used in 2013 but was severely out-competed by cool-season species.

§Camelina was used in 2012 but did not establish well at either site. In one farm field site (Conrad 2013) it became a severe weed problem in winter wheat.

Cover crop biomass

In 2013 to 2015 the above-ground biomass production at termination (initial pea bloom) ranged from ~1500 to 4000 lb/ac (dry matter) among site-years (Figure 10). The four FGs differed from each other in two of six site-years; in both those cases the fibrous root FG was 15 to 35% greater than the average of the other three functional groups. In 2015 only (also two of six site-years) the average of the three-FG treatments had 10 to 20% greater biomass than the full four-FG treatment. And at all three Gallatin Valley site-years the average of the three-FG treatments was 10 to 20% greater than the average of single FGs, but not at any of the northern Triangle locations. We have no explanation for this apparent regional difference in biomass response. **Overall we conclude that about half the time a six-species mix yielded greater biomass than a two-species mix, by approximately 10 – 20%.**

Soil water and nitrogen

We focused on the full mix and pea and summerfallow controls (Table 2-3) as the three most contrasting treatments for reporting soil water and nitrate and wheat yield and protein (Table 2-4). Data for other cover crop treatments were collected and analyzed but owing to few differences are not included here. Soil water did not differ between the Full and Pea treatments at any site-year (nor were there consistent differences among other cover crop treatments), but summerfallow held more soil water at termination than these two cover crop treatments in six of eight site-years. In those six site-years that average soil water difference was 2.2 to 2.3 inches. **Averaged over all site-years these cover crop treatments conserved 1.8 inches less soil water than under summerfallow**, compared with an average of 2.9 inches less water at the field scale (Table 2-2). It is likely that the greater soil water use at the field scale was due to delayed termination of cover crops.

Wheat yield and protein

Wheat yield following either cover crop treatment did not differ from fallow at the Gallatin Valley (**A** and **B**) locations likely due to generally superior overwinter soil water recharge (Table 2-4). However, **at the north central Montana (C and D) locations, wheat yield on summerfallow averaged 9.4 bu/ac greater than after the two cover crop treatments**, which generally did not differ from each other. This yield loss following cover crops was considerably less than the 17.4 bu/ac average yield loss reported for north central Montana in the field-scale study (Table 2-2). Again, this was likely because the field-scale cover crop treatments were generally allowed to grow longer, and use more soil water, than in the plot-scale study. Grain protein generally did not differ among these three treatments with the exception of 2.0 greater %-units following the pea cover crop compared with summerfallow and the full mix. Additional N cycling provided by the pea cover crop likely exacerbated drought stress at **C**onrad in 2015 via a more severe 'haying off' crop response. When all cover crop treatments were considered together a pattern emerged where cover crop treatments consisting only of **legumes had greater yield than those that did not contain legumes in two of four site-years (4.6 to 4.9 bu/ac) and greater grain protein (0.7 to 2.0 %-units) in all four-site years** (Figure 11).

Economic assessment of cover crops in this region would be premature prior to two conditions being met. First, it is crucial that cover crop management is understood sufficiently well that it can be managed optimally relative to costs and returns. Second, soil quality changes slowly and so economic assessment is best made over a suitably long time frame. Based on our results it is evident that incentive payments from USDA-NRCS are crucial to developing this practice to be economically optimal on farms in Montana.

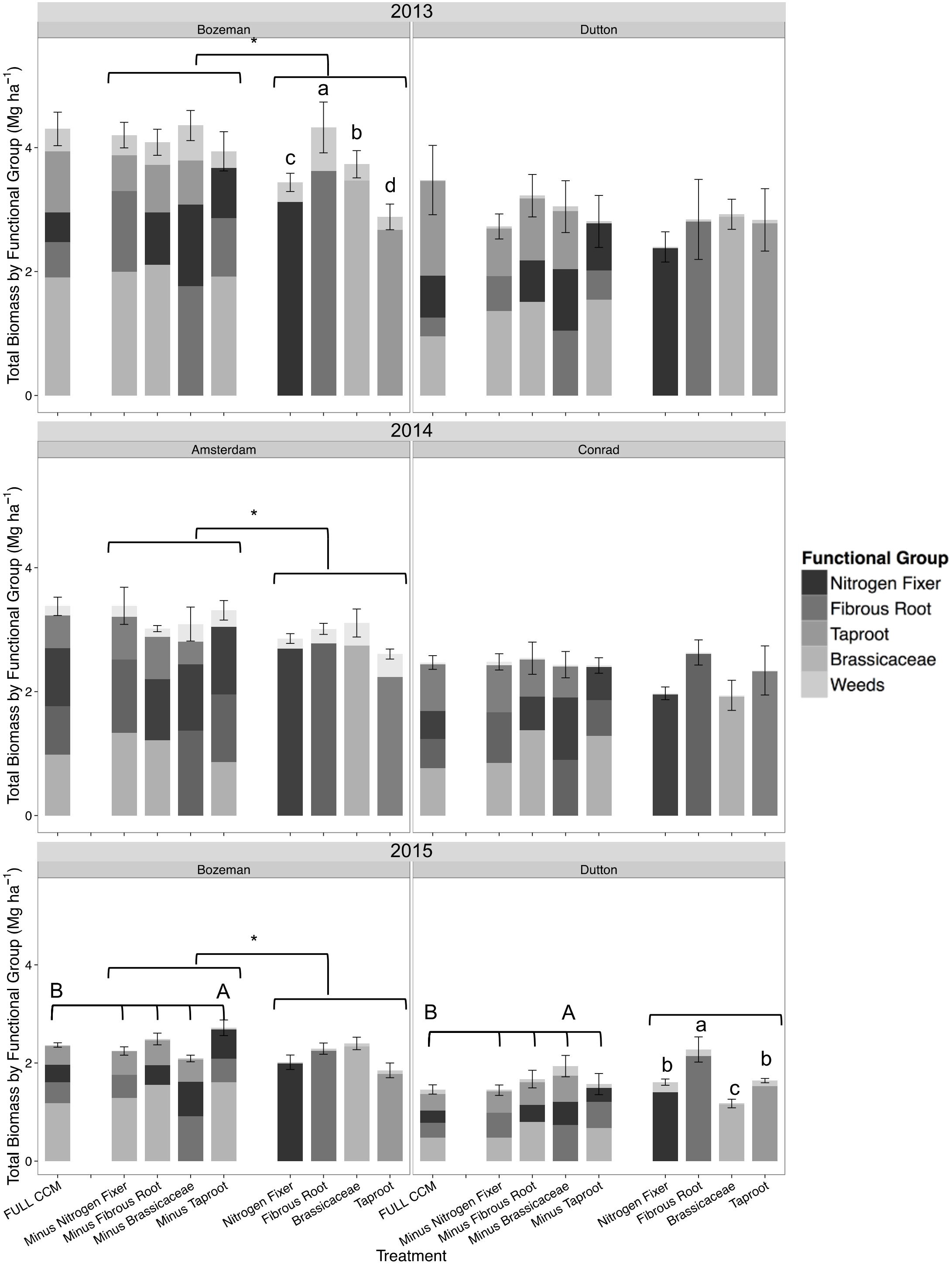

Figure 10. (Note that 1.0 Mg ha^{-1} = 893 lb/ac of dry weight biomass) Total cover crop biomass by treatment in each of six site-years using common seed densities (120 plants/m^2 = ~11 plants/ft^2). Shaded bars within totals are average ‘functional group’ contribution to the total biomass. Differences in total biomass within single functional group treatments are denoted with small letters. Differences between the FULL and the three functional group treatments are denoted by upper case letters. Differences between one- and three-functional groups are denoted with asterisk.

Table 2-4. Total cover crop biomass, soil water and nitrate-N to 3-ft depth at termination, and subsequent cereal crop yield and protein for cover crop mixture (CCM) vs sole pea cover crop and chem fallow at four plot-scale sites in Montana, in two years at each site.

Location	CCM vs Fallow	Total Biomass	Soil water	Soil N	Yield	Protein
		lb/ac	inches	lb/ac	bu/ac	**%**
Amsterdam					Spring wheat	
2012/13	CCM	900a	6.6a	58b	Hailed out 100%	
	Pea	680b	6.2a	71ab		
	Summerfallow	250c†	6.6a	90a		
Conrad					Spring wheat	
2012/13	MFR	380a	7.7b	18b	49.7ab	13.7a
	Pea	540a	7.4b	14b	44.2b	13.4a
	Summerfallow	0b	9.5a	32a	54.5a	13.4a
Bozeman					Winter wheat	
2013/14	CCM	3840a	7.6b	101c	61.3a	13.8a
	Pea	3440a	7.6b	158b	54.9a	13.9a
	Summerfallow	1160b	9.5a	222a	59.0a	13.2a
Dutton					Re-sown Spring wheat	
2013/14	CCM	3110a	5.6b	14b	41.1b	14.0a
	Pea	2380a	5.3b	24b	44.9ab	14.6a
	Summerfallow	110b	7.3a	56a	49.8a	14.4a
Amsterdam					Spring wheat	
2014/15	CCM	3020a	5.6b	14c	31.0a	13.2a
	Pea	2810a	5.0b	23b	31.3a	13.5a
	Summerfallow	1070b	7.5a	33a	31.1a	13.2a
Conrad					Spring wheat	
2014/15	CCM	2210a	6.3b	11b	16.3b	15.3b
	Pea	2130a	6.0b	17b	12.5c	17.3a
	Summerfallow	80b	9.4a	56a	28.2a	15.5b
Bozeman					Winter wheat	
2015/16	CCM	2120a	7.1b	28b	Data coming fall 2016	
	Pea	2160a	7.8b	77a		
	Summerfallow	30b	9.8a	88a		
Dutton					Winter wheat	
2015/16	CCM	1310a	7.4a	26b	Data coming fall 2016	
	Pea	1460a	8.1a	45a		
	Summerfallow	1250a	8.2a	36ab		

†Estimated from weed component in other treatments.

