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Impact of Crop Rotations and Soil Amendments on Long-Term No-Tilled Soybean Yield

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ABSTRACT

Continuous cropping systems without cover crops are perceived as unsustainable for long-term yield and soil health. To test this, cropping sequence and cover crop effects on soybean (*Glycine max* L.) yield were assessed. Main effects were 10 sequences of soybean, corn (*Zea mays* L.), and cotton (*Gossypium hirsutum* L.) grown on a Loring silt loam at the Research and Education Center at Milan (RECM), TN, and six cropping sequences of corn and soybean on a Maury silt loam at the Middle Tennessee Research and Education Center (MTREC), Spring Hill, TN. Sequences were repeated in 4-yr Phases (i.e., I, II, and III) from 2002 to 2013. Split-block treatments consisted of hairy vetch (*Vicia villosa* L.), Austrian winter pea (*Pisum sativum* L. *sativum* var. *arvense*), wheat (*Triticum aestivum* L.), poultry litter, and a fallow control. Continuous soybean yield was equivalent to all rotations (2.6 and 2.7 Mg ha^{-1}, respectively; $P = 0.23$), however, yield varied per phase ($P < 0.001$). Specifically, soybean yield in soybean-soybean-corn-cotton during Phase II and corn-corn-soybean-corn during Phase I (4.2 and 4.1 Mg ha^{-1}, respectively) exceeded continuous systems during Phases II and III ($P < 0.05$). Poultry litter increased yield 11% across locations and years compared to wheat cover crops ($P < 0.05$). Incorporating corn once within a Phase increased yield 8% relative to continuous soybean, whereas cotton (once or twice) within a rotation had no effect. Consequently, including corn once within a 4-yr rotation and poultry litter improved soybean yields, albeit no mono-cropping yield penalties occurred long-term.

Core Ideas

- Poultry litter increased yields by 11% across locations and years when compared to wheat cover crops.
- Yields in soybean–soybean–corn–cotton rotations during Phase II and corn–corn–soybean–corn during Phase I were greatest.
- Incorporating corn once within a 4-yr cropping cycle resulted in 8% greater yields than continuous soybean.
- Continuous cropping systems without cover crops are often perceived as unsustainable for long-term yields and soil health.

Considering that current stratospheric CO_2 levels are at 852 Gt C, with increases of approximately 4.3 Gt C yr^{-1} (Lal et al., 1998), alongside increased concerns of soil erosion, it is no coincidence that implementation of no-tillage has increased (West and Post, 2002). In 2012 alone, the area of no-till soybean in Tennessee was 78.9% of the total area planted (NASS, 2012). Soybean production worldwide also continues to increase, with 31 million ha planted in the United States (NASS, 2004). Consequently, implementation of management practices that conserve soil resources and promote C storage while improving yield is of upmost importance. Specifically, no-tillage resulted in less disruption of beneficial soil microbial populations, improved soil tilth due to greater aggregation, and increased soil fertility due to greater cation exchange capacity, (Franzluebbers, 2005; Lal, 2006). All of these benefits will potentially result in maximizing crop yield, which is a priority for producers. No-till crop yield is generally equal to or better than crop yield grown with conventional tillage (Tyler et al., 1983; Hussain et al., 1999). Vyn et al. (2000) observed that soybean yield in no-till systems were initially lower than those grown with conventional tillage; however, over a 25-yr period, yield reductions were not significant.

Soil aeration and infiltration may be reduced in no-tillage systems (Dick et al., 1991), but may be augmented by increased cropping sequence diversity, cover crops, and poultry litter (Tisdall and Oades, 1980). Stabilization of soil aggregates by the use of soil amendments (or poultry litter and cover crops) can increase water-holding capacity of soils, and thus positively impact crop growth (Watts and Torbert, 2011). In a study by Kabir and Koide (2000), winter wheat increased soil aggregation compared to a winter fallow control. Stable soil aggregates are also reportedly increased in corn–soybean rotations that include vetch and rye (*Secale cereal* L.) compared to winter fallows (Villamil et al., 2006). Increased water-holding capacity and soil aggregation is not a benefit exclusive to winter cover crops, since manure applications reportedly improve soil aggregation when compared to soils receiving no compost (Whalen et al., 2003).

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Abbreviations: CvR, continuous vs. all Rotations; DNS, data not shown; GR, glyphosate-resistant; MTREC, Middle Tennessee Research and Education Center; RECM, Research and Education Center at Milan; SOC, soil organic carbon; VNS, variety not stated.

Greater photosynthetic and microbial-based C additions, more complex crop rotations, and poultry litter additions have been implicated in increasing soil C accumulation (Ogle et al., 2005; Ashworth et al., 2014). Furthermore, crop rotation can also influence the amount and quality of soil organic N, since Drinkwater et al. (1998) suggest that lower C/N residues combined with greater temporal crop diversity, especially with legumes, increases C retention in soils. Consequently, including legumes in a high-residue cropping sequence such as corn may increase residue decomposition resulting in greater C residue additions (Ortega et al., 2002).

Continuous cropping may result in deleterious agricultural productivity long term, although beneficial rotation effects are controlled by many factors such as crop frequency/sequence and soil texture. Research has shown that annual corn–soybean rotations increase yield compared to their respective monoculture sequences (Porter et al., 1997; Meese et al., 1991; Mannering and Griffith, 2007). For instance, Crookston et al. (1991) measured increases in corn and soybean yield following five consecutive years of alternating corn/soybean compared to continuous cropping, and concluded that adding a third crop to the rotation could allow each crop to have the "first year effect," resulting in increased yield for each crop. Similarly, Wilhelm and Wortmann (2004) found that soybean in an alternating soybean–corn rotation yielded higher than continuous soybean in a 16-yr study. Conversely, a study examining the viability of a corn–soybean–wheat rotation concluded there was no yield advantage to a three-crop rotation, suggesting a longer time was needed between same crop plantings in rotations (Lund et al., 1993).

Crop rotation can also serve to counteract the potential build-up of weeds, diseases, and insects that can result from no-tillage. A tremendous amount of selection pressure for surviving weeds exists in monoculture systems. Rotating crops may alter the environment in which weeds are adapted, thereby reducing weed populations (Higgs et al., 1990). Several studies have shown reductions in soybean cyst nematode (*Heterodera glycines*) populations when soybean is rotated with a non-host crop such as corn (Howard et al., 1998; Chen et al., 2001). Specifically, *Sclerotinia* stem rot in soybean is reduced when cropping rotations are implemented (Kurle et al., 2001). Thus, crop rotations that include non-hosts crops may decrease disease and pest populations in the same manner as weed populations by disrupting disease and pest life cycles.

