Soil Management and Landscape Variability Affects Field-Scale Cotton Productivity

J. A. Terra, Joey N. Shaw,* D. W. Reeves, R. L. Raper, E. van Santen, E. B. Schwab, and P. L. Mask

ABSTRACT

A better understanding of interactions between soil management and landscape variability and their effects on cotton (*Gossypium hirsutum* L.) productivity is needed for precision management. We assessed management practices and landscape variability effects on seed cotton yield in a 9-ha, Alabama field (Typic and Aquic Paleudults) during 2001–2003. We hypothesize that landscapes have major effects on cotton productivity, but these effects vary based on management and climate. Treatments were established in replicated strips traversing the landscape in a corn (*Zea mays* L.)–cotton rotation. Treatments included a conventional system with or without 10 Mg ha^{-1} yr^{-1} dairy manure (CT$_{manure}$ or CT), and a conservation system with and without manure (NT$_{manure}$ or NT). Conventional systems consisted of chisel plowing/disking + in-row subsoiling without cover crops. Conservation systems combined no surface tillage with in-row subsoiling and winter cover crops. A soil survey, topographic survey, and interpolated surfaces of soil electrical conductivity (EC), soil organic carbon (SOC), and surface soil texture were used to delineate five zones using fuzzy *k*-means clustering. Overall (2001–2003), conservation systems improved cotton yield compared with conventional systems (2710 vs. 2380 kg ha^{-1}); neither manure nor treatment × year interactions were significant. The conservation system was more productive than the conventional system in 87% of the cluster × year combinations. Slope, EC, SOC, and clay content were correlated with yield in all treatments. Soil and terrain attributes explained 16 to 64% of yield variation, however, their significance fluctuated between years and treatments. In dry years, factor analyses suggested variables related with soil quality and field-scale water dynamics had greater impacts on CT yields than NT yields. Our results indicate that management zones developed using relatively static soil-landscape data are relatively more suitable for conservation systems, and these zones are affected by soil management. In addition, the impact of NT on yields is most apparent on degraded soils in dry years.

The sustained use of conventional tillage with crop monocultures has degraded soils in the southeastern USA. Research has shown that adoption of conservation systems that minimize tillage operations and include crop rotations with residues improve long-term soil quality and productivity (Reeves, 1997). However, degraded soil conditions caused by conventional practices make difficult the transition from conventional systems to conservation systems. Consequently, producers are sometimes reluctant to adopt conservation system practices despite the long-term benefits. In 2002, only 35% of the cotton grown on the Alabama Coastal Plain used conservation tillage (Conservation Technology Information Center, 2004). Because experiments are normally conducted at a plot scale, there are uncertainties about the performance of conservation practices when applied to heterogeneous field-scale conditions.

Field scale variability of soils and landscapes are major causes of spatial variability in crop yields (Kravchenko and Bullock, 2000; Li et al., 2001; Bronson et al., 2003). Soil water availability is related to crop productivity even in high rainfall regions like the Coastal Plain of Alabama (average ~1350 mm yr^{-1}), and is a major factor related to spatial variability of crop yields (Paz et al., 1998; Li et al., 2001). Hence, it is not surprising that yield variability is normally correlated with soil properties and terrain attributes that affect water holding capacity, drainage, and the field-scale water regime (Kravchenko and Bullock, 2000; Fraisse et al., 2001; Li et al., 2001). Because landscape attributes can be quantified and grouped (clustered), it is critical to evaluate how these attributes are related to productivity and soil properties. The ability to rapidly map soil EC offers great potential as a tool for constructing or refining management zones (Fraisse et al., 2001; Mueller et al., 2003), provided that the complex relationships between soil properties, productivity, and field-scale EC data are known. This has prompted the need to identify zones that can be grouped and managed in a similar way to optimize inputs and/or maximize profits for agronomic, economical, and environmental benefits (Plant, 2001; Fraisse et al., 2001). A fundamental understanding of factors controlling the systematic components of variability can lead to the development of rapid and cost-effective methods for constructing management zones.

The evaluation of the effects of site-specific agriculture should be assessed through both its impacts on productivity and soil quality. Although the underlying premise for the application of site specific agriculture and the development of management zones is the presence of spatial heterogeneity, temporal persistence of yield patterns are necessary for accurately establishing management zones based on yield data (Sawyer, 1994; Boydell and McBratney, 2002). Although the development of new technologies has allowed researchers to study the effects of soil properties and terrain attributes on crop yields (Kravchenko and Bullock, 2000; Fraisse et al., 2001), the impact of soil management systems has rarely been assessed at the landscape level (Ginting et al., 2003). Field-scale experiments and the use of harvesters equipped with yield monitors and global posi-

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Abbreviations: AAES, Alabama Agricultural Experiment Station; CT, conventional system; CTI, Compound Topographic Index; CT$_{manure}$, conventional system + manure; EC, soil electrical conductivity; GPS, global positioning system; NT, conservation system; NT$_{manure}$, conservation system + manure; RCB, randomized complete block design; SHWT, seasonal high water table depth; SOC, soil organic carbon; TDR, time domain reflectometry.

tioning systems (GPS) allow assessment of management practices across landscapes. Such trials conducted on strip plots are becoming an accepted methodology to complement plot-scale research (Mallarino et al., 2000). Thus, future research exploring the effects of management practices on crop productivity will increasingly consider landscape variability. Field-scale experiments on degraded soils comparing management systems allow a better understanding of the dynamics associated with the transition to conservation systems.

We hypothesize that landscapes have major effects on cotton productivity, but these effects vary based on management and climate. The objective of our research was to determine the relative and interactive effects of four soil management practices (conservation and conventional tillage systems with and without manure applications) with soil landscape variability on cotton productivity in a Southeastern Coastal Plain field.

MATERIALS AND METHODS

Site Description

A field-scale study was conducted (2001–2003) at the Alabama Agricultural Experiment Station's E.V. Smith Research Center in central Alabama, USA (85°53′50″ W, 32°25′22″ N). The site is a 9-ha field that had a long history of row cropping; mostly cotton, under conventional tillage (moldboard or chisel plowing) for the previous 30 yr. Soils at the site are mostly fine and fine-loamy, siliceous, subactive, thermic Typic, Oxyaquic and Aquic Paleudults. Initial soil fertility data (methodology explained below) indicated the surface soil (0- to 30-cm depth) had a pH of 6.5 (1:1 soil/water), 5.6 g kg^{-1} (sd ± 1.2) of SOC, and extractable (Mehlich I) P, K, Ca and Mg of 28 (sd ± 12), 96 (sd ± 23), 480 (sd ± 87), and 127 (sd ± 18) mg kg^{-1}, respectively.