Letters next to values within each site-year denote differences at *P* <0.10.

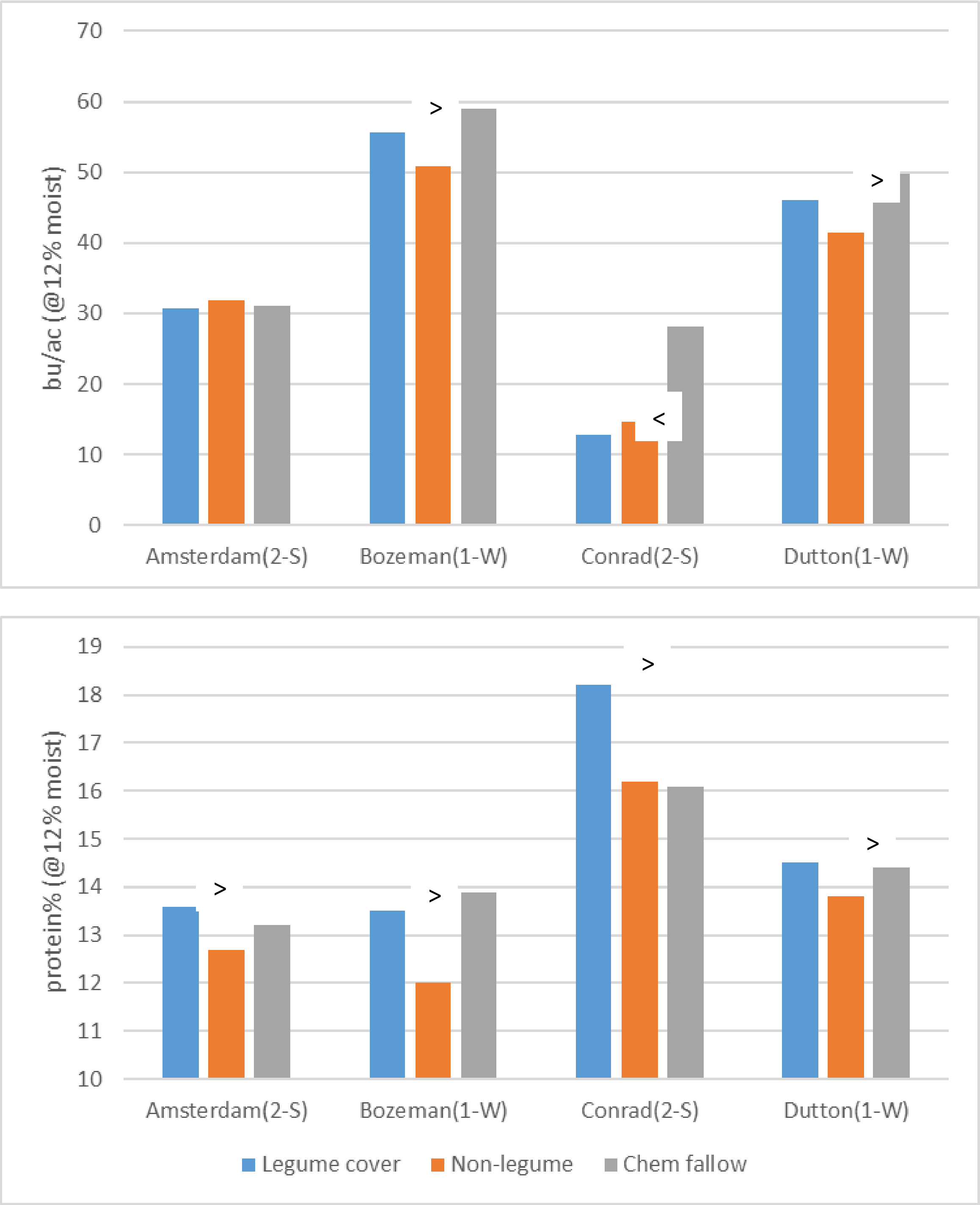

Figure 11. Wheat yield (upper panel) and protein (lower panel) following legume and non-legume cover crop treatments, compared with fallow, after one (**B**ozeman and **D**utton) or two (**A**msterdam and **C**onrad) cover crop cycles. '>' and '<' symbols represent comparison between legume and non-legume covers specifically (*P* < 0.10).

Objective 3) Soil Quality Indicators

3a. Soil quality indicators were measured in late March or early April the spring following cover crop treatments. We were fairly certain that growing cover crops in soils would increase biological activity relative to summer fallow at cover crop termination, but we were most interested in addressing s whether those differences would remain when the cash crop was starting to grow. The **A** and **C** sites have been sampled after one and two cycles of cover crop treatments, while at the time of this report only one cycle following the **B** and **D** sites has been completed, with cycle-2 results coming later in 2016 thanks to additional funding from the *Montana Fertilizer Advisory Committee*.

Soil Biology

Potentially Mineralizable Nitrogen

Potentially mineralizable nitrogen (PMN) is a measure of soil organic nitrogen that can be mineralized and made plant-available via microbially-mediated processes. PMN was calculated as the amount of nitrogen mineralized during a 14-day anaerobic lab incubation. In five of six site years, the presence of either Full Mix or Pea, or both, increased PMN compared to summer fallow with no consistent pattern between Pea and the Full Mix (Figure 12). **These results suggest that cover crops can increase mineralizable nitrogen to the soils, but that results will be site-dependent.**

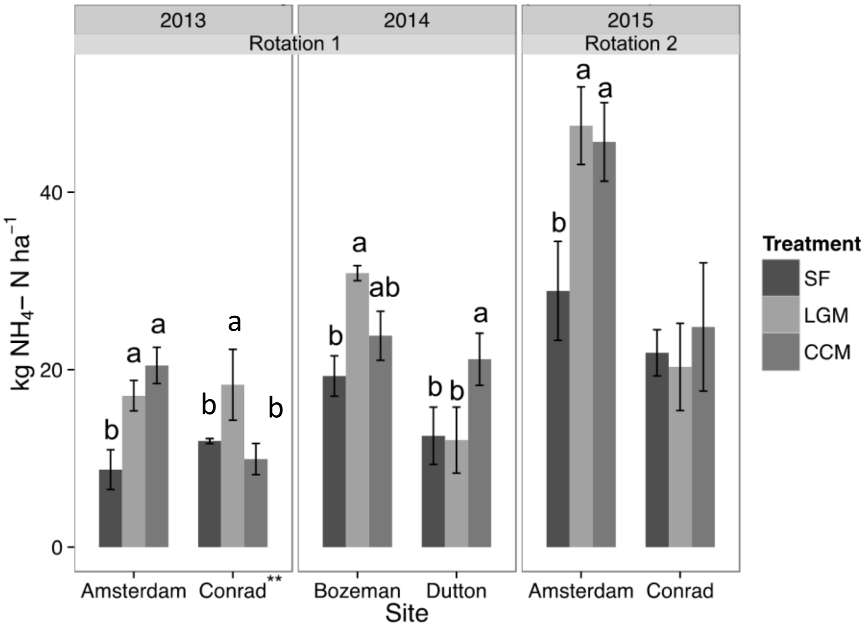

Figure 12. Mean PMN (kg NH_4-N ha^{-1}) and standard error bars following one and two rotations of Summer Fallow (SF), Pea (LGM), and Full Mix (CCM) at four sites. **Full Mix was the three functional group treatment excluding fibrous rooted crops at Conrad in 2013.

Soil microbial biomass

Microbial biomass was measured indirectly by quantifying the rate of microbial respiration after a yeast solution was added to soil samples and incubated for four hours. We expected that the presence and quantity of cover crop biomass would increase microbial biomass, and also that we would see greater differentiation after two full crop rotations. Following one cover crop cycle, microbial biomass increased only at one of four sites (Table 3-1). In 2012 at Amsterdam and Conrad, there was low biomass production. In 2013, cover crop biomass was high but microbial biomass differed in soils measured nine months after cover crop treatments only at Dutton. Following two cover crop rotations at Amsterdam, microbial biomass increased by 1.4 or 1.3 times after Full Mix or Pea, respectively, but not at Conrad (Table 3-1).

Table 3-1. Microbial respiration (µg CO_2 g soil^{-1} hr^{-1}) means and standard error from six site-years.

	----------------------Rotation 1			-----------------------	---------Rotation 2---------	
	-----------2012/13---------		---------2013/14---------		----------2014/15----------	
Treatment	Amsterdam	Conrad	Bozeman	Dutton	Amsterdam	Conrad
FULL	445 (20)	*257 (38)	574 (18)	361^{a} (46)	260^{a} (26)	294 (29)
PEA	403 (30)	354 (69)	591 (38)	237^{b} (20)	263^{a} (8)	212 (23)
FALLOW	369 (38)	341 (35)	550 (50)	211^{b} (35)	193^{b} (20)	261 (46)
p-value	0.24	0.17	0.76	**0.03**	**0.03**	0.34
LSD (0.05)	NS	NS	NS	103	54	NS

* In the FULL treatment at Conrad 2013, microbial respiration was measured in the three functional group treatment that excludes fibrous roots rather than the four functional group treatment.

Soil Enzymes

We expected that the same factors that affected microbial biomass (presence and abundance of cover crop biomass) would also affect enzyme activity. Soil extracellular enzyme activity was measured in one gram (about 1/28 oz) of field-moist soil by incubating soils with pNP-labeled enzyme-specific substrate for 1 h at 37 °C. When enzymes bind with the labelled substrates, the solution turns color, and enzyme activity is quantified spectrophotometrically. Enzymes analyzed include: β-1,4,-glucosidase (cellulose decomposition), β-1,4,-N-acetyl glucosaminidase (nitrogen cycling), arylsulfatase (highly correlated to microbial biomass), and acid and alkaline phosphatases (phosphate fertility). In addition to measuring the activity of individual enzymes, we calculated the geometric mean of all enzymes to summarize enzyme response in one value.

