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Spatial Scale Requirements for Precision Farming: A Case Study in the Southeastern USA

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ABSTRACT

Precision farming has created a critical need for spatial data on crop yield and related soil characteristics. However, because data are not without cost, users need practical guidelines for spatial resolution on which to collect soil and plant data. Our objectives were (i) to describe variation observed in crop response in the southeastern Coastal Plain of the USA, (ii) to compare it with variation in other regions, and (iii) to offer suggestions for precision farming practices in the southeastern Coastal Plain. From 1985 to 1995, corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.], and grain sorghum [*Sorghum bicolor* (L.) Moench] yields were mapped at from 10- to 20-m resolution in an 8-ha field at Florence, SC. Also available were topography (30-m resolution), depth to clay (15 m), and in 1993, plant height on one date (9 m), canopy temperature on four dates (1.5 m), and detailed crop and soil information at selected sites. Yield of all crops in all years was significantly ($P <$ 0.0007), though not strongly (median r^2 = 0.3), correlated with soil map unit. In 1993, infrared thermometer canopy temperature minus air temperature (ΔT_c) was correlated with soil map unit, even on the second day after a 46-mm rain. Spherical semivariograms fitted to yields had ranges from 57 to 252 m (median = 79 m) and nugget/sill ratios from 0.00 to 0.56 (median = 0.32). Semivariograms for canopy temperature and plant height had ranges from 43 to 77 m. If the spatial structure for common soil characteristics matches the spatial structure for crop response, Coastal Plain soils may require study at finer resolution than the >100-m grid that is commonly used in precision farming.

PRECISION FARMING, or site-specific agriculture, arose from the convergence of several trends in the agricultural industry. The national soil survey (Soil Survey Staff, 1992), which documents spatial variation in the soil resource, is sufficiently complete in important agricultural areas at a time of growing awareness of variability at the still smaller intrafield scale. The scale of interest in soil variability is matched by improvements in the ability to determine position accurately, using differential global positioning system (DGPS) receivers. Specialized controllers for farm equipment have been developed to alter pesticide and fertilizer application rates within fields. Using these controllers to fine-tune chemical inputs to match needs is purported to offer both economic and environmental rewards. The effect of soil variation and spatial control of inputs is ultimately reflected in yields, which are measured with combine-mounted, on-the-go yield monitors. These provide unprecedented spatial yield data, requiring modern computer hardware and software for analysis. Collectively, these trends have resulted in a rapidly expanding precision farming industry.

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Production of spatial data is orders of magnitude greater and with finer resolution than ever before, and yet these data still do not satisfy industry's needs for decision making in areas such as pesticide requirements, target plant populations, or fertilizer recommendations. Acquiring data in two dimensions quickly forces one to confront the squared relation between resolution and cost—doubling the linear resolution requires four times as many samples. Clearly, intensive soil and plant sampling should be made at sufficient resolution to obtain necessary data, but at no more than is necessary. Newly emerged industries lack the long-term experience to judge data resolution needs, meaning that research is needed to obtain such answers. Because soil resource variability is a result of complex interactions among soil parent material, climate, and local processes, data resolutions will likely be specific to regions or smaller scales. Few guidelines exist to help make these decisions in the southeastern USA. Our objectives were (i) to describe variation observed in crop response in the southeastern Coastal Plain, (ii) to compare it with variation in other regions, and (iii) to offer suggestions for precision farming practices in the southeastern Coastal Plain.

SPATIAL RESOLUTION REQUIREMENTS FOR POINT SAMPLES

Spatial data imply that values depend on position. A corollary is that values near each other are more related than those farther apart. This relationship becomes poorer with distance until eventually the samples are independent of one another. The distance at which samples are no longer related is a useful starting point, but requires objective analysis of spatial data, which is not well handled by classical statistics. A solution was first developed in the mining industry, resulting in the field of geostatistics (Journel and Huijbregts, 1978). These analytical tools were applied to soil characteristics during the 1970s and 1980s, providing an early documentation of spatial data needs (Warrick et al., 1986). The converse of the independence relationship with distance is redundancy with proximity. Taking data closer together than necessary involves not only direct sampling costs, but also additional data storage and analysis costs for little information gain. Thus, the first indication of

Abbreviations: DAP, days after planting; DGPS, differentially corrected global positioning system; TDR, time-domain reflectometry; ΔT_c, canopy temperature minus air temperature. *For soil series abbreviations, see Table 2.*

the resolution required is provided by the characteristics of the data.

