Precision Agriculture, 6, 379–398, 2005

Severity, Extent and Persistence of Spatial Yield Variation in Production Fields in the SE US Coastal Plain

E. J. SADLER sadlerj@missouri.edu
USDA-ARS, Cropping Systems and Water Quality Research Unit, Columbia, MO, 65211 USA

D. E. EVANS, B. K. GERWIG* AND J. A. MILLEN
USDA-ARS, Coastal Plains Soil, Water and Plant Research Center, Florence, SC, USA

W. THOMAS
USDA-NRCS, Kenansville, NC, USA

P. FUSSELL
NC Division of Soil & Water Conservation, NCDENR, 127 Cardinal Drive, Wilmington, NC 28405, USA

Abstract. In the US SE Coastal Plain, adoption of site-specific farming has lagged behind that in the upper Midwest. While reasons for this may be both social and economic, it appears that the importance of the problem represented by yield variation on production fields needs to be quantified before adoption would be considered by many farm operators. Our objective was to document the severity, extent and persistence of yield variation for corn, wheat and soybean during normal production in this region. Farmer combines were fitted with commercial yield monitors to produce yield maps. Corn, wheat and soybean yields were mapped for three years on more than 4900 ha (12,000 acres). For each cooperator, crop and year, summary statistics and cumulative yield distribution functions were also developed. Yield maps showed that substantial areas had yields either well below or above the mean for the cooperator-crop-year. For instance, 25% of Cooperator A's area had corn yields more than 30% below the mean yield of 5.06 Mg/ha and another 25% had yields more than 31% above that mean, which indicate the severity of yield variation. Variation from county to county had no consistent difference indicating that the extent of the variation is widespread. Variation was also persistent from year to year, with more than 50% of the area in 15 of 17 fields having stable yields relative to the field mean. These data show the potential importance of variable-rate management in the region and also hint at the potential environmental implications.

Key words: Yield monitor, yield map, yield distributions

Introduction

This work deals with three measures of yield variability: severity (magnitude), extent (spatial) and persistence (temporal). In the following, the three measures are

**Current address*: NC Division of Soil & Water Conservation, NCDENR, 3800 Barrett Drive, Raleigh, NC 27699, USA.

discussed separately, then the literature approaches to these measures are examined and, finally, the literature documenting the context of the study itself is presented.

Severity of yield variability has historically been described using some classical measure of variance, either variance itself, standard deviation, coefficient of variation (CV), range, interquartile range, or cumulative distribution functions (CDF's). However, these measures can convey no information about the clustering or patterns of variation. While some information about spatial structure can be represented using geostatistical tools, objective comparison from field to field and region to region remains somewhat problematic. For the present study, comparing fields across a region with visually similar patterns of yield variation, it would appear that comparing CV's is appropriate.

The spatial extent of yield variation is somewhat difficult to quantify and objectively evaluate. In general, the concept is fairly simple – is a field in this area similarly affected with variation as one in another somewhat distant area? However, classical statistics has no widely-accepted method to test this. Geostatistics would require theoretical aspects well beyond the scope of this paper. For the current time, it was concluded that describing the extent of variation with field-level CV's on a county-to-county basis would give an initial indication of the spatial extent of yield variation.

Persistence is a critical factor in planning and management of spatially variable fields. If the extreme yields occur in the same place from year to year (persistent patterns), then the causes of yield variation would appear to be soil-based or at least location-based. The predictability of the locations might warrant using pre-season, map-based, or prophylactic variable-rate applications. However, if the locations of the extreme yields move within fields from year to year, then the causes and effects are dynamic or transient, and any spatially variable-rate management would likely need to be adaptive during the season.

Literature treating spatial and temporal variability

The general topic of spatial variation was first assessed quantitatively in mining, resulting in the field of regionalized variables and geostatistics (Journel and Huijbregts, 1978). This toolset was applied to the characterization of soil physical properties (Nielsen *et al*., 1973, and many others) and was thus available when site-specific, or precision agriculture, developed in the 1990's. Some of the first to apply the tools linked spatial characteristics of soils to grain yield (e.g., Miller *et al*., 1988; Bhatti *et al*., 1991), while others compared spatial descriptors of soils, terrain and crop responses (e.g., Sadler, *et al*., 1998; Yang *et al*., 1998).

Adding the temporal dimension to the spatial ones required some method to normalize annual variability so that yields from different years and sometimes different crops, could be compared. Sadler *et al*. (1995) followed Schnug *et al*. (1993), who proposed dividing the point yield by the mean yield for the field to provide a relative yield with a mean of one. Lamb *et al*. (1997) divided point yield by the maximum point yield for the field which they called relative yield. Sadler *et al*. (1994), Ehgball and Power (1995) and Lark and Stafford (1997) computed a normalized yield by subtracting the mean from the point yield and dividing by the standard deviation to obtain a mean of zero and a standard deviation of unity. Colvin *et al.* (1997) reduced the effect of outliers on the result by using the median instead of the mean and the inter-quartile range instead of the standard deviation. Timlin *et al.* (1998) plotted the cumulative probability of exceeding a given yield in the year's distribution onto a surface map. Drummond *et al.* (2003) scaled multiple years of yield data for single crops to the long-term maximum and minimum, resulting in values between 0 and 1.

In many cases, the primary method of comparison among normalized yield maps has been visual inspection, supplemented at times with comparison of descriptive statistics among years. Porter *et al.* (1998) described 10 y variation by reporting the range and standard deviation of the yields during the period. Whelen and McBratney (2000) calculated a temporal variance. In other cases, where data were collected in plots whose locations remained stationary throughout the experiment, multiple pairwise correlations among years was conducted (Lamb *et al.*, 1997; Timlin *et al.*, 1998; Bakhsh *et al.*, 2000). Most of these efforts analyzed data obtained with stop-and-weigh harvest techniques that pre-dated on-the-go combine yield monitors. Yield data collected with yield monitors poses an additional problem in that data are not collected from the same points in each year.

For this type of data, some method of interpolating the yields onto a common grid of points is needed for comparison. This could be as simple as using the nearest neighbor but, in most cases, some method of interpolation is required. This problem is rather more severe when there are sparsely sampled areas and the sampling points are at varying distances from the common grid points in different years. For this case, Sadler *et al.* (1995) used an objective weighting scheme to account for the varying distance from the common grid point to yield points in multiple years. This weighting function was the inverse of the estimation of variance for the point in the year's kriging result. Where data are densely sampled, as with combine yield monitors, the more common procedure is either to average the yield monitor points within a rectangle centered on the grid or to interpolate onto a common fixed grid.

Objective comparison of yields among years has included multiple pairwise correlation mentioned above (Lamb *et al.*, 1997; Timlin *et al.*, 1998; Bakhsh *et al.*, 2000), rank correlation (Lamb *et al.*, 1997) and examination of accumulated change in rank during the experimental period (Colvin *et al.*, 1997). This last paper extended the comparison to a prediction of how many years of data were required to safely predict relative yield at a point in the field. Persistence of yield patterns, also discussed as stability of relative yield, was studied by Larsheid *et al.* (1997), who proposed a classification system into high, medium and low-yielding areas that were stable and unstable. Blackmore (2000) simplified this system into three categories considered useful to the manager: high-stable, low-stable, and unstable. In this system, high and low indicated if above or below the long-term mean, and stability indicated the temporal CV was $<30\%$.

A different approach to describing temporal variability was taken by Eghball and Power (1995), who used previous experience describing spatial variation to describe temporal yield variability using a fractal dimension. They concluded that different crops had significantly different temporal variability. Eghball *et al.* (1995) described the variability observed in a 40 y manure and fertilizer trial using fractals to differentiate between short-term and long-term variations. Eghball and Varvel (1997) used fractal dimensions to examine temporal variability for three years in each of three crops in seven crop sequences and concluded that temporal variability dominated spatial variability in the study.

