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RESEARCH

Effects of Enhanced Efficiency Fertilizers on Cotton Growth Characteristics

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Abstract

Use of enhanced-efficiency N fertilizers (EENFs) in row crop agriculture has not been well studied despite increasing interest in these N sources to increase crop yield while decreasing N loss. A field study was conducted in Central Alabama from 2009 to 2011 to compare EENFs to standard N sources in a high-residue conservation cotton production system. Nitrogen fertilizers evaluated were: urea; ammonium sulfate; urea-ammonium sulfate; controlled-release, polymer-coated urea (Environmenally Smart Nitrogen, ESN); stabilized urea (SuperU); poultry litter; poultry litter + AgrotainPlus; and an unfertilized control. Detailed plant growth characteristics were determined before defoliation. Generally, standard fertilizers resulted in the largest number of bolls and the highest boll dry weight. ESN tended to perform as well as the standards. Both poultry litter treatments performed poorly during the first year; however, poultry litter + AgrotainPlus was similar to the standards by the third year of study. In this study, the more expensive EENFs produced yields similar to those of standard fertilizers, suggesting that the former may be economically impractical at present. However, EENFs could become viable alternative fertilizer sources given their ability to reduce N loss from agricultural fields via leaching, runoff, and nitrous oxide flux. Additional research is needed on the benefits of EENFs in row-crop production systems.

USDA-ARS, National Soil Dynamics Lab., 411 S. Donahue Dr., Auburn, AL 36832. Mention of trade names or commercial products in this article are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA-ARS. USDA is an equal opportunity provider and employer. Received 20 Dec. 2013. *Corresponding author (brett.runion@ars.usda.gov).

Abbreviations: AS, ammonium sulfate; EENF, enhanced-efficiency N fertilizer; ESN, Environmentally Smart Nitrogen; GHG, greenhouse gas; NUE, nutrient use efficiency; PL, poultry litter; PLA, poultry litter + AgrotainPlus; SU, SuperU; U, urea; UAS, urea-ammonium sulfate.

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NITROGEN is a critical element needed for many important plant metabolic processes such as amino acid and protein synthesis. Since N is often the most limiting nutrient in agricultural production systems, additions of this vital nutrient help maximize yields. In the past, organic N sources (manures and legume rotations) were used in agricultural production systems; these have largely been replaced by synthetic N sources throughout most of the developed world (Smil, 2001). From 1961 to 2006, worldwide use of synthetic N increased from 11.6 to 104 million tonnes (Food and Agriculture Organization, 2009). As the world's population continues to grow, finding new and more efficient methods to meet N demand becomes increasingly crucial for agriculture.

Nitrogen nutrient use efficiency (NUE) is estimated at 30 to 50% for most agricultural systems (Delgado, 2002), and current N fertilization recommendations often exceed plant demand (Mulvaney et al., 2009). These factors leave the excess N subject to runoff and leaching, which pose risks to the environment and to human health (Spalding and Exner, 1993). Excess N can also be lost as nitrous oxide, a potent greenhouse gas (GHG) contributing to global climate change.

Synchronizing N application with plant uptake as a means of reducing N losses is a top priority among agricultural researchers (Balkcom et al., 2003). Further, reducing N losses by the use of EENFs is being assessed (Halvorson et al., 2013). Enhanced-efficiency N fertilizers include slow-release, controlled-release, and stabilized N sources developed to better synchronize N release with plant uptake. These types of fertilizers have been restricted to high-value systems such as horticultural crops and turf (Hauck, 1985). However, some EENFs may be economically viable for use in row-crop agriculture due to advances in fertilizer technologies (Halvorson et al., 2013). Environmentally Smart Nitrogen (Agrium Advanced Technologies, Loveland, CO) is a controlled-released urea fertilizer with a water-permeable polymer coating that allows gradual release of N during the growing season, when N release increases with moisture and temperature. AgrotainPlus (Agrotain International, St. Louis, MO) is a fertilizer supplement containing both urease [N-(n-butyl)-thiophosphoric triamide] and nitrification inhibitors (dicyandiamide). Super U (SU; Agrotain International, St. Louis, MO) is a stabilized urea source containing the same urease and nitrification inhibitors as AgrotainPlus that are uniformly distributed throughout the granule during the manufacturing process.

Renewed interest in use of manures has recently occurred due to the need to deal with large amounts generated by animal production systems and to the increasing cost of synthetic N fertilizers. The poultry industry in the United States generates about 11.4 million tonnes of broiler litter (a mixture of manure, feed, and organic bedding material such as peanut hulls or sawdust) each year (Mitchell and Tu, 2005). Land application of manure provides a nutrient source for agricultural crops, increases soil organic matter, and serves as a viable means for its disposal. However, there are concerns that land application of manure to row crops may result in water contamination through leaching and runoff (Williams et al., 1998) as well as increased emissions of the potent GHGs methane and nitrous oxide (Sistani et al., 2010). Use of nitrification and urease inhibitors, such as AgrotainPlus, with manure before land application may reduce N losses and improve NUE.

Alternative N sources, such as EENFs, have been investigated in high-value crops such as vegetables (Guertal, 2000); however, effects in row crops are only beginning to be studied (Nelson et al., 2009; Halvorson et al., 2011). This is critical since their use will not be adopted by producers until the effects on crop yields are elucidated, regardless of the potential environmental benefits. While better synchronization of N release with plant demand should increase crop growth and yield, this subject remains understudied. More research is needed to determine the response of differing crop systems under varying conditions since N release and plant uptake are known to vary by crop species, N source, climate, and soil type (Nelson et al., 2009; Cahill et al., 2010). The objective of this study was to evaluate the effects of differing N sources (standard inorganics, EENFs, and poultry litter) on cotton growth characteristics in the southeastern United States.

MATERIALS AND METHODS

Site Description

A field experiment was conducted at the Alabama Agricultural Experiment Station's E.V. Smith Research Center (32°25′19″ N, 85°53′7″ W) near Shorter, AL, USA from 2009 to 2011. The soil was a Marvyn loamy sand (fine-loamy, kaolinitic, themic Typic Kanhapludult), typical of the Southern Coastal Plains, which consists of deep, well-drained, moderately permeable soils formed from loamy marine sediment. The soil had an organic matter content of 6.3 g/kg, an average pH of 6.4, and a textural analysis of approximately 81, 4, and 5% sand, silt, and clay, respectively. Mean annual precipitation is approximately 1350 mm and average annual temperature is 18°C (Current Results, 2013), yielding a humid subtropical climate.

