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PREDICTING CROP WATER STRESS BY SOIL WATER BUDGETS AND CLIMATIC DEMAND

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SUMMARY:
A soil water budget model (SPAW) was adopted to provide daily crop water stress computations and was applied to 49 raingage sites in Missouri, Kansas, Iowa, and South Dakota for 1967-1976. Accumulative corn water stress computed for each year correlated well with reported county corn yields. Corn yields for the near-drought year of 1977 were estimated quite well using computed water stress and station correlations.

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Predicting Crop Water Stress by Soil Water Budgets and Climatic Demand [1]

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Much of our nations crop production is dependent upon precipitation to supply adequate soil moisture and often the yields are limited by crop water stress. In an age of tightening world food supplies and important export markets, there is a need for improving our assessment methods of crop yield forecasts, and the impact of crop water stress is a major variable. The dynamic supply of soil moisture and variable climatic demand on growing crops causes crop water stress to be predictable only through a complex soil water budget model which computes a daily assessment based on current status and daily weather.

To accurately simulate the many processes in the soil-plant-atmosphere system requires a reasonably complex series of relationships in a computer model. Recent advancements in both computer technology and physical system knowledge now indicate that modeling this system is feasible on a broad scale basis. The objective of this study was to develop, test, and calibrate a method of current soil moisture and crop water stress assessment which: 1) represents local soil, crops, and weather, 2) requires only readily available data, 3) can feasibly be applied to multi-state regions, and 4) will provide useful definition to crop water stress effects on crop yields.

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The Model

The soil-plant-air-water (SPAW) model reported by Saxton et al. (1974) was selected to provide the basic soil water budget estimates. Additions and revisions were made to the original model to estimate runoff, crop water stress, and water stress effects on crop growth and yield. The revised model was described by Sudar et al. (1979) along with calibration results using data from research stations.

A schematic of the SPAW model computations is shown in figure 1. Beginning at the top of the diagram, a daily potential evapotranspiration (ET) value estimated by pan evaporation data or another method is passed through relationships to separately consider intercepted water evaporation, soil water evaporation, and plant transpiration. These components combine to provide an estimate of daily actual ET (lower left, figure 1) which is withdrawn from the multilayered soil profile according to the specified root profile and water availability at that time. Infiltration, (daily precipitation minus runoff) wets the soil surface layers and soil water in all layers is redistributed by tension and conductivity relationships uniquely specified for each layer.

Plant transpiration calculations (right side, figure 1) include time distributions of canopy development (percent of soil shading), plant phenology (stage of maturation), and root density. Plant moisture stress variables include the water availability of each soil layer and the evaporative demand in a relationship adopted from that of Denmead and Shaw (1960). Crop water stress was defined as

$$\text{stress} = 1 - \frac{AT}{PT} \qquad (1)$$

where AT equals daily actual plant transpiration and PT equals potential transpiration.

