10-27-2015

Short-Term Soil Responses to Late-Seeded Cover Crops in a Semi-Arid Environment

M. A. Liebig
USDA-ARS, mark.liebig@ars.usda.gov

J. R. Hendrickson
USDA-ARS, john.hendrickson@ars.usda.gov

D. W. Archer
USDA-ARS

M. A. Schmer
USDA-ARS, marty.schmer@ars.usda.gov

K. A. Nichols
Rodale Institute

See next page for additional authors

Liebig, M. A.; Hendrickson, J. R.; Archer, D. W.; Schmer, M. A.; Nichols, K. A.; and Tanaka, D. L., "Short-Term Soil Responses to Late-Seeded Cover Crops in a Semi-Arid Environment" (2015). *Publications from USDA-ARS / UNL Faculty*. 1563.
https://digitalcommons.unl.edu/usdaarsfacpub/1563

Authors

M. A. Liebig, J. R. Hendrickson, D. W. Archer, M. A. Schmer, K. A. Nichols, and D. L. Tanaka

Agronomy, Soils & Environmental Quality

Short-Term Soil Responses to Late-Seeded Cover Crops in a Semi-Arid Environment

M. A. Liebig,* J. R. Hendrickson, D. W. Archer, M. A. Schmer, K. A. Nichols, and D. L. Tanaka

ABSTRACT

Cover crops can expand ecosystem services, though sound management recommendations for their use within semiarid cropping systems is currently constrained by a lack of information. This study was conducted to determine agroecosystem responses to late-summer seeded cover crops under no-till management, with particular emphasis on soil attributes. Short-term effects of late-summer seeded cover crops on soil water, available N, near-surface soil quality, and residue cover were investigated during three consecutive years on the Area IV Soil Conservation Districts Research Farm near Mandan, ND. Mean aboveground cover crop biomass was highly variable across years (1430, 96, and 937 kg ha^{-1} in 2008, 2009, and 2010, respectively), and was strongly affected by precipitation received within 14 d following cover crop seeding. During years with appreciable biomass production (2008 and 2010), cover crops significantly reduced available N in the 0.9-m depth the following spring ($P = 0.0291$ and 0.0464, respectively). Cover crop effects on soil water were subtle, and no differences in soil water were found between cover crop treatments and a no cover crop control before seeding cash crops the following spring. Late-summer seeded cover crops did not affect near-surface soil properties or soil coverage by residue. Soil responses to late-summer seeded cover crops did not differ between cover crop mixtures and monocultures. Late-summer seeded cover crops may enhance ecosystem services provided by semiarid cropping systems through biomass production and N conservation, though achieving these benefits in a consistent manner appears dependent on timely precipitation following cover crop seeding.

Incorporating cover crops in semiarid cropping systems can intensify agricultural production. Using cover crops to extend the traditional growing season through inter- and/or double-cropping allows livestock producers to increase forage availability, often at a time of the year when abundant, quality forage from grassland has declined (Rogler et al., 1962). Cover crops grown for forage also offer the potential to enhance desirable agroecosystem co-benefits, including improved nutrient-use efficiency and soil tilth (Dabney et al., 2010; Acuña and Villimil, 2014), reduced pests (Lundgren and Fergen, 2010), and increased yield and yield stability (Snapp et al., 2005). Realizing such benefits over the long term can translate to cropping systems with increased resilience and lower environmental impact, thereby creating a more sustainable agriculture.

Despite potential cover crop benefits, their accrual in cropping systems within the northern Great Plains of North America is largely constrained by climate. Short growing seasons, inadequate precipitation, and highly variable weather conditions combine to make crop production in the region risky (Bailey, 1995; Farahani et al., 1998). Historical investigations in the northern Plains found cover crops—when used as a replacement for bare fallow—induced water stress and therefore did not benefit production of subsequent crops (Sarvis and Thysell, 1936; Army and Hide, 1959). Recent regional investigations including cover crops following harvest of a cash crop have shown reduced levels of available N (Reese et al., 2014), increased ground cover in spring (Moyer and Blackshaw, 2009), increased water stress on subsequent crops (Reese et al., 2014), and neutral or negative effects on crop yield (Blackshaw et al., 2010; Reese et al., 2014).

Management recommendations for cover crop use in the northern Plains are currently restricted by a deficiency of published information. Moreover, previous regional investigations have focused on cover crop monocultures, whereas cover crop mixtures are preferentially employed by producers as a means to reduce production risk and capture diversity-enhanced resource use (Wortman et al., 2012b; Tilman, 1999). In this study, we sought to determine agroecosystem responses to late-summer seeded cover crops, with particular emphasis on

Published in Agron. J. 107:2011–2019 (2015)
doi:10.2134/agronj15.0146
Received 24 Mar. 2015
Accepted 12 June 2015

M.A. Liebig, J.R. Hendrickson, D.W. Archer, and D.L. Tanaka (retired), USDA-ARS, Northern Great Plains Research Lab., P.O. Box 459, Mandan, ND 58554-0459. M.A. Schmer, USDA-ARS, Agroecosystem Management Research Unit, 137 Keim Hall, Univ. of Nebraska, Lincoln, NE 68583. K.A. Nichols, Rodale Institute, 611 Siegfriedale Rd., Kutztown, PA 19530-9320. *Corresponding author (mark.liebig@ars.usda.gov).

Abbreviations: ALL, all cover crops; PM, proso millet; PTT, purple top turnip; S, soybean; SF, sunflower; ST, spring triticale; VP, vine pea; WC, winter canola.

soil attributes. Specifically, we were interested in quantifying effects of seven cover crops—planted in monoculture and mixtures—on soil moisture, available N, near-surface soil quality, and residue cover under no-till management. The following two hypotheses were used to guide the study:

1. Soil responses to late-summer seeded cover crops will be associated with aboveground biomass production.
2. The frequency and degree of soil responses to late-summer seeded cover crops will be greater for mixtures compared to monocultures.

MATERIALS AND METHODS

Site and Treatment Description

The research site was located approximately 6 km south of Mandan, ND, (46°46′12″ N, 100°54′57″ W) on the Area IV Soil Conservation Districts (SCD) Research Farm. The site possesses a semiarid continental climate, with evaporation typically exceeding precipitation in any given year (Bailey, 1995). Long-term (98 yr) mean annual precipitation is 412 mm, with 79% of the total received during the growing season (April–September). Long-term mean annual temperature is 4°C, though daily averages fluctuate from < –10°C in the winter to >20°C in the summer. Site topography is characterized as gently rolling uplands (0–3% slope). Soils are formed from a silty loess mantle overlying Wisconsin-age till, and are dominated by a mix of Temvik and Wilton silt loams (USDA: fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls; FAO: Calcic Siltic Chernozems).

