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The Utilization of Thermal Infrared Radiation Measurements from Grain Sorghum Crops as a Method of Assessing Their Irrigation Requirements *

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Summary. Field studies on irrigated grain sorghum (*Sorghum bicolor* L. Moench) crops were conducted in California for three years to evaluate the use of thermal infrared measurements to estimate water use and detect crop stress. These studies were conducted on a Yolo loam soil with different rooting volumes to limit the water availability. Data show that the stress-degree-day index (midday comparison of canopy-air temperature differences) provides a valid indicator of crop stress, and that the canopy-air temperature difference increases rapidly above zero when more than 65% of the available water is depleted. The canopy-air temperature difference is also related to leaf-water potential, with an increase above zero when the potential decreases below −1.1 MPa (=11 bars). Improvement of the performance of the stress-degree-day index through compensation for environmental variability was achieved by including measurements of the plant water stress which are related to available water extracted. It is concluded that remote sensing of emitted thermal radiation offers a promising technique which can be incorporated into irrigation management programs.

Irrigation scheduling requires some method of assessing the water availability to the crop with sufficient lead time to provide for a water application. If the method used does not provide sufficient warning, the crop yields will be reduced because of lack of water, while the other extreme could result in too much water applied and a waste of water and energy. Methods currently used are soil moisture measurements, plant measurements, and evapotranspiration models. The role of remote sensing into these various approaches has been investigated by a number of groups (Jackson et al. 1977; Jackson et al. 1980; Clawson and Blad 1982; Hatfield et al. 1980; Geiser et al. 1981).

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Remote sensing of a plant canopy includes both reflected and emitted radiation. Kanemasu et al. (1977) showed how an evapotranspiration model could be developed with a leaf-area index (LAI) obtained from Landsat data. Jackson et al. (1977) proposed that a stress-degree-day (SDD), a comparison of midday canopy and air temperatures, could be used to estimate water requirements in wheat. Ehrler et al. (1978) also found that leaf-wate potential was related to a comparison of canopy temperature, T_c, and air temperature, T_a. These data for wheat suggested that remote sensing inputs could be effectively utilized for evaluating crop stress and possibly irrigation scheduling.

Walker and Hatfield (1979) found that total water use during the reproductive stage of kidney beans could be related to the summation of stress-degree-day (SDD) in this growth period. Hatfield et al. (1980) suggested that 10–15 positive SDD's would be accumulated when 65% of the available water was extracted from the available rooting zone. In their data, they found that there was considerable daily variation in the stress-degree-day index due to meteorological changes. Idso et al. (1981 a) suggested that the canopy and air temperature differences ($T_c - T_a$) were a linear function of the vapor pressure deficit (VPD) when the crop was transpiring at potential rate and that this could be used to correct the plant water stress index by accounting for environmental variability. This linear relationship between ($T_c - T_a$) and VPD formed the well-watered baseline while at minimum or no evapotranspiration the canopy was warmer than air and was unaffected by the vapor pressure deficit. The plant water stress index was then calculated as a ratio of the distance between the well-watered and non-transpiring baseline equations relative to the distance from the well-watered baseline to the actual $T_c - T_a$ value for that day. A crop near potential would have an index value of 0 while a non-transpiring crop would have an index value of 1.0. When a crop was transpiring at less than potential, then the T_c–T_a value would be displayed to the right of the well-watered baseline and this would signal that the crop was under stress. However, Idso et al. (1981) and Gardner et al. (1981 a), both showed that a crop could be under stress yet have a negative T_c–T_a value. Jackson et al. (1981) combined net radiation with the canopy, wet- and dry-bulb temperatures to develop an energy balance approach termed the crop-water stress index. This crop-water stress index closely paralleled the removal of water from root zone. Jackson (1982) in evaluating the crop water stress index, stated that once-a-day measurements of crop stress may not be sufficient to quantify the stress level. Deviations could be caused by growth stage or crop senescence, recovery after an irrigation, and rooting depths. He suggested that a number of measurements during the day may be necessary to overcome these problems.

Canopy temperatures would appear to offer a valuable tool for inclusion in methods to assess crop water requirements or crop stress. This paper reports the findings from a study conducted on grain sorghum to evaluate the utility of thermal infrared inputs in evaluating irrigation requirements.