Cultural Practices and Treatments

Cotton (Suregrow 125 B/R) was seeded at 165 000 seeds ha^{-1} in 102-cm rows using a John Deere 1700 six-row unit vacuum planter (Deere & Company, Moline, IL)[1]. Planting dates for the 3-yr trial were 25 May 2001, 22 May 2002, and 28 May 2003. Cotton strips were fertilized before seeding with 45 and 56 kg ha^{-1} of P_2O_5 and K_2O, respectively. Nitrogen (NH_4NO_3) was broadcast during planting at rates of 135 kg N ha^{-1} in 2001, and 100 kg N ha^{-1} in 2002 and 2003. Other management practices, including fertilization, pesticide application, growth regulation, and defoliation, followed Alabama Agricultural Experiment Station (AAES, 1994) recommendations.

A factorial arrangement of two soil management systems with and without annual application of dairy bedding manure was evaluated in a corn–cotton rotation with both phases of the rotation present each year. The four treatments included: (i) a conventional system (CT); (ii) a conventional system + manure (CT_{manure}); (iii) a conservation system (NT); and (iv) a conservation system + manure (NT_{manure}). In the conventional systems, tillage operations were performed in fall (chisel plowing/disking), and in spring about 2 to 3 wk before seeding (field cultivation and in-row subsoiling). Conventional systems did not include cover crops, but winter weeds were not controlled. The conservation system included no surface tillage with non-inversion in-row subsoiling and a winter cover crop mixture of white lupin (*Lupinus albus* L.), crimson clover (*Trifolium incarnatum* L.), and fodder radish (*Raphanus sativus* L.) before corn and a mixture of black oat (*Avena strigosa* Schreb.) and rye (*Secale cereale* L.) before cotton. After the 2002 growing season, sunn-hemp (*Crotalaria juncea* L.) was included in the rotation sequence of the conservation systems between the corn and the rye-oat cover crop (Sept–Nov). The sunn-hemp was terminated using glyphosate (~1 kg ha^{-1} isopropylamine salt) and a mechanical roller; frost terminated any remaining plants. The rye-oat mixture (40 and 60%, respectively) was planted in late autumn at a rate of 110 kg seed ha^{-1} and terminated at anthesis in mid-April using glyphosate (~1 kg ha^{-1} isopropylamine salt) and a mechanical roller. All in-row subsoiling operations were performed immediately before planting with a KMC (Kelly Manufacturing Co., Tifton, GA) ripper to a depth of 40 cm to disrupt the inherent root-restricting hardpan of these soils. Subsoiling and planting operations were guided with a Trimble AgGPS Autopilot automatic steering system (Trimble, Sunnyvale, CA) with centimeter level precision.

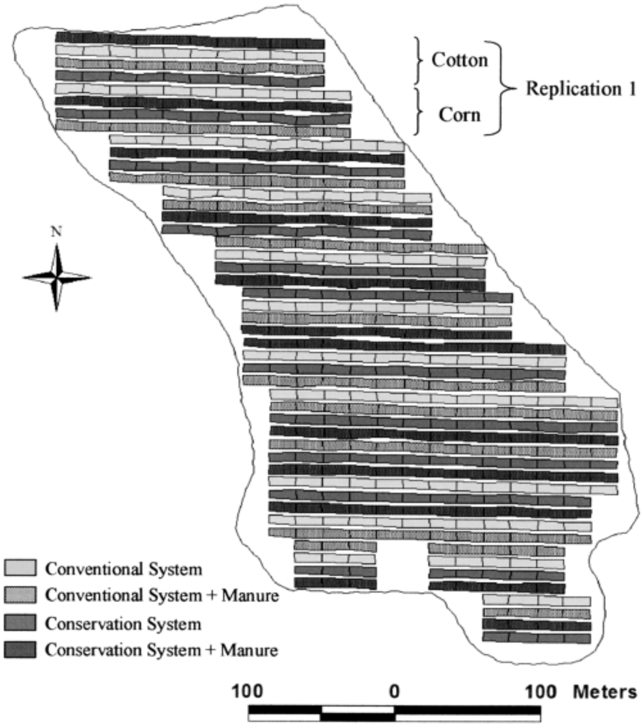

Fig. 1. Layout of strip treatments of the 9-ha field-scale experiment in east-central Alabama (2001–2003).

Dairy bedding manure was applied (and left on the surface) at rates of ~10 Mg ha^{-1} yr^{-1} (dry matter) in the CT_{manure} and NT_{manure} treatments, just before winter cover crop seeding in NT treatments. Overall, manure composition on dry weight basis for C, N, P, and K was 280 g kg^{-1}, 10.5 g kg^{-1}, 2.8 g kg^{-1} and 3.3 g kg^{-1}, respectively.

Treatments were established in 6.1-m wide by ~240-m long strips crossing the landscape in a randomized complete block design (RCB) with six replications (Fig. 1); a 2.45-m alley separated adjacent strips. Cells of 6.1 × 18.3 m were delineated in each strip, resulting in a total of 496 cells for the entire field. Since both phases of the rotation were present, 50% of these cells were in cotton annually.

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[1] Reference to trade or company name is for specific information only and does not imply approval or recommendation by USDA-ARS or Auburn University to the exclusion of others that may be suitable.

Data Collection and Measurements

An intensive soil grid sampling, an Order 1 soil survey, a digital elevation map, and a field-scale EC survey were developed at the beginning of the study (Dec. 2000–Feb. 2001) for soil and landscape variability characterization.

Soil samples were taken at the beginning of the test from the 496 (6.1 × 18.3-m) cells. Ten sampling cores (2.5 cm diam.), to a depth of 30 cm, were collected and composited within a 2.5-m radius from the cell center. Samples were dried at 55°C, ground to pass a 2-mm sieve, and analyzed for SOC by dry combustion (Yeomans and Bremner, 1991) using a LECO CN-2000 analyzer (Leco Corp., St. Joseph, MI). Particle-size distribution was determined for 82 of the samples using the pipette method following organic matter removal (Kilmer and Alexander, 1949).