Research was initiated in April 2008 by seeding an 8 ha field to dry pea (*Pisum sativum* L.) at 141,700 viable seeds ha^{-1} with 19-cm row spacing using a John Deere 750 no-till drill (Deere & Company, Moline, IL). Dry pea were inoculated before seeding with *Rhizobium leguminosarium*. No fertilizer was applied. In early August, dry pea seed was harvested with a John Deere 4420 combine. Harvested residue was spread uniformly over the soil surface using a chaff spreader.

On 21–22 Aug. 2008, 19 cover crop treatments were seeded into the dry pea residue using seven crops in monoculture or mixtures. Crops belonged to graminoid, leguminosae, asteraceae, brassicaceae families, and included proso millet (*Panicum miliaceum* L.; warm-season grass), spring triticale (*Triticale hexaploide* Lart.; cool-season grass), soybean [*Glycine max* (L.) Merr.; warm-season legume], dry pea (cool-season legume), sunflower (*Helianthus annuus* L.; mycorrhizal broadleaf), winter canola (*Brassica napus* subsp. *Rapifera*; non-mycorrhizal broadleaf), and purple top turnip (*B. rapa*; tuber/root crop). Eleven treatments represented cover crop mixtures, and one treatment served as a no cover crop control. Selection of cover crop treatments and seeding rates were determined in consultation with area farmers and SCD personnel, and are presented in Table 1. Seeding was conducted using a John Deere 750 no-till drill with 19-cm row spacing and 2.4-cm seeding depth. Neither inoculant nor fertilizer were applied with the cover crop seed. Plots were 9.1 by 36.6 m in size, and treatments were replicated four times. Cover crop treatments were allowed to grow until a killing frost without management intervention. In the following spring, four "response crops" (corn [*Zea mays* L.], spring wheat [*Triticum aestivum* L.], soybean, and dry pea) were seeded perpendicular to the cover crop strips, thereby creating a crop sequence/cover crop matrix. Following seeding of response crops, individual experimental units were 83.6 m^2 (9.1 by 9.1 m) in size.

All treatments were implemented again in 2009 and 2010 on nearby land (approximately 2 km apart) previously seeded to dry pea with the same management history, topography, and soil type. Cover crop seeding dates were 25–26 August during both years.

Measurements

Precipitation, air temperature, and solar radiation were monitored at a North Dakota Agricultural Weather Network (NDAWN) station within 3 km of each field used for the cover crop study. Daily data were downloaded from the NDAWN website and summarized for three time periods at each site

Table 1. Seeding rates for cover crop treatments.

Cover crop treatment (acronym)	Seeding rate						
	Purple top turnip	Proso millet	Spring triticale	Soybean	Vine pea	Winter canola	Sunflower
	viable seeds ha^{-1}						
Control							
Purple top turnip (PTT)	1,309,657						
Proso millet (PM)		1,606,183					
Spring triticale (ST)			2,471,050				
Soybean (S)				321,237			
Vine pea (VP)					741,315		
Winter canola (WC)						1,482,630	
Sunflower (SF)							59,304
All cover crops (ALL)	174,620	240,927	351,435	45,887	105,421	197,684	8,472
ALL minus PTT	0	273,051	411,838	53,229	123,540	247,104	10,166
ALL minus PM	218,275	0	411,838	53,229	123,540	247,104	10,166
ALL minus ST	218,275	273,051	0	53,229	123,540	247,104	10,166
ALL minus S	218,275	273,051	411,838	0	123,540	247,104	10,166
ALL minus VP	218,275	273,051	411,838	53,229	0	247,104	10,166
ALL minus WC	218,275	273,051	411,838	53,229	123,540	0	10,166
ALL minus SF	218,275	273,051	411,838	53,229	123,540	247,104	0
ALL minus PM and ST	261,930	0	0	64,242	148,248	296,525	11,861
ALL minus S and VP	261,930	321,237	494,205	0	0	296,525	11,861
ALL minus WC and SF	261,930	321,237	494,205	64,242	148,248	0	0

corresponding to the dry pea phase, cover crop growth phase, and the over-winter phase (NDAWN, 2015).

Aboveground cover crop biomass was measured by clipping one representative 0.25 m^2 quadrat in each plot immediately before a killing frost (Table 2). Collected biomass was separated by species, oven dried at 70°C for 48 h, and weighed.

Soil water content measurements were made for each cover crop treatment soon after cover crop seeding, immediately following a killing frost (except in 2010, when measurements were taken before a killing frost), and before response crop seeding with a neutron soil moisture meter (Model DR503; CPN International, Inc., Concord, CA) (Table 2). Using a single access tube installed in the center of each cover crop plot within the spring wheat response crop strip, meter readings were taken to a depth of 2.1 m in 0.3-m increments. The meter produced approximately 8000 recorded disintegrations per 30 s reading interval in standard, plastic-shielded counting mode. Site homogeneity across the three fields used for the study required a single calibration. The meter was calibrated by determining gravimetric water content of soil cores collected during installation of access tubes by measuring the difference in soil mass before and after drying at 105°C for 24 h (Gardner, 1986). Gravimetric soil water data were converted to volumetric water content using field-measured soil bulk density (Blake and Hartge, 1986). Soil water data were expressed as cm H_2O 0.3-m depth^{-1}.

Soil NO_3–N was measured before cover crop seeding and again in the spring before seeding response crops (Table 2). Two soil samples were collected with a 3.5-cm (i.d.) Giddings hydraulic probe to a depth of 0.9 m near the middle of each plot and partitioned into increments of 0 to 0.15, 0.15 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m (Giddings Machine Co., Windsor, CO). Soil cores within a plot were composited by depth increment. Collected samples were stored in a double-lined plastic bag and placed in cold storage at 5°C until processing. Within 4 wk of collection, soil samples were dried at 35°C for 3 to 4 d and mechanically ground to pass a 2.0-mm sieve. Identifiable plant material (>2.0 mm diam., >10 mm length) was removed during sieving. Soil NO_3–N was estimated from 1:10 soil-KCl (2 M) extracts using cadmium reduction followed by a modified Griess–Ilosvay method (Mulvaney, 1996), and were expressed on a volumetric basis using field-measured soil bulk density for each depth (Blake and Hartge, 1986).