Cover crop integration in cropping systems may also improve weed and insect control and increase soil fertility. Several studies have documented reduced weed emergence with cover crops such as rye and hairy vetch in soybean systems (Fisk et al., 2001; Reddy et al., 2003; Reddy and Koger, 2004), as cover crops compete with weeds for resources such as light, water, and nutrients. Insect populations may also be reduced, predominately because cover crops provide habitat for beneficial insects that regulate population levels (Creamer and Baldwin, 1999; Tillman et al., 2004). Incorporating cover crops during the off-season, as well as including greater temporal cropping diversity also reduces erosion and increases soil organic carbon (SOC), which has been reported previously by authors (Ashworth et al., 2014).

Given that soybean growth and development assumedly responds differently to previous cropping rotations and soil amendments over time and across varying soil types, research into their combined effects under no-tillage is necessary to make management recommendations that will improve soil quality and crop yield temporally and spatially. Therefore, the objective of this study was to determine individual and combined effects of cropping sequences and soil amendments (cover crops and poultry litter) and their interactions on soybean yield and soil properties at two locations, in no-till production systems.

MATERIALS AND METHODS

Field Site and Experiment Descriptions

The study was conducted at two locations to evaluate cropping system impacts when grown on different soil types and in different physiographic regions. One location was the MTREC, University of Tennessee (Spring Hill, TN; 36.02° N, 85.13°W) which is situated in the karst topography region (Natural Resources Conservation Service [NRCS], Major Land Resource Area [MLRA] 123 classified as the Nashville Basin in the Land Resource Region [LRR] "N"). Soil at this location was classified as a Maury silt loam (fine, mixed, active, mesic Typic Paleudalf), which is typical of the karst topography region in middle Tennessee, northern Alabama, central and western Kentucky, and southern Indiana. The second site was the RECM (Milan, TN; 35.54° N, 88.44° W) located in the eastern Gulf Coastal Plain that covers most of western Tennessee, western Alabama, a major portion of Mississippi, eastern Louisiana, and a small section of western Kentucky (NRCS MLRA 134, classified as the southern Mississippi Valley Loess, East Gulf Coastal Plain in LRR "P"). Soil at the RECM site was classified as a Loring B2 series (fine-silty, mixed, thermic Oxyaquic Fragiudalf).

The MTREC location has a mean annual precipitation of 114 cm and a mean annual temperature of 14.2°C. Prior to experiment initiation, this locale was in a 2-yr corn–soybean rotation, with half of the field being in corn and half in soybean each year.

The site was under no tillage with annual additions of dairy manure for 15 yr prior to initiation of this experiment. The RECM site has a mean annual precipitation of 107 cm and a mean annual temperature of 14.8°C. This site was under no-tillage for 16 yr prior to this study with corn planted in 2001, soybean in 2000, and cotton in 1999. During winters, this field site was planted to winter wheat for grain and was left fallow the winter prior to initiation of this study.

At both locations, this experiment was conducted as a split-block treatment design with four replications. Whole-block treatments consisted of cropping sequences (see Table 1 for whole plot sequences) and the split-block treatment consisted of four soil amendment treatments and a fallow control. At RECM, 10 cropping sequences of corn, cotton, and soybean were repeated every 4-yr defined as Phases [i.e., Phases I (2002–2005), II (2006–2009), and III (2010–2013); Table 1]. Cover crops of wheat, vetch, and Austrian winter pea, as well as poultry litter, and a fallow (winter weeds) control were repeated annually under no-tillage production. The same experiment without cotton was conducted at the MTREC location (seven sequences total; Table 1). This created 50 and 35 sequence × soil amendment combinations for RECM and MTREC, respectively.

Table 1. Cropping sequences from 2002 (Yr-0) to 2013 (Yr-12) at Tennessee Research and Education Centers at Spring Hill (MTREC) and Milan (RECM).

Crop sequence†	Research centers/years/crops			
	MTREC			
	Year			
	2002‡	2003	2004	2005
	2006	2007	2008	2009
	2010	2011	2012	2013
1	soybean	soybean	soybean	soybean
2	soybean	soybean	corn	soybean
3	corn	soybean	soybean	corn
4	corn	soybean	corn	soybean
5	soybean	corn	soybean	corn
6	soybean	corn	corn	soybean
7	corn	corn	soybean	corn
	RECM			
	Year			
	2002†	2003	2004	2005
	2006	2007	2008	2009
	2010	2011	2012	2013
1	soybean	soybean	soybean	soybean
2	soybean	soybean	corn	cotton
3	corn	soybean	corn	soybean
4	soybean	cotton	soybean	cotton
5	soybean	cotton	corn	soybean
6	corn	corn	soybean	cotton
7	corn	cotton	soybean	corn
8	cotton	soybean	cotton	corn
9	cotton	soybean	corn	cotton
10	cotton	corn	cotton	soybean

† Each sequence was repeated after the fourth year (Phase).
‡ 2002–2005 = Phase I; 2006–2009 = Phase II; 2010–2013 = Phase III.

In 2012, extreme drought (11.9 and 17.9 cm precipitation at RECM and MTREC, respectively; April–June; and high temperatures; data not shown [DNS]) occurred, and consequently crop establishment failures ensued. Therefore, data from this year were not included in Phase III (2010–2013) of this study. Similarly, failures occurred at MTES during 2010, and consequently results from this location/year combination were excluded.

Crop Establishment and Treatment Maintenance

Glyphosate [*N*-(phosphonomethyl)glycine]-resistant (GR) varieties/hybrids planted were USG 7440nRR soybean for Phase I and II (2002–2009; Table 1), DKC 6410 RR and DKC63-81 corn; and PM 1218 BG/RR and DP 117 RRBG cotton, respectively. Phase III cultivars were Phytogen 375 cotton; Augusta 6867 corn; and Halo 4:65 soybean. At both locations, soybean, corn, and cotton plots were planted at recommended University of Tennessee seeding rates of 64,247; 258,334 to 344,445; and 64,495 seeds ha^{-1}, respectively.