A second indication of the spatial resolution required is the representation of spatial data in existing databases. Webster and Oliver (1981) noted that from 25 to 50% of the variance in fields sized from 10 to 10 000 ha may occur within a few square meters. The question is what resolution captures the necessary variation? U.S. national soil survey maps are taken on a 1:12 000, 1:15 840, 1:20 000 (most common), or 1:24 000 scale (Mausbach et al., 1993). This means that the smallest resolvable detail on the map, say 1 mm, corresponds to a feature of 12 to 24 m in the field. For practical purposes, the minimum area of delineation is from 0.8 to 4.0 ha (Mausbach et al., 1993). For soils with no sharp changes in characteristics, such resolution would probably suffice. For instance, Steinwand et al. (1996) found that the 1:15 840 survey was sufficient for their fields in Iowa. However, the soils at Florence, SC, were mapped on a 1:1200 scale (USDA-SCS, 1986) to accommodate variation approaching field extremes within 10 m (Sadler et al., 1995b). Comparison of this 1:1200 map with the 1:20 000 Florence County survey map (Pitts, 1974) shows only a general resemblance. In particular, narrow bands of low-yielding soils are not represented on the large-scale map, because they are less than the minimum size for delineation. Although the spatial extent of these smaller inclusions is reported in the 1:1200 survey, the economic effect of the variable yields caused by small inclusions on the field-scale harvest has yet to be found. Detailed surveys published for site-specific management studies include 1:600 (Wibawa et al., 1993), 1:1200 (Sadler et al., 1995b), and 1:3305 (Steinwand et al., 1996).

A third indication of the spatial resolution required can be found from research and management practices in other regions. As grids become larger, the resolution of the data eventually becomes too coarse. Warrick et al. (1986) showed that the point at which this occurs depends both on the data being obtained and on the scale of the area of interest. Therefore, the remainder of this literature review includes only field-size areas (20–80 ha). Wollenhaupt et al. (1994) examined grid sizes from 32 to 97 m and concluded that the 97-m grid soil sampling interval was the maximum allowable for precision farming purposes. Mulla and Hammond (1988) sampled soils on 30-, 61-, and 122-m intervals and concluded that the last was too coarse for soil test maps in precision farming. Franzen and Peck (1993) found 30-m grids to be the maximum spacing for accurate application of fertilizer in precision farming. Similarly, Hergert et al. (1995) concluded that 61- to 91-m grids were the maximum spacing appropriate for Nebraska conditions. However, Thompson (1994) found that 61- by 61-m grid sampling did not provide sufficient resolution to optimize variable-rate N application. In the finest resolution located for this review, Wibawa et al. (1993) found that a 15-m grid sampling provided better data than a 1:600-scale soils map. Each of these studies has concluded that a finer resolution is needed to characterize spatial variation for precision farming than is currently used in commercial practice. Grid soil sampling reported for soil testing services include 101-m square grids (Macy, 1993; Holmes, 1993) and 101- by 134-m grids (Mann, 1993). This discrepancy is probably caused by a compromise between desired resolution and cost.

SPATIAL RESOLUTION CAPABILITIES

Real-Time Sensors

Sampling costs for point measurements, such as addressed above, usually dominate the considerations for choice of resolution. However, the cost structure for data obtained by on-the-go sensors is completely different. Here, a sensor typically is mounted on a mobile platform, such as a tractor or all-terrain vehicle that is moving through a field. Thus, spatial resolution in the longitudinal direction depends on the speed of the platform and the response time of the sensor. Spacing of the paths through the field determines lateral resolution and can be manipulated to affect overall spatial resolution (except for cases such as discussed below).

One on-the-go sensor that must operate at a speed and spacing controlled by factors other than its own characteristics is the combine-mounted yield monitor. It was created specifically to fit existing machinery, with an inherent range of operating speeds and machine widths. The width of the header may be the limiting factor for spatial resolution. Overall, it would be difficult to claim that accuracy in the forward direction must be much greater than some fraction (say, one-half) of the header width. The same could be said to hold for position determination; header width and errors in delay time through the machine may exceed errors in DGPS location (Lamb et al., 1995).

