Published May 6, 2016

Long-Term Corn Yield Impacted by Cropping Rotations and Bio-Covers under No-Tillage

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ABSTRACT

Cropping diversity and bio-covers are perceived as integral components of conservation tillage because of increased pest control and soil organic matter. Consequently, effects of cropping sequences and bio-covers on corn (*Zea mays* L.) yields were assessed. Main effects were 10 cropping sequences of corn, cotton (*Gossypium hirsutum* L.), and soybean (*Glycine max* L.) on a Loring silt loam (fine-silty, mixed, thermic Oxyaquic Fragiudalf) at the Research and Education Center (REC) at Milan, and seven cropping sequences of corn and soybean at the Middle Tennessee REC on a Maury silt loam (fine, mixed, active, mesic Typic Paleudalf). Sequences were repeated in 4-yr cycles (i.e., Phases I, II, and III) from 2002 to 2013. Strip-plot bio-covers consisted of hairy vetch (*Vicia villosa* L.), Austrian winter pea (*Pisum sativum* L. *sativum* var. *arvense*), wheat (*Triticum aestivum* L.), poultry litter, and fallow control. Across 12- yr, bio-covers, and locations, continuous corn and yields from all rotations were equivalent (7.6 and 7.9 Mg ha^{-1}, respectively; $P = 0.07$). However, among phase × sequence interactions, corn–soybean–corn–soybean rotation was highest yielding during Phase III (10.1 Mg ha^{-1}), which was greater than continuous corn during all phases ($P < 0.05$). Bio-covers, particularly poultry litter and hairy vetch, increased yields (across locations and years) when compared to wheat ($P < 0.05$). Incorporating soybean or cotton once within 4-yr cropping cycles was equivalent to continuous corn ($P > 0.05$). However, including soybean and cotton twice increased yields by 6 and 7%, respectively ($P < 0.05$). Results suggest including two crops within a 4-yr phase increases yields compared to continuous corn.

Core Ideas

- Increasing cropping sequence diversity promotes greater yields when two species are included in a rotation compared to continuous corn.
- Including soybean and cotton twice increased yields by 6 and 7%, respectively.
- Bio-covers, particularly poultry litter and hairy vetch, increased corn yields compared to wheat cover crops.

Published in Agron. J. 108:1–8 (2016)
doi:10.2134/agronj2015.0453
Received 15 Sept. 2015
Accepted 28 Mar. 2016

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Since the advent of agriculture, crop rotations have been implemented; however, chemical fertilizers and pesticides have replaced some of the perceived benefits (e.g., reduced pest pressure and fertilizer requirements) that crop rotations and cover crops provide. Continuous corn systems, defined as producing corn on the same parcel of land for 3 or more years, is widely thought to reduce corn yield compared to corn yield grown in soybean rotations (Gentry et al., 2013; Crookston et al., 1991). Grain yield penalties resulting from continuous corn are not clearly understood, although a study by Gentry et al. (2013) ascertained that penalties arose from reduced N availability, corn residue accumulation (high C/N ratio), and weather. Furthermore, based on predicted increases in corn prices because of grain demands for the Energy Independence and Security Act (2007), and increased requirements for livestock markets and human consumption, demands for corn are expected to continually increase, which will likely result in increased land area of mono-cropped corn.

Research has shown that, depending on soil texture, continuous corn can yield 95 to 100% of corn that is grown in rotations (Pedersen, and Lauer, 2002; Aldrich, 1964). Similarly, in a study by Crookston et al. (1991), yields of annually rotated corn were 10% greater than monoculture systems. Consequently, they suggest that a superior system would include at least three crops. Also, a summary of 28 studies in the United States comparing continuous corn with corn grown in rotations determined that all but two studies showed yield decreases, with reductions ranging from 2 to 19% (Erickson, 2008). In a 3-yr study, Pedersen and Lauer (2002) found that no-tilled corn–soybean rotations resulted in 12% greater yields than continuous corn, whereas Griffith et al. (1988) measured 20% greater corn yields when grown in rotations compared to continuous corn grown under no-tillage. Conversely, Hussain et al. (1999) found that continuous no-till corn yields were equal to yields grown with soybean rotations over an 8-yr period.

Numerous studies have also documented long-term benefits from crop rotations, bio-covers, and no-tillage (Franzluebbers, 2005; Thelen et al., 2010; Ashworth et al., 2014). Specifically, soil

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Abbreviations: RECM, Research and Education Center at Milan; MTREC, Middle Tennessee Research and Education Center; GR, glyphosate-resistant; SOC, soil organic carbon; DNS, data not shown; VNS, variety not stated; LRR, Land Resource Region: MLRA, Major Land Resource Area.

organic carbon (SOC) is considered an indicator of soil quality because of its crucial impacts on physical, biological, and chemical impacts surrounding soil tilth, and may be increased through no-tillage (Ashworth et al., 2014; Lal, 2006). Conservation tillage systems, in which a crop is planted directly into the previous crop's residue, is of interest due to increased no-tillage land area throughout the United States. This trend is also reflected in no-till land area found in Tennessee, with 80% of corn being no-till seeded (NASS, 2012). No-till drilling has shown to improve soil fertility due to a greater cation exchange capacity, aggregate stabilization, reduced soil erosion, and increased available moisture when compared to conventionally-tilled systems (Franzluebbers, 2005; Lal, 2006; West and Post, 2002). Consequently, conservation tillage coupled with best management practices (e.g., crop rotations and bio-covers) may enhance soil quality for long-term agricultural production, although little is known about interacting effects on crop yields.