Experimental Design and Treatments

A randomized complete block design was used with four replicate blocks based on slope. Nitrogen fertilizer treatments evaluated were as follows: urea (U; 46% N); ammonium sulfate (AS; 21% N); urea ammonium sulfate (UAS; 34% N); SuperU (SU; 46% N); ESN (44% N); poultry litter (PL; 4% N); poultry litter + AgrotainPlus (PLA; 4% N); plus an unfertilized control (C). The poultry litter (Table 1) used in this study was collected from a local poultry production facility and consisted of poultry manure and a bedding-material mixture of wood shavings and/or sawdust. The PLA treatment consisted of surface broadcasting poultry litter followed by AgrotainPlus (0.5 g/kg poultry litter) applied on top of the litter with a six-nozzle handheld boom attached to an electricity-powered sprayer. All fertilizers were surface broadcast applied by hand at a rate of 101 kg total N/ha.

The experimental site was farmed with no-till management using cereal rye (*Secale cereale* L.) as winter cover and cotton (*Gossypium hirsutum* L.) as the primary row crop. Rye was planted in November of each year at a rate of 100 kg/ha with a no-till grain drill and was killed each spring (7-10 days before planting cotton) with an application of glyphosphate (N-phosphosnomethyl glycine) at a rate of 1.15 kg a.i./ha followed by rolling. Cotton was planted at a rate of 17 seeds/m row each year. Deltapine

Table 1. Poultry litter chemical characteristics on a dry-weight basis.

Season	Moisture	C	N	P	K	Ca	Mg	Fe	Cu	Mn	Zn
	%			g/kg				mg/kg			
2009	15.1	34.4	40.4	20.6	42.1	32.7	11.0	3199	6430	596	620
2010	27.6	33.6	38.5	15.4	34.2	28.0	8.9	1443	244	440	358
2011	16.5	32.9	35.6	15.9	32.4	25.7	13.4	4931	203	843	464

454 BT Stack was planted on 12 June in 2009, Photogen 375 was planted on 13 May in 2010, and Deltapine 0949 BT 2 Roundup Flex was planted on 17 May in 2011.

Each experimental unit consisted of four planted rows spaced 1.01 m apart in 4.08-m by 7.62-m (31 m^2) plots. Plots within blocks were separated by a 1.01-m buffer (one unfertilized cotton row) and blocks were separated with a 7.6-m unfertilized alley. Nitrogen fertilizers were applied 5 to 6 weeks after sowing each year. Herbicides and insecticides were applied to cotton as needed based on Alabama Cooperative Extension System's recommendations. During periods of drought, cotton received supplemental irrigation as needed via an overhead lateral irrigation system. Cotton was chemically defoliated, and a boll opener was applied when 60 to 70% of the bolls were opened. After harvesting each year, cotton stalks were shredded with a rotary mower.

Harvest

Detailed cotton growth measurements were determined 3 to 4 weeks before chemical defoliation. A 1.52-m piece of plastic pipe was arbitrarily thrown into each of the outer two rows in each plot; all plants along the pipe length were cut at the ground line with handheld pruning shears. Bolls were removed by hand from all plants in each plot and placed into cloth bags in the field. Plants were then bagged by plot, returned to the laboratory, and placed into walk-in cold rooms (4°C) until detailed measurements were made. Bolls were counted and plant height recorded. Ground-line diameter of each plant was measured with high-precision digital calipers. Bolls and remaining aboveground plant parts were placed in separate paper bags and dried to a constant weight at 55°C in a forced-air drying oven.

Two additional plants in each outer row (four per plot) were randomly selected for vertical root-pulling resistance (Böhm, 1979; Prior et al., 1995). A manual winch (Model 527, Fulton, Milwaukee, WI) mounted on a portable metal tripod and a cable gripping tool (Model 72285K8, Klein Tools, Chicago, IL) attached to the cotton stalk were used to break the roots from soil. A scale (Model 8920, Hanson Northbrook, IL) was used to measure the peak force (load kg/plant) required to uproot the plant. The removed roots were soaked in water, washed free of soil with a soft bristle brush, placed in paper bags, and dried to a constant weight at 55°C in a forced-air drying oven. Undoubtedly, this extraction technique did not recover the entire root system; however, since cotton is a strongly tap-rooted plant, the majority of the root weight was recovered with this method. Further, as the same technique was employed for all plants, the relative amount of coarse roots removed should be comparable among treatments.

Data Analysis

Data analysis was conducted with the mixed model procedures (Proc Mixed) of the Statistical Analysis System (Littell et al., 1996). Error terms appropriate to the randomized block design were used to test the significance among years, N fertilizer treatments, and the interaction of Year × N. Height, diameter, and vertical root-pulling resistance data were averaged for each plot before analysis; all other data were totaled for each plot and placed on a per hectare basis before analysis. Means were separated with the PDIFF option of the LSMEANS statement; a significance level of $\alpha = 0.10$ was established a priori. Due to fact that there was structure within the N treatments (i.e., there was a group of three common inorganic N fertilizers and a group of three EENFs), we did not make adjustments (e.g., Fisher's Protected LSD) for multiple comparisons, which made it possible to find statistical separation among the 8 N treatments even when the effect of N alone or Year × N was not significant.

RESULTS AND DISCUSSION

Climatic Conditions

Rainfall and temperature were sufficient each year to produce an adequate cotton crop despite year-to-year variations (Fig. 1). Precipitation, measured at the Alabama Agricultural Experiment Station's E.V. Smith Research Center, totaled 832, 402, and 482 mm across the growing seasons in 2009, 2010, and 2011, respectively. Differences in rainfall percentages among these growing seasons ranged from 37% above to 34% below the 30-year average (Current Results, 2013). Average air temperatures were 24.2, 27.6, and 25.1°C for 2009, 2010, and 2011, respectively (Fig. 1), and did not deviate more than 1°C from the 30-year average during the course of this study, except in 2010 which was 15% above average.