Photography and Remote Sensing

A final category of sensed information is inherently spatial in nature—data acquired essentially simultaneously over a two-dimensional space. Such methods include aerial photography and various spectral scanning devices mounted on aircraft or satellites. Platform height and equipment resolution dominate spatial resolution capabilities. For the spatial resolutions typically reported in precision farming literature (10–100 m), it appears that satellite data would be of limited usefulness, although plans for higher-resolution satellites exist. Aircraft platforms would be suitable, were they commonly available, because the capabilities of the equipment could be matched by adjusting altitude, again controlling resolution. Another consideration, important because of the dynamic nature of the data obtained, is temporal resolution. Costs to put a platform in place are not trivial, and scheduling of data acquisition is rarely left to the farm manager. Weather conditions and equipment problems may impair data acquisition, causing important temporal information to be lost.

Variable-Rate Equipment

Yet a third indication of the resolution with which spatial data must be taken is the resolution capability of the devices that use the data. Most farm equipment has a fixed control width (boom width or cutting head width), traveling at some velocity through a field, at a position usually sensed by DGPS. Each of these three factors implies some spatial scale. The width of equipment commonly ranges from ≈3 to ≈20 m, suggesting a potential limit to spatial data requirements (unless segments of a boom can be controlled separately). Variable-rate controllers appear to be capable of operating fast enough to achieve suitable spatial resolution along the direction of travel for most precision farming needs at most field velocities. Normally, the speed of action of most switches and valves is fast enough to control rates within a distance smaller than the width of most farm equipment, which means that controller speed would not be the limiting factor. Accuracy of position determination ranges from ≈0.1- to ≈10-m resolution, and carries with it its own acquisition and storage cost–benefit compromise (Tyler, 1993).

A final category of data use that has only recently become possible is that of site-specific irrigation through center pivots or linear move machines (Duke et al., 1992; McCann and Stark, 1993; Camp and Sadler, 1994). Resolution here is built into the machine design. Costs increase as resolution is increased, because increased resolution requires more discrete control between contiguous elements. Better resolution implies sprinklers with smaller wetted radii, which means more valves, more pressure regulators, and so on. Sprinkler package design is critical for both uniformity of application and separation among control elements. These requirements must be matched to both the variability of the soils involved and to the use to which the machine is put, such as field crops, research plots, or high-value vegetables. Resolutions built into these three known site-specific irrigation machines are about 30 m (McCann and Stark, 1993), 20 m (Duke et al., 1992), and 10 m (Camp and Sadler, 1994). These differences reflect differences inherent in soils, as well as differences in intended use.

In summary, studies of soil surveys suggest that a resolution much finer than the national soil survey is necessary for precision farming. Research on variability of soil test levels in field-size areas has shown required resolution to vary from 30 to 100 m, probably reflecting regional variation in soils. Commercial testing services, operating on tens of thousands of hectares, have used grids of 100 m or more, but little scientific evidence exists to support adequacy. Data illustrating spatial resolution of on-the-go sensors are limited, but preliminary conclusions can be reached for equipment such as combines, where resolution in the transverse direction will never be finer than the header width. Although resolution in the forward direction of on-the-go yield measurement on a combine is not limited in the same way, uncertainty in position and uncertainty in delay through the machine probably amount to a limit similar to the width. Resolution capabilities of variable-rate controllers do not appear to limit the technology. Aircraft-based resolutions can be manipulated to be adequate, though resolutions for current satellite-based methods may be inadequate for many parameters. Irrigation machines for precision farming have been designed for 10- to ≈30-m resolution. While a single answer to resolution requirements cannot be made, these results develop a context in which to interpret our findings from the southeastern Coastal Plain of the USA.

MATERIALS AND METHODS

The Florence, SC, precision farming project was started in 1984 with an engineering and soil survey. The engineering survey provided benchmarks at ≈100-m spacing on the property boundary and flagged points on a 30-m grid. The soil survey was started on a 15-m grid, with delineations pursued between grid points, and was drawn on a 1:1200 scale (USDA-SCS, 1986; Karlen et al., 1990). The soil map unit boundaries were digitized and entered into an ARC/INFO[1] (ESRI, 1994) geographic information system (GIS) on a Sun SPARC 1+ workstation (Sun Microsystems, Mountain View, CA). The original surveys also provided elevations on a 30-m grid and depth to an increase in clay content on a nominal 15-m grid.