Following the first cover crop rotation, individual enzyme activities generally did not differ among Fallow, Pea, or Full Mix regardless of year or site, except for acid and alkaline phosphatases at Dutton and arylsulfatase at Bozeman (Figure 13). After the second rotation, only one of the six enzymes differed among the Fallow, Pea, and Full Mix treatments at each site. β-glucosaminidase activity at Conrad was 1.4 and 1.5 times greater following Full Mix than Pea and Fallow, respectively ($P = 0.04$), and acid phosphatase activity at Amsterdam was 1.3 times greater following a cover crop than summer fallow ($P< 0.01$). **After two crop rotations (A and C sites only), the geometric mean of five enzymes showed that cover crops have an influence on soil enzyme activity**. At Amsterdam in 2015, the presence of either Pea or the Full Mix resulted in a 30% increase in the geometric mean of enzyme activity compared to summer fallow ($P = 0.02$). At Conrad in 2015, the geometric mean was 1.4 and 1.5 times greater following the Full Mix than Pea or Fallow ($P < 0.01$).

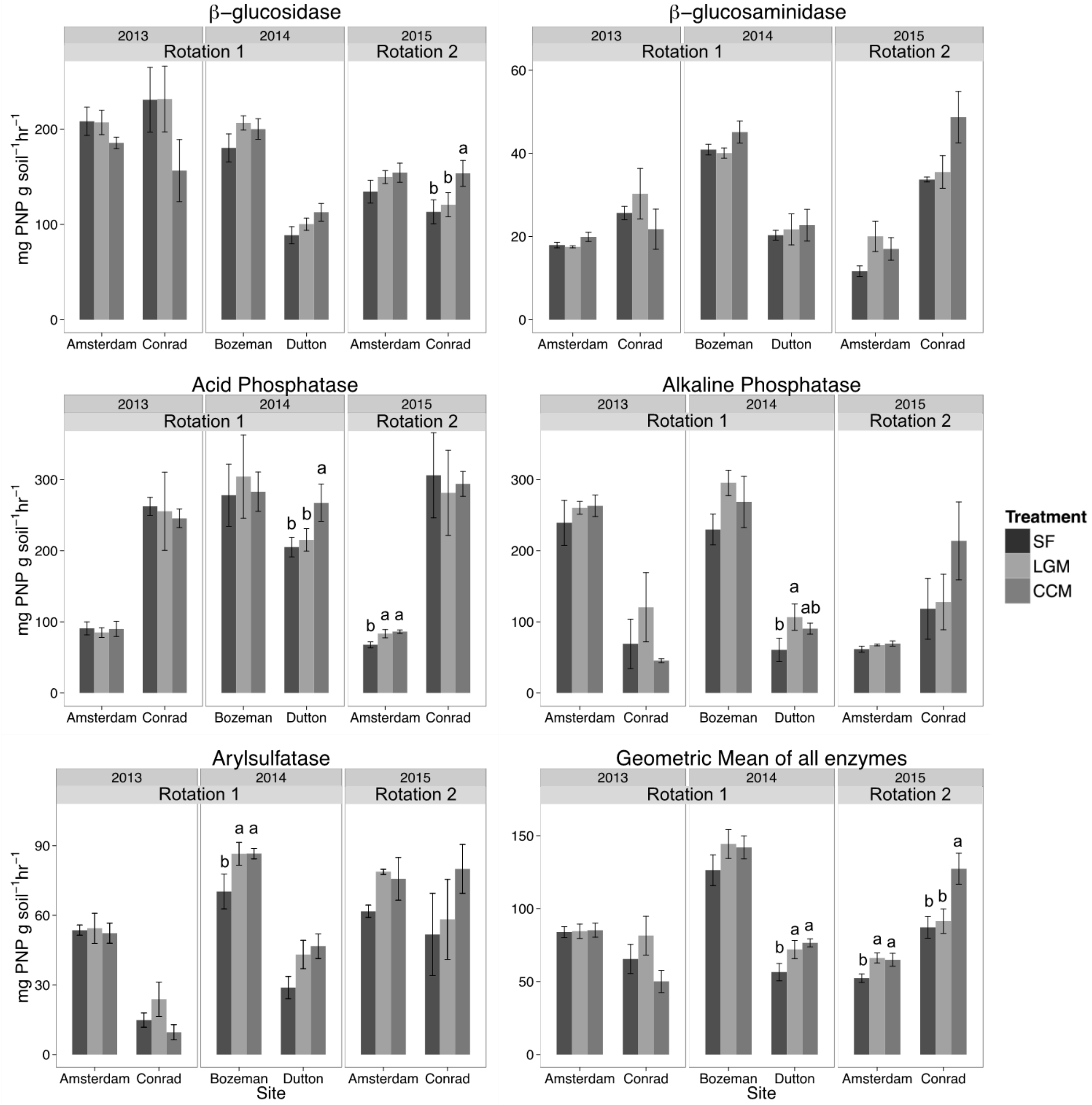

Figure 13. Mean enzymatic activity (mg PNP g soil^{-1} hr^{-1}) and standard error bars for β-glucosidase, β-glucosaminidase, acid and alkaline phosphatases, arylsulfatase, and the geometric mean of five enzymes following one and two rotations of Fallow (SF), Pea (LGM), and Full Mix (CCM). Different letters indicate differences among treatments within site years (*P* = 0.05) In the Full Mix treatment at Conrad 2013, enzymes were measured in the three functional group treatment that excludes fibrous roots.

Mycorrhizal Colonization

A mycorrhiza is a symbiosis between a plant and a root-colonizing fungus, that increases the host plant’s access to nutrients, specifically phosphorus. Mycorrhizae have not been a big consideration in conventional agriculture, because high fertilization rates largely eliminate the need for the host plant to form the symbiosis. The interest in mycorrhizae has grown with an increased emphasis in managing agricultural lands for soil quality. Mycorrhizae function to transform plant carbon into fungal biomass, supporting the soil food web, and contributing to aggregate stability. In the first year of the study, we measured mycorrhizal abundance in two ways: measuring the root colonization rate of Sudangrass plants that were grown in the greenhouse in soils from the different treatments, and also by collecting roots from wheat plants growing in soils with cover crop treatments the previous year. After the first year, we shifted our work to consider just the colonization levels of wheat, and that is the data reported here. At wheat anthesis, single plants were harvested for mycorrhizal colonization from the plots that the previous year had been in summer fallow, or grown with Pea or the Full cover crop mixture. Roots were cleared in KOH and stained with trypan blue so that fungal structures inside the roots could be quantified using slides and a compound microscope.

We expected that mycorrhizal colonization would be greater following a cover crop than summer fallow but that the extent of colonization would depend on the functional groups included in the mixture. Mycorrhizal colonization differed among the three treatments following the first rotation at two of four sites, but the trend was apparent at all sites (Figure 14). Mycorrhizal colonization of wheat at Conrad, which is a site with adequate to excessive Olsen P (28 ppm), increased from 11 to 20-22% following the Full Mix or Pea when compared with summer fallow (*P* = 0.15). At Amsterdam where Olsen P is much lower (<10 ppm), and overall mycorrhizal colonization was greater, plants growing in the Full Mix plots tended to have greater mycorrhizal colonization than those growing in Pea or Fallow treatments (*P* = 0.15). Bozeman had the highest mycorrhizal colonization of all sites and following one rotation, mycorrhizal colonization after summer fallow was 16-17% lower than Full Mix or Pea (*P* = 0.03). At Dutton, Full Mix resulted in greater colonization than Pea, with wheat growing in the previous year Fallow Treatment was intermediate between the two (*P* = 0.04). Following two rotations, there were differences between the three treatments at Conrad, where mycorrhizal colonization of wheat growing in soils with the Pea treatment was only 1.1 times greater than in CCM or SF treatments (*P* = 0.01). Mycorrhizal colonization levels did not differ between treatments at Amsterdam (*P* = 0.19).

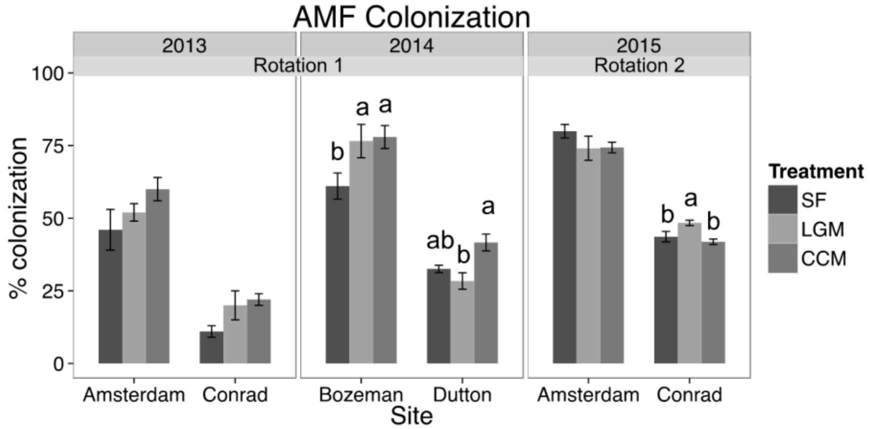

Figure 14. Mycorrhizal colonization (%) with standard error bars for wheat growing in sites following summer fallow (SF), Full Mix (CCM), and Pea (LGM) treatments. Letters denote significant differences among treatments at $P<0.05$.

For all of the biological indicators of soil quality, our results were somewhat supportive of the hypothesis that cover crop treatments will have a positive effect on soil parameters, but the results were not consistent across site years or between treatments. Dryland agriculture is dependent on precipitation inputs, and the potential for cover crops to positively affect soil quality, and the speed with which that occurs is likely to be correlated with the amount of cover crop biomass produced on a site. Our results suggest that changes to soil quality will take more years to resolve in the Northern Great Plains than in other regions of the country. We have one additional set of data to analyze from soil samples extracted April 2016, that represent soil quality after two rotations at **B**ozeman and **D**utton. With those results, we will have a more complete picture of cover crop effects after multiple rotations. Further, it is our plan to proceed with a longer term examination of soil biology differences after two additional cover crop cycles at the **A**msterdam and **C**onrad sites, pending funding acquisition from in-state sources.