Context of the project

In the US SE Coastal Plain, adoption of site-specific farming has lagged behind that in the upper Midwest. While the cause of this lag may be both sociological and economic in origin, we observed that the importance of the problem represented by spatial variation in yield was not appreciated by all regional farmers. While measurements on research fields had been documented (Karlen *et al.*, 1990; Sadler *et al.*, 1998), it appeared that producers needed a quantitative awareness of the severity, spatial extent and persistence of yield variation in production fields.

This report describes information found during four years of a project titled "Management Practices to Reduce Nonpoint Source Pollution on a Watershed Basis," which is part of the Agricultural Systems for Environmental Quality (ASEQ) Project funded by the US Department of Agriculture (USDA)-Cooperative States Research, Education, and Extension Service (CSREES). This multi-agency project for cooperative research and demonstration in Duplin County, North Carolina, USA, included as cooperators the Biological and Agricultural Engineering Department and Cooperative Extension Service of North Carolina State University; USDA-Natural Resources Conservation Service (NRCS) at the state, district and county levels; USDA-Agricultural Research Service (ARS) at Florence, South Carolina; US Geological Survey; and several local farmer-cooperators. A description of the overall project and area was given by Stone *et al.* (1995).

One objective of the ASEQ project was to improve adoption of precision farming as a best management practice. Related sub-objectives were: a) to show existing variation in crop yield with combine monitors; b) to use computer models to predict yield and relate precision farming to water quality; and c) to improve and encourage site-specific nitrogen management. Preliminary results from the first year of the site-specific farming objective were reported in 1998 (Sadler *et al.*, 1999), preliminary results over four years were reported in 2000 (Sadler *et al.*, 2000) and methods to subjectively delineate management zones were reported by Gerwig *et al.* (2000). This paper presents final results from subobjective (a), using harvest data for corn [*Zea mays* L.], wheat [*Triticum aestivum* L.] and soybean [*Glycine max* (L.) Mer.].

Materials and methods

The yield data were collected from cooperators in Duplin and Sampson Counties, North Carolina, with additional fields in Wayne, Bladen and Pender Counties proximal to the Duplin or Sampson County borders (Figure 1). One cooperator (A) operated two John Deere 9500[1] (Deere & Co., Moline, IL, USA) combines with 6m (20 ft) grain and 8 row corn headers on 760 mm (30 in) spacing. Both combines had

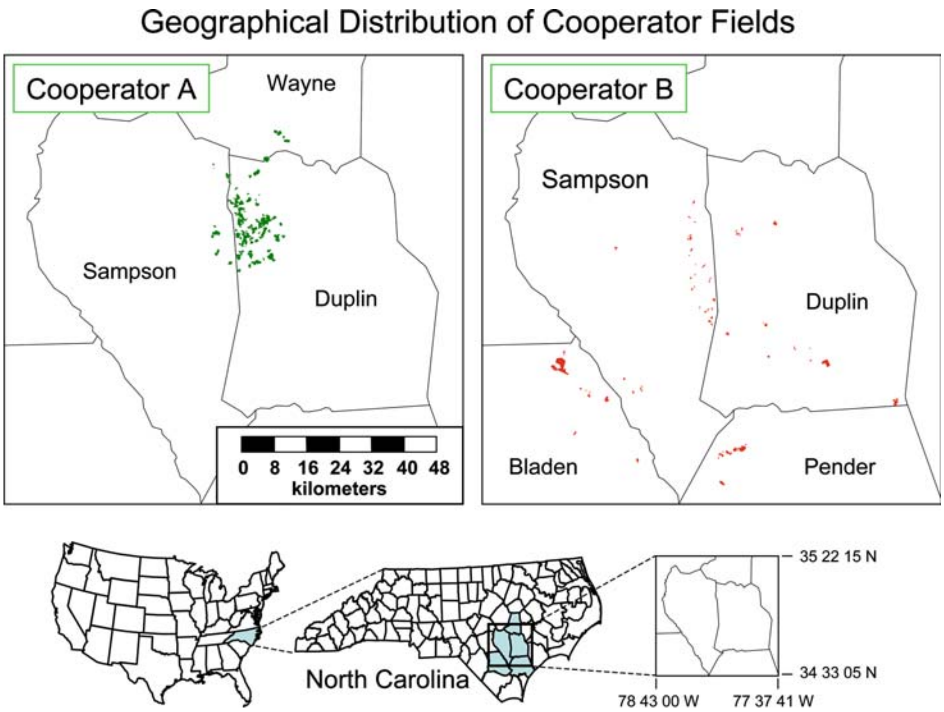

Figure 1. Geographic location of fields for the two cooperators mapped in the cooperative ASEQ Project.

GreenStar™ yield monitors installed in March 1997. The DGPS units used satellite-based differential correction. They wrote on 1s intervals to 5 MB data cards, which were read into JDMap® V2.1.1 software. Data were collected from this cooperator in 1997 and 1998. The other cooperator (B) operated two Case 2188 (Case IH, Racine, WI, USA) combines with 6m (20 ft) grain and 8 row corn headers on 760 mm (30 in) spacing. One machine previously had a yield monitor without DGPS (model AFS, Case IH). On that machine, a DGPS unit (GPS2000, AgLeader Technology, Inc., Ames, IA, USA) was installed before wheat harvest in June 1997. This unit used the Ft. Macon NC Coast Guard beacon for differential correction. The unit wrote on 2 or 3 s intervals to 1 MB cards, which were read into AgLink Basic V5.2.1 and, later, AgLink Advanced V5.5 (AGRIS Corp., Roswell, GA, USA) software. Data were collected from this cooperator from 1997 through 1999. Because only one of the two machines was equipped with the yield monitor and the two machines usually harvested fields together, data from portions of fields were usually acquired.

The monitors were calibrated using load totals determined with portable truck scales or scale tickets. During harvest, the operators entered field names, crops and activated the data collection. The data were examined for DGPS problems and operator artifacts, such as erroneous crop codes, field names, turns and trips across the field to unload with the header down. Errant passes were straightened, null passes and turns were deleted and field names and crop codes were corrected. Data from the two combines for Cooperator A were merged. When only one of the two combines could be calibrated using load totals, the calibration constant for the other yield monitor was adjusted to force equality of summed yield from representative passes where the two combines operated side by side.

Data from the AgLink and JDMap software were exported to shapefile format. These files were imported into ARC/Info (ESRI, Redlands, CA, USA), where county and soil survey attributes were applied. Analysis of yield monitor data relative to soil map units will be the subject of a later study. The resulting ARC/Info table was exported to ASCII format, then imported to SAS (SAS, 1990) for summary statistics.

Given that a common management practice in the area is the disposal of swine lagoon effluent via irrigation systems, fields were classified by the existence of such equipment. While it would be desirable to map the portions of the field receiving effluent or even to know the amount applied, disclosure of this information by cooperators and landowners would have required additional confidentiality agreements, so it was not collected. Therefore, the assumption was made that, if spray equipment existed in a field, it was probably used. This warranted analyzing the rainfed and spray fields separately.

Severity of yield variation was analyzed separately for year, cooperator, crop and existence of spray equipment. Descriptive statistics used included mean, median, quartiles, inter-quartile range, standard deviation and CV. Further, cumulative frequency distributions were plotted to summarize the large volumes of data.

Extent of yield variation was examined for the Cooperator B dataset, which included fields in four counties, stretching some 70 km N–S and about 80 km E–W. Again, descriptive statistics were computed and cumulative frequency distributions were plotted for comparison among counties to assess whether the extent of yield variation remained comparable over distance. Analysis of variance was conducted to test whether field-level coefficients of variation differed from county to county.

