FINAL REPORT, CONTRACT Cwb-11160

CLIMATOLOGICAL STUDIES

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MAY 15, 1967

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Introduction

This report will summarize the developments made on the prediction of soil moisture, pointing out the apparent solutions which have been made and problems which still must be considered. The different components of the prediction technique will each be briefly discussed. Figures from earlier reports will be reproduced in some cases to add clarity to the results and discussion presented here.

Prediction of soil moisture under variable field conditions is necessarily a complex procedure, since a number of variables are involved in the prediction. Too frequently the problem is over simplified to such an extent that unrealistic results may be obtained. What are considered to be the necessary factors will be discussed under the following headings.

a). Soil moisture characteristics

b). Precipitation and runoff

c). Potential evaporation

Early season evaporation loss from corn land

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d). Crop evapotranspiration

e). Moisture stress

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f). Comparison of November predictions made from April soil moisture samples

g). Soil moisture changes over the winter season

Soil Moisture Characteristics

The procedure, as reported here, has used plant available water as the factor to be computed. All computations are done on this measurement of soil moisture.

Plant available water is equal to the total soil moisture measured minus the wilting point, assuming the total amount does not exceed the field capacity. Field capacity must be known, since it was set as the upper limit of soil moisture. Field capacity is a difficult parameter to measure. There is no satisfactory laboratory method to determine this value and it must be determined in the field. Field capacity can be determined by adding water to the soil and allowing the excess to percolate through the soil. There is a gradual decrease of soil moisture during this process and a somewhat arbitrary "field capacity" value must be set. For our purpose it was set as three days after the surface water disappeared. The field capacity value will vary some with the season, presumably due to temperature effects. This was considered in our procedure by setting a higher value on certain soils for the spring period, when the soil is still relatively cold. This adjustment (Shaw and Runkles, 1956) was based on numerous field observations.

When free water was found in the profile (water content much above field capacity) an accurate prediction of soil moisture could not be made. The disappearance of this free water is affected by a number of factors other than those considered here. If soil moisture is to be predicted for these situations, additional techniques will have to be perfected which include the drainage factors controlling the disappearance of this water. Free water could be a factor of considerable importance in the wetter, eastern part of the corn belt where soil moisture may often be in excess in the spring. In predicting for Iowa soils, if no percolation occurred through the top foot for at least 4 weeks prior to August, the usual field capacity values could be used in August. Otherwise, the soil moisture value was somewhere between that predicted by the procedure, assuming no free water, and that assuming all the free water measured at an earlier sampling was still in the profile.

The wilting point must also be determined since it is the lower limit to which soil moisture can be reduced by plants. The wilting point was set equal to the 15-atmosphere percentage for all soils (Shaw, et al, 1959). This can be determined in the laboratory and was found to give excellent comparisons with dry soils sampled in the field. It must be determined for each site. The surface foot, of course, may be dry due to air drying. In some areas, with different types of soils than those in the midwest it appears that a value near 40 atmospheres may be nearer the true wilting point. However, the amount of water held in the soil between 15 and 40 atmospheres of tension is small.

Plant available water for most soils in the Corn Belt will be near 2 inches to 2½ inches per foot of soil. A sandy soil will be considerably less. Some heavier soils will hold more. With free water in the profile these values may approach 3½ inches per foot.

Precipitation and Runoff

An accurate precipitation reading is needed near the site for which soil moisture is being predicted.

Runoff must be computed for each daily precipitation amount. The soil moisture sites used in this study were selected on relatively flat sites with at most a few degrees slope, so that if any surface drainage occurred, it would be away from the soil moisture site. On sites with greater slope, the runoff procedure probably underestimates runoff. No rainfall intensity factor was included, only 24-hour rainfall amounts were used. The accuracy of the prediction technique could probably be increased if more refined and accurate techniques for computing runoff were used. As more accurate soil moisture and evapotranspiration data become available, the runoff factor will need to be examined more critically.

Runoff was computed, using as the antecedent precipitation index:

$$API = P_1/d_1 + P_2/d_2 + ... P_i/d_i + P_o/2 \qquad (1)$$

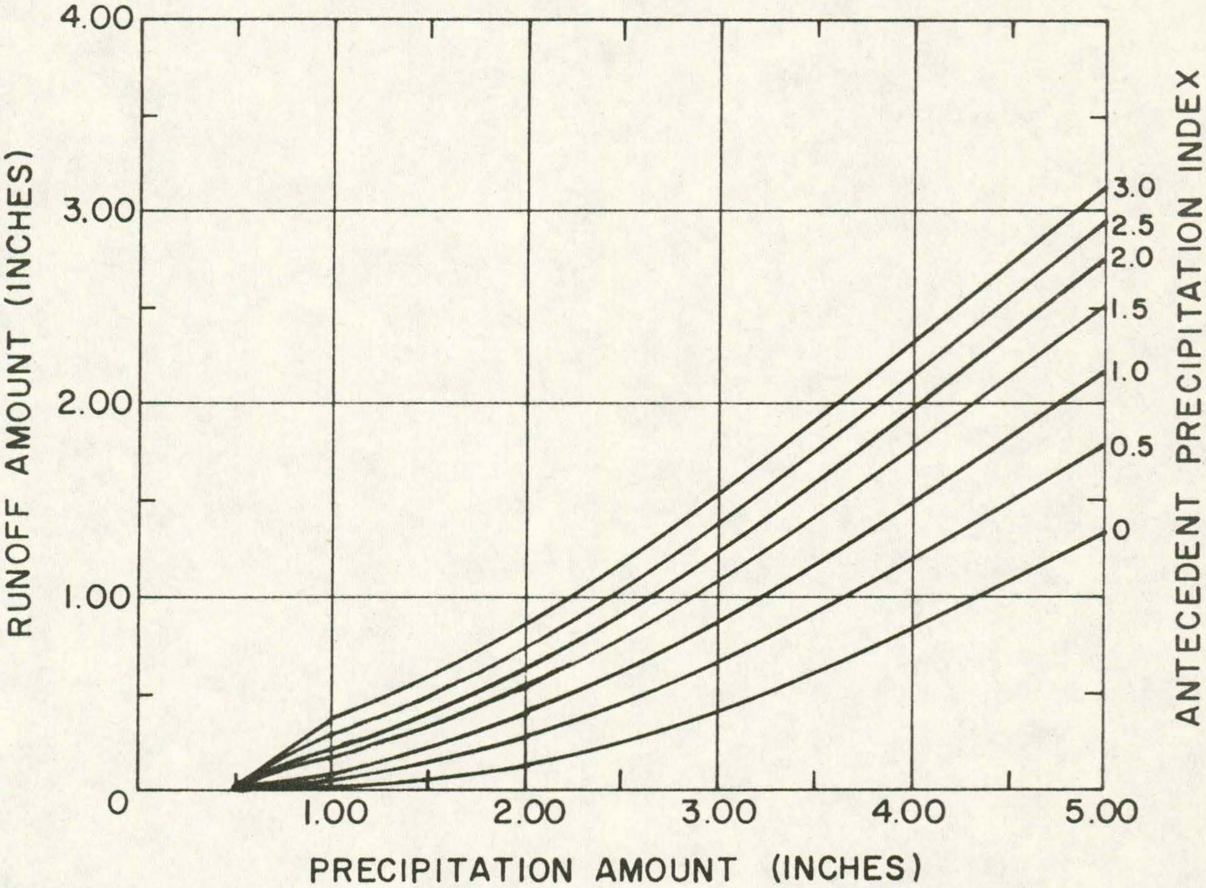
P_i is the precipitation that occurred i days prior to the day being considered. P_o is the precipitation amount for which runoff is being computed. The P_o term was used only when precipitation was 1 inch or more, otherwise, it was considered as 0. The P_o term was also considered as 0 for all rains from September 1 to November 1 when the combination of good crop cover and low intensity rains was assumed to result in less runoff. Later work indicates that it should be used for any period for rains of 2 inches or more intensity per day. The runoff amounts computed by this procedure were obtained from Figure 1.

Potential Evaporation

Early season evaporation loss from corn land

Ground conditions during the spring period vary. The residue from a previous crop, for example, may still remain on the surface of unplowed ground, a meadow crop may not yet be plowed under, the surface may have been plowed or, if planted, only a sparse ground cover exists. Solar radiation is high. Evaporation is largely determined by the availability of water for evaporation from the soil surface. The assumption was made that for corn land all evaporation occurred from the top 6 inches of soil and at a rate of 0.1 inch per day as long as any plant

Figure 1. Prediction of runoff from precipitation and antecedent precipitation index. (Buss and Shaw, 1960.)


4.00
3.00
2.00
1.00
0
RUNOFF AMOUNT (INCHES)
1.00
2.00
3.00
4.00
5.00
PRECIPITATION AMOUNT (INCHES)
3.0
2.5
2.0
1.5
1.0
0.5
0
ANTECEDENT PRECIPITATION INDEX

available water was present in the top 6 inches. This was assumed to occur from early or mid-April up to June 6. The same assumption could be made for soybeans. After that date enough crop cover is assumed present so that it must be considered.

From April to June this procedure estimated the top foot -0.26 inches low on the average, but the second foot averaged 0.30 inches too high. In the estimating procedure it is assumed that the top foot must be filled to field capacity before any moisture percolates to the next deepest layer. Under field conditions this assumption is not strictly true, with some percolation occurring from the top layer before it becomes saturated. Since the procedure gave the correct total moisture, no adjustment was made to correct for distribution errors. Assuming that evaporation occurs from the top six inches probably over estimates the depth of evaporation where no tillage operations have occurred, but should represent conditions quite well where these operations are shifting the soil. In a later study on predicting working days in the field (Shaw, 1965), sky cover was taken into account and the values listed in Table 1 were used. In most years, the difference between a uniform loss of 0.1 inch per day and the variable loss considering cloud cover is small when considered for periods of several days. Sky cover data may not be readily available for use in a soil moisture prediction technique.

Table 1. Soil evaporation in inches per day with different amounts of cloud cover.

	Sky Cover		
	Clear	Partly Cloudy	Cloudy
First day after rain			
Up to May 1	0.17	0.13	0.05
May 1 to June 6	0.20	0.15	0.05
All other days			
Up to May 1	0.12	0.08	0.05
May 1 to June 6	0.15	0.10	0.05

Evapotranspiration loss with adequate ground cover present

For corn, from June 7 through September 30, and for meadow, from early April through the entire season, open-pan evaporation is used as the starting value for estimating evapotranspiration. Open-pan evaporation is used as the estimator for the potential, which is then converted to evapotranspiration by considering the stage of crop development.

Use of the open-pan as an estimator for crop evapotranspiration has been questioned because the pan is physically much different than a crop cover. On some occasions the pan may be surrounded by a dry crop area which could introduce large advection effects. The Class A pan was accepted as a reference instrument by WMO and by the International Association of Scientific Hydrology for the International Geophysical year. The pan is sensitive to day to day changes but may also have considerable error due to advection of energy into the pan.

Class A evaporation pans are a circular tank made of galvanized iron or monel metal with a diameter of 122 cm. and a depth of 25.4 cm. Standard procedure mounts them on a wooden, slatted platform about 10 cm. high. This type of mounting exposes the sides of the pan so that radiation exchange can occur and allows heat transfer from the air through the bottom and side of the pan. Under certain conditions this added heat can increase the evaporation rate from the pan and introduce errors when these readings are used to estimate evaporation from other surfaces. The pan presents a somewhat different surface than a large water surface and presents a much different surface than a plant cover. However, the absorptivity of the water and the crop cover are not too greatly different. One could postulate that with an average conversion factor the water loss from the pan and from a crop surface with adequate moisture should be highly correlated.

However, under conditions where advection of heat is occurring, this advection of heat may be very different for the pan than for the crop surface. We are not concerned directly here with the adequency of soil moisture for the crop, since a crop moisture factor is included to adjust for this situation.

Kohler, et al (1955) proposed a method for estimating the heat transfer from a Class A pan. The transfer of sensible heat from the water surface (in equivalent inches of evaporation) was given by

$$Q_h = 0.000367P\ (0.37 + .0041\ U_p)\ (T_o - T_a)^{0.88} \qquad (2)$$

and, heat transfer through the pan was given by

$$Q_h' = 0.000367P\ (0.37 + .0041\ U_p)\ (T_o - T_a)^{0.88}\ \frac{(A_p)}{(A_w)} \qquad (3)$$

where P is atmospheric pressure in inches of mercury, U_p is wind movement over the pan in miles per day, T_o is the water surface temperature (and also the outer surface of pan) in ^oF, T_a the temperature in ^oF, Aw the area of the water surface and A_p the effective area of the outer face of the pan. A_p was estimated as 1.4 A_w. The magnitude of the advected heat energy is directly related to the difference in water and air temperature. They stated "over much of the United States there is not appreciable transfer of heat through the Class A pan (on an annual basis)". Using their relationship for 1000 ft. MSL and assuming $e_a/e_o = 0.7$ and $T_o - T_a = 3^oF$, with a total wind of 50 miles per day and pan water temperature of 80^oF., approximately 66% of the advected energy is utilized for evaporation. For the same conditions and wind movement of 200 miles per day this value becomes 72%. With a water temperature 5^oF. warmer than air temperature, equation 3 gives a heat transfer through the pan equivalent to near .05 inches of water per day with a total daily wind movement of 100 miles per day.

Transfer from the water to the air would be near .036 inches. If 70% of this energy is used in evaporation it would be equivalent to .06 inch evaporation. For a day with .30 inches evaporation this would be 20% of the total energy for evaporation. In Iowa in 1966 a number of days with evaporation near 0.30 inches had a pan water temperature of near 5°F above air temperature. In July and August, on 31 days the average water temperature was 4°F or more warmer than the average air temperature. Total evaporation for both July and August was about 5% below the long time average, in spite of the relatively high water temperature. Advection effects were apparently small.

Riley (1966) in Arizona evaluated the effects of heat transfer through the pan and found that 29% of the energy supplied to the pan was from this source. This was under evaporation conditions of about 0.60 inch per day. With an insulated pan, Riley found that water temperature was reduced 2°C. and evaporation rate reduced 28%. These Arizona rates are exceedingly high rates compared to what is measured in the North Central States. In Iowa, only about 10% of the July days have been over .40 inch with August somewhat lower. A quick examination of the records indicates a high percentage of these extreme evaporation days occurred in few years when particularly hot dry weather occurred. Even when the Corn Belt states are experiencing what is called "dry weather", pan evaporation rarely seems to reach values measured in the "arid" west.