A detailed soil survey (1:5000) was developed according to National Cooperative Soil Survey standards. Drainage classes were assigned for each map unit and a seasonal high water table depth (SHWT) was estimated using the Soil Interpretation Records.

The field was surveyed using a direct contact Veris 3100 Soil EC Mapping System (Veris Tech., Salina, KS) equipped with a submeter precision GPS. Geo-referenced EC data (mS m^{-1}) were recorded at 1-s intervals at 0 to 30 cm (EC_{30}) and 0 to 90 cm (EC_{90}) depths with a vehicle traveling a speed of ~4 km h^{-1} in transects spaced ~9 m apart. The field was at fallow during the survey and soil moisture conditions were near field capacity.

A Trimble 4600 L.S. Surveyor Total Station was used to determine elevations across the field. Elevation was recorded each second with a vehicle traveling ~5 km h^{-1} in concentric circles 5 m apart. Digital elevation models and terrain attributes were developed using the appropriate algorithms and commands in Arc/Info 8.0 (ESRI, Redland, CA). Terrain attributes included elevation, slope, profile, and plan curvature, flow accumulation, catchment area, and compound topographic index (CTI) (Moore et al., 1993).

Seed cotton yield was determined and geo-referenced across the field in all three seasons with a two-row John Deere 9920 spindle-picker (Deere & Company, Moline, IL) equipped with a submeter precision GPS and an optical sensor-based Ag Leader PF3000 yield monitor (Ag Leader Tech. Inc., Ames, IA). The four center rows of each strip treatment were harvested and yield records were obtained every second. A field digital scale was used to weigh harvested cotton within each strip. The initial and final 15-m records of each strip were excluded from the data to minimize edge effects. The yield within each cell was determined by averaging individual yield records using ArcView 3.3 (ESRI, Redlands, CA).

Data Manipulation and Statistical Analysis

The MIXED procedure in SAS (SAS Inst., Cary, NC), adjusting for spatial correlation, was used for overall field data analysis (Littell et al., 1996; Mallarino et al., 2000). For the overall mixed model, treatment, year, and their interactions were considered as fixed effects, while replication and its interactions were considered random effects (Terra et al., 2004). An F statistic with $P \leq 0.05$ was used to determine the significance of the fixed effects for all analyses.

Map units and terrain attributes were rasterized to a 5 × 5-m grid using Arc/Info. Ordinary kriging (Goovaerts, 1998) was used to interpolate SOC, EC, sand, silt, and clay content to the 5 × 5 m grid using GS+ (Gamma Design Software, Plainwell, MI). Average soil properties and terrain attributes for the 496 cells were also determined.

Pearson correlation coefficients were calculated between soil properties, terrain attributes and seed cotton yield for each year × treatment combination. Factor analysis was used to express variability of multivariate data in a few common factors, thus reducing the dimensionality of the original data (Khattree and Naik, 2000). The FACTOR procedure of SAS (Maximum Likelihood and Varimax orthogonal rotation) was used with soil and terrain attributes to create latent factors of correlated variables. Factors with eigenvalues > 1 were used for calculating factor scores for each of the 496 field cells (scores calculated using original data values and factor loadings) (Mallarino et al., 1999; Kaspar et al., 2004).

Regression models relating cotton yield to soil properties/terrain attributes, and between cotton yield and latent factors, were obtained for each treatment × year combination using stepwise regression in SAS ($P \leq 0.05$) (Freund and Littell, 2000).

The field was subdivided using a clustering procedure (Fraisse et al., 2001; Fridgen et al., 2004). The cluster analysis was performed with data that explained the majority of the multivariate data variability, and data that was highly correlated with cotton yield as evidenced by the correlation analysis. Clusters were created with a fuzzy k-means unsupervised classification of multivariate data using the Management Zone Analyst software (Fridgen et al., 2004). Two performance indices (fuzziness performance index and normalized classification entropy) were used to determine the optimal number of clusters for the field (Fridgen et al., 2004). Optimum numbers of clusters for each treatment × year combination were selected based on the reduction of within-zone yield variance (Fraisse et al., 2001). Finally, treatment effects were assessed separately within each cluster. Treatments were considered as fixed effects and sample cells within each cluster as repeated observations.

RESULTS AND DISCUSSION

Rainfall

Soil moisture is a major factor affecting yield temporal and spatial variability (Paz et al., 1998; Kravchenko and Bullock, 2000). Rainfall distribution differed greatly during cotton reproductive stages between the three seasons. According to data from the Auburn University Mesonet automated weather stations (AWIS Weather Service Inc), precipitation during July–Aug of 2001 and 2002 at the site was 46 and 64% below the long-term average (240 mm for Montgomery, Alabama), respectively. In contrast, 28% more rain than average was received during the same period in 2003. Rainfall from first bloom to peak bloom at the site was 73, 46, and 118 mm in 2001, 2002, and 2003, respectively.

Seed Cotton Yield Responses

For the entire field, seed cotton yield was significantly affected by year and soil management system, but was not affected by manure addition (Table 1). Averaged over years, conservation systems yields were 14% greater than conventional systems yields (2710 vs. 2380 kg ha^{-1}, respectively) (Terra et al., 2004). In 2001, conservation systems yields were 10% greater than conventional systems (3116 vs. 2827 kg ha^{-1}). In the 2002 drought, conservation systems yields were 24% greater than conventional systems (1616 vs. 1306 kg ha^{-1} respectively). In the

Table 1. Soil management system effects on seed cotton yields from a 9-ha field-scale experiment in east-central, Alabama. Data analyzed as a randomized complete block design (RCB) accounting for spatial correlation (2001–2003).

