CHANGES IN MOISTURE STRESS DAYS SINCE 1933

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Introduction

Dr. Shaw mentioned a possible upward bias in the Story County average corn yield in 1956 stemming from the soil bank program. Besides any such farm program or assessment effects upon the county and state corn yield statistics, there are many other and probably more serious confounding effects when we use area average yields and weather variables to estimate the weather, technology and crop relations. While those empirical studies may be "in the right ball park" in estimating the relative effects of weather and technology, it is difficult to correctly evaluate or visualize the results of such studies. The yield series represents an areal average of all technological factors -- changes in residual soil fertility, differences in fertilizer use, hybrid varieties, crop densities, mechanization and perhaps even an increase in supplemental irrigation.

We also average the weather variables over time and space. Under the same crop densities, soil moisture is always higher on the low-lying or bottom lands than on the more droughty hills. As a general rule, night-time temperatures are lower in the valleys than on hills. The slope and aspect bring in important differences in micro-climate. Therefore, we cannot consider the average weather variables and their relation to crop yields as other than an index for the area. To infer from such an empirical study that "so many inches of rainfall will result in so many bushels of corn" is only a little more reasonable than claiming a man standing with one foot in boiling water and the other in ice-water is comfortable at an average water temperature of 50°C.

If we could obtain significant crop-weather relations on an experimental plot basis this would help efforts to isolate the weather and technology effects. We then could build these relations into a more meaningful area picture. Stallings (6) and Auer2 have already used the experimental

1/Central area climatologist, U. S. Weather Bureau, Iowa State University, Ames, Iowa.
2/See the following paper of this report, Ludwig Auer and Earl O. Heady, "The Contribution of Weather and Yield Technology to Changes in U.S. Corn Production, 1939 to 1961."
plot yields as a weather or phenological index in estimating area crop yields. A search for an appropriate weather variable to estimate experimental plot yields would carry this another step further.

This is not the only reason for seeking meaningful weather-experimental plot yield relations. The results of all agricultural research are conditioned by the weather regime under which the research was performed. Usually it is assumed that by replicating the experiment over a number of years and at selected field stations the environmental effects will average out, leaving the experimental results representative of the general area or soil unit. Unfortunately, average weather seldom occurs and the average experimental results are the integrated response to a wide range of conditions.

If we eliminate any economic considerations, we can consider the corn yield potential as being controlled by five factors: (1) weather, (2) soil fertility and physical conditions, (3) genetic differences between varieties, (4) population or geometry of planting and (5) miscellaneous biological or environmental occurrences. To evaluate the yield effect from any one of these five factors, the effects from the other four have to be considered. In the work reported in this paper (1), the plot corn yields from the Iowa State University Agronomy farm four-year rotation experiment were used to examine the effect of weather on corn yields by either removing or evaluating the effects from the three technological factors. The purpose of the four-year rotation experiment from the date of its establishment in 1917 has been to study the long-term effects of those rotation and fertility practices and corn varieties used by most Iowa farmers. Thus, we might consider that the technology on the four-year rotation experimental plots might be something near the average in the central Iowa crop reporting district with the important exception that there were no commercial fertilizer applications on the experimental plots used in this analysis.

Experimental Procedure

We attempted to hold the soil fertility effect (2) fairly constant by analyzing the weather effects on yields within the same treatment. In this paper we shall discuss the results from only one treatment, plot 01 which received 8 tons of manure once every four years. Plot 01 is 1/10 acre in size, and the treatment was not replicated. There was no change in the manure application over the period of record, although there may have been temporary or accumulated changes in residual soil fertility. The yield date (3) were adjusted for improvement in hybrids by means of overlapping varietal corn yield test comparisons, with all yields adjusted to the equivalent of those for Iowa hybrid 4570, the hybrid variety used last in the four-year rotation experiment. The effect of stand (4) was considered as an interaction by
including it with the weather variable in a multiple regression model. There is little we can do with the miscellaneous biological and environmental effects until the first four effects are properly evaluated. This fifth factor was not considered and contributes to the variance from the regression yield estimates.