Crop rotation may affect soil nutrient availability because of greater residue diversity, especially in relation to C and N, and therefore may be an effective way to increase crop yields. Specifically, N dynamics are thought to play a predominant role in continuous corn yield penalties, since larger C/N ratio and volume residues such as that from corn may reduce mineralization compared to soybean residues (Kaboneka et al., 1997; Gentry et al., 2013). Furthermore, corn–soybean rotations that include both vetch (*Vicia villosa* L.) and rye (*Secale cereale* L.) as winter covers reportedly increase SOC compared with winter fallow rotations (Villamil et al., 2006). Consequently, despite corn producing high amounts of residue, studies have confirmed that continuous corn may result in comparable SOC levels to that of cotton/corn (Reddy et al., 2006; Ashworth et al., 2014) and corn–soybean rotations (Omonode et al., 2006).

Perhaps one of the most important contributions of bio-covers under any cropping system is the impact on soil N availability. Nitrogen is an essential nutrient for crop growth and plays a critical role in corn systems (Coulter and Nafziger, 2008). Previous research has shown that bio-covers can enhance soil fertility and subsequent crop yields under no-tillage (Ashworth et al., 2014; Ebelhar et al., 1984). A legume cover crop such as hairy vetch can increase available N due to N_2–fixation capabilities, thereby meeting part of the N diet for succeeding crops (Peoples et al., 2001). No-till corn yields were higher after legume cover crops such as hairy vetch when compared to fallow corn yields in field studies by Blevins et al. (1990) and Decker et al. (1994). Poultry litter, a bio-cover consisting of poultry manure and bedding materials, is a source of N and P that can also impact labile N and benefit microbial growth. Studies comparing N accumulation using poultry litter and ammonium nitrate have demonstrated higher levels of total N as well as nitrate following poultry litter applications (Nyakatawa et al., 2001; Mitchell and Tu, 2006). In addition, cereal cover crops such as rye and winter wheat can reduce nitrate leaching by capturing N from the preceding crop (Strock et al., 2004; Costa et al., 2000); however, cereal covers may not return N to soils, resulting in no yield benefit to subsequent row crops (Watts and Torbert, 2011). However, the extent of this is unknown for long-term corn systems under no-tillage; therefore more region-specific data are needed.

Given that crop rotations and bio-covers can help alleviate pathogen, pest, and weed issues associated with no-till, as well as potentially improve crop yields, research into their combined effects on corn yields in a no-tilled system is necessary to make management recommendations that will improve soil quality and crop yields. Therefore, the objective of this study was to determine impacts on corn yield from cropping system rotations and bio-covers, as well as their interactions under no-tillage production.

MATERIALS AND METHODS

Site Description and Experimental Design

The study was conducted at two University of Tennessee locations to evaluate cropping system impacts over a range of soil types and different physiographic regions. Each location was under long-term no-tillage where crops were planted directly into the previous crop residue. The first location was at the Middle Tennessee Research and Education Center (MTREC; 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, and classified as the Nashville Basin in the Land Resource Region [LRR] "N"). Soils at this location are classified as a Maury silt loam. This location is typical of the karst topography region in middle Tennessee, northern Alabama, central and western Kentucky, and southern Indiana. The MTREC has a mean annual temperature of 14.2°C and 114 cm of precipitation. Prior to experiment initiation, this site was under a 2-yr corn–soybean rotation, with half being under corn and the other soybean. The site was under no-till received annual additions of dairy manure for 15 yr prior to initiation of this experiment.

The second site was located at the Research and Education Center at Milan (RECM; Milan, TN; 35.54° N, -88.44° W)

Table 1. Cropping sequences 2002 (Year 0) to 2013 (Year 12) at Research and Education Centers at Middle Tennessee (MTREC; Spring Hill, TN) and Milan (RECM, Milan, TN) locations.

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

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

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 Southern Mississippi Valley Loess, East Gulf Coastal Plain in LRR "P"). Soils at RECM site are classified as a Loring B2 series. 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-till for 16 yr prior to experimentation. In 2001, the site was planted in corn, soybean in 2000, and cotton in 1999. During winters, RECM was planted with winter wheat for grain. The site was left fallow the winter prior study initiation.