Before planting, herbicides were used to kill existing vegetation and cover crops at both locations. Either paraquat (1,1'-dimethyl-4,4'-bipyridinium dichloride), glyphosate, or glufosinate ammonium [ammonium(±)-2amino-4-(hydroxymethylphosphinyl)butanoate] were applied in April of each year before corn, soybean, and cotton seeding. One or two applications of glyphosate were applied to soybean and corn plots at both locations in or around May or June of each year. For cotton plots at RECM, pesticide and plant growth regulation applications were consistent with recommended production practices and dates ranged from June through September each year. Glyphosate and clethodim {(RS)-2-9 [(E)-1-[(E)-3-chloroallyloxyimino] propyl]-5-[2-(ethylthio) propyli]-3-hydroxycyclohex-2-en-1-l-one} were the most common herbicides used all 4 yr on soybean and cotton. Def (S,S,S-tributyl phosphorotrithioate), Bidrin (dimethyl phosphate of 3-Hydroxy-N,N-dimethyl-cis-crotonamide) and Pix (1,1-dimethylpiperidinium chloride) were also applied for plant growth regulation on cotton.

Poultry litter plots received the equivalent of 67 kg N ha^{-1}, (ca. 4.4 t poultry litter ha^{-1}, assuming 50% bioavailability; A&L Analytical Laboratories, Inc., Memphis, TN). Similarly, wheat and fallow plots received 67 kg N ha^{-1}, while vetch and Austrian winter pea plots received 50 kg N ha^{-1} prior to planting in the form of urea. Corn plots received 129 kg N ha^{-1} in the form of urea (CH_4N_2O) and cotton plots received 33 kg N ha^{-1} as sidedress applications in May or June each year. Muriate of potash (KCl) was applied to all plots at 112 kg K_2O ha^{-1} in April of each year. Austrian winter pea, wheat, and hairy vetch cover crops were planted with no-till planters at RECM and MTREC (John Deere 1560, Deere & Company, Moline, IL; and Great Plains 1500, Plains Manufacturing Inc, Salina, KS, respectively). Row spacing was 19 cm in 13.8 by 104.6 m strips planted perpendicular to crop rows. Initially, canola (*Brassica napus* L.) was included in this study, but due to failures in establishment during the first Phase (2002–2005), this species was replaced with Austrian winter pea starting in Phase II. Austrian winter pea (variety not stated [VNS]), hairy vetch (cultivar Auburn Early), and wheat (VNS) cover crops were seeded at a rate of 56, 34, and 100 kg ha^{-1}, respectively. Cover crops were planted approximately mid-October through mid-November during the previous cropping year, and then terminated with herbicides prior to planting the summer crop the following year.

Eight-row plots of soybean at RECM and 12-row plots at MTREC were planted with a John Deere 1700 Maxemerge planter or a John Deere plateless planter in 76.2-cm-wide rows in plots that were 6.1 by 12.3 m and 9.2 by 12.3 m, respectively. Planting dates at both locales were between 29 April and 30 May. Annually, four rows per plot at MTREC and two rows at RECM were harvested between 23 September and 16 October. Harvested plot size for soybean was 3.1 by 12.3 m at MTREC and 1.5 by 10.8 m at RECM. Soybean and corn plots were harvested at RECM with an AC Gleaner combine (AGCO, Duluth, GA) in 2002 and thereafter with a two-row ALMACO SPC40 (ALMACO, Nevada, IA) combine, and at MTREC using a K-2 AC Gleaner combine with a three-row header for corn and 3.1 m grain platform for soybean. Measurements taken at both locations were plot weights and grain moisture content. Soybean plot weights were adjusted to a standard moisture content of 130 g kg^{-1} for data analysis.

At all locations and years, corn was planted between 12 April and 9 May. Three rows per plot (MTREC) or two rows (RECM) were harvested in each year between 29 August and 27 September at all locations and year combinations. In addition, cotton plots at RECM were planted with a six-row John Deere Maxemerge planter on 101.6 cm row spacing. Cotton was planted between 7 and 12 May, and harvest occurred between 10 September and 25 October.

Soil Sampling and Analysis

At the termination of Phase III (spring 2014), soil tests were conducted from 0- to 5- and 5- to 15-cm depths from each plot to determine soil pH and concentrations of P, K, Mg, and Ca, as well as SOC and N. Samples were ground to pass through a 1-mm sieve on a Wiley soil crusher (Thomas Scientific, Swedesboro, NJ) and Mehlich-1 extractable nutrients were measured by inductively coupled plasma using a 7300 inductively coupled plasma optical emission spectrometer (ICP–OES) DV (PerkinElmer, Waltham, MA). The pH was determined on a 1:1 soil/water ratio using an AS3010D Dual pH Analyzer (Labfit, Burswood, Australia). In addition, total soil N was determined via combustion (weight loss on ignition; Schulte and Hopkins, 1996). Soil C was measured by near infrared diffuse reflectance spectroscopy, using Labspec Pro scanning spectrophotometer (Analytical Spectral Devices, Inc., Boulder, CO) at 400 to 2500 nm from 2002 to 2006. Near infrared reflectance spectroscopy is a good predictor of SOC compared to the combustion method ($r^2 = 0.85$ [Wight et al., 2016a, 2016b]). Bulk density (rb, g cm^{-3}) was measured on a per plot, year, depth, and location basis. Given rb did not differ across plots ($P > 0.05$), mean rb values were utilized per depth, site, and locale to calculate Mg C ha^{-1}.

Analysis of Data and Model Development

Analysis of variance tests of yield and soil characteristics (i.e., pH, P, K, Ca, Mg, N, and C) were performed using the MIXED procedure of SAS (SAS V9.3; SAS Institute, Cary, NC). For the 12-yr dataset, cropping sequence (whole-plot) and soil amendments (split-block) were considered fixed effects and phase (i.e., 4-yr repetitions) was considered a repeated measure. For the repeated measure, an autoregressive covariance was used and found to be unimportant by a likelihood ratio test, so was dropped. The denominator degrees of freedom for the Type III *F* test were adjusted with the Kenward–Roger method (Gomez et al., 2005). Block, year, and location were considered random effects. When main effects or interaction confluences were found, mean separations were performed using the SAS macro "pdmix800" (Saxton, 1998) with Fisher's LSD and at a

Table 2. Mehlich-1 extractable nutrients and soil characteristics in the 0- to 15-cm depth per cropping rotation and soil amendment at the Middle Tennessee Research and Education Center (MTREC) and Research Education Center at Milan (RECM)] collected during spring of Phase III (2014).