Should one wonder as to the need to spend this time "homogenizing" the experimental plot yield or dependent data series, the estimated differences in yields between hybrid varieties used over the 30-year period, 1933-1962, on plot 01 are shown in Table 1.

The different varieties used over the 30-year period of record are shown in the left-hand column, the period in which each was grown in the second column and the estimated yield increase over the previous variety grown in the third column. The accumulated correction which was added to the respective corn yields to adjust to those for Iowa Hybrid 4570 is shown in the right-hand column. These estimates were constructed from differences between varieties in randomized replicated corn yield tests in the same fields and years. To eliminate possible differences in varietal yields due to differences in stand, only those yield differences between corn varieties with stand percentages within 5 percent were used. These overlapping comparisons were necessary since there was no single variety grown throughout the period which could be used as a standard against which to compare yields.

The initial increase from the average of the open pollinated varieties to the first hybrid used, Iowa 942, was 8.2 bushels per acre. However, the yield increase due to improvement in hybrids was estimated to be about nine bushels per acre from Iowa 942 to Iowa 4570. This undoubtedly contributes toward a steeper technology trend since 1940 than before as indicated in the previous paper by Dr. Shaw. While there may be weather-varietal yield interactions, we believe most of the improvement in yields due to improvement in varieties has been removed in the adjusted data series.

A scatter diagram of plot 01 yields (adjusted) on stands, shown in Figure 1, indicates the great variability in the experimental plot stands from year-to-year. The stands on plot 01 ranged from less than 5,000 plants per acre in 1935 to more than 18,000 plants in 1961. Before 1953, stands averaged about 7,500 plants per acre, since then about 15,000. If we disregard the open circles, which represent years in which weather is believed to have been the primary limiting factor, the scatter diagram shows a general yield increase with stand. The effect of stand on yield depends on the weather, and stand was included with the weather variable in a multiple regression model.
Figure 1. Ames Agronomy Farm 4-year rotation plot 01 corn yield on stand, 1933-1962.
Table 1. **Corn varieties and years planted at the Ames Agronomy Farm four-year rotation plots with estimated yield differences between indicated variety and Iowa 4570.**

<table>
<thead>
<tr>
<th>Corn variety* planted</th>
<th>Period</th>
<th>Average increase in yield between listed hybrid over next lower identified hybrid, bushels per acre</th>
<th>Bushels to be added to yields in indicated periods for equivalent Iowa 4570 yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iowa 4570</td>
<td>1957-62</td>
<td>+3.4</td>
<td>0</td>
</tr>
<tr>
<td>Iowa 4298</td>
<td>1951-56</td>
<td>+2.4 9.0</td>
<td>+3.4</td>
</tr>
<tr>
<td>Iowa 306</td>
<td>1942-50</td>
<td>+1.2</td>
<td>+5.8</td>
</tr>
<tr>
<td>Iowa 939</td>
<td>1940-41</td>
<td>+2.0 (over Iowa 942)</td>
<td>+7.0</td>
</tr>
<tr>
<td>&quot;Double-Double Hybrid&quot;</td>
<td>1939</td>
<td></td>
<td>+7.0</td>
</tr>
<tr>
<td>&quot;Double-Double Hybrid&quot;</td>
<td>1938</td>
<td></td>
<td>+7.0</td>
</tr>
<tr>
<td>Iowa 939 x US 13</td>
<td>1937</td>
<td></td>
<td>+7.0</td>
</tr>
<tr>
<td>Mixture 11 hybrids</td>
<td>1936</td>
<td></td>
<td>+9.0</td>
</tr>
<tr>
<td>Iowa 942</td>
<td>1935</td>
<td>+8.2</td>
<td>+9.0</td>
</tr>
<tr>
<td>(open pollinated)</td>
<td>1934</td>
<td></td>
<td>+17.2</td>
</tr>
<tr>
<td>Murphy strain (open pollinated)</td>
<td>1933</td>
<td></td>
<td>+17.2</td>
</tr>
</tbody>
</table>

