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NORMALIZING THE STRESS-DEGREE-DAY PARAMETER FOR ENVIRONMENTAL VARIABILITY*

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ABSTRACT

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Several experiments involving the measurement of foliage—air temperature differentials ($T_F - T_A$) and air vapor pressure deficits (*VPD*) were conducted on squash, alfalfa, and soybean crops at Tempe and Mesa, Arizona; Manhattan, Kansas; Lincoln, Nebraska; St. Paul, Minnesota; and Fargo, North Dakota. It is shown that throughout the greater portion of the daylight period, plots of $T_F - T_A$ vs. *VPD* yield linear relationships for plants transpiring at the potential rate, irrespective of other environmental parameters except cloud cover. This fact is used to develop a crop water stress index that is reasonably independent of environmental variability. Examples of its application to stressed soybeans and alfalfa are provided.

INTRODUCTION

The stress-degree-day concept of crop water stress assessment and yield prediction has proven to be of considerable utility (Idso et al., 1977, 1978a; Jackson et al., 1977; Walker and Hatfield, 1979). Briefly, it posits that if a crop is well supplied with water, transpiration will be at the potential rate and the crop will be relatively cool. When a certain fraction of the available soil moisture (dependent on environmental conditions) has been extracted from the root zone, however, transpiration will be reduced from potential and the crop will increase in temperature. At this stage, or sometime thereafter, the crop may also experience a reduction in photosynthesis that can lead to an ultimate decrease in final yield.

In using plant temperature measurements to quantify crop water stress within this context, we have employed the foliage—air temperature differential, obtained about an hour and a half past solar noon, with reasonable success (Idso and Ehrler, 1976; Ehrler et al., 1978a, b; Idso et al., 1978b,

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1979a, b, 1980; and Reginato et al., 1978). It is evident from basic energy balance considerations, however, that this parameter, which we have termed the stress-degree-day, may additionally be influenced by environmental factors other than soil moisture, such as air vapor pressure, net radiation, and windspeed (Gates, 1968). Indeed, Ehrler (1973) showed experimentally that for cotton the leaf—air temperature differential was highly dependent on the air vapor pressure deficit. Thus, it is important to determine the significance of these other factors and devise a means for adjusting for them, if necessary, in order to better quantify crop water stress arising from insufficient soil moisture. In this paper, we report results of an experimental program based on diurnal measurements at several locations that accomplishes these objectives for three specific crops, developing a crop water stress index that essentially normalizes the stress-degree-day parameter for environmental variability. Elsewhere (Jackson et al., 1981), we build on energy balance considerations to develop a similar index, and use once-a-day measurements over a season to depict the onset of stress.

EXPERIMENTS

Several experiments were conducted on a variety of different crops at a number of widely separated locations. In each case, the primary data collected included air wet- and dry-bulb temperatures and crop foliage temperature. The air temperatures were obtained from an aspirated psychrometer held about a meter above the crops; while the foliage temperatures were obtained with a Telatemp AG-42 infrared thermometer equipped with a 10.5—12.5 μm bandpass filter. (Trade names and company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.) The infrared thermometer was held to obliquely view the crops in such a way that only plant parts, and no underlying soil, could radiate energy to the instrument's sensor. At least two (east and west), and sometimes four (north, south, east, west), viewing directions were employed, with the resultant average temperatures being expressed as equivalent blackbody temperatures.

The first data to be presented pertain to a small planting of squash at Tempe, Arizona. The crop was mature and well supplied with water, having been irrigated daily for several days prior to the days of data acquisition. A unique aspect of this experiment was that the crop was viewed from essentially the same positions every time foliage temperatures were measured. Thus, as will be apparent shortly, there was very little scatter in the data, due to minimizing the component due to spatial variability. Frequencies of data acquisition on different days ranged from ten minutes to half an hour, with data on one day being obtained for a complete 24-hour period.

The second crop investigated was alfalfa. The primary data set for this crop was obtained at Mesa, Arizona, over the period March—June, 1980. As with the squash, the alfalfa was always well supplied with water; and data were obtained at approximately half-hour intervals over several clear-day periods. Since many different fields of much larger size were studied at different times, however, there is somewhat more scatter in these data than is exhibited by the squash data, since the alfalfa was probably never viewed from the same set of positions more than once.