At both locations, the experiment was conducted as a split-block (strip-plot) treatment design with four replications. Whole-block treatments consisted of cropping sequences (see Table 1 for whole plot sequences), with strip-block treatments comprised of five bio-covers. Bio-covers of wheat, vetch, Austrian winter pea, poultry litter, and a fallow (winter weeds) control were repeated annually under no-tillage production. Plot sizes were 6.1 by 12.2 m at both locations.

At RECM, 10 different cropping sequences of corn, cotton, and soybean were repeated in 4-yr cycles (i.e., Phases I, II, and III; Table 1) from 2002 to 2013. The same experiment was performed at MTREC without cotton (7 sequences total). This created 50 and 35 sequence ′ bio-cover combinations for RECM and MTREC, respectively. In 2012, extreme drought (5.7 and 6.2 cm total annual precipitation at RECM and MTREC, respectively; Table 2) and high temperatures (Table 2) occurred, and consequently crop establishment failures ensued; therefore, these data were not included in Phase III (2010–2013) of this study. Similarly, failures occurred at MTES during 2010, and consequently this location/year combination was excluded.

Crop Establishment and Treatment Maintenance

Glyphosate-resistant (GR) corn hybrids were DeKalb DKC 6410 RR (2002–2005), DeKalb DKC63-81 RR2/YGCB (2006–2008), and DeKalb 63-42 (2009). Glyphosate-resistant soybean cultivar USG 7440nRR (2002–2009) and GR cotton cultivars Paymaster PM 1218 BG/RR (2002–2005), and Delta Pine DP 117 RRBG (2006–2009) were used in Phases I and II, respectively. Glufosinate-tolerant cultivars for all crops were planted in Phase III (2010–2013) due to potential increases in GR weeds. Cultivars were Augusta 6867 corn; Halo 4:65 soybean; and Phytogen 375 WRF cotton. At both locations, corn, soybean, and cotton were planted at University of Tennessee recommended seeding rates of 64,247; 258,334–344,445; and 64,495 seeds ha^{-1}, respectively.

Table 2. Total monthly precipitation (rain) and mean monthly air temperature (MT) at the Research and Education Centers at Middle Tennessee (MTREC; Spring Hill, TN) and Milan (RECM, Milan, TN) from April to September during 2002 to 2013. 30 yr avg. represent averages from 1981 to 2010. Weather data were taken at research centers and obtained from the U.S National Oceanic and Atmospheric Administration (NOAA).

	April		May		June		July		August		September	
Year	Rain	MT	Rain	MT	Rain	MT	Rain	MT	Rain	MT	Rain	MT
	cm	°C	cm	°C	cm	°C	cm	°C	cm	°C	cm	°C
						MTREC						
2002	7.1	15.4	12.9	18.4	6.9	25.8	8.8	26.7	17.2	25.9	16.3	23.6
2003	12.4	15.0	24.2	19.1	14.1	21.4	16.3	24.7	8.8	25.6	17.1	20.5
2004	7.2	13.7	15.1	21.5	17.6	23.3	8.8	24.3	10.6	22.0	6.4	21.0
2005	15.9	14.0	3.2	17.0	15.6	23.1	16.9	26.3	22.6	26.3	6.2	22.8
2006	14.2	17.6	11.4	18.3	9.5	22.8	11.7	25.7	7.3	26.7	6.4	20.3
2007	2.5	13.1	2.2	20.3	3.3	24.1	2.9	25.0	1.5	28.8	3.4	23.1
2008	16.1	13.7	13.9	18.4	7.3	24.6	6.2	25.2	10.5	24.6	3.1	21.9
2009	13.6	13.9	35.7	19.2	4.6	24.3	17.0	23.4	6.2	24.0	26.6	21.6
2010	8.2	15.6	35.3	20.2	10.3	26.0	17.3	26.6	14.7	26.5	2.8	21.7
2011	23.1	15.8	10.0	18.5	17.4	24.9	9.1	26.9	4.7	25.7	16.2	20.0
2012	4.1	14.8	10.8	20.9	3.0	22.9	14.0	27.2	10.1	24.1	16.5	20.5
2013	18.6	13.6	8.4	18.1	12.8	23.4	13.8	23.5	9.3	23.6	12.8	21.3
30 yr avg.	12.1	14.0	14.9	18.8	11.1	23.6	11.3	25.5	7.6	25.1	10.0	21.2
						RECM						
2002	4.5	17.0	13.4	18.9	5.8	25.2	3.5	27.3	16.8	26.0	28.7	22.7
2003	8.6	16.1	27.8	20.4	8.0	22.1	5.9	26.0	11.4	25.9	8.6	20.1
2004	20.7	21.4	11.7	27.7	12.8	29.6	5.3	30.8	12.3	29.9	0.8	28.7
2005	19.2	15.0	1.5	18.5	12.9	24.0	13.5	25.9	20.5	26.6	9.6	22.6
2006	8.3	18.1	12.8	19.8	15.1	23.9	9.0	26.6	8.4	26.9	11.4	19.8
2007	8.4	13.1	5.8	21.7	11.2	24.8	5.5	25.5	3.2	29.6	18.4	22.7
2008	24.1	14.1	23.9	19.3	3.9	25.5	7.9	26.6	1.9	25.1	1.1	22.7
2009	8.2	14.9	23.0	20.1	5.6	26.0	20.1	24.6	5.7	24.5	12.0	22.4
2010	15.2	17.1	53.5	21.8	8.2	27.5	15.1	27.6	5.0	27.8	0.9	23.1
2011	24.9	10.9	28.5	13.8	17.3	20.4	3.6	22.0	2.9	19.5	25.9	14.1
2012	3.1	16.5	4.1	22.6	4.7	24.3	12.2	28.4	11.7	25.9	12.9	21.9
2013	27.6	14.2	24.8	19.5	13.8	24.9	17.7	24.5	7.4	24.8	15.0	22.4
30 yr avg.	14.9	11.6	14.2	19.9	10.9	24.4	10.0	26.2	8.4	25.7	9.0	21.5

