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Double-Crop Wheat and Soybean Yield Response to Poultry Litter Application

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Abstract

Poultry litter (PL) application and double cropping are management practices that could be used with conservation tillage to increase yields compared with conventional mono-cropping systems. The objective of this study was to evaluate winter wheat (*Triticum aestivum* L.) and soybean [*Glycine max* (L.) Merr.] yield response to PL alone and combinations of PL and inorganic N versus inorganic N alone when applied to the winter wheat in a double-cropping system. The study was conducted from 2014 to 2016 at two locations on a Marvyn loamy sand and a Lucedale fine sandy loam. Experimental design at each location was a randomized complete block design. Fertility treatments for winter wheat included an unfertilized control (PL_0N_0), inorganic N fertilizer (120 lb acre^{-1}, PL_0N_{120}), PL at the rate of 40 lb N acre^{-1} plus 80 lb acre^{-1} inorganic N ($PL_{40}N_{80}$), PL at the rate of 80 lb N acre^{-1} plus 40 lb acre^{-1} inorganic N ($PL_{80}N_{40}$), and PL at the rate of 120 lb N acre^{-1} ($PL_{120}N_0$). An unfertilized winter fallow treatment was also included to enable a comparison of yield between the mono- and double-cropped soybean. A combination of PL and inorganic N resulted in wheat yields comparable to those with inorganic N alone while PL alone yielded less. Double-cropping soybeans with winter wheat tended to improve soybean yield when compared with mono-cropped soybeans planted on the same date; however soybean yield was not consistently enhanced by the residual PL nutrients applied to wheat when compared with N fertilizer only treatment.

Poultry litter is widely used as an alternative nutrient source to inorganic fertilizer in the southeastern US. Application of PL to agricultural fields can increase soil organic matter (Watts et al., 2010b) and improve soil quality and productivity (Kingery et al., 1994), thereby enhancing crop production (Hirzel et al., 2007a; Mitchell and Tu, 2005; Reddy et al., 2004; Tewolde et al., 2009b; Watts and Torbert, 2011; Wiatrak et al., 2004;). However, unlike inorganic N fertilizer, which is 100% available for plants, litter N is mineralized slowly overtime. It is assumed that only 40 to 60% of the PL's total N will become available during the first year of application (Francesch and Brufau, 2004; Moore et al., 1998). The availability of litter N also depends on temperature; thus, it potentially changes depending on whether the litter is applied during the winter or summer months. Ruiz Diaz and Sawyer (2008) evaluated the plant availability of N from PL on corn (*Zea mays* L.) productivity and estimated the average first-year plant-available N to be 48% of the total N applied. Gordon et al. (2014) found the potentially available N coefficient for N uptake of winter wheat to be 0.31 when compared with urea ammonium sulfate regardless of PL application

Crop Management

Core Ideas

- Integration of poultry litter with inorganic N may improve wheat–soybean productivity.
- Double cropping may increase soybean grain yield compared with mono-cropping.
- Poultry litter alone was less effective on wheat production than inorganic N fertilizer.

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Abbreviations: EVS, E.V. Smith Research Center-Field Crops Unit; PAU, Prattville Agricultural Research Unit; PL, poultry litter; UAN, urea ammonium nitrate.

Conversions: For unit conversions relevant to this article, see Table A.

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Table A. Useful conversions.

To convert Column 1 to Column 2, multiply by	Column 1 Suggested Unit	Column 2 SI Unit
0.405	acre	hectare, ha
0.454	pound, lb	kilogram, kg
1.12	pound per acre, lb/acre	kilogram per hectare, kg/ha
1.12×10^{-1}	pound per acre, lb/acre	megagram per hectare, Mg/ha
2.54	inch	centimeter, cm (10^{-2} m)
1	parts per million, ppm	milligram per kilogram, mg/kg
1.609	miles, mi	kilometer, km
5/9 (°F – 32)	Fahrenheit, °F	celsius, °C
0.304	feet, ft	meter, m

timing and the total N rate applied, indicating that more than half of litter N would be available in succeeding years.