Beginning in 1985, an 8-ha field was farmed to match local practice. Uniform, conventional cultural practices were used. Spatial yield measurements were made using a plot combine (ALMACO, Nevada, IA) in a stop-and-weigh mode on 10- to 20-m^2 plots, the locations of which were determined using surveying techniques. Plot boundaries were overlaid onto the soil map, and corresponding soil map units were attributed to the plots. Corn (for the soil definitions and map, see Karlen et al., 1990) was grown in 1985, 1986, 1988, 1992, and 1993; winter wheat was harvested in 1987, 1989, 1991, and 1994; grain sorghum in 1987; and soybean in 1989, 1990, 1991, and 1994 (a wet fall prevented harvest in 1994). The number of plots per season ranged from 130 to 612 (Table 1). For additional information regarding cultural practices, see Karlen et al. (1990) and Sadler et al. (1995b).

During the 1993 corn season, which proved to be a severe drought, additional spatial measurements were taken on eight transects in the field. Plant height was measured manually on 7 June (59 days after planting [DAP]) at a nominal spacing of 9 m ($N = 125$). Canopy temperature was measured with an infrared thermometer (Model 4000, 4° field of view, Everest Interscience, Tustin, CA) on 10, 14, 17, and 19 June (62, 66, 69, and 71 DAP, respectively) at an average spacing of 1.4 m ($N = \approx 800$ each day). As the operator walked each transect, the infrared thermometer was held ≈0.2 m above the row, pointed down and forward at a 45° angle to avoid including soil in the field of view.

At one site on each transect, soil profile water content was measured using time-domain reflectometry (TDR). Probes were inserted horizontally to represent soil horizons to a depth of 1.0 m, resulting in either five or six probes per profile. These were connected to a TDR (Model 1502B, Tektronix, Beaverton, OR) during waveform acquisition using a multiplexing system installed on a two-wheel hand truck (Sadler and Busscher, 1993). These measurements were obtained on 44 dates.

On the eight TDR sites and three additional sites, detailed plant measurements were also made. These included leaf area index, yield components, and phenology. See Sadler et al. (1995a) for additional information.

Analyses of these data, both of the accumulated long-term yields and of the detailed measurements, included both traditional statistics and geostatistics. Analysis of variance was done using PROC GLM of SAS (SAS, 1989). Geostatistical analysis

[1] Tradenames are used for the convenience of the reader and do not constitute an endorsement by the USDA-ARS.

Table 1. Summary statistics and analysis of variance of yield as a function of soil map unit.

		Summary statistics				Analysis of variance				
Crop	Year	Mean	SD	CV	N	df, numerator	df, denominator†	F-value	Pr > F	r^2
		— kg ha^{-1} —		%						
Corn	1985	6319	1642	26	130	8	70	14.72	0.0001	0.63
	1986	1871	961	51	143	9	135	19.40	0.0001	0.56
	1988	3510	1586	45	330	13	285	37.43	0.0001	0.63
	1992	7310	1236	17	256	12	244	7.28	0.0001	0.26
	1993	2482	919	37	209	12	196	3.00	0.0007	0.16
	Mean‡	4100	2090	51	989	14	974	16.39	0.0001	0.19
Wheat	1987	4937	1058	21	287	12	182	10.29	0.0001	0.40
	1989	4143	572	14	612	13	468	3.95	0.0001	0.10
	1991	1953	454	23	422	11	312	7.26	0.0001	0.20
	1994	2341	1093	47	359	15	228	7.99	0.0001	0.34
	Mean‡	3257	1347	41	1360	15	1229	5.16	0.0001	0.06
Soybean	1989	1841	387	21	193	11	182	4.75	0.0001	0.22
	1990	2291	348	15	229	11	221	8.13	0.0001	0.29
	1991	1406	626	45	271	11	261	6.95	0.0001	0.23
	Mean‡	1821	598	33	700	11	688	4.66	0.0001	0.07
Sorghum	1987	3257	1177	36	249	13	171	9.75	0.0001	0.47

† Number is less than N because analysis of variance was performed on pure map units only. Others are hybrids.
‡ Mean for crop over years.

was done using GS+ (Gamma Design Software, Plainwell, MI), GEOPACK (Yates and Yates, 1989), and the kriging option of ARC/INFO. Determining correspondence of data points that did not register exactly was done using nearest-neighbor methods in ARC/INFO. Cokriging of yield with either canopy temperature or depth to clay was done using GEOPACK.