Corn was planted in 76.2 cm wide rows in plots that were 6.1 by 12.3 m and 4.6 by 12.3 m with a John Deere 1700 Maxemerge planter (Deere & Company, Moline, IL), thus creating eight-row plots, or with a six-row John Deere plateless planter at RECM and MTREC, respectively. At both locations and during the 12 study years, corn was planted between 12 April and 9 May. Two (RECM) or three (MTREC) center rows were harvested per plot each year between 29 August and 27 September. Corn plots were harvested at RECM with an AC Gleaner combine (AGCO, Duluth, GA) in 2002 and in all subsequent years with an ALMACO SPC 40 combine (ALMACO, Nevada, IA). At MTREC, corn was harvested using a K-2 AC Gleaner combine with a three-row header. Measurements taken at both locations at the time of harvest were plot weights and grain moisture content (%). Corn yields were adjusted to a standard moisture content of 155 g kg^{-1}.

Eight-row plots of soybean at RECM and six-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 4.6 by 12.3 m, respectively. Planting dates were between 29 April and 30 May at both locales. Each year, two center rows (RECM) or four center rows (MTREC) were harvested per plot between 23 September and 16 October. An AC Gleaner combine was used in 2002, and harvests in all subsequent years were conducted with an ALMACO SPC 40 combine at RECM and a K-2 AC Gleaner combine with a 3.1m wide grain header at MTREC. Measurements taken at harvests were plot weight and grain moisture, which was used to adjust yield to a standard moisture content of 130 g kg^{-1}.

Cotton was planted at RECM with a John Deere 1710 Maxemerge planter in 101.6 cm wide rows in plots that were 6.1 by 12.2 m, thus creating six-row plots. Cotton was planted between 7 May and 12 May, and harvest occurred between 10 September and 25 October. Two center rows were harvested each year with a Case IH 1822 cotton picker (Amsterdam, the Netherlands). Measurement taken at RECM during harvests was plot seed-cotton weight.

Poultry litter bio-cover plots received the equivalent of 67 kg N ha^{-1}, (ca. 4.4 t ha^{-1}, assuming 50% bioavailability; A&L Analytical Laboratories, Inc., Memphis, TN). Similarly, wheat and fallow bio-covers received 67 kg N ha^{-1}, while vetch plots received only 50 kg N ha^{-1} in the form of urea (CH_4N_2O) prior to planting due to calculated N contribution from vetch. Corn received 129 kg N ha^{-1} and cotton plots received 33 kg N ha^{-1} as sidedress applications in May–June each year. Muriate of potash (KCl) was applied to all plots in April of each year at a rate of 112 kg ha^{-1} (K_2O rate). Nitrogen was applied via a 10T and 1010T Series Drop Spreader (Gandy, Owatonna, MN) at RECM and MTREC, respectively. Poultry litter was applied with a New Idea 3726 Series (New Idea, Coldwater, OH) and an AGCO Hesston S431 Manure Spreader at RECM and MTREC, respectively. Austrian winter pea, wheat, and hairy vetch bio-covers were planted with a John Deere 1560 drill at RECM, and with a Great Plains 1500 No-Till Drill (Plains Manufacturing Inc, Salina, KS) at MTREC. 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. Bio-covers 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.

Before planting, burndown herbicides were used to kill existing vegetation and bio-covers. Either paraquat (1,1'-Dimethyl-4,4'-bipyridinium dichloride), glyphosate (*N*-(phosphonomethyl)-glycine), or glufosinate ammonium [ammonium(±)-2amino-4-(hydroxymethylphosphinyl)butanoate] were applied in April of each year prior to corn, soybean, and cotton planting. One or two post-emergence applications of glyphosate were applied post-emergence to soybean and corn plots in May or June annually during Phases I and II, whereas glufosinate was used for this purpose in Phase III. For cotton plots at RECM, the same herbicide applications were applied post-emergence. Insecticide and crop growth regulation chemicals were applied as needed from June through September each year. Glyphosate, glufosinate, and clethodim (cotton and soybean) (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 during Phases I to III. 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 used for additional insect control and plant growth regulation on cotton.

