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Soil Moisture and Moisture Stress Prediction for Corn in a Western Corn Belt State*

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美國 옥수수 西部主産地帶에서의 土壤水分과 作物水分障害 豫測硏究*

로버트 쇼**

INTRODUCTION

Iowa is in a very interesting position for a climatologist with respect to soil moisture. It is located in a transition zone between humid climates to the east, and dry climates to the west. As a result of this, soil moisture reserves may vary widely from year to year, and even from place to place within a year. A wet situation may prevail where free water can be found in the 5-foot profile and the tile are running.

We may have the maximum available water, without any free water being present, a field capacity condition. In many of Iowa's soils, this can mean a 10 to 12 inch reserve in the 5-foot profile. Or there may be very little available water in the profile. This variation in soil moisture reserves was what stimulated us to start our statewide soil-moisture survey in 1954.

My talk will cover a soil-moisture program developed from these data and used to predict the moisture under corn at any time during the growing season. It is therefore keyed to Iowa's "deep soil" conditions. As simple an approach as possible was used in developing the program. The idea was to develop a program that would predict soil moisture program. On an extremely variable glacial till soil, our samples have a standard error of ± 1 inch. For a more uniform loess soil, this sampling error is less than ½ inch. Many tests over the years indicate we are estimating soil moisture within those numbers. Some of you will immediately be con-

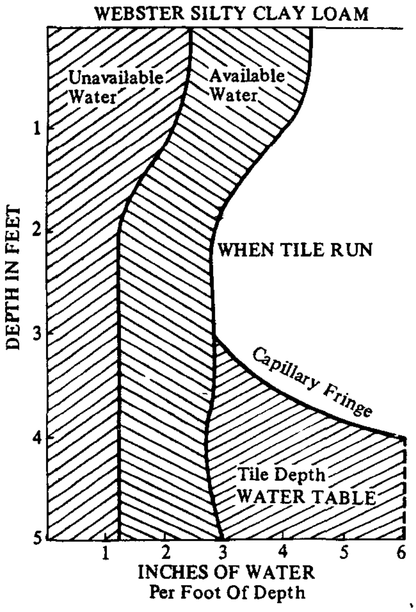

Fig. 1. Soil moisture profile with free water

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* 韓國作物學會 創立 第20周年記念심포지움 招請 演士의 심포지움 前 發表 特講, ** 美國 아이오와州立大 著名 教授.

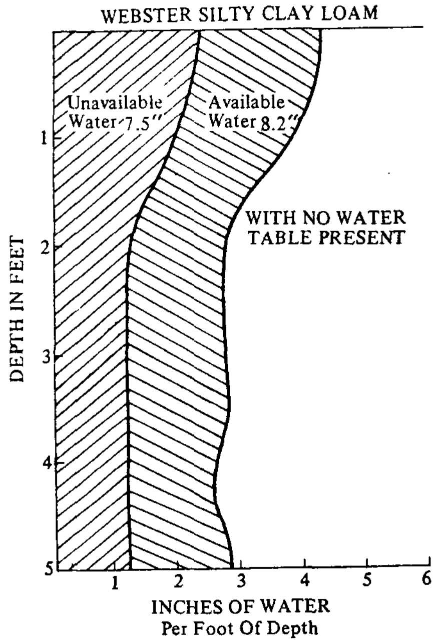

Fig. 2. Soil moisture profile at field capacity.

within the limits of the soil-moisture sampling cerned about the size of these limits, with sampling errors much larger than daily ET losses which may be only 0.2 to 0.25 inch, or less. Even though we estimate day to day changes in soil moisture, our goal is to estimate values on selected dates that are a considerable number of days apart. This we seem to be able to do. We can further explain a significant portion of our yield variation of corn, using a stress index developed from the soil-moisture program.

With that background, let me proceed and explain our program. First let's look at items that need to be considered, then I'll explain what we do.

SOIL MOISTURE PROGRAM

Saxton, Johnson and Shaw developed a flow chart for a soil moisture program (Figure 4). Potential ET, expressed by some measure of the drying power of the atmosphere, can be subdivided into 3 components, evaporation of intercepted water, soil evaporation, and transpiration. My program does not include intercepted water directly, but I would like to comment on it. Work that Leo Fritschen and I did many years ago indicated a full corn canopy could intercept almost 0.15 inch of rainfall, in rains over 1/2 inch. For research studies this could be very important if disregarded. For my purpose I ignored it, which says that it will be indirectly included in the transpiration term.