Research Center	Soil type/rotation/soil amendment	pH	P	K	Ca	Mg	N	C
			kg ha^{-1}				g kg^{-1}	Mg ha^{-1}
MTREC	Typic Paleudalf							
	Rotation							
	C/S/C/S†	5.5b‡	46ab	254b	1487abc	153bc	1.4b	7.64a
	S/S/S/S	5.4bc	33c	151e	1424c	154bc	1.2cd	6.75bc
	C/C/S/C	5.4bc	45ab	231c	1440c	141d	1.4ab	9.0a
	C/S/S/C	5.4bc	50a	233bc	1558ab	162ab	1.4ab	9.14a
	S/C/S/C	5.4bc	35bc	174d	1452bc	158bc	1.3bc	8.01b
	S/C/S/C	5.5b	30c	151de	1429c	151cd	1.1d	7.15c
	S/C/CS	5.6a	31c	148e	1583abc	170a	1.2d	6.36c
	Soil amendment							
	Fallow	5.4b	27b	166b	1422b	137b	1.2b	7.99b
	Hairy vetch	5.3c	25b	170b	1375b	139b	1.3b	8.34b
	Poultry litter	5.9a	99a	377a	1883a	229a	1.5a	8.88a
	Wheat	5.3c	24b	154b	1282c	131b	1.3b	8.07b
RECM	Oxyaquic Fragiudalf							
	Rotation							
	T/S/T/C	6.6bc	93abc	203cde	3058b	228de	1.4cde	7.09cde
	T/S/C/T	6.3e	97abc	219bcd	2771cd	248bcd	1.5abc	7.34bcd
	T/C/T/S	6.3e	88bc	221bc	2897bc	266abc	1.5ab	7.64bc
	C/T/S/C	6.5cd	79c	223bc	2979bc	271ab	1.5bcd	8.01ab
	C/C/S/T	6.3de	70c	207bcd	2598de	251bcd	1.4bcde	7.46bcd
	C/S/C/S	6.2e	64c	178fg	2489e	221e	1.3de	7.03cde
	S/S/S/S	6.6bc	97abc	197def	2865bc	186f	1.3e	6.54ef
	S/S/C/T	6.8ab	96abc	206bcde	2896bc	187f	1.3ef	6.42ef
	S/T/C/S	6.9a	99abc	169 g	3341a	181f	1.3ef	6.79de
	S/T/S/T	6.7b	127a	183efg	2965bc	182f	1.2f	6.73f
	Soil amendment							
	Fallow	6.6ab	54b	177b	2872b	225b	1.3b	6.73b
	Hairy vetch	6.3c	55b	154b	2744b	200c	1.4b	7.34ab
	Poultry litter	6.9a	234a	368a	3401a	315a	1.7a	7.95a
	Wheat	6.5b	58b	172b	2777b	219b	1.3b	6.73b

† C = corn; S = soybean; T = cotton per phase.

‡ Means followed by a letter in common are not significantly different based on $P \leq 0.05$ within analyte and either cropping rotation or soil amendment.

Type I error rate of 5% (SAS Institute, 2007). Post hoc contrast statements were used to determine any yield penalty from continuous cropping, as well as impacts from cropping sequences. Contrasts were implemented by defining a new factor in the ANOVA, comparing continuous soybean vs. sequences of soybean with 1 or 2 yr of corn, and similarly a separate contrast analysis for cotton. Soybean yield means within phases were used for analyses.

RESULTS AND DISCUSSION

Soil Test Results

Weighted averages of soil samples from 0 to 5 and 5 to 15 cm were calculated to determine cumulative cropping system and soil amendment impacts in the top 15 cm. Soil amendments affected all final soil characteristics [i.e., pH, P, K, Ca, Mg, N, and SOC ($P < 0.05$)], with each variable being greatest following poultry litter applications and all others being lower, excluding that for SOC under wheat cover crops (Table 2). Furthermore, the fallow control was not different from all soil amendment treatments for soil P, Ca, N, and SOC. Chemical characteristics were all significantly affected by cropping sequence. Greater rotation complexity and manure additions have proven to enhance C storage previously, due to more diverse substrate and lower C/N ratios in aboveground and belowground residues (McDaniel et al., 2014; Stockmann et al., 2013). Therefore, in general, corn–soybean–soybean–corn had the greatest levels of P, Ca, Mg, N, and SOC when compared to all cropping sequences and continuous soybean systems at MTES (Table 3). At RECM, the highest pH, P, and Ca levels were observed under a rotation with high temporal diversity (soybean–cotton–corn–soybean). This was perhaps due to greater residue diversity being favored by bacterial assemblages (Six et al., 2006). At both locations, there was less K, N, and SOC in the continuous soybean rotation than in sequences with greater sequence diversity ($P < 0.05$). In general, soybean produces about one-third the amount of residue as corn, but about twice as much K is removed in the grain (Wilhelm et al., 1986). Thus, these trends suggest less buildup of SOC and greater depletion of available K with increasing prevalence of soybean in cropping rotations.

Temporal Cropping Rotation Impact on Soybean Yield

Overall, analysis of the 12-yr study results revealed that the main effect of continuous soybean yield vs. soybean yield from all rotations (CvR) were equivalent (2.6 and 2.7 Mg ha^{-1}, respectively; $P = 0.23$ [Table 3]) when averaged across locations (as locations were not different [$P = 0.42$]). Similarly, previous work on the same plot area and during the same years (2002–2013) by authors observed equivalent continuous corn yield compared to corn yield from all rotations (Ashworth et al., 2016). However, various cropping sequences in the present study did result in yield increases over the continuous soybean cropping system (among Phases), as continuous soybean yielded lower than soybeans with greater cropping sequence diversity during Phases II and III ($P < 0.0001$). Furthermore, main effects of soil amendments ($P = 0.01$) and Phase × crop sequence (CvR) impacted ($P < 0.0001$) soybean yield (Table 3). Conversely, Phase, cropping sequence × soil amendment [within Phase × crop sequence (CvR)], and Phase × soil amendment did not impact soybean yield ($P < 0.05$). Neither were there interactions ($P < 0.05$) among Phases for soil amendment × crop sequence (CvR), Phase × crop sequence (CvR), sequence × soil amendment, nor Phase × soil amendment × crop sequence (CvR; Table 3).