The heat balance equation for the pan may be given as

$$H = R_n + Q_h + Q_h's + Q_h'b + LE \qquad (4)$$

where H is the heat added to the water, R_n is net radiation, $Q_h's$ and $Q_h'b$ are heat transfer through sides and bottom of pan and LE is latent heat transfer. For a corn crop, the heat balance has been given by Tanner (1960) as

$$\int_0^L c_p \nabla_H (\rho u T)\, \delta z + \int_0^Z \frac{LE}{R} \nabla_H \left\{ \frac{ue}{T} \right\} \delta z = R_N + S + A$$

$$+ LE + \int_0^Z C \rho_c \frac{\partial T}{\partial t} \delta z + \int_0^Z C_p \rho \frac{\partial T}{\partial t} \delta z + \int_0^Z \frac{LE}{RT} \frac{\partial e}{\partial t} \delta z \qquad (5)$$

These terms represent horizontal divergence of sensible energy, horizontal divergence of latent heat, net radiation, soil heat, sensible heat, latent heat of evaporation, change in heat stored in crop, change in heat stored in air within crop and change in the latent heat stored in the crop. In this equation ∇_H is $\partial/\partial x + \partial/\partial y$. For a 24-hour period the storage terms would normally be small. Under certain conditions the divergence (advection) terms could be large. In using open-pan evaporation to predict crop ET, we are comparing two surfaces which physically are much different, yet if advection is not large, have some similarity between their heat budget equations. In the soil moisture calculations which have been developed, no consideration has been given to excessive heat transfer through the pan. The results did not appear to show any measurable variation because of it, but may not have been evident because of the relatively long prediction periods used. Although most of the data used in the study were from relatively good weather years, 1966 was a year with low rainfall and many days with water temperature considerably warmer than air temperature.

Since the degree of saturation of the air surrounding the pan may be different than the air immediately above the pan, some degree of error may also be introduced. Turbulent transfer of water vapor is enhanced by the position of the pan above the surrounding surface and by the roughness of the surrounding surfaces. These factors are largely the cause of the pan coefficient being less than 1 when compared with larger water surfaces.

One other factor which on occasion must be considered is color of the bottom of the pan. If the pan is kept clean, this does not change, but due to algae growth or iron deposits in the water a colored pan bottom may occur. Ventkiteshwaran, et al (1959) tested different colored pans as to their effect on the evaporation rate. Painting the inside black resulted in the pan loss being 1.13 times that of a standard pan. Letting the water level drop 3 inches below the recommended height (no more than 2" below upper rim) resulted in a decrease of about 8% in the evaporation.

In comparing evaporation station exposures, the main difference often appears to be differences in wind exposure. When the Ames Agronomy Farm Weather Station was relocated in 1964, a short test period was available when the old and new locations could be compared. The old location has a clear exposure to the south, a house about 100 feet to the east and a large barn and timbered area about 100 feet to the north and northwest. It was considered a good exposure. The new location has a low building about 100 feet to the east, but with no other obstacles within several hundred feet. During the test period open-pan evaporation averaged 0.22 inches at the new location and 0.24 inches at the old location. Total wind movement at the new location was almost twice that at the new location. Operation of the anemometer at the old location was questioned, but calibration tests showed the two anemometers were almost identical. In this case, factors other than wind were affecting evaporation, with the low wind location having the greatest evaporation.

Fritschen (1960) compared two evaporating pans, one at the old Agronomy Farm, the other about 2 miles distant in an irrigated area which is located in a small stream valley where the wind movement is reduced. A tall corn crop was growing about 100 feet from this evaporation pan. Data were taken over a period of 85 days, during which rainfall was about 5½ inches below the normal of 12½ inches. Wind readings were not taken. The Agronomy Farm location which was not irrigated and at which the grass surrounding the open-pan area showed noticeable moisture stress had evaporation averaging only .01 inch per day greater; or less than a 5% difference.

In 1966, a pan was located in the same irrigated area and compared with the pan at the new Agronomy Farm about 8 miles distant. Exposure differences were similar to those just mentioned. Compared to the official station, wind was reduced 43% and evaporation 11%. Half of this difference was accounted for by 5 (out of 59) days, when rates near 0.4 to 0.5 occurred at the official station. If ET = f $\sqrt{u}$, (Rosenberg, et al, 1963) evaporation would have been expected to be reduced near 25%, instead of the 11% measured. Although the station locations had quite different wind movement, pan evaporation was quite conservative between the locations. In order to evaluate further the effect of wind on pan evaporation, data from two pans were compared. These were located about 100 feet apart. During a 30-day test period when the two stations were maintained in as near identical exposures as possible, the official station had wind movement 6% less than the other station with 1.5% less evaporation. The $\sqrt{u}$ relationship gives a 3% expected reduction in evaporation. Actual reduction between standard stations is less than the predicted by the $\sqrt{u}$ relationship. For a period of a month, a white picket fence was installed around the second station at a distance from the pan very close to the wire fence distance for the official station. On the average, the picket fence reduced wind movement 32% with a 16% reduction in evaporation. If ET = f $\sqrt{u}$, the evaporation reduction would have been expected to be 18%. This was with an average daily wind movement of 77 miles and average pan evaporation of .23 inch at the official station. Data for individual days were extremely variable.

For individual days, on the average, the greater the wind reduction, the greater the evaporation reduction. At high wind speeds, comparable reductions in wind speed did not cause as much reduction in evaporation as at low wind speeds. The very large scale turbulence eddies (feet in dimension) may have been reduced or removed by the picket fence arrangement used. This large eddy would be more important at low wind speeds hence the relatively greater reduction. At high wind speeds the effect on evaporation was less, but still gave an overall greater reduction than when standard stations were compared. When standard type stations are being compared, changes in wind speed probably cause little differential effect on the eddy size, thus, giving comparisons relatively insensitive to wind changes; but when a small enclosure like the picket fence is used to compare stations, eddy size is being affected differently at the stations. Under these conditions $E \approx f\sqrt{u}$. A number of factors were being modified by the picket fence.

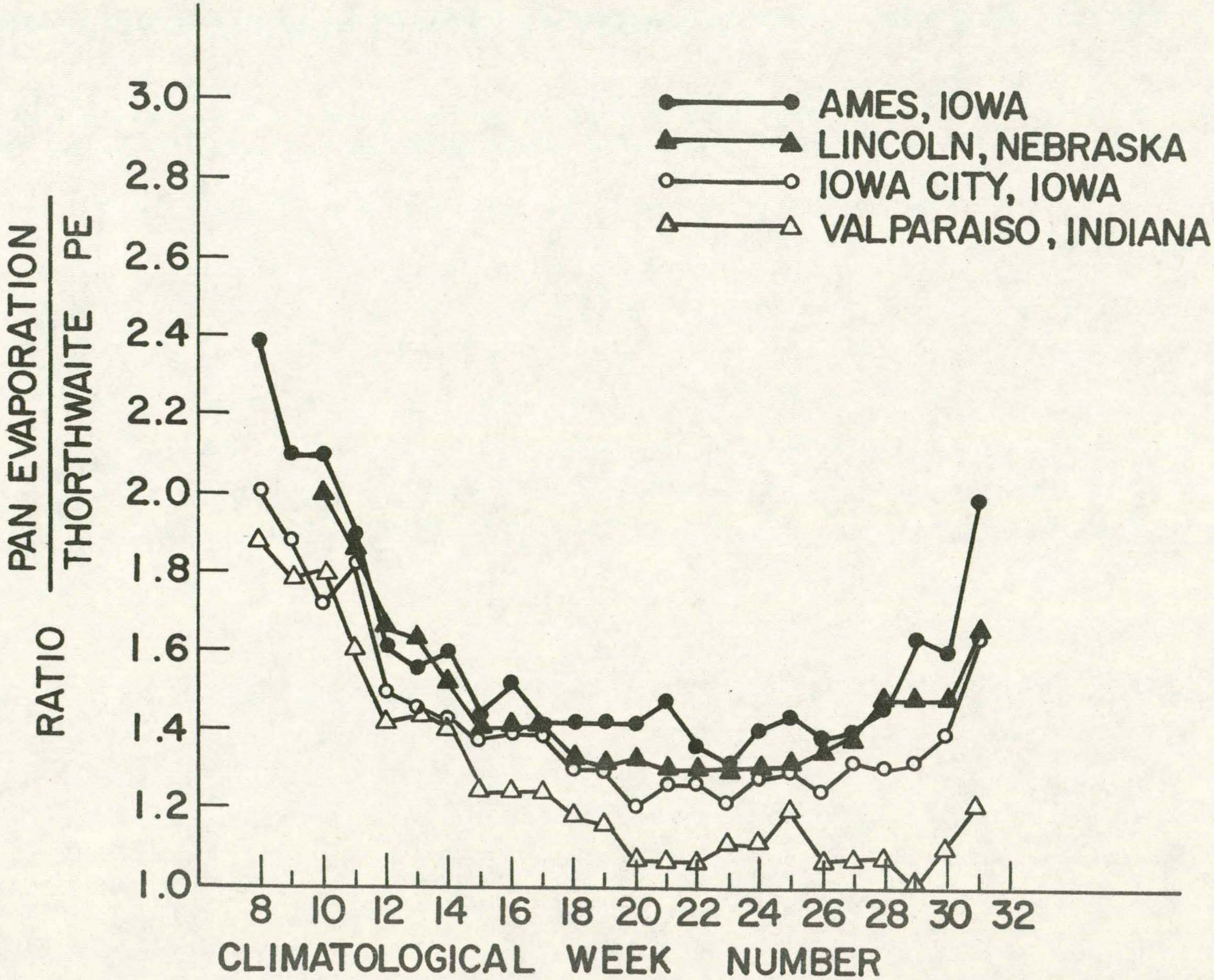
Although little if any difference in net radiation would be expected between the two stations (water temperatures were almost identical) net radiation measurements taken over the pans were compared for selected clear sky periods. For individual reading differences of near 10% were obtained, but averaged over all periods the net radiation values were almost identical. A more complete evaluation of the effect of the picket fence would require a very detailed micrometeorological study, but does not appear to provide a valid method of evaluating the effect of wind speed (due to exposure difference) on evaporation.

Although the Class A evaporation pan has obvious disadvantages, the question which can be raised is: "what should be used for the estimate of potential evaporation in a soil moisture prediction method such as is being discussed here?" A lysimeter, if available could estimate only one set of conditions at one location. Heat budget measurements would do the same. Expense alone would limit general use of these techniques, although physically they are much sounder.

There are a large number of "potential evaporimeters" which could be used; atmometers, Bellani plates, etc., or a large number of emperical prediction techniques. To the author it appears that each may have its own "calibration constants" for different geographic areas. The Thornthwaite PE method has been widely used and can be computed from readily available temperature data. This method is known to have some disadvantages.

Dale (1962) compared estimates of evaporation obtained by the Kohler and Thornthwaite procedures for South Dakota. The gradients obtained by these procedures were greatly different. Pelton, et al (1960) have shown the monthly Thornthwaite PE values are not in phase with solar radiation. However, since this method can be readily computed it was decided to compare it with pan evaporation measurements. Average weekly values of the ratio of pan evaporation/ Thornthwaite PE are shown in Figure 2. Data for Castana and Norwich, Iowa are similar to the top three curves shown. With the wide variance of Valparaiso from the other stations, further locations needed to be examined. Because of problems of obtaining edited pan data on punched cards, seasonal comparisons were not made, but the average ratio for August (roughly, climatological weeks 23-26) was computed for a number of stations. The geographical plot of these data are

Figure 2. Seasonal pattern of the ratio, open-pan evaporation/Thornthwaite PE for four selected stations.



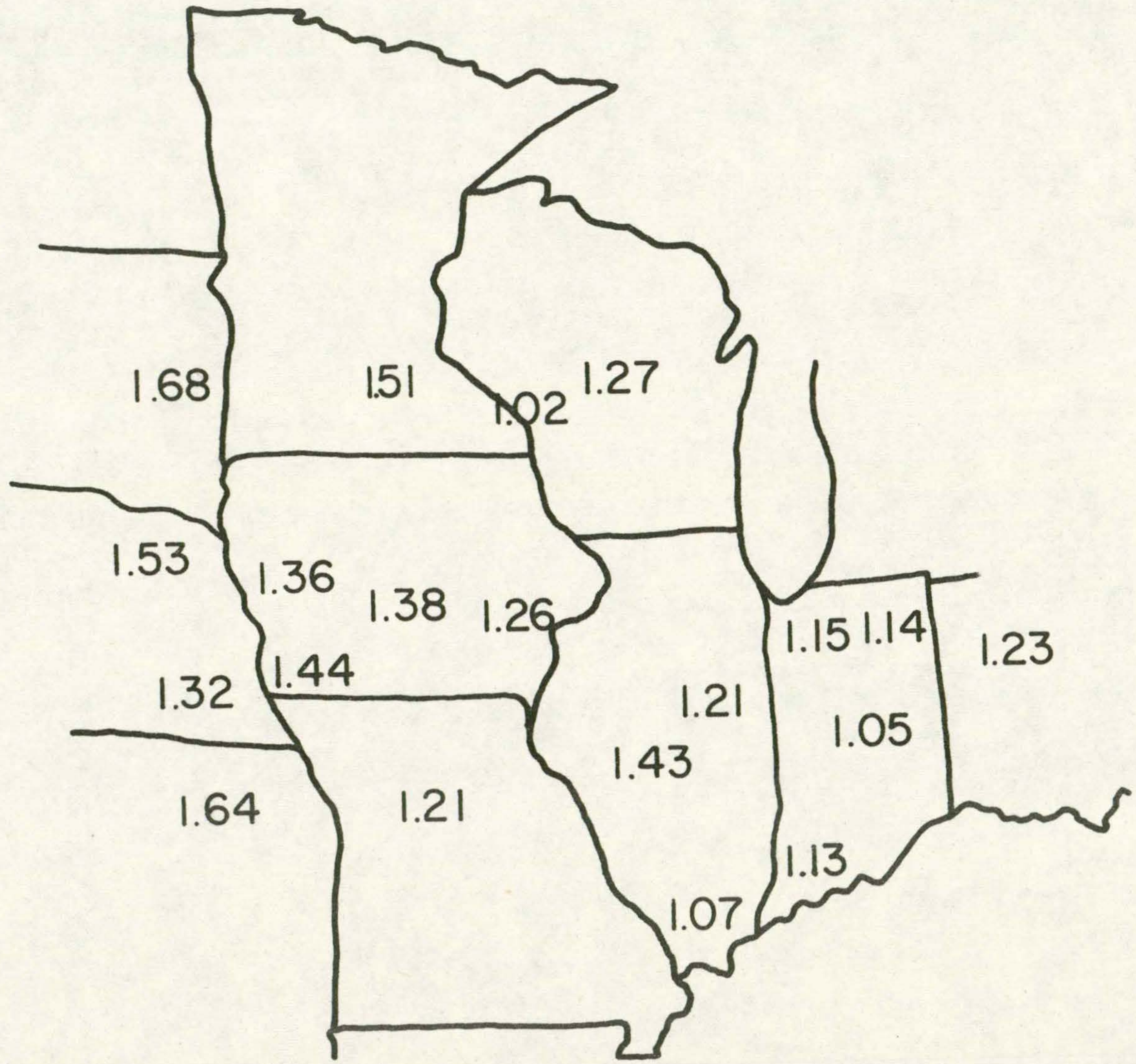
AMES, IOWA
LINCOLN, NEBRASKA
IOWA CITY, IOWA
VALPARAISO, INDIANA
RATIO PAN EVAPORATION / THORTHWAITE PE
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
8
10
12
14
16
18
20
22
24
26
28
30
32
CLIMATOLOGICAL WEEK NUMBER

shown in Figure 3. Although there are certain patterns appearing, with increasing values from south to north and east to west, they are not regular enough to draw any definite conclusions. With many stations for comparison possibly the pattern would be more evident. The ratios are obviously different in different geographical areas.

