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SITE-SPECIFIC ANALYSIS

Site-Specific Analysis of a Droughted Corn Crop: I. Growth and Grain Yield

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ABSTRACT

Soil in the southeastern USA Coastal Plain exhibits marked variation, especially near shallow depressions called Carolina Bays. This variation causes correspondingly severe variation in yield, particularly for corn (*Zea mays* L.) during drought. Though important to precision farming, these features often are overlooked in 1:20 000 scale county soil surveys. They are visible in 1:1200 scale soil surveys, but the ability to explain yield variation using soil map units at this scale must be unequivocally demonstrated before committing resources to such a detailed survey. Our objectives were (i) to compare paired samples of four soil map units to determine if grain yield variation were sufficiently explained to be of practical value, and (ii) to extend this evaluation to include data with greater spatial coverage. Corn grain yields were measured at 209 sites in an 8-ha field, including two Carolina Bays near Florence, SC. Site-specific effects of soil variation on crop phenology, biomass, and yield components were measured at 11 sites during a drought. Variations in yield components were large and sometimes compensatory (e.g., kernel number and mass), with distinctly different routes to sometimes similar final grain yields. Multiple sites within map units were frequently different at $\alpha = 0.05$. Analysis of variance for grain yield on soil map unit was statistically significant ($P < 0.001$) but of limited explanatory value ($r^2 = 0.16$). We conclude that to create soil management zones for precision farming, one must augment even detailed soil map units with additional spatial data, such as yield maps.

THE CURRENT TECHNOLOGY-DRIVEN INTEREST in precision agriculture has created increasing demand for agronomic knowledge. This knowledge, in the form of site-specific guidelines, recommendations, and simulation models, is both difficult and expensive to obtain on spatial scales appropriate for use in precision farming. These difficulties accrue for two reasons. First, classical, replicated, empirical statistical methods are not well suited to address spatial problems. Further, the multitude of causes and effects operating to create spatial variation within a field poses a challenge to even the most advanced experts or simulation models.

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Research needs in precision farming (Holzhey, 1993) included research and development both to account for soil variability, management, and temporal variability, and also to build new tools, including measurement of physical properties, determining influences of management, and integrated models of crop growth and nutrient fluxes. The need was emphasized for both field sampling and exploratory use of models, plus a better understanding of processes involved. These needs still exist, as seen in research and development needs listed in later conferences in the USA (Robert, 1996) and in Europe (Stafford, 1997).

The geostatistical treatment of spatial variability can describe variation in space of parameters of interest and illustrate relations among variables, but cannot directly address what cause-effect relationships exist, and so must instead rely on knowledge of the underlying science to provide such information. The application of geostatistics to precision farming in general was summarized by Mulla (1993) and Nielsen et al. (1995). Because of the underlying empirical basis of the approach, geostatistical results would be expected to apply best within regions very similar to those in which they were obtained. Limited work in the southeastern USA Coastal Plain includes descriptions of spatial variation of physical parameters for several soil types (Cassel et al., 1988), correlation of some crop parameters to the landform type (Thomas and Cassel, 1979; Simmons et al., 1989), and descriptions of grain yield and spatial observations (Sadler et al., 1995; Sadler, 1998).

Explaining spatial variation using simulation models in precision farming was summarized by Sadler and Russell (1997), who listed several difficulties in applying 1-D models to 3-D problems. Of these, some have been addressed, such as the programming overhead of accomplishing multiple runs. Others are more problematic, such as the scale of model application being much more resolved spatially than the scale of model development. One problem is that the causes of grain yield

Abbreviations: DAP, days after planting; DOY, day of year; GPS, global positioning system; LAI, leaf area index; TDR, time-domain reflectometry.

variation have not been determined, so they cannot yet be built into models; another is that model inputs are not readily available at the subfield scale needed (Robert, 1996; Sadler and Russell, 1997). This latter issue ties in with the difficulties mentioned above in the empirical approach to explaining variation; though done for different reasons, both empirical and theoretical approaches need spatial characterizations of the crop response and soil resource.

At least one crop response, grain yield, is now obtainable on large areas using commercial yield monitors. Grain yield maps from both research fields (Karlen et al., 1990; Sadler et al., 1995) and producers' fields (Sadler et al., 1999) in the southeastern Coastal Plain have documented variation in crop grain yields, including corn in both normal and drought years. However, it is not clear whether grain yields alone can serve as a bioassay of soil productivity, or whether within-season, temporal variation in weather would interact with the soil, through, for instance, water holding capacity, and thus require additional measurements. An ideal crop on which to test this question is corn, known to be sensitive to timing of water stress (Shaw, 1988).