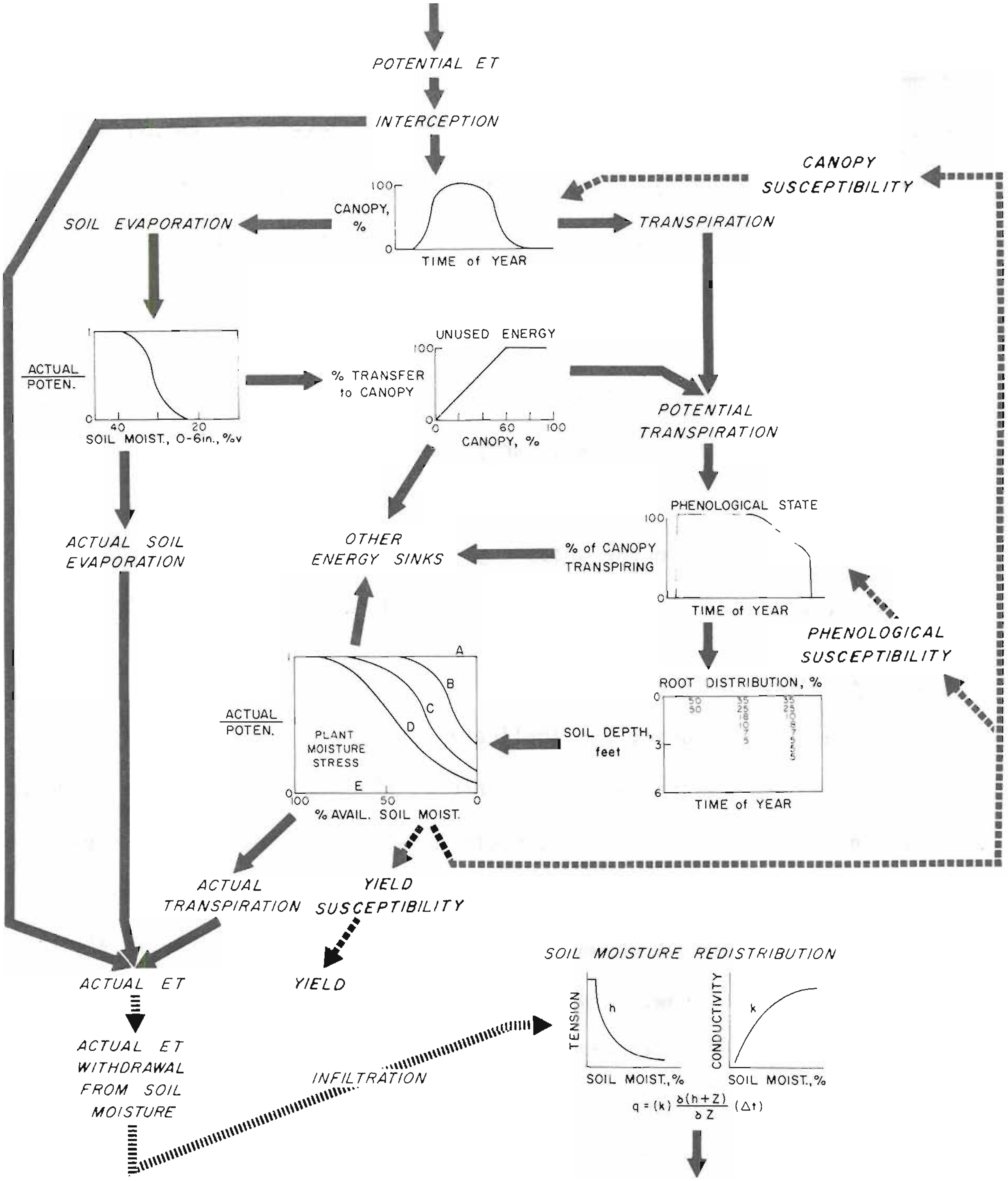

Figure 1. Schematic representation of the soil-plant-air-water (SPAW) model computations of hydrologic budget and crop water stress.

Daily water stress values were modified by relationships to compute effects on canopy growth, crop phenology, and crop yield. Canopy and phenology effects were set by stress ranges of no effect, linear increase, and no growth. For yield reduction, stress values were multiplied by a susceptibility (SUS) relationship based on stage of growth such that an end of growing season water stress index WSI is computed by

$$WSI = \Sigma(\text{stress} \times SUS) \quad (2)$$

The development of these relationships is described in detail by Sudar et. al. (1979) and based on work by Hiler and Clark (1971). The computed WSI values are the seasonaly integrated results of daily soil moisture profiles, root profiles, climatic demand, and crop stage.

Study Procedure

To test the accuracy and applicability of the expanded SPAW model and WSI values, two transects of connected climatic regions were selected as shown in figure 2. These transects were selected because of their large variability in precipitation and evaporative demand as shown by the isolines of average annual precipitation and average annual lake evaporation (V. T. Chow, 1964). Annual precipitation varies from 40 inches in northeast Missouri to less than 20 inches in western Kansas and South Dakota. Annual lake evaporation varies from 32 inches in northeast Iowa to near 60 inches in western Kansas.

Corn was selected as the representative crop over the study transects because of its economic importance and water stress susceptibility. Corn is not a major non-irrigated crop in the drier regions,

