RELATIONSHIP BETWEEN FOLIAGE TEMPERATURE AND WATER STRESS IN POTATOES[1]

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Abstract

Field studies were conducted in southern Idaho to evaluate the possibility of using thermal infrared measurements of potato foliage to detect soil water deficits. Concurrent measurements of foliage-air temperature differences (T_f-T_a), leaf water potential (ψ_{leaf}) and vapor pressure deficit (VPD) were obtained from differentially-irrigated Russet Burbank and Kennebec potatoes during the 1982 and 1983 growing seasons. Foliage-air temperature differences for well-watered potatoes were linearly related to VPD. Differences in T_f-T_a values between stressed and well-watered potatoes were relatively small in the early morning when evaporative demand was low. However, severe soil water deficits caused afternoon T_f-T_a values to rise as much as 8.0 C above non-stressed levels under conditions of high VPD.

Foliage-air temperature differences and VPD data were used to construct a plant water stress index (PWSI) which reflected the rise in T_f-T_a above non-stressed levels at a given VPD. The PWSI was linearly related to depressions in ψ_{leaf} caused by moderate to severe soil water deficits. However, the PWSI did not increase significantly above non-stressed values unless the soil matric potential ψ_{soil} fell below -70 kPa (centibars). Since potatoes are normally irrigated before ψ_{soil} falls below -60 kPa, it appears that foliage temperature measurements cannot be used to effectively schedule irrigation for this crop.

Resumen

Se condujeron ensayos de campo en el sur de Idaho para evaluar la posibilidad de aplicar mediciones térmicas de infrarrojo al follaje de la papa con el propósito de detectar deficiencias de agua en el suelo. Durante las temporadas de cultivo en 1982 y 1983, se obtuvieron mediciones paralelas

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de la diferencia entre las temperaturas del follaje y del aire (T_f-T_a), del potencial de agua de la hoja (ψ hoja) y del déficit de la presión de vapor (VPD) de los cultivares Russet Burbank y Kennebec bajo riego diferenciado. Las diferencias entre las temperaturas del follaje y del aire en los cultivos de papa bien irrigados fueron linearmente correlacionadas con el VPD. Las diferencias en los valores de T_f-T_a entre los cultivos con estrés de agua y los cultivos bien irrigados fueron relativamente pequeñas en tempranas horas del día cuando la demanda evaporativa era baja. Sin embargo, las severas deficiencias de agua en el suelo en horas de la tarde, provocaron el incremento de los valores T_f-T_a hasta de 8.0°C por encima de los niveles de los cultivos sin estrés de agua bajo condiciones de alto déficit de presión de vapor (VPD).

Introduction

Compared to other crop species, potatoes are quite sensitive to water stress (9, 14). Soil water deficits during tuber initiation and bulking have been shown to cause substantial reductions in potato yield and quality (4). Even relatively short periods of water stress can significantly decrease the quantity of marketable tubers (10). As a result, considerable emphasis has been placed on developing sophisticated irrigation management techniques for potatoes, particularly in warm, dry areas.

Recently, a great deal of attention has been given to the use of thermal infrared measurements of crop foliage as a means of assessing crop water status (1, 2, 5, 6, 8, 12, 13). In arid and semi-arid climates, daytime leaf temperatures of well-watered plants are normally cooler than air temperatures (7). However, as water becomes limiting, transpirational cooling of the leaves decreases and leaf temperature rises.

Idso, *et al.* (6) have proposed a method which utilizes this relationship to estimate the ratio of actual to potential evapotranspiration. Their approach is based on the premise that at any given vapor pressure deficit (VPD), there is a theoretical upper and lower limit of foliage-air temperature difference (T_f-T_a). The ratio of the difference between a measured T_f-T_a value and the lower limit of T_f-T_a, at the measured VPD, to the difference between the upper and lower T_f-T_a limits, is defined as the plant water stress index (PWSI). The index ranges from 0 for crops transpiring at the potential rate to 1.0 for non-transpiring crops.

Relatively close relationships have been reported between the PWSI and crop stress parameters such as leaf water potential (6, 13), soil water extraction (5, 8), and yield (12, 13) for a number of field crops. The objective of this study was to determine if foliage temperature measurements could serve as a reliable indicator of water stress in potatoes.