Materials and Methods

Studies were conducted on a Yolo loam soil at Davis, California, on grain sorghum (*Sorghum biocolor* L. Moench) to evaluate the relationship between water use, plant stress indicators, and canopy temperatures. These studies were conducted in 1978, 1979, and 1980 on Dekalb A28+ grain sorghum planted in 75-cm rows at a population of 130,000 plants per hectare. Differential irrigations, both in time and amount, were imposed at different stages of growth.

Beginning in 1979, a controlled rooting depth experimental site was developed which limited the rooting depth to 50, 100, and 150 cm, as compared to the natural profile of 300 cm. These plots were 5 m × 20 m in size. The plot was constructed by excavating the soil from the pit to the desired depth, laying in a solid sheet of 10-mil plastic at the bottom, and then refilling the pit with the original soil. The plastic barrier did not extend up the sides of the excavated area. The Yolo loam soil does not have any profile characteristics to the 150-cm depth, so the mixing of this upper soil layer did not impose any unnatural conditions. In 1979 and 1980, the differential irrigations were imposed at each rooting depth, including a natural profile of 300 cm. Measurements in each plot included soil moisture as measured by a neutron probe, canopy temperatures measured with an infrared thermometer, plant water status measurements with a pressure bomb or diffusion porometer. Neutron soil moisture measurements were made twice weekly with a Troxler depth gauge[1] with a 100 mCi A^{137} Br source at one access tube in each rooting depth treatment and four tubes in the field plots. Canopy temperatures were measured daily between 1330–1400 PST with a Barnes-PRT-5[1] infrared thermometer or a Telatemp AG-42[1]. Canopy temperatures were recorded as the mean at eight readings in each controlled rooting depth plot and 32 readings in each field plot. These data were acquired by viewing the canopy at an angle of 30° from the horizontal one meter above the canopy.

Physiological measurements were made between 1300–1400 PST on selected days and in selected treatments. Leaf water potential was measured on the upper leaves with a pressure bomb in 1978 and 1980, and in 1979, measurements were made with a thermocouple psychrometer to evaluate both the osmotic and turgor components. Diffusion resistance was measured on the upper fully-expanded leaf using a LI-COR diffusion resistance meter[1]. Net photosynthesis was measured with a leaf chamber in which the CO_2 concentration was sampled sprior to and after being shut over a leaf for 20 s. These measurements were used to characterize the canopy temperature response and were not continuous throughout the season.

Ancillary plant measurements of height, leaf area, dry weight and phenological stage were made throughout the growing season. Additional meteorological variables included dry- and wet-bulb temperatures at the time of the canopy temperature measurement. These were measured at a height 1 meter above the canopy surface.

Results and Discussion

Thermal Infrared Stress Measurements

Water use or evapotranspiration in grain sorghum was negatively related to the accumulated stress-degree-days over the reproduction portion of the growing season as shown in Fig. 1. Only the reproductive stage is shown because in the early season the "warm" soil background influences the canopy temperature reading and this contamination of the readings precludes a useful comparison of treatment differences in the early stages of growth. Fig. 1 shows that canopy-air temperature differences are indicative of the general water use by the sorghum crop; similar results were reported by Walker and Hatfield (1979) for kidney bean crops. Similar inverse relationships between stress degree days and water use were

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[1] Mention of a specific tradename or product does not imply indorsement or preferential treatment by the California Experiment Station

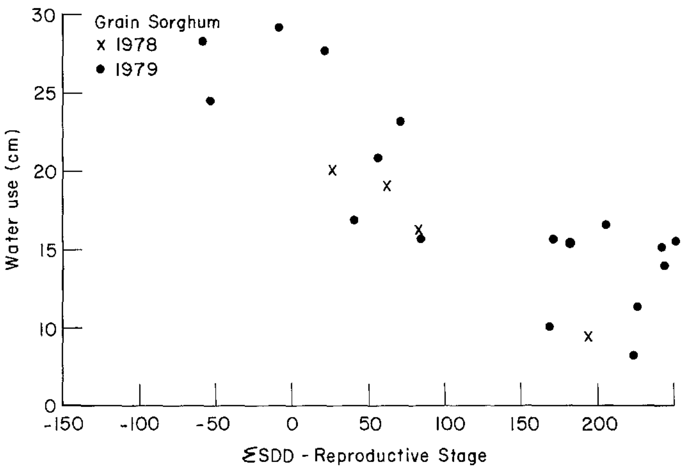

Fig. 1. Soil moisture use calculated from neutron soil moisture measurements and the summation of stress-degree-days derived from 1330 h canopy-air temperature differences for the reproduction stage of grain sorghum in 1978 and 1979, Davis, CA

reported for grain sorghum by Gardner et al. (1981 b), although they compared canopy temperatures with a well-watered reference plot.