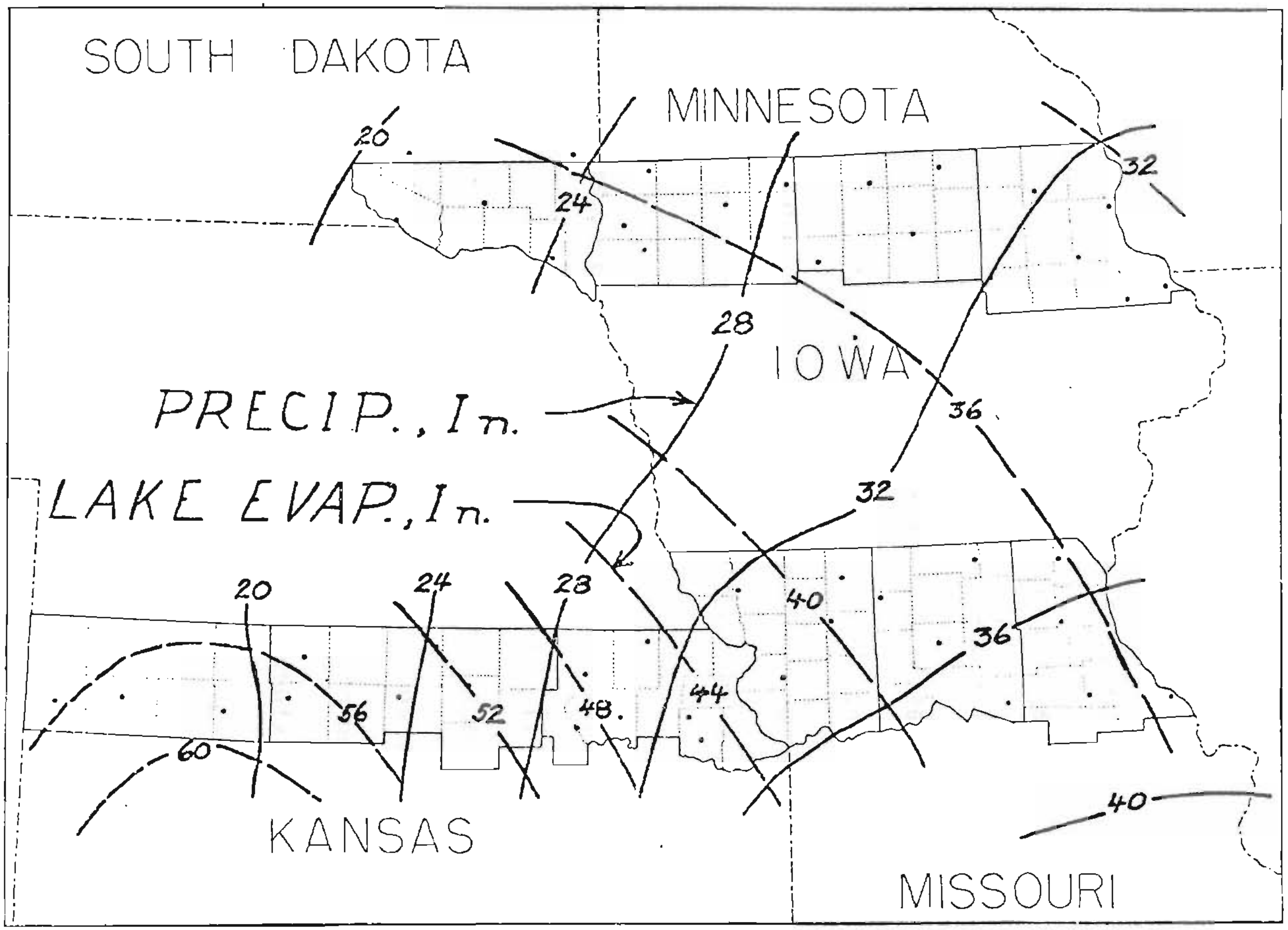

Figure 2. The two study transects with selected sites and average annual precipitation and lake evaporation.

but the transition from low to high probable water stress provides excellent test data for the prediction method. The model was calibrated with data from research plots in western Iowa and central Missouri.

To represent the 110 counties in the two transects, 49 raingage locations as reported by NOAA (formerly U. S. Weather Bureau) were chosen as study sites. (Shown in figure 2). Daily precipitation was available from each site and daily pan evaporation was prorated by average annual lake evaporation from the nearest reporting evaporation station. The period of study was selected as 1967-1976, plus the near-drought year of 1977 was used for verification. Representative soil profile descriptions for the major corn producing soils surrounding each site were obtained from the USDA Soil Conservation Service, and county corn yield data were obtained from the USDA Statistical Reporting Service.

A complete hydrologic soil water budget was computed for each day of each site for the 11 year study period. Daily precipitation and pan evaporation for each site was used along with a parameter set representing the crop and soil characteristics. The crop parameters of seasonal canopy and phenological development were held constant for all stations of both study transects. The soil profile was represented by 9 layers of depths of 1, 15, 30, 45, 61, 91, 122, 152, 213 cm. with the water holding and conductivity characteristics varied by depth and location according to soil profile descriptions. Several rooting densities were applied based on soil layer density characteristics.

