25 Spatial Corn Yield During Drought in the SE Coastal Plain

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Throughout the southeastern USA coastal plain, Carolina Bays are low, depressional areas that often have different soils and a wide variation in crop yield. Corn (*Zea mays*) appears to be the most susceptible to soil variation, especially during periods of drought. During 1993, a severe drought yr in this region, corn yields were measured at 209 sites within an 8-ha field where yield variation among soils had been evaluated for 12 crops. Site-specific effects of soil variation on crop phenology, biomass, and yield components were measured at 11 sites. Time-domain reflectometry (TDR) soil moisture probes were installed at eight of those sites, two within each of four map units. These were monitored from 40 days after planting until after maturity. Drought stress during vegetative growth caused severe leaf rolling in several areas, while other areas suffered no visually-apparent stress. This observation was supported by infrared thermometer measurements of canopy temperature (TC), which ranged from ambient air temperature (TA) to about 10°C higher. Rain following the period of drought reduced TC-TA to near zero for all soils, indicating that the stress was relieved. Plant height five days before the rain ranged from 0.48 to 1.34 m. Mid-silk leaf area index ranged from 1.15 to 2.56. Time of tasselling and black layer formation ranged over three weeks. Grain yield ranged from 104 to 318 g m^{-2} dry weight at the 11 primary sites and from 18.5 to 419.8 g m^{-2} in the entire field. Mean yield over 209 18-m^2 plots was 214.8 ± 79.3 g m^{-2} on a dry weight basis (2481 ± 916 kg ha^{-1} at 15.5% moisture). This high variation in crop yield presumably resulted in large differences in residual N since fertilizer applications were uniform across the entire field. We suggest that additional analysis and stochastic simulation are needed to estimate risk from such an occurrence and to develop environmentally safe N management practices for subsequent crops.

Site-Specific Management for Agricultural Systems.

CONTEXT OF FIELD STUDY

This research was conducted during the 12th cropping season of a study designed to document spatial variability of crop yield within a representative coastal plain field (Karlen et al., 1990; Sadler et al., 1993; 1994a). The field, which includes 14 soil map units (USDA-SCS, 1986), had been cultivated since 1985 using uniform conventional techniques. These included offset disking to incorporate weeds and crop residues, in-row subsoiling for row crops, and field cultivation to prepare the seedbed for planting. The field studies were 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. Preliminary results from the simulation studies suggested that the soil water balance was not being adequately described (Stone & Sadler, 1991). Field observations of grain fill occurring after models simulated crop maturity during 1992 indicated that crop phenology was also not correctly simulated. These observations suggested that more site-specific data were needed to calibrate the simulation models to coastal plain soils.

Our objectives were to evaluate in detail corn response to differences in soil characteristics. Paired samples within four soil map units were chosen to allow comparison within and among soil map units. Soil properties and plant growth characteristics were measured so that known weaknesses in simulation models could be addressed. Where possible, sampling strategies were designed to allow both soil-to-soil comparisons and geostatistical analysis.

FIELD STUDY - 1993

The field was disked on 9 and 23 March. Granular fertilizer was broadcast 30 March at an application rate of 17–40–121–15 kg ha^{-1} N-P-K-S. On 8 April, metolachlor herbicide [Dual[1] 8E, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide, Ciba-Geigy Corp., Greensboro, NC] was sprayed at an application rate of 2.8 kg ha^{-1} and incorporated. On 9 April, 'Pioneer Brand 3165' corn was planted using a KMC (Kelley Manufacturing Co., Tifton, GA) in-row subsoil unit with Case - IH (Chicago, IL) Model 800 planters. Broadleaf weeds were controlled on 11 May with 2,4-D [(2,4-dichlorophenoxy) acetic acid] herbicide (Weedar, Rhône-Poulenc Ag Company, Research Triangle Park, NC) at an application rate of 0.5 kg ha^{-1}. Sidedress N fertilizer was banded on both sides of the crop row on 28 May, at an application rate of 112 kg N ha^{-1}. Corn was harvested from 16 to 24 September using a plot combine (GWC, Inc., Nevada, IA).

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

REPRESENTATIVE SITES

Four soil map units were selected as being representative of the range of soils within the field. These included:

1) the predominant map unit, Norfolk loamy fine sand (NkA; moderately thick surface, deep water table, 0 to 2% slopes; Fine-loamy, siliceous, thermic Typic Paleudult; reclassified 3/88 to Fine-loamy, siliceous, thermic Typic Kandiudult),
2) a historically low-producing Coxville loam (Cx; Clayey, kaolinitic, thermic Typic Paleaquult),
3) a local inclusion that under-performed expectations for Goldsboro loamy fine sand (GoA; 0 to 2% slopes; Fine-loamy, siliceous, thermic Aquic Paleudult), and
4) Bonneau loamy fine sand (BnA; 0 to 2% slopes; originally mapped as Loamy, siliceous, thermic Grossarenic Paleudult; reclassified 3/90 to Loamy, siliceous, thermic Arenic Paluedult) that produced high yields in spite of having the lowest productivity rating.