Objective 3b The Effects of Single Functional Groups

The work for Objective 3b is only half completed, because *WSARE* funding took us only through the 2nd round of cover crop treatments at two of the four sites, and we are just starting the analysis of biological indicators of soil quality on samples collected April 2016 at **B**ozeman and **D**utton that will be discovered with funding from the *Montana Fertilizer Advisory Committee*. What we have learned so far is that changes in the soil biology parameters, when documented, are more often responding to cover crop biomass than to specific cover group groups. The species selected for our experiments were divided into functional groups, with the specific objective of being able to link soil responses to a group of plants, and ultimately serve as a framework within which producers could select cover crops.

For each of our specific parameters, we found that there were no differences in PMN following individual functional group treatments at **A**msterdam and **C**onrad in 2015 (**A**, $P = 0.86$; **C**, $P = 0.99$). For microbial biomass, respiration values did not differ between single functional group treatments at either **A**msterdam ($P = 0.12$) or **C**onrad ($P = 0.61$). There was, however, a positive correlation between the previous summer's aboveground cover crop biomass and the following spring's soil microbial biomass at **A**msterdam (Table 3-3; $r = 0.53$, $P < 0.01$), but not at **C**onrad. For soil enzyme activity, there were no differences in either individual soil enzyme activity among our four functional groups, nor were there differences in the geometric mean, accounting for all enzymes in one measure (Table 3-2). The geometric mean was also positively correlated to previous year cover crop biomass at **A**msterdam ($r = 0.38$, $P < 0.01$), but not at **C**onrad. And finally, for mycorrhizal colonization, there were no differences among single functional group treatments of the cover crops at either **A**msterdam or **C**onrad (Table 3-4).

It is risky to draw conclusions from only half of a data set, but the initial data suggests that in rain-fed cover crop systems that are biomass-limited, soil biological parameters will initially respond more frequently to cover crop biomass measures, rather than diversity. There are at least two caveats to that statement, the first being that we need long-term data to know whether soil quality indicators will respond to specific functional groups, in the same way that we see that wheat grain protein is higher following cover crop mixes including N-fixers. Secondly, we have measured a subset of soil quality indicators, and it is possible that other measures may respond more rapidly to cover crop treatments.

Objective 3c Identifying indicators which differ between cover crop treatments

Given the lack of response and the partial data set, we do not have the capacity to identify indicators which differentiate cover crop treatments. It is very likely that in the northern Great Plains, multiple rotations are required before this objective will be able to be measured. To that end we intend to continue the study sites at **A**msterdam and **C**onrad, pending acquisition of in-state funding sources, for two more cycles (4 yr) and assess differences amongst all cover crop treatments after four cycles.

Table 3-2. Mean enzymatic activity (standard error) of five enzymes and geometric mean following rotation two at **A**msterdam and **C**onrad in 2015 for single functional group treatments.

	β-glucosaminidase		β-glucosidase		Alkaline Phosphatase		Acid Phosphatase		Arylsulfatase		Geometric Mean	
Treatment	A	C	A	C	A	C	A	C	A	C	A	C
Nitrogen fixers	20.8 (2.2)	38.9 (9.6)	156.4 (15.5)	129.8 (17.5)	68.6 (1.9)	78.3 (12.5)	87.2 (8.0)	350.8 (26.9)	75.5 (5.61)	41.8 (11.8)	67.8 (4.2)	87.9 (14.2)
Fibrous roots	19.1 (2.0)	40.5 (3.1)	152.2 (2.2)	113.3 (9.9)	73.1 (2.8)	79.5 (8.6)	82.9 (7.2)	377.4 (18.7)	80.1 (8.2)	28.7 (6.4)	67.3 (4.3)	82.1 (6.8)
Brassicas	23.6 (3.1)	48.3 (5.2)	167.6 (8.8)	147.1 (18.7)	73.0 (2.2)	157.9 (53.7)	83.5 (1.9)	354.8 (72.6)	70.7 (7.2)	71.9 (27.0)	69.8 (3.7)	114.5 (15.2)
Taproots	21.1 (2.5)	42.9 (4.3)	156.1 (6.4)	138.5 (16.7)	68.7 (6.2)	112.8 (20.2)	86.0 (4.9)	317.3 (24.2)	71.0 (7.5)	45.2 (14.1)	67.0 (4.0)	96.3 (12.2)
P-value	0.62	0.75	0.73	0.59	0.78	0.31	0.97	0.81	0.82	0.47	0.97	0.43

Table 3-3. Correlation matrices (r) of soil biological response with the previous year's aboveground cover crop biomass production (Mg ha^{-1}).

Soil biological response	-------Rotation 2------	
	Amsterdam 2015	Conrad 2015
Microbial biomass	0.53***	0.07
β-glucosidase	0.27	0.22
β-glucosaminidase	0.39**	0.26
Arylsulfatase	0.23	0.04
Acid Phosphatase	0.57***	0.05
Alkaline Phosphatase	0.31	0.07
Geometric Mean	0.38**	0.09

*** <0.01; **<0.05; *<0.1

Table 3-4. Mean mycorrhizal colonization and microbial biomass (standard error) following two rotations of single functional group treatments at Amsterdam and Conrad in 2015.

	AMF (% roots colonized)		Microbial Biomass (μg CO_2 g soil^{-1} hr^{-1})	
Treatment	A	C	A	C
Nitrogen fixers	72 (3)	47 (2)	221 (20)	266 (34)
Fibrous roots	75 (3)	49 (4)	220 (12)	233 (26)
Brassicas	75 (2)	44 (3)	267 (10)	297 (34)
Taproots	79 (4)	40 (5)	222 (11)	255 (47)
P-value	0.18	0.27	0.12	0.61

Soil Chemistry

The soil chemistry aspects in this study related to the two principle macro-nutrients used in Montana cropping systems, nitrogen (N) and phosphorus (P).

<u>Nitrate-N</u> results were reported under Objective 2a. above, at both field- and plot-scales, since it made sense to discuss in proximity to cereal crop yield and protein responses.

<u>Olsen-P</u> concentrations were not different among cover crop treatments ($P<0.10$) at any of the six site-years, despite some apparently large differences at **C**onrad in both years (Table 3-5). High variability among the four blocks at **C**onrad made it hard to detect significant differences. Direct seeded systems often have high variability in soil test P levels because some samples have more subsamples collected from within P fertilizer bands from the previous year or years. Far more subsamples or blocks than was feasible to conduct in this study would be needed to determine if the apparent differences were significant or not.

Table 3-5. Olsen P concentrations in top 6 inches for each site year of CCM study measured in late March or early April in year after cover crops were grown.

	----------2013----------		----------2014---------		----------2015---------	
Treatment	Amsterdam	Conrad	Bozeman	Dutton	Amsterdam	Conrad
	----------------------- Olsen P concentration (mg kg^{-1}) -------------------------------					
Fallow	8.8	26.0	30.3	61.9	6.7	22.8
Pea	8.8	18.5	28.2	65.6	7.7	19.7
Full*	9.5	25.0	29.2	68.3	7.9	18.3
BC	--	--	--	--	7.4	15.2
FR	--	--	--	--	5.2	21.6
NF	--	--	--	--	7.0	20.9
TR	--	--	--	--	8.1	18.1
MBC	--	--	--	--	8.1	19.8
MFR	--	--	--	--	8.1	12.6
MNF	--	--	--	--	7.5	19.2
MTR	--	--	--	--	6.7	19.7
p-value	0.90	0.50	0.81	0.91	0.27	0.51

There were no Olsen P differences at $P<0.10$ in any site year.

* MFR used in place of Full at Conrad in 2013 due to downy brome infestation

Soil Physical Characteristics

The physical characteristics measured in this study were soil water content, soil temperature, water stable aggregates (WSA), and static cone penetration resistance (measure of compaction).

Soil water results were reported under Objective 2a. above, at both field- and plot-scales, since it made sense to discuss in proximity to cereal crop yield and protein responses.

Soil temperature

Soil temperature was measured with I-Buttons (Maxim Integrated, San Jose, California). In 2013, two I-Buttons were installed per plot 2-inches deep in the Fallow, Full, Pea, and four individual treatments at **B**ozeman and **D**utton approximately 3-4 weeks after seeding. This system was repeated in 2014 at **A**msterdam and **C**onrad except that additional I-Buttons were installed at 0.5 inches and 4 inches in the Fallow, Full, and Pea treatments. The I-Buttons recorded temperature every 2 hr until they were extracted between two and six weeks after termination.

To determine differences in soil temperature between cover crop treatments and fallow, analysis of variance (ANOVA) was used to compare average temperature differences between discrete 3-day blocks of time. Three-day averages were selected to give enough resolution to see patterns, while reducing diurnal fluctuations. We used ANOVA to compare discrete time periods on the whole series because we wanted to determine when, and for how long, treatments differed from fallow. Tukey's honest significant difference was used to analyze pairwise differences. All statistical analysis was performed using R statistical software (version 3.2.2).