Near-surface soil properties were measured in the spring of each year before seeding response crops in two cover crop treatments: seven-way cover crop mixture (ALL) and no cover crop control (Table 2). Six soil cores were collected in four locations in each plot from the 0- to 0.075-m depth using a 3.13-cm (internal diameter) step-down probe. Two sampling locations were within the cover crop row, while the other two locations were between cover crop rows. Collected soil cores were composited by location, stored in a double-lined plastic bag, placed in cold storage at 5°C, and analyzed within 2 wk of collection.

Soil processing involved weighing the total tared soil mass of each sample at field moisture content and then removing 12 to 15 g for assessment of gravimetric water content (Gardner, 1986). Soil samples were then split for chemical and biological analyses into two approximately equal portions. Samples for chemical analyses were dried at 35°C for 3 to 4 d and then ground by hand to pass a 2.0-mm sieve. Identifiable plant material was removed during sieving and discarded. Chemical analyses included assessments of soil pH and particulate organic matter carbon (POM-C). Soil pH was estimated from a 1:1 soil-water mixture (Watson and Brown, 1998), while POM-C was quantified by analyzing the C content of material retained on a 0.053-mm sieve by dry combustion (Gregorich and Ellert, 1993). Biological analyses included assessment of soil microbial biomass, which was estimated using the microwave irradiation method (Islam and Weil, 1998). Before this analysis, field-moist samples were split and passed through a 2.0-mm sieve. Fifty grams of sieved soil was incubated 10 d at 55% water-filled pore space in the presence of 10 mL of 2.0 M NaOH. Carbon dioxide content was determined by single end-point titration with 0.1 M HCl (Paul et al., 1999), and the flush of CO_2–C following irradiation was calculated without subtracting a 10-d control (Franzluebbers et al., 1999). Gravimetric data were converted to a volumetric basis using field-measured soil bulk density (Blake and Hartge, 1986). All data were expressed on an oven-dry basis.

Crop residue coverage of soil was measured in each cover crop treatment the spring of each year using the transect technique (Laflen et al., 1981) (Table 2). Measurements were made within soybean response crop plots immediately before seeding. Crop residue presence on the soil surface was counted along two 25 point transects equally spaced on a 7.6 m cable. Transects in a plot were oriented in a diagonal sampling pattern (V), which pointed in the direction of seeding. Crop residue intersecting with a point on the cable was counted as a contact, and the total number of residue contacts within a plot was recorded. Collected data were converted to percent soil coverage by residue before statistical analyses.

Data Analyses

A randomized complete block experimental design with four replications was adapted for the study. Data were analyzed by year using appropriate PROC MIXED models in SAS assuming cover crop treatment as a fixed effect (Littell et al., 1996). To evaluate potential diversity effects on measured variables, data were further analyzed by aggregating data into three groups:

Table 2. Dates of field and data collection activities associated with each site year.

	Site 1		Site 2		Site 3	
Activity	2008	2009	2009	2010	2010	2011
Seed cover crop	21–22 Aug.		25–26 Aug.		25–26 Aug.	
Aboveground cover crop biomass sampling	15 Oct.		26 Oct.		2 Nov.	
Soil water measurements	25 Aug., 20 Oct.	18 May	27 Aug., 5 Nov.	16 Apr.	31 Aug., 22 Oct.	11 May
Soil NO_3–N sampling		8 Aug., 6 May		19 Aug. 28 Apr.		19 Aug. 5 May
Near-surface soil sampling		18 May		11 May		5 May
Soil cover measurements		6 June		25 May		18 May

Table 3. Weather attributes during the study. Cumulative precipitation, mean air and soil temperature, mean solar radiation, and cumulative growing degree days provided for the dry pea, cover crop growth, and over-winter phases at each site.

Site/Phase	Dates	Length	Cumulative precip.	Mean air temp.	Mean soil temp.†	Mean solar radiation	Growing degree days‡
		d	mm	———— °C	————	$MJ\ m^{-2}\ d^{-1}$	d
Site 1							
Dry pea	15 Apr. 2008–20 Aug. 2008	128	292	16.0	15.3	22.5	1433
Cover crop growth	21 Aug. 2008–15 Oct. 2008	56	76	14.1	14.4	14.8	517
Over-winter	16 Oct. 2008–15 Apr. 2009	182	147	–6.7	0.5	9.6	76
Site 2							
Dry pea	15 Apr. 2009–24 Aug. 2009	132	362	15.1	13.6	21.5	1334
Cover crop growth	25 Aug. 2009–26 Oct. 2009	63	115	12.2	12.7	13.0	511
Over-winter	27 Oct. 2009–15 Apr. 2010	171	138	–5.0	0.5	8.9	83
Site 3							
Dry pea	15 Apr. 2010–24 Aug. 2010	132	299	16.9	14.7	21.5	1581
Cover crop growth	25 Aug. 2010–2 Nov. 2010	70	138	12.0	12.1	13.1	517
Over-winter	3 Nov. 2010–15 Apr. 2011	164	57	–7.7	0.5	9.0	36

† Soil temperature at 5-cm depth.

‡ 5°C base temperature used for growing degree days.

mixtures, monocultures, and a no cover crop control. Before statistical analysis, aboveground biomass data were summed across species for cover crop treatments with multiple species. Soil water and NO_3–N data were analyzed by individual and summed depths within each sampling time. The Tukey–Kramer method for multiple pairwise comparisons was used to identify differences between means using a significance criterion of $P \leq 0.05$. Variation of means was documented using standard error. Data for near-surface soil properties were averaged across sampling locations, as row-interrow differences were nonsignificant (data not shown). Where applicable, associations between measured variables were identified using Pearson correlation analysis.

Table 4. Aboveground cover crop biomass production for individual and aggregated cover crop treatments, 2008 to 2010. Cover crop treatments aggregated by monocultures and mixtures.