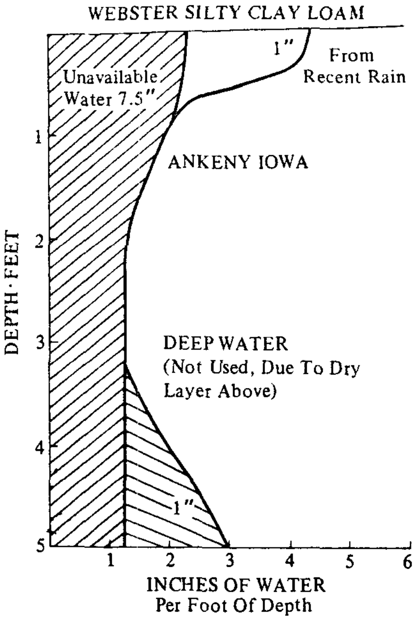

Fig. 3. Soil moisture profile with a dry condition

Next, one must separate evaporation and transpiration according to the crop cover. Evaporation will be a function of the atmospheric demand as well as the availability of water for evaporation from the top few inches of soil. Transpiration will obviously be a function of the amount of crop cover or stage of crop development. The depth where roots are extracting water must also be considered. If soil moisture is not "completely available" for transpiration, then the degree of reduction in transpiration must be considered. One must also decide how runoff will be handled, and how moisture will infiltrate into the soil.

The program calculations are all made in terms of plant-available moisture. The soil profile is divided into 6-inch increments down to 5 feet. In special cases a 7-foot depth is used. A "field capacity" value and a "wilting point" value must be determined for each increment. We determined field capacity from field measurements. Wilting point values are

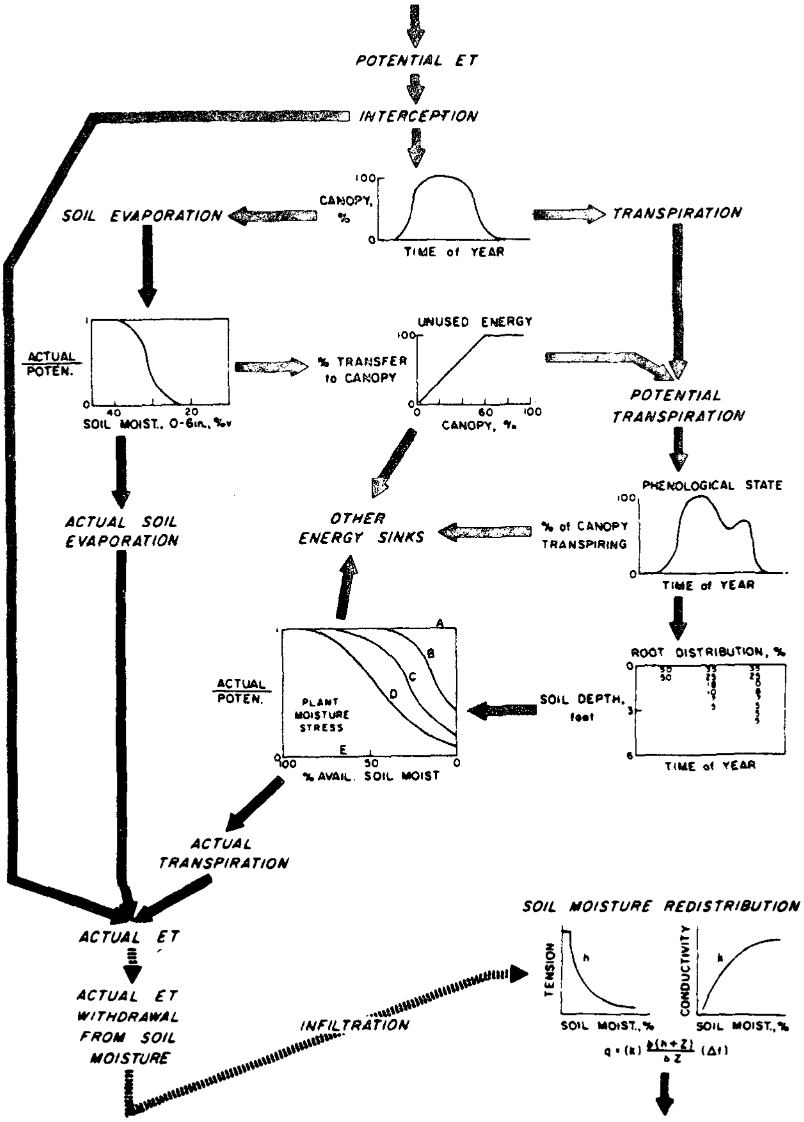

Fig. 4. Flow chart of ET calculations and soil moisture movement.

determined using the 15 bar value.

RUNOFF

An antecedent precipitation index was used to calculate runoff. All our soil-moisture sites were located on relatively flat land from which runoff could occur, but with no runon and ponding of any significance. Obviously, predicting values where runon could occur would be much more complicated. Two equations were used

$$\mathrm{API} = P_1/d_1 + P_2/d_2 + \ldots + P_i/d_i \qquad (1)$$

$$\mathrm{API} = P_1/d_1 + P_2/d_2 + \ldots P_i/d_i + P_0/2 \qquad (2)$$

P_1 is the rainfall for d_1, yesterday; P_2 is for 2 days past and P_0 is for today, the day for which the API is being calculated.