Mean 3-day soil temperatures in all cover crop treatments were cooler than fallow (*P*<0.1) at Bozeman from mid-June to mid-July, with differences as large as 11°F (Figure 15). The full eight-species treatment and the pea treatment differed from fallow for the longest duration (~55 days), beginning 46 days after seeding (May 2) and ending approximately 37 days after

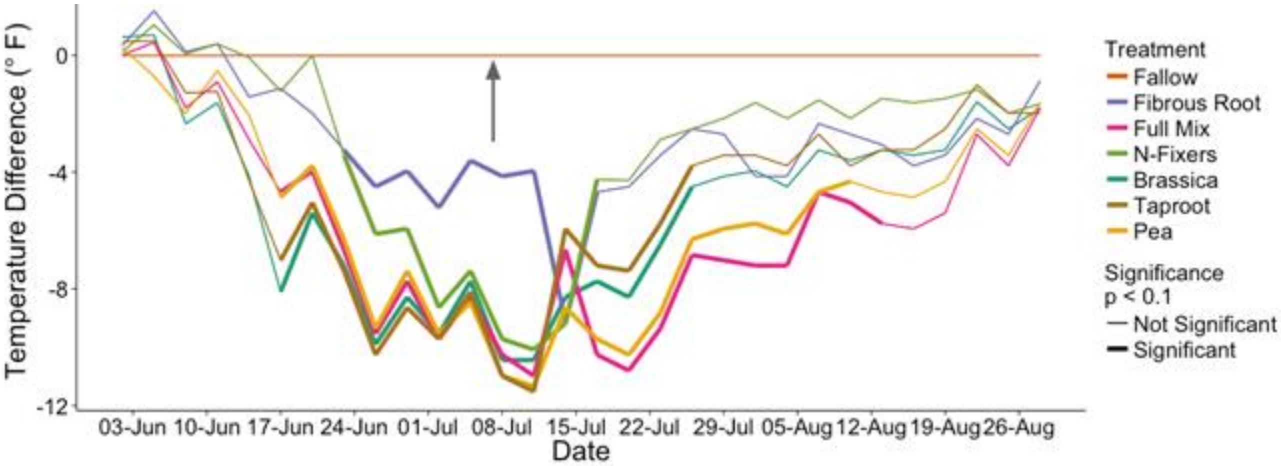

Figure 15. Cover crop soil temperatures (3-day means) at 2-inch depth compared with fallow at Bozeman during 2013. Horizontal zero-line represents fallow treatment and arrow represents cover crop termination date. Thicker lines represent when there is >90% chance that there are differences from fallow.

termination. Soil temperatures in the full eight-species mix were cooler than temperatures in the pea treatment from July 17 - 25 and August 1 - 3.

Soil temperatures in all cover crop treatments were cooler than fallow at Dutton for varying lengths of time from late June to mid-August, with differences as large as 9°F under the full mix and pea (Figure 16). The full eight-species mix and the pea treatment differed from fallow for the longest duration (~30 days), beginning 50 days after seeding (May 5) and continuously reducing temperature after termination for 9 days (full mix) to 23 days (pea). The longer cooling period for pea was likely in part due to incomplete kill from glyphosate. A 2nd spray of 2,4-D and bromoxynil completed the termination. Temperatures in the full eight-species mix at Dutton were warmer than the pea treatment from July 16 - 30.

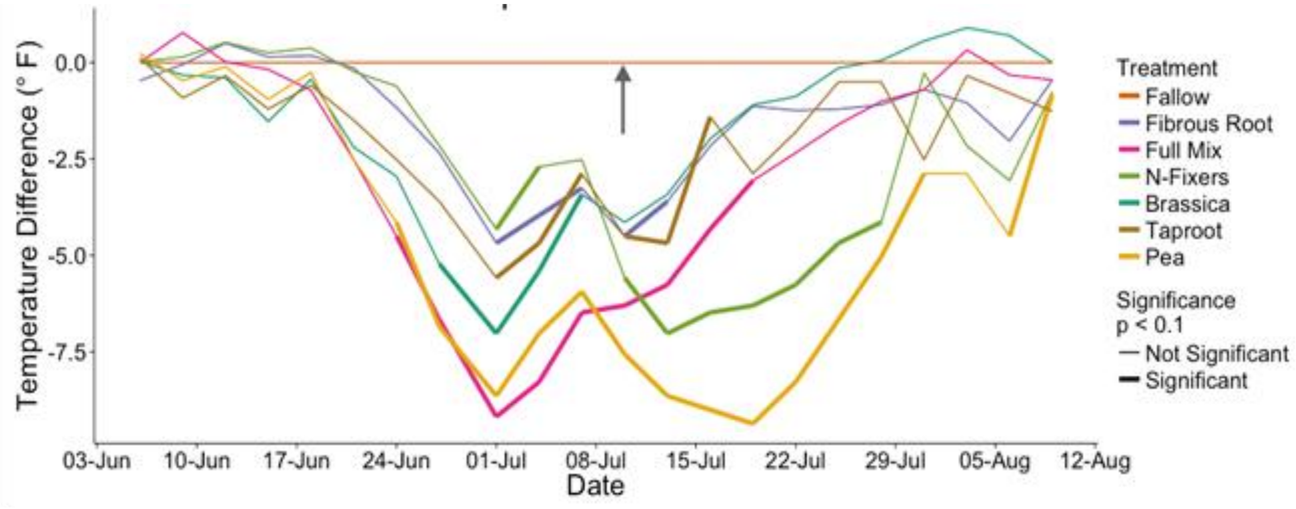

Figure 16. Cover crop soil temperatures (3-day means) at 2-inch depth compared with fallow at Dutton during 2013. Horizontal zero-line represents fallow treatment and arrow represents cover crop termination date. Thicker lines represent when there is >90% chance that there are differences from fallow.

At **A**msterdam in 2014, soil temperatures differed from fallow in all treatments except for the fibrous root mix during only a narrow window, between early - mid July (Figure 17). In the Full and Pea treatments, the cooling started approximately 56 days after seeding (May 8) and only persisted after termination for 6 days (Full) to 15 days (Pea). The magnitude of the cooling was also lower (5 to 6°F) than at **B**ozeman or **D**utton.

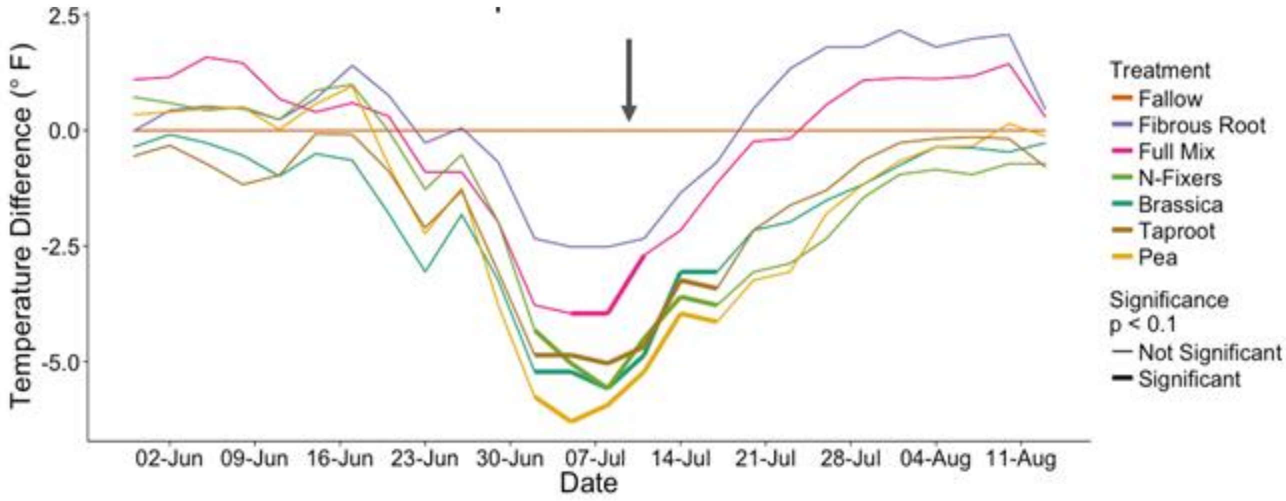

Figure 17. Cover crop soil temperatures (3-day means) at 2-inch depth compared with fallow at Amsterdam during 2014. Horizontal zero-line represents fallow treatment and arrow represents cover crop termination date. Thicker lines represent when there is >90% chance that there are differences from fallow.

Soil temperatures were cooler than fallow at Conrad from about June 23rd to July 10th for all treatments except the fibrous root mixture (Figure 18). The cooling period started 45 days (Full) to 51 days (Pea) after seeding (May 9) and lasted after termination for 7 days (Full) to 14 days (Pea) after termination.

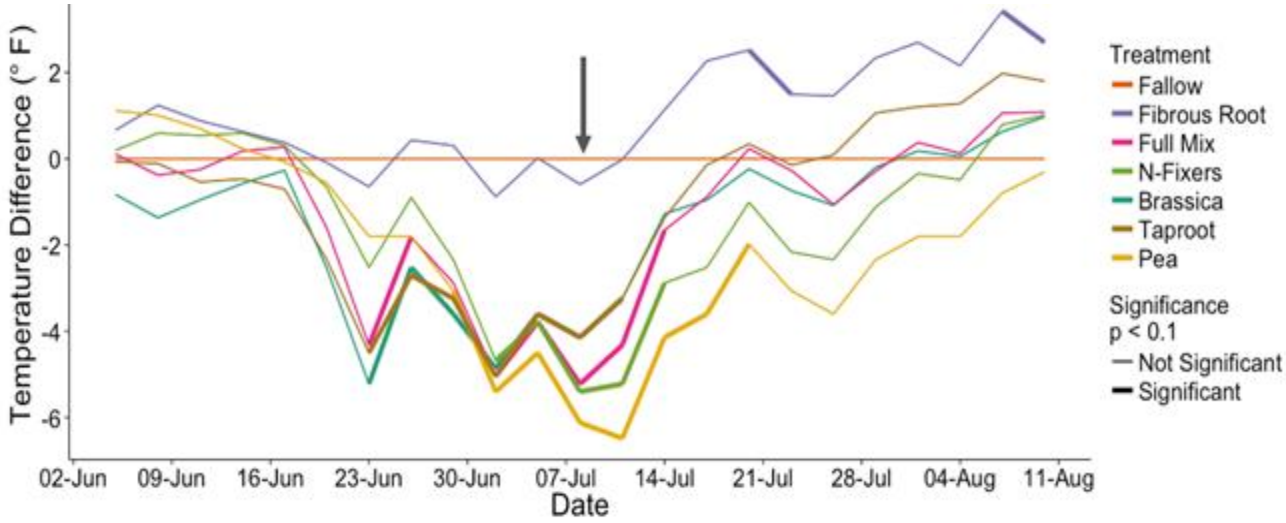

Figure 18. Cover crop soil temperatures (3-day means) at 2-inch depth compared with fallow at Conrad during 2014. Horizontal zero-line represents fallow treatment and arrow represents cover crop termination date. Thicker lines represent when there is >90% chance that there are differences from fallow.