Materials and Methods

Potato irrigation experiments were conducted at the University of Idaho Research and Extension Center, Aberdeen, Idaho, in 1982 and 1983 and at the Snake River Conservation Research Center, Kimberly, Idaho in 1982. The 1982 Aberdeen plots were established on a Declo silt loam. Russet Burbank potatoes were planted 5 May, 1982 at 22.9 cm intervals in 91 cm wide rows. The experiment consisted of three irrigation treatments with four replications arranged in a randomized complete block design. Individual 12.2 m by 12.2 m sprinkler-irrigated plots were separated from adjacent plots by an 18.3 m border. These plots were irrigated when tensiometer readings at the 20 cm depth dropped to either −30, −50, or −70 kPa (centibars). Sufficient water was applied at each irrigation to replace estimated evapotranspiration losses.

Leaf water potential (ψ_{leaf}) was estimated from measurements of xylem pressure potential using a pressure chamber. Measurements were taken on all plots between 0600 and 1700 h (MST) on 2, 9 and 18 August. Sampling frequency for individual plots ranged from 2 to 3 h. Measurements were also taken on four additional days during July and August. Each ψ_{leaf} determination was the average of three separate measurements on the upper leaves of plants from each plot.

Plant foliage temperature (T_f) was determined at the time of ψ_{leaf} measurement using a Teletemp AG-42 infrared thermometer (IRT).[3] The instrument was held so as to view the crop at an angle of 30° from the horizontal at right angles to the rows. Each T_f determination was the average of six readings (three facing north and three facing south). Wet and dry bulb (T_a) temperatures were determined concurrently using an aspirated psychrometer held approximately 1 m above the crop canopy.

At Kimberly, potatoes were grown on a Portneuf silt loam. A line source sprinkler system (3) was used to irrigate several different cultivars, including Russet Burbank and Kennebec. The cultivars were planted 28 April, 1982 in replicated four-row strips (91 cm row spacing) which were set at right angles to the sprinkler line. The line source system was used to produce a soil moisture gradient which decreased continuously from optimal irrigation near the sprinklers to zero irrigation approximately 15 m from the sprinkler line. Soil moisture was monitored at regular intervals along the irrigation gradient with a neutron probe. Tensiometers were also used near the line source.

Leaf water potential, T_f and wet and dry bulb temperatures were measured at various times between 0600 and 1700 h (MST) on 6, 11 and 27

[3]Mention of trade or company names in this paper does not constitute an endorsement, guarantee or warranty by the Idaho Agric. Expt. Stn. or the USDA and does not imply their approval to the exclusion of other products that may be suitable.

August. These measurements were taken at 1.5, 4.5, 7.5, 10.5 and 13.5 m from the line source in three plots of each cultivar. Each set of measurements was taken within a 20 min period. The techniques used were similar to those described for the Aberdeen site, although the individual sampling areas were only 1 m by 1.5 m.

On 16 May, 1983, plots of Kennebec potatoes were established at Aberdeen under sprinkler irrigation. Eight 5.5 m by 15 m plots were arranged in a randomized complete block design. All plots were irrigated to maintain the soil matric potential at the 20 cm depth above −50 kPa. On 12 August, the sprinkler system was removed and for the remainder of the growing season, half of the plots were kept well-watered (> −50 kPa) with a trickle irrigation system while the other half received no irrigation. During this period ψ_{leaf}, T_f and wet and dry bulb temperatures were measured daily between 1300-1400 h MST on all plots. All experiments were fertilized according to University of Idaho recommendations.

Results and Discussion

The line source plots at Kimberly provided the opportunity to compare T_f-T_a values for potatoes over a wide range of soil moisture conditions (Figure 1). The data presented for Kennebec on 11 August, 1982 are representative of the trends observed for both cultivars on all three sampling dates.

Foliage-air temperature differences for stressed plants at the outer edge of the plots changed very little throughout the morning and early afternoon (0930 to 1330 h). Conversely, T_f-T_a for well-watered potatoes near the line decreased markedly during the same period. The difference in T_f-T_a between well-watered and stressed plants increased from 3.1 C at 0930 h, to 6.0 C and 8.0 C at 1130 h and 1330 h, respectively.