The soil resource presents both opportunities and challenges. The USDA-NRCS county soil survey is an inviting resource, though the scale of the survey is more suited to explain interfield than intrafield differences. Despite lack of correlation between within-field grain yield and the county-level soil survey, availability of the data and mapping personnel make it important to determine if traditional survey methods can contribute to precision farming, even if applied at detailed scales.

A suitable research resource to evaluate this question on the USDA-ARS Research Center is a representative field mapped at 1:1200 scale (USDA-SCS, 1986). The field had been mapped for grain yield continually since 1985 following conventional local farmer practice, including disking, field cultivation, and in-row subsoiling for row crops. The field studies had been initiated to document inherent variation among and within soil map units and to provide data that could be compared with the results of mechanistic computer simulation models, including CERES-Maize (Tsuji et al., 1994). Preliminary results suggested that the models did not adequately describe the soil water balance (Stone and Sadler, 1991). Field observations of grain fill occurring well after models simulated crop maturity during 1992 suggest that they also did not correctly simulate crop phenology. Thus in the 1993 corn season, particular emphasis was placed on observations of these soil and crop characteristics.

The objectives of this paper were (i) to compare paired samples of four soil map units (mapped at 1:1200 scale) to determine if grain yield variation were sufficiently explained to be of practical value to precision farming, and (ii) to extend this evaluation to include data with greater spatial coverage.

Table 1. Soil types for sites in the study. Sites 1 to 8 had TDR measurements and 7 June measurements; the remaining three sites were added after observations made on 7 June and had neither of those data sets.

Sites 1, 2	A local inclusion that underperformed expectations for Goldsboro loamy fine sand (GoA; 0–2% slopes; fine-loamy, siliceous, subactive, thermic Aquic Paleudult).
Sites 3, 4	The predominant map unit, Norfolk loamy fine sand (NkA; moderately thick surface, deep water table, 0–2% slopes; fine-loamy, kaolinitic, thermic Typic Kandiudult), which has the highest expected yield.
Sites 5, 6	Bonneau loamy fine sand (BnA; 0–2% slopes; loamy, siliceous, subactive, thermic Arenic Paleudult), which produced high yields despite having the lowest productivity rating.
Sites 7, 8	A historically low-producing Coxville loam (Cx; fine, kaolinitic, thermic Typic Paleaqult).
Site 9	Emporia fine sandy loam (ErA; 1–2% slopes; fine-loamy, siliceous, subactive, thermic Typic Hapludult).
Site 10	Norfolk with a thicker surface horizon (NoA; thick surface, 0–2% slopes; fine-loamy, kaolinitic, thermic Typic Kandiudult).
Site 11	Noboco fine sandy loam (NfA; 1–2% slopes; fine-loamy, siliceous, subactive, thermic Typic Paleudult).

MATERIALS AND METHODS

Site

Research was conducted at the USDA-ARS Coastal Plains Soil, Water, and Plant Research Center, northwest of Florence, SC. An 8-ha field that included two Carolina Bays was chosen as representative of field size and soil types in the area. This field had a 9-yr history of grain yield mapping at the time of the study, as well as a 1:1200 scale soil survey conducted by USDA-SCS (now NRCS) staff in 1984. Geographic coordinates of the southwest corner of the field were 34°14′44″ N, 79°48′34″ W, as determined by averaging differential global positioning system (GPS) readings for a period of 1 h (Model GBX-6 with Coast Guard differential correction, Communication Systems International, Calgary, AB, Canada[1]).

Crop Culture

The field was disked on 9 and 23 Mar. 1993. Granular fertilizer was broadcast on 30 March at an application rate of 17–40–121–15 kg ha^{-1} N–P–K–S. On 8 April, metolachlor herbicide [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy1-methylethyl) acetamide, Ciba-Geigy, Greensboro, NC] was broadcast at an application rate of 2.8 kg ha^{-1} and incorporated. On 9 April (day of year [DOY] 99), 'Pioneer Brand 3165' corn was planted using a KMC in-row subsoil unit (Kelley Manufacturing Co., Tifton, GA) with Case-IH (Chicago, IL) Model 800 planters on 0.76-m spacing. On 11 May (DOY 131), 2,4-D [(2,4-dichlorophenoxy) acetic acid] was applied at a rate of 0.5 kg ha^{-1}. On 28 May (DOY 148), a sidedress N fertilizer of 112 kg N ha^{-1} was banded on both sides of the crop row. Corn was harvested from 16 to 24 September using a plot combine (GWC, Nevada, IA).

Representative Soils

Two sites were chosen for each of four soil map units to provide comparison within and among soil map units. The four soil map units were chosen to represent the range of soils within the field (Table 1). Each of these eight sites was instrumented with time-domain reflectometry (TDR) probes to monitor soil moisture to a depth of 1 m (Sadler et al., 2000).