Two sites were chosen for each map unit. The positions of these sites within the larger field are shown in Fig. 25–1. Site-specific characteristics that were determined after selection and installation of the TDR probes suggested that two of the sites were not as representative as desired. Site #1, which was to represent GoA, was placed by error on the boundary between GoA and Dunbar (Dn;

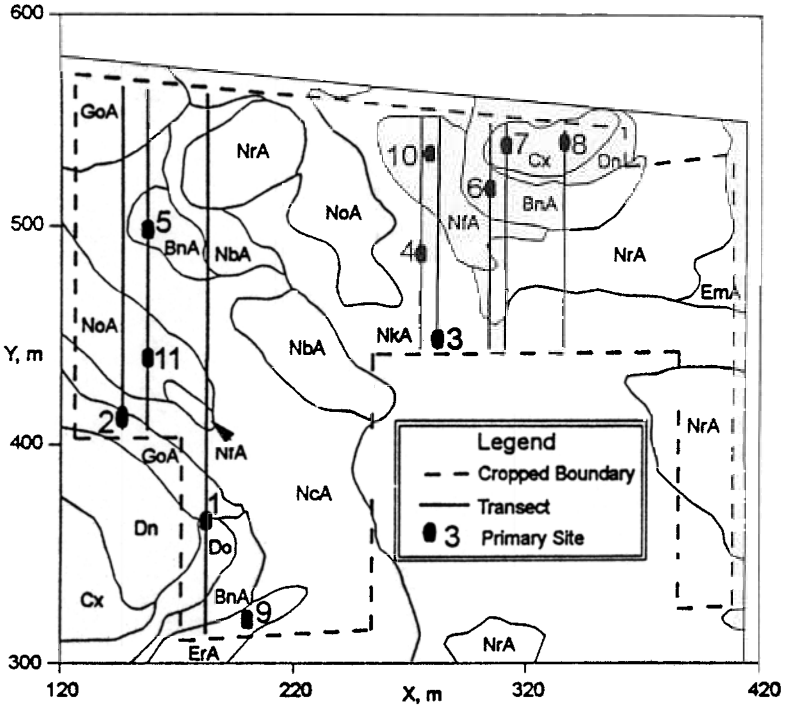

Fig. 25–1. Site plan for 1993 corn study. Locations for 8 TDR sites plus 3 additional representative sites are indicated, as are transect locations for spatial variation measurements during the season.

Clayey, kaolinitic, thermic Aeric Paleaquult), but the difference between these two inclusions is < between typical pedons of the two soils. Site #8, which was the second Cx location, was determined to encroach on an area recently disturbed during land forming around a drainage culvert. The differences between the two Cx sites in horizon depths and textures were small. The differences in strength that might exist between them because of the previous disruption may be significant.

Each of these eight sites was instrumented with time-domain reflectometry (TDR) probes to monitor soil moisture to a depth of 1 m. Probe depths were selected to represent the soil horizons at the site. A TDR (1502B, Tektronix, Inc., Beaverton, OR), laptop computer, switching devices, battery, and required cabling were assembled onto a 2-wheel hand truck (Sadler & Busscher, 1993) that was used to make the soil moisture measurements. The TDR traces from the 5–6 probes at each site were automatically obtained and reduced using the computer programs of Baker and Allmaras (1990). The season's soil water balances for these eight sites are shown in Fig. 25–2.

The most obvious difference among the soil types occurred because of the 46-mm rain on 12 June. As can be seen in Fig. 25–2, site #8 showed a greater increase in profile soil water than average (about 2x), and sites #1 and #5 showed a smaller increase (about 0.5x). After correcting for evaporation on days between the measurements, the best estimates of infiltration ranged from 21 and 33 mm for sites #1 and #5 to 98 mm for site #8. The latter was > twice the rainfall amount, indicating a large run-on to the site. Site #7, at 50 mm, also had a net increase larger than the rainfall amount. The remaining four sites

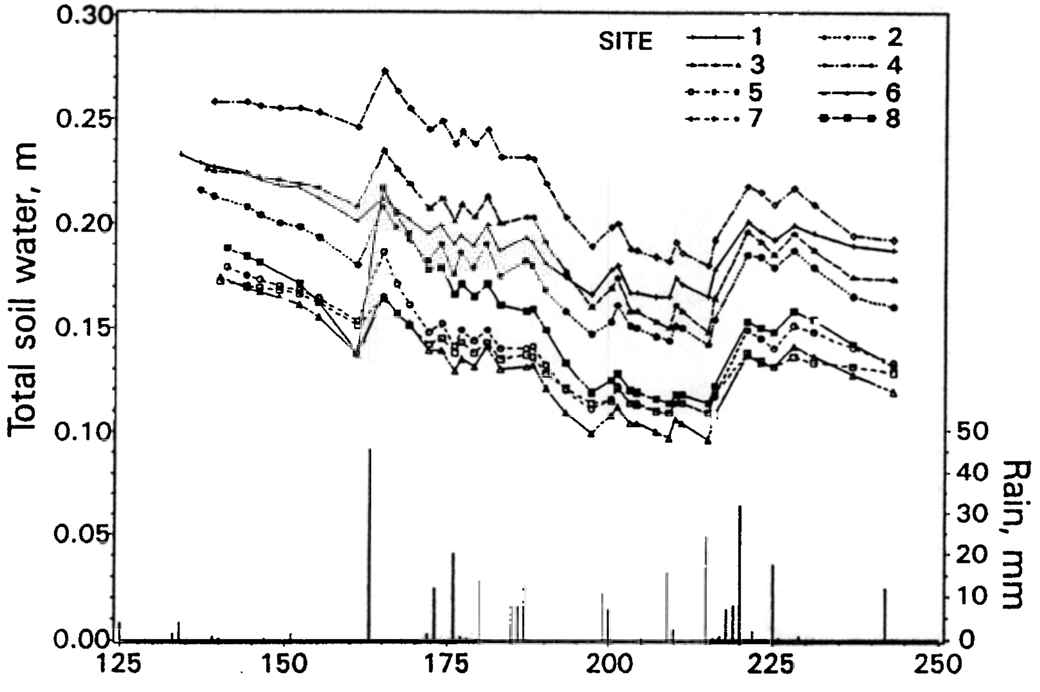

Fig. 25–2. Soil water balance at the 8 original representative sites. Rainfall is indicated on the right axis.