Equation 1 is used after Aug. 31. Equation 2 is used during the spring months when the ground is bare, or cover is sparse when runoff will be relatively high, and in the summer when high-intensity rains are expected to occur. P_0, the rainfall amount for the day being calculated, is used only for values

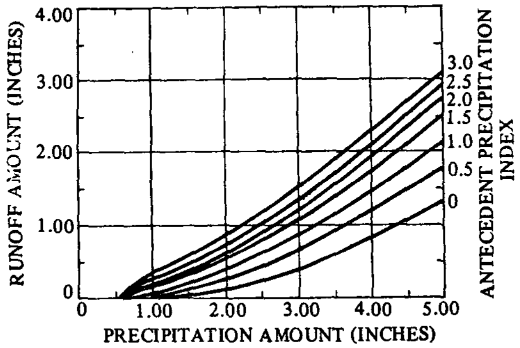

Fig. 5. Prediction of runoff from precipitation and antecedent precipitation index (after Buss and Shaw, 2).

greater than 1 inch. If 1 inch or less, Po = 0 and Equation 1 = Equation 2.

The API value was then used in Figure 5 to compute the runoff. This procedure does not directly take into account intensity, of the rainfall.

INFILTRATION

The precipitation remaining after runoff was infiltrated into the soil with the following simple procedure: The first increment (0-6 inches) is allowed to fill to field capacity. Any amount above this immediately moves to the second increment and the process is repeated. The process is repeated until all the water has been used, or until all layers are at field capacity. If all layers are at field capacity, and water remains, it is percolated out the bottom of the profile in what might be called "instant drainage". In poorly drained soils this step would require modification, i.e. as done by Dale in Indiana. It seems to promote no measurable error under Iowa conditions at the sites used. By midsummer we rarely measure free water in the 5-foot profile. Also remember—low elevation sites where water runs on are not included in our survey.

EVAPORATION AND EVAPOTRANSPIRATION

Early April through June 6

There may be a variable ground condition in the spring from plowed to crop residue to small corn plants. If a growing meadow crop, this procedure would require modification. All water loss was assumed to be by evaporation from the top 6 inches of soil. Solar radiation is relatively high during much of this period. The availability of water for evaporation is believed to be the prime factor that limits water loss. Water loss was assumed to average 0.1 inch/day. Water was assumed to be lost at this rate as long as any available water was present in the top 6 inches of soil. This ignores meteorological factors, and also any change in the rate of moisture transfer to the soil surface. Ideally, daily demand, and soil dryness should be included, but they would complicate the program. During the test period using 7 years of data, the average deviation or difference between the value measured by soil sampling in mid-June and that predicted from the program using the April sample was only 0.05". Over half the values were predicted within ½". We were as likely to overpredict as underpredict, but the error was small *for the period* used.

June 7 through September 30

As the corn plant grows, considerable change

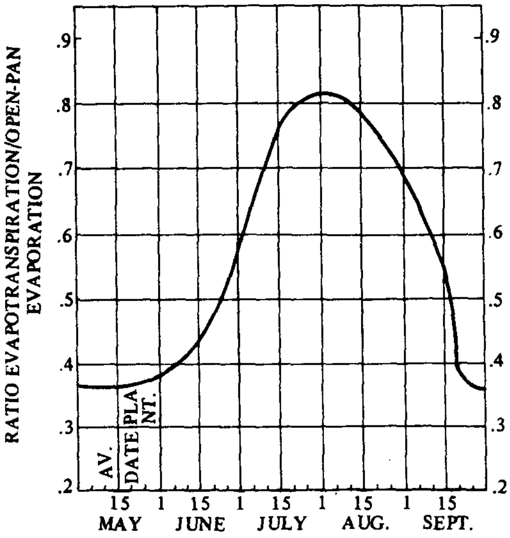

Fig. 6. Ratio of evapotraspiration of corn to open-pan evaporation throughout the growing season (after Denmead and Shaw, 3). On the average, 50% of the corn in Iowa is silked by July 31.

takes place in the ground cover. June 7 was selected as the arbitrary date when the prediction technique was changed. About that date a marked change is taking place in the ratio of ET to open pan evaporation, and it is a start of a week in the standard climatological year. Starting June 7, Class A pan evaporation was used as the starting point for estimating evapotranspiration. The daily pan evaporation is multiplied by the factor obtained from Figure 6. This relationship was developed assuming moisture was readily available for transpiration, but the soil surface condition was not specified. The dates used in this figure represent average values for Iowa. To adjust for seasonal development the silking date is input into the program (Ave. July 3). This is used as a floating reference point. If the crop is 10 days ahead of normal (silked July 21) the program automatically shifts all calendar dates 10 days earlier, for example this phase of the program would start May 28 instead of June 7. When soil moisture is not limiting ET = Pan x Conv. factor from Figure 6.