[1] Mention of trade names is for informational purposes only. No endorsement is implied by the USDA-ARS.

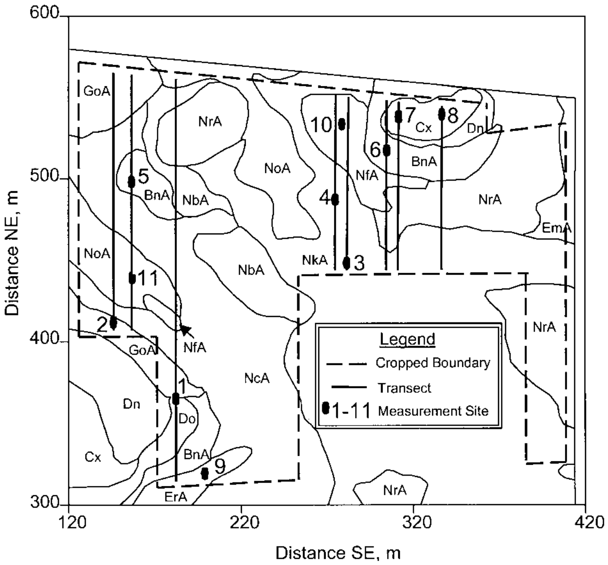

Fig. 1. Site plan for the 1993 corn study. Locations for eight original sites plus three additional representative sites are indicated, as are transect locations for spatial variation measurements during the season.

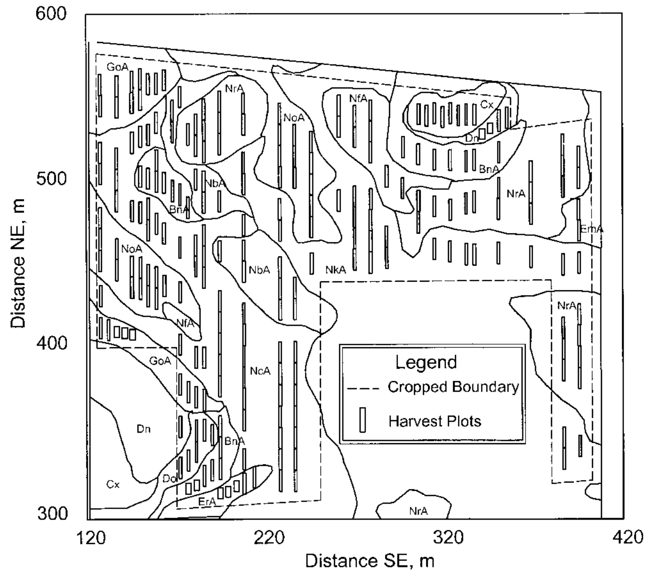

Fig. 3. Harvest plots overlaid on the soil map for the 1993 corn harvest.

Figure 1 shows the positions of these sites within the larger field. Surveying conducted after installation revealed that Site 1, which was to represent GoA, was placed by error near the boundary between GoA and Dunbar (Dn; clayey [revised July 1999 to "fine"], kaolinitic, thermic Aeric Paleaquult). However, the difference between these two units was less than between typical pedons of the two soils, and the two specific profiles were similar. All crop samples were taken from the GoA side of the site.

Low rain, high temperatures, and high radiation during the first 90 days after planting (DAP) (see Fig. 2) led to drought stress, which caused substantial differences in plant growth and development. By mid-June, we had decided to analyze grain yield, growth, morphology, and yield components at three additional sites (Sites 9–11 in Table 1). The Noboco is similar to the Norfolk, but with a higher water table during part of the year. Expected productivity on these three map units was similar to that of Norfolk.

From that time on, at all 11 sites, measurements were made of phenology, biomass, leaf area, and yield components at various growth stages during the season. The phenology measurements were made by repeatedly rating 10 plants each direction in the same rows as the TDR sites (20 plants at the three additional sites) for tasseling, silk emergence, and blacklayer. Dates were recorded when 50% of the plants had reached these developmental stages.

On 7 June (57 DAP), plant height, leaf area, and biomass had been measured on 3.05-m samples of crop row at Sites 1 to 8. At that time, height was determined using a ruler placed on the soil surface (flat culture) and measuring to the top of