Because only a fraction of the N in PL becomes available during the year of application and other PL nutrients accumulate in soil creating a reservoir of nutrients, the residual effects of PL application may maintain subsequent crop yields. The residual effects of PL have been reported in several studies (Adeli et al., 2015; Hirzel et al., 2007b; Malik and Reddy, 2002; Nyakatawa et al., 2001; Tewolde et al., 2011). Nyakatawa et al. (2001) reported that the residual effects of applying PL at 90 lb available N acre^{-1} for 2 years to cotton (*Gossypium hirsutum* L.) under a conservation tillage system increased corn grain yield by 13% when compared with the residual effects of inorganic fertilizer. Malik and Reddy (2002) similarly reported residual effects from applying PL to cotton for 5 years increased corn grain yield when compared with urea, the year after treatment application had ceased. They reported that applying PL at 36 and 108 lb N acre^{-1} increased corn grain yield by 9 and 81% compared with the control, respectively, while urea at the same N rates produced yields that were 1 and 55% (Malik and Reddy, 2002). Adeli et al. (2015) observed increased soybean productivity the first year (no treatment application) following 3 years of banding pelletized PL to cotton while no effects were observed the second and third year after pelletized PL application ceased.

Continuous land application of PL based on a crop's N demand can lead to excessive accumulation of soil nutrients (Bolan et al., 2010; Sharpley et al., 1993; Wood et al., 1996), especially P (Chang et al., 1991; Eghball, 2002), mainly because the N/P ratio of PL is much lower (about 1:1) than the ratio of N and P (> 3:1) needed from soil by crops (Mitchell, 1999). Watts et al. (2010b) reported that long-term application of PL increased Mehlich-1 extractable P by 78% and 175% when compared with inorganic fertilizer plots for soybean and corn cropping systems, respectively. After 4 years of PL application to corn, Sistani et al. (2010a) observed that Mehlich-3 P increased from an initial 31.4 ppm to approximately 63.0 ppm for 2.0 tons PL acre^{-1} and to 178 ppm for 6.0 tons PL acre^{-1}. Repeated PL applications may also lead to negative environmental consequences such as heavy metal accumulation, contribution to greenhouse gas emissions, and transportation of N and P with surface water runoff (Pote and Meisinger, 2014; Sistani et al., 2010b; Tewolde et al., 2009a; Watts et al., 2011). Therefore, sustainable PL management practices that include combining PL with inorganic N fertilizer are needed for crop production and environmental protection.

Wheat–soybean double-cropping systems are widely practiced in the mid-southern US, including Alabama (Touchton and Johnson, 1982), Louisiana (Board and Hall, 1984), Arkansas (Caviness et al., 1986), and Mississippi (Hovermale et al., 1992). This practice can improve fertilizer use efficiency, reduce fertilizer requirements, decrease soil erosion, increase soil organic matter, and reduce soil-water losses from runoff and evaporation (Heggenstaller et al., 2008; Sanford, 1982; Wesley and Cooke, 1988). Caviglia et al. (2011) reported 58 to 82% greater yield of soybeans under double-cropping systems than mono-cropping systems, even though mono-cropped beans were sown at the optimum planting date. Nash et al. (2012) applied different N sources (ammonium nitrate, urea, and polymer-coated urea) to wheat at various application dates and rates. They found wheat yield increased with N rate, but the increases varied across N sources and application dates while N management (sources, rate, and application timing) had minimal impact on double-cropped soybean yield and seed oil and protein concentrations. Presently, there is little information about the influence of PL applications on grain production from the wheat–soybean double-cropping systems in the southeastern US. The objectives of this research were to (i) evaluate the impact of PL and combinations of PL and inorganic N on wheat productivity; (ii) compare yields from wheat–soybean double cropping to a conventional soybean mono-cropping system; and (iii) investigate residual effects of PL applications to wheat on soybean production.