Analysis of variance tests of corn yields were performed using the MIXED procedure of SAS (SAS V9.3; SAS Inst., Cary, NC). Contrast statements were used to determine any yield penalty from continuous cropping, as well as impacts from bio-covers and cropping sequence interactions. For the 12-yr dataset, cropping sequence (whole-plot) and bio-covers (split-plot) were considered fixed effects and phase (i.e., three 4-yr cycles) was considered as repeated measure. For the repeated measure, an autoregressive covariance was tested and found to be unimportant by a likelihood test, so repeated measures were dropped. Phase was considered a fixed treatment effect to assess the long-term time effects of successive applications of cropping sequences; whereas, block, year, and location were considered random effects. When main effects or interactions were found, mean separations were performed using the SAS macro "pdmix800" (Saxton, 1998) with Fisher's least significant difference (LSD) at a Type I error rate of 5% (SAS Institute, 2007). Contrasts were implemented by defining new factors comparing all rotations with soybean and cotton occurring in sequences with corn. Other contrast factors were included to assess corn yield impacts from cotton and soybean occurring once, twice, or thrice depending on sequence.

RESULTS AND DISCUSSION

Overall analyses of the 12 study years revealed that main effects of continuous corn yields vs. corn yields from all rotations were equivalent (7.6 and 7.9 Mg ha^{-1}, respectively; $P = 0.07$) when averaged across bio-covers, Phases (4-yr cycles), and locations (as locations were not different [$P = 0.26$; Table 3]). However, various cropping sequences did result in increases in yield over continuous corn (within phase), as continuous corn yielded lower than corn with greater cropping sequence diversity during Phase III ($P < 0.0001$). Furthermore, main effects of bio-covers ($P = 0.001$) and cropping sequences (within 4-yr phases) impacted ($P < 0.0001$)

corn yields (Table 3). Also, cropping sequence × bio-cover (within Phase), cropping sequence × bio-cover (across phases), and phase × bio-cover did impact yield ($P < 0.0001$, $P = 0.01$ and $P = 0.02$, respectively; Table 3). Conversely, there were no interactions ($P < 0.05$) among phases for bio-cover ×crop sequence [continuous vs. all rotations (CvR)], phase × crop sequence (CvR), and phase × bio-cover × crop sequence (CvR; Table 3). These results indicate that the diverse weather conditions within phases had similar effects on corn yields.

Based on contrast statement results (soybean and cotton occurring once, twice, etc.), varying impacts occurred when cotton or soybean were included either once or twice within corn rotations per phase, as both crops impacted corn yields when included in rotations ($P < 0.0001$). Averaged across all phases, including soybean once within a 4-yr cropping cycle with corn resulted in corn yields that were equivalent to that of continuous corn (7.9 and 7.6 Mg ha^{-1}, respectively; DNS). However, including soybean twice within a 4-yr rotation increased yields by 6% compared to continuous corn across the entire study period ($P < 0.05$). Similarly, including cotton once within a phase did not increase corn yield above that of continuous corn (8.0 and 7.6 Mg ha^{-1}, respectively), whereas doubling cotton frequency increased yield by 7% ($P < 0.05$). Consequently, these results indicate that increasing cropping sequence diversity by 2 yr of soybean or cotton in a 4 yr cycle promotes greater corn yields compared to yields from continuous corn systems in 4-yr phases. These results were similar to those in a study conducted by Pedersen and Lauer (2002) that asserted corn after soybean yields were higher than continuous corn on a Plano silt loam soil (fine-silty, mixed, superactive, mesic Typic Argiudoll) in Wisconsin. Similarly, increases with higher soybean frequencies in corn rotations are supported by Lauer et al. (1997), who observed corn–soybean rotations yielded 13% greater than did continuous corn. Although, our study results suggest 6% increases may be more appropriate in soils of the Southeast.

Table 3. Analysis of variance results for corn yields averaged across Research and Education Centers at Middle Tennessee (MTREC; Spring Hill, TN) and Milan (RECM, Milan, TN) locations from 2002 to 2013. Cropping sequences were repeated in 4-yr phases with bio-covers being repeated annually.