*Pedigrees: Iowa 4570 (B14 x WP9) (187-2 x M14)  
Iowa 4298 (Os420 x 187-2) (WF-9 x M14)  
Iowa 306 (L289 x 1205) (WF9 x Os426)  
Iowa 939 (L289 x 1205) (Os420 x Os426)  
Iowa 942 (1234 x L289) (Os420 x Os426)

If we want to study the effect of weather on corn we need to consider the weather with respect to the corn or phenological calendar. Dates of corn silking were not available for the experimental plots, but average silking dates for the county, district and state have been recorded by the U.S. Weather Bureau and State Department of Agriculture (Iowa) since 1926. Fortunately, there is very little variation in dates of silking over the state within years. The state average date was close to the central crop reporting district average and was considered the best estimate of the experimental plot silking date. In Figure 2 the average state planting dates are shown as the bottom curve, and the average date of 75 percent corn silked in the "main" fields is the top curve. There is considerable variation in silking dates between years, with a range of three weeks between the earliest date, July 22, 1939, and the latest date, August 12, 1945. The average planting dates show less variation. Since the weather
in the vicinity of silking is commonly considered to be most critical to the corn crop, the 75 percent silking date was used to "anchor" the phenological calendar, and the weather variables were integrated within various periods from date of silking.

Moisture Stress Concept

Using the phenological calendar and the adjusted experimental plot corn yields, we examined several different weather variables for their yield-estimating ability. We shall describe only one in this paper -- moisture stress day concept. This is illustrated in Figure 3, which is from the moisture stress experiment by Denmead and Shaw (3). Each of the points on the chart represents a different potometer in which four corn plants were growing at different soil moisture levels on three different atmospheric energy level days. The measured soil moisture content in percent of the soil volume is shown on the abscissa. The amount of transpiration or millimeters of soil water lost in 24 hours from each potometer is shown on the ordinate. The soil in the potometers had a field capacity near 36 percent soil moisture and a 15-atmosphere or permanent wilting point near 22 percent. August 5, or the lower curve, is an example of a low energy or low moisture demand day. The day was overcast and humid. The corn in all of the potometers transpired about 1.5 mm. that day regardless of the soil moisture content, which in the different potometers ranged from field capacity to 23 percent, almost to the wilting point. Where soil moisture was below 23 percent on that day there was no longer sufficient soil moisture to maintain transpiration even at the low energy level. On August 13, a partly cloudy day, transpiration was about 4.5 mm. in 24 hours in the potometers where soil moisture ranged from field capacity to about 28 percent. Where soil moisture was below 28 percent transpiration decreased rapidly with decreasing soil moisture. On July 30, a clear, dry sunny day, the transpiration was 6.5 mm. in 24 hours with soil moisture at field capacity, but transpiration was decreased where soil moisture was just slightly below field capacity. Denmead and Shaw called the "break" in the curve the "turgor loss point," where the plant cells lose turgor and the stomates begin to close. It is this point which has been used to separate moisture stress from non-stress days.

From such curves, Denmead and Shaw prepared a curve of the estimated turgor loss points. The curve is shown in Figure 4. The abscissa has been converted to inches of evapotranspiration at field capacity in 24 hours. The ordinate has been scaled to percent of available field capacity in the corn root zone i.e., 0 is the 15-atmosphere or permanent wilting point, and 100 percent is field capacity. If the soil moisture profile holds 80 percent of the available field capacity, the corn would not be under moisture stress if evapotranspiration at field capacity
Figure 3. Actual transpiration rate as a function of soil moisture content.
Figure 4. Estimated percent available field capacity in the corn root zone at the turgor loss point, $\theta_{TL}$, as a function of the evapotranspiration rate at field capacity. Solid curve is from Denmead and Shaw, and Dashed curve is adjusted to 5 mm. aggregate Nicollet silt loam by soil moisture curve from Tamboli.
were less than .23 inch in 24 hours. But a potential evapotranspiration greater than .23 inch would indicate a stress day. Any combination of points falling below the curve would identify stress days, and points falling on or above the curve would identify non-stress days. Since cell turgidity is necessary for growth it was assumed that there would be little or no growth on a stress day, and that corn yields should be directly proportional to the number of non-stress days.