Height and Diameter

Plants were shorter in 2010 than in the other 2 years (Table 2), probably as a result of low rainfall during vegetative growth. As expected, the addition of fertilizer, regardless of source, increased cotton height compared to the unfertilized control averaged across all 3 years (Table 3). Plants receiving the standard fertilizers (AS and UAS) tended to be tallest, those receiving PLA and ESN were also among the tallest, while those treated with PL and SU were among

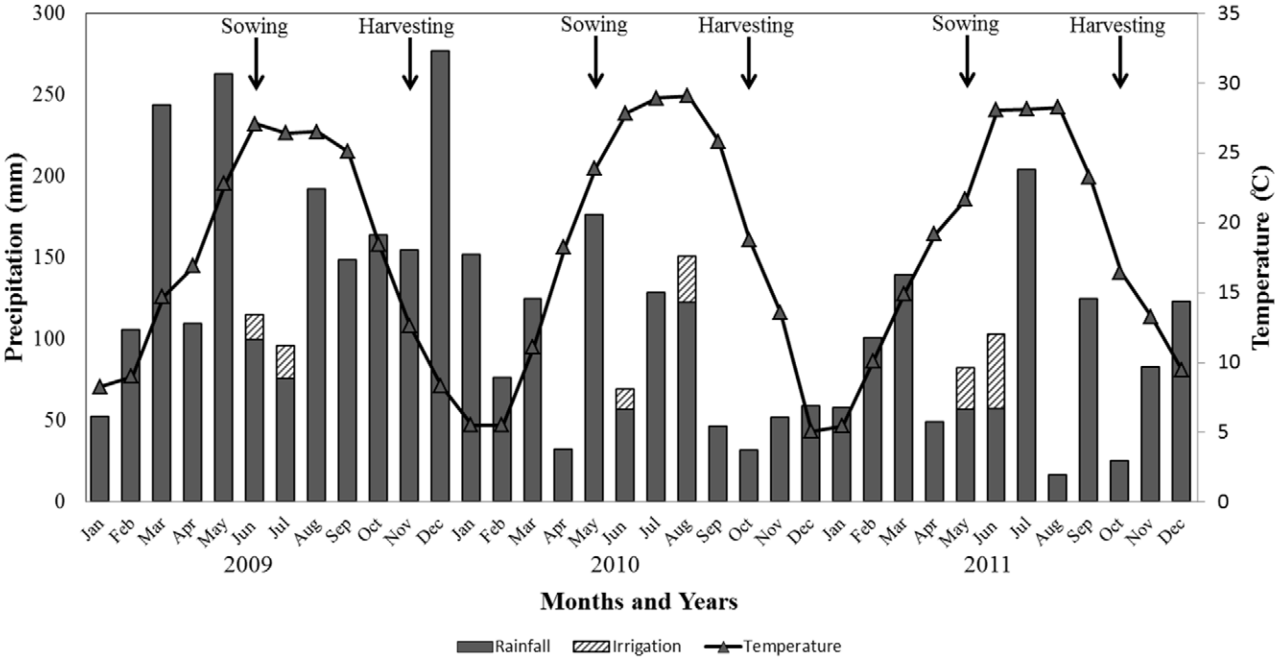


Figure 1. Monthly air temperature and rainfall totals at the Alabama Agricultural Experiment Station's E.V. Smith Research Center for 2009, 2010, and 2011.

Table 2. Characteristics of cotton averaged across all N treatments for the 2009, 2010, and 2011 growing seasons.

Season	Height	GLD†	Pull force	Bolls/plant	Bolls/ha	Boll dry weight/plant	Boll dry weight/boll
	cm	mm	kg/plant	no.	no. × 10^5	g	
2009	100.1 b‡	9.9 b	33.0 b	6.13 b	8.80 b	24.2 b	3.94 b
2010	76.3 c	8.2 c	57.5 a	9.57 a	11.20 a	25.3 b	2.75 c
2011	102.6 a	11.2 a	25.8 c	9.41 a	6.95 c	42.3 a	4.51 a
P > *F*	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

†GLD, ground-line diameter.

‡Values within a column followed by the same letter are not significantly different at α = 0.10.

Table 3. Characteristics of cotton grown using N sources—urea (U), ammonium sulfate (AS), urea ammonium sulfate (UAS), Environmentally Smart Nitrogen (ESN), Super U (SU), poultry litter + AgrotainPlus (PLA), poultry litter (PL)—and unfertilized control (C) averaged across the three growing seasons.

Treatment	Height	GLD†	Pull force	Bolls/plant	Bolls/ha	Boll dry weight/plant	Boll dry weight/boll
	cm	mm	kg/plant	no.	no. × 10^5	g	
U	92.2 cde‡	9.7 bc	39.4 ab	8.03 bc	8.98 c	29.3 bcd	3.72 bc
AS	99.6 a	10.0 bc	39.9 ab	9.68 a	10.42 a	31.6 abc	3.47 c
UAS	98.2 ab	10.1 b	41.4 a	9.52 a	10.14 ab	33.8 a	3.61 bc
ESN	94.8 bcd	9.8 bc	37.9 bc	8.89 ab	9.35 bc	33.8 a	3.87 ab
SU	89.6 e	9.6 c	39.6 ab	8.17 bc	9.16 c	27.8 cd	3.61 bc
PLA	95.2 bc	10.5 a	38.7 ab	8.90 ab	8.65 c	33.5 ab	3.74 abc
PL	90.9 de	9.6 c	38.0 bc	7.19 cd	7.73 d	27.7 cd	3.85 ab
C	83.4 f	8.6 d	35.3 c	6.57 d	7.42 d	26.4 d	4.00 a
P > *F*	<0.001	<0.001	0.036	<0.001	<0.001	0.003	0.007

†GLD, ground-line diameter.

‡Values within a column followed by the same letter are not significantly different at α = 0.10.