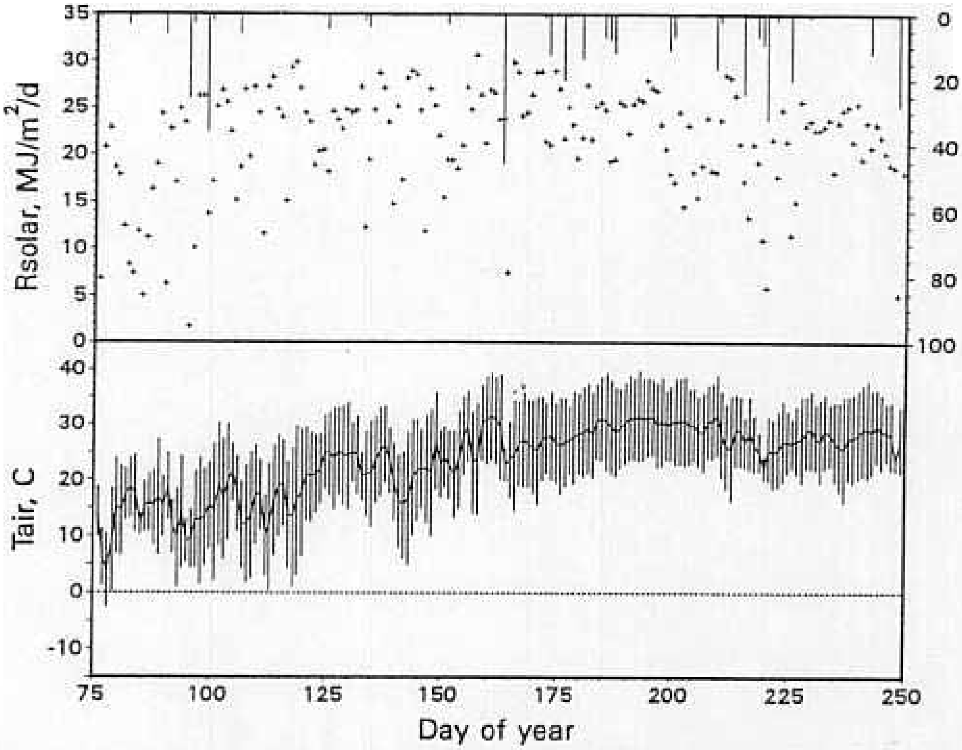

Fig. 25–3. Daily air temperature extremes, daily solar radiation, and daily rainfall during 1993.

ranged from 38 to 41 mm. Subsequent evaporation from the eight sites showed faster losses from site #8 and slower losses from sites #1 and #5.

By the time of this rain, at which time the corn was approaching the tasseling stage, the drought (Fig. 25–3) had caused substantial differences in plant height. Corn in three areas of the field was taller and more developed than the rest of the field. When emerging tassels confirmed the advanced development, we added these sites to the study and collected plant samples. These included an Emporia fine sandy loam (ErA; 1 to 2% slopes; Fine-loamy, siliceous, thermic Typic Hapludult), a Noboco fine sandy loam (NfA; 1 to 2% slopes; Fine-loamy, siliceous, thermic Typic Paleudult), and a Norfolk with a thicker surface horizon (NoA; thick surface, 0 to 2% slopes; Fine-loamy, siliceous, thermic Typic Paleudult; also reclassified 3/88 as Kandiudult). The Noboco is similar to the Norfolk, but has a higher water table during part of the yr. These three additional sites are identified as Nos. 9, 10, and 11, respectively, on Fig. 25–1.

Measurements of phenology, biomass, leaf area, and yield components at various growth stages during the season were made at these 11 sites. The phenology measurements were made by repeatedly rating the 10 plants in either direction adjacent to the TDR site (20 plants marked for three additional sites) for tasseling, silk emergence, and black layer. When 50% of the plants had reached these developmental stages, the dates were recorded. The data are reported in Table 25–1.

Table 25–1. Dates of 50% tasselling, silking, and black layer for the 11 primary sites. Date of planting (DAP) was 9 April (DOY 99), and date of emergence was 18 April (DOY 108). No differences were observed among soil types for emergence date.

Site		50% tasselling		50% silking		50% blacklayer	
#	Soil	Date	DAP	Date	DAP	Date	DAP
1	GoA	6/28	80	7/2			
2	GoA	6/26	78	6/30			
3	NkA	6/26	78	7/1			
4	NkA	6/29	81	7/4			
5	BnA	6/28	80	7/1			
6	BnA	6/23	75	6/27			
7	Cx	6/24	76	6/28			
8	Cx	6/23	75	6/24			
9	ErA	6/20	72	6/22			
10	NfA	6/20	72	6/21			
11	NoA	6/23	75	6/25			
min/max							

On 7 June, plant height, leaf area, and biomass were measured on 1-m samples of crop row. At this time, height was determined to the top of plant tissue directly above the stem (Table 25–2). When 50% of the plants had silks emerged, the same measurements were taken on 2-m samples of row. Height at this time was determined to the bottom of the tassel (Table 25–3). Leaf area was measured both times with a leaf area meter (Model Li 3100, LiCor, Lincoln, NE). Biomass was determined by weight of tissue after drying for three days at 70°C. At the 50% silk-emergence sample, potential kernel number for each ear was determined by multiplying the number of rows by the number of potential kernels in the rows (Table 25–4). Two 3.05-m rows were hand harvested to determine yield components at the time of the final combine harvest. A mechanical sheller was used to thresh the grain. Kernel number and dry weight were determined by counting and weighing subsamples (ranging from 340 to 754 kernels) of the shelled grain (Table 25–5).

ADDITIONAL SPATIAL MEASUREMENTS

Corn growth during 1993 was extremely variable because of the drought, so additional measurements were made in an attempt to document what appeared to be an unusual occurrence. The first was simply to record, on 7 June, plant height on 10-m intervals along the rows that included the eight sites (Fig. 25–1 shows transects). Results from the transect including site #1 are shown in Fig. 25–4. To further document the conditions at the primary sites, heights of all individual plants being monitored for phenology were recorded on 23 June. The variation within and among sites is shown in Table 25–6.