Site Description

Experiments were initiated in the winter of 2014 and again in the winter of 2015 in another field area at the Alabama Agricultural Experiment Station's E.V. Smith Research Center-Field Crops Unit (EVS) in Macon County, near Shorter, AL (32°25′ N, 85°53′ W) and Prattville Agricultural Research Unit (PAU) in Autauga County, near Prattville, AL (32°25′ N, 86°26′

Table 1. Initial soil properties from the E.V. Smith Research Center (EVS) and Pratteville Agricultural Research Unit (PAU) and poultry litter properties on a dry-weight basis used for fertilization in the 2014–2015 and 2015–2016 growing seasons.

Property†	EVS soil		PAU soil		Poultry litter	
	2014–2015	2015–2016	2014–2015	2015–2016	2014–2015	2015–2016
pH (1:1 soil:water)	5.8	6.5	6.3	6.3	–	–
Moisture content (%)	–	–	–	–	17.9	18.5
Total C (%)	0.35	0.38	0.99	0.89	27.0	28.4
Total N (%)	0.03	0.05	0.90	1.00	3.78	3.58
C to N ratio	11.7	7.6	11	8.9	7.13	7.93
P (%)	0.002	0.002	0.002	0.003	1.94	1.97
K (%)	0.005	0.006	0.02	0.02	3.76	3.68
Ca (%)	0.02	0.02	0.09	0.07	4.11	3.47
Mg (%)	0.005	0.007	0.01	0.01	0.94	0.97
Na (%)	0.003	0.003	0.004	0.003	1.62	1.55
Cu (ppm)	2.18	1.36	1.46	0.99	565	716
Fe (ppm)	10.5	7.9	8.0	11.7	2222	4132
Mn (ppm)	9.9	7.8	61.0	59.8	634	655
Zn (ppm)	1.9	2.9	2.9	1.9	578	690

† P, K, Ca, Mg, Na, Cu, Fe, Mn, and Zn values represent Mehlich-1 extractable nutrient concentrations for soil and total nutrient concentrations for poultry litter.

W). Thus, the study consisted of four separate experimental sites (two sites at EVS and two sites at PAU). Different experimental sites were chosen in 2015 to prevent the cumulative effect of PL on soil nutrients from influencing yield the second year. Approximately 48 mi separates the EVS sites from the PAU sites. Soils were a Marvyn loamy sand at the EVS sites and a Lucedale fine sandy loam at the PAU sites during both years. Climate for both locations is humid subtropical with a mean annual precipitation of approximately 53.2 inches and an annual temperature of 64.4°F (Current Results, 2017). The initial soil properties for each experimental site are presented in Table 1. Before the study initiation in 2014 and 2015, the experimental plots at both research unit locations were under continuous (mono-cropped) soybean production.

Experimental Design and Treatments

The experiments were conducted as a randomized complete block design with six treatments replicated four times. Fertility treatments for the winter wheat included an unfertilized control (PL_0N_0), inorganic N fertilizer at the rate of 120 lb N acre^{-1} (PL_0N_{120}), PL at the rate of 40 lb acre^{-1} total N plus 80 lb acre^{-1} inorganic N ($PL_{40}N_{80}$), PL at the rate of 80 lb acre^{-1} total N plus 40 lb N acre^{-1} inorganic N ($PL_{80}N_{40}$), PL at the rate of 120 lb acre^{-1} total N ($PL_{120}N_0$), and unfertilized winter fallow (not cropped to wheat). At each location, the plots were 12 by 25 ft with a 4-ft buffer separating the plots within each block and a 20-ft buffer separating the blocks. The properties of the PL used for this study are shown in Table 1. Urea (46% N) was used as the inorganic N fertilizer source. All wheat fertility treatments were double-cropped with soybeans that received no N fertilization. Soybeans planted to the winter wheat fallow treatment (mono-cropped soybeans) were compared with the double-cropped wheat–soybeans. Both mono-cropped soybeans and double-cropped soybeans were planted the same date to prevent climatic variability from influencing growing conditions. Wheat grain yield at PAU was not collected in 2016 due to extensive weed pressure.