	RCB adjusted by Semivariogram			
	Year			
Treatment	**2001**	**2002**	**2003**	**Mean**
	kg ha^{-1}			
Conventional system	2757	1259	2967	2333
Conventional system + manure	2897	1353	3027	2427
Conservation system	3099	1607	3414	2703
Conservation system + manure	3137	1626	3426	2719
Standard error treatment means	81.2	56.0	88.1	58.2
	$P > F$			
Test for fixed effects				
Management system	<0.01	<0.01	<0.01	<0.01
Manure	0.13	0.23	0.57	0.22
Manure × management system	0.22	0.41	0.61	0.37
Year				<0.01
Year × manure				0.64
Year × management system				0.09

wet 2003 season, conservation systems yields averaged 14% greater than conventional systems (3420 vs. 2997 kg ha^{-1}). Yield reduction in the dry year (2002) relative to the wet year (2003), was 57 and 53% in conventional and conservation systems, respectively. The greater yields obtained in the conservation system in the dry 2001 and 2002 seasons compared with conventional systems was attributed to the advantage of conservation systems on soil water use efficiency (Lascano et al., 1994; Reeves, 1994). The lack of a yield response to manure additions during the study was probably due to the addition of sufficient nutrients with inorganic fertilizers, and concurs with the general finding that manure impacts on soil quality and productivity are largely obtained after more than 10 yr (Reeves, 1997; Endale et al., 2002).

Soil Properties and Terrain Attributes

Soils ranged from well-drained upland Paleudults to moderately well and somewhat poorly drained soils in concave and relatively lower landscape positions. Nine soil map units were identified in the field, indicating significant soil variability (Fig. 2). Soils in the study area mainly vary due to differences in both drainage class and surface horizon texture (mostly due to historical erosion). Elevation range was almost 3 m, and slope gradients ranged between 0 and 8%.

The EC_{30} was correlated with slope ($r = 0.66$) and clay content ($r = 0.43$), as observed in other studies (Mueller et al., 2003; Shaw and Mask, 2003) (Table 2). Similar spatial patterns were observed between the soil survey, some terrain attributes, and EC (Fig. 2), suggesting that EC variability for this field was related to soil-terrain characteristics. The highest EC was generally found in eroded areas with higher clay content and lower SOC. Positive correlation of SOC with CTI ($r = 0.48$) indicates landscape hydrology largely affects C distribution, while negative correlation of SOC with EC_{90} ($r = -0.42$) and slope ($r = -0.41$) suggests that historical erosion also plays a major role on soil C spatial variability at this site.

Seed Cotton Yield Relationships with Soil and Terrain Attributes

Correlation coefficients relating soil and terrain attributes with cotton yield for each year and management system are presented in Table 3. Although correlations varied among treatments and years, elevation, slope, CTI, EC_{30}, clay content, and initial SOC were generally the most highly correlated variables to seed cotton yield under most treatment × year combinations. However, differences between years and treatments were found. In dry years (2001 and 2002), EC, clay content, and slope were negatively correlated with yield, indicating eroded areas of poor soil quality largely affected yields under those conditions. Areas in the field presenting high values for these variables corresponded to areas of eroded and degraded soils, which are inherently less productive due to limitations in water storage capacity and other soil physical and chemical properties. The SOC and CTI were positively correlated with yield in 2001 and 2002, particularly in conventional systems. Since CTI is sometimes referred to as a wetness index, it's positive correlation with yield in dry years is not surprising. Despite SOC being relatively low in the field (5.6 g kg^{-1}), it was also significant for explaining yield variability in dry years. The relatively higher correlation between yield and CTI in conventional compared with conservation systems suggests for dry conditions, terrain attributes suggestive of the field-scale water regime were relatively more significant in conventional systems.

In contrast, in the wetter 2003 season, most correlations between yield and terrain attributes were opposite those observed in 2001 to 2002. Elevation, depth to SHWT, EC, and clay content were positively correlated with yield suggesting that variables related to drainage and runoff (i.e., soils at low elevation with high SHWT were too wet) played a significant role in 2003 yield variability. Our data suggests these effects were slightly more evident in the conservation systems, where surface residues reduce evaporation, and increase water holding capacity and infiltration (Lascano et al., 1994).

Results were generally consistent with other studies (Kravchenko and Bullock, 2000; Li et al., 2002; Bronson et al., 2003). For example, SOC was more consistently correlated with Midwestern USA corn and soybean yields than other soil and terrain attributes (Kravchenko and Bullock, 2000). In the Kravchenko and Bullock (2000) study, elevation and slope were mostly negatively correlated with corn and soybean yields, and the greatest effect of terrain on yield was observed during extreme weather conditions (either wet or dry). In another study, cotton lint yields in Texas were found to be greatest in lower slope positions (Bronson et al., 2003). Similar to our results in 2001 and 2002, this Texas study found a negative correlation between clay content and yield. In another study in Texas, cotton lint yield was negatively correlated with elevation and clay content, and positively correlated with sand and water content (Li et al., 2002). Corwin et al. (2003), in a California study, reported that cotton yield was positively correlated with soil water content ($r = 0.42$), clay content ($r = 0.36$), and EC ($r = 0.51$).