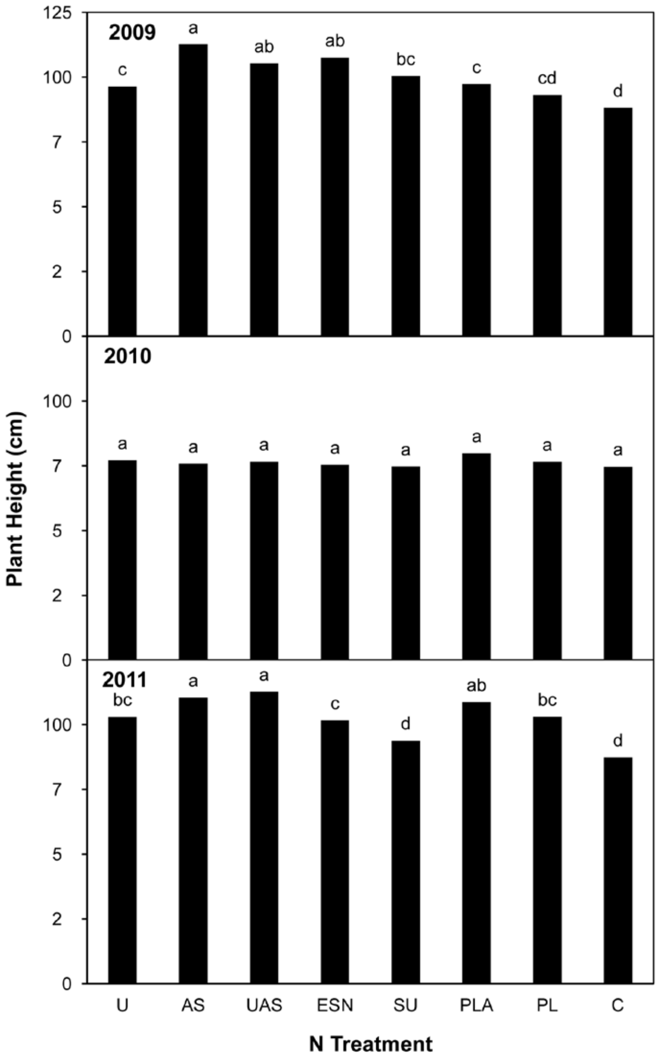


Figure 2. Cotton plant height for N sources—urea (U), ammonium sulfate (AS), urea-ammonium sulfate (UAS), Environmentally Smart Nitrogen (ESN), Super U (SU), poultry litter + AgrotainPlus (PLA), poultry litter (PL)—and unfertilized control (C) during 2009, 2010, and 2011. The year × N interaction was significant at *P* < 0.001. Bars with the same letter are not different (*P* ≤ 0.10) according to LSMeans separation.

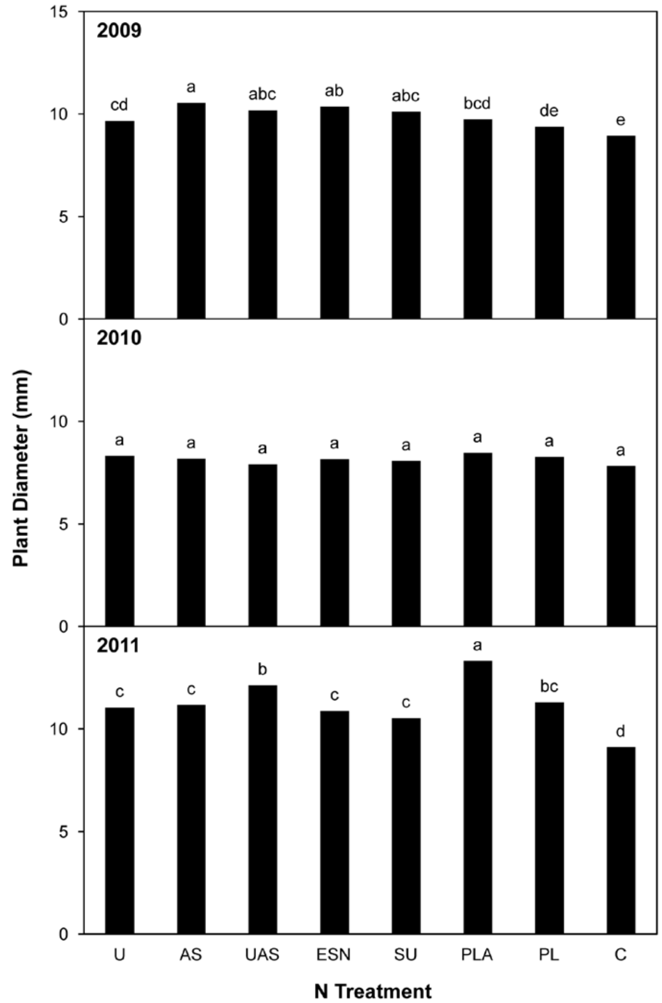


Figure 3. Cotton plant diameter for N sources—urea (U), ammonium sulfate (AS), urea-ammonium sulfate (UAS), Environmentally Smart Nitrogen (ESN), Super U (SU), poultry litter + AgrotainPlus (PLA), poultry litter (PL)—and unfertilized control (C) during 2009, 2010, and 2011. The year × N interaction was significant at *P* < 0.001. Bars with the same letter are not different (*P* ≤ 0.10) according to LSMeans separation.

the shortest when averaged across all 3 years (Table 3). In 2010, fertilizer N source had no effect on plant height (Fig. 2). In 2009 and 2011, plants receiving the standard fertilizers (AS and UAS) tended to be tallest, while the control plants were shortest. Plants receiving the two poultry litter treatments (PL and PLA) were among the shortest in 2009, but among the tallest in 2011. Plants in the ESN treatment were among the tallest in 2009 but among the shortest in 2011. The large amount of rainfall in 2009 probably aided N release from the polymer coating of ESN (Haderlein et al., 2001) such that more N was available during vegetative growth; the low rainfall from April through June in 2011 may have delayed N release from ESN until the end of vegetative growth, resulting in smaller plants. Variable effects of ESN across years were also noted for barley (Blackshaw et al., 2011). SU plants tended to be among the shortest in 2011 (Fig. 2).

Average plant diameter differed among the 3 years of the study, being smallest in 2010 and largest in 2011 (Table 2). As with plant height, all fertilizers increased cotton diameter compared with the unfertilized control averaged across all 3 years (Table 3). Plants receiving PLA had the largest diameters, followed by all three standard fertilizers and ESN, with SU and PL being smallest when averaged across all 3 years (Table 3). Again as with plant height, fertilizer N source had no effect on plant diameter in 2010. Also, diameters in 2009 tended to be largest for plants receiving AS and ESN and smallest for C and PL (Fig. 3). In 2011, PLA plant diameters were significantly larger, and C diameters were significantly smaller than all other treatments (Fig. 3).

In general, C plants were smallest (height and diameter) throughout the study and the standard fertilizers (AS and UAS) resulted in the largest plants (Fig. 2, 3).