Table 25–2. Corn growth characteristics measured on 6/7/93.

Site			Plants	sd	Height	sd	LAI	sd	Weight	sd
#	Soil	n[†]	# m^{-2}		m		m^2 m^{-2}		g m^{-2}	
1	GoA	3	4.6	0.9	0.682	0.013	0.3783	0.0220	60.6	4.8
2	GoA	3	4.2	0.2	0.911	0.136	0.6580	0.3508	92.4	26.1
3	NkA	3	3.7	0.9	0.612	0.045	0.1577	0.0341	42.8	6.9
4	NkA	2	4.7	1.2	0.608	0.052	0.2037	0.1282	47.4	13.8
5	BnA	3	3.9	0.4	0.625	0.031	0.1747	0.071	41.5	2.6
6	BnA	1	5.2		0.873		0.4380		80.1	
7	Cx	1	6.0		0.821		0.4407		80.1	
8	Cx	1	3.4		1.228		1.2232		130.9	
	min/max		0.567		0.495		0.129		0.317	

[†] n refers to number of 1-m samples taken.

Table 25–3. Corn growth characteristics measured at silking, from a single 2m sample.

Site #	Soil	Harvest Date	Height m	Leaf area m^2 m^{-2}	Dry Weight g m^{-2}
1	GoA	7/2	0.897	0.8537	---
2	GoA	6/30	1.313	0.8073	211.4
3	NkA	7/1	1.001	0.7521	---
4	NkA	7/9	1.270	0.6367	---
5	BnA	7/1	1.018	1.1361	---
6	BnA	6/28	1.075	1.0532	241.1
7	Cx	6/28	1.326	0.9459	280.3
8	Cx	6/28	1.655	1.3910	353.9
9	ErA	6/28	1.278	1.6717	288.8
10	NfA	6/24	1.486	1.2714	198.2
11	NoA	6/24	1.482	0.9981	288.8
min/max			0.542	0.381	0.560

Table 25–4. Potential kernels per plant determined at silking. Means and standard deviations computed from individual plant measurements.

Site		Mean	sd	Mean	sd	Mean	sd
#	Soil	rows ear^{-1}		kernels row^{-1}		kernels ear^{-1}	
1	GoA	14.4	1.6	44.8	2.9	640.8	56.3
2	GoA	17.3	2.7	37.3	6.2	643.1	143.0
3	NkA	14.5	1.4	50.9	2.1	736.5	62.7
4	NkA	14.8	1.8	42.2	4.8	623.9	115.2
5	BnA	14.4	1.3	49.9	4.2	717.4	80.3
6	BnA	15.0	2.7	39.4	4.1	587.4	93.7
7	Cx	14.5	1.1	39.6	4.4	573.8	70.0
8	Cx	15.5	1.1	41.7	7.6	648.4	139.7
9	ErA	13.2	1.2	41.9	4.3	550.3	62.2
10	NfA	15.5	1.4	43.2	5.0	669.9	105.6
11	NoA	13.5	2.1	43.4	5.2	590.3	133.3
min/max		0.763		0.733		0.747	

Table 25–5. Yield components taken at harvest. Means and standard deviations are calculated from two 3.04-m samples per soil type. Plot yield is in dry weight; spatial yield is from the four nearest harvest plots and is also expressed here as dry weight.

Site		Plant density	sd	Ear density	sd	Ker-nel #	sd	Kernel wt	sd	Plot yield	sd	Spatial yield	sd
#	Soil	# m^{-2}		# m^{-2}		# ear^{-1}		g kernel^{-1}		g m^{-2}		g m^{-2}	
	GoA	4.9	0.30	3.7	0.91	231.1	63.1	0.189	0.040	173.8	118.2	139.5	29.1
2	GoA	6.7	0.30	4.5	0.30	175.2	17.1	0.156	0.064	128.4	71.0	129.3	35.6
3	NkA	6.0	.22	5.4	0.30	242.7	32.4	0.232	0.023	301.6	27.2	255.6	52.7
4	NkA	5.2	.22	3.0	1.22	195.3	7.4	0.181	0.018	103.6	28.4	154.5	61.2
5	BnA	6.2	0.30	6.0	0.61	222.8	18.1	0.210	0.038	287.9	102.2	257.	31.0
6	BnA	5.6	0.61	5.2	0.61	159.4	32.6	0.151	0.006	125.1	35.4	138.2	92.4
7	Cx	5.4	.52	4.9	.52	153.7	22.9	0.165	0.011	126.5	48.6	128.3	75.5
8	Cx	5.6	0.00	4.5	0.91	378.2	75.2	0.190	0.009	317.8	14.7	327.4	81.3
9	ErA	4.7	0.61	4.3	0.61	283.3	40.6	0.189	0.021	228.5	24.4	200.2	23.2
10	NfA	4.9	0.91	4.5	0.30	369.0	86.8	0.146	0.010	248.3	91.2	180.4	67.0
11	NoA	4.9	0.30	4.9	0.30	389.7	9.2	0.145	0.014	277.7	8.1	222.0	63.0
min/max		0.701		0.500		0.394		0.625		0.326		0.392	

Table 25–6. Variation in plant height, measured to the topmost leaf tip, on 23 June, 1993. Areas sampled were used for 50% silking and black layer determination.