It is encouraging that in this study the 1978 and 1979 data fit into the same population. Data for 1980 from these experiments are not available due to prolonged periods of instrumentation failure and an incomplete record.

Based on the relationship shown in Fig. 1 it is reasonable to expect that the stress-degree-day approach could provide inputs into methods of improving irrigation scheduling; however, for such applications it is necessary that the time period be expressed in days rather than a complete phenological stage as shown in Fig. 1.

In the Yolo loam soil with a natural rooting depth, a grain sorghum crop will grow roots deep into the profile to extract water in order to avoid stress. The controlled rooting volume thus allows for the evaluation of the stress-degree-day approach under a wider range of soil moisture conditions than would be possible in the natural rooting depth.

Data in Fig. 2 represent the 50 cm plot that was maintained without water until 69 days after planting and then was maintained in a well-watered condition until maturity. Also shown on this graph is the daily values of the stress-degree-day throughout the growing season (Fig. 2). Early in the growing season, until 30 days after planting, the daily stress-degree-days show elevated values due to the "warm" soil background relative to leaf temperature. However, this portion of the growing cycle does not use much water if soil evaporation is kept to a minimum. It is evident that as the soil moisture became limiting, the daily stress-degree-day values were generally positive (Fig. 2). When the crop was rewatered at 69 days after planting, the stress-degree-day values decreased below zero and the canopy was cooler than air. The response of the crop was almost immediate after rewatering occurred, generally within two to three days. On Fig. 2, the zero line for $T_c - T_a$ occurs at the extraction limit of 65% of the available water and when the water availability dropped below this point, leaf temperatures were generally elevated above air temperatures. Several features are evident in Fig. 2 which are illustrative of some problems with the stress-degree-day method. On 52 and 61 days after planting, the canopy temperatures were depressed below air, even though the soil moisture was almost depleted. An opposite effect of having the canopy warmer than air when the soil water was adequate indicates that some adjustments may be necessary to develop a reliable predictive tool.

Similar effects were noted for a 100 cm rooting depth that was irrigated during mid-season and then maintained without further irrigation until later stages of growth (Fig. 3). Again, as shown in Fig. 2, when 65% of the available water was extracted, the leaf temperatures became elevated above air temperatures. There was no indication of leaf-temperature rise in the early portion of the season which could be due to a period of warm days with high vapor pressure deficits at this time. Gardner et al. (1981 a) found that leaf temperatures could be cooler than air in corn when the plants were still experiencing yield-limiting stress. If the procedure suggested by Idso et al. (1981 a) compensates for environmental variability, then the T_c–T_a values during this period would be below those normally expected during this part of the season.

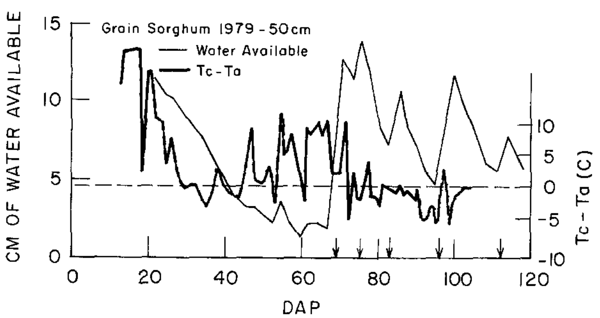

Fig. 2. Pattern of seasonal soil moisture use and canopy minus air temperature difference for grain sorghum grown in a 50 cm deep soil profile in 1979