Data that Denmead and I obtained indicated a relation exists between the atmospheric demand and the level of soil moisture needed to meet that demand. Relationships obtained from his thesis study are shown in Figure 7. The θ_{TL} points represent the conditions when visible signs of stress (wilting) were evident. Notice that these points occurred at quite different levels of soil moisture for the 3 days shown. Also notice how the transpiration decreased from the potential value at different soil moisture values for the different demand levels. Defining the points where these breaks occur has had considerable discussion in the literature. This discussion has become confused because of different terms used. We used available water (FC – WP). Ritchie has used extractable water. I don't have time to define it—but the two terms are different, and most of the disagreement in the literature is due to not reconciling the differences in definition before comparing results. Because our original work was done with restricted rooting volumes, and because a rather unusual soil was used in the containers, some adjustments had to be made to fit our original data to field conditions. The curves we now use for the period up to silking are shown in Figure 8.

A high demand day is one in which Class A pan evaporation is greater than 0.30 inch. A low demand day is one in which Class A pan evaporation is less than 0.20 inch. A medium demand day is then from 0.20 to 0.30 inch. One could use other systems, i.e., Penman, Thornthwaite, or Priestley to do the same thing. I felt that pan evaporation was a simple, but sensitive way, of doing it.

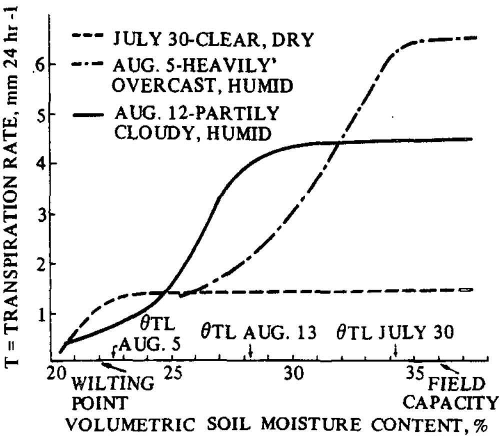

Fig. 7. Daily transpiration for 3 days plotted as a function of soil moisture (Denmead and Shaw, 1962).

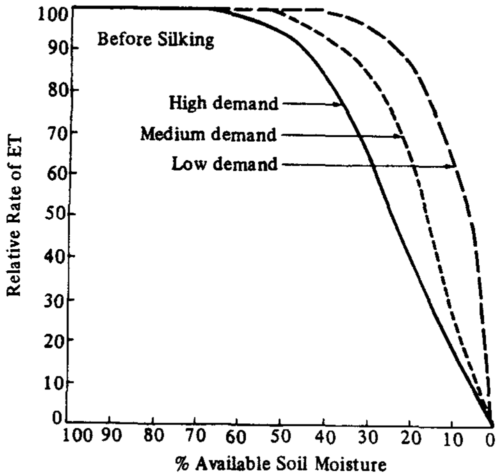

Fig. 8. Relative ET rates for different atmospheric demand rates prior to Aug. 1.

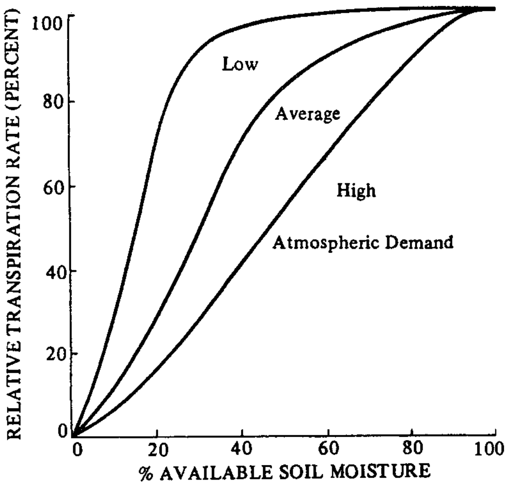

Fig. 9. Relative ET rates for different atmospheric demand rates for Aug 1 and later.

The percent available soil moisture in the root zone (I'll define that in just a minute) is used for each day to determine the relative ET. For example, if we have a day in which there is 70% available in the root zone, the relative ET rate would be 100% of potential, regardless of the type of day. If there was only 40% available moisture in that root zone, ET would be 82% of potential for a high demand day, 91% for a medium demand day, and 100% for a low demand day. These would be the values before silking. After silking, because we assume that roots are not growing into areas of new moisture, another set of curves are used which give greater ET reductions for comparable soil moisture conditions (Figure 9). Comparable values then were 55%, 80%, and 100%.

Table 1. Water extraction from the soil profile at different depths during the growing season. Values for each date are given as the percentage of evaporation or evapotranspiration that occurs from each of the depths listed.