Cultural Practices

Wheat (AGS 2060; Georgia Seed Development, Plains, GA) was sown at a rate of 120 lb acre^{-1} using a Great Plains 1205NT drill (Great Plains Manufacturing, Inc., Salina, KS) in mid-November of each year for both locations (EVS and PAU). Poultry litter was applied to wheat at the time of sowing. Urea was applied to wheat in early March, except for the PL_0N_{120} treatment, in which half of the urea was applied at sowing and the other half in early March. Both PL and urea were surface-broadcast by hand. Soybeans (Pioneer 96M60 in 2015 and Pioneer 95M70 in 2016; DuPont Pioneer, Johnston, IA) were sown at a rate of 70 lb acre^{-1} in mid-June of each year using the same drill. On the day of planting, soybeans were

Table 2. The application rate of inorganic nitrogen (N), phosphorus (P), and potassium (K) to wheat and soybean for each treatment in 2015 and 2016 for the E. V. Smith Research Center (EVS) and the Prattville Agricultural Research Unit (PAU).

Treatment	Wheat			Soybean		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
	lb acre^{-1}					
Fallow	–	–	–	–	40	40
P_0N_0	0	40	40	–	40	40
P_0N_{120}	120	40	40	–	40	40
$P_{40}N_{80}$	120	47, 50†	48, 49	–	40	40
$P_{80}N_{40}$	120	94, 101	96, 99	–	0	0
$P_{120}N_0$	120	141, 151	144, 148	–	0	0

† The values are for 2015 and 2016 study year, respectively, due to the different nutrient properties of poultry litter used in these 2 yr.

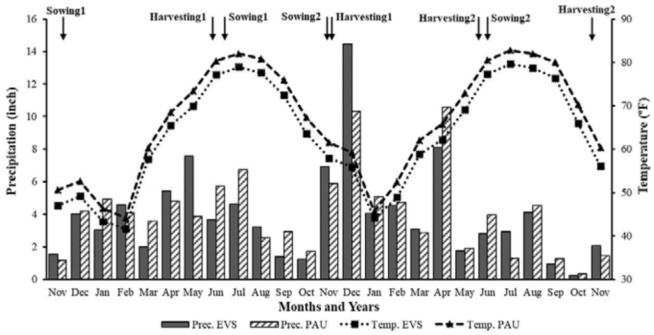

Fig. 1. Monthly average air temperature and precipitation totals at the Alabama Agricultural Experiment Station's E. V. Smith Research Center (EVS) and Prattville Agricultural Research Unit (PAU) for 2014, 2015, and 2016. Sowing1 and Harvesting1 are for the wheat–soybean production in 2014–2015, and Sowing2 and Harvesting2 are for the repeated wheat–soybean production in 2015–2016.

inoculated with *Bradyrhizobium japonicum*. No N fertilizer (PL or urea) was applied to the soybean crop. Triple superphosphate (0–46–0) and KCl (0–0–60) were applied to the PL_0N_0 and P_0N_{120} treatments at wheat sowing and to all treatments at soybean sowing according to Auburn University's soil-testing recommendations. The amount of inorganic P and K applied for each treatment at both locations is shown in Table 2. Both wheat and soybean were sown using a 7.5-inch spacing, resulting in there being 19 rows per plot.

Data Collection

During the growing season, 10 plants, randomly chosen within each plot, were used to determine plant height when wheat reached tillering (Feeke's 2.0-3.0), late stem extension (Feeke's 7.0–8.0), and the late heading (Feeke's 10.5) stages and when soybean reached the full seed (R6) to beginning maturity (R7) stage. Plant height was determined by measuring from the soil surface to highest growing point of the main stem. Wheat was harvested each year during the beginning of June and soybean during the beginning of November. Wheat and soybean grain yield was determined by mechanically harvesting a 5-ft wide by 25-ft long swath from the central area of each plot using an ALMACO SPC 40 plot combine (ALMACO, Nevada, IA, USA) at EVS and a Massey Ferguson 8XP plot combine (Massey Ferguson, Duluth, GA, USA) at PAU. Wheat grain weights were adjusted to a moisture content of 13.5% and soybean grain to a moisture content of 13%. Precipitation and air temperature data were collected from weather stations located at each experimental site.