		No.	Mean height	Std. dev.	C.V.	Min	Max	
#	Soil	-	m	m	%	m	m	min/max
1		19	1.00		23.26	0.51	1.37	0.372
2		19	1.14		10.01	0.86	1.30	0.662
3		20	1.23		10.52	0.86	1.42	0.606
4		20	1.07		16.58	0.69	1.35	0.511
5		20	1.18		15.18	0.84	1.65	0.509
6		22	1.29		11.18	0.94	1.60	0.588
7		20	1.34		11.23	1.07	1.60	0.669
8		22	1.72		9.21	1.37	2.08	0.659
9		21	1.69		8.50	1.45	1.93	0.751
10		20	1.85		11.80	1.27	2.11	0.602
11		19	1.47		8.02	1.24	1.65	0.752
								0.242
			0.541	0.478	0.345	0.352	0.616	

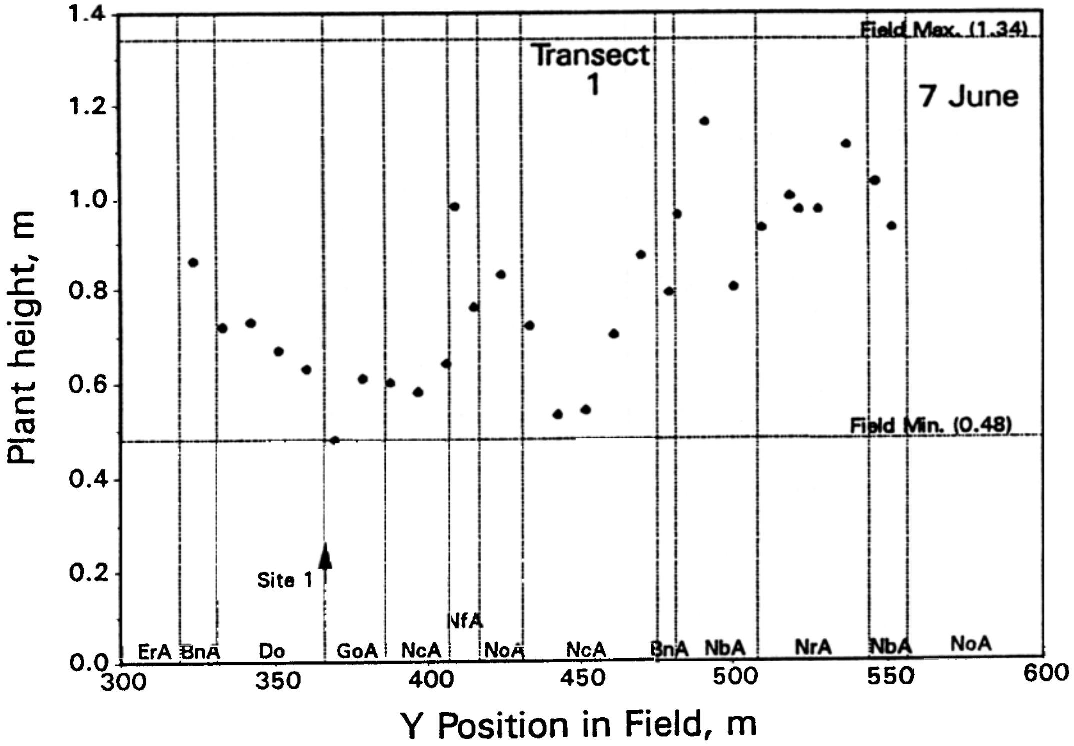

Fig. 25–4. Plant heights measured on 10-m spacings during the season. Transect corresponds to number 1 on Fig. 25–1.

The second measurement was also obtained opportunistically. On 10 June, the more-stressed areas in the field were visually distinct from others that were not apparently stressed. The plants in stressed areas were as short as 0.48 m; the non-stressed plants were up to 1.34 m tall. Other signs included severe leaf rolling, with the associated straightening, to the point that many plants did not extend > about 15 cm into the space between the rows. The stressed plants also had a blue-gray cast. In contrast, the areas with the tallest plants showed no visually-apparent stress: no rolling, normal leaf position, and typical green coloring.

Attempts on such short notice to locate a thermal scanner to image the field were not successful, so we made infrared thermometer (IRT; Everest Interscience, Tustin, CA; model 4000, 4° field of view) measurements on the same transects. To do this, an IRT was connected to a datalogger (CR21X, Campbell Scientific, Logan, UT) mounted on a platform strapped to the operator's waist. The operator walked along the row at a steady pace, pointing the IRT forward and down at a 45° angle above the row. The datalogger recorded the temperature at 1-s intervals. A manual switch allowed the operator to start and stop at known locations. Assuming the pace was steady (average was 1.4 m s^{-1}) allowed computation of location from the time of the individual measurements. The first such measurements were made on 10 June during the most severe stress period. After the 46-mm rain on 12 June, measurements were made on 14, 17, and 19 June.

Data from transects 1 and 5 are shown in Fig. 25–5 and 25–6. Transect 1 includes site #1, which appeared to be the area with the most severe stress. Transect 5 includes site #11 (NoA), which never showed visible signs of stress. The timing of the four sets of measurements shows the severity of the drought stress before the rain, near total relief of stress afterwards, and the development of drought conditions nearly as severe as before. The variation in the canopy temperature increased with drought stress. This was suggested by Aston and Van Bavel (1972) as an early indicator of the need for irrigation. Cloudiness in the humid Southeast may prevent successful implementation of field-scale variation in IRT readings as an irrigation scheduler. It may be possible, however, to isolate an indicator area, for which a limited transect might be made during cloud-free periods. The first 40 m of transect 5 might be such an area, because it includes the GoA, NcA, and NoA soils, which span the range of response observed in the field.