Dates	Percent of E or ET which comes from respective depths	Depths from which water was extracted
to June 7	100	1st 6 inches
June 8 to 14	100	1st foot (equally from each 6 inches)
June 15 to 27	67.7, 33.3	1st, 2nd foot
June 28 to July 4	60, 20, 20	1st, 2nd and top half of 3rd foot
July 5 to 11	60, 20, 20	1st, 2nd and 3rd foot
July 12 to 18	60, 15, 15, 10	1st. 2nd, 3rd and top half of 4th foot
July 19 to 25	60, 15, 15, 10	1st, 2nd, 3rd and 4th foot
July 26 to Aug. 1	60, 10, 10, 10, 10[a]	1st, 2nd, 3rd, 4th and upper half 5th foot
	60, 15, 15, 10[b] 10[a]	1st, 2nd 3rd and 4th foot
After Aug. 1	60, 10, 10, 10, 10[a]	1st, 2nd, 3rd, 4th and 5th foot
	60, 15, 15, 10	1st, 2nd, 3rd and 4th foot

To compute the percent available soil moisture in the rooting zone, the depth of rooting also had to be estimated. The following table shows how rooting depth progresses. It also shows the amount of water extracted from each depth (Table 1). As now used, our program has three different rooting depths, or more correctly, depths of extraction. Normal conditions use a depth of 5 feet; if certain wet conditions are met extraction is only to 4 feet, and if certain "dry" conditions are met in May and June, water can be extracted from a depth of 7 feet. If moisture is not available in any scheduled increment, that moisture extraction is prorated among those scheduled increments which do have moisture.

Evapotranspiration per day then is equal to:

PAN EVAP X RATIO FOR CROP DEV
X STRESS OR RELATIVE ET FACTOR

On days when the ET loss was reduced because of stress, one other factor was considered..If recent rains had added water to the surface soil, some of the reduced transpiration could be replaced by soil evaporation. As long as water was available in the top 6 inches of soil, up to 0.1 inch evaporation could be taking place if the energy was present to cause this evaporation. For example, on a day in which the potential rate was 0.25" and ET was calculated as only 0.14" (down 0.11 from potential), evaporation of 0.10 inch could take place, making the total loss 0.24". On a day when the potential rate was 0.25" and ET was calculated as 0.20", evaporation of 0.05" could occur. ET + added evaporation could not exceed the calculated potential.

October 1 and Later

Transpiration was assumed to essentially cease after Oct. 1 because of maturation of the crop. Loss was assumed to be only by evaporation from the top 6 inches of soil and was computed as 0.35 x pan evarpoation.

HOW WELL DOES IT WORK

As I mentioned earlier, we started sampling soil moisture in 1954 and have continued it each year since then. Originally we sampled four times a year: Mid-April, mid-June, early August and early October. This gave us many pieces of data to check the program. We are confident enough in the program now that we only sample in mid April and early October. These times provide a check point at the end of the season. Also, since I seldom have the weather data assembled until November or December, the fall survey also gives Extension people information at the time they need it on next years moisture reserve, an item of much interest to our farmers. The spring sample gives us a starting point for the new season, plus checking for any changes which took place over the winter. In our climate, gains in soil moisture during the winter are usually small because of a frozen soil and low precipitation. When significant precipitation does occur, changes in the soil moisture are difficult to predict, but on the average are about 25% of the precipitation which occurs.

STRESS INDEX

An an extension of the soil moisture program we now computed a seasonal stress index for corn. This is now computed from two simple equations

$$SI = 1 - (STET + EVAP)/ET \qquad (1)$$

or

$$SI = 1 - STET/ET \qquad (2)$$

where STET is the actual ET which occurs, EVAP is the evaporation from the surface 15 cm of soil and ET is evapotranspiration when the moisture supply is not limiting. The second equation is used only when STET is less than or equal to 0.04 inch (1 mm) and pan evaporation is greater than 0.30 inch (a high demand day) whatever evaporation occurred under those conditions (high demand-low soil moisture) was considered as having no effect on reducing stress on the plant. The index for each day can range from 0 (no stress) to 1 (no STET).

The stress index is calculated for each day for a period from 40 days before to 44 days after silking

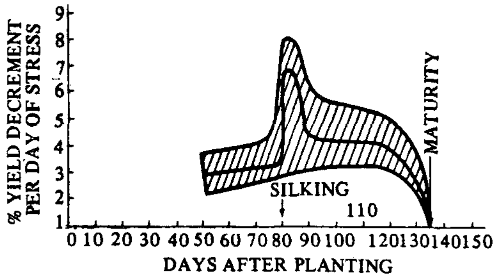

Fig. 10. Schematic diagram of relationship between age of crop and percentage yield decrement due to one day of moisture stress.

(85 days) with relative weighting factors assigned to each 5-day period relative to silking. The weighting factors were based on data accumulated by a number of researchers (Figure 10). Actual weighting factors used are shown in Table 2. Accumulative effects due to severe stress are given additional weighting factors:

a) When 2 or more consecutive 5-day unweighted stress index values were both 4.5 or greater, an additional weighting factor of 1.5 was used.

b) when the index for two of the periods 1 before, 2 before or 3 before silking were 3.0 or greater, an additional weighting factor of 1.5 was used.

c) when the unweighted index for both the 1 before and 1 after periods are both 4.5 or greater, a crop failure is indicated.