Data Analysis

Wheat and soybean data analyses were performed separately using the MIXED procedure of SAS 9.4 (SAS Institute Inc., 2013). Significant interactions ($P \leq 0.05$) were detected between locations (EVS and PAU) and two study years (2014–2015 and 2015–2016) for both wheat and soybean yield. Thus, data for each cropping systems and experimental location were analyzed separately by year. Mean separation was conducted using the LSMEANS statement in proc mixed, and Tukey's honest significant difference test at a 0.05 probability level was used to identify significant differences among treatments. Wheat grain yield at PAU in 2016 was not included in our final analysis due to extensive weed pressure.

Weather Conditions

Generally, monthly temperatures among growing seasons were normal and did not deviate much (more than 2 to 3 degrees) from the 30-year average during the course of this study (Fig. 1). In contrast, precipitation varied markedly among the 2 years of study. The EVS location had total rainfall of 48.3 inches in 2014–2015 with 28.0 and 16.4 inches during the wheat and soybean growing seasons, respectively, and 50.2 inches in 2015–2016 with 36.0 and 10.5 inches during the wheat and soybean growing seasons, respectively. The PAU location had total rainfall of 49.2 inches in 2014–2015 with 27.5 and 16.9 inches occurring during the wheat and soybean growing seasons, respectively, and 51.3 inches in 2015–2016 with 35.5 and 10.6 inches during the wheat and soybean growing seasons, respectively. This resulted in a wetter wheat growing season and drier soybean growing season in 2016 versus 2015.

Wheat Growth and Grain Yield Responses to Fertilization

Plant height of wheat varied with treatment, year, and location and was inconsistently affected by the PL and inorganic N treatments relative to the unfertilized control at the various growth stages (Table 3). Combining PL and inorganic N often resulted in taller plants, especially with the $PL_{80}N_{40}$ treatment at PAU in 2016 at the late stem extension (T2, the end of March) when plant height was up to 81% greater compared with the unfertilized control and 45% greater compared with the inorganic N treatment. The single PL ($PL_{120}N_0$) application resulted in taller plants than that of the unfertilized control at the T2 growth stage, except at EVS in 2015, but the difference at PAU in 2015 was no longer significant at the late heading stage (T3). Still, $PL_{120}N_0$ influence on plant height was not always as great as the other fertilization treatments at T3, sometimes resulting in shorter plants than the inorganic N or the combined PL and inorganic N application treatments. This response may be due to slow mineralization of litter N not being able to satisfy the high N requirement of wheat during the stem elongation stage, with potentially only 40 to 60 kg N ha^{-1} available from PL in the first year (Francesch and Brufau, 2004; Moore et al., 1998).

Table 3. Response of plant height (inches) measured at the various growth stages for cropping system and fertilizer sources at the E. V. Smith Research Center (EVS) and the Prattville Agricultural Research Unit (PAU) in 2015 and 2016.