From the standpoint of developing a procedure for estimating soil moisture on a large scale basis, the only practical approach seems to be one in which the estimator for potential evapotranspiration is readily and extensively available. This would exclude a number of the more refined methods that require data which are available either at only first-order stations, or require special data. Evapotranspiration, which is the result of the integration of a number of meteorological factors, must be relatively conservative over large areas, provided there is equal availability of water. On this basis it appears that pan evaporation can be used, in spite of a rather sparse network. More highly refined methods, which may be more accurate in predicting day-to-day changes, cannot be adequately tested for soil moisture prediction such as is being conducted here, because of the limitations on accuracy of the soil moisture measurements, which fluctuate not only in the predominantly heterogeneous glacial till but also with infiltration time after a rain. The present technique, using open-pan data, is believed to predict soil moisture within the limits of accuracy of the presently measured soil moisture data.

One could possibly use ratios such as shown in Figure 3 to estimate missing evaporation pan data for a station, or particularly when a number of days have questionable data because of heavy rainfall. The error involved in this is appreciable.

Figure 3. Mean August value of ratio, open-pan evaporation/Thornthwaite PE.

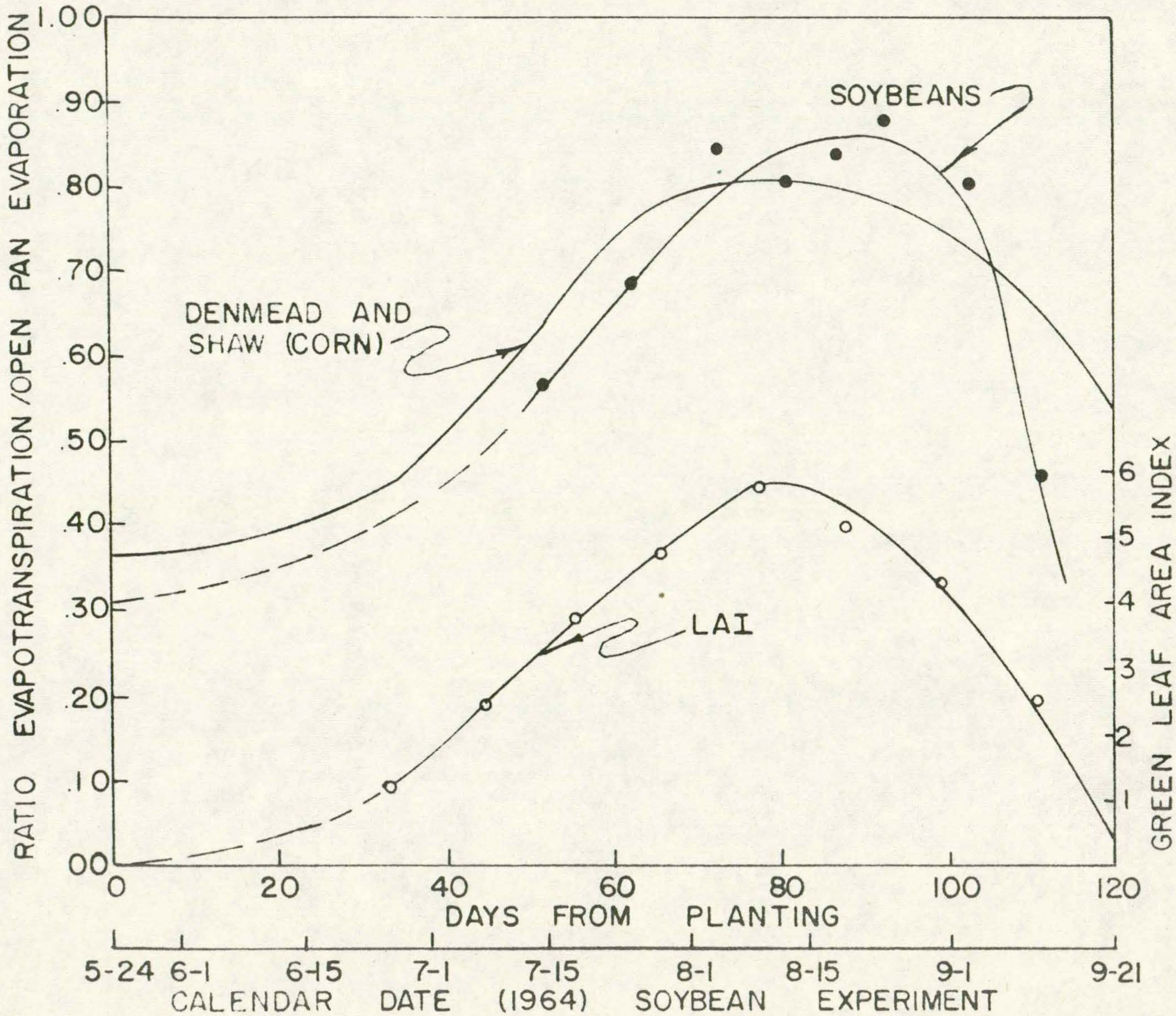

1.68
1.51
1.27
1.02
1.53
1.36
1.38
1.26
1.15
1.14
1.23
1.32
1.44
1.21
1.05
1.43
1.64
1.21
1.13
1.07

Mean values of PE for different levels of open-pan evaporation were computed for Ames. There is a gradual rise in PE as open-pan evaporation increases, but at a much slower rate. At low levels of evaporation mean PE exceeds mean pan evaporation. At high levels of evaporation, mean PE is less than half of open-pan evaporation. For any level of open-pan evaporation, the standard deviation of the PE values is about the same. Errors in predicting small values of evaporation could be several hundred percent from the true value; for high rates of evaporation the error would be much smaller, possibly down to 20-30% of the true value. With this large error it was decided that further examination of using the Thornthwaite PE as a predictor was not warranted. This would also indicate the comparison with other methods, such as Pierce's, would show wide variability because of the difference in the ratio of the estimators used for potential evaporation.

Crop Evapotranspiration

As a crop cover grows, considerable change takes place in the ground cover produced by the crop. More loss is by transpiration and less by evaporation. The change in crop cover was taken into account by developing a curve which represented the changing ratio of evapotranspiration with no stress/open-pan evaporation. These relationships for corn and meadow have been presented in other papers (Denmead and Shaw, 1959; Shaw, 1962; Shaw, 1963; and Shaw, 1964). In Figure 4 the relationship for corn is reproduced along with one developed for soybeans. The leaf area index curve (LAI) is also shown for soybeans. A leaf area index of 4 means the leaf area (1 side of leaf only) over an area is 4 times that area. Although the leaf patterns of corn and soybeans are very different, their canopy patterns as far as evapotranspiration is concerned are little different. Early ground cover development in soybeans is slower than for corn,

Figure 4. Non-stress evapotranspiration/open-pan evaporation ratio shown as a function of time for corn (Denmead and Shaw, 1959) and soybeans. Data points are for soybeans. LAI data is for soybeans.


RATIO EVAPOTRANSPIRATION /OPEN PAN EVAPORATION
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
00
SOYBEANS
DENMEAD AND
SHAW (CORN)
LAI
GREEN LEAF AREA INDEX
6
5
4
3
2
1
0
20
40
60
80
100
120
DAYS FROM PLANTING
5-24
6-1
6-15
7-1
7-15
8-1
8-15
9-1
9-21
CALENDAR DATE (1964) SOYBEAN EXPERIMENT

but by the time of maximum leaf area, ground cover is greater due to the more flat type of leaf orientation and growth habits of the soybean plant. This should give a slightly higher evapotranspiration/pan ratio. The rapid decline late in the season will depend upon the variety, but is due to leaf drop with maturity. The relationship between the ratio and LAI for soybeans is very close. Although the LAI for corn is different, the seasonal shape of the curve would be similar to that shown in Figure 4. As management practices change, such as narrow row spacing, or other crops are considered, curves expressing this relationship must be developed. Accurate prediction cannot be done unless the stage of development is considered. The seasonal pattern for meadow shown in Figure 5 (Shaw, 1962) is quite different because of the difference in seasonal growth pattern.

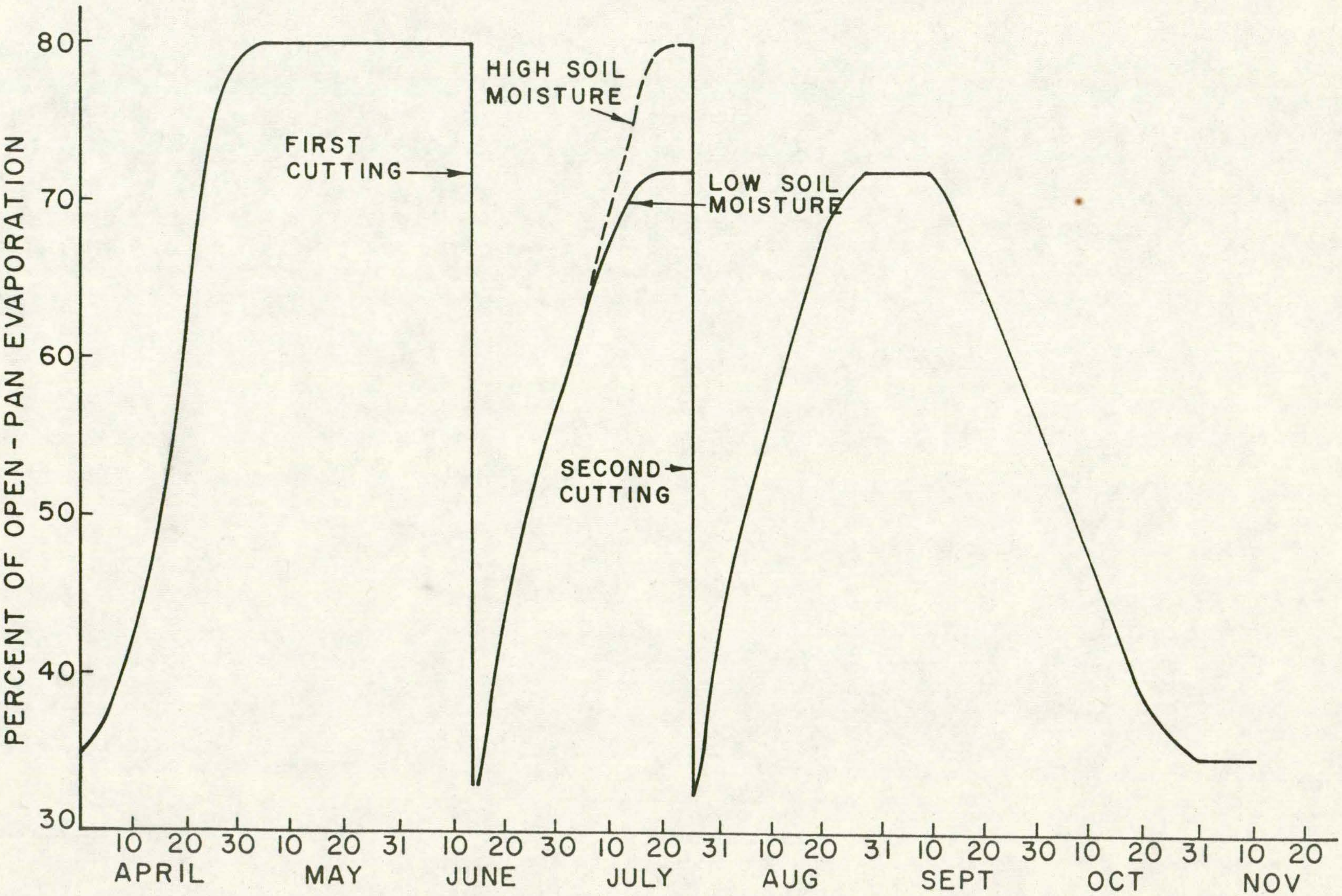
In addition to considering above ground factors in estimating evapotranspiration the zones of extraction of soil moisture must be considered. Water extraction patterns for corn (Shaw, 1963) are reproduced in Table 2.

Table 2. 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, 10a	1st, 2nd, 3rd, 4th and upper half 5th foot
	60, 15, 15, 10b	1st, 2nd, 3rd and 4th foot
After Aug. 1	60, 10, 10, 10, 10a	1st, 2nd, 3rd, 4th and 5th foot
	60, 15, 15, 10	1st, 2nd, 3rd and 4th foot

a. Used only if first 4 feet all have < 50 percent available moisture.
b. Used if any of first 4 feet have > 50 percent available moisture; however, after Aug. 1, the percent available is always computed on the total available water in the 5-foot profile.

Figure 5. Non-stress evapotranspiration/open-pan ratio shown as a function of time for meadow.

