MEASURING WATER STRESS ON ALFALFA AND OTHER CROPS WITH INFRARED THERMOMETRY

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Introduction

Irrigation management requires that some method identify when the crop is under stress due to lack of water and that the method be able to detect stress before the crop is damaged due to water stress. It is this last criterion that is often the most difficult to implement; an advance warning that determines when and how much water should be applied to a unit of land. Crop stress can be identified by numerous methods which include: a soil moisture budget, actual/potential evapotranspiration, stomatal resistance, leaf water potential, leaf color or leaf temperature. One of the distinct advantages of techniques which do not involve a direct measure is that large areas can be surveyed quickly and the results obtained without delay or elaborate processing schemes.

Remote sensing involves the measure of a surface parameter without direct physical contact. The parameters of a surface that can be measured include reflected solar radiation and emitted longwave radiation. All leaves act as spectral filters and absorb the visible wavelengths and reflect the near-infrared wavelengths. This difference allows for the detection of green leaves as compared to bare soil because the bare soil exhibits little difference in reflectance patterns between the visible and near-infrared wavelengths. In fact, the amount of biomass may be estimated with the ratio of near-infrared to visible reflectance; however, one cannot rely on an approach of detecting a change in biomass as providing an early warning of water stress.

Emitted longwave radiation is a function of the surface temperature of an object; for a canopy this would be the temperature of the leaves and stems of a crop. For a crop surface the surface temperature is related to the availability of water for transpiration. It is this approach that has been under investigation in a joint project between the University of California-Davis and the U.S. Water Conservation Laboratory at Phoenix, Arizona and has focused on a number of crops including alfalfa. The objective of these experiments has been to develop procedures where thermal infrared radiation can be used for early stress detection and incorporate these measurements into irrigation management schemes.

Rationale Behind Thermal Infrared Measurements

All objects which have a temperature above absolute zero emit energy and the energy emitted is proportional to the fourth power of the temperature. Therefore, the warmer a body the more energy emitted and it is this energy which can be detected. Thermal infrared sensors are sensitive to wavebands which contain energy in either the 8-14 μm or 10.5-12.5 μm region and these regions of the atmosphere are least absorptive of these wavelengths. This process is the one by which radiation cooling occurs at night and allows for radiation frost to occur. The units which have been developed to measure thermal infrared radiation are called infrared thermometers because the readout or display is given in terms of temperature rather than energy units. The price of these units ranges from $1,000 to $12,000 with a number of units which are applicable to agriculture in the $1,500-$3,000 category. The advantage of these units is that one does not have to have contact with the surface in order to obtain its temperature and that a large number of readings can be obtained very quickly. It is these advantages which makes an infrared thermometer an attractive device to determine the water status of a crop.

The theory behind the use of an infrared thermometer to obtain a measure of water stress involves an examination of the energy balance of a crop. One can describe the energy available and the utilization of that energy as follows:

$$R_N = H + LE + G + P \qquad (1)$$

where

- R_N net radiation = $(1-\rho)\ S_t + Ld - \varepsilon\sigma T_c^4$ and ρ = albedo of the crop, S_t the solar radiation, Ld the longwave radiation from the sky and $\varepsilon\sigma T_c^4$ the longwave radiation emitted by the surface. T_c represents the canopy temperature.

- H sensible heat flux, energy used to heat the air.

- LE latent heat of vaporization, energy used in evaporation of water from the leaf.

- G soil heat flux, energy used to warm the soil

- P the energy stored as photosynthesis or growth of the crop

If one expands this equation one finds that the comparison of canopy and air temperature is an important term as shown in Eq. 2. In practice the soil heat flux (G) term is zero for a day and the photosynthetic term (P) is very small compared to H + LE so that only the H and LE terms are considered.

$$R_N = k_1 \frac{(T_c - T_a)}{r_a} + k_2 \frac{(R_s(T_c) - e_a}{r_s + r_a} \qquad (2)$$

In Eq. 2, k_1 and k_2 are constants, T_a is the air temperature above the crop, r_a the resistance to air movement of heat or water vapor, r_s the stomatal resistance, $e_s(T_c)$ the saturation vapor pressure of the canopy temperature and e_a the actual vapor pressure of the air.