Site	Treatment	Wheat					Soybean	
		2015			2016		2015	2016
		T1†	T2	T3	T2	T3		
EVS	Fallow	–	–	–	–	–	19.7 ± 0.48	14.5 ± 0.29 c
	PL_0N_0	4.45 ± 0.17 ab‡	18.4 ± 0.55	32.9 ± 0.60 b	16.0 ± 0.55 c	20.6 ± 0.44 d	19.7 ± 0.47	14.9 ± 0.32 c
	PL_0N_{120}	4.06 ± 0.17 c	19.8 ± 0.52	35.6 ± 0.49 a	17.6 ± 0.57 bc	24.5 ± 0.43 b	19.9 ± 0.43	15.7 ± 0.37 bc
	$PL_{40}N_{80}$	3.65 ± 0.24 c	19.1 ± 0.56	34.6 ± 0.46 ab	18.7 ± 0.50 b	25.1 ± 0.38 b	18.5 ± 0.45	17.0 ± 0.56 ab
	$PL_{80}N_{40}$	4.81 ± 0.28 ab	20.1 ± 0.46	35.9 ± 0.51 a	21.5 ± 0.49 a	26.9 ± 0.34 a	18.2 ± 0.47	17.8 ± 0.50 a
	$PL_{120}N_0$	4.89 ± 0.17 a	18.6 ± 0.56	33.1 ± 0.55 b	18.6 ± 0.60 b	22.3 ± 0.46 c	19.7 ± 0.47	15.8 ± 0.27 bc
PAU	Fallow	–	–	–	–	–	23.2 ± 0.35 B	25.2 ± 0.74 B
	PL_0N_0	5.20 ± 0.17	8.4 ± 0.61 B	33.3 ± 0.47 B	9.81 ± 0.46 D	15.5 ± 0.39 C	26.3 ± 0.39 A	27.2 ± 0.45 AB
	PL_0N_{120}	5.28 ± 0.25	20.4 ± 0.36 A	36.5 ± 0.36 A	12.3 ± 0.33 C	22.3 ± 0.85 AB	26.2 ± 0.43 A	27.7 ± 1.01 AB
	$PL_{40}N_{80}$	5.12 ± 0.18	20.4 ± 0.43 A	36.1 ± 0.30 A	15.4 ± 0.48 B	23.4 ± 0.42 A	27.3 ± 0.47A	26.6 ± 0.69 AB
	$PL_{80}N_{40}$	5.71 ± 0.23	21.5 ± 0.41 A	36.1 ± 0.91 A	17.8 ± 0.52 A	24.0 ± 0.36 A	26.8 ± 0.43 A	26.9 ± 0.66 AB
	$PL_{120}N_0$	5.67 ± 0.24	20.5 ± 0.61 A	35.2 ± 0.49 AB	18.3 ± 0.59 A	20.8 ± 0.60 B	26.9 ± 0.35 A	28.1 ± 0.86 A
		P > F						
EVS		< 0.0001	0.0583	< 0.0001	< 0.0001	< 0.0001	0.0314	< 0.0001
PAU		0.0944	0.0004	0.0002	< 0.0001	< 0.0001	< 0.0001	0.0482

†T1, tillering stage; T2, late stem extension stage; T3, late heading stages. For 2016, the wheat height at T1 was too small to measure; thus, no data are presented at this growth stage.

‡Means and standard errors within a column followed by the same letter or with no letter assignment are not significantly different at P < 0.05. Lowercase and uppercase letters show multiple comparisons of treatments at the EVS and PAU locations, respectively.

Wheat plant height, averaged across treatments and location, at the T3 stage was significantly greater in 2015 than 2016 (34.9 vs. 22.5 inch). This difference was likely due to greater and more even distribution of rainfall in 2015, resulting in improved soil moisture availability during the growing season (Fig. 1).

Plant height is an important trait for determining the performance of a wheat crop. In particular, a shorter plant is often associated with an earlier ear emergence, leading to a reduction in grain yield (Law et al., 1978) while tall plants are more susceptible to lodging (Berry et al., 2003). In this study, application of PL plus urea ($PL_{80}N_{40}$ and $PL_{40}N_{80}$) and urea alone (PL_0N_{120}) typically produced taller plants and greater grain yield when compared with unfertilized control and the PL alone ($PL_{120}N_0$). This suggests that the plant height under the $PL_{80}N_{40}$ treatment might be appropriate for wheat productivity, and a similar level of grain yield can be achieved with either a combination of PL and inorganic N application or conventional inorganic fertilizer application that provided 120 lb acre^{-1}N.

There were significant treatment × year (P = 0.0013) and treatment × location (P = 0.0313) interactions for wheat grain yield. These interactions reflect the impact of rainfall and soil properties on crop performance. Thus, results are presented and discussed separated by year and location when such interactions occurred.

Inorganic N (PL_0N_{120}) and treatments with PL combined with inorganic N (i.e., $PL_{40}N_{80}$, $PL_{80}N_{40}$) had the highest grain yield in 2015 at both locations (Table 4). Compared with the unfertilized control in 2015, the PL_0N_{120} treatment significantly increased grain yield by 135 and 131% at EVS and PAU, respectively, and the $PL_{80}N_{40}$ treatment increased grain yield by 119 and 111% at EVS and PAU, respectively. No differences were observed at EVS in 2016 due to variability among treatments and very low yields, and the wheat was not harvested in PAU in 2016 due to extensive weed pressure. The increased variability among treatments at EVS and increased weed pressure at PAU most likely occurred as a result of higher-than-normal rainfall during the 2016 growing season (e.g., EVS had more than 14 inches of rainfall in December 2015). Savala et al. (2016) found similar results in a 2-year field experiment in North Carolina. They observed greater wheat yield when poultry manure (60

Table 4. Effect of poultry litter and urea application on wheat grain yield (lb acre^{-1}) for 2015 and 2016 at the E.V. Smith Research Center (EVS) and Prattville Agricultural Research Unit (PAU).