Two estimates were needed to classify a day as one with moisture stress or no stress: the moisture supply or soil moisture in the corn root zone, and the atmospheric demand for moisture or potential evapotranspiration for each day. The method of estimating these two variables will not be given here except to indicate that the potential ET was estimated from evaporation pan measurements (4), and the soil moisture was estimated as described by Shaw (5) (2).

The seasonal march of soil moisture is shown in Figure 5 for three years. Calendar date is on the abscissa and percent of available soil moisture in the corn root zone on the ordinate. The corn root zone includes only the top 6 inches at planting time and is gradually increased in depth to 5 feet by August 1. The lower curve is for 1954, a year in which several gravimetric measurements were available through the season to check the accuracy of the daily soil moisture estimates. The solid line represents the estimates, and the squares are the gravimetric measurements. The estimated and measured soil moisture shows good agreement. The open circles are the estimates of the percent available soil moisture needed in the corn root zone to prevent moisture stress in corn. These estimates were plotted only when they were above the available soil moisture curve, indicating moisture stress days. The top curve shows the soil moisture regime in 1958, the most favorable year "moisture stress-wise" of any in the last 30 years. Soil moisture remained near field capacity through July, and there were only two moisture stress days the entire season. The middle curve is that for 1956, the driest year on plot 01 since 1936, with moisture stress almost every day in July and August.

Moisture Stress and Experimental Plot Corn Yields

A scatter diagram of the adjusted plot 01 corn yields on the number of non-stress days in the period six weeks before silking to three weeks after silking is shown in Figure 6. The maximum number of non-stress days, or most favorable season moisture stress-wise, cannot exceed 63 days, the number of days in the nine-week period, six weeks before to three weeks after silking. We have indicated there were two general stand levels in the 30-year record studied. The open circles are the years
Figure 5. Estimates of daily percent available soil moisture in corn root zone for the seasons of 1954, 1956 and 1958 at Ames, Iowa, on well-drained soils having an available field capacity of 8.7 inches.
Figure 6. Agronomy Farm 4-year rotation plot of corn yield on number of non-stress days in 9-week period 6B-3A.
prior to 1953 with stands of less than 10,000 plants per acre. There are no open circles above 100 bushels per acre, even though there were some very favorable years moisture stress-wise. The solid circles indicate the years since 1953 with higher stands, at least 12,000 plants per acre. These higher stands allowed the plot 01 corn yields to exceed 100 bushels with favorable weather. In 1956, a year with higher stands, the plot corn yield was about the same as in 1934 and 1936, with approximately the same kind of weather, moisture stress-wise.

When there were less than 30 non-stress days, the moisture-stress effect seemed to exert the major control on yields; there was a linear relationship between the plot 01 corn yields and the number of non-stress days. Above 30 NSD, stand became of increasing importance, but up to about 40 NSD moisture stress still seemed to limit yields. For example, 1953, 1954 and 1955 were in the higher stand period, but the yields for these years were still below 100 bushels. Above 40 NSD there was increasing scatter, indicating that stand and possibly some weather effect other than moisture stress was the limiting factor. There is some evidence of a curvilinear effect which would indicate that some stress may be favorable, perhaps in encouraging deeper root penetration and greater proliferation to more fully exploit the available soil fertility.