Cover crop treatment	Aboveground cover crop biomass 2008	2009	2010
	————	$kg\ ha^{-1}$	————
Purple top turnip (PTT)	2889a†	73	1310ab
Proso millet (PM)	259cd	8	4bc
Spring triticale (ST)	1944ab	349	1550a
Soybean (S)	75d	26	34bc
Vine pea (VP)	985bcd	190	1308ab
Winter canola (WC)	2018ab	14	567abc
Sunflower (S)	16 d	7	2bc
All cover crops (ALL)	1905ab	122	1201ab
ALL minus PTT	1014bcd	87	1007abc
ALL minus PM	1692ab	128	1008abc
ALL minus ST	1585abc	76	750abc
ALL minus S	1586abc	104	1198ab
ALL minus VP	1145bcd	61	720abc
ALL minus WC	1956ab	141	1198ab
ALL minus SF	1172bcd	96	1197ab
ALL minus PM and ST	1909ab	66	1231ab
ALL minus S and VP	2030ab	93	1343ab
ALL minus WC and SF	1558abc	90	1239ab
Monoculture	1169	95	682
Mixture	1596	97	1099

† Individual treatment values in a column with unlike letters differ at $P \leq 0.05$. No differences in aboveground cover crop biomass were observed between monocultures and mixtures in any year.

RESULTS

Weather conditions during the dry pea phase were relatively constant between years, with narrow ranges of cumulative precipitation (292–362 mm), mean air temperature (15.1–16.9°C), and growing degree days (1334 –1581 d; 5°C base temperature) (Table 3). Mean length of the cover crop growth phase was 63 d, and ranged from 56 to 70 d. Cumulative precipitation received during the cover crop growth phase increased each year (76, 115, and 138 mm for 2008, 2009, and 2010, respectively). Mean air and soil temperatures during the cover crop growth phase were approximately 2°C warmer in 2008 compared to 2009 and 2010. While mean solar radiation mirrored temperature trends between years during the cover crop growth phase (14.8 $MJ\ m^{-2}\ d^{-1}$ in 2008 vs. 13.0 and 13.1 $MJ\ m^{-2}\ d^{-1}$ in 2009 and 2010, respectively), growing degree days across years were nearly constant (Mean = 515 d; Range = 511 to 517 d). The over-winter phase during the final year of the study was dryer and colder than the previous over-winter phases (Table 3).

Aboveground cover crop biomass was greatest in 2008 (1430 ± 178 $kg\ ha^{-1}$), least in 2009 (96 ± 19 $kg\ ha^{-1}$), and intermediate in 2010 (937 ± 115 $kg\ ha^{-1}$) (Table 4). Differences in cover crop biomass between years were likely driven by variation in weather conditions. As reviewed above, mean solar radiation and air and soil temperatures were greater during the cover crop growth phase in 2008 compared to 2009 and 2010, thereby providing improved growing conditions in the former. Additionally, precipitation timing was likely a key determinant affecting biomass production, as 23, 1, and 92 mm of precipitation was received during the first 14 d following cover crop seeding in 2008, 2009, and 2010, respectively (NDAWN, 2015; data not shown).

Among cover crop treatments, purple top turnip produced significantly more aboveground biomass compared to four monocultures (proso millet, soybean, vine pea, sunflower) and three mixtures (ALL minus proso millet, ALL minus vine pea, ALL minus sunflower) in 2008 (Table 4). No differences in

Table 5. Soil water content in 0.3 m increments to a depth of 2.1 m for individual and aggregated cover crop treatments, 20 Oct. 2008. Depths possessing a significant response indicted with a *P* value and treatment means.

	Soil water content by depth, cm H_2O 0.3-m depth^{-1}						
Cover crop treatment	0.3	0.6	0.9	1.2	1.5	1.8	2.1
P value (individual treatments)	0.0059	0.0299	ns	ns	ns	ns	ns
No cover crop control	9.1a	8.3ab					
Purple top turnip (PTT)	8.4ab	7.8ab					
Proso millet (PM)	7.8ab	6.4ab					
Spring triticale (ST)	6.6ab	7.1ab					
Soybean (S)	7.7ab	5.7ab					
Vine pea (VP)	8.1ab	6.4ab					
Winter canola (WC)	8.3ab	8.2ab					
Sunflower (S)	8.0ab	6.8ab					
All cover crops (ALL)	7.5ab	6.9ab					
ALL minus PTT	7.0ab	6.2ab					
ALL minus PM	7.3ab	7.9ab					
ALL minus ST	7.7ab	7.3ab					
ALL minus S	7.7ab	7.2ab					
ALL minus VP	8.4ab	8.0ab					
ALL minus WC	6.6ab	6.5ab					
ALL minus SF	6.2b	5.1b					
ALL minus PM and ST	8.9a	8.6a					
ALL minus S and VP	7.7ab	7.9ab					
ALL minus WC and SF	7.0ab	7.2ab					
P-value (aggregated treatments)	0.0274	ns	ns	ns	ns	ns	ns
No cover crop control	9.1x						
Monoculture	7.8y						
Mixture	7.5y						
Depth mean across treatments	7.7	7.1	8.6	9.9	10.5	10.9	11.4

† Individual treatment values in a column with unlike letters differ at $P \leq 0.05$ (a, b, c used for individual treatments; x, y, z used for aggregated treatments). ns = Treatment effects not significant at $P \leq 0.05$.

aboveground cover crop biomass were observed among treatments in 2009, while in 2010, greater aboveground biomass was observed with spring triticale compared to proso millet, soybean, and sunflower.

No differences in aboveground cover crop biomass were observed when treatments were aggregated by monocultures and mixtures (Table 4). Ranges in aboveground cover crop biomass, however, were narrower among mixtures compared to monoculture treatments. For mixtures, aboveground cover crop biomass ranged from 1014 to 2030, 61 to 141, and 720 to 1343 kg ha^{-1} in 2008, 2009, and 2010, respectively, whereas among monoculture treatments, aboveground cover crop biomass ranged from 16 to 2889, 7 to 349, and 2 to 1550 kg ha^{-1}.

Late-summer seeded cover crops had a subtle effect on soil water. No differences in soil water content were observed among treatments immediately after cover crop seeding or before seeding response crops the following spring (data not shown). Across all treatments, soil water in the surface (0.3 m) depth after seeding was 5.7, 6.0, and 6.8 cm in 2008, 2009, and 2010, respectively. Only after a killing frost in 2008 were differences in soil water content observed among treatments. Soil water at 0.3 m was greater in the no cover crop control (9.1 cm) and ALL minus proso millet and spring triticale (8.9 cm) compared to ALL minus sunflower (6.2 cm) ($P = 0.0059$) (Table 5). Significant treatment effects extended to 0.6 m during this same time period, with greater soil water in ALL minus proso millet and spring triticale (8.6 cm) compared to ALL minus sunflower (5.1 cm) ($P = 0.0299$). Among aggregated treatments, soil water at 0.3 m was significantly greater in the no cover crop control compared to monocultures and mixtures (9.1 cm vs. 7.8 and 7.5 cm, respectively; $P = 0.0274$) (Table 5). Soil water below 0.3 m did not differ among aggregated treatments.