Fixed effect	df	*F* value	*P* > *F*
Bio-cover	4	6.46	0.001
Continuous vs. all rotations (CvR)	1	3.39	0.07
Bio-cover × CvR	4	2.08	0.08
Sequence (Phase × CvR)	35	4.27	<0.001
Sequence × bio-cover(CvR)	52	2.05	<0.001
Sequence × bio-cover (Phase × CvR)	140	1.36	0.01
Phase	2	0.39	0.68
Phase × bio-cover	8	2.24	0.02
Phase × CvR	2	1.97	0.14
Phase × bio-cover × corn	8	0.64	0.74

Among all phase × sequence interactions, the corn–soybean–corn–soybean rotation during Phase III was the highest yielding (10.1 Mg ha^{-1}), which was greater than continuous corn during all phases (Fig. 1; $P < 0.05$). Lowest yields occurred under the cotton–soybean–cotton–corn, cotton–corn–cotton–corn, and soy–corn–corn–soy rotations (5.6, 6.7, and 6.5 Mg ha^{-1}, respectively) during Phase II (2006–2010). Finally, the soybean–corn–corn–soybean and cotton–soybean–cotton–corn sequences were

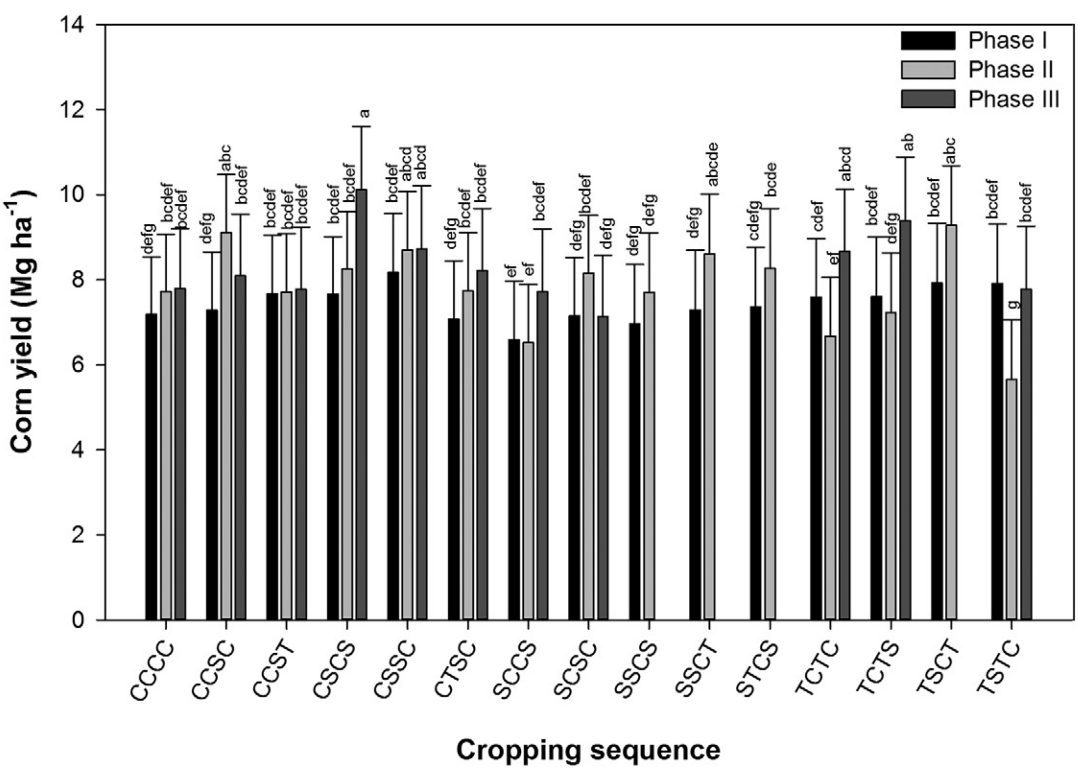

Fig. 1. Corn yields by cropping sequence averaged across Research and Education Centers at Middle Tennessee (MTREC; Spring Hill, TN) and Milan (RECM, Milan, TN) locations. Yields are averaged per phase (i.e., 3, 4-yr cycles) from 2002 to 2013, totaling 12 study years. Vertical bars are the standard error. C = corn; S = soybean; T = cotton. Sequences are repeated every 4 yr. Experimental locations were not different ($P = 0.25$), whereas phase x sequence varied ($P < 0.0001$) for corn yields; hence the interactions are reported. Different letters indicate a significant difference at an α level of 0.05; LSD = 1.52.

the lowest yielding rotations among all sequences tested in this study (7.0 and 7.1 Mg ha^{-1}, respectively; data not shown [DNS]).

When averaged across all years (2002–2013), cropping sequences, and locations, bio-covers impacted corn yields (P < 0.05). Yields were greatest following poultry litter applications and hairy vetch cover crop (7.9 and 7.9 Mg ha^{-1}, respectively) when compared to wheat bio-covers (7.2 Mg ha^{-1}). Corn yields following Austrian winter pea (only included in Phases II and III) and fallow winter weeds bio-covers did not differ. In addition, when combined across locations, bio-covers per cropping phase differed (P < 0.05), with wheat cover crops during Phases I and II being lowest (6.9 and 7.1 Mg ha^{-1}, respectively Fig. 2). Lower relative yields during these phases to Phase III could have been due to 2 out of the 4 yr in Phase III having rainfall greater than the 30-yr average from May to September at both locations (Table 2). Conversely, hairy vetch during Phase III resulted in the highest corn yield (8.5 Mg ha^{-1}; Fig. 2). These results are similar to findings in other studies. No-till corn yields were higher after legume cover crops such as hairy vetch when compared to fallow corn yields in two studies by Blevins et al. (1990) and Decker et al. (1994). Corn yields likely benefit from N additions provided by legume cover crops and flushes of P from the poultry litter (Watts and Torbert, 2011). A study performed by Endale et al. (2004) found that no-till and poultry litter increased corn yields by 27% when compared to fallow systems, whereas ours only increased 12% from Phase I to II. However, the application rate of poultry litter in the aforementioned experiment was more than twofold that in the experiment discussed herein.