Additional data on well-watered alfalfa were obtained in June of 1980 at Manhattan, Kansas, and Lincoln, Nebraska, and in July at St. Paul, Minnesota. Some significantly stressed alfalfa plots were also monitored at Lincoln and St. Paul, and at Fargo, North Dakota.

The final crop to be included in this study was soybeans, well-watered fields of which were observed at Manhattan, Lincoln, and Fargo. The latter site also had a severely stressed plot of soybeans that was monitored.

RESULTS AND ANALYSES

Figure 1 presents the results of the squash experiment in the format of a foliage—air temperature differential ($T_F - T_A$) vs. air vapor pressure deficit (*VPD*) plot. Focusing first on the results of the 24-hour data set of 9—10 June, we see that as the sun begins to rise, the plant foliage, which was initially about 7°C below air temperature, begins to warm. However, this warming — relative to the air — only lasts for about two to three hours, whereupon the foliage starts to cool relative to the air. This relative cooling is then seen to proceed as a linear function of the air vapor pressure deficit until about two to three hours before sunset, whereupon the foliage—air temperature differential begins to move towards a value that is specified by the nighttime radiation balance and which persists until morning.

The daytime results for the next three days were essentially identical to the linear portion of the 24-hour data set; and we postulate that this linear relationship is a manifestation of potential evaporation. It is well known, for instance, that the stomates of most temperate region agricultural crops close at night and gradually open in the morning in response to increasing illumination. Thus, until the stomates reach a critical degree of openness, potential evaporation does not prevail, and radiant and convective heat exchange terms dominate in the energy balance of the canopy. Consequently, we see the canopy foliage increasing in temperature relative to the air in the early morning, as the radiant heat load on the crop increases with the ascending sun. The stomates are also gradually opening during this period, however, and the rate of increase of T_F relative to T_A becomes more muted with time, until the degree of stomatal openness that may be described as critical for potential evaporation has been achieved. Then the linear relationship sets in and persists until decreasing illumination in the late afternoon initiates stomatal closure and again leads to a departure from the linear $T_F - T_A$ vs. *VPD* line that we feel is characteristic of the potential evaporation state.