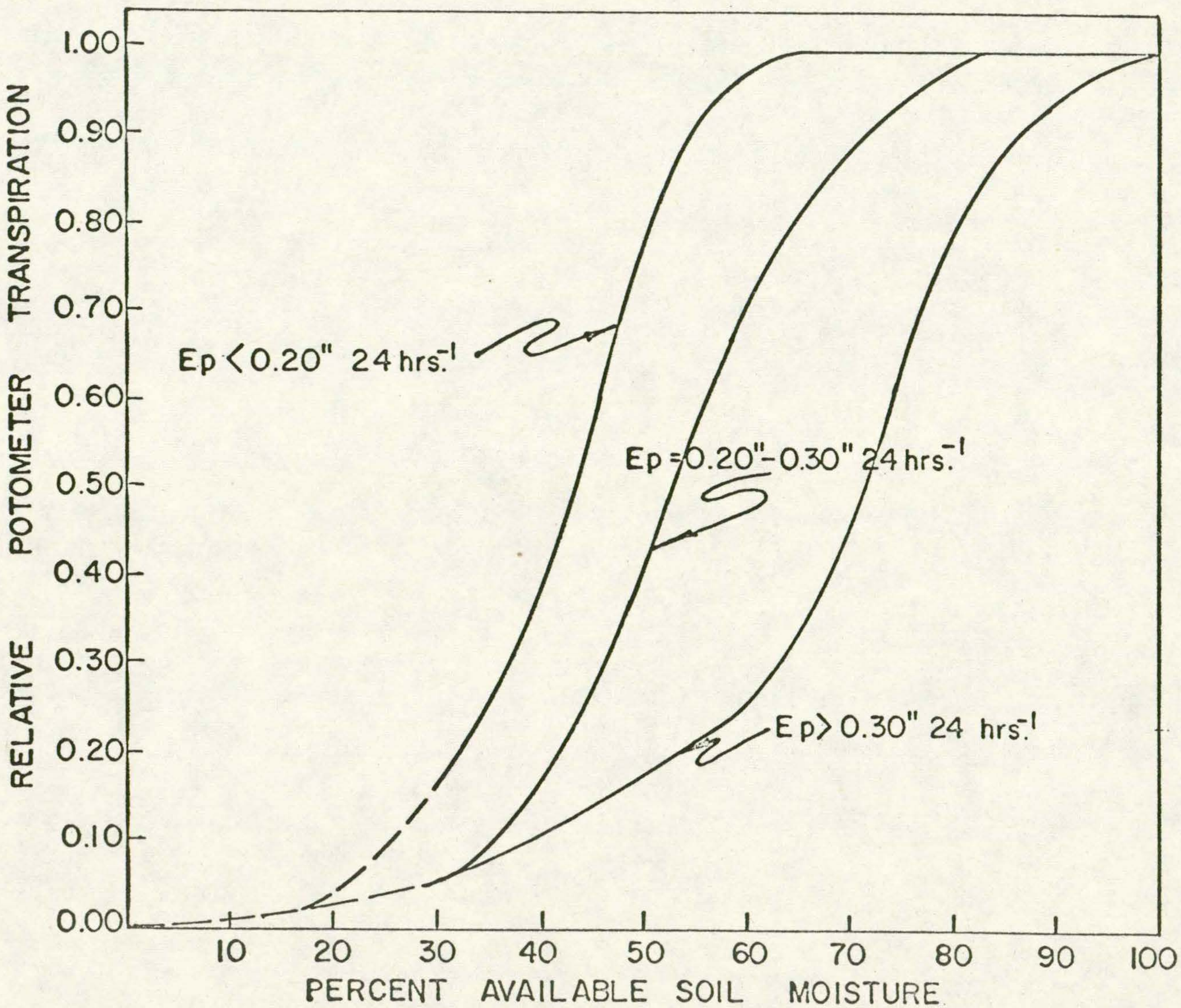

PERCENT OF OPEN - PAN EVAPORATION
80
70
60
50
40
30
FIRST
CUTTING
HIGH SOIL
MOISTURE
LOW SOIL
MOISTURE
SECOND
CUTTING
10 20 30 10 20 31 10 20 30 10 20 31 10 20 31 10 20 30 10 20 31 10 20
APRIL
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV

The same extraction pattern was used for soybeans. Meadow was similar but the extraction pattern reflected the earlier seasonal development. An extraction pattern needs to be developed which reflects the changes in the rooting habit of the crop for which soil moisture is being predicted, under the particular soil conditions and management practices being used. With adequate water, this problem is relatively simple since the bulk of moisture removal comes from the shallower depths. However, as the moisture supply is reduced, large differences in rooting patterns may occur. Fertilizer helps most plants root deeper, corn seems to root slightly deeper than soybeans, bluegrass is relatively shallow rooted, alfalfa is deep rooted. Soils with heavy subsoils may not have roots as deep as a good permeable soil. These factors become more important under drier conditions but are an essential requirement for correct soil moisture predictions.

Moisture Stress

It has been quite conclusively shown that the availability of soil water to the plant is a balance between how much is in the soil and how much demand is being placed on the plants by this atmosphere. This subject was discussed extensively in earlier contract reports. In brief, this says that as the atmospheric demand becomes higher, the soil moisture content necessary to meet this demand must be higher. With a low demand, only a small supply of soil moisture is necessary, with a high demand there must be a high supply of soil moisture or the plant will be under stress. If the water supply does not meet this demand, transpiration will be reduced and the plant is under some degree of moisture stress. We are concerned here with the reduction in evapotranspiration due to this lack of soil moisture. Laing's data (1966) obtained from 20-gallon containers are reproduced in Figure 6. These are similar to data for corn shown by Denmead and Shaw (1962).

Figure 6. Average relative daily transpiration rates for three groups of days with open-pan evaporation rates shown in body of figure, drawn as a function of percent available soil moisture.



RELATIVE POTOMETER TRANSPIRATION
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
10
20
30
40
50
60
70
80
90
100
PERCENT AVAILABLE SOIL MOISTURE
Ep < 0.20" 24 hrs.⁻¹
Ep = 0.20"-0.30" 24 hrs.⁻¹
Ep > 0.30" 24 hrs.⁻¹

This relation has resulted in generally good predicted values. However, during 1965 when a long period without rain occurred, there appeared to be some constant underestimation of the soil moisture extraction based on experimental plot data which were available. Field samples also indicated this to some degree. In the original program the correction for stress was based on the percent available moisture in the root zone. With a long period without rain, which depleted moisture in the shallow layers to zero, the weighting effect of this on the percent of available moisture in the root zone is large and appears to cause some underestimation of the moisture extraction. Other research data indicate the reduction in extraction as the soil moisture decreases used in the original program may have been too large. Our moisture predictions (except as just noted) do not indicate this, but the entire procedure may well have a "calibration" constant built unintentionally into it. If the moisture extraction with stress was changed, some other factor would also have to be changed in order to give the correct estimated values. Part of the difference may have been due to different procedures used for determining the soil water potential and the problems in converting relatively small soil container data over to field conditions with a variable profile. Converting water loss from these containers to loss under field conditions may also involve errors.

Laing (1966) tried a modification of the original procedure for predicting soil moisture under soybeans. This procedure considered the wettest 18 inches of the root zone. The printed output of the soil moisture estimation computer program (Dale and Hartley, 1963) provides estimates of inches of available soil moisture by 6-inch profile increments to a depth of 5 feet. The problem remains as to what layers to average to arrive at a water content for the root zone which may or may not occupy the whole profile. A set of rules were developed to answer this problem which are based on certain assumptions concerning the behavior of plant roots. In this description the 6-inch profile increments are numbered 1-10 beginning at the surface layer.

1. At the beginning of the growing season layers 1 and 2 are averaged until the average water content of layers 1-3 exceeds 1-2. Thereafter, layers 1-3 are averaged.

2. Whenever the water content of layer 1 drops below 32% of the available, then layers 2-4 are averaged.

3. This process continues down the profile (to 5 feet) as the layers nearer to the surface dry, always averaging three 6" increments on each day. The dropping of a layer once it has reached 32% available is not done if the layer below is less than 32%.

4. A return to the surface layers (1-2 or 1-3 whichever is the greatest) is made if this zone is greater than the three layers averaged on the previous day. This is necessary to take care of a situation where a long period has elapsed and then a heavy rain wets the surface layers.

5. Once the water in the surface layers has been utilized down to 32%, a return is made to the layers which were being averaged immediately prior to the rainfall.

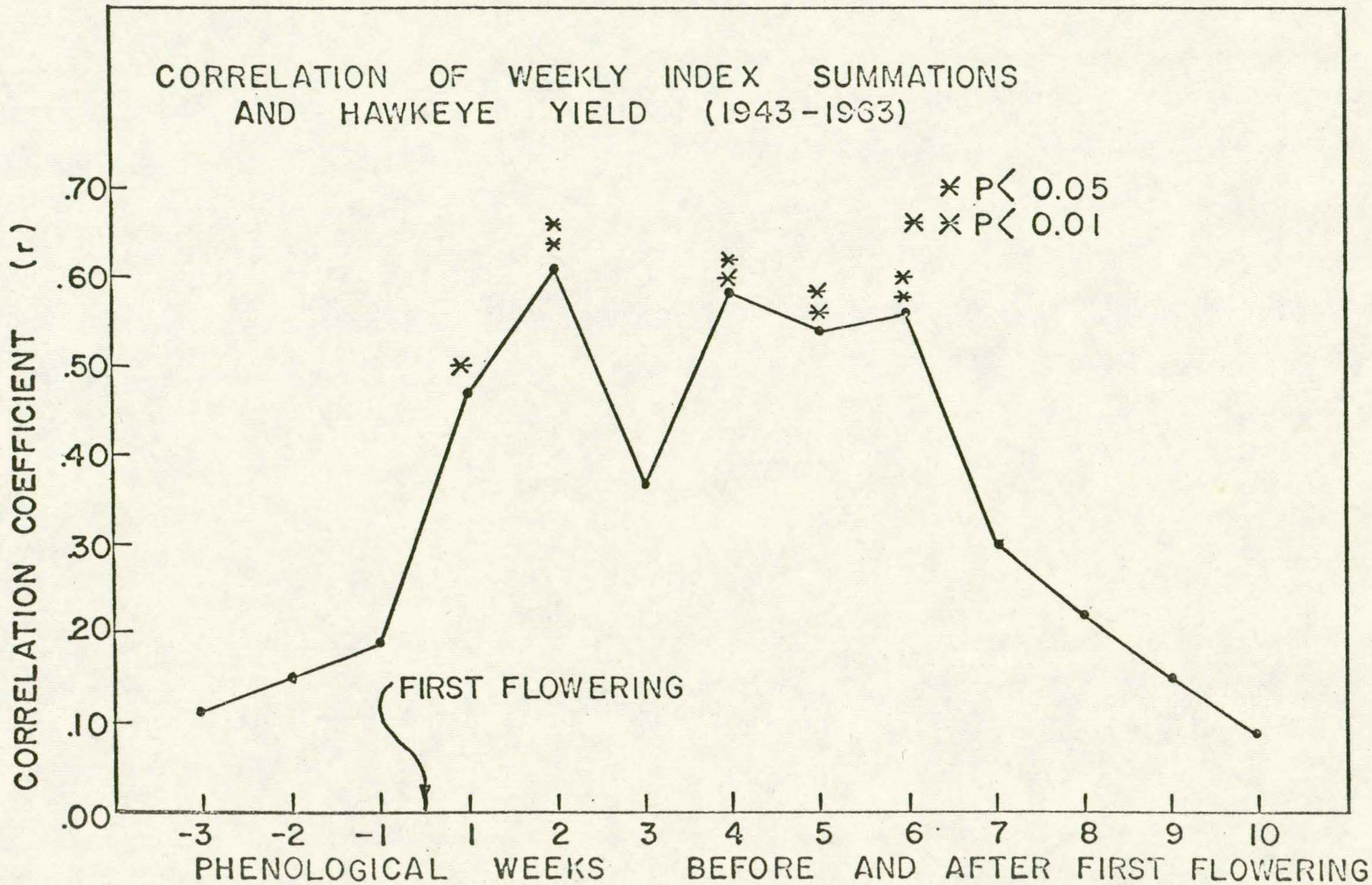
By application of the above rules, each year is treated on the same basis to arrive at an average available soil moisture content (volumetric or PAV percent available) in the hypothesized "wettest 18 inch" root zone. The figure of 32% available was chosen since this soil moisture condition appears to be the boundary where decreased capillary conductivity completely masks the effects of day-to-day weather changes on relative turgidity. In other words, below 32% the soil factors of the water environment are completely controlling plant-water relations. Peters (1957) has shown that corn roots do not elongate in soils maintained at between 4 and 5 atmospheres of tension. This tension is approximately equivalent to 32% available soil moisture in Nicollet soil.

In most years this procedure resulted in no change in the soil moisture content under soybeans compared with the old procedure for corn. In a few years with long periods of low rainfall some difference was measured.

Other than experimental plot data collected in 1965, no soil moisture data were available to check the modified soil moisture procedure for soybeans. As an indirect check, a weather index was computed for each day, using 1) average soil matric potential in the rootzone as computed, 2) open-pan evaporation and 3) interaction of 1 and 2 to compute a daily 1400 relative turgidity value. This value was converted to a relative photosynthesis value ranging from 0.10 to 1.00 which estimated the effect on the plant's production (1.00 indicates no stress). The values of this index were accumulated for periods ranging from 1-10 phenological weeks in length through the growing season. These values were related to a 21-year (1943-1963) period of soybean yield data where the same variety has been grown under similar management conditions[1/]. The correlation coefficients for the association between the weekly phenological water stress index and the mean yield of Hawkeye soybean are shown in Figure 7. The low correlation in week 3 is probably an artifact of the sample and should not be regarded as physiologically important. The apparent association of the early weeks (periods 1 and 2) with yield may be an illustration of the "climatological effect" which has been described by Dale and Shaw (1965) in corn. The non-independence of weekly stress indicies in this work resulted in high correlations for periods where greatest physiological effects were not expected. In other words, where stress conditions occur early there is a climatologically greater chance of having stress later, and at a physiologically important stage of growth.

1/ Soybean yield data provided by C. R. Weber.

Figure 7. Correlation coefficients for the association between phenological week water stress index (P/P_o) and the mean yield of Hawkeye from 1943-1963 at Agronomy Farm, Ames, Iowa.


CORRELATION OF WEEKLY INDEX SUMMATIONS
AND HAWKEYE YIELD (1943-1963)
* P< 0.05
** P< 0.01
CORRELATION COEFFICIENT (r)
.70
.60
.50
.40
.30
.20
.10
.00
FIRST FLOWERING
-3 -2 -1 1 2 3 4 5 6 7 8 9 10
PHENOLOGICAL WEEKS BEFORE AND AFTER FIRST FLOWERING

The accumulated index for the most critical seven-week period is shown in Figure 8. A summation value of 49 would indicate no stress occurred during the 7-week period. The data points show a concentration of years with high yields with only 6 years having yields less than 35 bushels per acre. Considering the number of factors unaccounted for in the index, the explanation of 74% of the yield variation is very good, and indicates the soil moisture values predicted must be quite good.