Variography was used to indicate the range and spatial structure of the data. First, to meet assumptions of variography, spatial data were detrended. The procedure included fitting a plane surface to each dataset using SAS PROC REG, evaluating the plane surface at each data point, and subtracting the surface from the raw data. This produced a detrended dataset with mean of zero and variance reduced from that in the original data by a fraction equal to R^2 of the plane surface.

RESULTS AND DISCUSSION

Results from 1985 to 1988 showed a significant correlation between yield and map unit, with highly significant F ($P < 0.0001$) and r^2 from 0.40 for 1987 wheat to 0.63 for 1988 corn (Karlen et al., 1990). Results from 1989 to 1995 indicated that no r^2 values exceeded those for the first five crops (Table 1). This shift was presumably caused by weather or long-term change in the soil; cultural procedures were not altered. Results of an analysis of yield as affected by depth to clay (data not shown) produced results similar to those reported by Karlen et al. (1990), in that significance existed only for some soils and the direction of the effect was not consistent.

Table 2. Canopy minus air temperature (ΔT_c) for corn on four dates during June 1993. Means are for map unit, and minimum significant difference is by Waller's test (α = 0.05) in SAS PROC GLM. Rainfall of 46.5 mm occurred on 12 June.

	10 June 1993 (mean T_{air} = 38°C)			14 June 1993 (mean T_{air} = 28°C)			17 June 1993 (mean T_{air} = 30°C)			19 June 1993 (mean T_{air} = 31°C)		
	Soil†	Mean	N	Soil†	Mean	N	Soil†	Mean	N	Soil†	Mean	N
		°C			°C			°C			°C	
1	Do	11.1	27	Do	2.1	24	Do	6.9	25	Do	5.8	27
2	Dn	8.1	6	Dn	2.1	7	NcA	4.4	150	BnA	4.9	57
3	NcA	7.3	157	NfA	1.9	86	GoA	3.0	65	ErA	4.7	4
4	BnA	6.9	87	GoA	1.9	65	ErA	3.0	4	NkA	4.4	112
5	GoA	6.8	69	Cx	1.7	36	BnA	2.8	81	NcA	4.2	159
6	ErA	6.8	4	NcA	1.7	146	NkA	2.6	131	Dn	3.2	2
7	Cx	5.2	37	NbA	1.7	27	Dn	2.4	7	GoA	2.8	68
8	NkA	4.7	135	NkA	1.7	132	NoA	2.2	75	NrA	2.3	50
9	NfA	3.6	86	BnA	1.6	82	NrA	2.0	91	NoA	2.0	78
10	NrA	3.4	93	ErA	1.5	4	NbA	1.6	28	Cx	1.6	9
11	NoA	3.1	78	NrA	1.3	91	NfA	1.2	83	NfA	1.5	88
12	NbA	2.1	31	NoA	1.3	73	Cx	0.9	36	NbA	0.7	30
MSD (0.05)‡		1.7			0.5			1.0			1.9	
Field mean ΔT_c		5.4			1.7			2.8			3.3	

† Soil descriptions: BnA, Bonneau lfs (Arenic Paleudults). Cx, Coxville l (Typic Paleaquults). Dn, Dunbar lfs (Aeric Paleaquults); Do, Dunbar lfs, overwash. ErA, Emporia fsl (Typic Hapludults). GoA, Goldsboro lfs (Aquic Paleudults). NbA, Noboco lfs, mod. thick surface (Typic Paleudults); NcA, Noboco lfs, thick surface; NfA, Noboco fsl. NkA, Norfolk lfs, mod. thick surface, deep water table (Typic Kandiudults); NoA, Norfolk lfs, thick surface; NrA, Norfolk fsl.
‡ MSD, minimum significant difference.

Table 3. Crop yield geostatistics for the 13 crop-years in the precision farming project at Florence, SC.