Results

The annual water budget and stress values shown in figure 3 provide

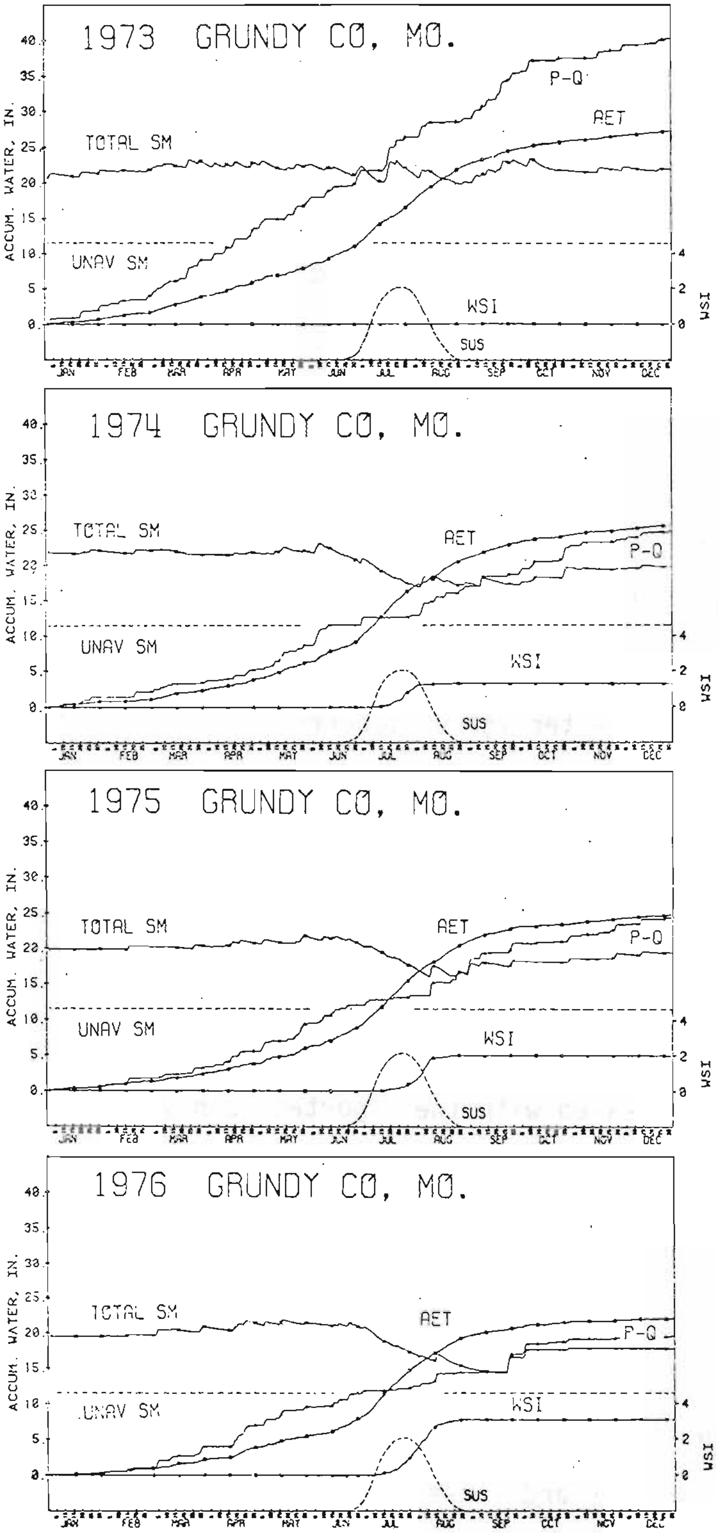

Figure 3. Examples of hydrologic, soil moisture, and crop water stress variation throughout the year.

examples calculations. Whenever the rate of accumulative infiltration (P-Q) was less than the rate of actual ET (AET), the total soil moisture (Total SM) was reduced. The dynamics of the soil moisture reduction and replenishment became a key to crop water availability. As the total soil moisture approached the quantity of unavailable soil moisture (UNAV SM), crop water stress was more likely. As stress occurred during the period of yield susceptibility, the Water Stress Index (WSI) accumulated according to the degree of stress weighted by the susceptibility (SUS) curve.

The four years shown in figure 3 represent a range of years from very wet where WSI equaled near zero to relatively dry years where considerable crop water stress occurred and the WSI index values accumulated rapidly. A significant amount of yield-reducing water stress occurred in a relatively few days, but the conditions leading up to that situation reflected the hydrologic sequence over the past several months or year.

The accumulated WSI values of each growing season of the study site were correleated with the reported corn yields of one or more counties represented by the site. Correlations were made for the 1967-1976 period, but 1977 WSI values were also computed to be used as an independent verification for estimation ability because it was a near drought year and highly variable over the study region. The WSI values were quite sensitive to the soil characteristics assigned to the soil profile and these are difficult to realistically represent. However, once calibrated for a given site, the index values became meaningful for future predictions. Similarly, the inherient potential for crop yield of a given site or county is quite variable due to factors other than crop water stress. These factors contribute to the variability of the correlations among the 49 study sites and preclude extensive transfer or comparison of the WSI - yield correlations without further refinement and study to allow more accurate estimation of this spatial variation. The utility of the WSI - yield correlations is that once derived for a calibration period, future effects of crop water stress can be assessed using the same parameter set for that site.

Figures 4 and 5 show ten examples of the WSI-yield correlations. One station was selected from each of the ten climatic regions which comprise the two study transects. Figure 4 shows those from the South Dakota-Iowa transect. The 1977 values are shown but were not used in the statistical correlation. The potential yields shift upward significantly as the regions progress eastward (a to d). The northeast Iowa region had less yield variation and poorest WSI correlation. This may be the result of improper soil characteristic assignments, effects of bottom land subirrigation, or some other relationship not properly represented in the model.

Figure 5 shows the six example correlations for the southern transect progressing from western Kansas to northeast Missouri. (a to f). Only five years of data were available for the western and central Kansas sections because the irrigated and non-irrigated crop yields were separated only during the latter years. Although the acreage of non-irrigated corn is small in these two sections, the reported yields are highly correlated with the computed WSI values.