Treatment	EVS		PAU†	Mean
	2015	2016	2015	
PL_0N_0	1266 ± 181 b‡	609 ± 140	1940 ± 223 b	1271 ± 190
PL_0N_{120}	2973 ± 182 a	990 ± 198	4485 ± 261 a	2816 ± 446
$PL_{40}N_{80}$	2372 ± 394 a	1016 ± 149	4076 ± 82.6 a	2488 ± 399
$PL_{80}N_{40}$	2777 ± 301 a	1323 ± 264	4097 ± 176 a	2733 ± 366
$PL_{120}N_0$	1510 ± 87.6 b	694.0 ± 124	2681 ± 292 b	1628 ± 265
	P > F			
	< 0.0001	0.1195	< 0.0001	–

† No wheat yield data are presented for PAU in 2016 due to extensive weed pressure.

‡ Means and standard errors within a column followed by the same letter or with no letter assignment are not significantly different at P < 0.05.

Table 5. Effect of poultry litter and urea application and cropping system on soybean grain yield (lb $acre^{-1}$) for 2015 and 2016 at E.V. Smith Research Center (EVS) and Prattville Agricultural Research Unit (PAU).

	EVS		PAU		
Treatment	2015	2016	2015	2016	Mean
Fallow	649.9 ± 103 b†	334.0 ± 103	1522 ± 36.4	1538 ± 113	1014 ± 143
PL_0N_0	1137 ± 85.6 a	162.9 ± 46.9	1712 ± 24.2	1462 ± 46.7	1162 ± 159
PL_0N_{120}	1282 ± 111 a	310.6 ± 82.8	1684 ± 90.2	1376 ± 207	1251 ± 149
$PL_{40}N_{80}$	1200 ± 117 a	160.1 ± 56.4	1722 ± 64.0	1671 ± 337	1227 ± 180
$PL_{80}N_{40}$	1129 ± 84.2 a	369.7 ± 211	1826 ± 63.7	1611 ± 164	1292 ± 153
$PL_{120}N_0$	1150 ± 36.3 a	154.2 ± 35.2	1676 ± 143	1662 ± 146	1197 ± 170
	P > F				
	0.0013	0.5328	0.1329	0.8749	–

†Means and standard errors within a column followed by the same letter or with no letter assignment within a column are not significantly different at P < 0.05.

lb $acre^{-1}$ N) was applied in combination with urea ammonium nitrate (UAN, 60 lb $acre^{-1}$ N) while applying PL only had the lowest grain yield when compared with the other fertilizer treatments and was not significantly different from the control. Because nutrient mineralization of manure when applied to soil is microbially driven, it can be influenced by abiotic factors such as soil temperature, soil moisture, and soil properties (Eghball et al., 2002). Watts et al. (2010a) evaluated the seasonal influence of N mineralization from soil amended with composted dairy manure and reported N mineralization was minimal during winter months. Other researchers have shown N mineralization decreases with decreasing temperature (Cassman and Munns, 1980; Eghball, 2000; Watts et al., 2007). Therefore, lower yields with PL only could be related to the slow mineralization capacity of the litter not being able to supply enough plant-available N during the growing season (Rasnake, 2002); thus, the N requirement of wheat was not satisfied.