Crop	Year	Mean	SD	CV	N	Active† Lag	Active† Step	Nugget†	Sill†	Range†	r^2	Nugget/Sill
		kg ha^{-1}	kg ha^{-1}	%		m	m	kg^2 ha^{-2}	kg^2 ha^{-2}	m		
Corn	1985	6319	1642	26	130	175	9	0.173	2.34	73	0.95	0.074
	1986	1871	961	51	143	200	12.5	0.005	0.70	59	0.69	0.007
	1988	3510	1586	45	330	250	25	0.001	1.73	72	0.82	0.001
	1992	7310	1236	17	256	270	10	0.527	1.53	156	0.89	0.345
	1993	2482	919	37	209	240	10	0.321	0.77	77	0.76	0.416
Wheat	1987	4937	1058	21	287	220	11	0.314	1.00	115	0.98	0.316
	1989	4143	572	14	612	220	11	0.151	0.35	213	0.95	0.430
	1991	1953	454	23	422	260	10	0.081	0.19	80	0.79	0.420
	1994	2341	1093	47	359	250	10	0.001	1.83	252	0.98	0.001
Soybean	1989	1841	387	21	193	220	10	0.059	0.15	57	0.90	0.399
	1990	2291	348	15	229	220	20	0.068	0.12	112	0.83	0.557
	1991	1406	626	45	271	220	10	0.088	0.29	79	0.80	0.308
Sorghum	1987	3257	1177	36	249	280	14	0.278	1.26	79	0.79	0.221

† Active lag, the distance to which variograms are computed; active step, the lag increment used. Nugget, semivariance at zero spacing. Sill, semivariance at spacing > range. Range, distance after which values are not correlated.

For the four dates during 1993, field means for corn canopy minus air temperature (ΔT_c) were 5.4, 1.7, 2.8, and 3.3°C (Table 2). The 10 June (62 DAP) ΔT_c ranged from 1.5°C below to 19°C above air temperature, which was 38°C. The mean for soil map units ranged from 2.1°C for NbA (Noboco lfs, moderately thick surface) to 11.1°C for Do (Dunbar lfs, overwash). Rainfall totaling 46 mm occurred on 12 June (64 DAP), relieving water stress. The next three dates show the progressive recurrence of stress.

Statistical analysis of these data show that there was a correlation ($P < 0.001$) between ΔT_c and soil map unit for all four dates. While expected on the first and last date, or possibly even the third, the existence of a relationship on the second date, 2 d after the rain, is particularly surprising. Soil moisture measurements at eight sites (Sadler et al., 1995a) indicated that infiltration in excess of 21 mm had occurred (46-mm rain; median infiltration ≈37 mm). Conventional expectations would hold that stress should not have recurred quickly enough to be detected in 2 d. However, mean ΔT_c ranged from 1.3°C for NoA (Norfolk lfs, thick surface) and NrA (Norfolk fsl) to 2.1°C for Dn (Dunbar lfs) and Do (Dunbar lfs, overwash). Researchers familiar with arid-area data may be surprised by the high values, but canopy temperatures above air temperature are common in the humid Southeast, where higher ΔT_c values are needed to dissipate radiative heating against the humidity gradient (Evans and Sadler, 1987; Sojka et al., 1990).

Corn canopy height on 7 June 1993 (59 DAP) also showed a correlation with soil map unit ($F = 7.51$, $P < 0.0001$, $r^2 = 0.40$), with a minimum mean of 0.68 m on Do (Dunbar lfs, overwash) and NcA (Noboco lfs, thick surface) and a maximum of 1.01 m on NfA (Noboco fsl). However, final yield was not significantly related to plant height at that time.

Geostatistical analysis of these data included calculating the semivariograms and fitting the best spherical model to the data using GS+. Summary statistics and variogram model parameters are shown for spatial crop yields in Table 3. Corn in 1985, 1986, and 1988 and wheat in 1994 had low nugget semivariances relative to the sills (<8%). This is consistent with strong spatial structure and low local variance. Eight of the 13 crop-years had a nugget semivariance of 30% or more of the sill, indicating either high local variation or low field-scale variation. The range parameter, indicating the distance beyond which values are no longer correlated, varied from 57 m for the 1989 soybean to 252 m for the 1994 wheat, with a median of 72 m.