It's unclear why there were differences in length of the cooling periods and temperature differences from fallow, especially at Amsterdam where cooling period was much shorter than at other three sites. Presumably, biomass would largely dictate this, yet **A**msterdam had higher biomass than **C**onrad and similar biomass as **D**utton. The time that it took for cover crops to die and desiccate would strongly influence the length of cover crop cooling; presumably herbicide kill was more effective at **A**msterdam. Finally, **A**msterdam has the lightest colored surface soil of the four sites because it is the only site with calcium carbonate at the surface, which would reflect more light from fallow soil resulting in less benefit of shading.

Maximum daily soil temperature (3-day mean) differences among treatments were greatest at the 0.5-inch depth at both **A**msterdam and **C**onrad in 2014 (Figures 19 and 20). At **A**msterdam, the highest temperature variability was at the 0.5-inch depth, especially in Fallow, followed by Full, then Pea. **At Conrad, daily maxima at 0.5 inches approached 100ºF in fallow**, a temperature that would result in high rates of evaporation and likely be detrimental to many soil organisms, whereas temperatures under the cover crops were almost always below 90ºF. There were no major differences among depths between Full and Pea at **C**onrad.

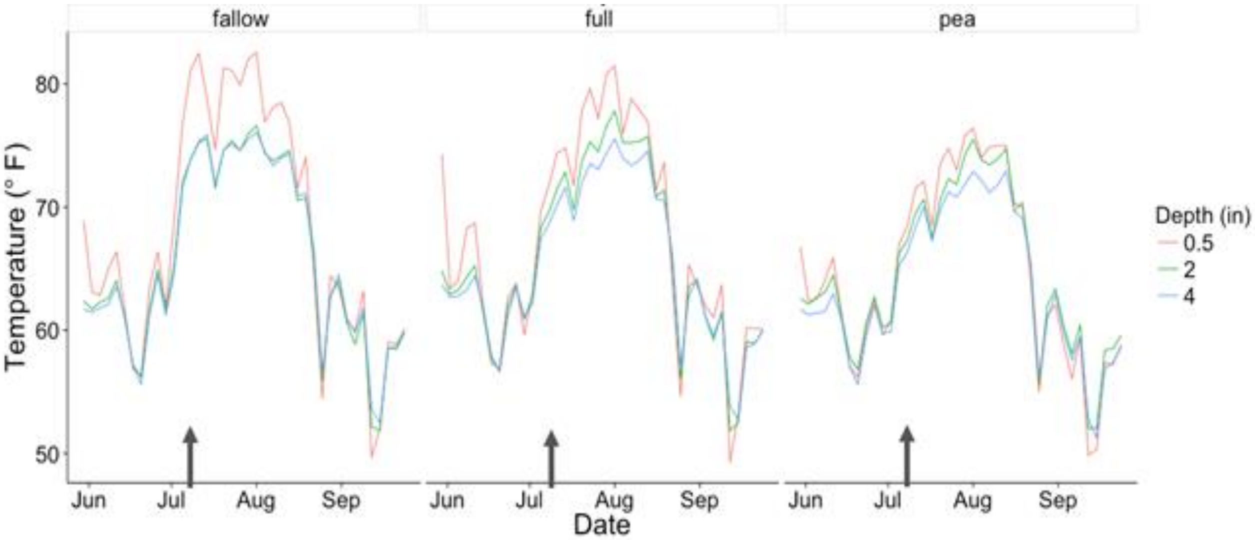

Figure 19. Three-day means of daily maxima soil temperatures at Amsterdam in 2014 at three different soil depths (0.5, 2.0, and 4.0 inches) under fallow, Full, and Pea treatments. Arrows represent cover crop termination date.

Water Stable Aggregates (WSA) and Penetration Resistance

Soil sampling was conducted in late March or early April in each wheat year to determine if there were any cover crop effects that persisted into the growing season. Six random subsamples per plot were collected from the upper 6 inches, and the sample composited and air-dried prior to WSA (and Olsen P) analysis. Maximum penetration resistance was measured with a static cone penetrometer in 3-inch increments down to 12 inches at six random locations within each plot.

Water stable aggregates (1 to 2 mm) were measured in fallow, Full, and Pea treatments in 2013 and 2014 and in all 11 treatments in 2015 (**A**msterdam and **C**onrad) using a method adapted from Kemper and Resenau (1986). Only at **C**onrad in 2013 were differences among treatments found; specifically, WSA in pea (779 g kg^{-1}) was higher than in MFR (553 g kg^{-1}), with WSA in fallow (640 g kg^{-1}) intermediate (Table 3-6). In the other five site-years, there were no differences among treatments. Mean 2015 cover crop biomass (incl. weeds) per treatment was not correlated with WSA at either **A**msterdam (*P*=0.20) or **C**onrad (*P*=0.67).

Aggregation is largely a function of soil texture, organic matter, root exudates, and microbially synthesized compounds such as glomalin, which is made by arbuscular mycorrhizal fungi. Two cycles of cover crops may simply be too short to have a substantial effect on concentrations of root exudates, microbial products, or soil organic matter. We also found relatively high variability in WSA for lab duplicates (average SEM = 66 g kg^{-1}; n=15), likely due to high inherent variability in aggregate strength; this would have decreased the potential for finding differences among treatments. Finally, these soils all had relatively high amounts of fines (silt loams and clay loams) resulting in high levels of background WSA based on fallow controls in 2013 and 2014 (ranging from 640 g kg^{-1} at Amsterdam in 2013 to 888 g kg^{-1} at Bozeman in 2014). High background levels of WSA would make it less likely that cover crops could substantially affect WSA.

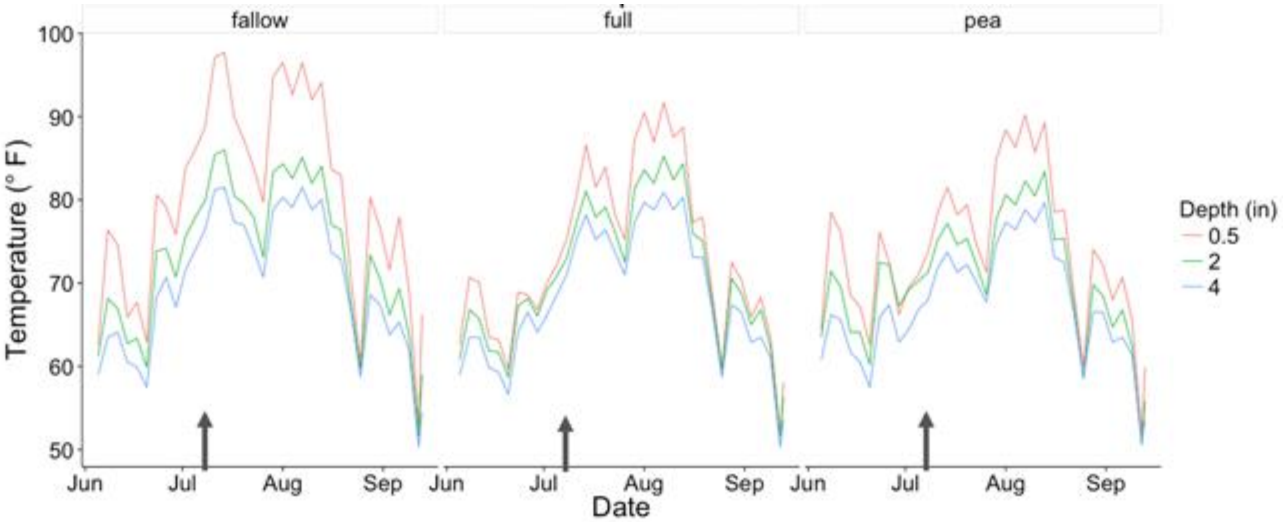

Figure 20. Three-day means of daily maxima soil temperatures at Conrad in 2014 at three different soil depths (0.5, 2.0, and 4.0 inches) under fallow, Full, and Pea treatments. Arrows represent cover crop termination date.

Table 3-6. Water stable aggregates (1 to 2-mm fraction) in top 15 cm for each site year of CCM study. Soils collected in April in year after cover crops were grown. To convert g kg^{-1} to %, divide by 10.

	----------2013----------		----------2014---------		----------2015---------	
Treatment	Amsterdam	Conrad	Bozeman	Dutton	Amsterdam	Conrad
	----------------------- **Water Stable Aggregates (g kg^{-1})** -------------------------------					
Fallow	711	636ab	879	638	450	791
Pea	708	779a	888	646	439	676
Full*	734	553b	889	707	449	817
BC	--	--	--	--	426	783
FR	--	--	--	--	439	774
NF	--	--	--	--	402	692
TR	--	--	--	--	381	634
MBC	--	--	--	--	336	748
MFR	--	--	--	--	386	735
MNF	--	--	--	--	402	758
MTR	--	--	--	--	457	719
p-value	0.84	0.06	0.72	0.92	0.37	0.27
LSD$_{0.10}$	--	162	--	--	--	--

If two means are followed by the same letter, there is >90% chance that they are not different.

* MFR used in place of Full at Conrad in 2013 due to downy brome infestation

Table 3-7. Mean penetration resistance of six subsamples in the 0 to 3-inch depth increment for each site year of CCM study measured in late March or early April in year after cover crops were grown. To convert kg cm^{-2} to psi, multiply by 14.2.