Table 2. Relative weighting factors used to evaluate the effect of stress on corn yield. Periods are 5-day periods relative to silking (after Shaw, 1974)

Period[a]	Weighting factor	Period	Weighting factor
8 before	0.50	1 after	2.00
7 before	0.50	2 after	1.30
6 before	1.00	3 after	1.30
5 before	1.00	4 after	1.30
4 before	1.00	5 after	1.30
3 before	1.00	6 after	1.30
2 before	1.75	7 after	1.20
1 before	2.00	8 after	1.00
		9 after	0.50

The sum of all the 5-day weighted values is the seasonal stress index.

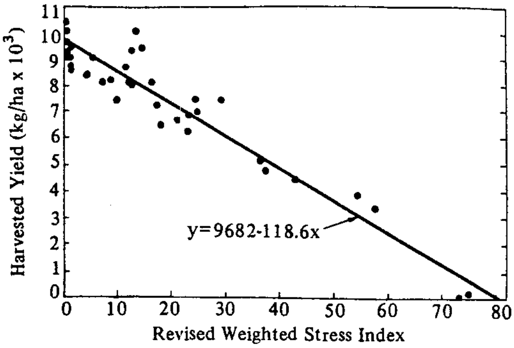

Fig. 11. Weighted stress index-yield relationship using optional 152-cm or 213-cm rooting depth, Nicollet silt loam moisture characteristics and the modified stress index equation.

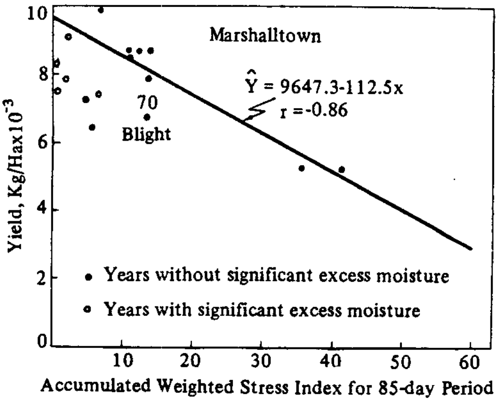

Fig 12. Relationship between weighted-stress index and corn yield near Marshalltown.

The stress index-yield relation has undergone a number of revisions over the years. Our current relation used is shown in Figure 11. These are sites where no excess water occurred and represent data over several recent years. This relationship assumes a potential yield of 9682 kg/ha (154 bu/A). One can convert this to other potential yield levels by letting the 0 stress intercept be that yield value, and the 0 yield value 81.6 + units of stress. The same number of units of stress are assumed to produce 0 yield, regardless of the potential yield. Our data indicate the regression lines for different yield levels converging near the same stress value. In using this equation we start with the potential yield and reduce the yield as the season progresses. This gives us an estimate of how much yield has been lost at any desired date during the season.

Some interesting side-benefits have developed from this work. In the early years of testing we frequently found a wide range of yields occurring low-stress values. Low stress occurred when we had a good growing season, as well as those that were too wet in the spring, and had good moisture later.

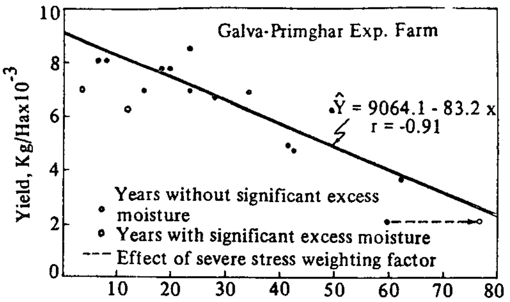

Fig. 13. Relationship between weighted-stress index and corn yield at the Galva-Primghar Experimental Farm.

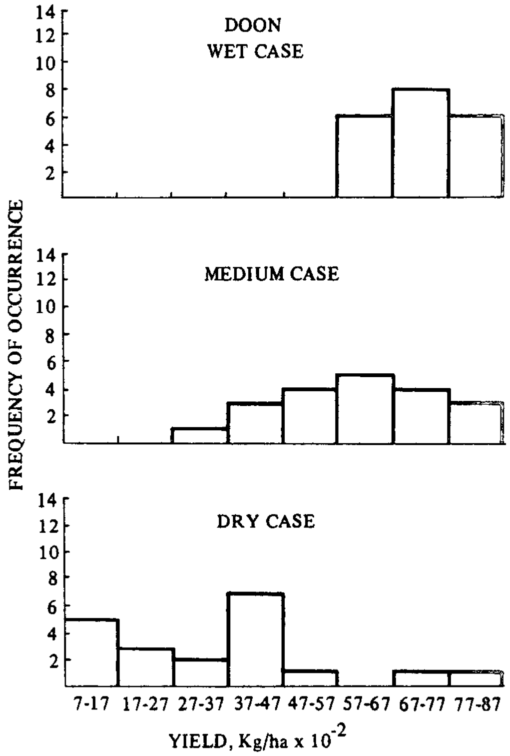

Fig. 14. Distribution of corn yields at Doon, as predicted by Y = 8616.8 x 135.3X, over the period 1951 to 1970 for three different spring moisture conditions.