For an actively growing, well-watered crop, the largest term will be LE, about 75-80% of the available energy, and the canopy will be cooler than air. Under conditions of high net radiation and low relative humidities an actively transpiring crop will be cooler than air and will become warmer than air as water becomes limiting to the root system. It is this relationship which has prompted the use of thermal infrared measurements for detection of crop stress and irrigation scheduling.

Development of the Stress-Degree-Day Concept

From Eq. 2., it is shown that a direct comparison of the canopy and air temperature can be related to crop stress. In fact, it was proposed that this comparison could be called the stress-degree-day since a crop under stress would be warmer than air. Thus, the stress-degree-day was calculated as

$$SDD = T_c - T_a \qquad (3)$$

All that was left was to determine the best time to acquire this measurement since it was obvious that an individual couldn't spend all day collecting data. Through several experiments of the diurnal course of canopy temperatures, it was found that the maximum canopy temperature occurred between 1330 and 1400 hours or 1:30 to 2:00 pm standard time. This then alleviated the need for several measurements during the day.

Initially the use of the stress-degree-day concept (SDD) was limited to yield comparison. It was found that the more stress a crop was subjected to during the reproductive stage the lower the yield. Idso et al. (1977) showed this to be true for wheat and postulated that there were many pathways that a crop could exhibit in the accumulation of stress and the final yield. Results from their 1976-77 experiments on wheat are given in Fig. 1. Later, Walker and Hatfield (1979) showed that the concept would work for multiple planting dates of kidney beans (Fig. 2) and showed that the accumulation of stress was related to the total water use by the crop (Fig. 3). In Fig. 1, the various lines represent the daily accumulation of stress and the upturns or downturns are related to various irrigation treatments. These initial results suggested that it would be possible to determine the water use by a crop utilizing the stress-degree-day approach and when an irrigation would be necessary to insure maximum yield yet achieve the highest water use efficiency. It was found that the daily evapotranspiration was related to the SDD and that when the maximum ET occurred the crop was at its coolest and as the crop warmed the daily ET declined. This relationship is shown in Fig. 4 for wheat, and alfalfa behaves similarly although seasonal experiments have not been conducted yet at Davis. Over numerous experiments it has been found that evapotranspiration is related in the manner as shown in Fig. 4; however, there is a difference in the slope of the relationship, i.e., each crop has a different evapotranspiration rate and a different $T_c - T_a$ difference relative to water deficit.

In experiments originally conducted on wheat, it was found that 10 SDDs were accumulated on an Avondale loam at Phoenix (Jackson et al., 1977). However, on the Yolo silt loam at Davis 15 SDDs were accumulated when 65% of the available water was extracted from the upper meter of soil. This difference is related to the soil moisture holding capacity of the soil and suggests that for the various soil types there would be a different SDD threshold dependent on the soil type. This aspect needs to be addressed before the SDD concept can be implemented on a large variety of soil conditions.

On studies in which the daily values of $T_c - T_a$ were measured, it has been found that there is a large amount of variability from day-to-day. For a person trying to implement this variability it would cause concern about the validity of the stress-degree-day approach. An example of the daily variation in $T_c - T_a$ for two differing treatments in grain sorghum is given in Fig. 5. The daily vairation can be explained by a number of factors but the primary reason is the vapor pressure deficit, and even from a casual analysis this could be expected from Eq. 2. In fact, in trying to quantify the differences between locations in the SDD behavior, the vapor pressure deficit has been found to be a useful parameter. The relationship between $T_c - T_a$ and the vapor pressure deficit has been found to behave in a very unique way. This behavior for alfalfa is shown in Fig. 6. Two distinct features are evident from the data presented in Fig. 2; there is an upper baseline above which the canopy will not become warmer than air and is constant over the range of vapor pressure deficits, and a linear line which allows the canopy to become cooler than air as the vapor pressure deficit increases. These data were collected at a variety of locations ranging from Phoenix, Arizona to St. Paul, Minnesota (Idso et al., 1980a). The physical interpretation of the two lines is that the upper line relates to a dry crop that is no longer transpiring while the lower line represents a crop which is transpiring at the maximum rate. In practice, the actual values for a crop on any given day lie between the two lines. Because of this behavior, we have proposed a Crop Water Stress Index which is derived as the ratio of the distance from the lower baseline to the actual $T_c - T_a$ value for the day to the total distance between the two lines of the given vapor pressure deficit for the day. For example, if a crop were well-watered and transpiring at the maximum rate, the ratio would be zero, and if it was warmer than the ambient air temperature then close to one. These relationships need further evaluation and comparison to other methods for quantifying stress to determine their practicality for assessing crop stress.