Persistence of yield variation was examined for 17 fields from Cooperator A that had same-crop yield maps from the same area in two successive years. This required procedures to account both for annual variation in yield and for non-alignment of data points from year to year. To normalize the inter-annual variation, the relative yield was calculated by dividing the yield for each data point by the field mean for that year. To overcome the problem that data points are not co-located in space, the data were interpolated to a common 10 m grid using the default kriging option in SURFER (Golden Software, Golden, CO, USA).

Yield at a point was classed relative to magnitude and stability according to a procedure similar to that of Larsheid *et al.* (1997) and illustrated graphically in Figure 2. The magnitude of yield at a point was evaluated by computing the average relative yield. Values of 1.0 ± 0.2 were classed as medium (M), those >1.2 were classed high (H) and those < 0.8 were classed low (L). The line corresponding to average yield $= 1.0$ is shown extending from (0, 2) to (2, 0), with the $\pm 20\%$ band denoting the medium yield range. Stability was evaluated by computing the temporal coefficient of variation. If CV $< 30\%$, represented by the band centered on the 1:1 line (where CV $= 0$), the point was classed as stable (S). If CV $> 30\%$, it was classed as unstable (U). Thus, there were six possible classifications in this 2-way system, as

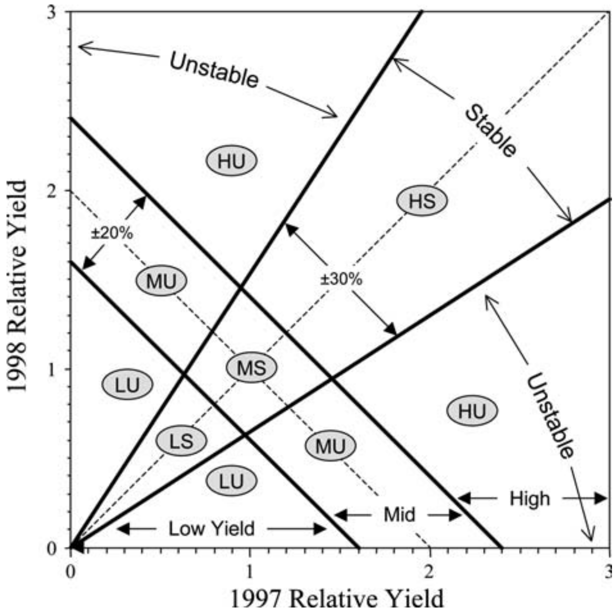

Figure 2. Classification method used to describe persistence of yield patterns.

seen in the figure. This procedure was conducted for the 17 fields, classed-post maps were done using SURFER and summary statistics showing fractions of fields in each class were created.

Results and discussion

Description of the data set

Total crop area mapped for yield was 4926 ha. The spatial extent and location of all fields mapped, identified by cooperator, are shown in Figure 1. The areas represented by these yield maps collected for each year, crop, spray practice and cooperator are shown in Table 1. Corn yields were obtained all three years. In 1998, wheat and some corn data for Cooperator B were lost during a computer failure. In 1999, the field data collection was scaled back to only Cooperator B. Note that in 1999, the corn harvest was interrupted by heavy rains and flooding during Hurricane Floyd. Therefore, the areas harvested before and after the hurricane were retained separately. All soybean harvest that year was conducted after the hurricane; so presumably, all soybean yields were affected by the event.

Severity

An example yield map composite for a 1997 rainfed corn field for Cooperator A is shown in Figure 3. This gives a visual impression of the severity of the yield variation

Table 1. Summary statistics for yield monitor project by cooperator, crop, year and existence of spray equipment

							Yield(Mg/ha)						
Crop	Coop	Yr	Spray	Fields	Area ha	Points	Mean	St Dev	CV	Y25	Median	Y75	IQR
Corn	A	97		59	389	309842	4.81	1.86	39	3.60	4.78	5.98	2.38
Corn	A	97	+	19	124	98084	6.20	2.44	39	4.70	6.65	7.98	3.28
Corn	A	98		113	704	605102	3.30	2.06	62	1.62	3.09	4.72	3.09
Corn	A	98	+	20	89	76744	5.91	2.58	44	4.22	6.44	7.77	3.56
Cooperator total, mean				211	1305	1089772	5.06			3.54		6.61	
Corn	B	97		9	135	50305	4.39	2.34	53	2.87	4.31	5.94	3.07
Corn	B	97	+	9	231	91416	5.01	3.50	70	2.25	4.26	7.13	4.88
Corn	B	98		8	13	5222	2.86	1.75	61	1.46	2.81	4.06	2.60
Corn	B	98	+	6	15	5983	4.13	2.30	56	2.21	4.19	6.09	3.89
Corn	B	99		15	83	36141	5.04	2.71	54	2.95	4.85	7.23	4.28
Corn	B	99	+	16	73	33191	6.42	2.37	37	4.83	6.82	8.17	3.34
Corn	B*	99		17	32	15871	3.40	2.03	60	1.89	3.17	4.60	2.70
Cooperator total, mean				80	583	238129	4.47			2.64		6.17	
Crop total				291	1888	1327901							
Soybean	A	97		85	545	456922	1.77	0.73	41	1.31	1.81	2.24	0.92
Soybean	A	97	+	2	16	13150	1.46	0.53	37	1.12	1.48	1.81	0.68
Soybean	A	98		106	514	450530	1.66	0.70	42	1.19	1.67	2.14	0.96
Soybean	A	98	+	7	36	32117	2.03	0.66	32	1.63	2.07	2.47	0.84
Cooperator total, mean				200	1110	952719	1.73			1.31		2.16	
Soybean	B	97		44	224	99828	1.63	1.33	82	0.43	1.39	2.46	2.03
Soybean	B	97	+	1	37	14492	1.58	0.78	49	1.04	1.68	2.13	1.08
Soybean	B	98		29	257	110883	1.38	0.90	65	0.59	1.31	2.01	1.43
Soybean	B	98	+	5	47	42076	1.47	0.87	59	0.77	1.34	2.12	1.34
Soybean	B*	99		27	116	48189	1.41	0.92	65	0.59	1.41	2.16	1.57
Soybean	B*	99	+	2	17	5351	0.89	0.60	68	0.46	0.88	1.22	0.75
Cooperator total, mean				108	698	320819	1.39			0.65		2.02	
Crop total				308	1808	1273538							
Wheat	A	97		25	364	298499	2.52	0.93	37	1.89	2.50	3.17	1.28
Wheat	A	97	+	1	13	12680	2.92	0.72	25	2.63	3.05	3.38	0.75
Wheat	A	98		61	440	384888	2.02	0.90	45	1.32	2.21	2.69	1.37
Wheat	A	98	+	7	38	33681	2.41	0.76	32	1.94	2.43	2.92	0.98
Cooperator total, mean				94	855	729748	2.47			1.94		3.04	
Wheat	B	97		15	109	28834	2.51	1.41	56	1.37	2.51	3.56	2.20
Wheat	B	99		46	217	98375	1.87	0.97	52	1.16	1.89	2.55	1.39
Wheat	B	99	+	4	48	23991	2.07	1.10	53	1.24	2.00	2.86	1.62
Cooperator total, mean				65	375	151200	2.15			1.26		2.99	
Crop total				159	1230	880948							
Project Grand Total				253	1656	710148							