Laing's procedure was tested on the corn data and gave little change. Layers below the surface foot frequently dropped below 32% by extraction of soil moisture before the top foot reached stress value, due to rainfall added to the top foot. A modified procedure was used in which after July 5, if the top foot had less than 32% available the % available soil moisture was computed as the percent in the root zone, less the top foot. The highest figure (top foot, entire root zone or root zone minus top foot) was used. The effect of this was to extract soil moisture at a more rapid rate at first. This higher rate of extraction resulted in a lower percent available moisture which then reduced the rate. Calculation on several years of data gave a maximum amount of greater extraction of about 0.5 inch out of the profile in about 3 years out of 10. There was no effect in about half the years. Once the moisture difference reached near ½ inch, the procedure gave almost identical results to the old method. Moisture was becoming low enough that the two methods gave almost identical percent available moisture. It is intended to program this procedure into the computer program.

In the dry summer of 1966 the prediction technique for meadow was tested in the field at Ames[2/]. Alfalfa was maintained under natural conditions and all rainfall kept off other selected plots for the month of August. Both situations

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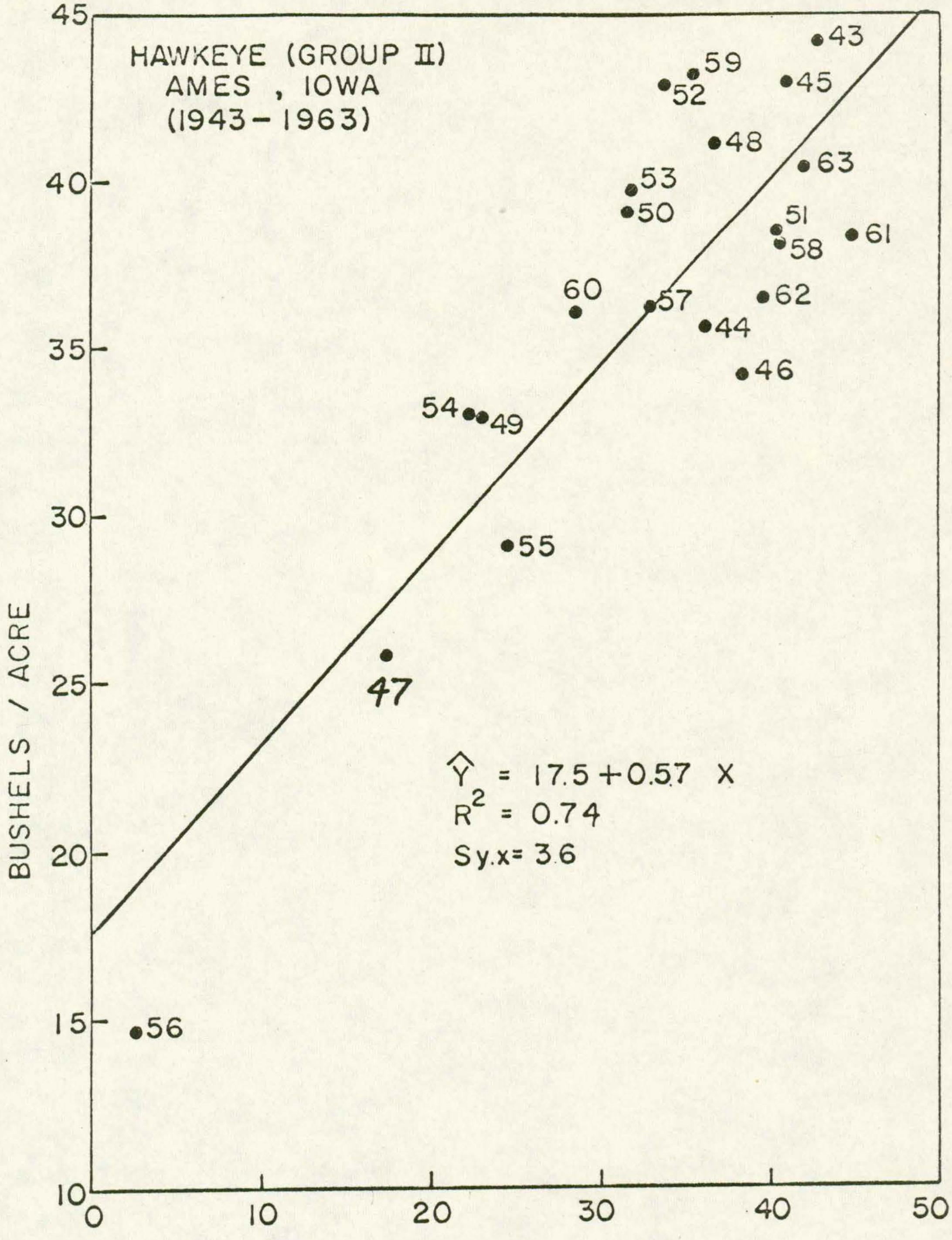
2/ This experiment was conducted by Enrique Marchesi.

Figure 8. Yield of Hawkeye variety from 1943-1963 at Ames, Iowa plotted as a function of the seasonal summation (weeks 1-7) of the water stress index (P/P_o) for each day (maximum value = 49).



HAWKEYE (GROUP II)
AMES , IOWA
(1943 - 1963)
43
59
52
45
48
63
53
50
51
58
61
60
57
62
44
46
54
49
55
47
56
$\hat{Y}$ = 17.5 + 0.57 X
R^2 = 0.74
Sy.x= 3.6
BUSHELS / ACRE
Σ P/Po
45
40
35
30
25
20
15
10
0
10
20
30
40
50

provided low soil moisture conditions. Soil moisture samples were collected on approximately a 10-day basis. Using the procedure which was reported in Cwb contract 10278 the results shown in Table 3 were obtained. The differences were within the errors in the soil moisture sampling and indicate the stress factor used for meadow resulted in the proper extraction pattern.

Table 3. Comparison of observed and predicted soil moisture for selected periods for alfalfa plots at Ames, Iowa. 1966.

Period	Treatment	Difference between measured and predicted soil moisture (Total, 0-5 feet)
Aug. 1-11	Covered	0.16 inches
Aug. 11-23	Covered	0.35 inches
Aug. 23 - Sept. 2	Covered	0.29 inches
Aug. 1-11	Natural	0.06 inches
Aug. 11-23	Natural	0.03 inches
Aug. 23 - Sept. 2	Natural	0.11 inches

Relative turgidity and meteorological conditions

In predicting the water balance for a crop, the total area of interest must be considered. Interest may be in the water balance per se, or in the water balance as a tool in weather-crop yield relationships. Hydrologists, for example, are generally most interested in the water balance as it applies directly to water yield. Agriculturists are interested in the water balance as an indication of present and possible future supplies of water for their crops, but are generally even more interested in the weather-yield relationships involved. Because of this latter interest it is necessary to examine soil moisture - water balance relations to see that plant relations are adequately represented, both as plant use (transpiration) may affect the prediction and as the level of soil moisture predicted may affect the crop.

In the previous section, data were presented for soybeans showing a good relationship between crop yields and predicted soil moisture values. In report Cwb-10849 some data were presented showing the relationship between corn yields and non-moisture stress days (weather index) for Ames and Castana, Iowa, Mandan, North Dakota and Wooster, Ohio. The non-stress day determination, $\theta_{TL} = f(ET_{FC})$, (i.e., the soil moisture content at which plant turgor is lost, θ_{TL}, is a function of the evapotranspiration rate at field capacity), was experimentally derived from a visual inflection point of the curve constructed from plotting actual evapotranspiration versus soil moisture content. This must be an accurate limit to fully exploit the moisture balance work in weather - crop relations. A direct plant measurement best determines the effect of moisture stress on the plant. Relative turgidity measurements provide a direct means of defining the moisture condition in the plant. The upper, actively photosynthesizing leaves are chosen for this. Relative turgidity is defined as:

$$RT = \frac{\text{weight of fresh leaf - weight of dry leaf}}{\text{weight of turgid leaf - weight of dry leaf}} \times 100$$

To obtain values of relative turgidity, leaves are selected in the field and weighed to obtain the fresh weight. The leaves are then floated on distilled water with the top side uppermost. The samples are floated for sixteen hours at temperatures near 25°C under an illumination of 100 foot candles of light. The samples are then removed, blotted to remove excess water and weighed to determine the turgid, or fully water saturated, weight. After drying at 75° for two hours the dry weight is obtained. The percent relative humidity is computed as shown. This provides a direct measurement of the water status in plant tissue.

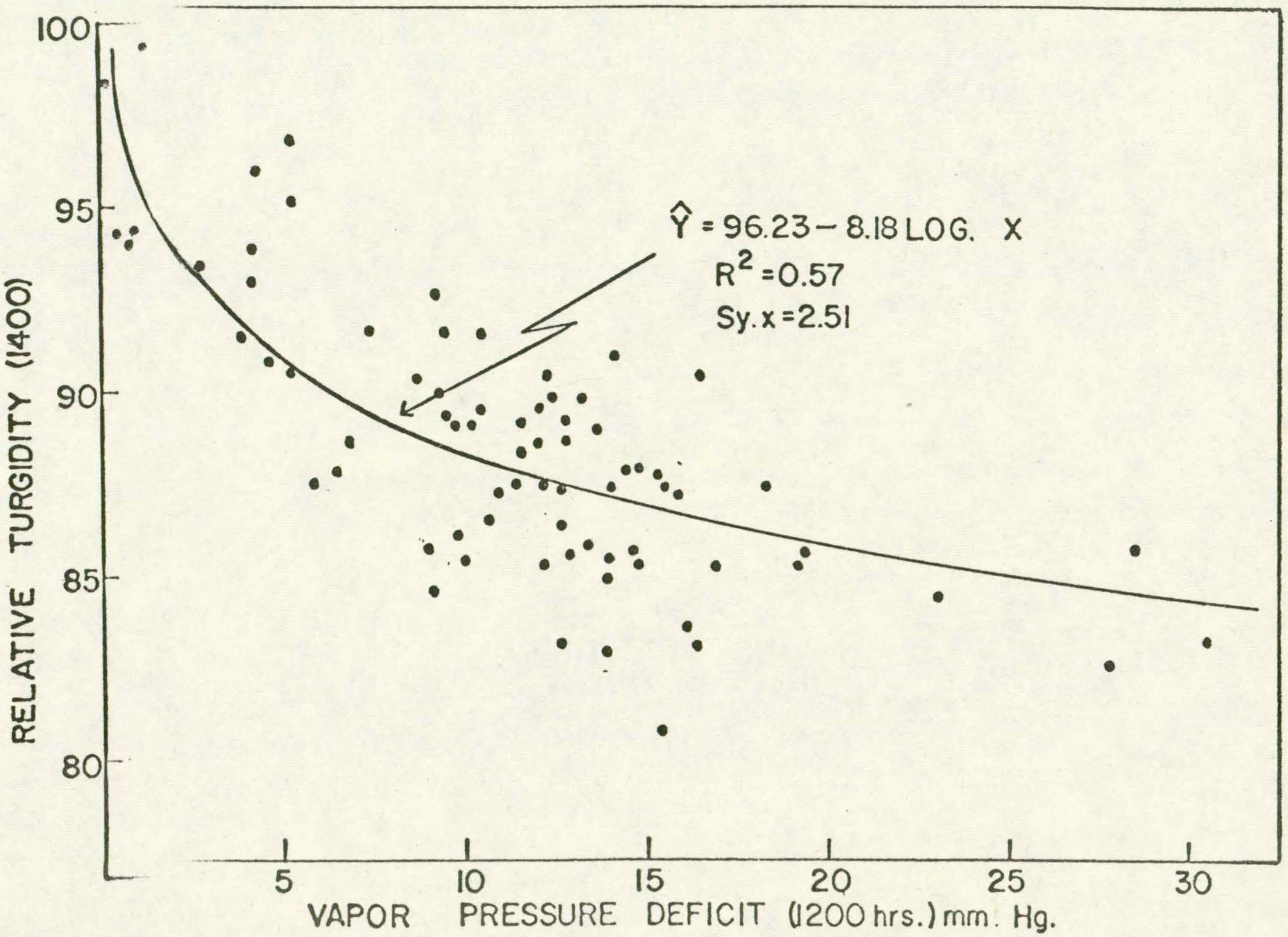
Work done at Iowa State has shown that the limits assumed for non-stress conditions were suitably selected. Laing (1966) obtained data for three widely different types of atmospheric demand days as shown in Table 4. He found that the relative turgidity of soybeans at which an appreciable reduction in transpiration occurred was 84-86%. Similar values would be expected for corn. This value of relative turgidity is the same as that at which the critical levels of soil moisture shown occurred for the different days. Visual observations on soybeans have indicated the first obvious signs of wilting occur near 84% relative turgidity. It does appear that the limits for stress or non-stress conditions have been properly chosen.

A further examination of the relationships between relative turgidity and meteorological parameters may provide information as to which parameters are the most important in predicting water balances and at the same time relate closely to plant response.

When the soil moisture is maintained at or near field capacity the influence of soil factors on the degree of the water absorption lag in the plant is at a minimum. Under these conditions an investigation of the relationship between various meteorological parameters and the degree of daily maximum water deficits in a plant is facilitated. A large number of relative turgidity samples have been collected under these conditions from both potometers and in the field at 1400 hours. This represents the time of maximum water deficit in the plant leaf.

A scatter diagram of these soybean RT data is presented in Figure 9, as a function of the vapor pressure deficit of the air measured at screen height at the experimental site. The log of vapor pressure deficit (e_s-e_a) when fitted to these data explained 57% of the variation. A regression model containing the

Figure 9. Relative turgidity at 1400 hours plotted as a function of noon vapor pressure deficit (measured at screen height) where the soil was maintained at field capacity in 1963, 1964 (potometers) and 1965 (field data). Each data point represents the mean RT on the particular day for all potometer or field measurements where the soil was held at field capacity.



$\hat{Y}$ = 96.23 − 8.18 LOG. X
R^2 = 0.57
Sy.x = 2.51
RELATIVE TURGIDITY (1400)
100
95
90
85
80
5
10
15
20
25
30
VAPOR PRESSURE DEFICIT (1200 hrs.) mm. Hg.