In recent studies we have related the Crop Water Stress Index to leaf water potential in alfalfa and have found that the values of the stress index we originally proposed correlate very well with the leaf water potentials observed during midday (Idso et al., 1980b). These recent developments lead us to believe that it would be possible to schedule irrigations with infrared thermometry and a measure of the vapor pressure deficit

Implementation of Infrared Thermometry in Irrigation Scheduling

One of the advantages of infrared thermometry is that one can make a large number of measurements within a field very quickly and that the measurements could be made from the cab of a pickup. Caution should be taken when the crop is small to avoid "seeing" a large amount of soil background with the infrared thermometer. I have found that an angular measure of canopy temperature is less affected by soil background than a vertical measurement (Hatfield, 1979). In small plots where measurements are made each day, it takes about 10 minutes to complete 20 sets of measurements, and in a large field study where detailed measurements were made in 10 fields, it required 20-30 minutes to complete the transect from start to finish. With all of these measurements a more uniform sampling of the field was done because there was a tendency to sample a large number of points and, in fact, each reading takes less than five seconds to complete. The potential then exists for using handheld infrared thermometers for irrigation scheduling.

The obvious question that arises is that if this technique is so good, why isn't it being used in all of California? There are two parts to the answer; one, the technique is fairly new and some of the data and relationships given in this paper were developed and tested this last summer and two, there is a cost for the infrared thermometer which can range from $1,500-3,000. I would believe that it is the first answer which would hold back the implementation because the cost can be amoritized over several fields and crops, and would potentially pay for itself with increased water savings.

In the research there are a number of tems which have to be resolved These are

1) Is the crop water stress index independent of soi type or must separate relationships be developed for each soil?

2) What value of the crop water stress index should be obtained before rewatering?

3) Can the crop water stress index be molded into a crop like alfalfa where multiple growth periods are found and numerous field operations must be accommodated? It is possible to develop the crop water stress index to the point where the irrigation practice would leave sufficient stored water for regrowth and alleviate some potential weed problems.

4) How many readings in a field will be necessary to obtain a proper value of the stress index?

All of these are important questions which we are trying to solve as quickly as possible. Questions 1 and 2 we hope to have some partial answers for alfalfa by this winter. The answer to 3 lies in implementing this type of schedule around a farmer's operation and possibly through some trial and error. For number 4, I believe we are close to providing a realistic value for the number of readings and this will be solved before we start any implementation programs.

Conclusions

Infrared thermometry can provide a useful measure of crop stress, a measure that is easily obtained over many locations on a field. The use of such a technique is tied directly to the water status of a crop and is a direct measure of the crop water status. Through continued research we will determine how this concept can be used to evaluate crop water needs and schedule irrigations. Imagine being able to drive by a field and point an instrument at the crop which determines when and how much to irrigate. With the continued use of technology we will increase our water use efficiency and maintain a high quality product in alfalfa.

Literature Cited

Hatfield, J. L. 1979. Canopy temperatures: The usefulness and reliability of remote measurements. Agron. J. 71:889-892.

Idso, S. B., R. D. Jackson and R J Reginato, 1977 Remote sensing of crop yields. Science 196:19-25.

Idso, S. B., R. D. Jackson, P. J. Pinter, Jr., R. J. Reginato and J. L. Hatfield. 1980a Normalizing the stress-degree-day parameter for environmental variability. (Submitted to Agric. Meteorol.)

Idso, S. B., R. J. Reginato, D. C. Reicosky and J. L. Hatfield. 1980b. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. (Submitted to Agron. J.)

Jackson, R. D., R. J. Reginato and S. B. Idso. 1977. Wheat canopy temperatures: a practical tool for evaluating water requirements Water Resources Res. 13:651-656

Walker, G. K. and J. L. Hatfield. 1979. Test of the stress-degree-day concept using multiple planting dates of red kidney beans. Agron. J. 71:967-971.