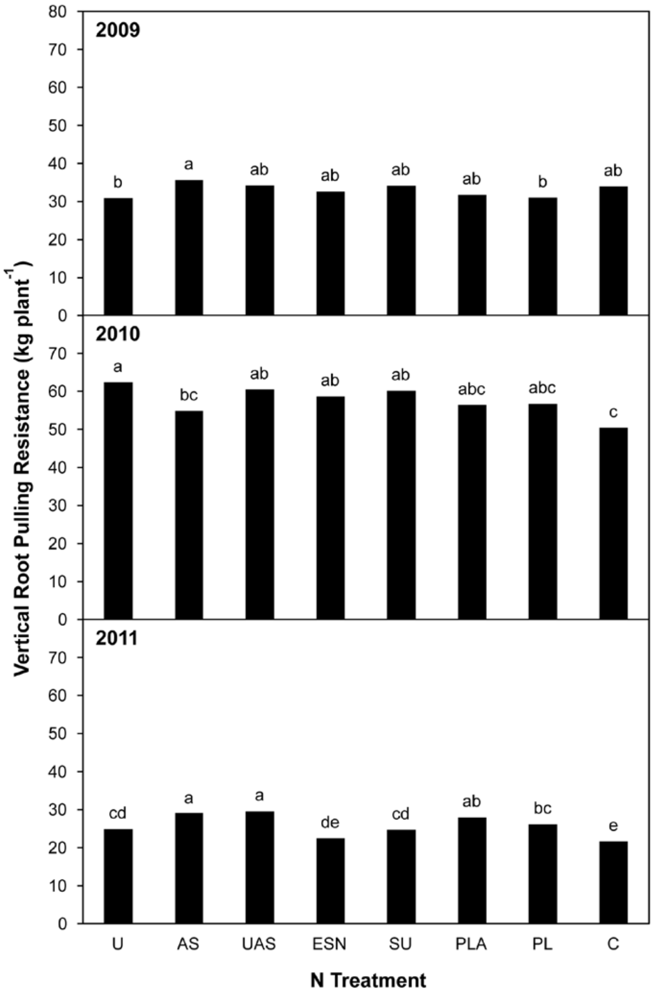


Figure 4. Vertical root-pulling resistance for cotton plants grown using N sources—urea (U), ammonium sulfate (AS), urea-ammonium sulfate (UAS), Environmentally Smart Nitrogen (ESN), Super U (SU), poultry litter + AgrotainPlus (PLA), poultry litter (PL)—and unfertilized control (C) during 2009, 2010, and 2011. The year × N interaction was significant at $P = 0.036$. Bars with the same letter are not different ($P \leq 0.10$) according to LSMeans separation.

Plants receiving ESN were among the largest in the first year but among the smallest in the last year. Plants receiving the two PL treatments were among the smallest in the first year but were among the largest by the last year of the experiment, particularly when AgrotainPlus was applied (Fig. 2, 3). Poultry litter mineralizes slowly, with only 50 to 60% N available the first year and the remainder becoming available in subsequent years. This may explain why heights for the PL treatments were initially low but increased by the final year of the experiment.

Vertical Root-Pulling Resistance

Vertical root-pulling resistance (pull force) differed among the 3 years of the study and was highest in 2010 and lowest in 2011 (Table 2). Pull force is largely influenced by soil moisture at the time of measurement (Böhm, 1979). The 2010 growing season was the driest, and measurements were taken when soil moisture was low (2.3%). In 2011, measurements were taken within a day following a rainfall event (11.1%), and in 2009, the wettest year, the soil moisture was also high (12.4%) compared with 2010. Overall, the pull force exhibited a significant negative correlation with soil moisture ($P < 0.001$). The size of the root system also influences pull force (Prior et al., 1995), and the pull force was positively correlated with root dry weight in all years ($P < 0.005$). Averaged across years, pull force was highest for UAS and lowest for the control (Table 3). Given that soil moisture did not vary significantly among N treatments within any year, differences among N treatments likely resulted from fertilizer effects on root size. Pull force varied among N treatments in all 3 years. In 2009, the greatest pull force occurred in plants receiving AS, which were significantly higher plants receiving U and PL (Fig. 4). In 2010, pull force was greatest for U plants and lowest for the control. In 2011, UAS and AS had the highest pull force, and the control was lowest again. Plants treated with urea had the highest pull force in 2010 but were among the lowest in 2009 and 2011. Perhaps more urea was lost and less was available for root growth in the wetter years. The EENFs ESN and Super U, which are also urea based, had high pull forces in 2009 and 2010 but were among the lowest in 2011 (Fig. 4). It is possible that moisture affected N release from these EENFs differently among the 3 years due to differences in timing of rainfall events.

Boll Counts

The number of plants per hectare varied among the 3 years (145,000 in 2009; 118,000 in 2010; 77,000 in 2011), probably a result of differences in rainfall during sowing and emergence. The excessive rainfall in spring 2009 (Fig. 1) delayed sowing until June, but conditions at that time were favorable for plant emergence and survival. Despite the fact that 2010 was the driest year, there was adequate rainfall in May at the time of sowing. In 2011, it was very dry from April through June (Fig. 1). Although supplemental irrigation was added during this time, the dry conditions before, during, and after sowing resulted in sporadic skips within rows and low plant survival. There were no significant effects of N treatment on plant counts in any of the 3 years (data not shown).

The number of bolls per plant was higher in 2010 and 2011 than 2009 (Table 2). Plant density is known to affect number of bolls per plant (Nichols et al., 2004), with wider spacing producing more bolls per plant primarily due to increased light interception (Metwally et al., 2012). The tighter plant spacing in 2009 resulted in fewer bolls per plant. Bolls per hectare also varied among the 3 years, with 2010 highest and 2011 lowest (Table 2). The lower number of plants in 2011 resulted in fewer total bolls, despite a high number of bolls per plant. Even though there were more plants in 2009, the lower number of bolls per plant resulted in fewer bolls per hectare than in 2010.

Averaged across years, N treatment had a significant effect on boll counts. The standard fertilizers (AS and

Table 4. Biomass and biomass allocation (dry-weight basis) among cotton plant parts averaged across all N treatments for the 2009, 2010, and 2011 growing seasons.

Season	Boll dry weight	Leaf + stem dry weight	Root dry weight	Total dry weight	Bolls	Leaf + stem	Root
	g				%		
2009	3476 a†	2613 a	765 a	6854 a	50.8 a	37.9 ab	11.3 a
2010	2963 c	2177 b	680 b	5820 c	51.0 a	37.3 b	11.7 a
2011	3122 b	2518 a	779 a	6420 b	49.1 b	38.8 a	12.1 a
P > *F*	<0.001	<0.001	0.014	<0.001	0.044	0.109	0.358

†Values within a column followed by the same letter are not significantly different at α = 0.10.