In northeast Kansas (figure 5c), corn acreages are significant and were highly correlated with the computed WSI values. It is realistic

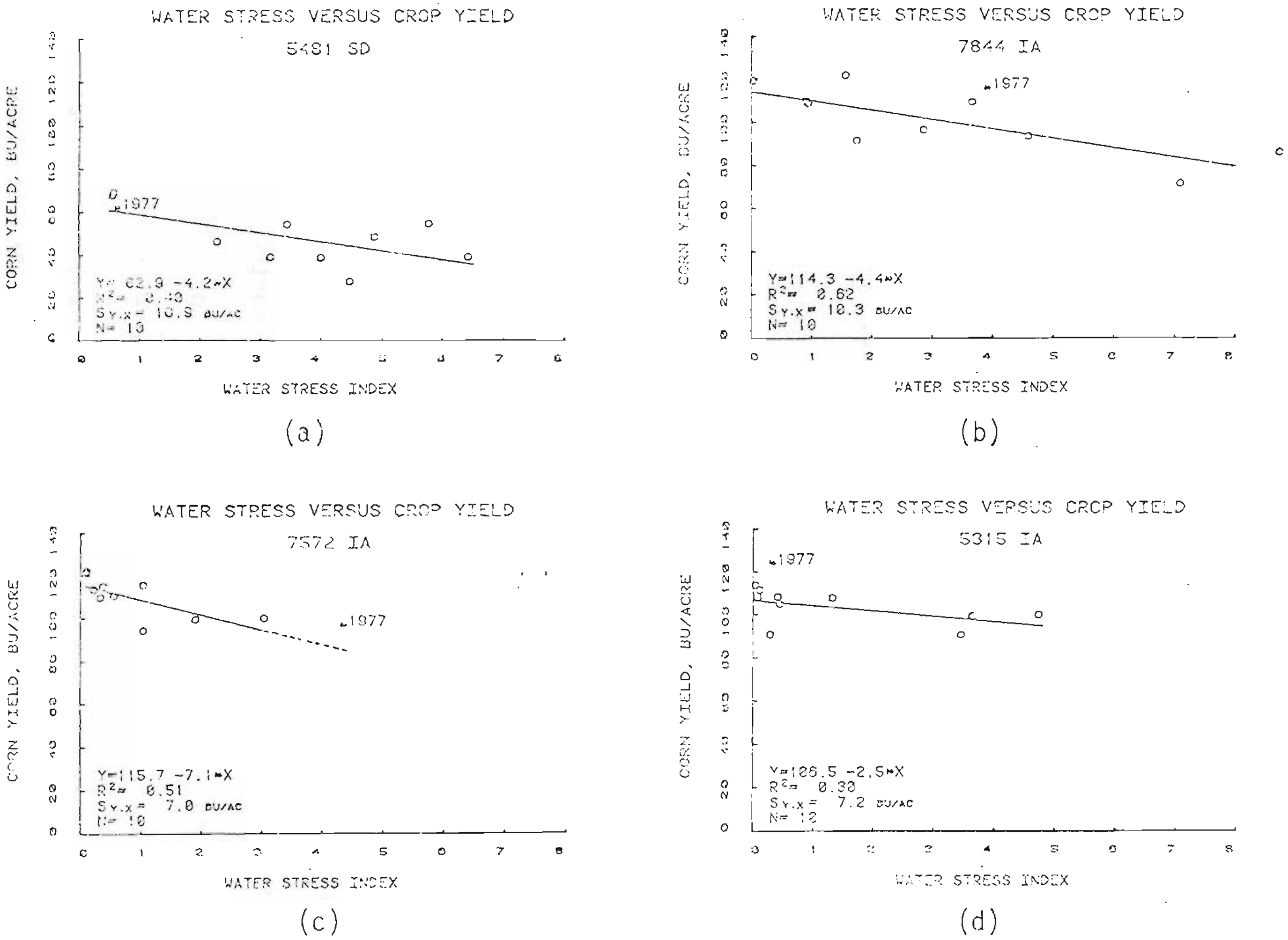

Figure 4. Correlations of corn yield with water stress index (WSI) values for example stations in the South Dakota-Iowa transect.