Based on post hoc contrast results, varying impacts occurred when cotton or corn were included either once or twice within soybean rotations per cropping Phase ($P = 0.44$ and $P = 0.001$, respectively). Specifically, including cotton once or twice within a Phase did not increase soybean yield above that of continuous soybean (2.5, 2.6, and 2.6 Mg ha^{-1}, respectively; Table 4). However, when averaged across all phases, including corn once within a 4-yr Phase resulted in 8% greater soybean yield compared to that of continuous soybean systems, albeit including two rotations of corn was not different than continuous soybean yield (Table 4). Similarly, a concurrent experiment

Table 4. Contrast statement results for soybean yields following cotton and corn occurring once or twice within a 4-yr rotation (i.e., Phases I, II, and III) from 2002 to 2013 averaged across two Tennessee Research and Education Centers (Spring Hill, MTREC; Milan, RECM).

Soybean in rotation vs. continuous cropping	Soybean yield
	Mg ha^{-1}
1 cotton in rotation†‡	2.5ns§
2 cotton in rotation	2.6ns
Continuous soybean	2.6ns
1 corn in rotation	2.8a¶
2 corn in rotation	2.5b
Continuous soybean	2.6ab

† Per 4-yr Phase.
‡ Cotton only occurred at RECM, whereas corn occurred in sequences at both locations.
§ ns, not significant.
¶ Means followed by a letter in common are not significantly different based on $P < 0.05$ within either cotton ($P < 0.0001$) or corn ($P = 0.0013$) rotations.

Table 3. Analysis of variance for soybean yields averaged across Research and Education Centers at two locations in Tennessee (MTREC, Spring Hill, and RECM, Milan. Cropping sequences were repeated in 4-yr Phases with soil amendments being repeated annually from 2002 to 2013.

Fixed effect	Num df	Den df	*F* value	*P* > *F*
Soil amendment treatments	4	1324	3.66	0.01
Continuous vs. all Rotations (CvR)	1	35	1.48	0.23
Soil amendment × CvR	4	1324	1.33	0.26
Phase	2	17	1.63	0.22
Phase × soil amendment	8	1324	0.15	0.99
Phase × CvR	2	1350	8.08	0.001
Phase × soil amendment × CvR	8	1324	0.57	0.79
Sequence (Phase × CvR)	35	363	11.17	<0.001
Sequence × soil amendment (Phase × CvR)	140	1324	0.26	1.00

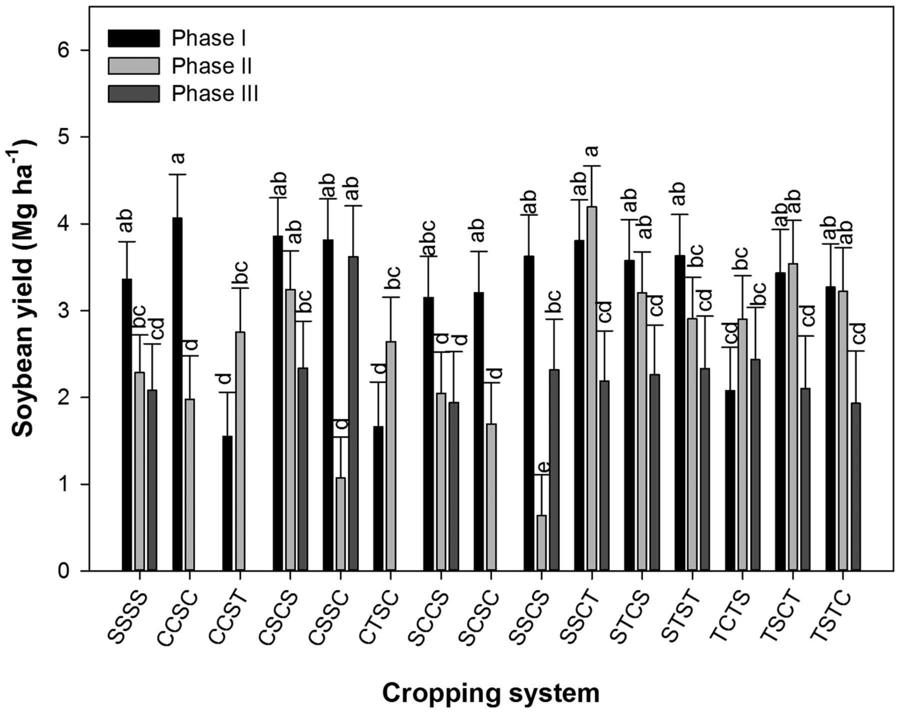

Fig. 1. Soybean yields per Phase (i.e., 3, 4-yr Phases) from 2002 to 2013, by cropping sequence, averaged across Tennessee Research and Education Centers at Spring Hill (MTREC) and Milan (RECM). Vertical bars are the standard error. Experimental locations were not different (P = 0.25), whereas Phase × sequence varied (P < 0.0001) for soybean yields; hence the interactions are reported. C = corn; S = soybean; T = Cotton. Sequences are repeated every 4 yr. Different letters indicate a significant difference among Phase × sequences at an a level of 0.05; LSD = 1.52.