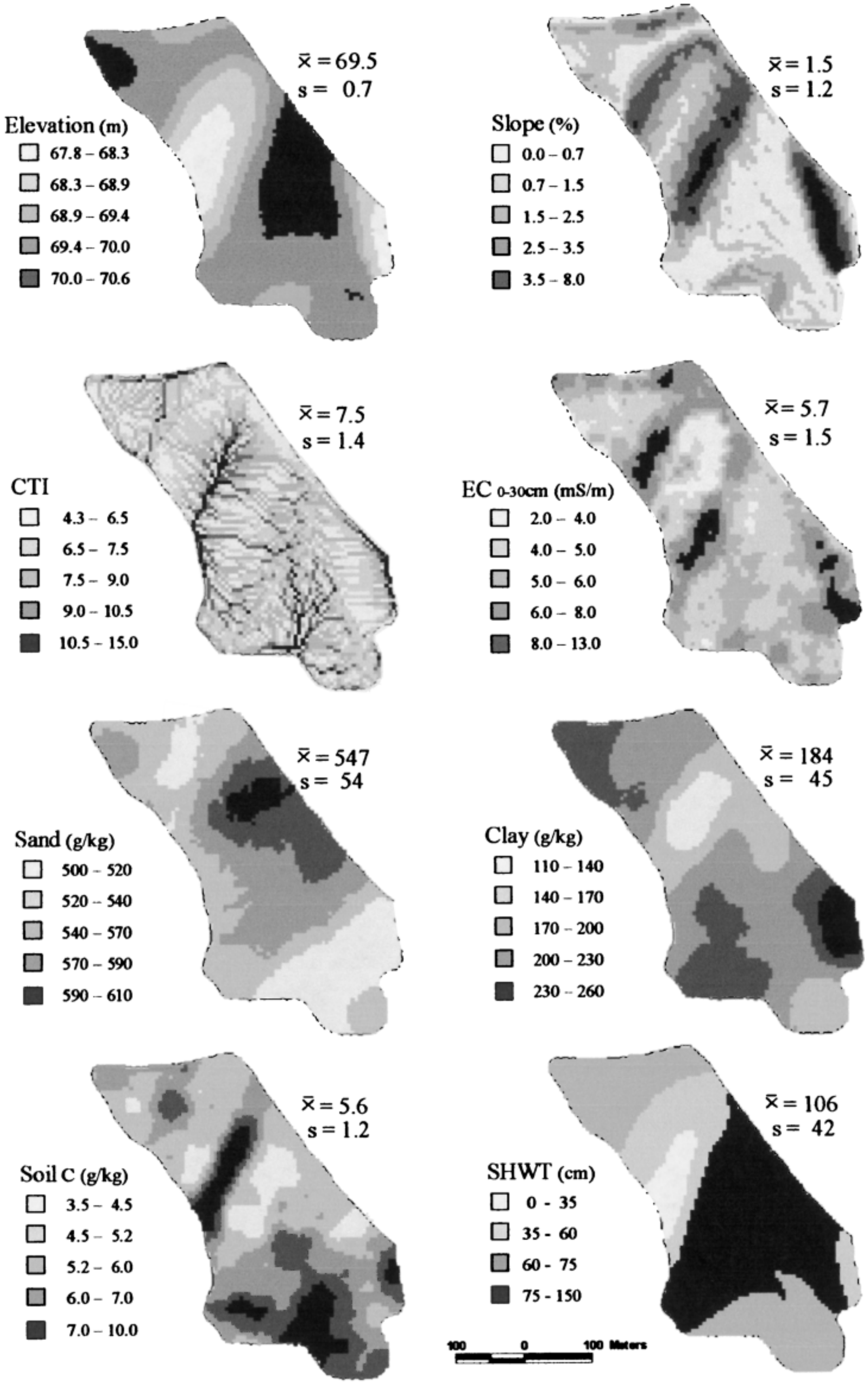

Fig. 2. Interpolated surfaces of elevation, slope, compound topographic index (CTI), soil electrical conductivity (EC), sand content and clay content (0–30-cm), soil organic C (0–30-cm), and seasonal high water table (SHWT) on a 9-ha field-scale test in east-central Alabama.

Regression models relating soil properties and terrain attributes with cotton yield explained between 16 and 64% of the variability, depending on year and treatment (Table 3). In the two dry seasons (2001 and 2002), generally higher coefficients of determination were found for the conventional systems compared with conservation systems, while the opposite trend was observed for the wet year (2003). Slope, EC, SOC, elevation, and clay or silt content were generally the most significant parameters in the regression models. However, their relative contribution to the model was highly variable among treatments and years. For example, in the dry seasons, SOC and EC_{30} were largely significant in the conventional system regression models, while slope was more

Table 2. Pearson correlation coefficients between soil properties (0- to 30-cm depth) and terrain attributes on a 9-ha field-scale experiment in east-central, Alabama ($n = 496$, $P \leq 0.05$).

Variables†	ELEVA	Slope	PROF	PLAN	ln CA	CTI	EC_{30}	EC_{90}	Sand	Silt	Clay	SHWT
Slope	−0.41		–	–	–	–	–	–	–	–	–	–
PROF	−0.46	NS		–	–	–	–	–	–	–	–	–
PLAN	0.28	−0.16	−0.38		–	–	–	–	–	–	–	–
ln CA	−0.58	0.19	0.41	−0.51		–	–	–	–	–	–	–
CTI	−0.25	−0.39	0.41	−0.45	0.74		–	–	–	–	–	–
EC_{30}	−0.14	0.66	NS	NS	NS	−0.38		–	–	–	–	–
EC_{90}	NS	0.45	−0.12	NS	NS	−0.36	0.78		–	–	–	–
Sand	−0.12	NS	0.17	NS	0.14	NS	−0.32	NS		–	–	–
Silt	−0.27	−0.23	NS	NS	0.12	0.19	−0.15	NS	−0.36		–	–
Clay	0.34	0.17	−0.16	NS	−0.23	−0.25	0.43	NS	−0.63	−0.50		–
SHWT	0.55	0.12	−0.21	0.14	−0.26	−0.23	NS	NS	0.22	−0.64	0.33	
SOC	−0.17	−0.41	−0.13	0.16	0.29	0.48	−0.31	−0.42	−0.25	0.39	NS	−0.29

† ELEVA = elevation; PROF = profile curvature; PLAN = plan curvature; In CA = natural log of catchment area; CTI = Compound Topographic Index; EC_s = electrical conductivity 0–30 cm; EC_d = electrical conductivity 0–90 cm; SHWT = seasonal high water table depth; SOC = soil organic carbon.
‡NS = not significant at $P \leq 0.05$ level.

Table 3. Correlation coefficients (r) and coefficients of determination (R^2) from stepwise regression relating seed cotton yields with soil properties (0- to 30-cm depth) and terrain attributes for each year and treatment on a 9-ha field-scale experiment in east-central Alabama ($P \leq 0.05$; $n \approx 60$).

	2001				2002				2003			
Treatment†	CT	CTM	NT	NTM	CT	CTM	NT	NTM	CT	CTM	NT	NTM
Variables‡												
Elevation	−0.33§	−0.29§	NS¶	NS	NS	NS	0.30§	0.27	0.26	0.50	0.48	0.30
Slope	−0.33	−0.36	−0.38	−0.24§	−0.39	−0.66§	−0.61§	−0.40§	NS¶	NS	NS	NS
PROF	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
PLAN	0.43	0.37	0.31	NS	NS	NS	NS	NS	NS	−0.37	NS	NS
ln CA	NS	NS	0.27	0.26	0.35	NS	NS	NS	−0.25	−0.47§	−0.29	NS
CTI	0.38	0.44	0.32	0.30	0.46	0.44	0.34	NS	NS	−0.34	NS	NS
EC_{30}	−0.56§	−0.61§	−0.48§	−0.40	−0.45	−0.69§	−0.49	−0.35	NS	0.30	0.29	0.37§
EC_{90}	−0.50	−0.52	−0.35	NS	NS	−0.38	−0.42	NS	0.29§	NS	0.30§	0.26
Sand	NS	NS	0.33	0.36	0.27	NS	NS	NS	NS	−0.55§	NS	NS
Silt	0.25	0.28	NS	NS	0.35	0.49§	NS	NS	NS	NS	−0.52§	−0.63§
Clay	−0.36	−0.36	−0.46§	−0.48§	−0.48§	−0.48	NS	NS	NS	0.42	0.49	0.37
SOC	0.46§	0.51§	NS	NS	0.52§	0.32	0.52§	0.31	NS	NS	−0.31	−0.49
SHWT	−0.40	−0.34	−0.29	NS	NS	NS	NS	NS	NS	NS	0.51	0.68§
R^2	0.46	0.56	0.31	0.29	0.42	0.64	0.56	0.16	0.19	0.43	0.57	0.59