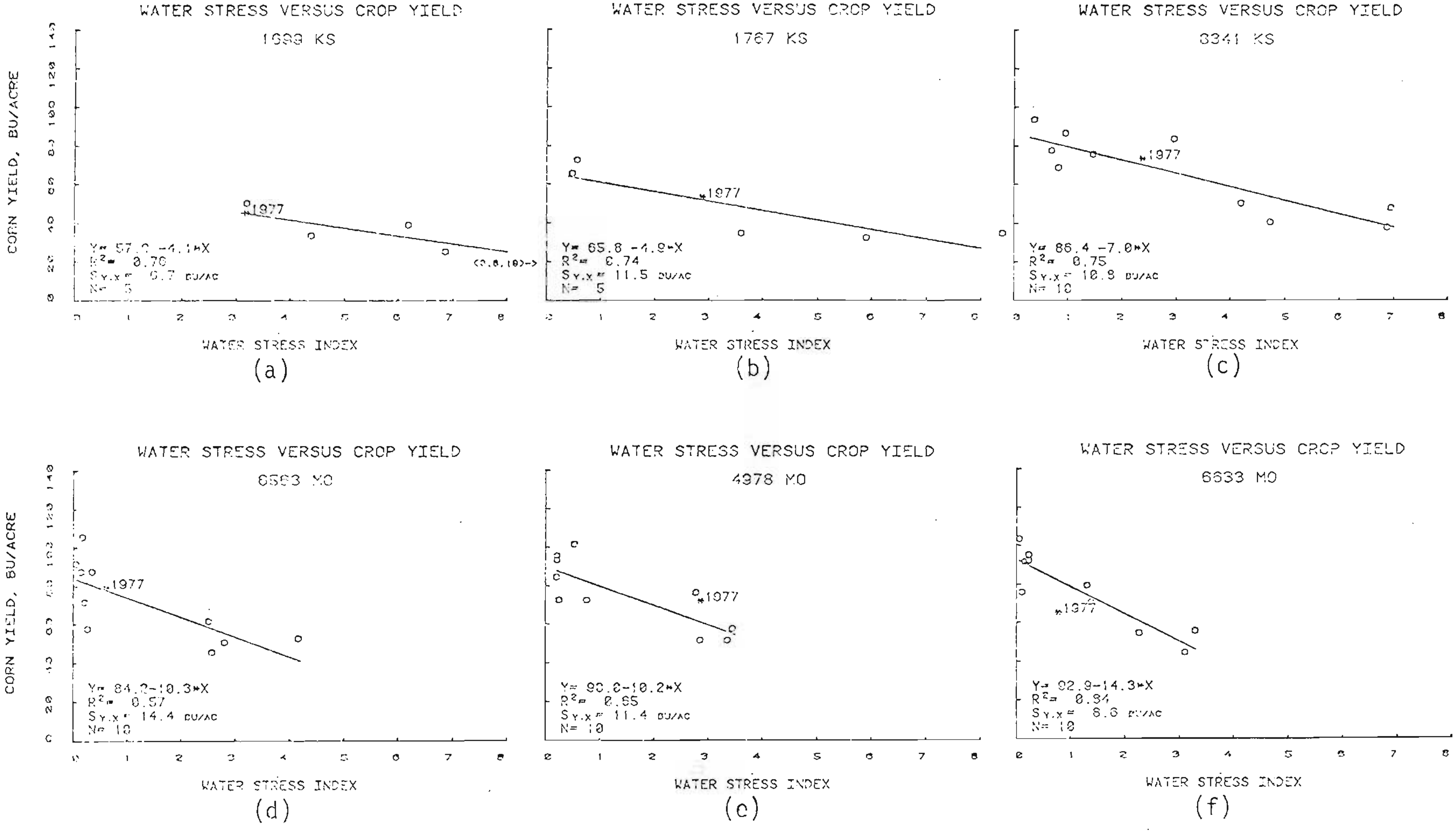

Figure 5. Correlations of corn yield with water stress index (WSI) values for example stations in the Kansas-Missouri study transect.

to find that crop water stress frequently limits production in this transition zone, but these results clearly demonstrate that the WSI values are a sensitive and reasonably accurate representation of this crop water stress effect.

The three Missouri examples (figure 5-d, e, and f) show more years of little water stress than the drier regions but a few years of significant crop yield reduction correlate with large WSI values, thus they are identified as the result of crop water stress. This region has large areas of claypan soil with low water holding capacity and an occassional intensive dry period during July and August which together result in crop water stress.

All of these correlations contain the variability caused by other yield reduction factors such as insects, disease, weeds, excess water, etc. plus yield sampling accuracy. And the point precipitation and pan evaporation values are quite subject to spatial variation in this region of frequent convective type rains. Even so, these effects tend to average sufficiently to allow reasonably good soil water budgets and crop water stress definition by the daily soil water budgets and daily climatic data.

A summary of the yield-WSI correlation results for all 49 stations over the two study transects is given in table 1. In general, consistently better correlations (R^2) were obtained in the regions subject to soil moisture variability and water stress. Part of this results from the lack of yield variability and very flat correlation lines in the wetter regions (northeast Iowa and northeast Missouri). The average standard deviations about the means and correlation lines (S_y and $S_{y.x}$) show that accounting for crop water stress by the WSI values improves

Table 1. Correlation results of corn yield versus water stress index (WSI) for all sites in the study transects.