*Harvested after Hurricane Floyd

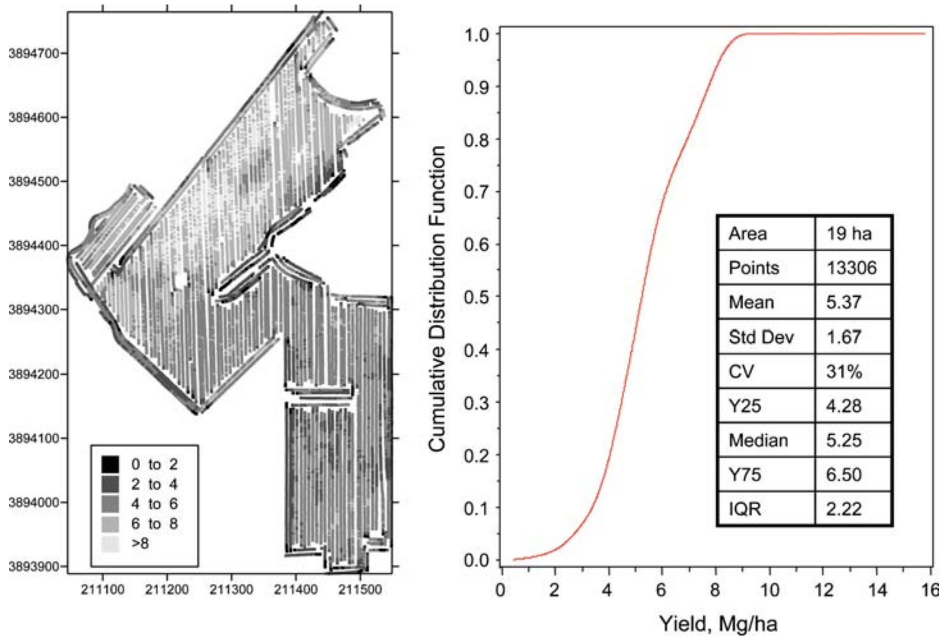

Figure 3. Example of yield map and its representation as a cumulative distribution function, obtained for a rainfed corn field harvested by Cooperator A in 1997.

encountered in the SE Coastal Plain. The field mean yield was 5.4 Mg/ha, but 25% of the field was greater than 6.6 Mg/ha (20% higher than the mean) and 25% was less than 4.2 Mg/ha (20% lower than the mean.) Many areas with extreme yield differences, because they were reasonably contiguous, would appear to be suitable for grouping into management zones for precision farming.

Presentation of large volumes of data using yield maps allows a rapid visualization of patterns, but is not suitable for quantitative analysis of yield relative to expected yields, nor of the area impacted by yield variation. For example, the issue of comparing actual yields with expected yields is addressed by examining long-term, statewide trends, which are presented in Figure 4. One can see that for corn, the three years of this study had statewide mean yields below the trend line. The worst year, 1998, was 25% below the 5.88 Mg/ha trend value. On the other hand, wheat yields were centered around expectations and soybean yields were slightly or significantly below the trend, especially in 1999, when yields were 17% below the trend line. Table 2 shows these data for 1997–2001, along with North Carolina state mean commodity prices. The 2000–2001 data are included to provide the reader with a clearer impression of the longer-term trends than is possible with prices from the 3 y study period. These historical data allow the reader to evaluate the economic impact of yield variation. They are reflected in the figures, which have dual axes to reflect both yields and gross receipts based on the 5 y mean prices.

The second issue, that of quantitatively evaluating how much of the area had low or high yields, is addressed here by presenting summaries in the form of cumulative

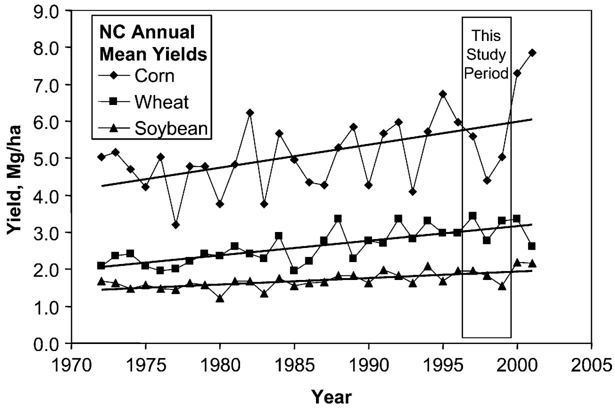

Figure 4. North Carolina statewide mean yields for corn, wheat and soybean, 1972–2001. (http://www.nass.usda.gov, last accessed 7 May 2005)

distribution functions (CDF) of yield for crop and year. This presentation is not without its shortcomings, however. The reader is cautioned that any two distributions are not strictly comparable in the sense one might expect from controlled experiments. Differences in the spatial mix of soils within and among fields may very well cause differences in distributions. Further, statistical tests of similarity between distributions usually show significance for very large datasets, whether or not the differences are meaningful from a practical standpoint. All that said, the larger the dataset, the more robust the comparison, in that the distributions of soils mapped will tend toward the same county or multi-county distribution. Therefore, while the most-reliable inferences are made by analyzing a single CDF, multiple CDF's can be compared if one proceeds cautiously.

Figure 5 shows the CDF's for corn. Within the context of the historical data in Figure 4, the summary statistics in Table 1 combined with the CDF curves in Figure 5 allow one to gain an understanding of the severity of the variation in yield. Recall that the first year, 1997, had statewide average yields of 5.6 Mg/ha, marginally

Table 2. North Carolina commodity prices and mean yields, 1997–2001. (http://www.nass.usda.gov, last accessed 7 May 2005)

	Crop					
	Corn		Wheat		Soybean	
Year	\$/Mg	Mg/ha	\$/Mg	Mg/ha	\$/Mg	Mg/ha
1997	111.18	5.6	117.33	3.4	244.93	2.0
1998	91.54	4.4	93.50	2.8	184.43	1.8
1999	89.18	5.0	85.43	3.3	169.03	1.5
2000	78.96	7.3	86.17	3.4	165.37	2.2
2001	92.71	7.9	93.50	2.6	154.00	2.2

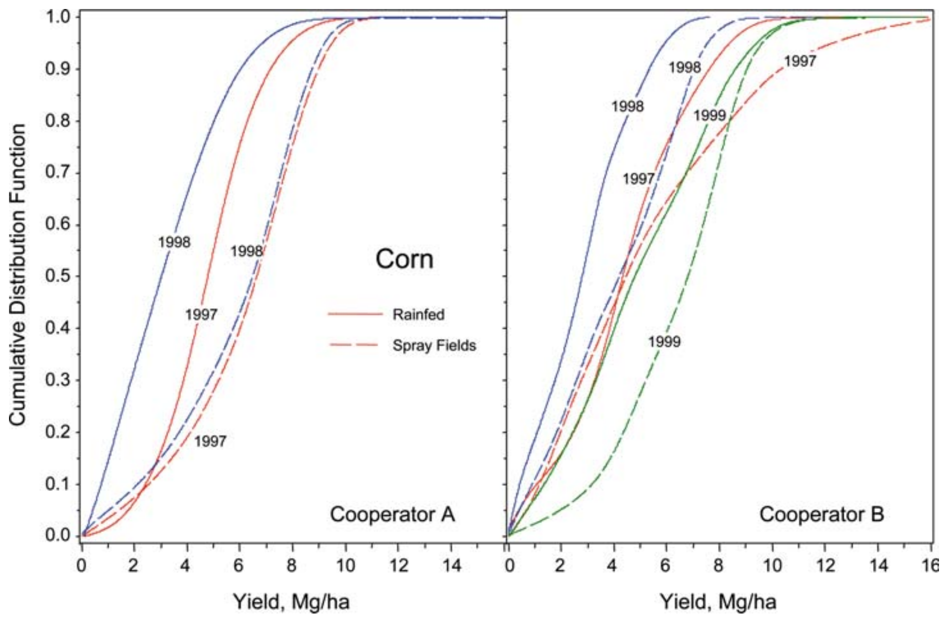

Figure 5. Cumulative distribution functions for corn yield. Data are presented for cooperator, year and existence of spray equipment.

below the trendline value of 5.8 Mg/ha. The cooperators here had somewhat lower mean yields, 4.81 and 4.39 Mg/ha, indicating that this area of the state may have been more severely impacted by the dry season. For Cooperator A, considering only non-spray fields, the 25th and 75th percentile values from this CDF shown in Table 1 are 3.60 and 5.98 Mg/ha. This means that ¼ of the mapped yields were less than 75% of the mean yield and another ¼ of the yields were more than 25% higher. This is one of the least-variable corn data sets in the study and the lowest CV obtained for non-spray fields. Further, this CDF is nearly symmetrical, as evidenced by the near equality of the mean and median. As seen below, other data sets were neither so narrowly distributed nor so symmetric.