† CT = conventional system; CTM = conventional system + manure; NT = conservation system; NTM = conservation system + manure.
‡ PROF = profile curvature; PLAN = plan curvature; CA = catchment area; CTI = Compound topographic index; EC_{30} = electrical conductivity 0–30 cm; EC_{90} = electrical conductivity 0–90 cm; SHWT = seasonal high water table depth; SOC = soil organic carbon.
§ Variable retained in stepwise regression model.
¶ NS = not significant at $P \leq 0.05$ level.

frequently retained for explaining yield variability in conservation systems. However, no clear relationships were observed between treatments and independent variables in the 2003 season.

Table 4. Factor loadings from principal factor analyses for measured soil properties and terrain attributes on a 9-ha field-scale experiment in east-central Alabama.

Variable	Factor 1	Factor 2	Factor 3	Factor 4
	Coefficients			
Elevation	−0.25	−0.36	−0.24	0.86
Slope	0.75	−0.09	0.07	−0.27
Plan curvature	−0.05	−0.52	0.03	0.10
Profile curvature	−0.01	0.43	0.20	−0.30
Catchment area	0.01	0.81	0.15	−0.30
Compound Topographic Index	−0.42	0.90	0.06	−0.02
Electrical conductivity (0–30 cm)	0.93	0.04	−0.34	0.04
Electrical conductivity (0–90 cm)	0.79	−0.02	−0.10	0.13
Clay (0–30 cm)	0.21	−0.13	−0.68	0.21
Sand (0–30 cm)	0.01	0.05	0.95	0.16
Soil organic carbon (0–30 cm)	−0.42	0.33	−0.23	−0.24
Seasonal depth water table	0.14	−0.18	0.13	0.64
Eigenvalue	2.54	2.25	1.75	1.56
Variance explained	0.21	0.19	0.15	0.13

Seed Cotton Yield Relationships with Latent Variables

Multivariate analysis techniques such as principal component or factor analysis have been used to analyze the effects of soil properties and terrain attributes on yield (Mallarino et al., 1999; Kaspar et al., 2004). The FACTOR procedure of SAS (Maximum Likelihood and Varimax orthogonal rotation) was used with soil and terrain attributes to create groups of correlated variables (latent variables) that describe data variability (Mallarino et al., 1999; Kaspar et al., 2004). We extracted four latent variables out of the original 12 correlated variables. The factor loading and the first four eigenvalues of the correlation matrix are presented in Table 4. The first four factors had eigenvalues > 1 and explained 69% of the data variability. The EC and slope had the highest loading factors for the first factor, hence, the latent variable was considered to be related to 'soil degradation'. The second factor was dominated by CTI and catchment area; this latent variable was identified as 'runoff and wetness'. The third latent variable was called 'texture' because the loadings were dominated by sand and clay content. Finally, the last latent variable was related with 'soil drainage' since elevation and

Table 5. Multiple regression model parameters relating seed cotton yield with the latent variables developed by factor analysis in the 9-ha field-scale experiment in east-central Alabama (2001–2003).

			Factor and latent variable name†				
Year	Treatment‡	Intercept	Factor 1 degradation†	Factor 2 runoff/wetness	Factor3 texture	Factor 4 drainage	R^2
2001	CT	2722	−131	NS§	NS	−91	0.39
	CTM	2888	−152	57	NS	−87	0.50
	NT	3101	−125	NS	114	NS	0.28
	NTM	3149	−126	NS	146	NS	0.24
2002	CT	1283	−110	79	NS	NS	0.29
	CTM	1403	−159	45	NS	NS	0.48
	NT	1634	−144	44	NS	46	0.43
	NTM	1649	−87	NS	NS	NS	0.12
2003	CT	2978	NS	NS	−60	68	0.11
	CTM	3058	NS	−40	−103	59	0.43
	NT	3426	59	NS	NS	180	0.37
	NTM	3482	131	NS	NS	146	0.39

† Factors explained in text.
‡ CT = Conventional System; CTM = Conventional System + Manure; NT = Conservation System.
NTM = Conservation System + Manure.
§ NS = not Significant at $P \leq 0.05$ level.

depth to seasonal water table had the highest loading factors.

Coefficients of determination between the factors and cotton yield for each year × treatment combination are presented in Table 5. A lower portion of the yield variation (10–50%) was explained using the four latent variables compared with the original soil and terrain attributes. Nevertheless, this approach allowed for an improved interpretation of soil and terrain attributes effects on cotton yields between years and treatments.

The latent variable ‘soil degradation’ accounted for the highest portion of cotton yield variation on all treatments in the 2001 and 2002 dry seasons, and was negatively related with yield. In both years, Factor 1 was the first latent variable selected for the stepwise regression for the conventional systems, and was more correlated to conventional than conservation yields (data not shown). This suggests that during dry seasons, eroded and degraded conditions had higher impact on cotton productivity of conventional systems compared with conservation systems.

The latent variable ‘runoff and wetness’ (Factor 2) was of minor importance in conservation systems, but was the second most important term in conventional system regression in dry years. This implies that in dry conditions, factors related to runoff and water movement across landscapes had greater effects on yield of conventional systems compared with conservation systems. As stated before, we speculate that residue cover in conservation systems had positive effects on infiltration across the entire field independent of the landscape position.

The latent variable ‘texture’ (Factor 3) was positively associated with yield of conservation systems in the year 2001, but was negatively associated with yield of conventional systems in the wet year (2003). No effects of this latent variable were observed either on conservation or conventional yields in the driest year (2002).