At mid-morning, evaporative demand was low and thus transpiration was relatively low at all soil moisture levels. As evaporative demand increased later in the day, transpirational cooling near the line increased and T_f became much cooler than T_a. However, T_f-T_a values for the severely-stressed plants actually increased during the day due to the combined effects of increased radiation absorption and reduced transpiration. These results support the observation of Ehrler, *et al.* (2) that maximum T_f-T_a differences occur in the early afternoon.

In addition to IRT measurements of foliage temperature, ψ_{leaf} measurements were also taken to provide an independent measure of plant water stress. Early afternoon data for Russet Burbank and Kennebec on 6 and 11 August are presented to compare a broad range of ψ_{leaf} and T_f-T_a values (Figure 2). Since the relationship between these two variables was similar for the two cultivars, both data sets were fit with a single linear regression.

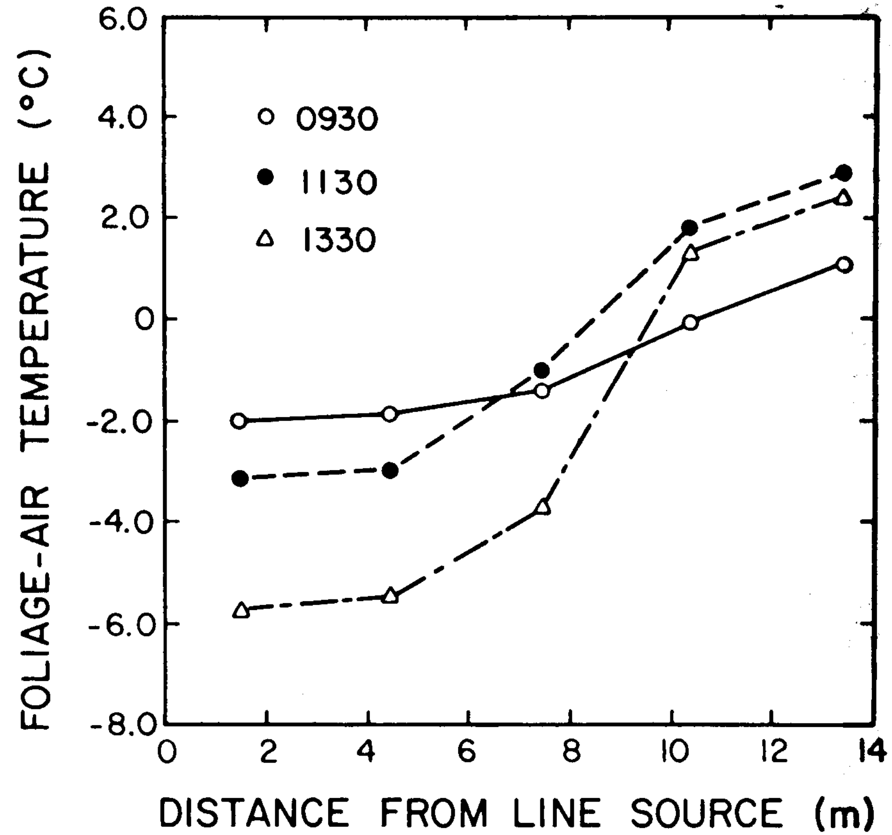

FIG. 1. Foliage-air temperature differences for Kennebec potatoes measured at selected times along a soil moisture gradient on 11 August, 1982. Potatoes were well-watered near the sprinkler line and severely-stressed at the outer edge of the plots. In all cases, standard deviations were less than ±0.8 C.

Leaf water potential was inversely related to T_f-T_a ($r^2 = 0.89$). Similar results have been reported for wheat (1) and sorghum (5). However, the differences in ψ_{leaf} between stressed and non-stressed conditions were much greater for these other crops.

Leaf water potentials of well-watered potatoes generally fell between −0.9 MPa (−9.0 bars) and −1.1 MPa. Foliage temperatures of these plants were also much cooler than T_a. However, as soil water deficits increased, T_f increased relative to T_a and became warmer than T_a at ψ_{leaf} < −1.3 MPa. The lowest ψ_{leaf} values measured in this study were approximately −1.4 MPa, which is apparently near the lower limit of ψ_{leaf} for potatoes (15).