The second year, 1998, had a severe drought during the growing season and resulted in statewide average corn yields of 4.40 Mg/ha, or 75% of the trend value of 5.88 Mg/ha. Again, the cooperating farmers in this study fared worse than the state average, with means of 3.30 and 2.86 Mg/ha. For both, the CV was much higher, at 62 and 61% and the distributions were decidedly skewed, with the CDF being nearly linear below the median. The 25th percentile values for Cooperator A were less than half the median and the linearity of the CDF allows the mean yield in those low-yielding areas to be quickly estimated at about ½ the 25th percentile value. So, for the 704 ha of non-spray field area mapped for Cooperator A in 1998, one fourth, or more than 175 ha, yielded an average of 0.8 Mg/ha. Given that standard fertilizer practice is for a target yield of 7.5 Mg/ha, this means that almost 90% of fertilizer N applied to that 175 ha was not taken up in grain. The magnitude of this unaccounted-for N would justify further study into the fate of this fertilizer. Further,

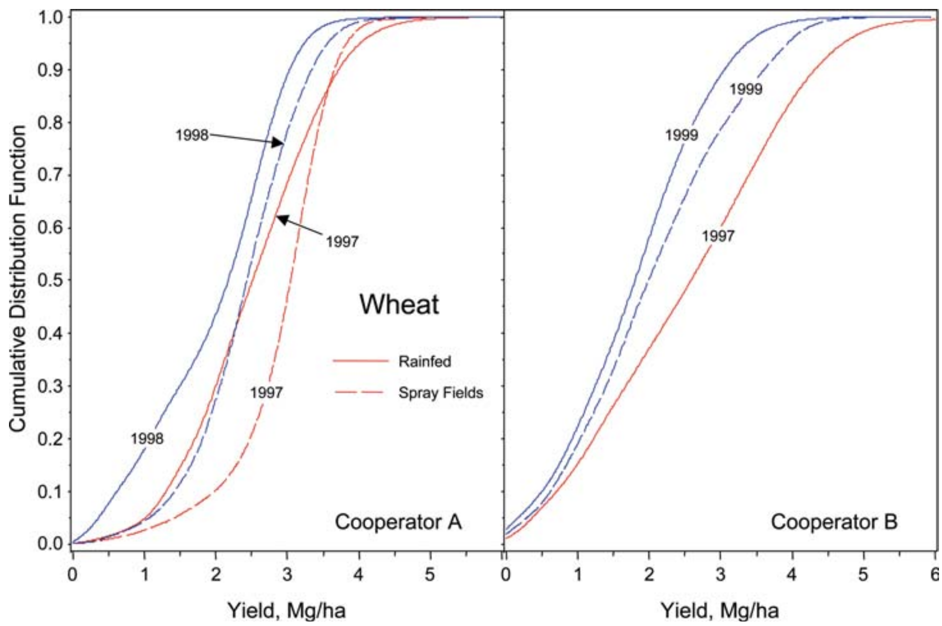

Figure 6. Cumulative distribution functions for wheat yield. Data are presented for cooperator, year and existence of spray equipment.

given the 1997 corn price of \$111.18/Mg (Table 2), these areas represent only \$89/ha, compared with the mean of \$367/ha and the target yield value of \$834/ha.

The third year, 1999, is presented only for fields harvested before >400 mm of rain during Hurricane Floyd since it caused much of the grain to fall below a height that could be harvested. This allows direct comparison to the data from the prior two years. The data collected after the hurricane is presented separately for the reader's comparison but will not be discussed further here.

The corn yield results for spray fields showed higher means and, except for 1997 for Cooperator B, higher medians. For that exception, both the 25th percentile and median values were actually lower for spray fields than non-spray fields, despite higher means and 75th percentile values. There are several possible explanations for such differences, the most plausible seeming to be that parts of the spray fields were not actually sprayed. If this were the case, and if the fertilization for the field was both low to accommodate the effluent's contribution to fertility and applied uniformly, then the non-spray areas of the field would suffer from under-fertilization. This hypothesis is supported by the fact that this one dataset is the only one for which the variance was increased from the non-spray to spray case.

Wheat yields generally decreased during the three years, with medians in 1997 of 2.5 and 2.51 Mg/ha for Cooperators A and B decreasing to 2.21 in 1998 for A and 1.89 Mg/ha in 1999 for B (Figure 6). The CDF's for spray fields showed general increases at all yield levels except in the top 10% of the CDF for Cooperator A in 1997, which represents a single 13 ha spray field. Both CDF's for Cooperator A

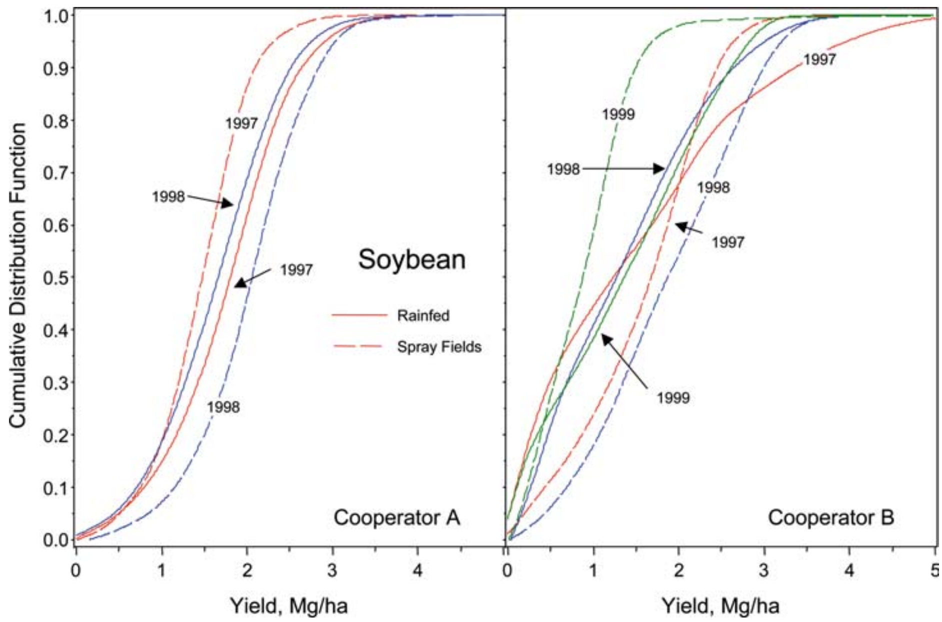

Figure 7. Cumulative distribution functions for soybean yield. Data are presented for cooperator, year and existence of spray equipment.

showed more effect at low yields than high ones, with less area in spray fields having low yield. Spray fields were less variable than non-spray fields for Cooperator A and about equally variable for Cooperator B.

Median soybean yields were not high in any year, the maximum for any non-spray field being 1.81 Mg/ha (Figure 7). The CDF's for the first cooperator in 1997 and 1998 were virtually identical for non-spray fields, but the apparent effect of the spray fields was in opposite directions those two years, with spray fields having consistently lower yields in 1997 and consistently higher yields in 1998. A similar picture emerged for Cooperator B in 1998 and 1999, with similar non-spray field CDF's, but higher spray field yields in 1998 and lower spray-field yields in 1999. For Cooperator B in 1997, widely different CDF's cross at roughly the 70^{th} percentile. It is interesting to note that up to that point, the non-spray field CDF was fairly similar to the CDF's from 1998 and 1999 for Cooperator B.