The stress or non-stress day is a non-dimensional variable which only identifies whether or not the corn plant was under moisture stress. An entire season of cloudy, cool weather, even with relatively dry soil, might produce no moisture stress conditions, but there would be a lack of energy for crop growth. To correct for this deficiency, an energy index -- a summation of potential evapotranspiration on non-stress days -- was investigated. However, it was found associated with about the same amount of variation in the plot 01 corn yields as found with the non-stress day variable described here. In a solar radiation limiting area it would be expected to do better.

Several multiple regression models were used, but in this paper we shall discuss only one, using the 30-year period of record, 1933-1962. The variables used were yield on plot 01 in bushels per acre, the last two digits of year (to consider any linear trend in residual soil fertility), stand in number of corn plants per acre, stand$^2$, NSD or the number of non-stress days in the nine-week period, 6B - 3A, NSD$^2$, and the interaction stand X NSD. The regression equation:

$$
Y_{01} = -4.3 - 1.32 \text{year} + 0.78 \text{stand} - 0.0041 \text{stand}^2 \\
+ 3.93 \text{NSD} - 0.0500 \text{NSD}^2 + 0.0125 \text{stand} \times \text{NSD}
$$
was associated with 83 percent of the variance in the adjusted plot 01 yields. The F value of 18.95 was highly significant for 6 and 23 degrees of freedom. The partial regression coefficients for NSD and NSD² were significant to the .01 level. Trend and the stand X NSD interaction coefficients were significant at the .05 level. Stand and stand² coefficients were not significant. The negative trend coefficient of 1.32 bushels per acre per year estimates the average residual fertility decrease over the last 30 years under the plot 01 technology of 8 tons of manure every four years. A word of caution: the partial regression coefficient for trend, or the estimate of residual fertility loss, is only as good as the selection of the other variables in the equation. But some such multiple regression technique of considering the weather and other technological factors is necessary to evaluate this residual fertility trend.

The regression plot 01 yield estimates on NSD, evaluated for 1962 and three different stand levels are shown in Figure 7. As might be expected, the fitted multiple regression curves indicate the same pattern as the scatter diagram. The estimated yields for the three stand levels of 8, 12 and 16,000 plants per acre are much the same for nine-week seasons with less than 30 NSD. The corn yield differences between stand levels increase between 30 and 40 NSD, but below about 40 NSD there is still no difference between stands of 12,000 and 16,000. Here again, then, it appears that below 30 NSD under the plot 01 technology (as well as on plots with higher manure applications not shown here) it is the moisture stress variable which is limiting yields. Between 30 and 40 NSD the moisture stress becomes less important and stand becomes more important. Above about 40 NSD stand level is of major importance. The benefits of favorable weather cannot be realized unless stand (and other technological) levels are increased.

**Probabilities of Moisture Stress**

What are the probabilities of receiving less than 30 and 40 NSD in the nine-week period, 6B - 3A? An estimate of these probabilities at the Ames Agronomy Farm -- and probably in central Iowa on Nicollet or Clarion soils which hold about nine inches of available water in the top five feet of soil profile -- is shown in Figure 8. The number of non-stress days in the 63-day period, six weeks before silking to three weeks after silking, is shown on the abscissa. The percent chance of having the indicated number or less NSD for corn is shown on the ordinate, based on the 30-year period, 1933-1962. Assuming the past 30 years provides the best estimate of the weather regime over the next few years, the probability of having 30 or less NSD is about 28 percent, or about three in 10 years. The chance of having 40 or fewer NSD is 50 percent. Thus, moisture stress conditions would appear to be a limiting factor under the plot 01 technology in about half of the years.
Figure 7. Estimates Ames Agronomy Farm 4-year rotation plot 01 corn yields on number of non-stress days in 9-week period, 6B-3A, for stands of 8,000, 12,000 and 16,000 plants per acre evaluated for 1962.
Figure 8. Chance of having indicated number or less non-stress days for corn in the 9-week period, 6B-3A, on Nicollet silt loam with 9.0 inches available field capacity, Ames, Iowa based on 30-year record, 1933-1962.
Changes in Moisture Stress Conditions Since 1933

The actual (adjusted) plot 01 corn yields with the regression estimates are shown chronologically as the lower chart in Figure 9. Year is on the abscissa and the plot 01 corn yield in bushels per acre on the ordinate. The regression equation seems to fit the extremely low yields remarkably well. The yield trend is upward and is due to the resultant effect between stand increase and residual fertility decrease and the weather. We can see that it is primarily the 30's on the left end of the regression and the high yields since 1957 on the right end which probably provide the trend. The 20-year period from 1937 through 1956 would probably give us little trend in yields, if not even a negative trend.