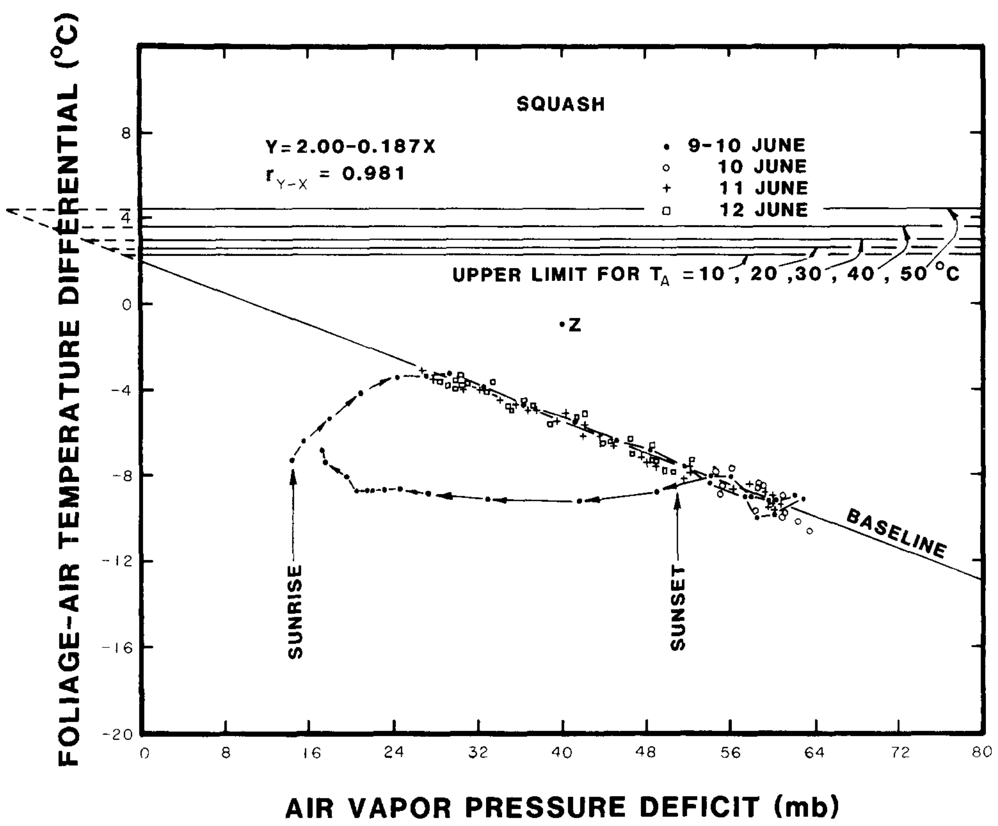

Fig. 1. Foliage—air temperature differential vs. air vapor pressure deficit for well-watered squash grown at Tempe, Arizona, in June 1980.

Figures 2 and 3 contain similar data presentations for alfalfa and soybeans for the daylight periods of several days. In contemplating the results of all three figures, we note the following points. (1) The relationships are all linear. (2) The relationships for the three crops are not identical, indicating that each crop has its own unique relationship of this type — although it is likely that there are probably other crops that may have results identical to some of these. (3) Throughout the period of time that a state of potential evaporation exists, the air *VPD* appears to be sufficient to adequately specify the foliage—air temperature differential. This fact is especially significant when it is realized that net radiation varies considerably over the period from two to three hours after sunrise to two to three hours before sunset, and from the added information that the Mesa alfalfa data were gathered at windspeeds ranging from essentially calm to almost gale conditions. Furthermore, air temperatures at the times of data acquisition varied from just over 10°C to over 40°C. Cloud cover, however, does affect the $T_F - T_A$ vs. *VPD* relationships. The data presented here pertain to clear