The squares shown in Figure 12 represent years when it was too wet in May and June—the profile was filled to field capacity, with percolation at least once during each month in that period and with one month having at least 2 inches of percolation. We cannot predict how much the yield will be reduced, only that it will be reduced.

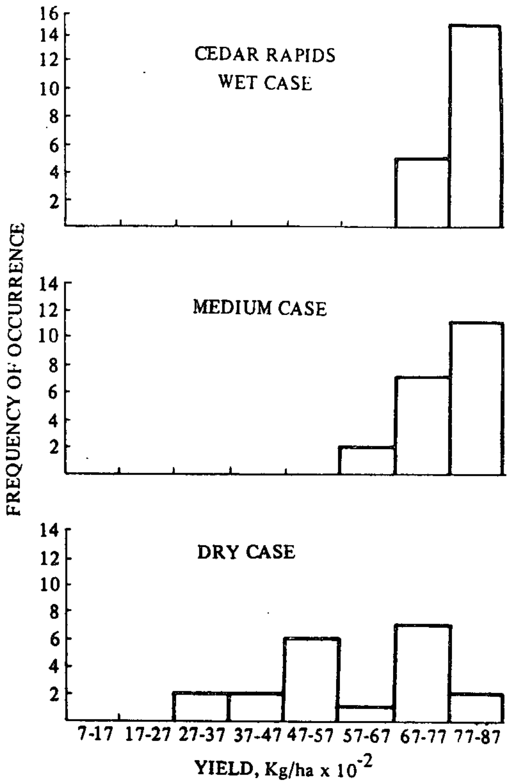

Fig. 15. Distribution of corn yields at Cedar Rapids, as predicted by Y = 8616.3 x 135.3X, over the period 1951 to 1970, at three different spring moisture conditions.

As we move toward northwest Iowa, excess water occurs much less frequently. Only two years showed this at the Galva-Primghar Research Center. The bottom dashed arrow shows an example of what the additional weighting factor for severe stress does. This yield relation was developed several years ago at a lower yield base than we use now.

We've also used the procedure to project yield outlooks with different levels of soil moisture reserve in the spring. Over a 20-year period we assumed that soil moisture on April 15 of each year started out at 20%, 60% or 100% of field capacity in the 5-foot profile. However, the actual weather data for each year subsequent to April 15 were used to

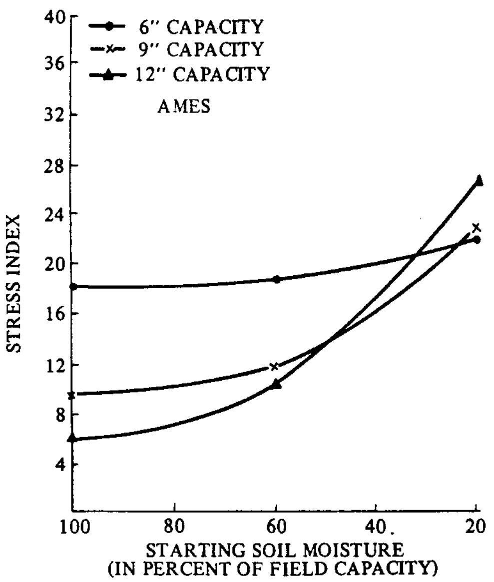

Fig. 16. Relationship between a moisture-stress index and starting soil moisture for field capacity values of 6, 9, and 12 inches, at Ames.

calculate the stress index. Doon, in extreme northwest Iowa shows high yields produced if they start at field capacity. Unfortunately they seldom start there, but are usually in the low to medium starting situation. At Ceder Rapids, in east central Iowa they usually start out with good moisture, so yield reductions due to stress are small. Remember though that these calculations do not take into account excess moisture. By knowing the soil moisture situation in the early spring, we can project the probabilities of getting different yield reductions due to stress. The farmer can use this information in his planning. We use the fall information for a preliminary outlook.

We've also used the program to see how the capacity of the soil and the starting moisture interact to affect the index and the seasonal outlook with a low capacity soil. Where you are in the spring makes little difference. Spring rains usually fill the profile. With a high capacity soil the starting level is very important.

Questions were asked in the mid 70's about the severity of the recent droughts. We went back in history and estimated the drought conditions using the soil-moisture program. The 1977 drought is not included here. It would rate near the top in central Iowa. The 1974 drought ranked 6th in west central Iowa. The 1975 drought was 7th in west central Iowa, 6th in central Iowa and 5th in eastern Iowa.