STATION		CORRELATION RESULTS				
NAME	U.S.W.B. NUMBER	a	b	R^2	Sy.x	Sy
SOUTH DAKOTA						
- Southeast						
Stickney	8007	63.9	- 4.2	.59	9.6	14.1
Pickstown	6574	55.8	- 3.0	.57	7.5	10.9
Menno	5481	62.9	- 4.2	.40	10.9	13.3
Sioux Falls AP	7667	82.2	- 4.5	.41	14.7	18.0
Vermillion 2 SE	8622	95.5	- 6.9	.69	12.2	20.7
				Mean:	11.0	15.4
IOWA						
- Northwest						
Little Rock	4863	124.7	- 8.2	.70	12.5	21.6
Sioux Center	7700	107.5	- 5.3	.41	16.4	20.1
Remsen	6975	105.2	- 8.8	.65	11.2	17.7
Spencer 1 N	7844	114.3	- 4.4	.62	10.3	15.8
Ringstead	7058	114.2	- 4.8	.29	11.8	13.3
				Mean:	12.4	17.7
- Northcentral						
Humbolt 2	3985	120.9	- 3.9	.55	7.3	10.3
Forest City	2977	117.1	-11.8	.42	10.6	13.1
Sheffield	7572	115.7	- 7.1	.51	7.0	9.4
St. Ansgar	7326	104.5	-16.2	.57	12.2	17.5
Ames	0200	120.4	-22.9	.47	7.8	10.2
				Mean:	9.0	12.1
- Northeast						
Waterloo	8706	109.8	- 4.5	.41	7.6	9.3
Spillville	7855	98.3	- 2.5	.32	8.5	9.7
McGregor	5315	106.5	- 2.5	.30	7.2	8.1
Strawberry Pt.	8009	105.7	- 0.8	.02	6.9	6.6
Cascade	1257	105.3	- 3.1	.10	8.1	8.1
Dubuque AP	2367	105.1	-12.9	.16	8.2	8.4
				Mean:	7.8	8.4
KANSAS						
- Northwest						
Goodland AP	3153	90.5	- 7.5	.59	10.9	14.8
Colby 1 SW	1699	57.9	- 4.1	.76	6.7	12.0

(continued)

STATION		CORRELATION RESULTS				
NAME	U.S.W.B. NUMBER	a	b	R^2	Sy.x	Sy
KANSAS (Northwest, continued)						
Norton Dam	5852	58.0	- 3.9	.65	9.2	13.4
Morland	5483	92.1	- 8.7	.99	1.1	10.2
				Mean:	7.0	12.6
- Northcentral						
Phillipsburg	6374	68.7	- 5.3	.75	8.0	13.8
Webster Dam	8648	89.4	- 8.4	.66	13.3	18.5
Glen Elder Dam	3100	63.9	- 4.1	.61	12.4	17.3
Lovewell Dam	4857	68.1	- 3.3	.34	19.5	20.8
Concordia AP	1767	65.8	- 4.9	.74	11.5	19.5
				Mean:	12.9	18.0
- Northeast						
Frankfort	2872	78.0	- 5.7	.71	8.5	14.8
Tuttle Creek Lake	8259	84.9	- 5.4	.69	9.1	15.3
Onaga	6014	81.0	- 6.1	.94	4.5	16.6
Sebatha Lake	7073	85.4	- 9.6	.63	13.7	21.1
Valley Falls	8341	86.4	- 7.0	.75	10.8	20.5
Perry Lake	6333	86.6	- 5.7	.83	9.0	20.3
				Mean:	9.3	18.1
MISSOURI						
- Northwest						
Skidmore	7813	101.8	- 6.5	.39	16.3	19.7
Gower	3300	94.9	- 8.2	.82	10.3	22.7
Ridgeway 6WNW	7130	94.0	-13.3	.81	8.3	18.1
Pattonsburg	6563	84.2	-10.3	.57	14.4	20.7
				Mean:	12.3	20.3
- Northcentral						
Spickard 7W	7963	92.4	- 8.2	.73	9.6	17.4
Stet 4 SSE	8063	92.8	- 7.4	.69	13.6	23.0
Linneus	4978	90.0	-10.2	.65	11.4	18.2
Livonia	5014	91.3	- 7.9	.66	7.4	11.8
Moberly Radio	5671	90.8	- 7.1	.76	9.8	18.7
				Mean:	10.4	17.8
- Northeast						
Luray	5130	91.9	- 8.8	.48	11.4	14.9
Steffenville	8051	95.2	- 5.2	.40	13.9	17.0
Perry	6633	92.9	-14.3	.84	8.6	20.0
Clarksville L&D	1640	94.3	-12.6	.71	11.6	20.3
				Mean:	11.4	18.1

the yield estimates considerably, particularly for years which are limited by crop water stress. Equally important, the method offers: 1) the potential of continuous daily evaluation of specific crops and soils at any time during the growing season, 2) calibration and adjustment with actual measurements and observations should they be available, and 3) input of probable data for the remainder of the growing season to project likely water stress and crop production results. This method provides more flexibility and accuracy than the Palmer Index (Palmer, 1965) or Crop Moisture Index now frequently reported.

Estimates of 1977 crop yields based on the ten-year correlations of each study site and the computed 1977 WSI value for that site are compared with observed yields in figure 6. An R^2 of 0.78 shows good agreement although the higher yields tended to be underestimated for this particular year. The significant result is that those sites which experienced significant drought and reduced yields were quantitatively identified and separated from often near-by sites which, although dry, had timely precipitation and much less crop water stress. The 0200 Iowa Station (Ames) was a noteable example where none of the previous ten years had yields below 100 bu/a or a WSI greater than 1.0, yet the 1977 results showed a two county yield of 36 bu/a and a computed WSI equal to 4.1.