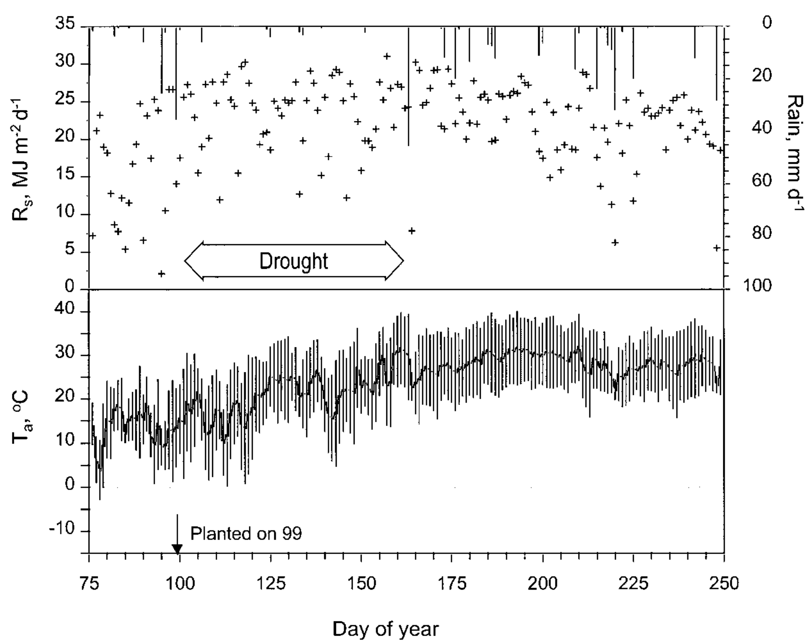

Fig. 2. Daily air temperature (T_a) extremes, daily solar radiation (R_s), and daily rainfall during 1993. Note the lack of appreciable rain from Day 100 to Day 164, with high temperatures and solar radiation.

Table 2. Days after planting (DAP) to 50% tasseling, silking, and blacklayer for the 11 sites. Date of planting was 9 Apr. 1993, and date of emergence was 18 Apr. 1993. No differences were observed among soil types for seedling emergence date.

Site	Soil	50% tasseling DAP	50% silking DAP	50% blacklayer DAP
1	GoA	80	84	123
2	GoA	78	82	114
3	NkA	78	83	121
4	NkA	81	86	123
5	BnA	80	83	128
6	BnA	75	79	116
7	Cx	76	80	111
8	Cx	75	76	112
9	ErA	72	74	111
10	NfA	72	73	110
11	NoA	75	77	119
Minimum		72	73	110
Maximum		81	86	128
Range		9	13	18
Min./max.		0.889	0.849	0.859

Table 4. Corn height, leaf area index, and aboveground biomass measured near midsilk, from a single 2-m sample. Height is an average of all plants in sample; the other values are totals for the sample.

Site	Soil	Sampled DAP	Height	LAI	Biomass
			m	$m^2\ m^{-2}$	$g\ m^{-2}$
1	GoA	84	0.90	0.85	–†
2	GoA	82	1.31	0.81	211
3	NkA	83	1.00	0.75	–
4	NkA	91	1.27	0.64	–
5	BnA	83	1.02	1.14	–
6	BnA	80	1.08	1.05	241
7	Cx	80	1.33	0.95	280
8	Cx	80	1.66	1.39	354
9	ErA	80	1.28	1.67	289
10	NfA	76	1.49	1.27	198
11	NoA	76	1.48	1.00	289
Minimum			0.90	0.64	198
Maximum			1.66	1.67	354
Range			0.76	1.04	156
Min./max.			0.54	0.38	0.56

† Biomass samples lost in handing.

plant tissue directly above the stem. At 50% silking, the same measurements were taken on single 2-m samples of row at all 11 sites, but with height determined from the end of the stalk, which had been cut at the soil surface, to the bottom of the tassel. For the same 2-m samples, total leaf area was measured with a leaf area meter (Model Li3100, Li-Cor, Lincoln, NE), and total aboveground biomass was calculated as the mass of tissue after drying for 3 d at 70°C. At this time, potential kernel number for each ear was found by multiplying the number of rows by the number of potential kernels in the rows. At the time of the final combine harvest, two 3.05-m samples of row were hand-harvested to determine final yield components. A mechanical sheller was used to thresh the grain. Subsamples (ranging from 340 to 754 kernels) were dried for 3 d at 70°C; then kernel number and dry mass were determined.

Additional Spatial Measurements

Plant Height Measurements

Corn growth was extremely variable because of the drought, so on 7 June, at the time of plant height measurements at Sites 1 to 8, plant height was also measured at 10-m intervals along the rows that included those sites (Fig. 1 shows transects). On 23 June, heights were recorded for all plants monitored for phenology at all 11 sites.

Plot Grain Yield Measurements

Site-specific harvest plots were obtained similarly to earlier years (Karlen et al., 1990). Individual plots (~18 m^2) were planned based on computer-aided drawings of the field (Fig. 3) and were flagged in the field. Then, a field plot combine was used to harvest the corn. Plots were attributed to the corresponding soil type from the map. Grain yields from the four harvest plots nearest to each of the 11 representative sites were extracted for comparison. Relative yield was calculated by dividing all plot yield data by the mean yield for the field. Maps were produced by kriging with GSLIB geostatistical software (Deutsch and Journel, 1992).