Geostatistical analyses of all collateral data are shown in Table 4, with the 1993 corn yield repeated for comparison. As expected, ΔT_c shows much more variation than yield, with field-scale CVs from 53 to 88%. The local variance is large relative to the field variance, as shown by nugget/sill ratios ranging from 0.32 to 0.43. The ranges of the four ΔT_c datasets are smaller than those for that year's corn yield (and for most of the other

Table 4. Collateral spatial data obtained during the 1993 season and during the survey. Corn yield is repeated from Table 3 for comparison.

Variable	Year	Mean	SD	CV	N	Active Lag	Active Step	Nugget†	Sill†	Range	r^2	Nugget/Sill
				%		m	m			m		
Yield, Mg ha^{-1}	1993	2482	919	37	209	240	10	0.32	0.77	77	0.76	0.42
ΔT_c (10 June), °C	1993	5.4	3.7	69	810	80	2	4.22	13.23	45	0.97	0.32
ΔT_c (14 June), °C	1993	1.7	0.9	53	773	100	4	0.41	0.89	69	0.77	0.46
ΔT_c (17 June), °C	1993	2.8	2.2	79	776	100	2	1.77	4.09	66	0.84	0.43
ΔT_c (19 June), °C	1993	3.2	2.8	88	831	100	2	3.62	8.32	43	0.90	0.44
Plant height, m	1993	0.835	0.187	22	125	220	10	0.005	0.030	44	0.54	0.17
Elevation, m‡	1984	41.5	0.9	2	314	500	50	0.062	0.713	483	0.98	0.09
Clay depth, cm	1985	32.1	10.5	33	497	300	20	54.8	93.8	88	0.91	0.58

† Nugget and sill are expressed in units squared (with units as specified for each row).
‡ Elevation above sea level.

yield data as well). The ranges for plant height on 7 June (59 DAP) and depth to clay are comparable to the ranges for ΔT_c, which is consistent with expected relationships among these parameters.

An early objective of this work was to use depth to clay as a covariate for cokriging yield, because depth to clay is the primary physical characteristic used to discriminate among many similar soil map units. Given the greater intensity of the depth-to-clay dataset, we proposed that cokriging would decrease the estimation variance of the interpolated yield output. After the correspondence between the 209 yield plots and depth to clay was developed (data not shown), it was found that the variance in both yield and depth to clay resulted in a cross-semivariance that was not well suited to cokriging. Deleting the half of the points in the semivariogram that had fewer pairs resulted in a cross-semivariance that would operate in GEOPACK, but the resulting interpolated yield was little different from the simple kriged yield, and the estimation variance was actually higher (data not shown). This is consistent with Yates and Warrick's (1987) observation that the covariates need to be reasonably well correlated in order to improve the estimate. The difference between canopy and air temperature (ΔT_c), though intensively sampled in one direction, was sparsely sampled in the other (just eight transects), and too few data pairs resulted for successful cokriging. The quality of the semivariograms suggests that remotely sensed temperature data, with its better spatial coverage, may be of some value for cokriging.

SUMMARY AND CONCLUSIONS

As a result of analyses of long-term spatial yield and of intensive drought-year measurements, the following conclusions and recommendations can be made. First, field crop yields in the southeastern Coastal Plain of the USA were significantly related to soil map unit at the 1:1200 scale, but the relationship was too weak to be of more than limited predictive value for precision farming. The significant relationship between ΔT_c and soil map unit on all four sampling dates implies that water stress was caused by differences in soils. We conclude that remotely sensed canopy temperature (probably from an aircraft platform, to avoid clouds) could be a useful tool to detect water stress for precision farming.

Yield measurements showed that quantitatively important yield differences may occur in distances as short as 10 m. Such differences in plant uptake and residue mean that adapting fertility and other practices would require collateral soil test measurements at much finer resolution in the southeastern Coastal Plain than currently practiced elsewhere. Thus, grid-based sampling to capture all meaningful variation may be prohibitively expensive. Alternative sampling schemes are necessary, perhaps using soil mapping, yield mapping, or aerial photography to indicate areas needing characterization. Similar and more extreme short-range differences in canopy temperature suggest that irrigation management in precision farming may need even finer spatial resolution.

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