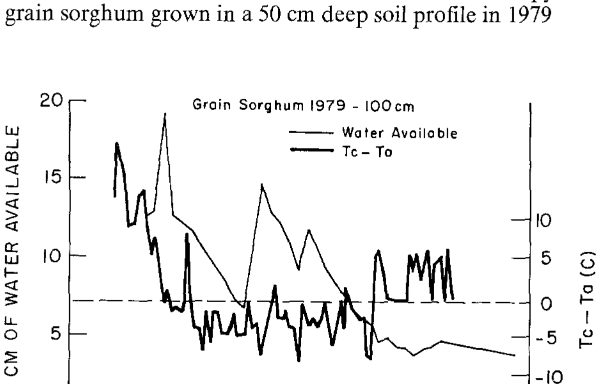

Fig. 3. Pattern of seasonal soil moisture use and canopy minus air temperature difference for grain sorghum grown in a 100 cm deep soil profile in 1979

All other plots for the 1979 and 1980 data exhibit these trends and, therefore, it is reasonable to expect that measurements of leaf temperature would be indicative of impending crop stress. From the data collected to date, the value of stress-degree-days that would be detected becomes positive after 65% of the available water has been extracted. However, the daily variation in the meteorological conditions limit the usefulness of this method. Once this level of depletion occurs, the daily values increase very quickly. The daily weather variation suggests that this aspect needs refinement as suggested by Idso et al. (1981a) and Jackson et al. (1981).

As a further evaluation of the stress-degree-day approach to quantify crop stress, the leaf-water potential and T_c–T_a data for 1978, 1979 and 1980 are given in Fig. 4. These data each represent the average of a minimum of four leaf samples only for selected days with plants subjected to no prior stress. The fit is good with the largest deviation at very negative leaf-water potentials where the problems in attaining a good water potential measurement are greatest. These data would suggest that in grain sorghum, as the leaf-water potential decreases below – 1.1 MPa (≡ 11.0 bars) the leaf becomes warmer than the air. Thus the canopy air temperature difference could be effectively used as a possible signal for critical leaf water potential. This aspect needs more study to fully evaluate the varietal differences and the effect of osmotic adjustment on leaf water potential and T_c–T_a relationships. Additional data on net photosynthesis and stomatal resistance for these same plots exhibit a similar relationship as leaf-water potential. Net photosynthesis decreased rapidly as leaf temperatures increased above air temperature and stomatal resistance began to increase rapidly. These two physiological parameters relative to T_c–T_a need much more additional research.

In 1981 experiments, with the same variety of grain sorghum grown in various irrigation treatments, the well-watered baseline (of 2.14–1.81 VPD) was derived and used to calculate the plant water stress index (PWSI) for each rooting depth throughout the 1979 growing season. The plant water stress index is calculated in

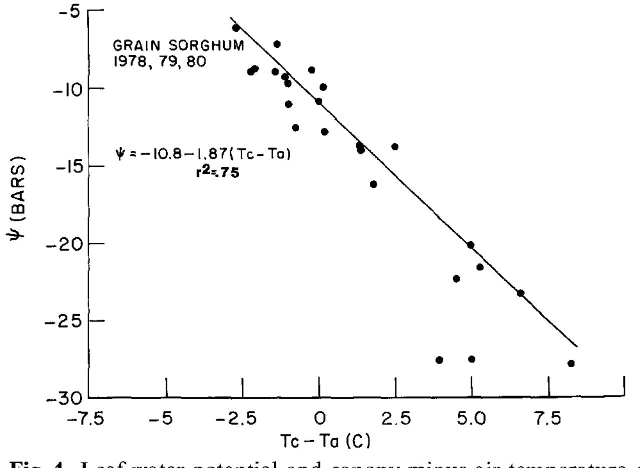

Fig. 4. Leaf water potential and canopy minus air temperature difference for upper leaves in a grain sorghum canopy for 1978, 1979 and 1980