	----------2013----------		----------2014---------		----------2015---------	
Treatment	Amsterdam	Conrad	Bozeman	Dutton	Amsterdam	Conrad
	------------ **Penetration Resistance for 0 to 3 inch depth (kg cm^{-2})** ----------------					
Fallow	16.3	9.5	7.5	4.4	21.1	5.5bc
Pea	19.2	9.9	6.1	5.0	20.7	5.8abc
Full*	18.3	10.1	7.3	5.0	21.5	5.5bc
BC	--	--	--	--	20.3	7.2a
FR	--	--	--	--	19.8	4.4c
NF	--	--	--	--	21.5	6.6ab
TR	--	--	--	--	20.4	5.1c
p-value	0.18	0.85	0.48	0.47	0.83	0.07
LSD$_{0.10}$	--	--	--	--	--	1.4

* MFR used in place of Full at Conrad in 2013 due to downy brome infestation

If two means are followed by the same letter, there is >90% chance that they are not different.

Penetration resistance was measured to determine the level of compaction; however, drier soils can increase penetration resistance incorrectly suggesting differences in compaction that were simply due to differences in soil moisture. We measured penetration resistance in April when soils generally have reached field capacity for soil moisture in the upper foot, yet this wasn't always the case. Soil water was measured in some, but not all site-years and treatments near the time of penetration resistance measurements. We also have soil water data at termination (see Soil Water section above) that helped us estimate whether penetration resistance differences could have been water related.

In the top depth (0 to 3 in.), there were only treatment differences at **C**onrad in 2015 (Table 3-7). The fibrous and taproot treatments had lower penetration resistance than brassica or N fixers, though there was no difference between Full, Pea, and fallow treatments. Compacted plow layers are typically deeper than this depth, and freeze-thaw perturbations are generally largest in this surface layer, making compaction less of an issue. Differences in root density and size in this surface horizon were likely not large enough after one or two CC cycles to importantly affect penetration resistance in five of the six site-years. The larger penetration resistance at **A**msterdam was likely a result of calcium carbonate in that site's surface horizon, combined with drier April conditions.

Penetration resistance was not different among treatments in the 3 to 6-inch depth increment at either site in 2013, or at **B**ozeman in 2014 (Table 3-8). There were differences at at both sites in 2015. Soil water contents were not different in the upper 6 inches among the three treatments there, meaning the treatment differences do not appear to be water related. It's possible that undecomposed roots would increase the resistance of these soils or affect freeze-thaw changes in bulk density. The nitrogen fixing (NF) treatment had higher penetration resistance at Amsterdam in 2015 than all other treatments, yet this treatment also had the lowest soil water content at termination. Penetration resistance after fallow at Conrad (2015) was lower than in all but the Full treatment. While tap rooted species were expected to decrease compaction by creating macropores with their roots, the likelihood of encountering a macropore with six measurements of a ~ 0.4 inch diam. probe is likely small, and it's conceivable that larger roots could compress the soil more than finer roots.

Table 3-8. Mean penetration resistance of six subsamples in the 3 to 6-inch depth increment for each site year of CCM study measured in late March or early April in year after cover crops were grown. To convert kg cm^{-2} to psi, multiply by 14.2.

	----------2013----------		----------2014---------		----------2015---------	
Treatment	Amsterdam	Conrad	Bozeman	Dutton	Amsterdam	Conrad
	---------------- Penetration Resistance for 3 to 6 inch depth (kg cm^{-2}) ---------------					
Fallow	19.0	11.5	9.9	6.9	21.3b	6.6d
Pea	19.4	12.0	10.7	9.4	21.2b	10.7b
Full*	21.2	12.1	10.4	9.7	21.4b	8.2cd
BC	--	--	--	--	21.0b	9.7bc
FR	--	--	--	--	20.7b	11.0ab
NF	--	--	--	--	24.1a	9.3bc
TR	--	--	--	--	21.2b	12.7a
P-value	0.16	0.88	0.23	0.48	0.06	0.04
$LSD_{0.10}$	--	--	--	--	1.7	1.8

* MFR used in place of Full at Conrad in 2013 due to downy brome infestation

If two means are followed by the same letter, there is >90% chance that they are not different.

There were no differences in penetration resistance for the 6 to 9-inch depth at four of six site-years (Table 3-9). At **D**utton in 2014, penetration resistance after fallow was less than after Pea or Full treatments, most likely due to soil water content differences. At **C**onrad in 2015, the pea and N fixers had higher penetration resistance than all but the taproot treatment. Soil water measured four days after penetration resistance sampling found that N fixers, pea, and taproot treatments had about 0.3 inches less water in the upper foot than the other four treatments so these differences may not be related to soil compaction.

Table 3-9. Mean penetration resistance of six subsamples in the 6 to 9-inch depth increment for each site year of CCM study measured in late March or early April in year after cover crops were grown. To convert kg cm^{-2} to psi, multiply by 14.2.

	----------2013----------		----------2014---------		----------2015---------	
Treatment	Amsterdam	Conrad	Bozeman	Dutton	Amsterdam	Conrad
	------------------- Penetration Resistance for 6 to 9 inch depth (kg cm^{-2}) ----------------------					
Fallow	13.9	12.9	10.0	8.7b	16.0	10.0c
Pea	15.2	13.6	10.1	11.7a	15.6	13.0a
Full*	15.6	14.5	10.1	11.5a	14.8	11.3bc
BC	--	--	--	--	16.9	11.4abc
FR	--	--	--	--	16.5	11.0bc
NF	--	--	--	--	17.4	11.9ab
TR	--	--	--	--	16.1	12.5ab
p-value	0.32	0.47	0.95	0.09	0.77	0.09
$LSD_{0.10}$	--	--	--	2.4	--	1.6

* MFR used in place of Full at Conrad in 2013 due to downy brome infestation

If two means are followed by the same letter, there is >90% chance that they are not different.

Penetration resistance in the 9 to 12-inch depth was only different among treatments at Conrad in 2015, and again, was more likely due to soil water differences than true treatment effects (Table 3-104).

In summary, while penetration resistance can detect compacted layers, there did not appear to be consistently large differences in penetration resistance among treatments, in part due to interactions with soil water content.

Table 3-10. Mean penetration resistance of six subsamples in the 9 to 12-inch depth increment for each site year of CCM study measured in late March or early April in year after cover crops were grown.

	----------2013----------		----------2014---------		----------2015---------	
Treatment	Amsterdam	Conrad	Bozeman	Dutton	Amsterdam	Conrad
	------------ Penetration Resistance for 9 to 12-inch depth (kg cm^{-2}) ------------------					
Fallow	13.3	14.2	10.2	9.0	14.2	10.3c
Pea	13.2	16.3	10.0	12.4	15.4	18.2a
Full*	14.4	15.6	9.3	13.1	14.8	11.5bc
BC	--	--	--	--	15.5	12.9bc
FR	--	--	--	--	14.2	12.1bc
NF	--	--	--	--	16.6	16.9a
TR	--	--	--	--	16.1	15.1ab
p-value	0.28	0.43	0.35	0.21	0.18	0.02
$LSD_{0.10}$	--	--	--	--	--	3.9

* MFR used in place of Full at Conrad in 2013 due to downy brome infestation

If two means are followed by the same letter, there is >90% chance that they are not different.

3b. More refined comparisons among all CCM treatments will begin in 2015 after the 2nd iteration of cover crops prior to spring wheat seeding.

> It was logical to include comparisons among the full set of CCM treatments in reporting for 3a. above.

3c. More refined assessment of soil quality changes awaits soil measurement after the 2nd iteration of cover crops at all sites. This information is intended to guide Montana farmers in customizing cover crop practices for their farm.

> Again, this was logical to include in the report for 3a. above. Note that we think it's important to track these soil responses in the longer term and so are attempting to follow two of the sites (**A**msterdam and **C**onrad) for two additional crop cycles, partially due to the enthusiasm for these growers in searching for potential long-term soil change. Although WSARE was unwilling to fund this longer-term research we appreciate that WSARE funding got us to this point, and are hopeful we can complete this investigation with in-state funding sources and thus leverage WSARE funding in a complementary manner.

Objective 4. Introduce growers and agricultural professionals ("audience") to the potential sustainable aspects of CCM's

We organized a Field Day at Amsterdam in 2012 with help from the Gallatin County Conservation District and NRCS that was attended by approximately 50 people. Dr. Jones gave two presentations (Shelby, 2011; Billings, 2012) on cover crops to 150 people. Dr. Miller gave a presentation to 50 NRCS agents at a *Soil Health Workshop* in Billings (2011) on MSU's research findings on the use of legume cover crops in Montana. **A video that included portions of the Field Day ("Mixed Cover Crops: An Introduction") was uploaded to YouTube and has received over 3,000 views.**

In 2013 participated in 100th Anniversary Field Day at the MSU Northern Ag Research Center near Havre, MT to present cover crop cocktails research to 200 people.

We assessed audience understanding at our 2nd Field Day in 2014 at Conrad, which was organized by us with help from the National Center for Appropriate Technology and MT Salinity Control Association. Those that filled out that evaluation said that their awareness and understanding was improved, and that they would share results with other. **One useful outcome from this field day was our new understanding that a termination target date of June 15 to preserve summerfallow crop insurance coverage levels was a false notion.**

Objectives 5. and 6. Educate audience about effects of CCM's on subsequent crop and economics, and the effects of CCM's on soil quality, including functional group benefits, based on our study

Outreach on this project was extensive. Specifically, the PIs on this project presented results of this study more than 40 different times to mainly producer audiences (Table P) for over 1,800 direct contacts, well over our total goal of 800 direct contacts. The PIs, and their graduate students, also presented at several regional and international conferences (Table CP). In May, 2014, Dr. Miller was invited to a policy summit in Kansas City, MO, to present cover crop research findings to various USDA agencies (NRCS, RMA, APHIS Wildlife Services) and the National Crop Insurance Council. Dr. Jones presented findings from this study on an ASA webinar on cover cropping in semi-arid regions.