Although a close relationship between ψ_{leaf} and T_f-T_a was obtained during these two measurement periods, it is important to note that afternoon

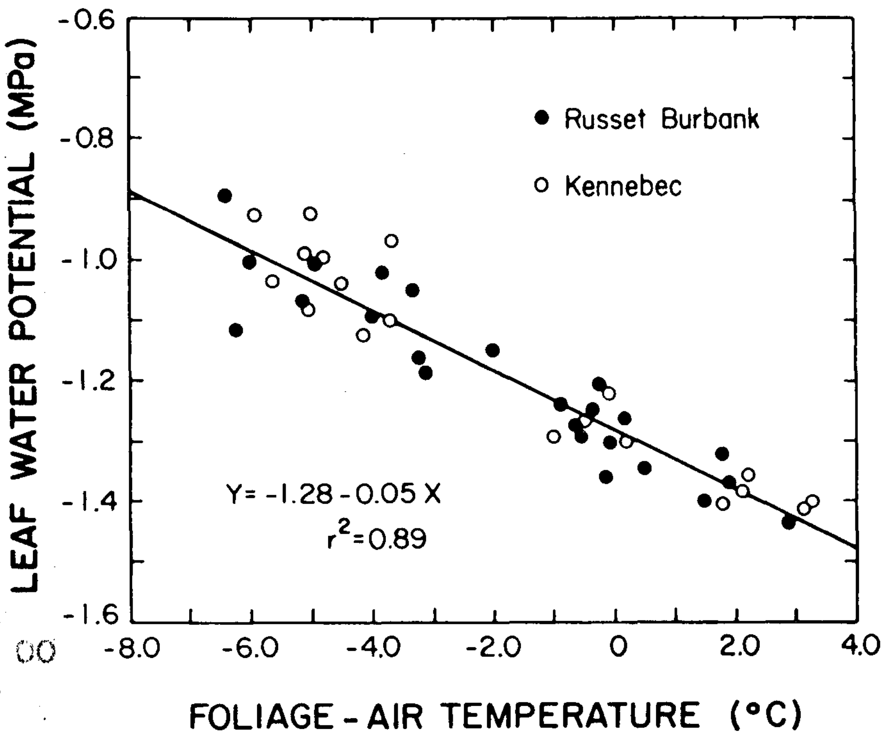

FIG. 2. Relationship between afternoon T_f-T_a and ψ_{leaf} for differentially-stressed potatoes. Measurements were taken at Kimberly, Idaho between 1300 and 1400 h on 6 and 11 August, 1982.

micrometeorological conditions were very similar on both days. When additional measurements taken under a wide range of VPD conditions were included in the data set, the correlation between these two variables was not nearly as good ($r^2 = 0.17$).

Idso, *et al.* (6) reported similar results for alfalfa and proposed a technique to "normalize" the relationship between T_f-T_a and ψ_{leaf} to account for the effects of VPD. Their approach was to first construct a plant water stress index (PWSI) from T_f-T_a and VPD data and then relate this index to depressions in ψ_{leaf} which resulted from soil water deficits. We chose to use this procedure as a means of quantifying potato water stress.

Calculation of PWSI—A regression of T_f-T_a vs corresponding VPD measurements from well-watered potatoes (> −50 kPa) in each of the three experiments was used to determine the lower limit of T_f-T_a (Figure 3). The slope of the linear regression used to fit these data is similar to those obtained for alfalfa (6), cotton (13) and sorghum (5). An extrapolation of this linear relation to the point of zero vapor pressure gradient between foliage and air was used to estimate the upper limit of T_f-T_a for non-transpiring potatoes.

Since this upper limit is considered to be independent of VPD, it is designated as a horizontal (dashed) line.

O'Toole and Hatfield (11) recently reported that windspeed has a significant effect on the upper limit of T_f-T_a for crops with rough canopies such as corn and sorghum. They proposed a means of correcting the upper limit to account for windspeed effects. However, this correction was found to have little effect on crops with aerodynamically smooth canopies. Since canopies of potatoes under full cover are relatively smooth, we did not correct these data for windspeed but instead used the aforementioned method of Idso, *et al.* (6). Although this procedure produces different upper limits for different T_a values, the differences are relatively small for small intercept terms. The upper limit of T_f-T_a for potatoes was estimated to be 1.1 C, assuming an average temperature of 30 C.