Table 4. Comparison of atmospheric demand conditions, open-pan evaporation and critical level of soil moisture.

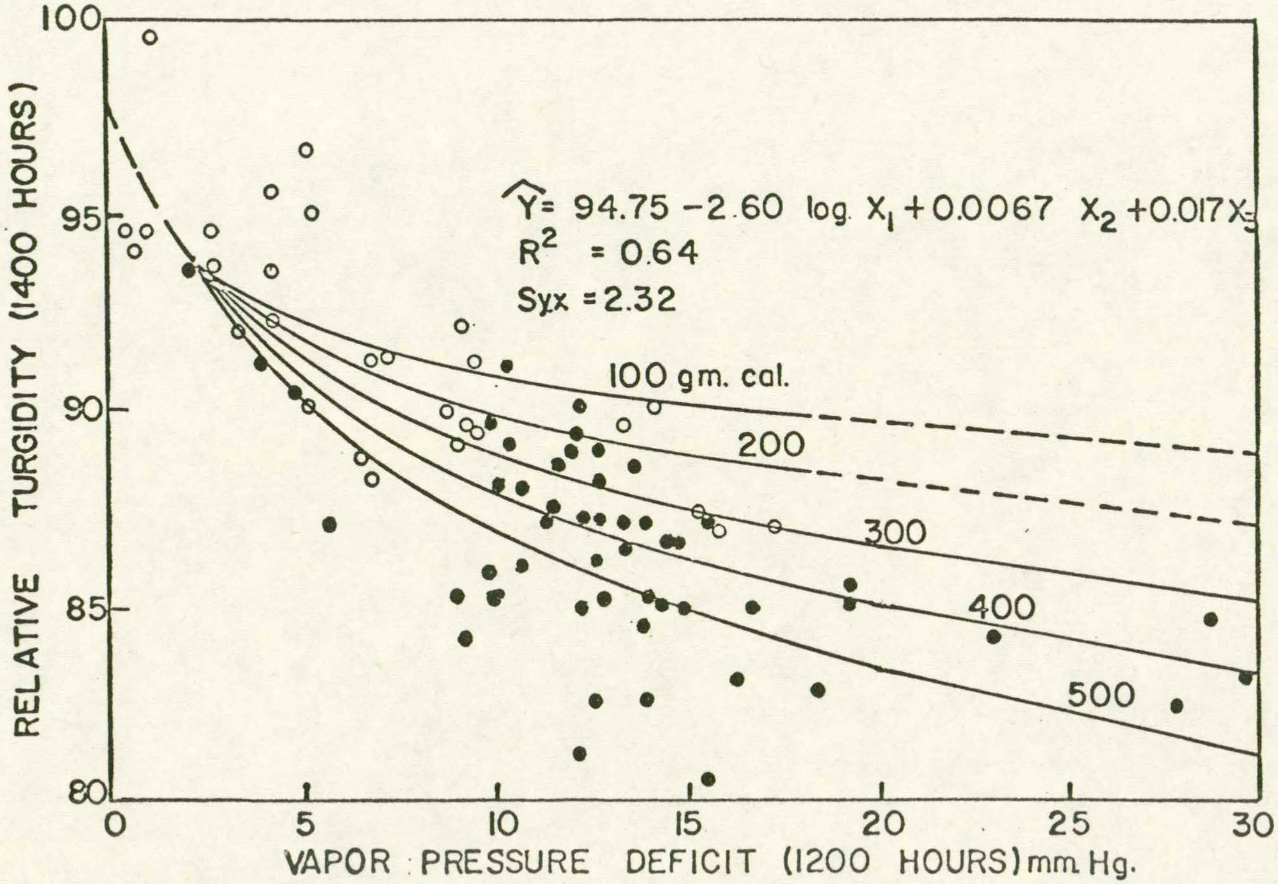
Net radiation gm. cal/day	e_s-e_a (m.m)	Pan evap. (m.m.)	Critical soil moisture level (%)
435	16.0	8.7	90
140	4.8	3.0	60
143	1.3	3.5	45

linear and quadratic terms for e_s-e_a explained a slightly greater proportion of the variation, but the regression line was difficult to interpret in terms of the mechanisms involved. In Figure 9, it can be seen that the log regression line and the data points show a rapid decrease in relative turgidity at vapor pressure deficits up to about 5 mm., with a leveling off at higher deficits. This can be explained in terms of transpiration - stomatal relationships. With increasing energy supply (net radiation), increasing vapor pressure deficits will tend to increase the transpiration rate. An increase in the transpiration rate on a daily basis will decrease leaf turgor (hydration) at some rate. Decreased leaf turgor will cause the turgor operated stomatal closure mechanism to increase the resistance to transpiration and decrease transpiration at some critical level of turgor. In the species used here, wilting symptoms occur at approximately 85-83% relative turgidity, and at this level the stomata have already undergone some degree of closure.

The leveling off in the rate of decrease of relative turgidity with increase in the vapor pressure deficit occurs in the relative turgidity range from 90 to 84%. These data would thus support the conclusions made by various workers that the stomatal closure mechanism reduces the degree of internal water stress under extreme conditions. This appears in the Shaw soil moisture prediction method as a factor which reduces the water loss when the plant is under stress.

The rate of transpiration is dependent upon not only the vapor pressure gradient but also the energy required for latent heat of evaporation and the transfer of the water vapor into the atmospheric sink. The interaction of incoming energy measured as solar radiation received up to 1400 hours and the vapor pressure deficit of the air at noon is explained to some extent by the data presented in Figure 10. A multiple regression equation containing the logarithmic term for e_s-e_a, the linear term for solar radiation and the interaction of these terms was associated with 64% of the variation in relative turgidity measured at 1400 hours. An accurate description of these results in terms of theoretical considerations is somewhat limited since there is a strong correlation between daily solar radiation received and the e_s-e_a at 1200 hours ($r = 0.83$). The dashed segments of the predicted curves represent the region where low radiation (and most likely low air temperatures) could not be associated with high e_s-e_a under most natural conditions. The equation does show the effects of the interaction of high radiation and high e_s-e_a on the development of plant water deficits. Daily wind movement did not prove significant in the equations tested with these relative turgidity data. The importance of wind as a predictor of evapotranspiration appears to be a debatable question. In the humid eastern areas of the U.S., correspondence and personal communications indicate it is of little consequence, but in the drier areas west of Iowa similar information indicates wind may be of considerable importance. This may reflect the relatively greater advective effects occurring under drier, hotter conditions.

Figure 10. Relative turgidity at 1400 hours plotted as a function of noon vapor pressure deficit. The multiple regression equation including terms for log vapor pressure deficit (X_1), linear terms for solar radiation up to 1400 hours (X_2), and the interaction of X_1 and $X_2 = X_3$, is shown in the body of the figure. Estimated RT at various levels of solar radiation data, closed circles = data $>$ mean of solar radiation data.



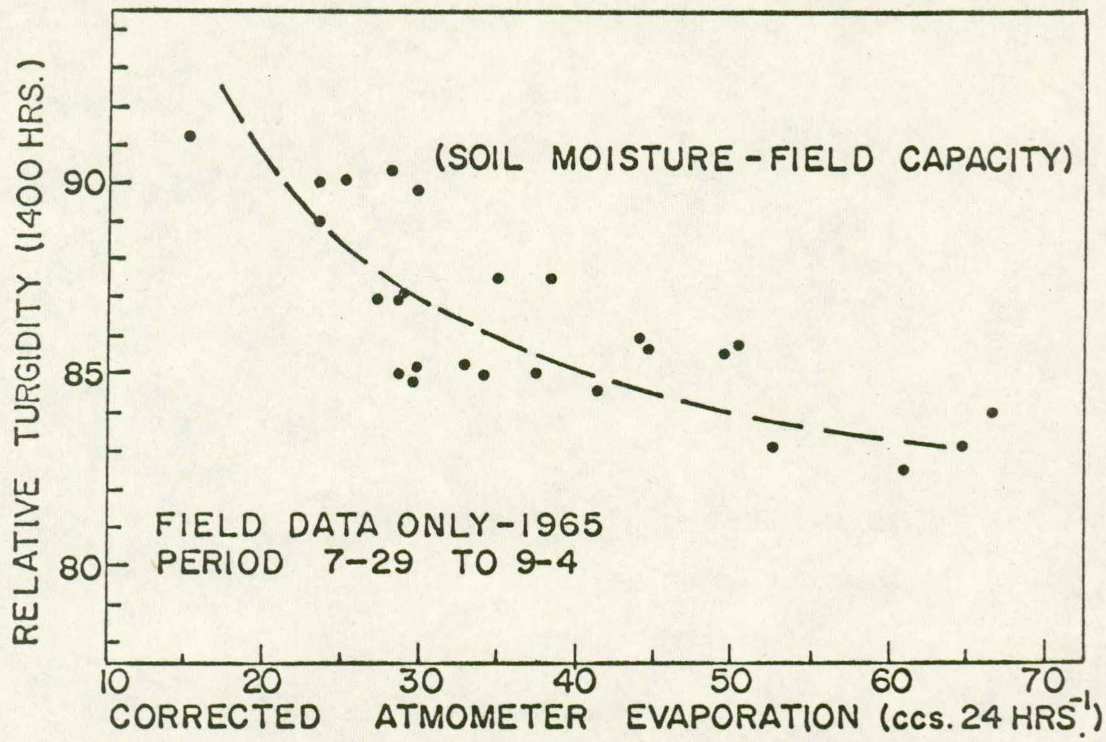
$\hat{Y}$ = 94.75 − 2.60 log. X_1 + 0.0067 X_2 + 0.017 X_3
R^2 = 0.64
Syx = 2.32
100 gm. cal.
200
300
400
500
RELATIVE TURGIDITY (1400 HOURS)
VAPOR PRESSURE DEFICIT (1200 HOURS) mm Hg.
100
95
90
85
80
0
5
10
15
20
25
30

The relationship of the daily minimum relative turgidity under near field capacity conditions in the field and in potometers to Class A open-pan evaporation are shown in the bottom portion of Figure 11. Although these data show considerable variation, they do indicate that increasing open-pan evaporation is not related linearly to the development of mid-afternoon water deficits. A similar relationship appears to exist between Bellani plate evaporation and the relative turgidity of a field canopy near field capacity. This is another illustration of the reduction in the magnitude of the water deficit brought about by stomatal closure and again emphasizes the importance of the stress factor in predicting soil moisture. The level of evaporation at which this effect becomes quite evident is near 6-8 mm open-pan evaporation per day. This is near .25 to .30 inch per day. The .30-inch level corresponds to the level set for high atmospheric demand in the soil moisture prediction technique.

Comparison of November Predictions Made from April Soil Moisture Samples

Using the 360 program, soil moisture under corn was computed for 18 years, 1948-65 at Norwich, Iowa City, and Castana-Cherokee, Iowa. From 1954 to 1965, the estimates were begun with the first soil moisture profile measurement of the season, usually about the first week in April, and daily estimates continued through to November 30 of each year. The comparison of the estimated total available soil moisture in the top five feet with that measured later in the season at the respective locations, usually in November are shown in Figure 12 for Norwich, Iowa City, Castana, and Ames, Iowa. It should be pointed out that comparisons between estimates and measurements in previous contract reports on soil moisture

Figure 11. Relative turgidity (1400 hours) plotted against corrected Bellani plate atmometer evaporation (1965 field data) and daily open-pan evaporation (1963, 1964, 1965 field and potometer data).


(SOIL MOISTURE-FIELD CAPACITY)
RELATIVE TURGIDITY (1400 HRS.)
FIELD DATA ONLY-1965
PERIOD 7-29 TO 9-4
90
85
80
10 20 30 40 50 60 70
CORRECTED ATMOMETER EVAPORATION (ccs. 24 HRS.$^{-1}$)