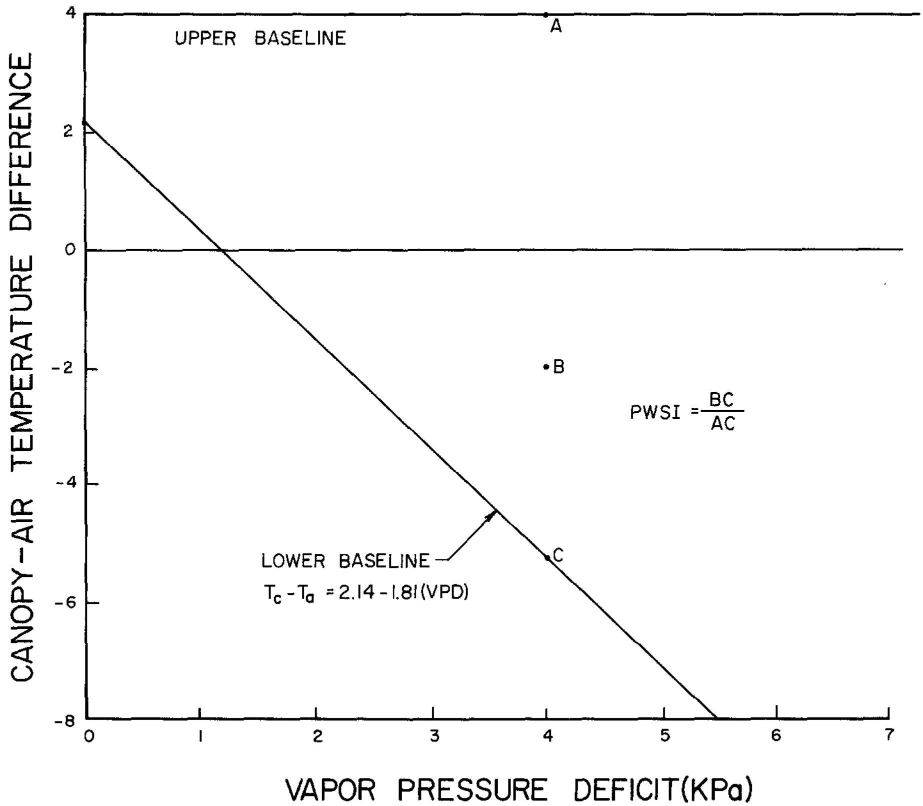

Fig. 5. Graph for calculation of plant water stress index (PWSI)

the manner described by Idso et al. (1981a) and for illustrative purposes, an example is given in Fig. 5. On a given day the PWSI is calculated by measuring the VPD and T_c–T_a (Point B) and then calculating the T_c–T_z for the lower baseline (Point C) and then extrapolating the lower baseline to set the canopy temperature at zero vapor pressure gradient (Point A). The PWSI would then be the ratio of the distances BC over AC (Fig. 5). At high vapor pressure deficits the canopy can be cooler than air and still under a large degree of stress. In alfalfa it was found at high VPD's the canopy was cooler than air and the calculated PWSI was 0.5 which was related to a decrease in leaf water potential from – 0.8 to – 1.5 MPa. Similar effects were noted in grain sorghum. Idso et al. (1981b) found good agreement between PWSI and leaf water potential and suggest that the PWSI may be a good technique for assessing soil water availability. Results for a 50-cm depth with frequent irrigations are given in Fig. 6 and show that the PWSI follow the extraction of water from the soil.

Similar results were found for each rooting depth and irrigation treatment. Examination of Fig. 6 shows that the PWSI and available soil water extracted followed each other closely throughout several drying cycles. Several features which were also found in the other rooting depths and irrigation treatments are evident in

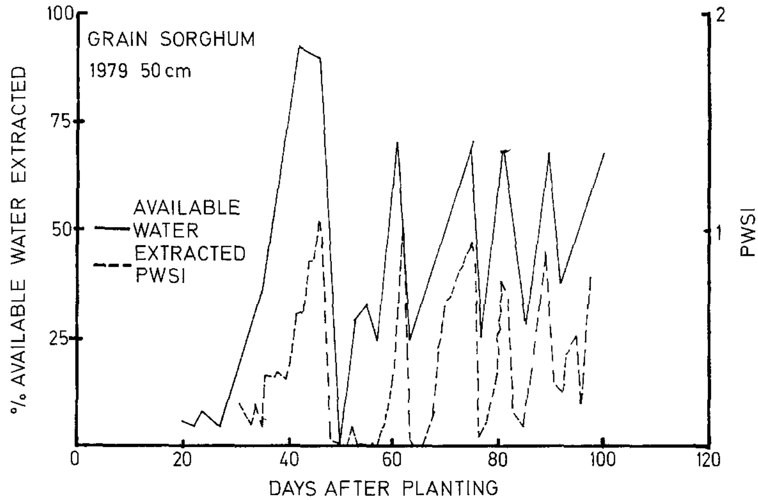

Fig. 6. Pattern of available water extracted and the plant water stress index for a 50 cm deep soil profile grain sorghum crop with frequent irrigations throughout the growing season

Fig. 6. The PWSI returned to zero following a large irrigation and remained near zero until some water had been extracted from the profile. The length of time that the PWSI remains at the zero level depends upon the amount of the irrigation, e.g., with the small irrigation amounts very frequently the PWSI did not decrease to zero but did exhibit a decline. This would be typical of light showers in a rainfed condition and shows the responsiveness of the PWSI to changes in the soil water content.