UAS) had the highest bolls per plant and bolls per hectare while PL and C had the lowest (Table 3). While both ESN and PLA had a relatively high number of bolls per plant and did not differ from the highest treatments (AS and UAS), they did tend to produce significantly fewer bolls per hectare. These patterns tended to hold across all 3 years (Table 5).

Cotton Biomass

Boll dry weight differed among the 3 years with 2009 > 2011 > 2010 (Table 4). These trends corresponded with final harvest lint yields (Watts et al., 2013). Boll dry weight per plant was greater in 2011 than in 2009 or 2010 (Table 2). Boll dry weight per boll also varied among years with 2011 > 2009 > 2010 (Table 2). It is known that boll size is inversely related to plant density (Bednarz et al., 2005), and significant negative correlations of plants/ha with boll dry weight per plant were observed in this study (P = 0.005). Thus, the lower number of plants per hectare led to plants with larger bolls in 2011. However, boll dry weight per hectare was still greatest in 2009, due to the much larger number of plants with moderately sized bolls. In 2010, a medial number of plants yielded the largest number of bolls per hectare; however, boll size (dry weight per boll) was smallest, resulting in the lowest boll dry weight per hectare.

Averaged across years, boll dry weight was highest for UAS and ESN and lowest for PL and C (Table 6); boll dry weight per plant followed this same trend (Table 3). However, boll dry weight per boll was greatest for C and lowest for the standard fertilizers (Table 3). In general, boll dry weight per boll was inversely related to bolls per hectare, indicating that treatments which produced the greatest number of bolls tended to produce the smallest bolls on a dry-weight basis.

Nitrogen had no effect on boll dry weight in 2010 (Fig. 5). In 2009, boll dry weight was lower for PL and C than all other N treatments except PLA and U. In 2011, boll dry weight was higher for UAS than U, SU, PL, and C. Boll dry weight per plant tended to follow this same pattern except that PLA, in addition to UAS, was higher than for most other treatments (Table 5). Boll dry weight per boll showed few effects of N treatment in 2009, with ESN and SU higher than PL and C (Table 5). In 2010, the opposite was observed with C and PL higher than all standard fertilizers and SU. In 2011, ESN and U had the highest dry weight per boll and AS was lowest. In general, the standard fertilizers (AS and UAS) and ESN

Table 5. Characteristics of cotton grown using N sources—urea (U), ammonium sulfate (AS), urea ammonium sulfate (UAS), Environmentally Smart Nitrogen (ESN), Super U (SU), poultry litter + AgrotainPlus (PLA), poultry litter (PL)—and unfertilized control (C) during the 2009, 2010, and 2011 growing seasons.

Treatment	Bolls/plant	Bolls/ha	Boll dry weight/plant	Boll dry weight/boll
	no.	no. × 10^5	g	
		2009		
U	6.0 bcde†	8.70 bc	24.0 bcd	4.01 ab
AS	7.3 a	9.87 a	28.4 a	3.92 ab
UAS	6.5 abc	9.91 a	25.6 abc	3.96 ab
ESN	6.8 ab	9.25 ab	27.9 ab	4.07 a
SU	6.2 bcd	8.79 bc	25.0 abc	4.05 a
PLA	5.7 cde	8.33 cd	22.7 cde	3.95 ab
PL	5.2 e	7.53 d	19.6 e	3.79 b
C	5.4 de	7.99 cd	20.5 de	3.80 b
		2010		
U	9.6 bcd	11.92 bc	23.9 a	2.48 cd
AS	12.3 a	13.70 a	26.4 a	2.28 d
UAS	11.0 ab	12.80 ab	25.3 a	2.35 d
ESN	10.5 abc	12.38 ab	27.4 a	2.63 bcd
SU	9.6 bcd	11.69 bc	22.9 a	2.40 cd
PLA	8.7 cde	10.24 cd	25.3 a	2.93 bc
PL	7.9 de	9.31 de	24.9 a	3.17 b
C	7.0 e	7.53 e	26.2 a	3.77 a
		2011		
U	8.5 c	6.33 c	40.0 bc	4.67 ab
AS	9.5 bc	7.70 a	40.1 bc	4.22 c
UAS	11.2 ab	7.71 a	50.5 a	4.52 bc
ESN	9.4 bc	6.41 c	46.2 ab	4.92 a
SU	8.7 c	6.98 abc	38.3 bc	4.38 bc
PLA	12.3 a	7.39 ab	52.4 a	4.35 bc
PL	8.4 c	6.36 c	38.7 bc	4.58 b
C	7.3 c	6.68 bc	32.5 c	4.43 bc
Pr > *F*‡	0.014	<0.001	0.023	<0.001

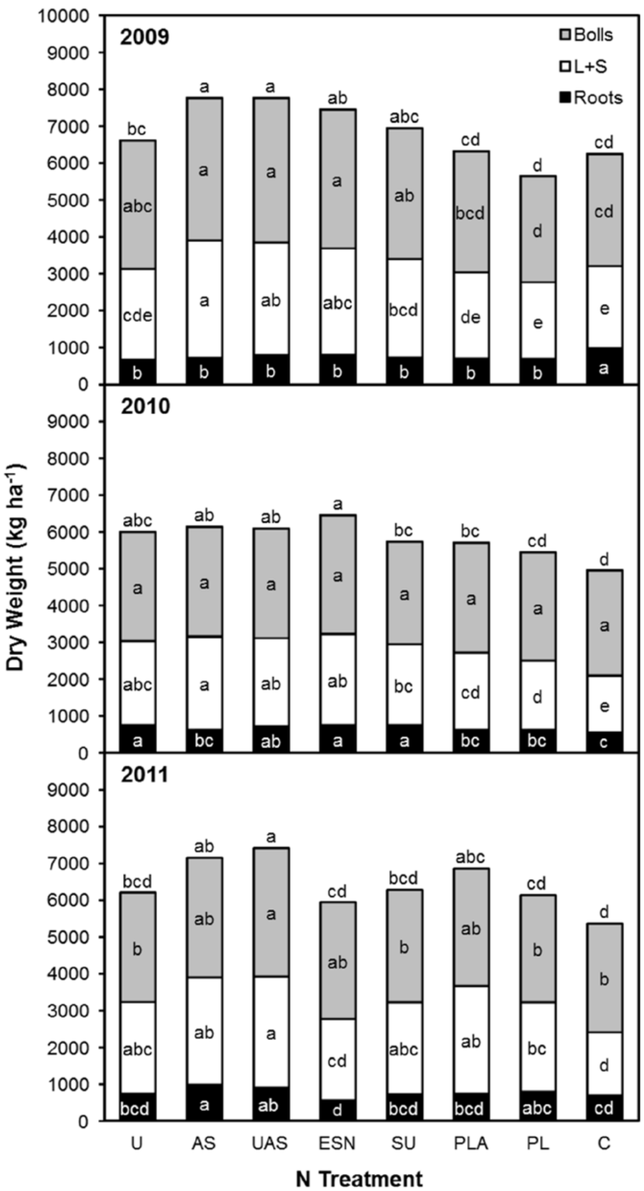
†Values within a column within a year followed by the same letter are not significantly different at α = 0.10. Note: even when Pr > F for N treatment was not significant, pairwise comparisons resulted in differences among N treatments.