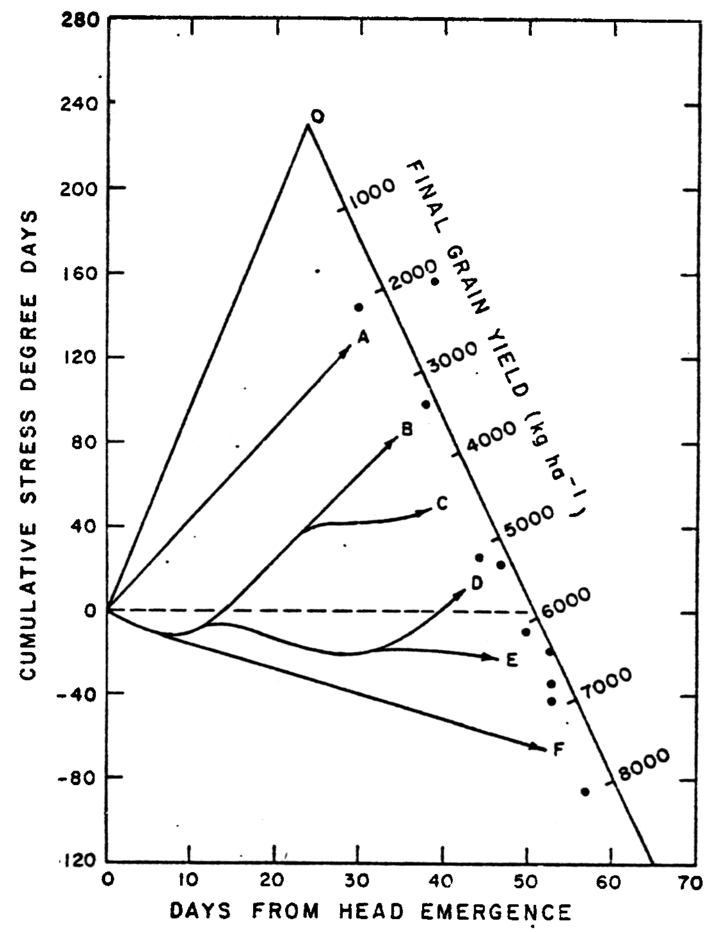

Figure 1. Accumulation of stress-degree-days from heading to maturity as related to yield of Produra wheat (Idso et al., 1977).

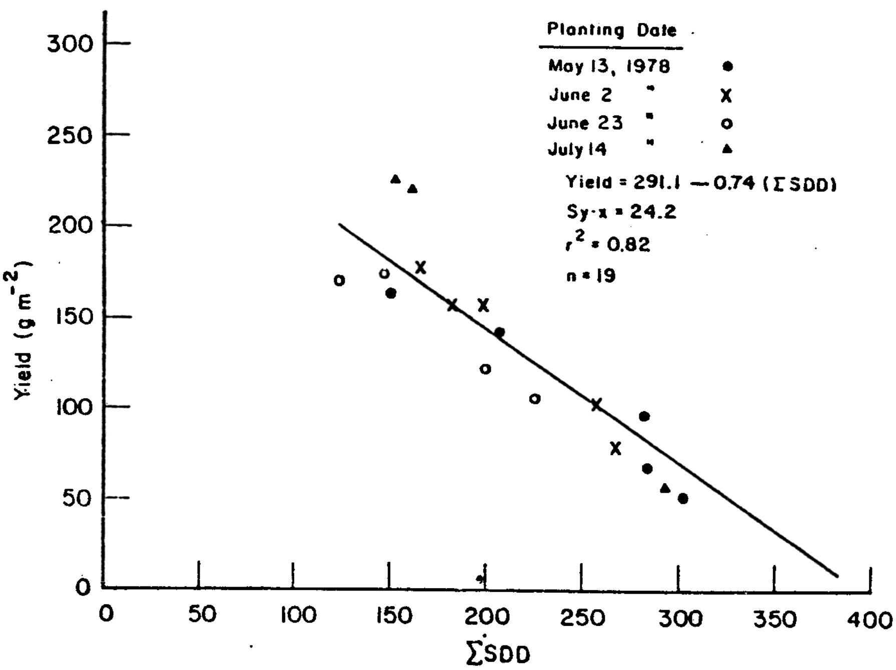

Figure 2. Yield of red kidney beans as a function of the summation of stress-degree-days from flowering to maturity (Walker and Hatfield, 1979).