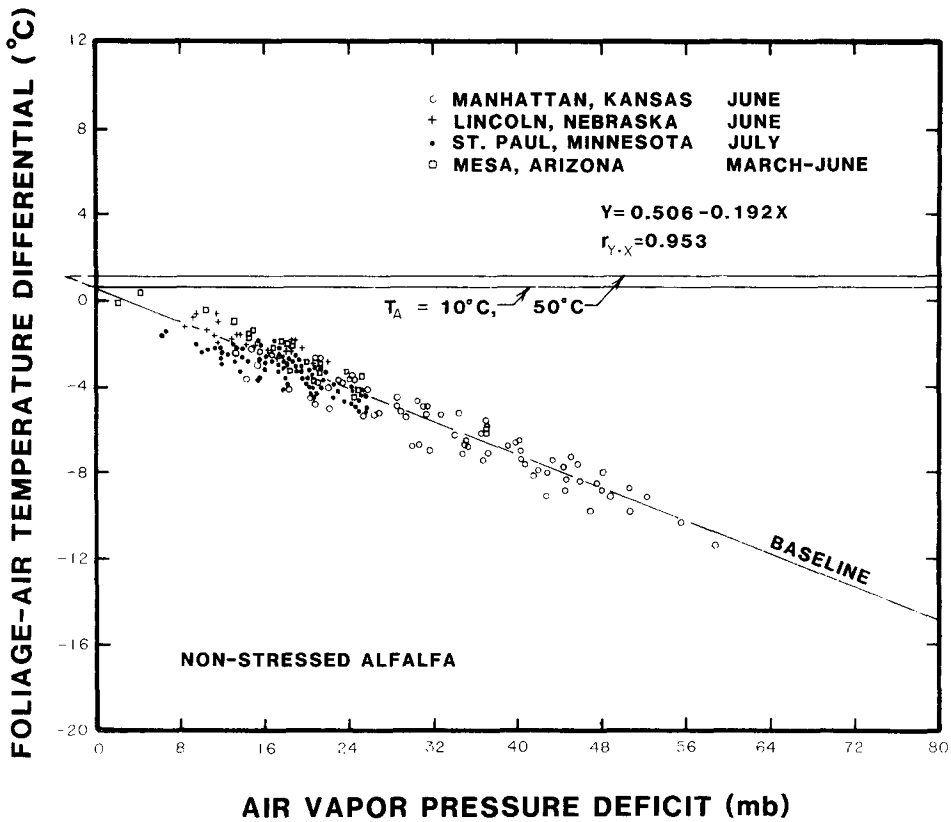

Fig. 2. Foliage—air temperature differential vs. air vapor pressure deficit for well-watered alfalfa grown at a variety of specified sites and dates during 1980.

skies and some thin cirrus conditions. For other types of cloudiness, the relationships begin to fall apart, presumably due to changing illumination effects on stomates.

Since data from all of the different locations for well-watered alfalfa and soybeans define a single relationship for each crop, we will now utilize that fact to derive a procedure for normalizing the stress-degree-day parameter for environmental variability, which is essentially completely specified by the air *VPD*.

We begin by noting that if a particular $T_F - T_A$, *VPD* data point falls on a non-water-stressed baseline, a state of potential evaporation exists, which we equate with a condition of negligible plant water stress. However, as soil water is depleted from the root zone, or as the evaporative demand of the atmosphere increases, a point will occur where the crop can no longer transpire at the potential rate. Foliage temperatures will thereafter increase; and subsequent $T_F - T_A$, *VPD* data points will be located somewhere above the non-water-stressed baseline. Thus, the first question we ask ourselves is,

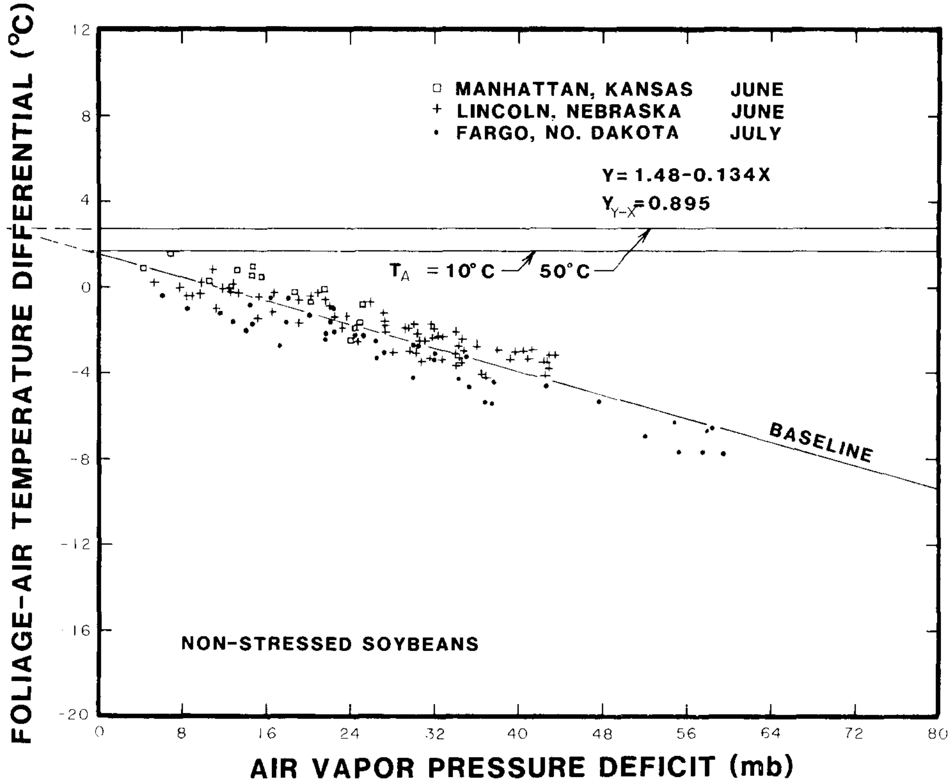

Fig. 3. Foliage—air temperature differential vs. air vapor pressure deficit for well-watered soybeans grown at the specified sites and dates.