Extent

County-level values obtained in this study for Cooperator B, which represent the broader area (see Figure 1), are shown in Table 3. (For comparison, the county-level data reported by the state agricultural statistics service are shown in Table 4. Data for 2000–2001 are provided to illustrate the longer-term trends.) Bear in mind that sub-setting these data often produces a small dataset and that different distribution of soils in mapped fields may cause a confusion between the variation among soil

Table 3. Descriptive statistics, obtained during the study, for corn, wheat and soybean, expressed by county for Cooperator B

Year	County	Spray	No. Fields	Area Ha	Yield (Mg/ha) Mean	St Dev	CV	Y25	Median	Y75	IQR
Corn											
97	Bladen		4	91	4.96	2.13	43	3.51	4.61	6.39	2.89
97	Bladen	+	2	172	3.88	2.43	63	1.93	3.57	5.33	3.40
97	Duplin		1	23	4.38	1.95	45	3.09	4.47	5.94	2.84
97	Pender	+	6	55	9.57	3.38	35	7.59	9.54	11.63	4.04
97	Sampson		4	22	2.03	2.08	103	0.34	1.11	3.44	3.10
97	Sampson	+	1	3	3.14	2.45	78	1.18	2.49	4.64	3.45
98	Duplin		8	13	2.86	1.75	61	1.46	2.81	4.06	2.60
98	Duplin	+	6	15	4.13	2.30	56	2.21	4.19	6.09	3.89
99	Bladen		7	53	4.01	2.32	58	2.21	3.78	5.75	3.54
99	Bladen	+	3	26	6.88	1.93	28	5.61	7.28	8.27	2.65
99	Duplin		7	24	6.92	2.50	36	5.13	7.34	8.85	3.72
99	Duplin	+	8	37	6.25	2.54	41	4.46	6.45	8.18	3.72
99	Pender		1	6	6.19	2.03	33	4.66	6.63	7.78	3.12
99	Pender	+	5	11	5.89	2.53	43	4.04	6.44	7.82	3.78
99*	Pender		1	2	1.94	0.75	39	1.48	1.95	2.39	0.90
99*	Sampson		16	31	3.52	2.05	58	2.01	3.36	4.75	2.74
Soybean											
97	Bladen		14	142	1.26	1.19	94	0.26	0.86	2.02	1.76
97	Pender		4	25	1.88	0.63	33	1.65	2.01	2.24	0.59
97	Pender	+	1	37	1.58	0.78	49	1.04	1.68	2.13	1.08
97	Sampson		26	57	2.29	1.51	66	0.97	2.18	3.52	2.55
98	Bladen		24	237	1.41	0.91	65	0.60	1.34	2.06	1.46
98	Bladen	+	4	46	1.46	0.87	59	0.77	1.33	2.11	1.33
98	Sampson		5	20	1.06	0.64	60	0.49	0.99	1.57	1.08
98	Sampson	+	1	1	1.79	0.92	51	0.97	1.79	2.65	1.68
99*	Bladen		5	31	0.67	0.66	98	0.11	0.42	1.18	1.07
99*	Bladen	+	1	16	0.90	0.61	67	0.47	0.90	1.23	0.76
99*	Duplin		19	82	1.64	0.87	53	0.96	1.72	2.35	1.39
99*	Duplin	+	1	0	0.51	0.29	57	0.26	0.52	0.75	0.50
99*	Sampson		3	3	0.99	0.55	56	0.46	1.01	1.47	1.00
Wheat											
97	Duplin		5	60	2.74	1.43	52	1.68	2.92	3.79	2.10
97	Sampson		10	49	2.19	1.31	60	1.21	1.97	3.07	1.86
99	Bladen		23	151	1.79	0.96	53	1.10	1.82	2.45	1.35
99	Bladen	+	2	15	1.77	0.95	54	1.09	1.72	2.43	1.33
99	Pender		3	6	1.69	0.80	47	1.07	1.72	2.25	1.18
99	Pender	+	2	34	2.19	1.13	52	1.31	2.15	3.07	1.76
99	Sampson		20	60	2.06	1.00	49	1.27	2.05	2.82	1.54

*Harvested after Hurricane Floyd

types and the variation in space for a similar soil. For those solely interested in spatial variation, regardless of cause, this is not a large problem.

In 1997, data for corn were available from three counties. Coefficients of variation for Bladen and Duplin counties were essentially equal (43% and 45%), but the CV

Table 4. County-level and statewide historical yields for corn, wheat and soybean for comparison to project results. (http://www.agr.state.nc.us/stats/cntysumm/index.htm, last accessed 7 May 2005)

		Year									
		1997		1998		1999		2000		2001	
Crop	County	Area ha	Yield Mg/ha	Area ha	Yield Mg/ha	Area ha	Yield Mg/ha	Area ha	Yield Mg/ha	Area Ha	Yield Mg/ha
Corn	Bladen	9312	5.5	10121	4.0	8462	4.5	7935	7.7	7692	6.5
	Duplin	18219	5.2	14170	3.3	12551	4.7	13765	6.7	12874	7.3
	Pender	5263	5.3	6073	3.4	3806	4.9	4049	6.2	4008	6.9
	Sampson	12551	5.0	9312	2.2	7166	4.3	8583	7.5	8623	8.2
	Wayne	12955	4.8	9555	3.4	7733	4.8	8421	8.2	8300	7.7
	NC State	352227	5.6	311741	4.4	259109	5.0	259109	7.3	253036	7.9
Soybean	Bladen	6073	1.7	8907	1.7	8704	1.7	10283	2.2	9312	1.6
	Duplin	18421	1.8	20648	1.9	20445	1.8	20405	2.1	20850	2.0
	Pender	5668	1.9	6275	1.7	7085	1.5	7692	2.4	6518	2.2
	Sampson	20243	1.9	25506	1.5	22672	1.3	22874	2.2	21862	2.2
	Wayne	22672	2.0	27530	1.9	23684	1.8	22996	2.4	23482	2.4
	NC State	538462	2.0	572874	1.8	526316	1.5	550607	2.2	546559	2.2
Wheat	Bladen	2024	3.0	2105	3.0	2713	3.3	2267	2.6	1619	2.3
	Duplin	9312	3.2	10121	2.6	8502	3.2	8502	3.0	6883	1.8
	Pender	2227	3.2	2024	3.2	2308	2.8	1903	3.2	810	1.9
	Sampson	7490	3.3	8704	2.8	8907	3.4	10121	3.4	7004	1.8
	Wayne	11538	3.2	13968	2.8	10040	3.0	9312	3.2	9717	2.0
	NC State	271255	3.4	275304	2.8	234818	3.3	222672	3.4	190283	2.6

for Sampson County was 103%. One can see that the standard deviations for the three counties were almost equal, ranging only from 1.95 to 2.13 Mg/ha and that the more than 50% lower mean yield in Sampson County caused a CV more than twice as high as the others. The range of CVs in Bladen, Pender and Sampson Counties for spray fields was from 35 to 78%. In 1999, the range across Bladen, Duplin and Pender Counties for non-spray fields was from 33 to 58% and for spray fields, from 28 to 43%. It does not appear, from this subjective approach that there were any consistent differences in yield variation among counties.