Data Analysis

The data collected in 1993 allowed an examination of variation in several physiological and physical characteristics of the crop, both in space and across soil map units. The four paired samples of soil types allowed direct comparison between the two sites per map unit using *t*-tests (SAS Inst., 1989). For transect measurements and plot grain yields, analysis of variance was used with soil map unit as a class variable (SAS Inst., 1989). Where possible in all tables, standard deviations, extremes, and the ratio between the minimum and maximum measurement are provided to document how much variation existed both in the samples and among soil types.

Table 3. Corn population, height, leaf area index, and aboveground biomass measured on 7 June 1993. These measurements preceded establishment of Sites 9–11.

Site	Soil	*n*†	Plants	sd	Height	sd	LAI	sd	Mass	sd
			no. m^{-2}		m		$m^2\ m^{-2}$		$g\ m^{-2}$	
1	GoA	3	4.6	0.9	0.68	0.01	0.38	0.02	61	5
2	GoA	3	4.2	0.2	0.91	0.14	0.66	0.35	92	26
3	NkA	3	3.7	0.9	0.61	0.05	0.16	0.03	43	7
4	NkA	2	4.7	1.2	0.61	0.05	0.20	0.13	47	14
5	BnA	3	3.9	0.4	0.62	0.03	0.18	0.07	42	3
6	BnA	1	5.2	–	0.87	–	0.44	–	80	–
7	Cx	1	6.0	–	0.82	–	0.44	–	80	–
8	Cx	1	3.4	–	1.23	–	1.22	–	131	–
Minimum			3.4		0.61		0.16		42	
Maximum			6.0		1.23		1.22		13	
Range			2.6		0.62		1.05		89	
Min./max.			0.57		0.50		0.13		0.32	

† *n* is the number of 3.05-m samples. Numbers varied because of concerns that destructive sampling would affect growth of corn remaining in the small map units.

Table 5. Potential kernels plant^{-1} determined at midsilk (see Table 1 for dates). Means and standard deviations computed from individual plant measurements on 8 plants site^{-1}.

Site	Soil	Mean	sd	Mean	sd	Mean	sd
		rows ear^{-1}		kernels row^{-1}			
1	GoA	14.4	1.6	45	3	644	56
2	GoA	17.3	2.7	37	6	643	143
3	NkA	14.5	1.4	51	2	736	63
4	NkA	14.8	1.8	42	5	624	115
5	BnA	14.4	1.3	50	4	717	80
6	BnA	15.0	2.7	40	4	587	94
7	Cx	14.5	1.1	40	4	574	70
8	Cx	15.5	1.1	42	8	648	140
9	ErA	13.2	1.2	42	4	550	62
10	NfA	15.5	1.4	43	5	670	106
11	NoA	13.5	2.1	43	5	590	133
Minimum		13.2		37		550	
Maximum		17.3		51		736	
Range		4.1		14		186	
Min./max.		0.76		0.73		0.75	

RESULTS AND DISCUSSION

Number of days from planting to tasseling, silking, and blacklayer (Table 2) had ranges from 9 to 18 d, or 11 to 15% of the maximums. As seen by later dates at the more stressed sites, stress delayed tasseling and silking. Sites 1 and 4, clearly visibly stressed during the early season, tasseled 8 and 9 d after Sites 9 and 10, chosen because they were not visibly stressed. Site 10 had the earliest midsilk date; Site 4 was 13 d later. No clear-cut result was obtained for days to maturity.

If stress delayed silking and shortened the grainfilling period, as suggested by Shaw (1988), differences in timing of maturity might be masked. Although differences in timing were relatively less than differences in other parameters, such subtle differences may prove important. This is because most simulation models drive phenology primarily with air temperature. With air temperature typically a common input across soil types at a location, most models cannot account for differences in timing of maturity across soil types. Thus, a small variation in timing may prove disproportionately important.

Plant population, height, leaf area index (LAI), and biomass on 7 June are shown in Table 3 for Sites 1 to 8 (Sites 9–11 were selected after this sampling date). Minimum values of population and height were about 50% of maximums. Minimum aboveground biomass was approximately 32% of maximum, and minimum LAI was about 13% of maximum. The minimum population and the maximum for the other parameters occurred at Site 8. The plant heights in Table 3 were taken on a single date, irrespective of development. Plant heights in Table 4 are at the same stage of development, near midsilk. Variation in height remained the same as on 7 June, while variation in LAI and biomass had moderated.