Mineralization of organic N likely contributed to increases in soil NO_3–N between fall and spring during the first 2 yr of the study. Pre-plant baseline values in 2008 and 2009 were 43.3 ± 1.7 and 18.7 ± 0.7 kg N ha^{-1} for the 0- to 0.9-m depth, whereas mean values across treatments in the following spring increased to 62.7 ± 3.9 and 45.6 ± 1.4 kg N ha^{-1} (Fig. 1). A limited change in fall vs. spring soil NO_3–N during the third year of the study (29.0 ± 1.2 vs. 29.8 ± 0.6 kg N ha^{-1}) may have been influenced by limited N mineralization due to dry and cold conditions overwinter.

Spring soil NO_3–N was significantly affected by cover crop treatment in 2009 and 2011 (Table 6). In 2009, significant responses to individual and aggregated treatments were observed to a 0.6-m depth, whereas in 2011, only subsurface depths (>0.3 m) were affected by cover crop treatments (Table 6). Treatment effects on soil NO_3–N were observed for the cumulative 0 to 0.9-m depth during both years for individual treatments and in 2009 for aggregated treatments.

Treatment effects on soil NO_3–N within individual depth increments generally followed trends across the 0- to 0.9-m depth, so results for the latter serve as a focus for this report. Individual cover crop treatments in 2009 were apportioned into three groups based on spring soil NO_3–N levels (Fig. 1), with the no cover crop

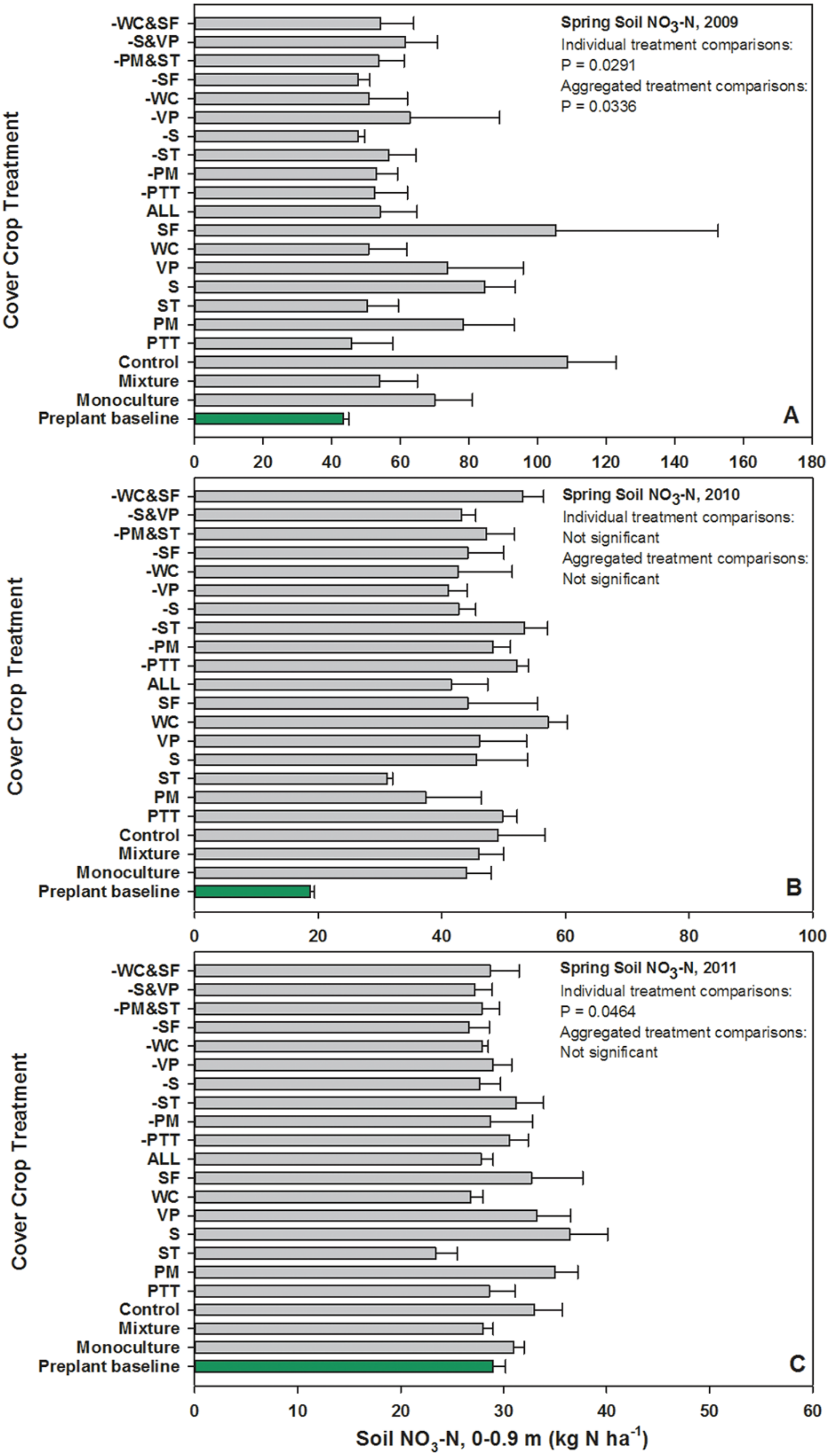

Fig. 1. Spring soil nitrate at 0 to 0.9 m for individual and aggregated cover crop treatments, 2009 to 2011. Years possessing a significant treatment response indicated with a P value. Baseline soil nitrate measured before seeding cover crops shown in green. Bars reflect standard error of the mean. Treatment acronyms: PTT, purple top turnip; PM, proso millet; ST, spring triticale; S, soybean; VP, vine pea; WC, winter canola; SF, sunflower; ALL, all cover crops;-PTT, ALL minus PTT;-PM, ALL minus PM;-ST, ALL minus ST;-S, All minus S;-VP, ALL minus VP;-WC, ALL minus WC;-SF, ALL minus SF;-PM&ST, ALL minus PM and ST;-S&VP, ALL minus S and VP;-WC&SF, ALL minus WC and SF.