Once the upper limits of T_f-T_a were specified, the PWSI for corresponding pairs of T_f-T_a and VPD measurements were calculated as follows:

$$\mathrm{PWSI} = \frac{(T_f\text{-}T_a) - (T_f\text{-}T_a)_L}{(T_f\text{-}T_a)_U - (T_f\text{-}T_a)_L}$$

where $(T_f\text{-}T_a)_U$ and $(T_f\text{-}T_a)_L$ are the upper and lower limits of T_f-T_a, respectively, at a given VPD. Thus for a measured T_f-T_a value of −2.2 C at VPD = 3.6 kPa, the calculated PWSI would be 0.56.

The data for the three experiments indicated that when soil matric potential (ψ_{soil}) was less than −70 kPa, PWSI values were consistently greater than zero. Therefore, data from plots with ψ_{soil} ranging from −70 kPa to near the wilting point are also presented in Figure 3 for comparison with data from well-watered potatoes. In contrast, when ψ_{soil} fell between −50 to −70 kPa (data not shown), PWSI values similar to those for "well-watered" potatoes were obtained, i.e., small positive or negative values.

Data obtained from the Aberdeen plots on 2 August, 1982 support the observation that T_f-T_a for potatoes begins to rise above non-stressed levels when ψ_{soil} approaches or falls below −70 kPa (Figure 4). Mean ψ_{soil} readings on this date were −28, −54 and −72 kPa for the −30, −50 and −70 kPa treatments, respectively.

During the morning, T_f-T_a values were similar for all three treatments. However at midday, T_f-T_a for potatoes in the −30 and −50 kPa plots differed from those in the −70 kPa plots by approximately 1 to 2 C. This difference continued throughout the afternoon even though T_f-T_a steadily decreased in all treatments. Evidently, soil water deficits in the −70 kPa plots were sufficient to elevate T_f-T_a above non-stressed levels but were not severe enough to completely stop transpiration.

To differentiate between the soil-induced and atmospheric-induced portions of ψ_{leaf}, a plot of ψ_{leaf} versus VPD was constructed for well-watered Russet Burbank and Kennebec potatoes and fit by a logarithmic regression