Potential values of yield components, determined at silking (Table 5), include rows ear^{-1}, kernels row^{-1}, and kernels ear^{-1} for each site. In general, the components are compensatory, with those having high rows ear^{-1} having moderate to low kernels row^{-1}, or vice versa. Site 2 had the highest rows ear^{-1} and the lowest kernels row^{-1}, making the product intermediate. Site 8 had intermediate values for all parameters. Conversely, Site 3 had moderately low rows ear^{-1} and the highest kernels row^{-1}, resulting in the highest value for kernels ear^{-1}. Site 9 had the lowest rows ear^{-1} and moderately low kernels row^{-1}, resulting in the lowest value for kernels ear^{-1}.

Harvest yield components are given in Table 6 for each site. Populations are somewhat different than those measured on 7 June with different sampling (see Table 3), further documenting short-range variation in these parameters. Ear density ranged from 3.0 to 6.0 m^{-2}. This was more than the variation in plant density, meaning there was wide variation in the number of barren plants (from 0 to 2.2 m^{-2}). As seen in potential values for yield components at silking, several of the values are compensatory. Site 3, for instance, had the second highest ear density, the highest kernel mass, and an intermediate kernel number, resulting in the second-highest grain yield. On the other hand, Site 8 had intermediate values for all yield components but kernel number, and the result was the highest grain yield. Sites 10 and 11 had the two lowest kernel mass and two of the three highest kernel numbers. Sites 2 and 4 had low kernel numbers, had intermediate to low ear densities and kernel masses, and produced the two lowest grain

Table 6. Yield components measured at harvest. Means and standard deviations are calculated from two 3.05-m samples per site. Plot yield is in dry mass; spatial grain yield is from the four nearest harvest plots, expressed here as dry mass.

Site	Soil	Plant density	sd	Ear density	sd	Kernel no.	sd	Kernel mass	sd	Plot grain yield	sd	Spatial grain yield	sd
		no. m^{-2}		no. m^{-2}		no. ear^{-1}		g kernel^{-1}		g m^{-2}		g m^{-2}	
1	GoA	4.9	0.3	3.7	0.9	231	63	0.19	0.04	174	118	140	29
2	GoA	6.7	0.3	4.5	0.3	175	17	0.16	0.06	128	71	130	36
3	NkA	6.0	1.2	5.4	0.3	243	32	0.23	0.02	302	27	256	53
4	NkA	5.2	1.2	3.0	1.2	195	7	0.18	0.02	104	28	155	61
5	BnA	6.2	0.3	6.0	0.6	223	18	0.21	0.04	288	102	257	31
6	BnA	5.6	0.6	5.2	0.6	159	33	0.15	0.01	125	35	138	92
7	Cx	5.4	1.5	4.9	1.5	154	23	0.16	0.01	126	49	128	75
8	Cx	5.6	0.0	4.5	0.9	378	75	0.19	0.01	318	15	327	81
9	ErA	4.7	0.6	4.3	0.6	283	41	0.19	0.02	228	24	200	23
10	NfA	4.9	0.9	4.5	0.3	369	87	0.15	0.01	248	91	180	67
11	NoA	4.9	0.3	4.9	0.3	390	9	0.15	0.01	278	8	222	63
Minimum		4.7		3.0		154		0.15		104		128	
Maximum		6.7		6.0		390		0.23		318		327	
Range		2.0		3.0		236		0.09		214		199	
Min./max.		0.70		0.50		0.39		0.63		0.33		0.39	

Table 7. Variation in plant height, measured to the topmost leaf tip, on 23 June 1993. Areas sampled were used for 50% silking and blacklayer determination.

Site	Soil	*n*	Mean height	sd	C.V.	Minimum	Maximum	Range	Min./max.
			m	m	%	m	m	m	
1	GoA	19	1.00	0.23	23.3	0.51	1.37	0.86	0.37
2	GoA	19	1.14	0.11	10.0	0.86	1.30	0.44	0.66
3	NkA	20	1.23	0.13	10.5	0.86	1.42	0.57	0.61
4	NkA	20	1.07	0.18	16.6	0.69	1.35	0.66	0.51
5	BnA	20	1.18	0.18	15.2	0.84	1.65	0.81	0.50
6	BnA	22	1.29	0.14	11.2	0.94	1.60	0.76	0.59
7	Cx	20	1.34	0.15	11.2	1.07	1.60	0.53	0.67
8	Cx	22	1.72	0.16	9.2	1.37	2.08	0.71	0.66
9	ErA	21	1.69	0.14	8.5	1.45	1.93	0.49	0.75
10	NfA	20	1.85	0.22	11.8	1.27	2.11	0.84	0.60
11	NoA	19	1.47	0.12	8.0	1.24	1.65	0.41	0.75
Minimum			1.00	0.11	8.0	0.51	1.30	0.41	0.37
Maximum			1.85	0.23	23.3	1.45	2.11	0.86	0.75
Range			0.85	0.12	15.2	0.94	0.81	0.45	0.38
Min./max.			0.54	0.48	0.35	0.35	0.62	0.48	0.50

yields. These two sites also had the highest number of barren plants, with 2.2 fewer ears m^{-2} than plants m^{-2}. This meant that ~1/3 of the resources were applied to nonproductive plants. Timing of reduction in yield components suggested variation in the timing of stress in the field. This is examined in a companion paper (Sadler et al., 2000) that reports soil water content and subsequent crop response to water stress.