"How far above the non-water-stressed baseline can a $T_F - T_A$, *VPD* data point rise in the limit that obtains when transpiration goes completely to zero?"

To answer this question, we begin by noting that as the air *VPD* decreases, the evaporative demand of the atmosphere decreases and transpiration rates consequently decrease too. Thus, as the *VPD* of the air decreases, the $T_F - T_A$ value for a potentially evaporating crop rises at a rate defined by the slope of the non-water-stressed baseline. At the ultimate *VPD* limit of zero, when the atmosphere is in a state of saturation, we might thus expect transpiration to cease, and take the value of the intercept of the non-water-stressed baseline and the ordinate as the upper limit to which $T_F - T_A$ would rise in the absence of transpiration. However, this conclusion will only be true if the intercept is zero. If it is positive, as we have found for all crops investigated to date, there will still be a positive vapor pressure gradient between the foliage and the air, and evaporation will not be completely suppressed.

In order to overcome this final vapor pressure gradient and reduce it to zero, we can imagine the creation of a super-saturated atmosphere of negative *VPD* and extend the crop's non-water-stressed baseline into this negative *VPD* region. We next calculate the vapor pressure difference that exists between foliage and air for the empirically observed temperature difference that exists at $VPD = 0$, travel that distance back along the graph's abscissa into the negative *VPD* region, and then go up to find the point of intersection with the extension of the non-water-stressed baseline. We take the $T_F - T_A$ value at that point to be the maximum value that can be obtained in the absence of transpiration.

At such a point of no transpiration, however, $T_F - T_A$ will obviously be specified by radiant and convective energy exchanges. Thus, as these factors may vary in both random and systematic ways, we cannot expect a limit defined as above to be always instantaneously correct. Such a limit is only an approximation of what can be expected in the mean. Nevertheless, such a limit does provide an adequate basis for defining a crop water stress index where we are primarily concerned with detecting deviations from a non-water-stressed baseline, where the effects of the radiant and convective energy environments are overpowered by those of the vapor pressure gradient.

Consider next the value of the vapor pressure gradient between foliage and air at $VPD = 0$. It is a strong function of temperature, and for greatest accuracy should be evaluated at the particular value of T_A pertaining to the data point in question. On Fig. 1, we have plotted the different upper limits that result for T_A values of 10, 20, 30, 40, and 50°C, which for a $T_F - T_A$ value of 2°C at zero *VPD* yield foliage—air vapor pressure gradients of 1.7, 3.0, 5.1, 8.2, and 12.8 mb, respectively; and in Figs. 2 and 3 we have done this for the extremes of $T_A = 10$°C and 50°C.

Within this framework, then, a crop water stress index may be readily defined. Suppose at a time when the air *VPD* is 40 mb, the value of $T_F - T_A$ is −1°C, so that the point Z on Fig. 1 represents the status of the crop, which in this case is squash. Now, if the crop had been sufficiently supplied with water to evaporate at the potential rate, $T_F - T_A$ would have been −5.5°C, as obtained from intersecting the non-water-stressed baseline at $VPD = 40$ mb. Conversely, if the crop had not been transpiring at all, and T_A was 30°C, let us say, then $T_F - T_A$ would be expected to have been about 3°C, in the mean. With this information we define the crop water stress index to be the ratio of the vertical distance above the non-water-stressed baseline that the point Z has conceptually traveled in falling below the potential evaporation rate to the total possible distance that it could conceptually travel, which in this example is −1°C − (−5.5°C) divided by 3°C − (−5.5°C) or 4.5°C/8.5°C = 0.53. Thus, we see that as the ratio of actual to potential evaporation goes from 1 to 0, the crop water stress index goes from 0 to 1.