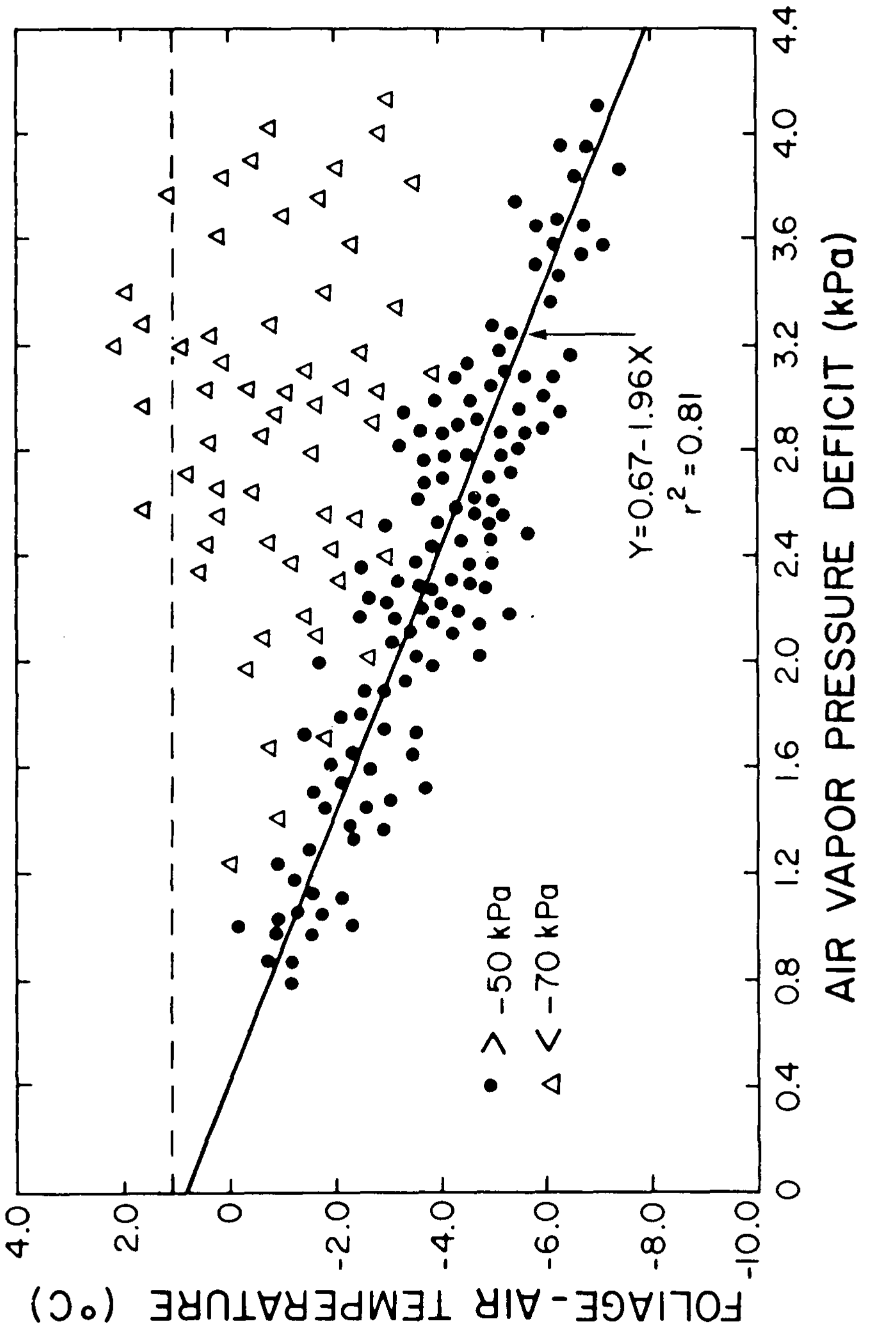

FIG. 3. Relationship between T_f-T_a and VPD for well-watered (> − 50 kPa) and stressed (< −70 kPa) potatoes.

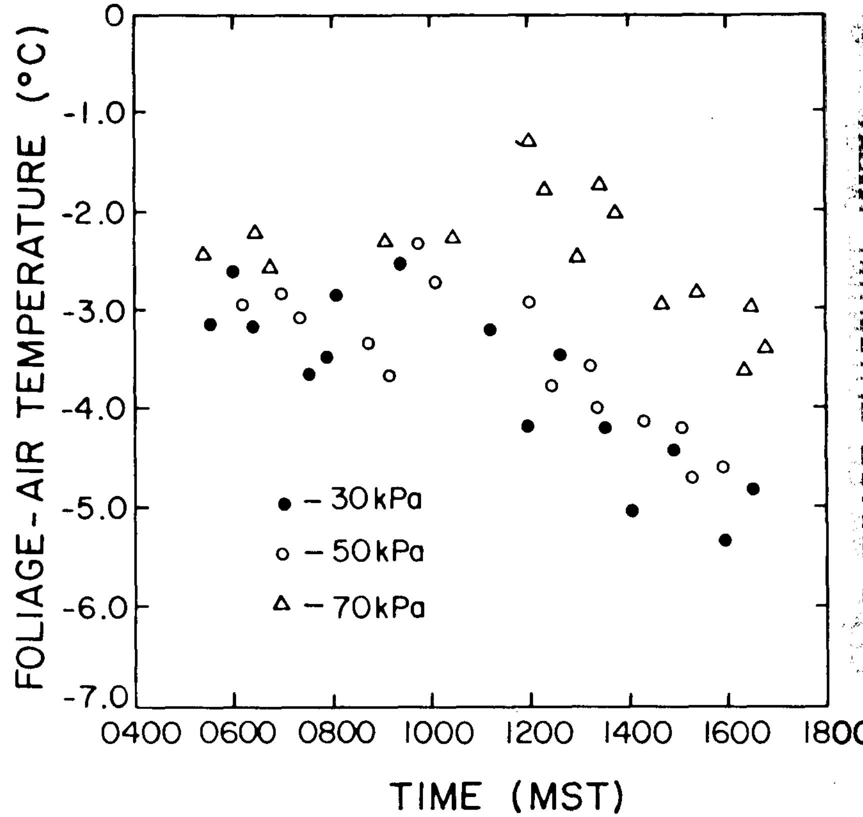

FIG. 4. Foliage-air temperature differences as a function of time for differentially-stressed Russet Burbank potatoes. Measurements were taken at Aberdeen on 2 August, 1982.