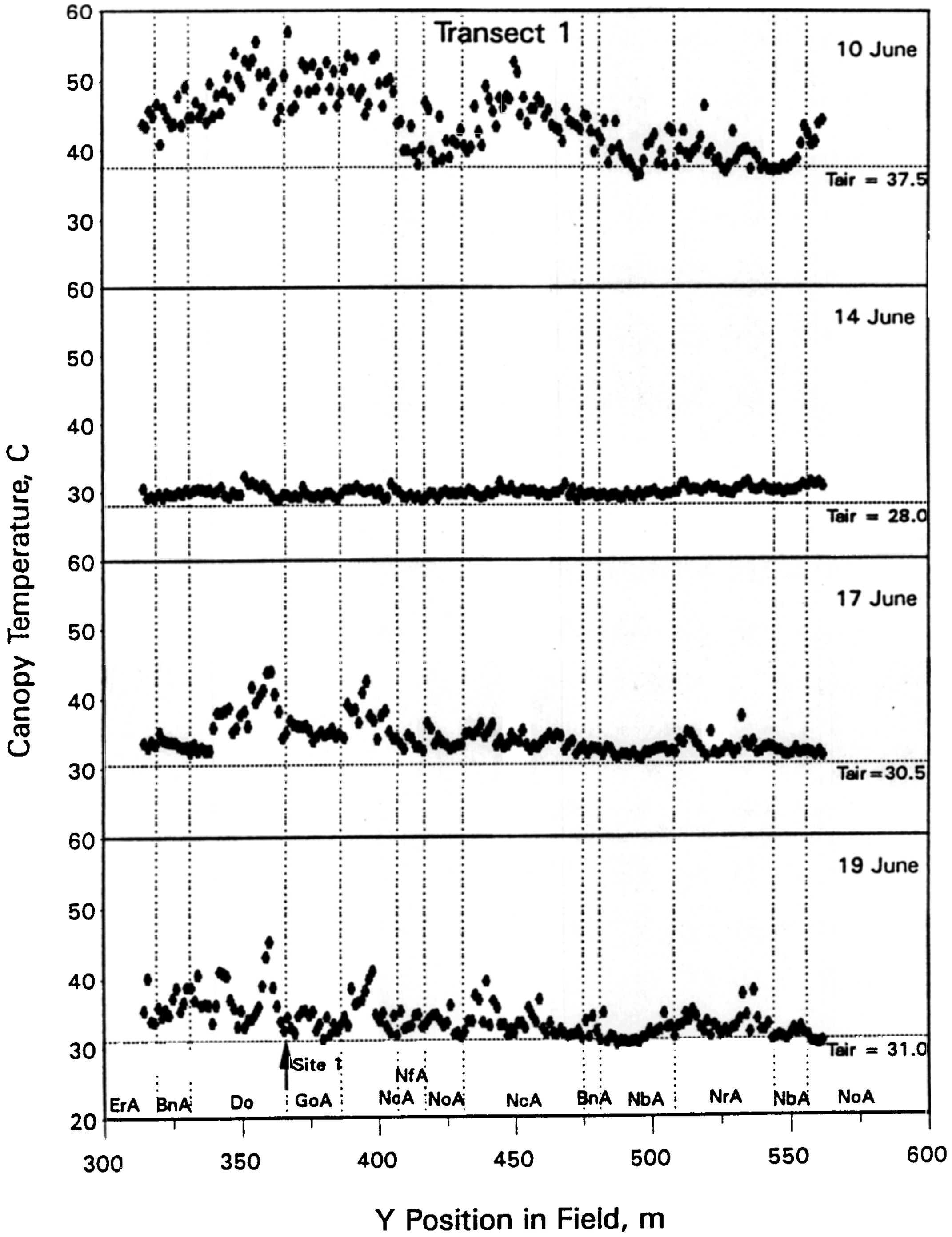

Fig. 25–5. Crop temperature measured with an IRT as a function of distance along transect #1 for one date before and for 3 dates after a 46-mm rain. The area around site #1 was apparently the most stressed in the field.