Based on yield results from cotton or soybean occurring twice within a phase, selected sequences × bio-cover interactions were compared in Table 4. Within the sequence × bio-cover (Phase) interaction, highest yields occurred within Phase III (2010–2013) for the corn–soy–corn–soy rotation and with the Austrian winter pea and hairy vetch cover crops (11.2 and 11.3 Mg ha^{-1}, respectively). Lowest corn yield combinations occurred under the cotton–soy–cotton–corn and soy–soy–corn–soy rotations and under fallow and wheat cover crops, respectively (4.0 and 5.1 Mg ha^{-1}, respectively; DNS). Similarly, when averaged across phases (sequence × bio-cover), Austrian winter pea cover crop included in the corn–soybean–corn–soybean sequence was the greatest (9.6 Mg ha^{-1}; P < 0.05), which was greater than the poultry litter and wheat covers in the same rotation (8.2 and 7.8, Mg ha^{-1}, respectively; Table 4). Interestingly, none of the bio-covers resulted in yield increases in the continuous corn sequence above that of the fallow control (Table 4). Consequently, following corn with soybean or cotton per annum with either Austrian winter pea or hairy vetch under no-tillage may be remunerating, whereas including cotton and soybean less than two times within a 4-yr cycle, along with either wheat cover crops or with no cover (fallow), may not be advantageous for long-term corn yields in soils of the Southeast.

Favorable yields under systems with high frequencies of corn could be resultant of greater residues, and subsequently more favorable soil aggregation and greater C stocks (Lal, 2005). In our silt loam soils, lack of declining yields due to continuous corn may have resulted from beneficial corn–mycorrhizal associations (Johnson et al., 1991), greater macro-invertebrate populations such as oligochaetes (Whalen and Fox, 2006), or microbiological assemblages (Turco et al., 1990). Further, over the past decade, advances in crop genetics (i.e., herbicide and insect resistant traits) and agricultural technologies may have lessened long-term yield penalties.

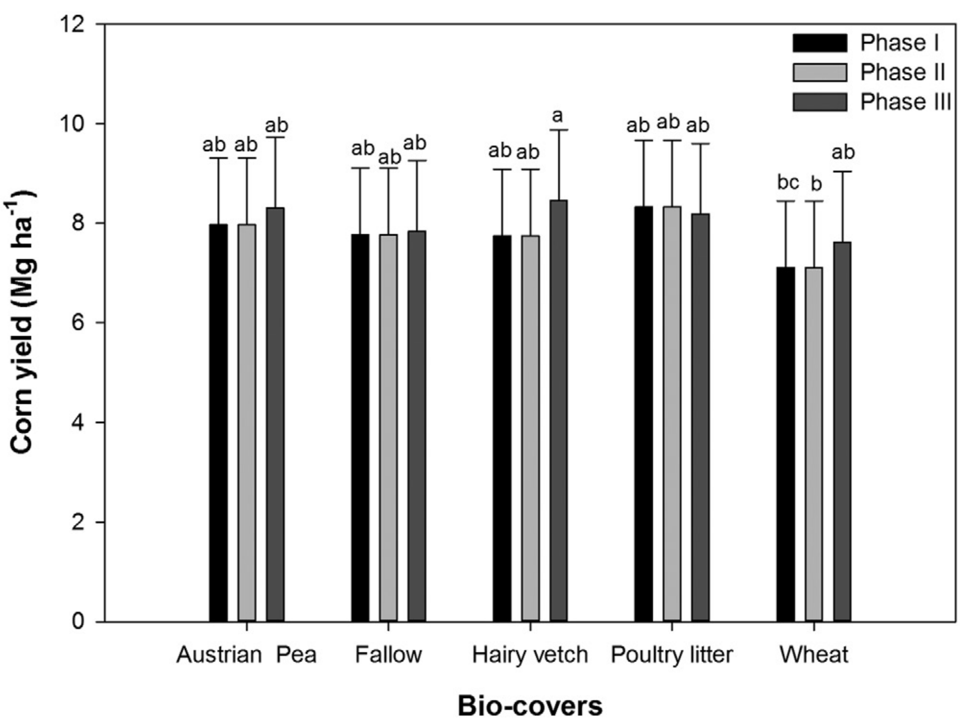

Fig. 2. Corn yields by bio-covers per phase (i.e., 3, 4-yr cycles) averaged across cropping sequence and locations [University of Tennessee Research and Education Centers at Middle Tennessee [MTREC; Spring Hill, TN] and Milan [RECM, Milan, TN]) from 2002- 2013. Vertical bars are the standard error. Experimental locations were not different (P = 0.25); whereas yield varied by phase x sequence (P = 0.022), hence the interaction is reported. Austrian winter pea was not established during Phase I of this study and was therefore had vegetation equivalent to that of the fallow treatment. Missing data occurred due to extreme drought in 2007. Different letters indicate a significant difference at an α level of 0.05; LSD = 1.76.