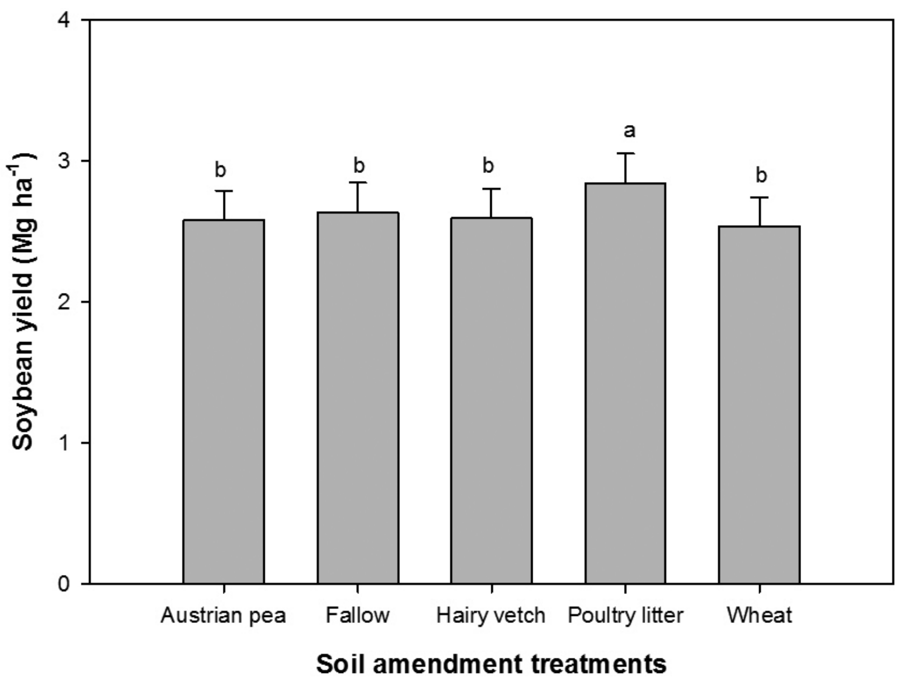

Fig. 2. Soybean yields by soil amendments per Phase (i.e., 3, 4-yr Phases) averaged across cropping sequence at Tennessee Research and Education Centers at Spring Hill (MTREC) and Milan (RECM) from 2002 to 2013. Vertical bars are the standard error. Austrian winter pea was not established during Phase I of this study and therefore had vegetation equivalent to that of the fallow treatment. Location effect was not significant (P = 0.25), whereas yield varied by soil amendment (P = 0.006); hence the interaction is reported. Different letters indicate a significant difference at an a level of 0.05; LSD = 1.76.

in the same plot area found that including soybean twice within a 4-yr rotation increased corn yield by 6% compared to continuous corn across 12 yr, whereas including cotton once within a Phase did not increase corn yield above that of continuous corn (Ashworth et al., 2016). Consequently, this study indicates that increasing cropping sequence diversity by 1 yr of corn in a 4-yr Phase promotes greater soybean yield compared to yield from a continuous soybean system in 4-yr Phases, perhaps due to the breaking of pest cycles.

Given soybean susceptibility to pests such as soybean cyst nematode, which can cause up to 30% yield reductions (Noel and Edwards, 1996), it was hypothesized that continuous soybean yield would decline long term, particularly during Phase III. A study conducted by Pedersen and Lauer (2002) asserted that the first year soybean rotation after 5 yr of corn produced 8% greater yield than other sequences on a Plano silt loam soil (fine-silty, mixed, superactive, mesic Typic Argiudoll) in Wisconsin. However, in the present study among the Phase × crop sequence (CvR) interaction, soybean yield within rotations were greatest during Phase II, whereas continuous soybean yield during the same Phase were lowest, with all other combinations not differing (DNS). However, during Phase III continuous yield were not different than yield from all rotations; as such this hypothesis was rejected ($P > 0.05$). Although, externalities such as rainfall could have been influential, considering 2 out of the 4 yr in Phase III had rainfall exceeding the 30-yr average from May to September at both locations (DNS). Conversely, at RECM during Phase II for 3 out of the 4 yr, lower than average precipitation was observed, coupled with greater than average temperatures from July–August (DNS).

Despite climatic variation within Phases, various cropping sequence yield exceeded that of continuous soybean ($P < 0.05$). Among all Phase × sequence interactions, the soybean–soybean–corn–cotton rotation during Phase II and the corn–corn–soybean–corn rotation during Phase I sequences were the highest yielding (4.2 and 4.1 Mg ha^{-1}, respectively), which was greater than continuous soybean yield during Phases II and III (Fig. 1; $P < 0.05$). This could be in part due to above average rainfall during August for all 4 yr of this Phase at both locations and above average mean monthly temperatures, as well as greater temperatures and precipitation than 30-yr averages during June and July for 2 out of the 4 yr during Phase I. Lowest yields occurred under the soybean–soybean–corn–soybean sequence during Phase II (2006–2010). Therefore, in general, highest yielding rotations were the corn–corn–soybean–corn, cotton–soybean–cotton–corn, and the corn–soybean–corn–soybean rotations during all Phases (Fig. 1). Similarly, conventionally tilled soybean in cropping rotations yielded higher than continuous soybean in research conducted by Wesley et al. (2001) in Mississippi, whereas, Wilhelm and Wortmann (2004) found that soybean in an alternating soybean–corn rotation yielded higher than continuous soybean in a 16-yr study.

Soil Amendment Influence on Long-Term Soybean Yield

When averaged across all years (2002–2013), cropping sequences, and locations, soil amendments impacted soybean yield ($P < 0.05$). Yield was greatest following poultry litter applications (2.9 Mg ha^{-1}) when compared to wheat, Austrian winter pea, hairy vetch, and the fallow control (Fig. 2), although there was no confluence for soil amendments and crop rotation sequences ($P > 0.05$). Soybean yield likely benefited from the flushes of P under the poultry litter treatment, presumably because of the significant role P plays in nodulation and N_2 fixation capacities of soybean (de Mooy and Pesek, 1966; Mullen et al., 1988; Drevon and Hartwig, 1997). Previous research has also shown that poultry litter applications can serve to increase soybean yield (Adeli et al., 2005). This could also be due to the stimulation of SOC formation under greater flushes of N and P (Table 2) which are required for microbial biomass assimilation and correlated to microbial biomass C (DeForest and Scott, 2010; Ashworth et al., 2014). Similarly, an 8-yr study conducted in Illinois found no soybean yield benefits from the inclusion of cover crops into cropping rotations (Olson et al., 2010).

CONCLUSIONS

Diverse cropping rotations and cover crops are perceived as requirements for sustained long-term crop yield, and as key tenets for maintaining soil health. Yield benefits from diverse cropping rotations occurred within 4-yr Phases on our silt loam soils, specifically, soybean yield in the soybean–soybean–corn–cotton rotation during Phase II and the corn–corn–soybean–corn rotation during Phase I were greater than continuous soybean yield during Phases II and III. Therefore, including corn once within a 4-yr cropping Phase resulted in 8% greater soybean yield vs. yield of continuous soybean. In addition, cropping sequence and soil amendments asserted various influences on soil characteristics, with long-term poultry litter applications resulting in greater soil N, P, K, and SOC storage. Soil amendments also affected soybean yield, considering P fertility and availability plays a key role in optimum soybean nodulation. As such, no-tillage soybean yield were highest under a high P and K soil amendment (poultry litter) compared to cover crops and the fallow control. Therefore, based on these 12-yr yield, including corn once within a 4-yr cropping rotation with poultry litter may improve soybean yield over continuous soybean cropping systems long term.