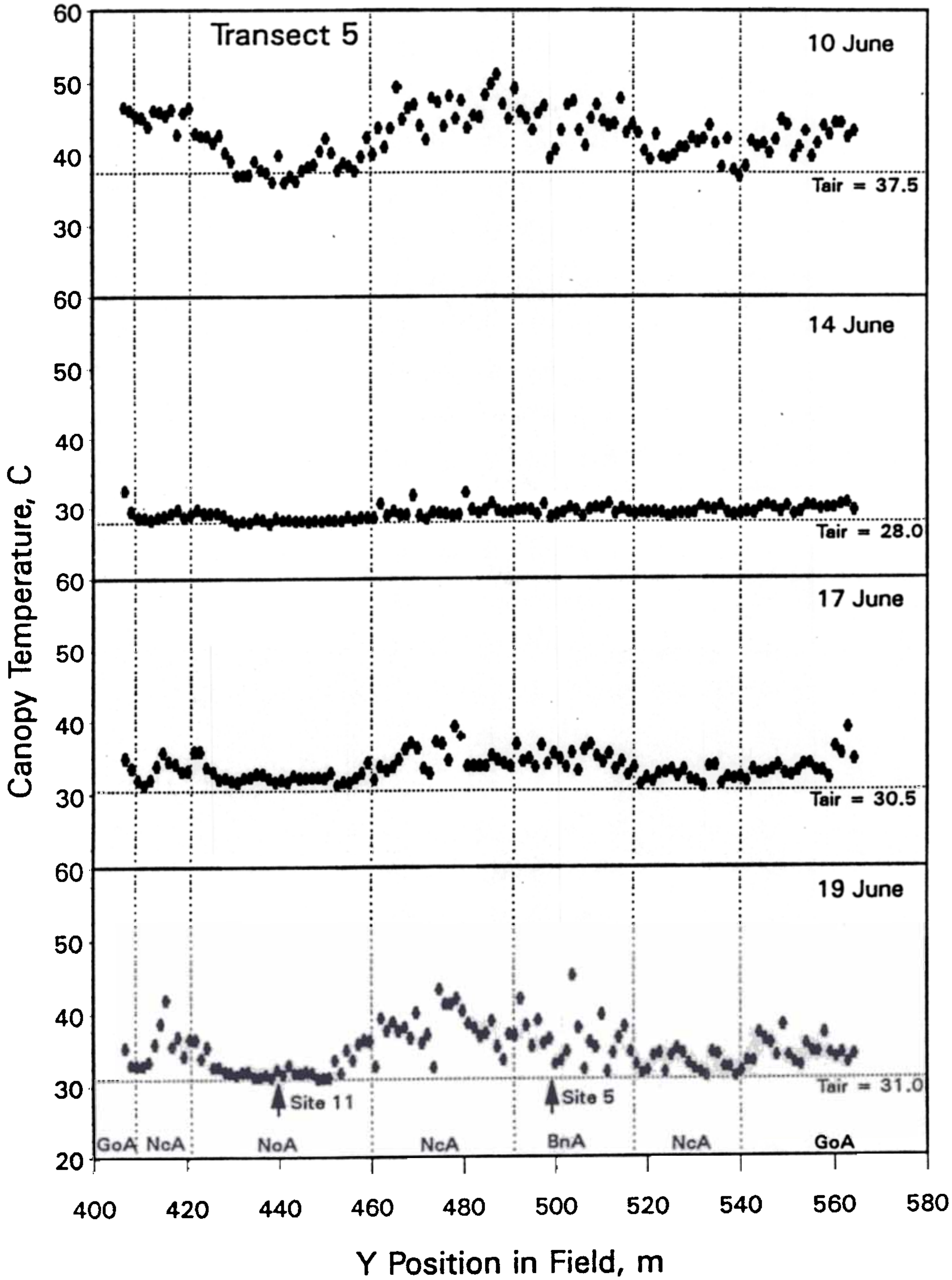

Fig. 25–6. Crop temperature measured with an IRT as a function of distance along transect #5 for one date before and for 3 dates after a 46-mm rain. The NoA site noted was never observed to be stressed.

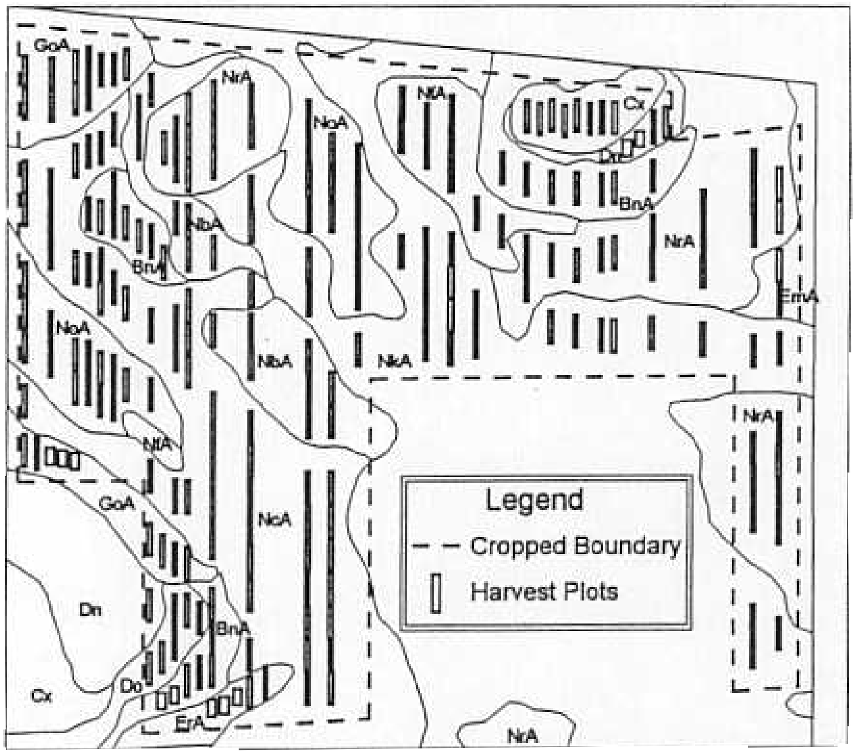

Fig. 25–7 Harvest plots overlaid on the soil map for 1993 corn harvest.

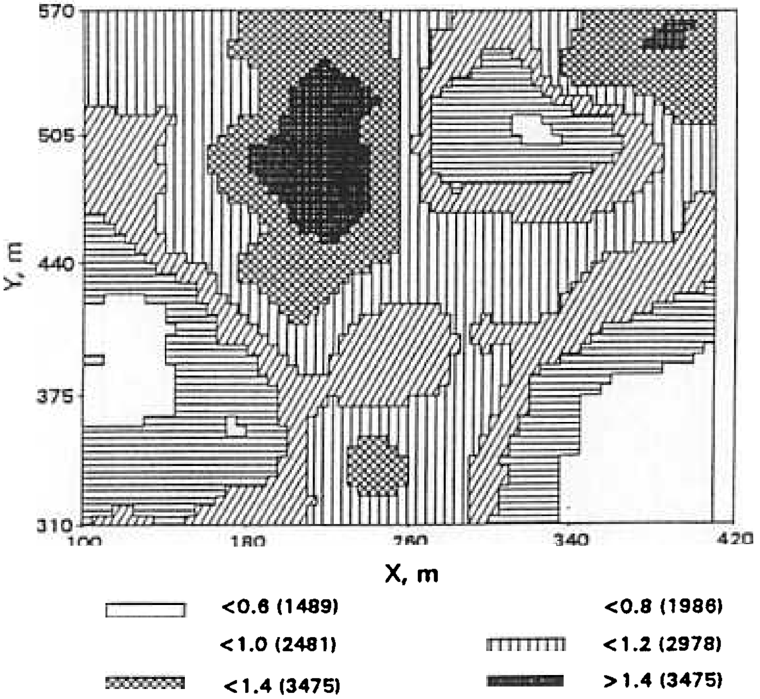

Fig. 25–8. Relative corn yield, computed as harvest plot yield divided by the field mean, kriged and mapped over the sampling area.