Table 4. Corn yields from indicated cropping sequences and bio-covers at the Research and Education Centers at Middle Tennessee (MTREC; Spring Hill, TN) and Milan (RECM, Milan, TN) locations. Yields are averaged across Phases (i.e. 3, 4-yr cycles) from 2002 to 2013.

Cropping sequence	Bio-cover	Corn yield
		Mg ha^{-1}
Continuous corn†		
	Austrian winter pea	7.55c‡
	Fallow (winter weeds)	7.68c
	Hairy vetch	7.68c
	Poultry litter	7.90bc
	Wheat	7.07c
Corn/soybean/corn/soybean†		
	Austrian winter pea	9.59a
	Fallow (winter weeds)	8.82ab
	Hairy vetch	9.00ab
	Poultry litter	8.21b
	Wheat	7.79c
Cotton/corn/cotton/corn§		
	Austrian winter pea	7.25c
	Fallow (winter weeds)	7.56c
	Hairy Vetch	8.45ab
	Poultry litter	7.19c
	Wheat	7.80bc
Corn/cotton/soybean/corn§		
	Austrian winter pea	7.49c
	Fallow (winter weeds)	7.80bc
	Hairy vetch	8.17bc
	Poultry litter	7.89bc
	Wheat	7.05c

† Averaged across both locations (RECM and MTREC) and phases.

‡ Means followed by a letter in common are not significantly different based on $P \leq 0.05$. Sequence × biocover interaction influenced yield ($P < 0.0001$); Least Significant Difference = 1.12.

§ Sequence occurred only at RECM for all phases.

CONCLUSIONS

Crop rotations and bio-covers integrated in no-tillage systems have previously resulted in increased yields; therefore, it was hypothesized that continuous corn yields would decline long-term, particularly during Phase III of this study. However, results of this 12-yr study suggest there may be minimal yield penalties from continuous corn production on soils tested herein. When averaged across phases, locations, and bio-covers, yield of continuous corn was equivalent to yield of corn averaged across all rotation combinations, although this long-term study did indicate yield benefits from increasing rotation diversity in corn production systems. Specifically, the inclusion of soybean or cotton twice within a 4-yr cropping cycle increased yields 6 and 7%, respectively, whereas including cotton and soybean once within a 4-yr cycle was analogous to that of continuous corn.

Previous research has also shown that the use of bio-covers can enhance crop yields by supplying nutrients to succeeding crops. In this study, there were yield benefits from bio-covers, particularly poultry litter and hairy vetch compared to wheat; however, none of these were different from the fallow control (excluding wheat). Therefore, strictly from a yield standpoint, wheat as a winter cover crop would not be recommended, although alternative uses such as winter grazing, hay, or baleage may warrant planting a winter cover of wheat. It was perplexing that poultry litter applications resulted in equivalent ($P > 0.05$) corn yields to that of a winter fallow, as it was hypothesized that corn would positively respond to greater P and N flushes. Furthermore, it was not expected that corn yields would be adversely affected by wheat cover crops, although this reduction could have been caused by reduced N levels as wheat is a high C/N crop. Lower soil N after winter wheat have been reported elsewhere (Kravchenko and Thelen, 2007; Dabney et al., 2001), which may have negatively impacted subsequent corn yields.

In addition to yield benefits arising from increasing cropping rotation diversity (either soybean or cotton twice within a 4-yr cropping cycle) and the integration of legume cover crops and bio-covers, subsidiary ecological benefits such as reduced nematodes, promotion of beneficial insect populations, and reduced leaching of soil nitrate to ground water may occur. Based on these 12-yr yields, a moderate to no yield penalty existed for continuous corn, whereas yield benefits can arise from cover crops (e.g., hairy vetch) and poultry litter applications compared to wheat when examined across years and locations. Consequently, ecosystem services may occur by increasing cropping rotations and bio-covers in no-tillage systems throughout the southeast.

ACKNOWLEDGMENTS

Authors extend gratitude to the directors at the Milan (Blake Brown) and Middle, TN (Kevin Thompson) Research and Education Centers (RECM and MTREC, respectively) for making this long-term research project possible. In addition, authors thank support staff including Jimmy McClure, Jason Williams, and Chris Bridges (RECM) and Roy Thompson (MTREC) for their help in data collection and field operations.

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