On 7 June, plant height varied widely on the field scale. Heights ranged from 0.48 m near Site 1 to 1.34 m near Site 10. The plant height variation within and among sites on 23 June (Table 7) illustrated the variation in height observed over a distance of a few meters. Here, the heights were measured for all individual plants used for phenology evaluation ($n \sim 20$). In general, variation among map units appeared larger than that within map units, but the magnitudes were so similar that they reduced confidence in comparisons among map unit.

Evaluation of Within-Site Differences

Results of the *t*-test comparisons between sites within soils are given in Table 8. There were three separate sets of plant height measurements at each of Sites 1 to 8. For all three sets, at both Cx and GoA, the two sites within soils were significantly different at $\alpha = 0.05$. For two of the three sets at BnA and for one of the three sets at NkA, the two sites were different within soils. Overall, in 9 of 12 possible comparisons for plant height, the sites within soils were not the same according to the *t*-test at $\alpha = 0.05$.

Potential yield components, measured on 8 June, illustrate both the soil-to-soil differences and the compensation observed in several of the parameters. For BnA and NkA, rows ear^{-1} were similar between sites within soils, but kernels row^{-1} were different, and the product was different. For Cx, no parameter was significantly different between sites. For GoA, both components were different, but because of an inverse relationship, the product was not different. Final yield components, determined at harvest, were limited to $n = 2$ at each site, and the *t*-test appeared to lack the power to differentiate between sites for soils. In only 4 of 28 possible comparisons were the differences significant at $\alpha = 0.05$.

Two of those four significant differences, however, were obtained for grain yield. In addition, when the four closest plot grain yields were tested with the *t*-test, three of the four comparisons indicated that the means were significantly different between sites within soil (BnA, Cx, and NkA). This occurred despite the limited power of a *t*-test with just four measurements per site.

Evaluation of Transect and Spatial Data

Transect plant heights, measured on 7 June, included 125 data points on 11 soil map units. Analysis of variance using map unit as a class variable produced a significant

Table 8. *T*-test comparisons between sites within soils. Values are Prob > |*t*| values, and *n* indicates the number of measurements per site.

Parameter	BnA	Cx	GoA	NkA	*n*
Height, 7 June	0.0000*	0.0000*	0.0001*	0.9274	8–32
Height, midsilk	0.6679	0.0001*	0.0002*	0.1503	2–12
Height, 23 June	0.0374*	0.0000*	0.0219*	0.0021*	19–22
Rows ear^{-1}, 8 June	0.5677	0.0824	0.0217*	0.7645	8
Kernels row^{-1}, 8 June	0.0002*	0.5177	0.0081*	0.0010*	8
No. kernels, 8 June	0.0099*	0.1983	0.9679	0.0292*	8
Seed % N at harvest	0.3989	0.0593	0.8382	0.2594	2
Grains ear^{-1}	0.1254	0.0660	0.4435	0.0306*	2
Plants m^{-2}	0.3118	0.8600	0.0299*	0.5528	2
Ears m^{-2}	0.2929	0.7643	0.3333	0.1165	2
Kernel size, g	0.1595	0.1410	0.6060	0.1318	2
Kernels ear^{-1}	0.1381	0.0562	0.3499	0.1815	2
Grain yield, g m^{-2}	0.1672	0.0334*	0.6877	0.0192*	2
Four closest plot grain yield, g m^{-2}	0.0157*	0.0115*	0.1923	0.0464*	4

* Significant at the 0.05 probability level.