‡Pr > F is for Year × N interaction.

Table 6. Biomass and biomass allocation (dry weight basis) among cotton plant parts grown using N sources—urea (U), ammonium sulfate (AS), urea ammonium sulfate (UAS), Environmentally Smart Nitrogen (ESN), Super U (SU), poultry litter + AgrotainPlus (PLA), poultry litter (PL)—and unfertilized control (C) averaged across the three growing seasons.

Treatment	Boll dry weight	Leaf + stem dry weight	Root dry weight	Total dry weight	Bolls	Leaf + stem	Root
	g				%		
U	3132 cde†	2413 b	730 ab	6275 c	49.9 bcd	38.4 bc	11.7 bc
AS	3365 abc	2872 a	790 ab	7027 ab	47.8 d	40.9 a	11.3 bc
UAS	3464 a	2813 a	819 a	7096 a	48.8 cd	39.6 ab	11.6 bc
ESN	3383 ab	2532 b	706 b	6621 bc	51.3 b	38.1 bc	10.7 c
SU	3131 cde	2455 b	738 ab	6324 c	49.6 bcd	38.6 bc	11.8 bc
PLA	3157 bcd	2453 b	696 b	6306 c	50.3 bc	38.7 bc	11.0 bc
PL	2904 e	2132 c	705 b	5741 d	50.8 bc	36.9 c	12.3 ab
C	2959 de	1821 d	749 ab	5529 d	53.8 a	32.8 d	13.5 a
P > *F*	0.002	<0.001	0.365	<0.001	0.002	<0.001	0.056

†Values within a column followed by the same letter are not significantly different at $\alpha = 0.10$.



resulted in the largest total boll dry weight per hectare (Fig. 5). While ESN resulted in similar boll dry weights as the standard fertilizers, the added cost of ESN is not supported from this study. However, the potential environmental benefits (e.g., reduced N loss through leaching, runoff, and GHG emissions) may make ESN a viable alternative (Halvorson et al., 2011). Further, a number of different government incentives to encourage the use of environmentally friendly farming practices are available (NRCS, 2013); ESN can qualify for such programs (Agrium Advanced Technologies, 2013).

The dry weight of remaining aboveground tissues (leaves + stems; L+S) was less in 2010 than 2011 and 2009 (Table 4), probably a result of the lower rainfall in 2010. When averaged across years, N had a significant influence on L+S dry weight, with AS and UAS highest and PL and C lowest (Table 6). This general pattern was seen through all 3 years of the study (Fig. 5). Plants receiving PLA were among the treatments having the smallest L+S dry weight in 2009 and 2010 but were among the largest in 2011 (Fig. 5). As previously mentioned, the slow mineralization of poultry litter allows more N to become available over successive seasons of application, explaining its increasing effect on biomass over the course of the experiment. As was noted for both height and diameter, ESN plants were among the heaviest L+S in 2009 and

Figure 5. (left) Cotton biomass (dry weight basis) for N sources—urea (U), ammonium sulfate (AS), urea-ammonium sulfate (UAS), Environmentally Smart Nitrogen (ESN), Super U (SU), poultry litter + AgrotainPlus (PLA), poultry litter (PL)—and unfertilized control (C) during 2009, 2010, and 2011. L+S = leaf plus stem dry weight. The Year × N interactions were significant at $P = 0.296$ for boll dry weight; $P = 0.119$ for leaf + stem dry weight; $P = 0.002$ for root dry weight; and $P = 0.119$ for whole-plant dry weight. Bars with the same letter are not different ($P \leq 0.10$) according to LSMeans separation. Note: even when Pr > F for Year × N treatment was not significant, pairwise comparisons resulted in differences among N treatments.

2010 but were among the lightest in 2011, probably due to differing rainfall patterns among years.

As with L+S dry weight, root dry weight was lower in 2010 than 2009 and 2011 (Table 4). However, N had much less effect on root dry weight than on L+S dry weight when averaged across years, with UAS higher than ESN, PLA, and PL (Table 6). In 2009, C plants had significantly greater root dry weight than all other N treatments but were among the lowest in the other 2 years (Fig. 5). Plants will tend to allocate biomass to the organ required for obtaining the most limiting resource (Chapin et al., 1987). Given that C plants received no fertilizer N, it seems logical they would allocate photosynthate to building roots to more thoroughly explore the soil profile for needed nutrients, as was seen in 2009. There might have been sufficient residual soil N in control plots in 2009 to allow for root construction, but N might have been depleted in subsequent years to a point where construction of all plant tissues was limited. It is also possible that differences in rainfall and/or plant genetics affected root construction in 2010 and 2011. In 2010, the greatest root dry weight occurred with ESN, SU, and U, which were heavier than all other treatments except UAS (Fig. 5). In 2011, AS and UAS plants had the greatest root dry weight and ESN had the least. The seasonal difference in ESN effects has been previously discussed.

Differences in whole-plant dry weight per hectare among years tended to mirror boll dry weight (the largest component) with 2009 > 2011 > 2010 (Table 4). When averaged across years, total dry weight among N treatments followed the same pattern as for boll dry weight but statistical differences varied slightly; UAS was higher than all other treatments except AS, and PL and C were lower than all other treatments (Table 6). In general, the standard fertilizers, with the exception of U, had greater plant dry weight than the EENFs.