To give some examples of what actual field data look like in this format, we have presented in Figs. 4 and 5 some raw temperature results for stressed soybeans and alfalfa at Fargo, North Dakota; and in Fig. 6 we have converted

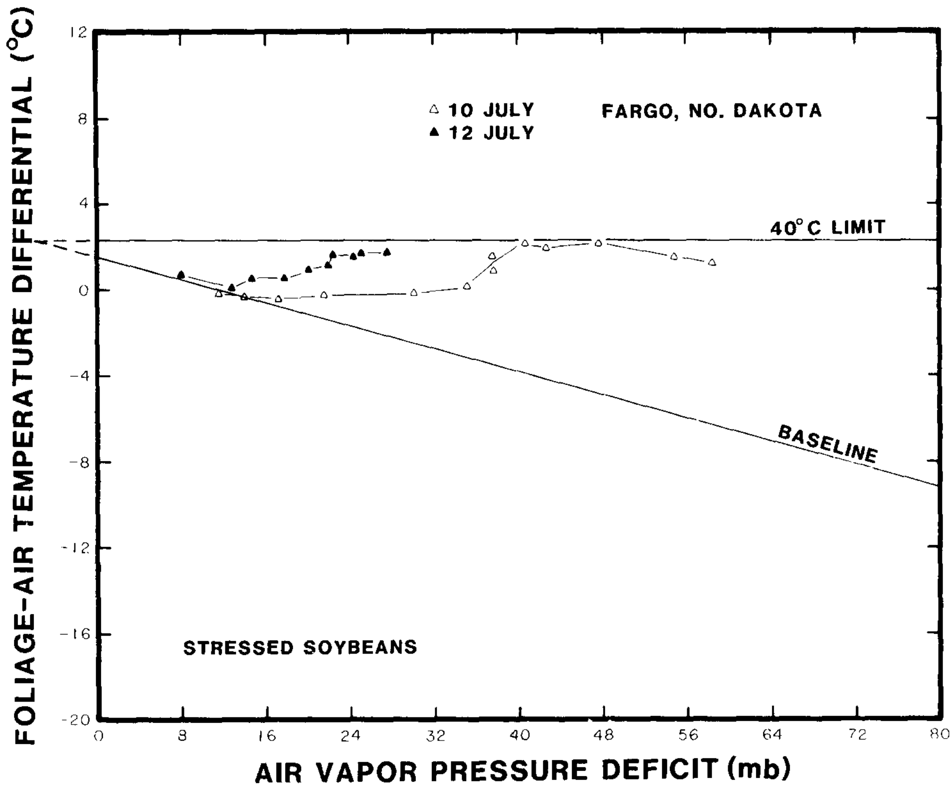

Fig. 4. Foliage—air temperature differential vs. air vapor pressure deficit for severely stressed soybeans growing at Fargo, North Dakota.

these data into the format of the crop water stress index. The soybeans, in this instance, were still fairly young, and covered only about 10% of the ground. Thus, with their rather limited rooting volume, they experienced a dramatic rate of stress development, as this hot and dry day progressed (maximum air temperature was 39°C and minimum relative humidity 17%). The alfalfa, on the other hand, with its well-developed root system, showed a much greater buffering capacity to stress development, although it too showed a significant increase in stress in the afternoon. Maximum stress for both crops occurred about one to two hours after solar noon, indicating that this is a good time for once-a-day measurements, as used by Jackson et al. (1981) to quantify the stress history of several differently irrigated wheat plots.

CONCLUSIONS

Throughout the greater part of the day — from about two to three hours after sunrise to two to three hours before sunset — plots of $T_F - T_A$ vs.