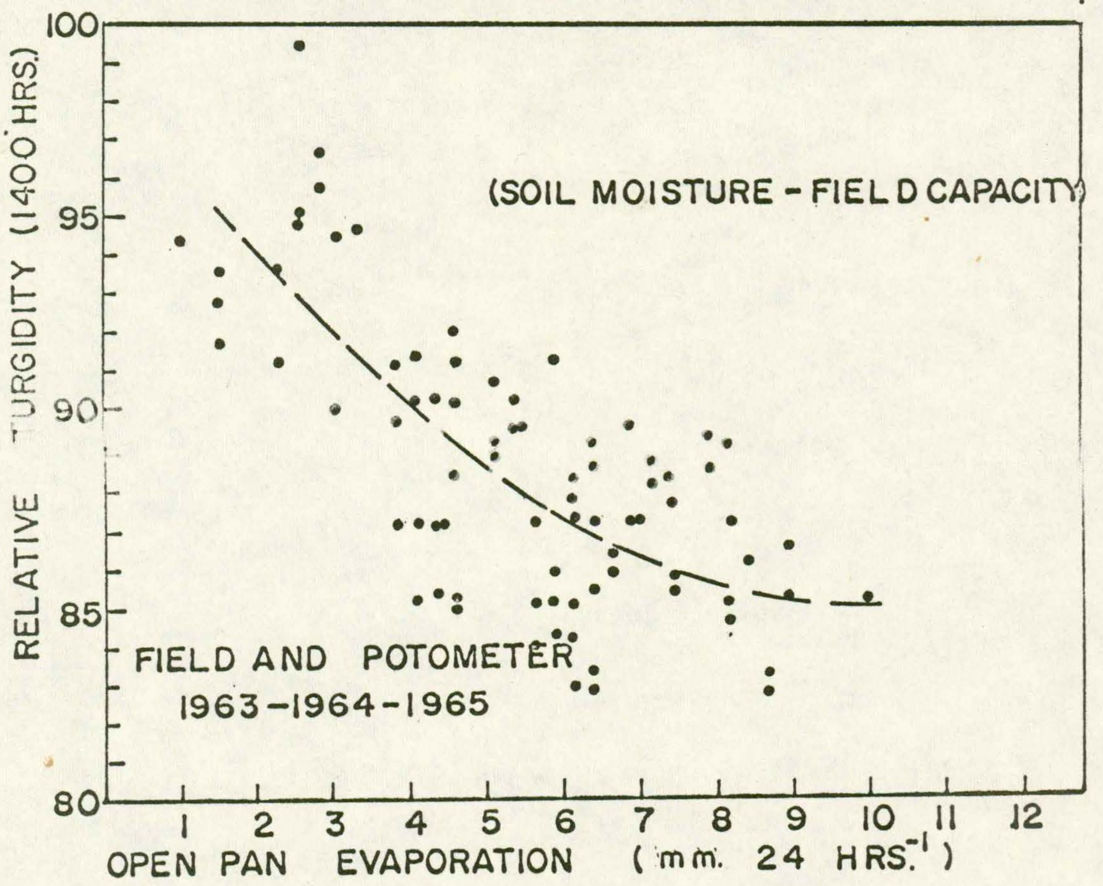
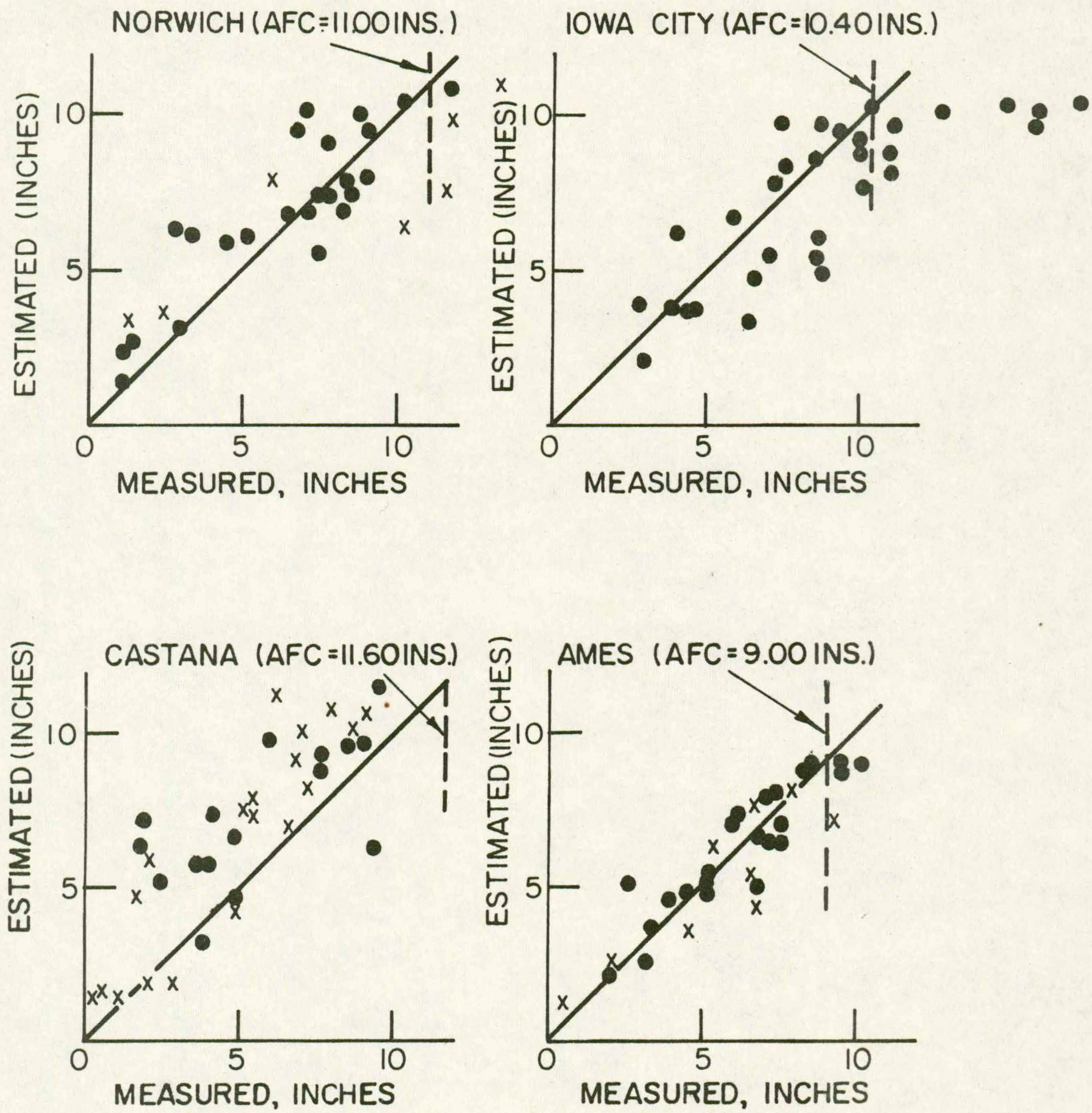

(SOIL MOISTURE - FIELD CAPACITY)
RELATIVE TURGIDITY (1400 HRS.)
FIELD AND POTOMETER
1963-1964-1965
100
95
90
85
80
1 2 3 4 5 6 7 8 9 10 11 12
OPEN PAN EVAPORATION (mm. 24 HRS.$^{-1}$)

Figure 12. Comparison of estimated soil moisture in top 5 feet (budgeted from April measurement) with soil moisture measurements under corn made in June, August, and November.


NORWICH (AFC=11.00 INS.)
IOWA CITY (AFC=10.40 INS.)
CASTANA (AFC=11.60 INS.)
AMES (AFC=9.00 INS.)
ESTIMATED (INCHES)
MEASURED, INCHES
0
5
10

have pooled all Iowa locations and have also been estimated for only a period of two months, from one measurement (April, June, August, or November) to the next. The estimates in Figure 12 are not corrected to the June, or August measurements but are continued from the April measurement through the season.

The 45° lines represent the desired relation. They are not computed regressions. The estimates appear best for Ames and Norwich, and exhibit an upward bias for Castana. The soil moisture measurement plots are in the immediate proximity of the weather stations at these three locations. At Iowa City, however, the soil moisture measurements were about 25 miles from the weather station. Iowa City was used because it is the only evaporation station in east central Iowa and provides the evaporation argument needed in the Shaw method (1963). This helps to explain the scatter at Iowa City, but the relation appears unbiased. The variability in Figure 12 arises not only because of estimating errors, but also from measurement of soil moisture on different plots as the crops are rotated from year-to-year. Soil constants differ between plots.

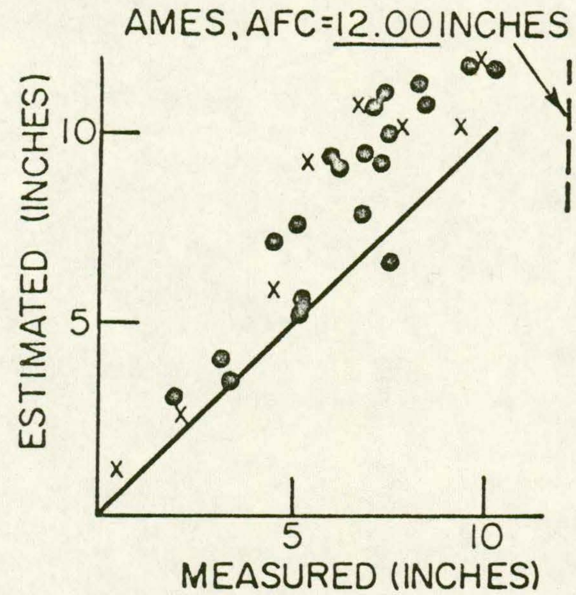
The April soil moisture under corn following meadow (first year corn) is not always the same as that for second-year corn. If sufficient moisture is not received to raise all plots to field capacity in the spring, first-year corn will be drier, since meadow continues to grow and use moisture longer in the fall than corn. On Figure 12, the x's represent first year corn measurements. The fact that there is no distinctive pattern indicates that usually sufficient rainfall is received to increase soil moisture under first-year corn to that under second-year corn by the time of the first check measurement in June.

The dashed lines indicate the assumed available field capacities (AFC) for the respective soils. They represent a bound for the estimates. The greater measurements at Iowa City are due to temporary water tables where water was retained in the profile above the field capacity values. There have been no measurements beyond the assumed available field capacity at Castana, and it appears to be too high. Although even higher values have been measured experimentally, the high AFC has been questioned by soils specialists. The evaporation and rainfall measurements were taken on the same farm, but at a different site from the soil moisture plots. The assumed available field capacity value has an effect upon the soil moisture estimates. The scatter diagram in Figure 13 was prepared to show the comparison of estimates using an assumed 12-inch AFC rather than a 9-inch AFC for Ames, Iowa. If the Ames available field capacity were assumed to be 12 inches, instead of 9, the estimated amounts are biased upward. From this we might expect that a lower assumed AFC for Castana would improve the soil moisture estimates and remove what appears to be a bias in the values. It is interesting to note, however, that the number of non-stress days (NSD) at Castana as computed for 1954-1962 by Dale (1964), who adjusted the estimates to the current measurement through the season (estimates identical to measurements for those dates), are very close to those tabulated from the computer run starting from April, as shown in Figure 14. Future calculations for Castana will use a 9.6-inch available field capacity.

Soil Moisture Changes over the Winter Season

Dale and Shaw (1965) used the November 30 estimated budget to select the following season's April 1 soil moisture "measurement" to begin the budget. Shaw (1965) has reported that some change in soil moisture can occur between these dates, but because of little cold season precipitation and frozen ground the

Figure 13. Comparison of estimated and measured soil moisture values for Ames, Iowa using available field capacity (AFC) values of 9.00 and 12.00 inches.


AMES, AFC=12.00 INCHES
ESTIMATED (INCHES)
MEASURED (INCHES)
10
5
5
10

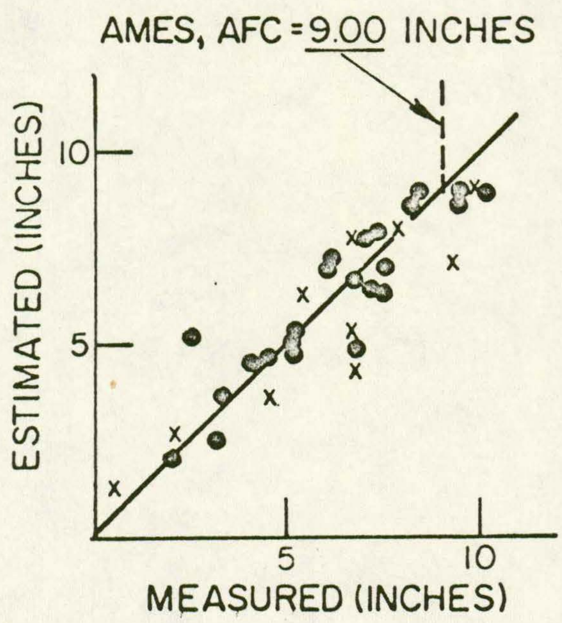
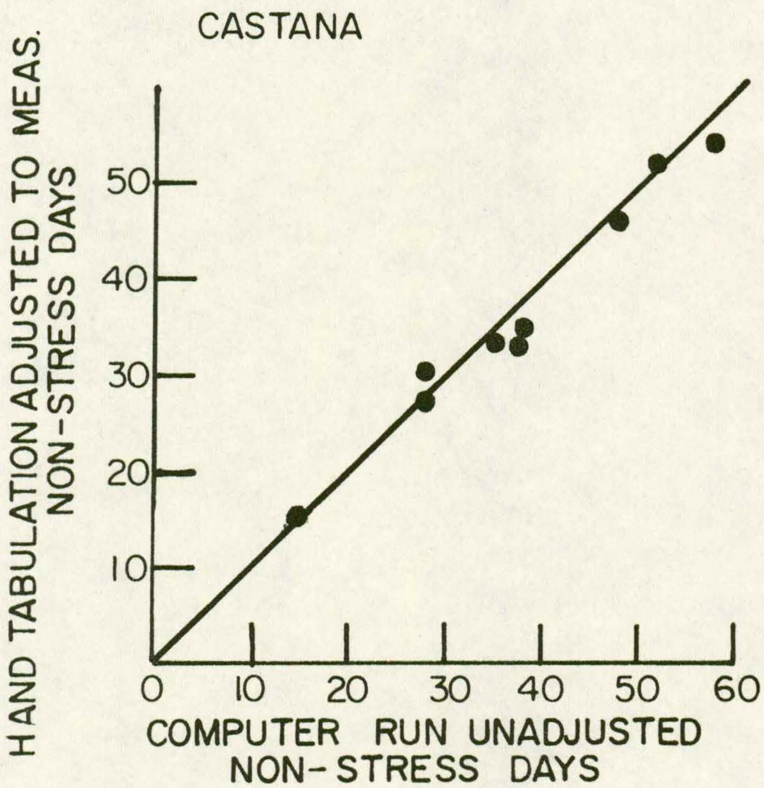
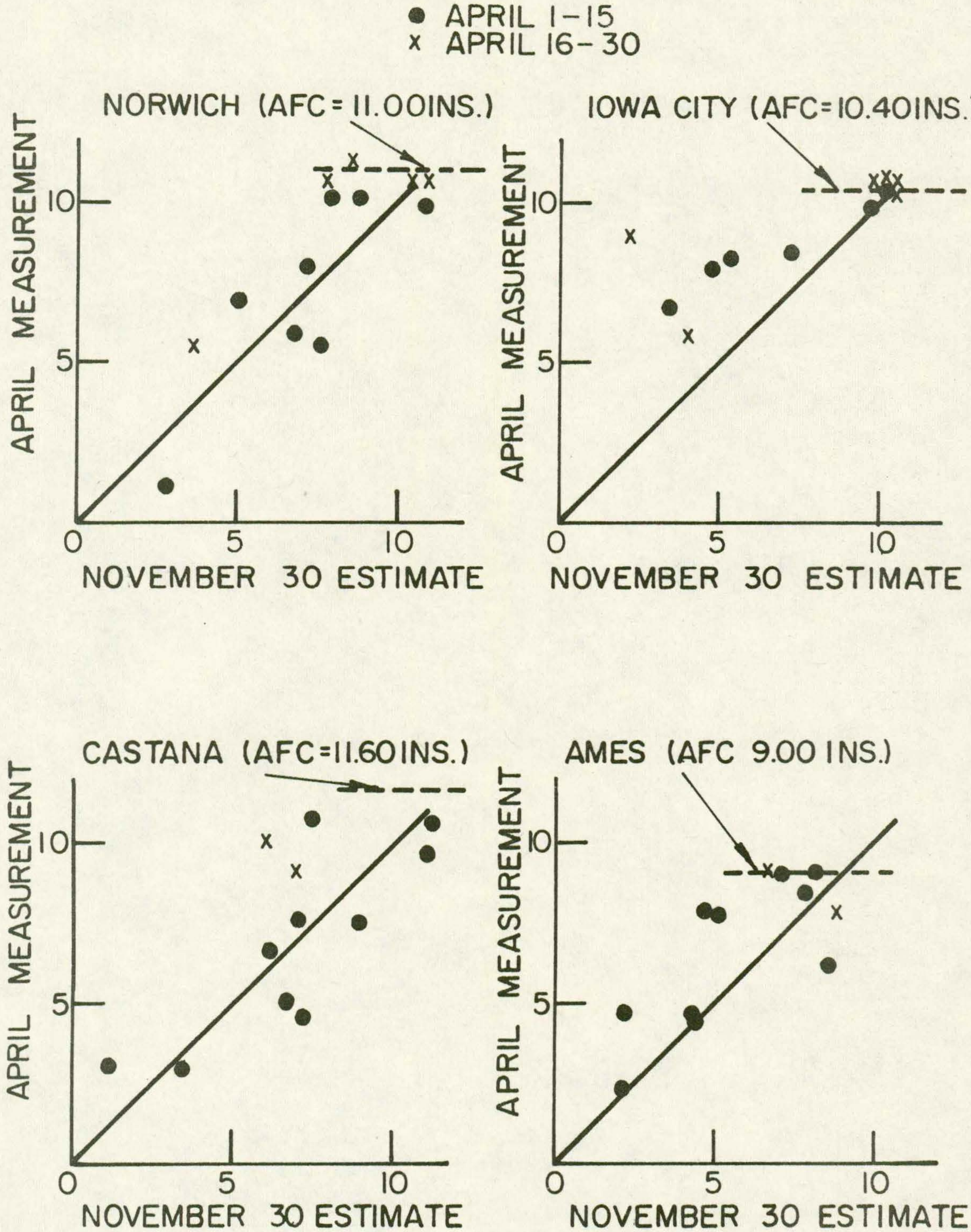

AMES, AFC=9.00 INCHES
ESTIMATED (INCHES)
MEASURED (INCHES)
10
5
5
10

Figure 14. Castana 6B-3A non-moisture stress days comparison between unadjusted computer run and estimates adjusted to occasional measurements (1954-1962). (6B-3A is period 6 weeks before to 3 weeks after corn silking.)