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REFERENCES

Adeli, A., K.R. Sistani, D.E. Rowe, and H. Tewolde. 2005. Effects of broiler litter on soybean production and soil nitrogen and phosphorus concentrations. Agron. J. 97:314–321. doi:10.2134/agronj2005.0314

Ashworth, A.J., F. Allen, A. Saxton, and D. Tyler. 2014. Soil organic carbon sequestration rates under crop sequence diversity, bio-covers, and no-tillage. Soil Sci. Soc. Am. J. 78:1726–1733. doi:10.2136/sssaj2013.09.0422

Ashworth, A.J., F.L. Allen, A.M. Saxton, and D.D. Tyler. 2016. Long-term corn yield impacted by cropping rotations and bio-covers under no-tillage. Agron. J. 108(4):1495–1502. doi:10.2134/agronj2015.0453

Chen, S., P.M. Porter, C.D. Reese, and W.C. Stienstra. 2001. Crop sequence effects on soybean cyst nematode and soybean and corn yields. Crop Sci. 41:1843–1849. doi:10.2135/cropsci2001.1843

Creamer, N.G., and K.R. Baldwin. 1999. Summer cover crops. HIL-37. North Carolina Coop. Ext. Serv. http://www.ces.ncsu.edu/depts/hort/hil/pdf/hil-37.pdf (accessed Mar. 2015).

Crookston, R.K., J.E. Kurle, P.J. Copeland, H.J. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83:108–113. doi:10.2134/agronj1991.00021962008300010026x

DeForest, J.L., and L.G. Scott. 2010. Available organic soil phosphorus has an important influence on microbial community composition. Soil Sci. Soc. Am. J. 74:2059–2066. doi:10.2136/sssaj2009.0426

de Mooy, C.J., and J. Pesek. 1966. Nodulation responses of soybeans to added phosphorus, potassium, and calcium salts. Agron. J. 58:275–280. doi:10.2134/agronj1966.00021962005800030009x

Dick, W.A., E.L. McCoy, W.M. Edwards, and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. Agron. J. 83:65–73. doi:10.2134/agronj1991.00021962008300010017x

Drevon, J.J., and U.A. Hartwig. 1997. Phosphorus deficiency increases the argon-induced decline of nodule nitrogenase activity in soybean and alfalfa. Planta 201(4):463–469. doi:10.1007/s004250050090

Drinkwater, L.E., P. Wagoner, and M. Sarrantonio. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature (London) 396:262–265. doi:10.1038/24376

Fisk, J.W., O.B. Hesterman, A. Shrestha, J.J. Kells, R.R. Harwood, J.M. Squire, and C.C. Sheaffer. 2001. Weed suppression by annual legume cover crops in no-tillage corn. Agron. J. 93:319–325. doi:10.2134/agronj2001.932319x

Franzluebbers, A.J. 2005. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil Tillage Res. 83:120–147. doi:10.1016/j.still.2005.02.012

Gomez, E.V., G.B. Schaalje, and G.W. Fellingham. 2005. Performance of the Kenward–Roger method when the covariance structure is selected using AIC and BIC. Commun. in Statistics-Simulation and Computation 34(2):377–392. doi:10.1081/SAC-200055719

Higgs, R.L., A.E. Peterson, and W.H. Paulson. 1990. Crop rotation: Sustainable and profitable. J. Soil Water Conserv. 45:68–70.

Howard, D.D., A.Y. Chambers, and G.M. Lessman. 1998. Rotation and fertilization effects on corn and soybean yields and soybean cyst nematode populations in a no-tillage system. Agron. J. 90:518–522. doi:10.2134/agronj1998.00021962009000040013x

Hussain, I., K.R. Olson, and S.A. Ebelhar. 1999. Impacts of tillage and no-till on production of maize and soybean on an eroded Illinois silt loam soil. Soil Tillage Res. 52:37–49. doi:10.1016/S0167-1987(99)00054-9

Kabir, Z., and R.T. Koide. 2000. The effect of dandelion or a cover crop on mycorrhiza inoculum potential, soil aggregation, and yield of maize. Agric. Ecosyst. Environ. 78:167–174. doi:10.1016/S0167-8809(99)00121-8

Kurle, J.E., C.R. Grau, E.S. Oplinger, and A. Mengistu. 2001. Tillage, crop sequence, and cultivar effects on Sclerotinia stem rot incidence and yield in soybean. Agron. J. 93:973–982. doi:10.2134/agronj2001.935973x

Lal, R. 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degrad. Dev. 17(2):197–209. doi:10.1002/ldr.696

Lal, R., J.M. Kimble, R.F. Follet, and C.V. Cole. 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Sleeping Bear Press, Chelsea, MI.

Lund, M.G., P.R. Carter, and E.S. Oplinger. 1993. Tillage and crop rotation affect corn, soybean, and winter wheat yields. J. Prod. Agric. 6:207–213. doi:10.2134/jpa1993.0207

Mannering, J.V., and D.P. Griffith. 2007. Value of crop rotation under various tillage systems. AY-230. Purdue Univ. Coop. Ext. Serv., West Lafayette, IN.

McDaniel, M.D., L.K. Tiemann, and A.S. Grandy. 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24:560–570. doi:10.1890/13-0616.1

Meese, B.G., P.R. Carter, E.S. Oplinger, and J.W. Pendleton. 1991. Corn/soybean rotation effect as influenced by tillage, nitrogen, and hybrid cultivar. J. Prod. Agric. 4:74–80. doi:10.2134/jpa1991.0074

Mullen, M.D., D.W. Israel, and A.G. Wollum. 1988. Effects of *Bradyrhizobium japonicum* and Soybean (*Glycine max* (L.) Merr.) Phosphorus nutrition on nodulation and dinitrogen fixation. Appl. Environ. Microbiol. 54:2387–2392.