The analysis of variance, testing for equality of mean CV among counties, was also not significant in 9 out of 12 possible tests and the 3 that were significant were inconsistent across crop and year. For instance, Bladen County was equally variable to Sampson County in five two-way comparisons and more variable in one. There was similarly no significant difference in the CVs for Bladen County and Pender County in four of six two-way comparisons and, in the other two, the relative positions were reversed. This also happened in the comparisons between Bladen and Duplin Counties; two comparisons showed no difference and the other two were opposites. The CV for Sampson County was greater than that for Pender County in one of four comparisons. The CV for Duplin County was never significantly different from that for either Pender or Sampson County. This test is subject to criticism because of low numbers of fields in some cases, but still lends credence to the conclusion that similar variations in yield occurred throughout the dataset.

Table 5. Field-by-field distribution of stability and yield classification for the 17 fields with 2 years of data from cooperator A

Field	Area ha	1997 Yield Mg/ha	1997 cv %	1998 Yield Mg/ha	1998 cv %	Stability	Yield Level High %	Yield Level Mid %	Yield Level Low %	Yield Level Total %
Rainfed fields										
34	18	4.80	27	2.36	43	Stable	18	38	27	83
						Unstable	13	3	1	17
						Total*	32	41	28	
36	15	3.39	36	1.35	75	Stable	8	16	19	43
						Unstable	36	9	12	57
						Total	44	25	31	
37	13	3.92	44	1.35	49	Stable	19	23	19	61
						Unstable	18	16	5	39
						Total	37	40	24	
40	8	5.29	43	2.84	50	Stable	26	32	23	81
						Unstable	11	5	2	19
						Total	37	38	25	
47	20	4.93	40	2.19	51	Stable	21	28	21	69
						Unstable	12	14	5	31
						Total	33	42	25	
54	11	6.18	31	4.96	35	Stable	19	46	23	88
						Unstable	7	5	1	12
						Total	26	51	23	
59	14	4.62	35	2.25	48	Stable	13	32	28	73
						Unstable	19	6	2	27
						Total	32	38	30	
65	24	5.22	35	4.65	42	Stable	22	34	24	80
						Unstable	13	7	1	20
						Total	35	40	24	
66	17	5.52	33	5.68	34	Stable	17	45	22	84
						Unstable	9	6	0	16
						Total	26	51	22	
78	34	4.63	45	1.41	83	Stable	12	8	11	31
						Unstable	34	24	11	69
						Total	46	33	21	
80	9	5.76	31	5.32	28	Stable	19	48	24	91
						Unstable	6	3	1	9
						Total	25	51	25	
84	10	3.20	64	2.90	74	Stable	25	14	26	65
						Unstable	23	5	6	35
						Total	49	19	32	
87	12	5.56	24	1.56	47	Stable	12	44	19	75
						Unstable	15	8	2	25
						Total	27	52	21	
90	46	5.37	31	1.26	55	Stable	14	30	15	58
						Unstable	20	16	6	42
						Total	34	46	21	
91	18	4.71	29	0.86	74	Stable	10	30	11	51
						Unstable	21	22	7	49
						Total	30	52	18	

Table 5. Continued

Field	Area Ha	1997 Yield Mg/ha	1997 cv %	1998 Yield Mg/ha	1998 cv %	Stability	Yield Level High %	Yield Level Mid %	Yield Level Low %	Yield Level Total %
Spray Fields										
46	15	5.51	47	4.23	58	Stable	28	23	31	81
						Unstable	16	3	0	19
						Total	43	26	31	
60	22	7.46	30	5.87	38	Stable	27	27	35	89
						Unstable	10	1	0	11
						Total	36	28	35	

*Totals may differ from 100% due to rounding error.

Persistence

Within the total data set, the only crop suitable for analysis of persistence in yield variation was corn. Further, since Cooperator B used multiple combines to harvest the same field, but only one with a yield monitor, there was not enough information to conduct this analysis on the Cooperator B dataset. However, for Cooperator A, 17 same-field corn yield maps were identified (Table 5), with 15 non-spray fields and 2 spray fields represented. These data were normalized for year-to-year variability by dividing yield by the mean for the field. Then, the relative yield was interpolated to a common 10 m grid. The classification as to stability and magnitude of yield produced field-by-field distributions as seen in Table 5. An example of the spatial distribution of these classes in a 1997 rainfed corn field (same as that for Figure 3) is shown in Figure 8. Out of the 17 field set, six rainfed fields and both spray fields had 80% or more of the area with stable relative yields, meaning the multi-year CV was $< 30\%$. At the other extreme, only 2 of the 15 non-spray fields had more than 50% of the area classed as unstable.

In the 15 field dataset, irrespective of the field's overall stability, from 11 to 28% of the area evaluated had stable, low yields. These suggest areas where producers might profitably consider not growing crops, depending on size, location and shape of the low-yield areas. In this non-spray dataset, from 8 to 26% of the area had high, stable yields. These areas might be profitably managed with slightly higher target yields than other areas in the fields.

In the two spray fields, 81 and 89% of the area was stable. With such a small sample, it would be difficult to conclude that spray fields had more or less persistent yield patterns, although one might expect this to be the case if the source of instability were related to water as a limiting factor. Both fields had more than 30% low stable yields, which we speculate might have been caused by low fertility in non-sprayed areas of the fields. The spray fields did have the highest two fractions of high-stable yields in the entire 17 field dataset, at 27 and 28%.

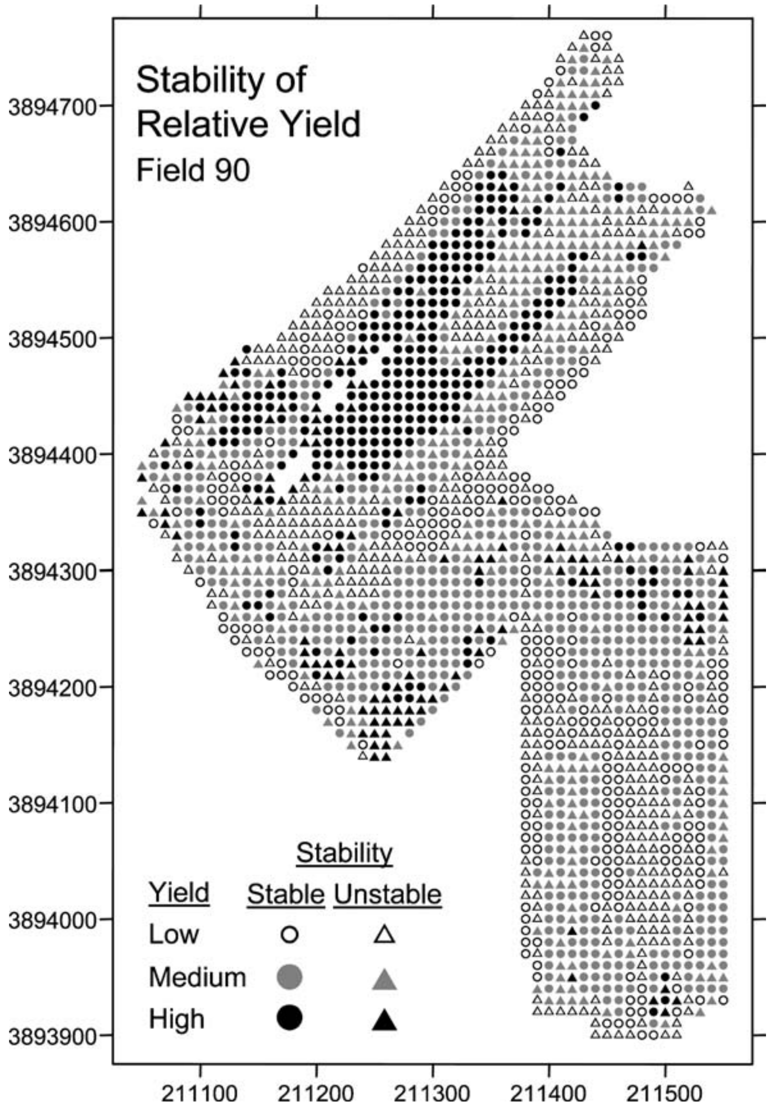

Figure 8. Example of classification method applied to a single field (same field as in Fig. 3).