Table 6. Summary of P values from analysis of variance for cover crop effects on spring soil NO_3–N at multiple depths, 2009 to 2011. *P* values presented for comparisons across individual treatments as well as treatments aggregated by monocultures, mixtures, and a no cover crop control.

Year	Depth	*P* value	
		Individual treatments	Aggregated treatments
	m		
2009	0–0.15	0.0259	0.3700
	0.15–0.3	0.0023	0.0077
	0.3–0.6	0.0003	0.0391
	0.6–0.9	0.2572	0.1088
	0–0.9	0.0291	0.0336
2010	0–0.15	0.6093	0.8344
	0.15–0.3	0.8583	0.7209
	0.3–0.6	0.2355	0.5337
	0.6–0.9	0.0580	0.8837
	0–0.9	0.3129	0.8771
2011	0–0.15	0.5990	0.4288
	0.15–0.3	0.2854	0.9298
	0.3–0.6	0.0036	0.0667
	0.6–0.9	<0.0001	0.0124
	0–0.9	0.0464	0.2123

control and sunflower treatments highest (105–109 kg N ha^{-1}), purple top turnip lowest (46 kg N ha^{-1}), and all other treatments intermediate (48–85 kg N ha^{-1}). In 2011, spring soil NO_3–N fell within a narrower range than in 2009, with significant differences limited to levels under sunflower (36 kg N ha^{-1}) being greater than under spring triticale (24 kg N ha^{-1}) ($P = 0.0464$). Individual cover crop treatments with numerically lower levels of spring soil NO_3–N included purple-top turnip, ALL minus soybean, and ALL minus sunflower in 2009 (46–48 kg N ha^{-1}), proso millet, spring triticale, and ALL minus vine pea in 2010 (31–41 kg N ha^{-1}), and spring triticale, winter canola, and ALL minus soybean in 2011 (23–27 kg N ha^{-1}). Spring soil NO_3–N differed among aggregated treatments only in 2009 (Fig. 1), where the no cover crop control had significantly greater soil NO_3–N at 0 to 0.9 m (108.7 ± 14.2 kg N ha^{-1}) compared to mixtures (54.0 ± 3.0 kg N ha^{-1}) ($P = 0.0336$).

When differences in spring soil NO_3–N between the no cover crop control and individual treatments (as a surrogate of cover crop NO_3–N uptake) were regressed against aboveground cover crop biomass, significant associations were observed during each year of the study ($r = 0.85$, 0.50, and 0.76 for first, second, and third year of the study, respectively (all $P \leq 0.05$; $n = 19$)). A similar outcome was observed when the same variables were regressed across all years ($r = 0.74$; $P \leq 0.0001$; $n = 57$).

Table 8. Summary of P values from analysis of variance for near-surface soil property comparisons between a seven-way cover crop mixture (ALL) and a no cover crop control, 2009 to 2011.

Soil property, 0–0.1 m	2009	2010	2011
Soil bulk density	0.1777	0.9707	0.0597
Soil pH	0.0927	0.3804	0.6838
Particulate organic matter C	0.8298	0.7774	0.9446
Microbial biomass C	0.3494	0.9881	0.6511

Soil coverage by residue did not differ among individual cover crop treatments or treatments aggregated by monocultures, mixtures, and a no cover crop control (Table 7). Mean soil coverage by residue was exceptionally high in each year of the study, ranging from 85 to 95%. The lowest soil coverage by residue was 58%, observed in 2009 within the vine pea treatment, which was still well above the 30% guideline used to define conservation tillage (Conservation Technology Information Center, 2015).

Near-surface soil properties did not differ between the seven-way cover crop mixture (ALL) and the no cover crop control (Table 8). Only in 2011 did a noticeable trend emerge, with slightly lower soil bulk density in the no cover crop control compared to the mixture (1.22 Mg m^{-3} vs. 1.25 Mg m^{-3}; $P = 0.0597$), presumably due to a lack of field operations (i.e., cover crop planting) in the former.

DISCUSSION

Agroecosystems are increasingly looked on to provide ecosystem services beyond production of food, feed, fiber, and fuel (Syswerda and Robertson, 2014). Incorporation of cover crops in annual crop production systems represents an approach to potentially expand ecosystem services provided by agroecosystems (Schipanski et al., 2014). Quantifying agronomic and environmental responses following integration of cover crops in annual crop production systems is necessary to understand effects on ecosystem services. Moreover, identifying potential trade-offs among ecosystem services is an essential prerequisite to offering sound management recommendations for agricultural producers (Power, 2010).

Outcomes from this study suggest late-summer seeded cover crops in annual crop production systems in the northern Great Plains of North America can provide biomass production and N conservation. These attributes, characterized by provisioning and supporting ecosystem services, respectively, offer opportunities to producers to expand the traditional growing season while minimizing loss of important crop nutrients. However, as discussed below, there are notable caveats inherent to this region that require careful consideration before adopting this form of cover crop use.

Table 7. Soil coverage by residue immediately before seeding cash crop, 2009 to 2011. *P* values from analysis of variance represent treatment comparisons for individual and aggregated cover crop treatments.

Year	Soil coverage by residue			*P* value	
	Mean	Min.	Max.	Individual cover crop treatments	Aggregated cover crop treatments†
	%				
2009	85	58	98	0.0735	0.0972
2010	94	82	100	0.4871	0.3494
2011	95	86	100	0.6178	0.9969

† Cover crop treatments aggregated by monocultures, mixtures, and a no cover crop control.

Production of aboveground cover crop biomass was highly variable during the study. Cover crop seeding, done in mid-August, was inherently risky given limited availability of heat units before a killing frost. Mitigating this production risk may be achieved through the selection of cool-season cover crops within the selected planting timeframe, as biomass produced from warm-season monocultures in this study were consistently lowest among treatments. However, as observed in 2009, an absence of timely precipitation soon after seeding relegated all cover crops to negligible production. Dry conditions and mid-August seeding limited cover crop biomass production at one site under no-till management in western South Dakota (200–630 kg ha^{-1}; Reese et al., 2014), underscoring challenges producers face when considering use of late-seeded cover crops in this region.