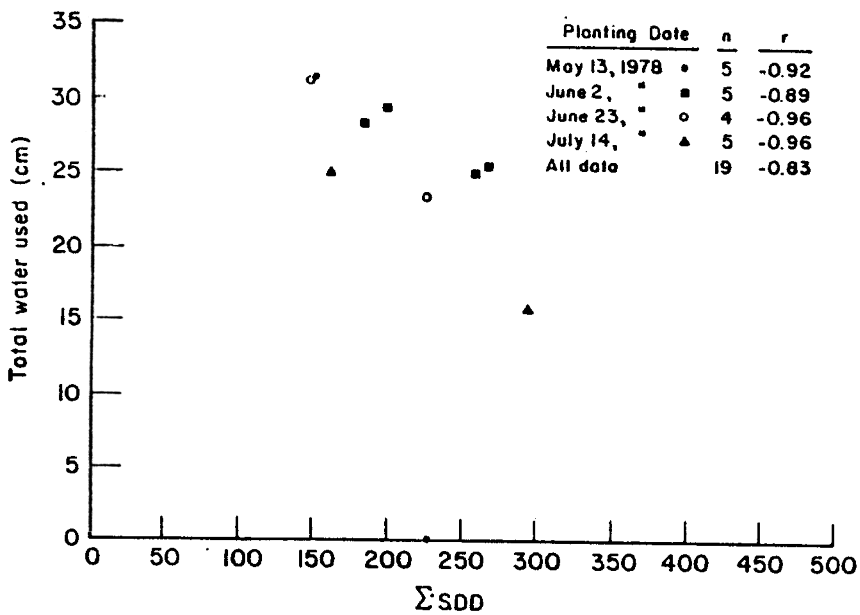

Figure 3. Relationship of seasonal water use to the summation of stress-degree-days from flowering to maturity (Walker and Hatfield, 1979).

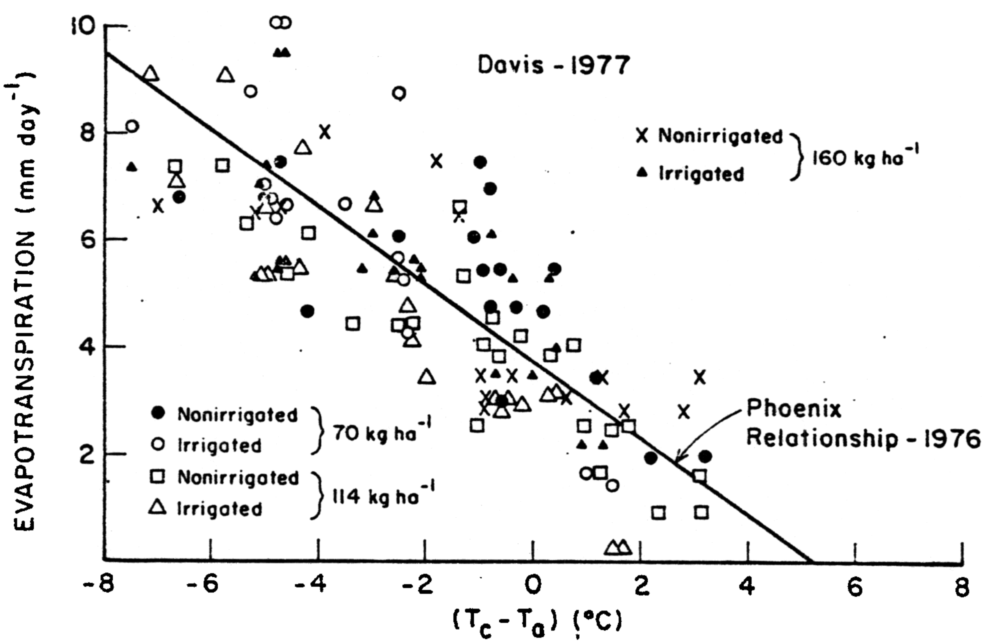

Figure 4. Evapotranspiration from Produra wheat as related to daily stress-degree-days in 1977-78.