SPATIAL YIELD SAMPLING

Site-specific harvest plots were obtained in a manner similar to other yrs. Individual plots (18 m^2) were planned based on CAD drawings of the field, and then were flagged in the field. As mentioned above, the field plot combine was used to harvest the corn. Plot yields were determined and attributed to the corresponding soil type from the map (Fig. 25–7). Yields from harvest plots proximal to the 11 representative sites are reported with data from the sites in Table 25–5. The relative yield map of the entire field is shown in Fig. 25–8. It was produced by dividing all yield data by the mean yield for the field and then kriging (Sadler & Busscher, 1992; Sadler et al., 1994a).

SMALL- VS. LARGE-SCALE VARIABILITY

Variability in this and other fields exists on scales ranging from the small (plant-to-plant in a row; <1 m) to the large (field sections; >100 m). Accounting for the large-scale variability was the original intent of soil mapping. In this field, as observed in 1993 (Fig. 25–9) and before (Karlen et al., 1990), variation within map units approaches the magnitude of variation among map units. Yields between separate inclusions of the same map unit are often markedly different. For these reasons, sampling strategies used in the project have evolved from those that allow primarily map-unit comparisons to those that also allow strictly spatial comparisons (i.e., kriging) as well. Both techniques require coordinate locations of yield plots, which have always been determined for this project.

The 1993 study 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 of soil water balance and various physiological characteristics, although between only two sites per unit. Where possible, in all tables, standard deviations and the ratio between the minimum and maximum measurement are provided so that the reader may judge how much variation existed, both in the samples and among soil types. Table 25–6 in particular shows variation in plant height both within and among samples of about 20 plants. In general, variation among map units appears larger than that within map units, but the magnitudes are so similar that they reduce confidence in comparisons among map units. The transects of plant height (Fig. 25–4) and canopy temperature (Fig. 25–5 and 25–6) also support the need for spatial analysis. Comparison of the soils map (Fig. 25–1) and the kriged yield map (Fig. 25–8) suggests some, but not total, correspondence.

Several preliminary conclusions can be derived from the 1993 results. First, under drought stress, large differences in most measurable parameters can be obtained, both within and among map units. The water balance showed measurable differences in rainfall/runoff partitioning for single storms, as well as noticeable variation in rate of water use. The IRT measurements documented the variation in canopy temperature in space, the recovery after rain, and the subsequent reoccurrence of stress. This confirms the recommendation by Aston and van Bavel (1972) that increased spatial variation in canopy temperature may

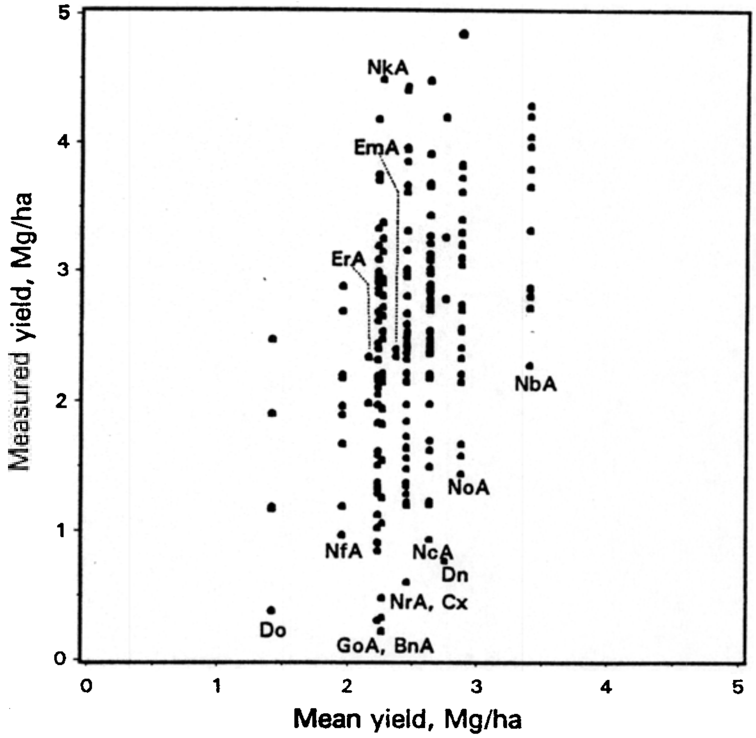

Fig. 25–9.Individual harvest plot yields plotted against the mean yield for each map unit. Plot area was 18 m^2 for each of 209 plots. Mean yield was 2481 ± 916 kg ha^{-1}, and the range was from 214 to 4849 kg ha^{-1}, all expressed at 15.5% moisture.

SUMMARY AND CONCLUSIONS

be a useful early indicator of water stress.

Variation in timing of tasselling, silking, and black layer was about 15% of the maximum. Stress appeared to delay tasseling and silking, but no clear-cut result obtained for time of maturity. If stress delayed silking, but shortened the grainfilling period, as suggested by Shaw (1988), differences among soils in timing of maturity might be masked. Although differences in timing were relatively < differences in other parameters, most simulation models rely primarily on air temperature to drive phenology. Because air temperature would be the same across soil types, models are not likely to account for variation in timing of maturity. Variation in LAI and biomass during vegetative growth on 7 June was very large - 87% and 68% of the maximum, respectively. Variation in height on that day was about 50% of the maximum. By mid-silk, variation in LAI had dropped to 62% and variation in biomass had dropped 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 38% and 30% of the maximum. Final yield at the 11 primary sites varied from 125 to 318 g m^{-2} dry weight; for this, the range is 67% of the maximum. Yield over the entire field (209 plots) averaged 2481 ± 916 kg ha^{-1} and ranged from 214 to 4849 kg ha^{-1}, all expressed at 15.5% water content.

Such large differences in grain yield indicate that large differences in residual N may exist across this field. Although one could not have foreseen the severity of the drought, an operator will have to deal with potential leaching if fertilizer application for subsequent crops do not account for the residuals. Additional analysis and stochastic simulation could help estimate risk from such an occurrence.

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