The Northern Ag Network interviewed Dr. Jones in 2014 about this project and the project is highlighted on MSU's Soil Fertility webpage (http://landresources.montana.edu/soilfertility/covercrops.html). That webpage received over 1,000 visits in 2015 alone. In addition, there were five press releases on the study (Table CP), and five videos posted on YouTube (Table VO). The videos have been viewed over 5,000 times helping us greatly exceed our project goal of 4,000 indirect contacts when combined with webpage visits, press releases, and the radio interview. We also presented results from this study in a regional e-newsletter (Nutrient Digest), which is shared with agency personnel, extension agents, crop advisers, researchers, and producers in the 13 western U.S. states.

Our post-study survey of 500 randomly selected producers mailed in Feb 2015 found that 25% of respondents were aware of our study. Given that we drew this random set from a list of 24,000 Montana producers, and had a 40% response rate, between 2,400 and 6,000 Montana producers knew about our study (depending on extent of non-respondent bias). We also learned that 25 percent of respondents had tried cover crops, the barriers and incentives for cover crop adoption, producers' perspectives on benefits of mixed species cover crops, and questions producers hope future research will address. The survey and a summary of the results are posted on the cover crop webpage listed at the top of this paragraph (weblink valid Apr 28, 2016).

Table P. Extension presentations about or including mixed cover crop research results, 2011-present.

Year/month		Location	Audience	Locations	Hours	Number present
2011	Dec	Shelby	Producers	1	1	50
2012	June	Amsterdam	Producers, Agency personnel, Crop advisers	1	1	60
	Dec	Billings	Producers, Agency personnel, Crop advisers	1	1	100
2013	Oct	Great Falls		1	0.5	30
		Cover crops discussed but not main focus		7	6.25	320
	Dec	Helena	MT Seed Trade Assoc.	1	1	80
2014	Feb	Great Falls	Producers	1	1	12
	July	ASA Webinar	Agency personnel, Crop advisers, Researchers	1	0.67	62
	Nov	Sidney	Producers, Crop advisers, Researchers	1	0.33	33
	Dec	Hardin	Producers	1	1	30
	Dec	Great Falls	Producers	1	0.33	150
2015	Jan	Bozeman	Producers, Crop advisers	1	1	45
	Apr	Bozeman	Ext agents	1	1.0	60
	Jul	Havre	Producers, Crop advisers	1	0.5	100
	Nov	Bozeman	Producers, Crop advisers	1	1	50
	Nov	Billings	Producers, Crop advisers	1	1	100
	Nov	Missoula	Producers	1	1.25	18
	Dec	Bozeman	Producers, Crop advisers	2	0.67	70
		Cover crops discussed but not main focus		3	1.5	275
	Dec	Great Falls	Producers, Crop advisers	1	0.25	200
2016	Feb	Sheridan/Helena	Producers	2	1.5	54
	Feb	Three-Forks	Producers, Agency personnel, Crop advisers	1	0.75	73
		Cover crops discussed but not main focus		11	11	293
Cover crops main focus				22	16.75	1377
Cover crops discussed				21	19	788
Total				43	35.75	2165

Table CP. Conference proceedings/presentations, and press releases.

Conference proceedings	
2013	Tallman, S., P. Miller, C. Zabinski and C. Jones. 2013. Multi-species cover crops in fallow-wheat no-till systems in Montana. ASA-CSA-SSSA Conference Abstracts. Tampa, FL, November 3-6, 2013.
	Miller, P., M. Liebig, M. Burgess, C. Jones, J. O'Dea, S. Kronberg and D. Archer. 2013. Research experience with cover crops in the semi-arid northern U.S. Great Plains. ASA-CSA-SSSA Conference Abstracts. Tampa, FL, November 3-6, 2013.
2015	Jones, C., P. Miller, M. Burgess, S. Tallman, M. Housman, J. O'Dea, A. Bekkerman, and C. Zabinski. 2015. Cover cropping in the semi-arid west: effects of termination timing, species, and mixtures on nitrogen uptake, yield, soil quality, and economic return. In: Western Nutrient Management Conference Proceedings. 11:39-44. Reno, NV. Mar 5-6, 2015
	Jones, C., R. Kurnick, P. Miller, K. Olson-Rutz, and C. Zabinski. 2015. Cover Crop Decision Making: Information Sources and Barriers/Incentives for Adoption Based on a Montana Producer Survey. American Society of Agronomy Annual Meeting Abstracts. Minneapolis, MN. Nov 15–18, 2015.
	Housman, M., S. Tallman, J. Jones, C. Zabinski, and P. Miller. 2015. Cover Crop Diversity to Improve Soil Health in Dryland Wheat Systems of Montana. American Society of Agronomy Annual Meeting Abstracts. Minneapolis, MN. Nov 15–18, 2015.
2016	Miller, P., R. Engel, M. Housman, C. Jones, S. Tallman, and C. Zabinski. Cover Crops in Montana – Buying Land. Great Plains Soil Fertility Conference. Vol. 16: 89-95.

Press Releases and Interviews		
2012	June	Cover crop mixtures field day
2014	March	Cover crop video release
	May/June (3 total)	Cover crop farm tours
	June (radio PSAs)	Cover crop farm tours
	June	Northern Ag Network Interview
2015	Feb	Mixed cover crop study and survey
	Oct & Dec	Cover crop survey results

To evaluate the effectiveness of our outreach, we conducted three evaluations in Fall 2015 at workshops on soil health and cover crops. Of a total of 119 audience members, 51% had heard of our study prior to that day. Of those, 63% said the study had changed their understanding of cover crops, 37% had changed their management as a result of our study, and another 47% were more likely to change their management. This strongly suggests that this study had a substantial impact on management practices. Perhaps most importantly, the first graduate student on this project, Susan Tallman, was hired more than a year ago as a regional agronomist for the MT-NRCS, where she is putting her findings from this study directly into action as a regional agronomist specializing in cover crop implementation.

Table VO. Videos and other materials.

Videos	Views as of 4/27/16	link
Cover Crop Research by MSU: Part 1 (Perry Miller, 30 minutes, by NCAT)	368	https://www.youtube.com/watch?v=ROJBWz7Yr80
Cover Crop Research by MSU: Part 2 (Clain Jones, 8 minutes, by NCAT)	290	https://www.youtube.com/watch?v=rpTjxepXPT0
Mixed Cover Crops: An Introduction (Clain Jones, Susan Tallman, 7 minutes)	3632	https://www.youtube.com/watch?v=JWMT-uXyWZM&list=LLruDmHD_y2DQmi1G7SXzv8g&index=3
Cover Crop Cocktails Thesis Defense (Susan Tallman, 55 minutes)	233	https://www.youtube.com/watch?v=OZ9L58DlhLg
Mixed Cover Crops (Clain Jones, 24 minutes, by NCAT)	1133	https://www.youtube.com/watch?v=GJNw4mByH8s
Other		
Survey of Montana producers to learn their perceptions of cover crops and cover cropping practices: Mailed to 500 Montana producers		http://landresources.montana.edu/soilfertility/documents/PDF/2015CCSurvey.pdf
Cover crop survey report		http://landresources.montana.edu/soilfertility/documents/PDF/reports/2015CCSurveyReport.pdf
Cover crop survey results to be published in MSU College of Ag Annual Research Report		http://landresources.montana.edu/soilfertility/documents/PDF/reports/CoAReportCCMSurveyResults2016.pdf
Effects of Cover Crop Termination Timing, Species, and Mixtures on Yield, Protein, Economic Return, and Soil Quality. C. Jones and P. Miller. 2015. Nutrient Digest. Vol 7 (3).		http://landresources.montana.edu/soilfertility/documents/PDF/reports/NutDigF2015.pdf
Cover crop website providing links to publications, presentation, reports, and other information		http://landresources.montana.edu/soilfertility/covercrops.html

Objective 7. Enhance adoption, if study results warrant, of CCM's.

Economic adoption of cover crop mixtures awaits further discovery of optimization of soil changes over time, and cost of cover crop management. Results from our survey and much communication with various stakeholders suggests firmly that in Montana capturing value from the cover crop in the form or hay or grazing will be crucial to widespread adoption. That may in turn beg additional questions since grazing, as with any other practice, can be mismanaged with respect to soil quality goals. In Montana in 2014 there were 193,000 acres in some form of annual crop management other than for harvest (i.e. wildlife food plots, cover crop, green manure, forage harvest, or grazing) which increased to 236,000 acres in 2015 (USDA NASS – Montana). However, the crop category specific to 'cover crops and green manures' declined from 14,400 acres to 12,100 acres over the same time frame while grazing increased by the same amount, and annual crop forage harvest increased from 163,000 to 207,000 acres. These data highlight the importance of engaging grazing/forage within cover crop management in Montana.

Impacts and Contributions/Outcomes: (how does this research benefit producers or consumers in the Western Region)

This research project has impacted USDA-NRCS policy for dryland cover crop adoption through reconsideration of termination timing, optimal seeding densities, and need for grazing/forage utility to make this practice profitable in Montana. Given that cover crops are being promoted aggressively for soil improvement by USDA-NRCS, it is crucial to understand the interaction of cover crop management and soil-climatic context, especially at the decadal time scale. Soil change occurs slowly and it is important to match grower expectations accordingly. With our monitoring of farmer-conducted, USDA-NRCS-advised on-farm trials we provided objective data that demonstrates the real challenge of managing soil water and nitrogen in the immediate term, and that soil water use and subsequent crop yield loss can be minimized via termination near first bloom of pea. Perry Miller was invited to summarize his cover crop research findings (including this current study) at a USDA policy summit in Kansas City in May 2014. **There it was evident how rare is long term research on cover crops, and how precariously national policy must be set in the absence of robust regional research.** Although our bid for WSARE funding to extend this research to a longer time frame met with rejection, we will endeavor to secure other funding sources to advance this research into a more meaningful time frame. Also, sparked partially by this WSARE study, a coordinated research effort to discover optimal cover crop species, and mixes, for strategic grazing was implemented across seven agricultural research centers in 2016. This research should help drive cover crop management efficiently to logical implementation.