Soybean Growth and Yield Response Double Cropping and Fertilization

Soybean height under wheat–soybean double cropping was significantly greater than that under the winter fallow treatment in 2015 at PAU and in 2016 for $PL_{40}N_{80}$ and $PL_{80}N_{40}$ at EVS and $PL_{120}N_0$ at PAU (Table 3). Soybean height tended to be higher in plots receiving PL, regardless of the rate of PL received compared with the control plots or plots that received inorganic N for the preceding wheat crop in 2016 at EVS. Plants in the single PL application ($PL_{120}N_0$) plots were 16 and 12% taller than the winter fallow control plots at PAU in 2015 and 2016, respectively. The $PL_{40}N_{80}$ and $PL_{80}N_{40}$ plots were 17 and 23% taller than those in winter fallow control plots, respectively, and 14 and 19% taller than the unfertilized winter wheat control plots at EVS in 2016, respectively. Moreover, the $PL_{40}N_{80}$ and $PL_{80}N_{40}$ plots also increased soybean plant height by 18 and 16% compared with the winter fallow control at PAU in 2015. Our results were consistent with Adeli et al. (2015), who reported soybean plants grown in plots that received pelletized broiler litter in spring of the preceding 3 years were significantly taller than plants in the unfertilized control or inorganic N plots. The present study suggests applying poultry litter to a winter crop may also positively benefit the succeeding summer crop in a double cropping system.

Statistical analysis for soybean grain yield indicated significant treatment × year (P = 0.0138) and treatment × year × location interactions (P < 0.0001). These interactions reflected the impact of climatic conditions and soil properties on crop performance. As a result, data are presented and discussed separately by year and location when such interactions occurred.

Average soybean yield was greater in 2015 (1391.5 lb $acre^{-1}$) than 2016 (901.0 lb $acre^{-1}$) (Table 5), probably due to increased and more evenly distributed rainfall during the summer growing season (Fig. 1). In 2016, yield at EVS was considerably lower than average. Overall, soybean grain yield was greater at PAU (1621.9 lb ha^{-1}) than EVS (670.7 lb ha^{-1}), probably due to more favorable soil texture (Table 1), which has a higher water- and nutrient-holding capacity that may have reduced the impact of low and irregular rainfall in 2015.

Soybean yield was 74 to 97% greater in the wheat–soybean double cropping compared with the winter fallow–soybean mono-cropping system in 2015 at EVS while a cropping system difference was not detected in 2016 at EVS or in either year at PAU (Table 5). Caviglia et al. (2011) reported no yield difference between mono- and double-cropped soybean productivity if the seed was sown on the same date. A long-term field study found soybean yield varied through the years with mono-cropped soybeans producing greater yields than that of no-till double-cropped soybeans in 6 of 11 years, which was attributed to seasonal differences in rainfall and temperature (Crabtree et al., 1990). Results from Crabtree et al. (1990) suggest double-cropping could potentially increase soybean productivity under appropriate weather conditions (adequate rainfall), which may be due to the previous wheat crop protecting the soil by serving as cover during winter months and the residual wheat nutrients enhancing the soil nutrient levels for soybean growth in summer.

No significant soybean grain yield differences were observed among N sources (Table 5). Watts and Torbert (2011) reported soybean grain yield increased in 8 out of 9 years when poultry litter was applied to a fine sandy loam (Appalachian Plateau region). When soybean was planted in a loam soil (Blackland Prairie region) following 3-year pelletized broiler litter applications to cotton, soybean productivity increased in the first year after the last application but not the following 2 or 3 years when compared with residual UAN application (Adeli et al., 2015). The present study shows that residual effects of a single application of PL to winter wheat may not increase the double-cropped soybean grain yield on a Coastal Plain soil (less productive than the Appalachian Plateau and Blackland Priarie soil).

Implications

Compared with inorganic N fertilizer, a single application of PL was less effective on winter wheat yield, likely due to the litter's slow N mineralization rate. A combination of PL and inorganic N produced wheat yields equivalent to or greater than that of inorganic N application, and the residual nutrients from PL additions slightly enhanced soybean productivity. Wheat–soybean double cropping improved soybean growth and yield compared with the fallow–soybean mono-cropping system, which may be due to the wheat protecting the soil during winter months and the residual nutrients from the winter wheat crop enhancing soil productivity for soybean growth. Therefore, a combination of PL and inorganic N fertilizer use for a wheat–soybean cropping system could potentially provide sustainable yield production.

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