By combining stress index values from the soil moisture sites with a simple technology relation provided by Louis Thompson I compared the estimated corn yields in countries where we had mois-

Table 3. Ranking and stress index values for the 13 most severe moisture stress years out of the 26 years 1933-36 and 1954-75.

Western Iowa			Central Iowa			Eastern Iowa		
Year	Rank	Index	Year	Rank	Index	Year	Rank	Index
1936	1	100*	1956	1	64.6	1936	1	52.3
1955	2	84.2	1936	2	63.6	1957	2	37.2
1970	3	69.5	1934	3	61.8	1934	3	33.4
1934	4	60.5	1933	4	32.4	1955	4	31.4
1956	5	41.5	1966	5	31.1	1975	5	26.6
1974	6	40.8	1975	6	31.1	1966	6	19.2
1975	7	40.2	1971	7	29.9	1958	7	17.0
1971	8	33.0	1955	8	29.1	1935	8	16.5
1933	9	30.5	1954	9	21.9	1933	9	15.6
1959	10	30.4	1935	10	21.6	1964	10	15.1
1968	11	30.4	1970	11	20.9	1965	11	13.6
1935	12	26.8	1965	12	20.4	1960	12	11.2
1967	13	24.6	1967	13	19.7	1963	13	10.0

* Indicates crop failure

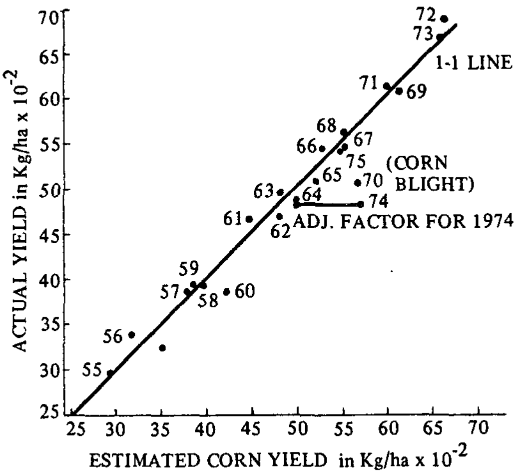

Fig 17. Comparison of estimated corn yields in counties where moisture sites were located with the actual corn yields harvested in those countries.

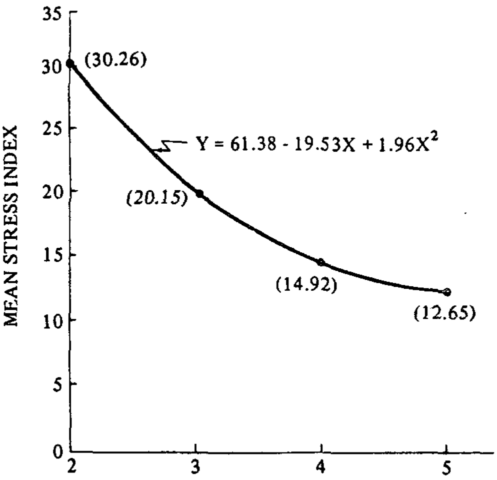

Fig. 18. Relationship between the mean annual stress index and the depth of maximum rooting.

ture sites with the actual yields harvested (USDA report). The relationship was surprisingly good, considering we used one site to estimate stress over a county. We missed in the right direction in 1970, a corn blight year, and in 1974, an early freeze year. The technology trend is very obvious.

We've also used the program to evaluate the potential yield increases for irrigation. Our high capacity soils show little potential except in NW Iowa. Low capacity soils show a high potential.

It has those assumed in the original program. One of my students has made extensive revision of certain parts of it to represent conditions on a reclaimed mine soil. This program allows the soil to reach saturation, then gradually lose the excess moisture—quite different from the original "instant drainage". A loop was written in the program so that rainfall could enter the profile through the large cracks that develop when the soil is dry. At this time there is zero runoff. Certain other changes were made to more closely represent the reclaimed soil conditions. One of the factors we wanted to examine was the effect of the depth of "good" soil put on top of the "waste" soil to get a better idea of how the good soil should be used. As you can see, there was a big decrease in the stress index if 3 ft of soil were used, instead of 2, but the effect decreased with increasing soil depth. The data represent 20 years of weather data. One of the requirements in reclamation is that the area be brought back to a 3 year average before the area was mined. Over the 20-years we used, 3 year averages ranged from 3208 to 8366 kg/ha (51 to 133 bu/A). How can one evaluate such a situation without some measure of the weather variation?

I feel that this program works very well for the Iowa conditions under which it was developed. Before being used in other areas, all the assumptions used to be considered to see if modifications are required. It has allowed us to examine several aspects of the impact of Iowa weather on agriculture, in a quantitative manner which we could not do without a program of this type. I would hope that certain aspects of the program would be useful in other areas.