Conclusions

The graphed cumulative distribution functions show visually and the summary statistics show quantitatively that corn, wheat and soybean yield varies in space with a severity that would appear to be important both economically and environmentally. Further and as expected, the yield variation appeared to occur throughout the spatial extent of the data set, as represented by county-to-county yield variation. And third, there appeared to be some persistence in yield patterns, with only 2 of 17 fields evaluated having less than 50% stable relative yield. This would indicate that map-based variable-rate applications could be used with some degree of confidence. In particular, from 11 to 28% of the area in these fields had stable, low yields, which would strongly suggest that either a reduction in inputs or a cropping system change could have potential for economic and environmental benefits.

Acknowledgments

The authors gratefully acknowledge the funding support given by USDA-CSREES project No. 95–4604. They also thank the three co-PI's on the project, Dr. Frank Humenik (NCSU Biological and Agricultural Engineering Dept., Raleigh, NC, USA), Dr. Patrick Hunt (USDA-ARS, Florence, SC, USA) and Mr. George Stem (USDA-NRCS, Raleigh, NC, USA).

Note

1. Mention of trademarks is for information only. No endorsement implied by USDA-ARS or its cooperators.

References

Bakhsh, A., Jaynes, D. B., Colvin, T. S. and Kanwar, R. S. 2000. Spatio-temporal analysis of yield variability for a corn-soybean field in Iowa. Transactions of the ASAE **43**(1), 31–38.

Bhatti, A. U., Mulla, D. J. and Frazier, B. E. 1991. Estimation of soil properties and wheat yields on complex eroded hills using geostatistics and thematic mapper images. Remote Sensing of the Environment **37**, 181–191.

Blackmore, S. 2000. The interpretation of trends from multiple yield maps. Computers and Electronics in Agriculture **26**(200), 37–51.

Colvin, T. S., Jaynes, D. B., Karlen, D. L., Laird, D. A. and Ambuel, J. R. 1997. Yield variability within a central Iowa field. Transactions of the ASAE **40**(4), 883–889.

Drummond, S. T., Sudduth, K. A., Joshi, A., Birrell, S. J. and Kitchen, N. R. 2003. Statistical and neural methods for site-specific yield prediction. Transactions of the ASAE **46**(1), 5–14.

Eghball, B., Binford, G. B., Power, J. F., Baltensperger, D. D. and Anderson, F. N. 1995. Maize temporal yield variability under long-term manure and fertilizer application: fractal analysis. Soil Science Society of America **59**, 1360–1364.

Eghball, B. and Power, J. F. 1995. Fractal description of temporal yield variability of ten crops in the United States. Agronomy Journal **87**, 152–156.

Eghball, B. and Varvel, G. E. 1997. Fractal analysis of temporal yield variability of crop sequences: implications for site-specific management. Agronomy Journal **89**, 851–855.

Gerwig, B. K., Sadler, E. J. and Evans, D. E. 2000. Evaluating techniques for defining management zones in the SE coastal plain. In: *Proceedings 5th International Conference on Precision Farming,* edited by P.C. Robert, R.H. Rust, and W.E. Larson (ASA/CSSAS/SSSA, Madison, WI, USA), (unpaginated CDROM).

Journel, A. G. and Huijbregts, C. J. 1978. *Mining Geostatistics*. (Academic Press, London, UK).

Karlen, D. L., Sadler, E. J. and Busscher, W. J. 1990. Crop yield variation associated with Coastal Plain soil map units. Soil Science Society of America Journal **54**, 859–865.

Lamb, J. A., Dowdy, R. H., Anderson, J. L. and Rehm, G. W. 1997. Spatial and temporal stability of corn grain yields. Journal of Production Agriculture **10**(3), 410–414.

Lark, R. M. and Stafford, J. V. 1997. Classification as a first step in the interpretation of temporal and spatial variation of crop yield. Annals of Applied Biology **130**, 111–121.

Larscheid, G., Blackmore, B. S., Moore, M. 1997. Management decisions based on yield maps. In *Proceedings First European Conference on Precision Agriculture,* edited by J. V.Stafford, (BIOS Scientific Publishers Ltd., Oxford, UK), pp. 895–903.

Miller, M. P., Singer, M. J. and Nielsen, D. R. 1988. Spatial variability of wheat yield and soil properties on complex hills. Soil Science Society of America Journal **52**, 1133–1141.

Nielsen, D. R., Biggar, J. W. and Erh, K. T. 1973. Spatial variability of field-measured soilwater properties. Hilgardia **42**(7), 215–259.

Porter, P. M., Lauer, J. G., Huggins, D. R., Oplinger, E. S. and Crookston, R. K. 1998. Assessing spatial and temporal variability of corn and soybean yields. Journal of Production Agriculture **11**(3), 359–363.

Sadler, E. J., Busscher, W. J. and Evans, D. E. 1994. Normalization of multiple-year spatial yield data for site-specific management. Agronomy Abstracts. (ASA, Madison, WI, USA) p. 357.

Sadler, E. J., Busscher, W. J. and Karlen, D. L. 1995. Site-specific yield histories on a SE Coastal Plain field. Ch 11. In: *Site-specific Management for Agricultural Systems*, edited by P. C. Robert, R. H. Rust and W. E. Larson (ASA/CSSA/SSSA, Madison, WI, USA), pp. 153–166.

Sadler, E. J., Busscher, W. J., Bauer, P. J. and Karlen, D. L. 1998. Spatial scale requirements for precision farming: A case study in the southeastern USA. Agronomy Journal **90**(2), 191–197.

Sadler, E. J., Millen, J. A., Fussell, P., Spencer, J. and Spencer, W. 1999. Yield mapping of on-farm cooperative fields in the SE Coastal Plain. In Precision Agriculture: *Proceedings of the 4th International Conference* edited by P. C. Robert, R. H. Rust, and W. E. Larson, (ASA/CSSAS/SSSA, Madison, WI, USA), pp. 1767–1776.

Sadler E. J., Gerwig B. K., Millen J. A., Thomas W. and Fussell P., 2000. Experiences with site-specific farming in a demonstration project in the SE Coastal Plain. In *Proceedings of the 5th International Conference on Precision Farming* edited by P. C. Robert, R. H. Rust, W. E. Larson, (ASA/CSSA/SSSA, Madison, WI, USA), (unpaginated CDROM).

SAS 1990. *SAS Language: Reference,* Version 6, First Edition. (SAS Institute, Inc., Cary, NC, USA) 1042 p.

Schnug, E., Murphy, D., Evans, E., Haneklaus, S. and Lamp, J. 1993. Yield mapping and application of yield maps to computer-aided local resource management. In: *Soil Specific Crop Management*, edited by P. C. Robert, R. H. Rust and W. E. Larson (ASA/CSSA/SSSA, Madison, WI, USA), pp. 87–93.

Stone, K. C., Hunt, P. G., Coffey, S. W. and Matheny, T. A. 1995. Water quality status of a USDA water quality demonstration project in the Eastern Coastal Plain. Journal of Soil and Water Conservation **50**(5), 567–571.

Timlin, D. J., Pachepsky, Y., Snyder, V. A. and Bryant, R. B. 1998. Spatial and temporal variability of corn grain yield on a hillslope. Soil Science Society of America Journal **62**, 764–773.

Whelan, B. M. and McBratney, A. B. 2000. The ''null hypothesis'' of precision agriculture management. Precision Agriculture **2**, 265–279.

Yang, C., Peterson, C. L., Shropshire, G. J. and Otawa, T. 1998. Spatial variability of field topography and wheat yields in the Palouse region of the Pacific Northwest. Transactions of the ASAE **41**(1), 17–27.