After examination of the various rooting depths, it appeared that there may not be a unique daily PWSI which indicated the available soil water remaining in the profile, although the curves between plots were very similar. A summation of PWSI

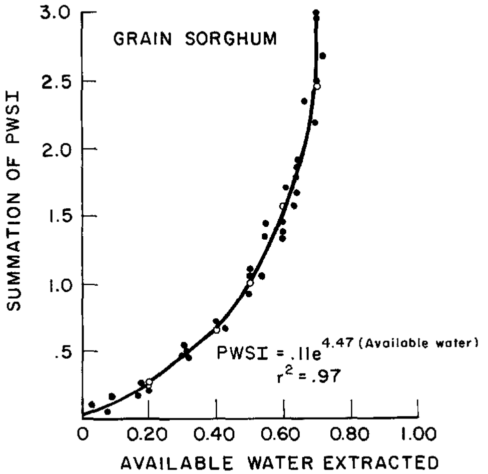

Fig. 7. Summation of the plant water stress index relative to available soil water extracted for grain sorghum

may be more useful since water extracted is a cumulative process from the point of recharge. The 1979 data for all of the different rooting depths is given in Fig. 7. The fit is extremely good for the range of data encountered in this study. A PWSI summation of 1.5 would indicate an extraction of 60% of the available water and if any other amount were chosen, then the PWSI value could be easily set. This relationship, when applied to the 1980 and 1981 growing seasons, performed very well, although the variety and the growing conditions were very similar. A curve of this type, if developed for other crops, could be of considerable value in predicting the soil moisture availability since the relationship falls along a given curve and could predict a given date of expected soil water depletion. This would require an estimation of canopy temperatures from meteorological forecasts and would need to be assessed before implementing an irrigation scheduling program.

Irrigation scheduling can be aided with a measurement of thermal infrared radiation.

The available soil-water and leaf-water potential data shown indicates that the stress-degree-day concept is a valid indicator of crop stress. Further refinements, such as those suggested by Idso et al. (1981 a) and Jackson et al. (1981), improve the capability of this technique. The change in the leaf-air temperature is very closely related to the availability of water, which suggests a critical soil-water content when stress becomes detrimental to crop growth. Jackson (1982), however, found that in using the crop water stress index he could not obtain a precise measurement of soil moisture solely from canopy temperature. He suggested that measurements of spectral reflectance may need to be combined with those of thermal infrared emission and that more than one measurement a day may be required. Further evaluations with experimental results combining both approaches will be needed to answer this question. From the data presented here for the sorghum crop, it would appear that the thermal infrared emission alone may be sufficient. However, the combination of both reflectance and emission may be necessary to extend this approach to other crops and to other environments.

Further studies will be needed to evaluate the technique for more crops and against other methods. Clawson and Blad (1982) showed that a comparison of canopy temperatures with those of a well-watered reference could be used to schedule irrigations and that although yield reductions occurred there was also a water saving. Similar results on grain sorghum were found at Davis without any yield reduction, but with a 10% decrease in water applied (Hatfield and Sully, unpublished data). Geiser et al. (1981) and Clawson and Blad (1982) found good results when scheduling irrigations with canopy temperatures and these data support their findings. Remote sensing inputs could be made easily and quickly over large areas allowing a more complete examination of entire fields or farms.

It is concluded that a plant water stress index based on canopy-air temperature differences and vapor pressure deficit provides a measure which is closely related to soil moisture availability. When the PWSI was summed over time the summation was related to soil water availability for a series of rooting depths and from this it appeared that the technique should be applicable for different seasons and rooting depths. The technique is quite simple and the data can be easily obtained for a variety of crops or fields on a given farm thus providing a method in which irrigation amounts could be easily and accurately assessed.

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