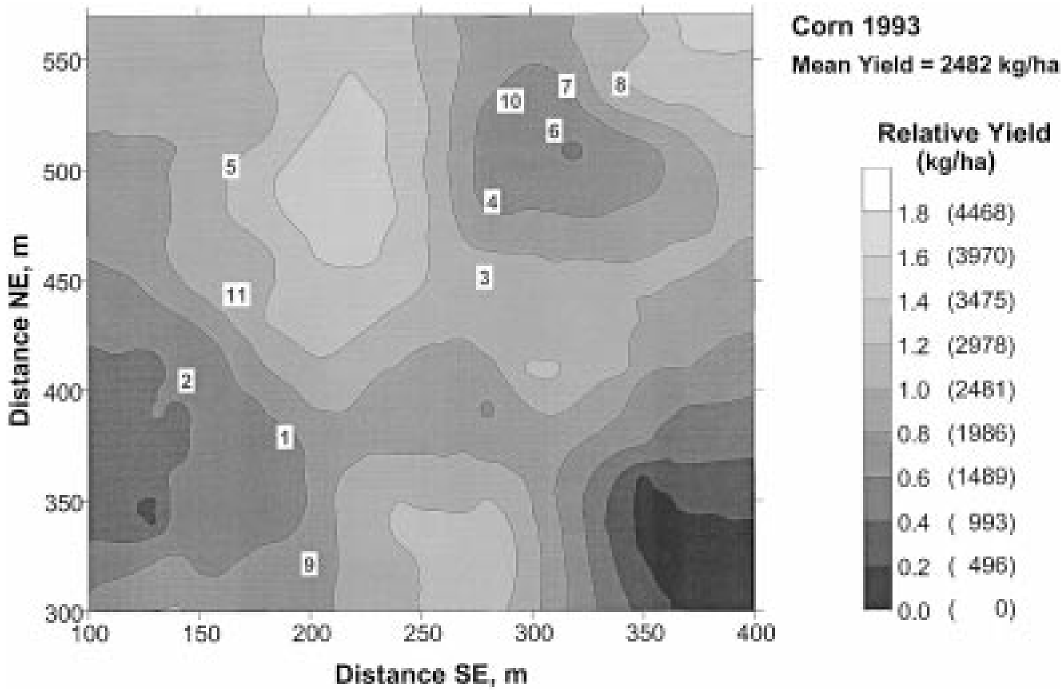

Fig. 4. Relative corn yield, computed as harvest plot yield divided by the field mean, kriged and mapped over the sampling area. Numbers show locations of sites.

relationship (Prob > F = 0.0001) that explained 40% of the height variation on that date. That 60% of the variation was not explained is consistent with the observation above that 9 of 12 possible t-tests for plant height indicated that significant differences existed within soils.

Grain yield (155 g kg^{-1} moisture) for the 209 plots in the entire field averaged 2481 ± 916 kg ha^{-1} and ranged from 214 to 4849 kg ha^{-1}. Comparison of the soils map (Fig. 1) and the kriged map from plot combine grain yields (Fig. 4) suggests some, but not total, correspondence. Analysis of variance using map unit as a class variable was statistically significant (Prob > F = 0.0007), but the relationship could explain little grain yield variation (r^2 = 0.155). Again, both the t-tests and analysis of variance consistently indicated that variation within soil map units was sufficiently large that soil map units alone did not explain an appreciable amount of the grain yield variation.

These data indicated that corn growth under stress in the southeastern Coastal Plain is quite complex. Under drought stress, large differences are seen in most measurable parameters, both within and among map units. Variation in LAI and biomass during vegetative growth on 7 June was very large—87 and 68% of the maximum, respectively. Also on that day, variation in height was about 50% of the maximum. By midsilk, variation in LAI had dropped to 62% of the maximum and in biomass to 44% of the maximum. Variation in potential kernel number was about 25% of the maximum observed. By harvest, the actual kernel number was, as expected, more variable—about 61% of the maximum. Minimum kernel weight and ear number per unit ground area were, respectively, 38 and 30% of the maximum. Final grain yield at the 11 sites varied from 125 to 318 g m^{-2} dry mass with a range equaling 67% of the maximum.

Very little correlation was found among any simple combination of crop characteristics. Specifically, final number of kernels per ear was not dependent on potential number, on mass per kernel, nor on LAI at midsilk. As pointed out by a reviewer, the biomass and final grain yield information hints that harvest index might be a worthwhile candidate for modeling final grain yield after drought stress.

SUMMARY AND CONCLUSIONS

The season's results illustrate that not only is there considerable variation in grain yield for this field, there is also considerable variation in how these yields were achieved. Fully explaining the relationships among crop, soil, and weather that were represented in this severe test are almost certainly beyond classical statistical methods and may well be beyond the capabilities of current process-level models. However, if such interactions are significant in the more typical, nondrought case, then future modeling efforts should address these relationships to develop the knowledge base needed to fully implement precision farming technologies.

Aside from the complexities of the relationships observed, the season's results conclusively prove that, despite the detail embodied in the 1:1200 scale soil survey used, grain yield variation within soil map unit was too large for the soil survey alone to be used to create homogenous soil management zones for use in precision farming in the southeastern USA Coastal Plain. These results support the need for on-the-go measurements of soil properties and plant response that could be used in conjunction with soil surveys to create management zones that can be used, either in models or by themselves, to predict grain yield.

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