Unlike boll dry weight, whole-plant dry weight showed a significant influence of N treatment each year (Fig. 5). Whole-plant dry weight, as with other plant parts, tended to be highest for plants receiving AS and UAS and lowest for C, PL, and PLA, with the exception of PLA in 2011. Further, ESN plants were among the heaviest in 2009 and 2010 but among the lightest in 2011. The U and SU treatments again tended to be in the mid-range for whole-plant dry weight in most years (Fig. 5). Others have found that EENFs failed to produce a consistent yield advantage over standard N sources (Mitchell and Osmond, 2012).

Biomass Allocation

Plants tended to allocate less dry weight to bolls and more to L+S in 2011 than in 2009 and 2010 (Table 4). Dry weight allocation to roots did not differ among the 3 years of the study. Across all years, C plants allocated more dry weight to bolls than all other treatments. Plants receiving ESN allocated more to bolls than did plants receiving UAS and AS, which were lowest (Table 6). This pattern was opposite of that found for allocation to L+S, where AS and UAS were highest and C and PL were lowest. Control and PL plants allocated more dry weight to roots and ESN was lowest (Table 6). In general, C and PL plants allocated more dry weight to bolls and/or roots and less to L+S, whereas AS and UAS plants allocated more to L+S and less to bolls and/or roots. Despite the fact that UAS and AS plants allocated less to bolls, boll dry weight was still high for these treatments.

In 2009, allocation to bolls was lower for C than U and PLA (Table 7). The opposite occurred in 2010 and 2011, where C had the highest allocation to bolls. Plants receiving AS and UAS allocated less to bolls in 2010 and 2011 than most other treatments. Fritschi et al. (2003) also observed that N fertilization decreased partitioning to fruit in cotton. In 2009 and 2010, the organics (PL and

Table 7. Biomass allocation (dry weight basis) among cotton plant parts using N sources—urea (U), ammonium sulfate (AS), urea ammonium sulfate (UAS), Environmentally Smart Nitrogen (ESN), Super U (SU), poultry litter + AgrotainPlus (PLA), poultry litter (PL)—and unfertilized control (C) during the 2009, 2010, and 2011 growing seasons.

Treatment	Bolls	Leaf + stem	Roots
		%	
	2009		
U	52.6 a[†]	37.2 bc	10.2 bc
AS	49.8 ab	40.7 a	9.5 c
UAS	50.5 ab	39.1 ab	10.4 bc
ESN	50.5 ab	38.7 ab	10.8 bc
SU	51.2 ab	38.5 ab	10.3 bc
PLA	52.1 a	36.7 bc	11.2 bc
PL	50.9 ab	36.9 bc	12.2 b
C	48.5 b	35.4 c	16.1 a
	2010		
U	49.1 cd	38.2 ab	12.7 ab
AS	48.3 d	41.4 a	10.3 c
UAS	48.5 d	39.6 ab	11.9 abc
ESN	49.9 cd	38.2 ab	11.9 abc
SU	48.3 d	38.4 ab	13.3 a
PLA	52.2 bc	36.9 bc	10.9 bc
PL	53.9 b	34.5 c	11.6 abc
C	57.6 a	31.0 d	11.4 abc
	2011		
U	47.9 c	39.9 ab	12.2 ab
AS	45.4 c	40.6 ab	14.0 a
UAS	47.5 c	40.1 ab	12.4 ab
ESN	53.4 ab	37.2 b	9.4 c
SU	49.3 bc	38.9 ab	11.8 abc
PLA	46.7 c	42.4 a	10.9 bc
PL	47.7 c	39.2 ab	13.1 ab
C	55.1 a	32.0 c	12.9 ab
$P > F$[‡]	0.002	0.195	0.009

[†]Values within a column within a year followed by the same letter are not significantly different at $\alpha = 0.10$. Note: even when Pr > F for N treatment was not significant, pairwise comparisons resulted in differences among N treatments.

[‡]Pr > F is for Year × N interaction.

PLA) tended to allocate more to bolls than most other treatments but were among the lowest in 2011. This, again, could be due to these treatments having a high cumulative available N by the final year of study.

Compared with other treatments, control plants allocated the least to L+S throughout the study (Table 7). Allocation to L+S showed few differences among the standard fertilizers and the EENFs. Dry weight allocation to L+S for PL and PLA was low in 2009 and 2010 but increased by 2011.

The control had the highest and AS the lowest allocation to roots in 2009 (Table 7). In 2010, AS again had the lowest allocation to roots but was significantly lower only than SU and U. In 2011, the trend reversed, and AS had the highest allocation to roots, whereas ESN and PLA had the lowest (Table 7). The root to shoot ratio closely mirrored allocation to roots (data not shown). This was expected given that root dry weight composed a small portion of total plant dry weight, indicating that shoot dry weight and total dry weight did not differ greatly.

Control plants allocated more biomass to roots and less to bolls and L+S in 2009; in subsequent years, C plants allocated more biomass to bolls and less to L+S. Perhaps as N became more limiting, C plants began allocating more biomass to reproduction and less to vegetative growth as a survival mechanism. When plants are adequately fertilized, they will put less photosynthate into roots and more into aboveground structures, as was seen in 2009. Why this trend did not continue (e.g., lower allocation to bolls for the inorganics) could be due to differences in rainfall patterns and/or genetics in the latter 2 years.

CONCLUSIONS

Nitrogen use efficiency of most fertilizers is 30 to 50%, with the remainder lost to runoff and leaching and as N_2O emissions to the atmosphere. Enhanced-efficiency N fertilizers are presently being developed and marketed for agricultural production to increase NUE and reduce N loss. This study examined the use of several N sources, including EENFs, for top dressing in a cotton production system in the U.S. Southern Coastal Plains. Generally, standard fertilizers such as ammonium sulfate and urea ammonium sulfate resulted in the largest number of bolls and the highest boll dry weight per hectare. Some of the EENFs, such as ESN, performed as well as the standard fertilizers through most of the study. The organic fertilizers tended to do poorly initially, probably because only about half the N from manure is available to plants during the year of application. However, adding AgrotainPlus to the poultry litter resulted in increased performance such that it was similar to the standards by the third year of study. The added cost of EENFs makes them economically unfeasible strictly from a yield standpoint. However, EENFs could become an environmentally viable option by reducing N loss from agricultural fields; this may become even more important since N_2O is an important GHG that possibly exacerbates climate change. Government incentives may also make EENFs more economically viable. More research is needed on the effects of EENFs, including timing of application and their use with manures, as management tools for cropping systems to optimize NUE, yield, and loss via leaching, runoff, and N_2O flux.

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