Summary and Conclusions

Because of the tightening food supply in the world and increased importance of U. S. food supply and exports, there is a need to develop improved methods for continuous assessment of crop yield estimations. A major part of our national crops are dependent on precipitation, and

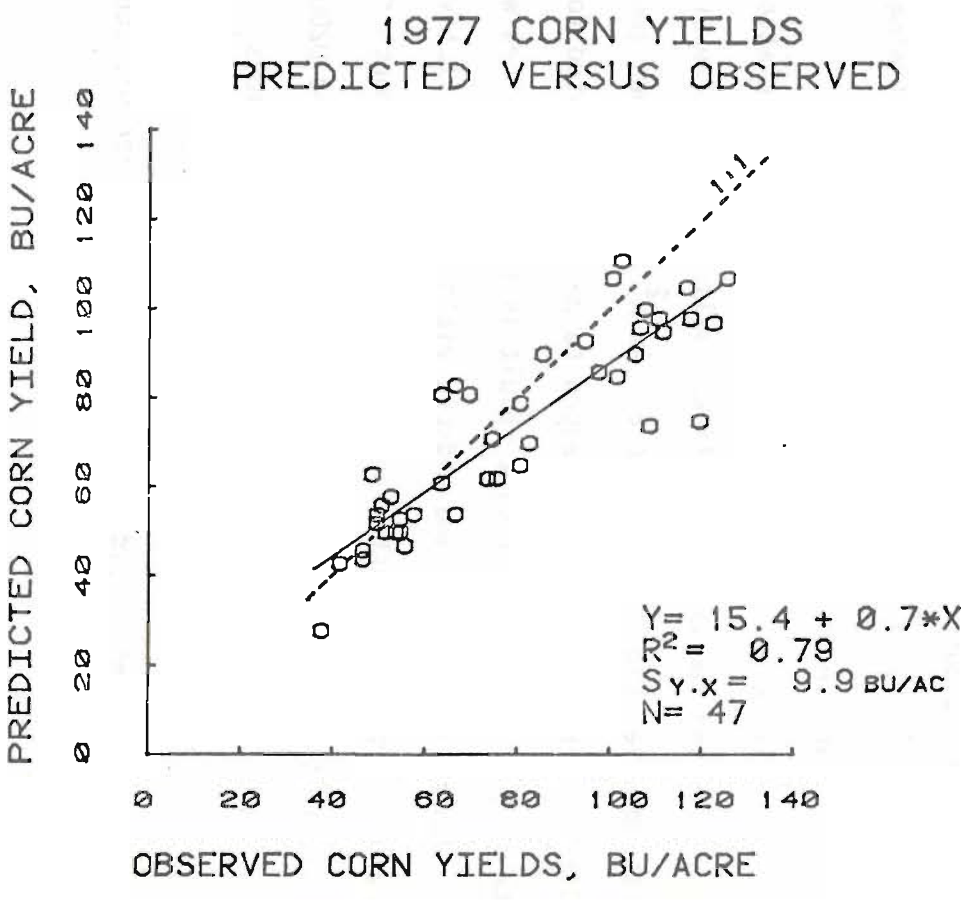

Figure 6. Predicted and observed 1977 corn yields for the sites over both study transects.

for many regions this becomes the dominant variable influencing year-to year production. Crop water stress results from a complex time series of weather, crop, and soil relationships which proceed in a highly dynamic state. Through a complex combination of relationships, the major processes of the soil-plant-air-water (SPAW) system can be represented in a digital computer model which will provide a reasonable simulation of the daily status of a local situation.

Through modification and adaptation of the SPAW model previously developed for soil water and evapotranspiration estimates, we were able to compute a water stress index (WSI) accumulated for each growing season which correlated well with county corn yields over two study transects of 110 counties represented by 49 study sites. Although the 1967-1976 correlations were unique for each study site because of soils, climate, inherient fertility, etc. for those counties, 1977 yield estimates agreed reasonably well with observed yields. Most important was the fact that those sites which experienced significant drought and crop water stress were readily identified and distinguished from often near-by sites which had less stress or even near-normal yields.

We conclude that a detailed method of soil water prediction utilizing daily climatic data can provide a sensitive estimation of crop water stress and its effect on crop yield. Specific parameters which represent crop and soil characteristics are yet sufficiently difficult to define such that each local region needs calibration; but once a parameter set is established, future years can be predicted with moderate to good accuracy. More experience and knowledge with the method will reduce required calibration. Even though the method is complex compared to current applied procedures, the relative minor costs of 1 to 2 cents per station per day make such an approach feasible on a broad regional basis with todays computing capability. Significant improvement in assessing weather and soil moisture effects on national crop yields could be achieved by implementation of this physically based method.

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