Nitrogen conservation is frequently cited as an important role for cover crops in annual crop production systems (Dabney et al., 2010). Outcomes from this study supported this role, as cover crops were effective at scavenging available N in 2 of 3 yr across the 0.9-m soil depth. Regression analyses suggested N conservation benefits were proportional to aboveground cover crop biomass production, thereby underscoring the importance of selecting cover crops with a high probability of growth within a limited production window. Moreover, aboveground cover crop biomass production may serve as a surrogate for estimating the need for supplemental N to meet early growth requirements of cash crops, as mineralized N from cover crop biomass would likely not be available until later in the growing season (Crandall et al., 2005). Observation of N conservation benefits at lower (>0.3 m) soil depths suggests a potential N scavenging role by cover crop roots over-winter (Jewett and Thelen, 2007). Accordingly, additional research on nutrient and cover crop root dynamics seems warranted.

Deficient soil water frequently limits crop production in semiarid regions (Farahani et al., 1998). Inclusion of cover crops in semiarid dryland cropping systems can serve to decrease soil water availability to subsequent cash crops, thereby decreasing yields (Reese et al., 2014). Findings from this study suggest soil water uptake by late-summer seeded cover crops did not generate differences in soil water status compared to a no cover crop control the following spring. Only in 2008, when substantial production of aboveground cover crop biomass served to draw-down soil water in the surface 0.6 m, were differences in soil water status observed in the fall. Differences in soil water status among treatments disappeared by spring, and were likely caused by ample over-winter precipitation and effective snow-catch by standing biomass (Merrill et al., 2007).

Soil fertility represents a supporting ecosystem service that serves as a foundation for agricultural production (Millennium Ecosystem Assessment, 2005). While the suite of soil assessments measured in this study were far from inclusive, no short-term benefits to soil fertility were resolved with cover crop use. Management-induced improvements in near-surface soil properties typically occur slowly in dryland cropping systems (Mikha et al., 2006), yet soil degradation can result in a single growing season through increases in soil disturbance and/or reductions in soil cover (Gilley et al., 2001). Enhanced residue decomposition with cover crop use may contribute to reduced soil cover, as nutrient accumulation by and subsequent decomposition of cover crop biomass can enhance breakdown of surface residue (Varela et al., 2014). Findings from this study suggest late-summer seeded cover crops did not significantly decrease soil coverage by residue, thereby inferring maintenance of an important regulating ecosystem service, erosion prevention.

Guiding hypotheses used for the study suggested pre-investigation inferences about soil responses and late-summer seeded cover crops were mixed. As reviewed above, soil responses to cover crops, while subtle overall, were associated with aboveground biomass production. Accordingly, the first hypothesis (soil responses to late-summer seeded cover crops will be associated with aboveground biomass production) was not rejected. The second hypothesis, focused on the frequency and degree of soil responses from cover crop mixtures and monocultures (presumed greater in the former), was rejected, as measured attributes in this study were not different between mixtures and monocultures. While cover crop mixtures may increase production stability, resilience, and resource-use efficiency compared to monocultures (Wortman et al., 2012a), resolving potential benefits to soil condition in the short-term remains elusive.

SUMMARY

A multi-year study was conducted near Mandan, ND, to investigate effects of late-summer seeded cover crops on soil attributes under no-till management. Cover crops were found to reduce soil NO_3–N levels in the spring compared to a no cover crop control in 2 of 3 yr, thereby providing N conservation benefits within a semiarid dryland cropping system. Late-summer seeded cover crops had negligible effects on soil water status, and cover crop-induced deficiencies in soil water were not observed in the spring before seeding cash crops. No short-term cover crop effects were detected on near-surface soil properties or soil coverage by residue in this study. The degree and frequency of soil responses to cover crops were associated with aboveground biomass production, while effects of cover crop mixtures and monocultures on soil attributes were similar. Collectively, findings from this study suggest late-summer seeded cover crops in annual crop production systems in the northern Great Plains of North America can provide agronomic and environmental benefits through biomass production and N conservation, though achieving these benefits consistently appears dependent on timely precipitation following cover crop seeding.

ACKNOWLEDGMENTS

We acknowledge the contribution of the Area IV SCDs in North Dakota for providing land to conduct research reported in this manuscript. Robert Kolberg, Delmer Schlenker, Marvin Hatzenbuhler, Nicanor Saliendra, Mary Kay Tokach, Jason Gross, Holly Johnson, Heather Dose, Dawn Wetch, Becky Wald, and Gary Brucker provided excellent technical support during plot establishment and maintenance, sample collection, sample processing and analyses, and data summarization. We also acknowledge Jay Fuhrer (USDA-NRCS) and members of the Burleigh County SCD for helpful guidance before initiating the study. The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, family status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) USDA is an equal opportunity provider and employer. Mention of commercial products and organizations in this manuscript is solely to provide specific information. It does not constitute endorsement by USDA-ARS over other products and organizations not mentioned.

REFERENCES

Acuña, J.C.M., and M.B. Villimil. 2014. Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. Agron. J. 106:860–870. doi:10.2134/agronj13.0370

Army, T.J., and J.C. Hide. 1959. Effect of green manure on dryland wheat production in the Great Plain area of Montana. Agron. J. 51:196–198. doi:10.2134/agronj1959.00021962005100040004x

Bailey, R.G. 1995. Description of the ecoregions of the United States. Misc. Publ. 1391. 2nd ed. USDA, Forest Serv., Washington, DC.

Blackshaw, R.E., L.J. Molnar, and J.R. Moyer. 2010. Suitability of legume cover crop-winter wheat intercrops on the semi-arid Canadian prairies. Can. J. Plant Sci. 90:479–488. doi:10.4141/CJPS10006

Blake, G.R., and K.H. Hartge. 1986. Bulk density. In: A. Klute, editor, Methods of soil analysis. Part1- Physical and mineralogical methods. 2nd ed. SSSA Book Ser. 5. SSSA and ASA, Madison, WI. p. 363–382.

Conservation Technology Information Center (CTIC). 2015. Tillage type definitions. CTIC, West Lafeyette, IN. http://www.ctic.purdue.edu/resourcedisplay/322/ (accessed 9 Jan. 2015).

Crandall, S.M., M.L. Ruffo, and G.A. Bollero. 2005. Cropping system and nitrogen dynamics under a cereal winter cover crop preceding corn. Plant Soil 268:209–219. doi:10.1007/s11104-004-0272-x

Dabney, S., J. Delgado, J. Meisinger, H. Schomberg, M. Liebig, M. Kasper et al. 2010. Using cover crops and cropping systems for nitrogen management. In: J.A. Delgado and R.F. Follett, editors, Advances in nitrogen management for water quality. Soil and Water Conserv. Soc., Ankeny, IA. p. 231–282.