Factor 4 (‘soil drainage’) was the most important latent variable explaining cotton yield variation of conservation systems in the wet year (2003). Although this factor was also related to conventional systems yields in 2003, its effect on conventional systems was not only greater in the 2001 dry season but was also opposite. During 2003, water often accumulated in field drainageways resulting in excessive wetness of those areas. The fact that field drainage was more highly correlated with conservation than with conventional systems yields in 2003 suggests that surface residue effects on infiltration and evaporation may have aggravated crop wetness stress in some landscape positions in this system.

Management Zones

Variable selection for cluster analysis was based both on factor loadings (Fraisse et al., 2001) and correlation with yield (Table 3 and 4). Elevation, slope, CTI, EC_{30}, EC_{90}, surface clay content, sand content, SOC and depth to SHWT were the variables selected for cluster analysis and zone delineation (Fig. 2). Performance indices (fuzziness performance index and normalized classification entropy) (Fridgen et al., 2004) differed in the optimal number of clusters for our field (2–6). The yield variance reduction as a function of number of clusters was used as an additional approach for obtaining the optimal number of zones for each treatment × year combination (Fraisse et al., 2001). In general, subdivision of the field into increasing number of clusters (2–6) reduced cotton yield variance on all treatment × year combinations (18–48%). However, differences on the optimum number of clusters and the total variance reduction were observed between years and treatments (Table 6).

In CT, the maximum decrease in yield variance was obtained by dividing the field into five to six clusters that explained 38% of the yield variance in 2001, 20% in 2002, and 16% in 2003. On the other hand, maximum variance reduction on CT_{manure} was achieved with four to six clusters, depending on the year. The variance proportion explained by these clusters on this treatment was relatively high and stable between years (39–46%). In contrast to CT, maximum yield variance reduction for NT was achieved in the driest (2002) and wettest (2003) seasons when six clusters explained 33 and 45%

Table 6. Within-cluster maximum cotton seed yield variance reduction (with optimum number of clusters) as affected by year and management system in a 9-ha field-scale experiment in east-central Alabama.

	Maximum yield variance reduction		
Treatment	**2001**	**2002**	**2003**
	(%)		
Conventional system	38 (6)†	20 (6)	16 (5)
Conventional system + manure	39 (6)	46 (4)	41 (5)
Conservation system	23 (4)	33 (6)	45 (6)
Conservation system + manure	17 (5)	18 (3)	48 (6)

† Values in parentheses represent the number of clusters needed to achieve maximum variance reduction.

of the yield variance, respectively. Maximum yield variance reduction for $\mathrm{NT}_{\mathrm{manure}}$ was observed in 2003 and required a higher number of clusters compared with the two dry seasons.

Fraisse et al. (2001) found that the optimum number of clusters for Missouri grain fields varied year to year due to weather conditions and crop. In their study, clusters explained a higher portion of the crop yield variability in dry years compared with wet years; they suggested that a larger number of clusters might be needed in relatively dry years. However, this was not the case for cotton in our study.

Since the maximum variance reduction was achieved with four to six clusters for most treatment × year combinations, we chose five clusters to compare yields of different treatments on the landscape (Fig. 3). Averages of soil properties and terrain attributes for each of the five clusters created are presented in Table 7.

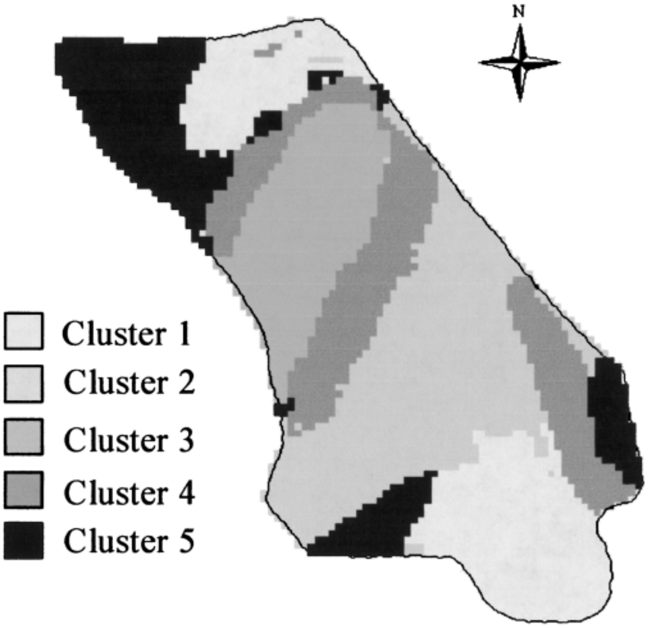

Fig. 3. Fuzzy *k*-means classification of a 9-ha field in east-central Alabama into five zones using the following soil properties (0–30 cm) and terrain attributes: elevation, slope, compound topographic index, electrical conductivity (0–30 and 0–90 cm), sand content, clay content, soil organic C, and seasonal high water table depth.

Cotton Yield Responses to Soil Management Systems within Clusters

Cotton yield responses to soil management practices within clusters were significant in most situations (Fig. 4). Conservation systems had equal or greater productivity than conventional systems in all cluster × year combinations. Although no clear effect from manure addition was found in the whole field analysis, manure increased yield in some clusters in the conventional system. Single degree of freedom contrasts indicated that $\mathrm{CT}_{\mathrm{manure}}$ had similar yields as NT on 6 out of 15 possible cluster × year combinations. Yield responses to manure amendments in conservation systems were not evident.

For discussion purposes we will concentrate on the three clusters (Clusters 2, 3, and 4) that typify the landscape variability (Fig. 3). Cluster 2 is an elevated area of relatively flat topography (summit) dominated by well drained soils (Typic Paleudults) with sandy surfaces and a deep SHWT. Manure increased the 2002 to 2003 yields in the conventional system in Cluster 2, but conservation systems had consistently higher yields than conventional systems in this upland landscape.

Cluster 3 corresponded to a concave drainage way position occupying the lowest elevation in the field with more poorly drained soils (Aquic and Oxyaquic Paleudults). This landscape accumulates eroded sediments from upslope areas and has relatively high SOC. No yield differences were observed between treatments on this cluster in the 2002 drought, but conservation systems resulted in greater yield than conventional in the other years.

Cluster 4, corresponded to areas situated on sloping eroded soils with high EC and clay content, and low SOC and CTI. Conservation systems yields on Cluster 4 were consistently greater than conventional system yields.