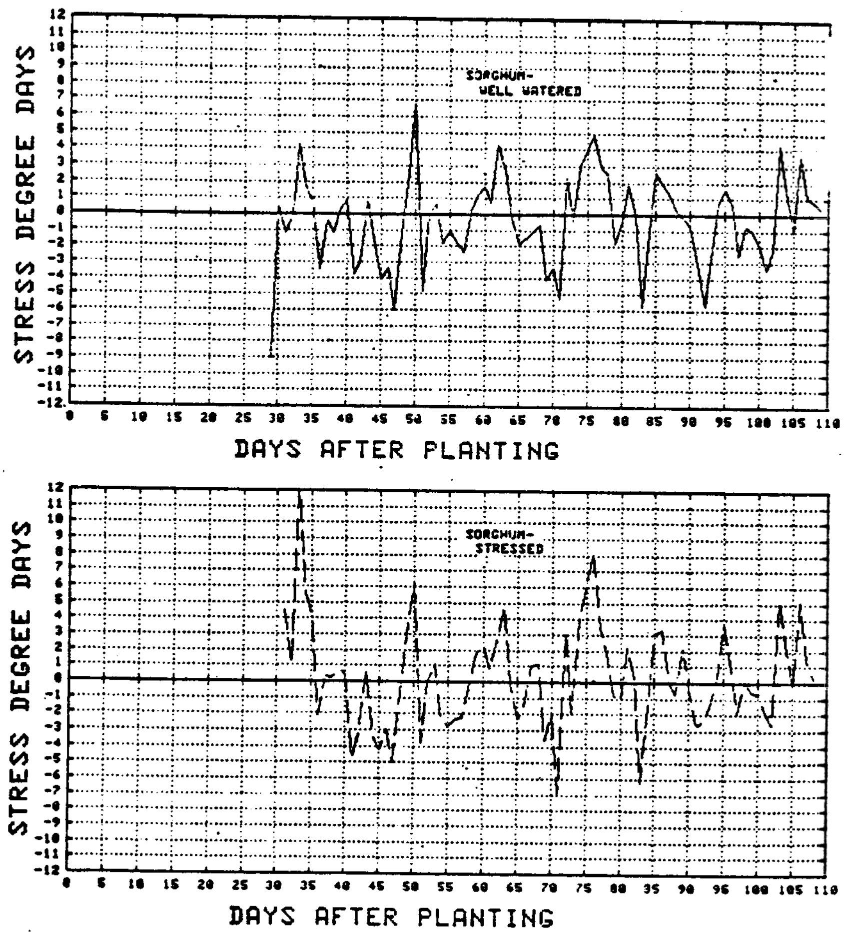

Figure 5. Daily variations of the stress-degree-day values measured in well-watered and stressed grain sorghum plots.

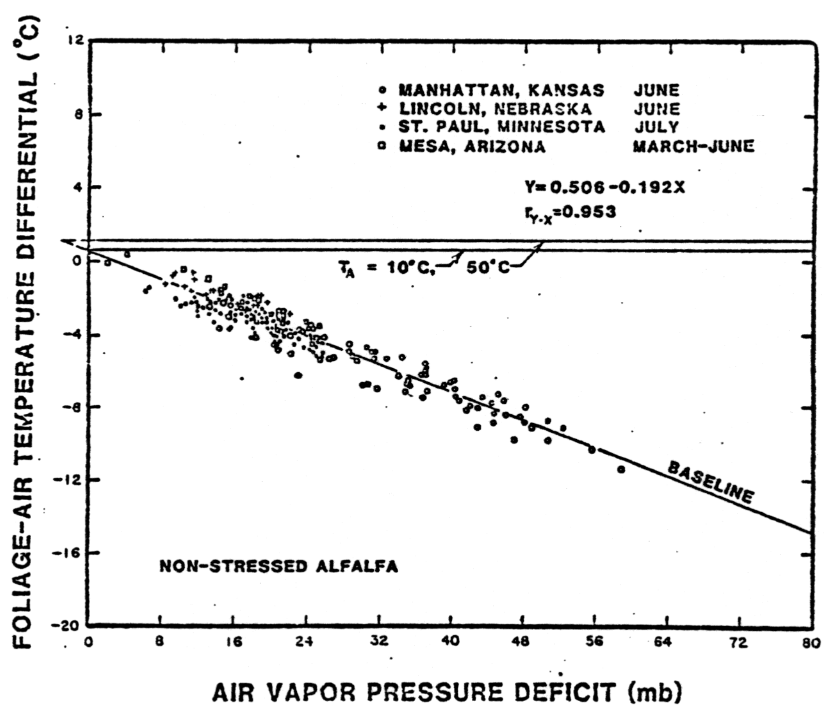

Figure 6. Foliage-air temperature differential vs. vapor pressure deficit for well-watered alfalfa at a variety of locations and dates in 1980.