In the top chart of Figure 9, the number of NSD's are shown for each year over the past 31 years. This chart shows roughly the same trend as the lower yield chart and is also primarily controlled by the dry 30's and favorable 1957-1962 period. Both curves show the estimate of trend depends upon the period selected, which I submit is due to weather "spells." We had some very favorable weather in the 40's, but the stands on plot 01 were not sufficient to realize the full benefit of this weather. The year 1963 has been included on the chart although it was not used in the regression. The important thing to note is that the last seven years have had above 40 NSD nine-week seasons. Thus, the lack of moisture-stress conditions was allowed the higher plot 01 stand levels their maximum effect these last seven years. The probability of getting another favorable year -- above 40 NSD -- is still 50-50, in fact, perhaps a little better now for 1964 with our full soil moisture profile. But one of these years we can expect a below 40 NSD season, which would not allow the higher stand levels to be fully effective.

While the precipitation variability over Iowa and time makes it extremely dangerous to compare moisture stress computations for one station, Ames, against the Iowa state average corn yield -- and we do not advocate its use -- a scatter diagram of the average Iowa corn yields on the estimated Ames NSD is shown in Figure 10. The state average corn yields are uncorrected for hybrids. The improvement in hybrids, increased use of fertilizer, increased plant populations and all other technological factors are included in the yield series. Yet, the scatter diagram shows much the same pattern as found in Figure 6, but of course, with less slope or increase in average state corn yield with NSD. If we disregard the state average corn yield in 1956 (although this was used in computed regression) or use Dr. Shaw's revised estimate of 32 bushels from Story County from the previous paper, the regression of yield on NSD appears almost linear up to about 40 NSD. Above 40 NSD
Figure 9. Lower solid line is estimated corn yield for Agronomy Farm 4-year rotation plot 01; open circles are the observed plot 01 corn yields, adjusted to hybrid Iowa 4570; dashed line is the linear yield trend. Upper solid line is the number of non-stress days in the 9-week period, 6B-3A, for each year, 1933-1962, at Ames, Iowa; dashed line is linear NSD trend.
Figure 10. Iowa state average corn yields on number of non-stress days in 9-week period 6B-3A at Ames, Iowa, 1933-1962.
there is increasing scatter, some of which is due to our single station estimate of the number of non-stress days in each season and some undoubtedly to an increase in technology. The regression equation shown in the figure was associated with 74 percent of the variance in the average state corn yield series from 1933-1962.

The estimate of the trend for technology of +0.72 bushels per acre per year was significant to the .01 level. This compares favorably with Dr. Thompson's estimated increase of +0.70 and Dr. Shaw's +0.86 figure provided in the previous paper. The two regressions drawn on Figure 10 are the evaluation of the regression equation for 1933 and 1962, the first and last years of the period of record used in computing the regression. Since there is no interaction term included in the regression model, the technology increase is averaged through all years, and I believe it incorrectly shows that the state average yields would be higher for low NSD in 1962 than 1933.

Thus, a total of more than 40 NSD (at Ames) also appears to be necessary to realize the benefits from the increase in technology on a state basis. Undoubtedly it is technology which has produced the steep upward trend in yields the last few years, but this increase due to technology is only possible because of the above 40 NSD weather we have enjoyed the last seven years. We cannot expect this favorable weather to continue indefinitely any more than we can expect to continue throwing heads on tossing a coin merely because we have just had a run of seven heads.
Bibliography