Farahani, H.J., G.A. Peterson, and D.G. Westfall. 1998. Dryland cropping intensification: A fundamental solution to efficient use of precipitation. Adv. Agron. 64:197–223. doi:10.1016/S0065-2113(08)60505-2

Franzluebbers, A.J., R.L. Haney, F.M. Hons, and D.A. Zuberer. 1999. Assessing biological soil quality with chloroform fumigation-incubation: Why subtract a control? Can. J. Soil Sci. 79:521–528. doi:10.4141/S99-010

Gardner, W.H. 1986. Water content. In: A. Klute, editor, Methods of soil analysis. Part 1–Physical and mineralogical methods. 2nd ed. SSSA Book Ser. 5. SSSA and ASA, Madison, WI. p. 493–544.

Gilley, J.E., J.W. Doran, and B. Eghball. 2001. Tillage and fallow effects on selected soil quality characteristics of former conservation reserve program sites. J. Soil Water Conserv. 56:126–132.

Gregorich, E.G., and B.H. Ellert. 1993. Light fraction and macroorganic matter in mineral soils. In: M.R. Carter, editor, Soil sampling methods and analysis. Can. Soc. Soil Sci. Lewis Publ., Boca Raton, FL. p. 397–407.

Islam, K.R., and R.R. Weil. 1998. Microwave irradiation of soil for routine measurement of microbial biomass carbon. Biol. Fertil. Soils 27:408–416. doi:10.1007/s003740050451

Jewett, M.R., and K.D. Thelen. 2007. Winter cereal cover crop removal strategy affects spring soil nitrate levels. J. Sustain. Agric. 29:55–67. doi:10.1300/J064v29n03_06

Laflen, J.M., M. Amemiya, and E.A. Hintz. 1981. Measuring crop residue cover. J. Soil Water Conserv. 36:341–343.

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS system for mixed models. SAS Inst., Cary, NC.

Lundgren, J.G., and J.K. Fergen. 2010. The effects of a winter cover crop on Diabrotica Virgifera (Coleoptera: Chrysomelidae) populations and beneficial arthropod communities in no-till maize. Environ. Entomol. 39:1816–1828. doi:10.1603/EN10041

Merrill, S.D., D.L. Tanaka, J.M. Krupinsky, M.A. Liebig, and J.D. Hanson. 2007. Soil water depletion and recharge under ten crop species and applications to the principles of dynamic cropping systems. Agron. J. 99:931–938. doi:10.2134/agronj2006.0134s

Mikha, M.M., M.F. Vigil, M.A. Liebig, R.A. Bowman, B. McConkey, E.J. Deibert, and J.L. Pikul, Jr. 2006. Cropping system influences on soil chemical properties and soil quality in the Great Plains. Renew. Agric. Food Syst. 21:26–35. doi:10.1079/RAFS2005123

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: Synthesis. Island Press, Washington, DC.

Moyer, J.R., and R.E. Blackshaw. 2009. Fall-seeded cover crops after dry bean and potato in southern Alberta. Can. J. Plant Sci. 89:133–139. doi:10.4141/CJPS08038

Mulvaney, R.L. 1996. Nitrogen–Inorganic forms. In: D.L. Sparks, editor, Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA and ASA, Madison, WI. p. 1123–1184.

NDAWN. 2015. North Dakota Agricultural Weather Network. North Dakota State Univ., Fargo. http://ndawn.ndsu.nodak.edu/index.html (accessed 8 Jan. 2015).

Paul, E.A., D. Harris, M.J. Klug, and R.W. Ruess. 1999. The determination of microbial biomass. In: G.P. Robertson, D.C. Coleman, C.S. Bledsoe, and P. Sollins, editors, Standard soil methods for long-term ecological research. Oxford Univ. Press, New York. p. 291–317.

Power, A.G. 2010. Ecosystem services and agriculture: Tradeoffs and synergies. Philos. Trans. R. Soc. Lond., B 365:2959–2971. doi:10.1098/rstb.2010.0143

Reese, C.L., D.E. Clay, S.A. Clay, A.D. Bich, A.C. Kennedy, S.A. Hansen, and J. Moriles. 2014. Winter cover crops impact on corn production in semiarid regions. Agron. J. 106:1479–1488. doi:10.2134/agronj13.0540

Rogler, G.A., R.J. Lorenz, and H.M. Schaaf. 1962. Progress with grass. Bull. 439. North Dakota Agric. Exp. Stn., Fargo.

Sarvis, J.T., and J.C. Thysell. 1936. Crop rotation and tillage experiments at the Northern Great Plains Field Station, Mandan, N. Dak. Tech. Bull. 536. USDA, Washington, DC.

Schipanski, M.E., M.E. Barbercheck, M.R. Douglas, D.M. Finney, K. Haider, J.P. Kaye et al. 2014. A framework for evaluating multifunctionality of cover crops in agroecosystems. Agric. Syst. 125:12–22. doi:10.1016/j.agsy.2013.11.004

Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron. J. 97:322–332.

Syswerda, S.P., and G.P. Robertson. 2014. Ecosystem services along a management gradient in Michigan (USA) cropping systems. Agric. Ecosyst. Environ. 189:28–35. doi:10.1016/j.agee.2014.03.006

Tilman, D. 1999. The ecological consequences of changes in biodiversity: A search for general principles. Ecology 80:1455–1474.

Varela, M.F., C.M. Scianca, M.A. Taboada, and G. Rubio. 2014. Cover crop effects on soybean residue decomposition and P release in no-tillage systems of Argentina. Soil Tillage Res. 143:59–66. doi:10.1016/j.still.2014.05.005

Watson, M.E., and J.R. Brown. 1998. pH and lime requirement. In: J.R. Brown, editor, Recommended chemical soil test procedures for the North Central Region. NCR Publ. 221 (revised). Bull. SB1001. Missouri Agric. Exp. Stn., Columbia. p. 13–16.

Wortman, S.E., C.A. Francis, M.L. Bernards, R.A. Drijber, and J.L. Lindquist. 2012a. Optimizing cover crop benefits with diverse mixtures and an alternative termination method. Agron. J. 104:1425–1435. doi:10.2134/agronj2012.0185

Wortman, S.E., C.A. Francis, and J.L. Lundquist. 2012b. Cover crop mixtures for the western Corn Belt: Opportunities for increased productivity and stability. Agron. J. 104:699–705. doi:10.2134/agronj2011.0422