CASTANA
HAND TABULATION ADJUSTED TO MEAS.
NON-STRESS DAYS
10
20
30
40
50
0
10
20
30
40
50
60
COMPUTER RUN UNADJUSTED
NON-STRESS DAYS

change is usually small. It was necessary to estimate the beginning April soil moisture measurement prior to 1954. As a basis for this, scatter diagrams of the actual April measurement compared to the previous November 30 estimate for 1954-1965 were plotted and are shown in Figure 15. Unless the measurements were taken fairly early in April, there is a good chance that the soil will be thawed and additional rainfall will be received. Therefore, the dots represent those April measurements taken in the first half of the month and the x's in the second half. The assumption that the starting April 1 soil moisture profile is approximately the same as the previous November 30 estimate seems adequate for all but Iowa City, where soil moisture in the spring shows a definite increase over that in the fall. The southeast part of Iowa has slightly heavier winter precipitation than the rest of the state, and a greater gain over the winter period may be expected. This will be incorporated in future soil moisture computations for Iowa. The starting soil moisture in April should not be assumed to be the same as for the previous fall. Calculations and observations for the period November 1966 to April 1967 show the soil moisture change ranged from a loss of -0.1 in west central Iowa to a gain of almost 3 inches in south eastern Iowa. Using the winter procedure reported under contract Cwb-10554, estimation of the change from November to April was with ½ inch of the measured value for over half of approximately 20 stations, and on only two stations was the difference greater than 1 inch.

Figure 15. Comparison of estimated November 30 soil moisture (budgeted from previous April measurement) with following April soil moisture measurement (following corn), 1954-1965.


● APRIL 1-15
x APRIL 16-30
NORWICH (AFC = 11.00 INS.)
IOWA CITY (AFC = 10.40 INS.)
CASTANA (AFC = 11.60 INS.)
AMES (AFC 9.00 INS.)
APRIL MEASUREMENT
NOVEMBER 30 ESTIMATE
0
5
10

Concluding Remarks

Of the data tested since the study was first started on soil moisture prediction, the method which has been developed has worked within the limits of soil moisture sampling errors for all data except the Coshocton, Ohio lysimeter data. In early tests made on these data, our method considerably underestimated the ET losses from the lysimeters. In a comparison with Pierce's method (Pierce, 1966) his gave ET losses 1.14 times greater than the Iowa procedure. His method was calibrated to the lysimeter data. In a recent communication[3/], it was reported that a 20% reduction was made by Pierce in his formula to bring it in line with recent adjustments made in the lysimeter data. This would bring our estimates much closer to the lysimeter readings, although actual computations were not made. Some differences should be expected in comparing Pierce's method based on temperature with ours based on evaporation pan as was shown by the variable ratio shown in Figure 2. Emperical procedures such as these can be tested ad infinitum without reaching positive conclusions using data which are currently available. Until a network of observations, such as properly operating lysimeters, is installed which will give accurate daily evapotranspiration values under a range of field conditions, no conclusive statement can be made as to which method gives the best results, and how adequate these results really are. A network of lysimeters, although expensive would be invaluable in providing data which would finally settle the controversy of emperical soil moisture prediction techniques. Possibly such a network could become part of the National Agriculture Weather Service.

3/ Personal communication, Ted Pierce, November 14, 1966.

These soil moisture calculations and stress computations have been and are being used for a number of studies in Iowa. Dale (1966) used this procedure to compare seasonal patterns of available soil moisture at locations in Iowa, (Figure 16). Such data are useful in comparing different areas in land resource studies. The soil moisture can be used to provide comparisons of stress conditions for different locations and periods. The procedure has been used to construct records for periods before soil moisture data were taken. In Figure 17, the stress probabilities for an 18-year and 30-year period are compared (Dale, 1966).

The technique using open-pan evaporation data as the measure of potential evaporation is believed to predict soil moisture within the limits of accuracy of presently measured soil moisture data. It is intended to use this procedure, making any refinements which seem feasible, both as a means of supplying soil moisture values for their own use and as a means of supplying such data for moisture stress studies.

Figure 16. Seasonal march of average soil moisture in the top five feet under corn on well-drained land for indicated Iowa locations and available field capacities, 1948-1965. (Dale, 1966.)

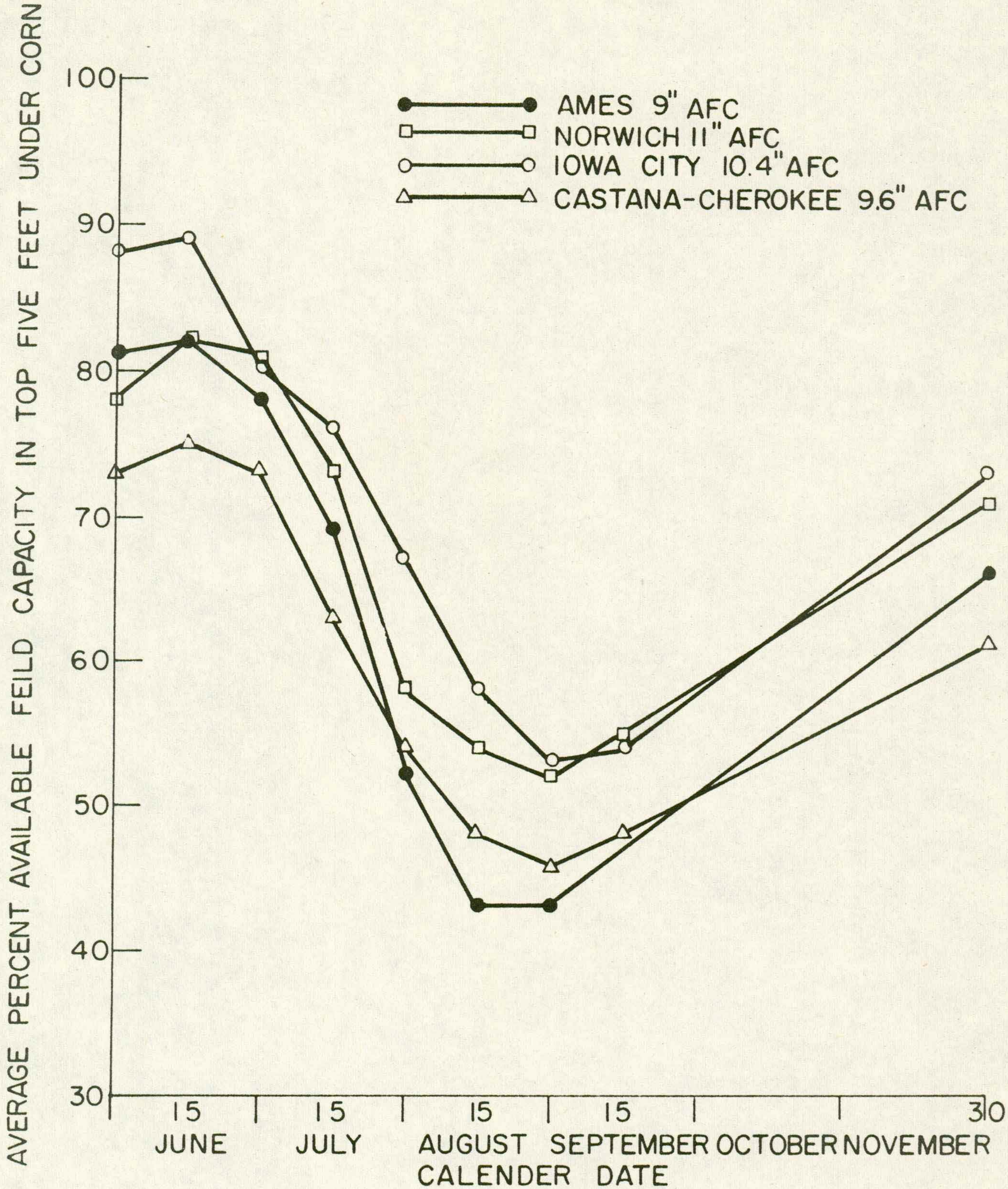
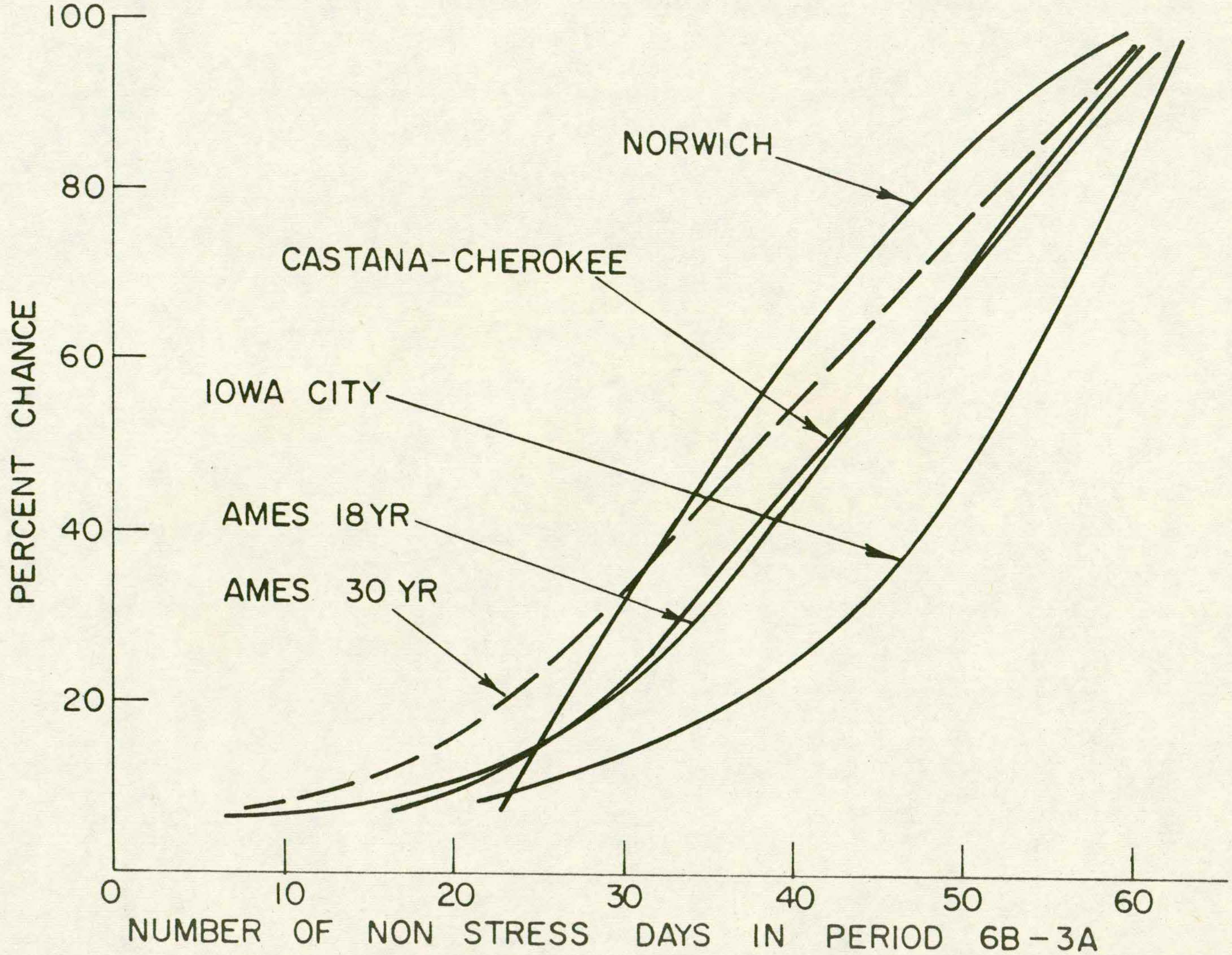

AMES 9" AFC
NORWICH 11" AFC
IOWA CITY 10.4" AFC
CASTANA-CHEROKEE 9.6" AFC
AVERAGE PERCENT AVAILABLE FEILD CAPACITY IN TOP FIVE FEET UNDER CORN
100
90
80
70
60
50
40
30
15
15
15
15
30
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
CALENDER DATE

Figure 17. Frequency of indicated number or fewer non-stress days for corn in the 63-day period, 6 weeks before silking to 3 weeks after, for indicated locations, 1948-1965 and for Ames, 1933-1965.



100
80
60
40
20
0
10
20
30
40
50
60
PERCENT CHANCE
NUMBER OF NON STRESS DAYS IN PERIOD 6B - 3A
NORWICH
CASTANA-CHEROKEE
IOWA CITY
AMES 18 YR
AMES 30 YR

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