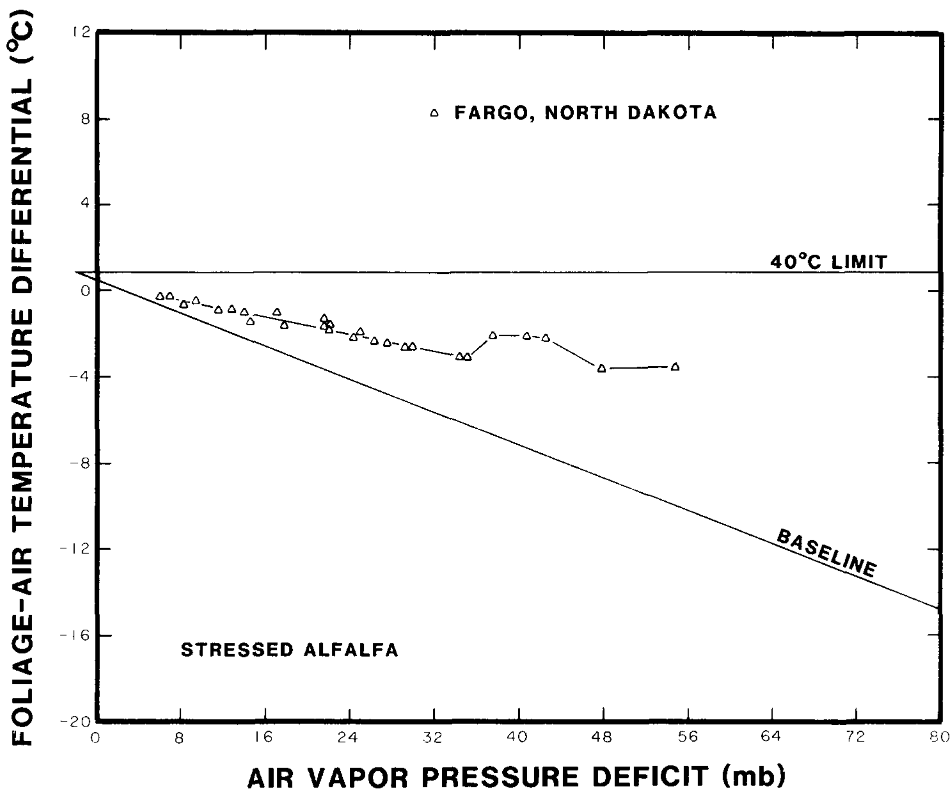

Fig. 5. Foliage—air temperature differential vs. air vapor pressure deficit for significantly stressed alfalfa growing at Fargo, North Dakota.

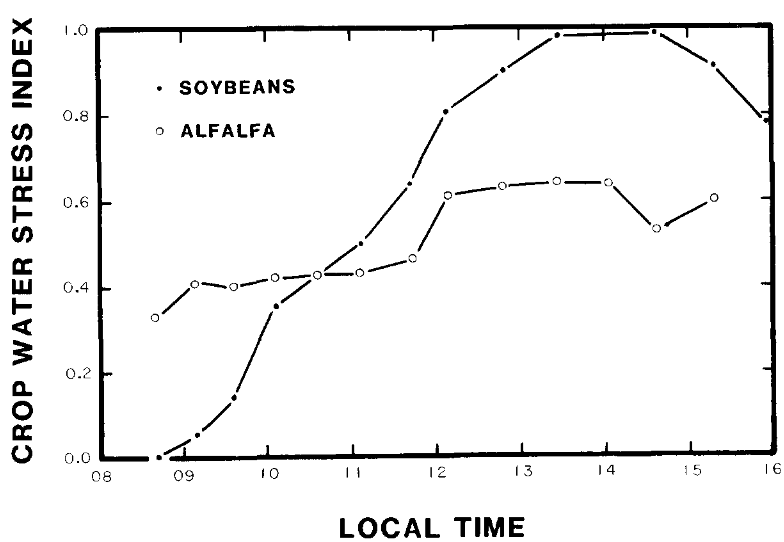

Fig. 6. The crop water stress index as a function of time for severely stressed soybeans and significantly stressed alfalfa at Fargo, North Dakota.

VPD for well-watered squash, alfalfa, and soybeans yielded unique linear relationships under all climatic conditions investigated, so long as the crops did not experience significant shading due to clouds. We postulate that the existence of such linear relationships provides a simple criterion for identification of a potential evaporation state, i.e., that potential evaporation may be said to prevail when $T_F - T_A$, *VPD* data points fall within the error bounds associated with these linear relationships. These findings also provide a ready means for normalizing the stress-degree-day parameter for environmental variability, by converting it into the crop water stress index described herein. It is evident from the data presented, however, that defining stress in this fashion limits our ability to confidently quantify it under conditions of low *VPD*, where the entire range of $T_F - T_A$ variability approaches the degree of scatter inherent in the data.

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