Evaluated over all years, maximum relative yield differences between conservation and conventional systems were observed in Clusters 2 and 4 (19 and 16%, respectively), and minimum relative yield differences were observed in Clusters 1 and 3 (7 and 10%, respectively).

In 2001, conservation systems and conventional systems had maximum yields within Cluster 3, and minimum yields within Cluster 4. In 2002, Clusters 4 and 5 were the low yielding clusters for both systems, and the highest yields in conventional systems were obtained in Cluster 3. Finally, in the wet year, clusters of highest and lowest productivity were virtually the same for both systems (Clusters 2 and 3, respectively). Although rainfall disparities existed, yield differences between the highest and the lowest productivity clusters in conservation systems was 17 to 18% in all years. In contrast, yield differences between the high and low yield clusters in conventional systems were 18% in 2001, 35% in the driest year (2002), and 12% in the wet year (2003). The aggregate of these findings suggests conservation systems reduce cotton yield variability on these Coastal Plain soils.

Table 7. Average soil properties (0–30 cm) and terrain attributes within the five clusters developed by *k*-means clustering in a 9-ha field-scale experiment in east-central Alabama.

Variables†	Elev	Slope	CTI	EC_{30}	EC_{90}	SHWT	Sand	Clay	SOC
	m	%		—— mS m^{-1} ——		cm	—— g kg^{-1} ——		
Cluster1	**69.8**	**1.0**	**7.5**	**5.5**	**6.7**	**79**	**519**	**182**	**6.3**
Cluster 2	**70.1**	**0.8**	**7.5**	**5.0**	**6.3**	**150**	**556**	**191**	**5.6**
Cluster 3	**68.5**	**1.7**	**8.1**	**4.6**	**6.0**	**61**	**573**	**143**	**6.0**
Cluster 4	**69.4**	**3.3**	**6.8**	**7.2**	**7.6**	**132**	**552**	**193**	**4.7**
Cluster 5	**69.6**	**1.3**	**7.4**	**5.6**	**5.9**	**73**	**533**	**211**	**5.5**

† Elev = elevation; CTI = Compound Topographic Index; EC_{30} = soil electrical conductivity 0–30 cm; EC_{90} = soil electrical conductivity 0–90 cm; SHWT = seasonal high water table depth; SOC = soil organic carbon.

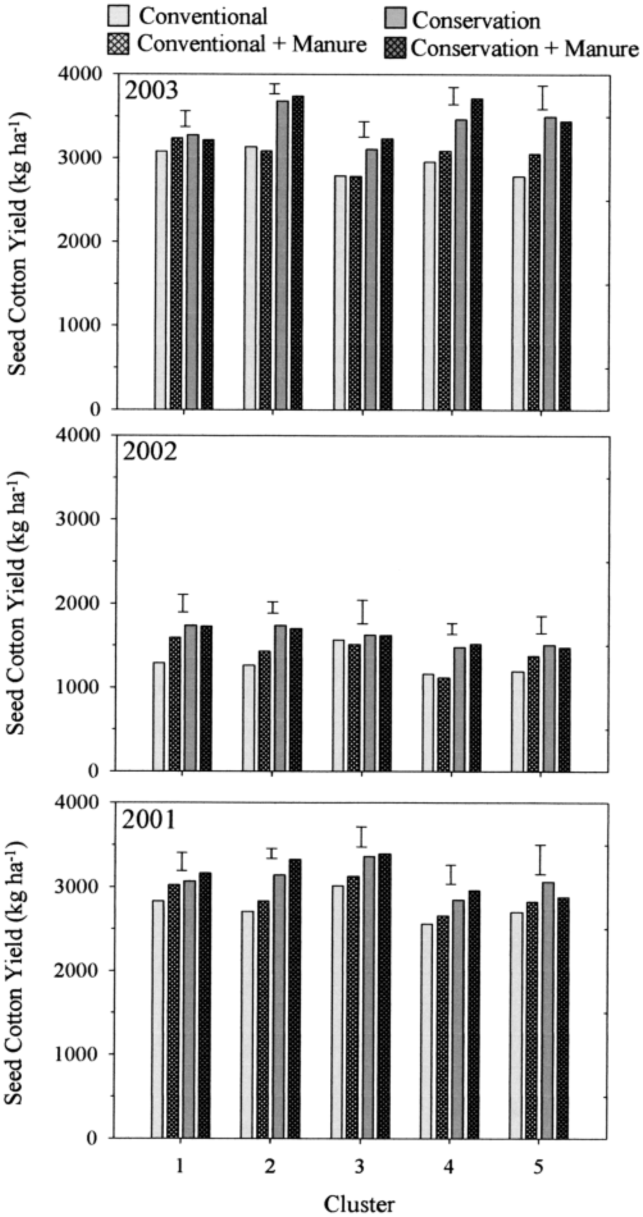

Fig. 4. Effect of soil management system and manure addition on seed cotton yields within five clusters of a 9-ha field-scale experiment in east-central Alabama (2001–2003). Vertical bars indicate LSD $_{(0.05)}$.

CONCLUSIONS

Elevation, slope, CTI, EC, texture, and SOC were most highly correlated with seed cotton yield under most treatment × year combinations. Soil and terrain attributes explained 16 to 64% of yield variation, but their significance varied between years and treatments. Factor analysis was a useful tool for identifying groups of correlated field variables (latent variables) that were related to cotton yield. In dry years, latent variables linked with soil degradation and runoff and wetness were more highly related to conventional systems yields than to conservation system yields.

Field subdivision into increasing number of clusters reduced cotton yield variance on all treatment × year combinations. In extreme rainfall years (2002 and 2003), a higher proportion of variance reduction was obtained for NT than CT, suggesting that soil management practices affect management zones. Our data suggests that for our site, cluster analysis using terrain variables was more suitable for delineating management zones in NT than in CT.

In our 3-yr trial, conservation systems averaged 14% greater yields than conventional systems over the entire field. The maximum relative difference between conservation systems and conventional system yields (33%) was observed in 2002 within Cluster 4, suggesting that conservation systems have greater yield response relative to conventional systems in dry years on eroded landscape positions with degraded soils in these southeastern coastal plain settings. However, conservation systems had higher yield than conventional systems in most cluster × year combinations suggesting that this management practice can increase cotton productivity and improve yield stability under several environmental conditions even during the transition period from conventional to conservation practices.

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