NASS. 2004. 2004 Tennessee tillage systems. Natl. Agric. Statistical Serv. http://www.nass.usda.gov/Statistics_by_State/Tennessee/Special_Surveys/NT070504.pdf. (accessed Mar. 2015).

NASS. 2012. Tennessee tillage systems. Natl. Agric. Statistical Serv. http://www.nass.usda.gov/Statistics_by_State/Tennessee/Quick_Facts/tillage.pdf (accessed Oct. 2015).

Noel, G.R., and D.I. Edwards. 1996. Population development on *Heterodera glycines* and soybean-maize rotations following introduction into a noninfested field. J. Nematol. 28:335–342.

Ogle, S.M., F.J. Breidt, and K. Paustian. 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72:87–121. doi:10.1007/s10533-004-0360-2

Olson, K.R., S.A. Ebelhar, and J.M. Lang. 2010. Cover crops effects on crop yields and soil organic content. Soil Sci. 175:89–98. doi:10.1097/SS.0b013e3181cf7959

Ortega, R.A., G.A. Peterson, and D.G. Westfall. 2002. Residue accumulation and changes in soil organic matter as affected by cropping intensity in no-till dryland agroecosystems. Agron. J. 94:944–954. doi:10.2134/agronj2002.9440

Pedersen, P., and J.G. Lauer. 2002. Influence of rotation sequence on the optimum corn and soybean plant population. Agron. J. 94:968–974. doi:10.2134/agronj2002.0968

Porter, P.M., J.G. Lauer, W.E. Lueschen, J.H. Ford, T.R. Hoverstad, E.S. Oplinger, and R.K. Crookston. 1997. Environment affects the corn and soybean rotation effect. Agron. J. 89(3):442–448. doi:10.2134/agronj1997.00021962008900030012x

Reddy, K.N., and C.H. Koger. 2004. Live and killed hairy vetch cover crop effects on weeds and yield in glyphosate-resistant corn. Weed Technol. 18(3):835–840. doi:10.1614/WT-03-228R

Reddy, K.N., R.M. Zablotowicz, M.A. Locke, and C.H. Koger. 2003. Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield in the lower Mississippi River delta. Weed Sci. 51(6):987–994. doi:10.1614/P2002-169

SAS Institute. 2007. SAS/STAT 9.3 User's guide. SAS Inst., Cary, NC.

Saxton, A.M. 1998. A macro for converting mean separation output to letter groupings in Proc Mixed. In: Proceedings 23rd SAS Users Group International, Nashville, TN. 22–15 Mar. 1998. SAS Inst., Cary, NC. p. 1243–1246.

Schulte, E.E., and B.G. Hopkins. 1996. Estimation of soil organic matter by weight-loss-on-ignition. In: F.R. Magdoff et al., editors, Soil organic matter: Analysis and interpretation. SSSA Spec. Publ. 46. SSSA, Madison, WI. p. 21–31.

Six, J., S.D. Frey, R.K. Thiet, and K.M. Batten. 2006. Bacterial and fungal contributions to carbon sequestration in agroecosystems. Soil Sci. Soc. Am. J. 70:555–559. doi:10.2136/sssaj2004.0347

Stockmann, U., M.A. Adams, J.W. Crawford, D.J. Field, N. Henakaarchchi, M. Jenkins et al. 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164:80–99. doi:10.1016/j.agee.2012.10.001

Tillman, G., H. Schomberg, S. Phatak, B. Mullinix, S. Lachnicht, P. Timper, and D. Olson. 2004. Influence of cover crops on insect pests and predators in conservation tillage cotton. J. Econ. Entomol. 97:1217–1232. doi:10.1093/jee/97.4.1217

Tisdall, J.M., and J.M. Oades. 1980. The effect of crop rotation on aggregation in a red-brown earth. Aust. J. Soil Res. 18:423–433. doi:10.1071/SR9800423

Tyler, D.D., J.R. Overton, and A.Y. Chambers. 1983. Tillage effects on soil properties, diseases, cyst nematodes, and soybean yields. J. Soil Water Conserv. 38:374–376.

Villamil, M.B., G.A. Bollero, R.G. Darmody, F.W. Simmons, and D.G. Bullock. 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. Soil Sci. Soc. Am. J. 70:1936–1944. doi:10.2136/sssaj2005.0350

Vyn, T.J., T.D. West, and G.C. Steinhardt. 2000. Corn and soybean response to tillage and rotation systems on a dark prairie soil: 25 year review. No. 196 In: Proceedings, 15th Conferenceof International Soil Tillage Research Organization, Fort Worth, TX. 2–6 July 2000. Purdue Univ., West Lafayette, IN. p. 1–10.

Watts, D.B., and H.A. Torbert, III. 2011. Long-term tillage and poultry litter impacts on soybean and corn grain yield. Agron. J. 103:1479–1486. doi:10.2134/agronj2011.0073

Wesley, R.A., C.D. Elmore, and S.R. Spurlock. 2001. Deep tillage and crop rotation effects on cotton, soybean, and grain sorghum on clayey soils. Agron. J. 93:170–178. doi:10.2134/agronj2001.931170x

West, T.O., and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. 66:1930–1946. doi:10.2136/sssaj2002.1930

Whalen, J.K., Q. Hu, and A. Liu. 2003. Compost applications increase water-stable aggregates in conventional and no-tillage systems. Soil Sci. Soc. Am. J. 67:1842–1847. doi:10.2136/sssaj2003.1842

Wight, J., F.L. Allen, A.J. Ashworth, N. Labbe, T. Rials, and D. Tyler. 2016a. Comparison of near infrared reflectance spectroscopy with combustion and chemical methods for soil carbon measurements in agricultural soils. Commun. Soil Sci. Plant Anal. 47:731–742. doi:10.1080/00103624.2016.1146750

Wight, J., A.J. Ashworth, and F. Allen. 2016b. Organic substrate, clay type, texture, and water effects on NIR carbon measurements. Geoderma 261:36–43. doi:10.1016/j.geoderma.2015.06.021

Wilhelm, W.W., J.W. Doran, and J.F. Power. 1986. Corn and soybean yield response to crop residue management under no-tillage production systems. Agron. J. 78:184–189. doi: 10.2134/agronj1986.00021962007800010036x

Wilhelm, W.W., and C.S. Wortmann. 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and temperature. Agron. J. 96:425–432. doi:10.2134/agronj2004.0425