(Figure 5). The resulting curve was used to characterize depressions in ψ_{leaf} caused by evaporative demand. Leaf water potentials of stressed potatoes would be depressed below this curve. For a given pair of ψ_{leaf} and VPD measurements, the atmospheric-induced portion of ψ_{leaf} could then be subtracted from measured values leaving the "normalized" leaf water potential (ψ_{leaf}*) which is solely dependent on soil-water deficits (6).

When ψ_{leaf}* values for differentially-stressed potatoes at the three sites were plotted against corresponding PWSI values, a linear relation was obtained (Figure 6). The maximum difference in ψ_{leaf}* between the extremes in soil water availability was approximately 0.3 MPa. Others have also reported small differences in ψ_{leaf} between stressed and non-stressed potatoes (15, 16). Much larger differences have been reported for wheat (1, 2), alfalfa (6) and cotton (13). The slope of the ψ_{leaf}* versus PWSI relation is also much smaller than those reported for alfalfa (6) and cotton (13). This is to be expected since potato tuber development is much more sensitive to soil

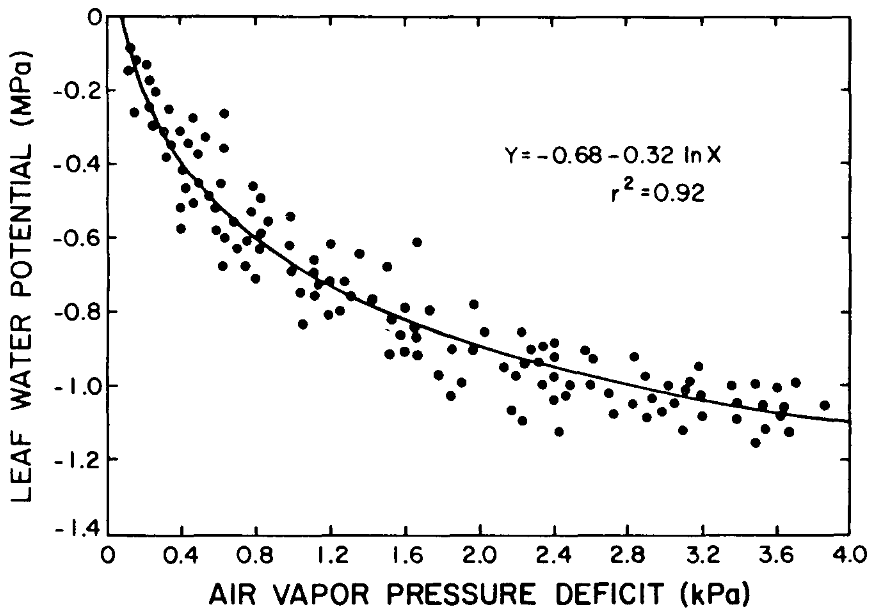

FIG. 5. Leaf water potential of well-watered potatoes as a function of VPD.

water deficits than the development of many field crops and potatoes tend to close stomata at relatively high ψ_{leaf} values (9).

Optimal ψ_{soil} for potato production has been reported to range from -20 to -60 kPa (9). Irrigating at ψ_{soil} values greater than -20 kPa may reduce tuber yield and quality through impaired aeration while allowing ψ_{soil} to fall below -60 kPa may reduce production and translocation of photosynthates.

Jackson (7), in his recent review of crop temperature and water stress, suggested that foliage temperature may not be an adequately sensitive indicator of potato irrigation requirements due to the need to maintain relatively high soil moisture levels throughout the growing season. The results of our study indicate that this is indeed the case.

Although infrared measurements of potato foliage temperature can be used to detect and quantify severe water deficits, ψ_{soil} apparently must decrease below -70 kPa before any appreciable change occurs in the T_f-T_a versus VPD relationship. However, potatoes are usually irrigated at ψ_{soil} values greater (less negative) than -70 kPa to avoid quality and yield reductions. This effectively eliminates the potential use of foliage temperature measurements as a means of scheduling irrigation for potatoes.

Differences in ψ_{leaf} between non-stressed and moderately-stressed potatoes also appear to be too small to provide useful information for irrigators. Thus it appears that the only reliable techniques for scheduling irrigation for potatoes will continue to be direct measurement of soil moisture with tensiometers, neutron probes, etc. and/or the use of evapotranspiration models.

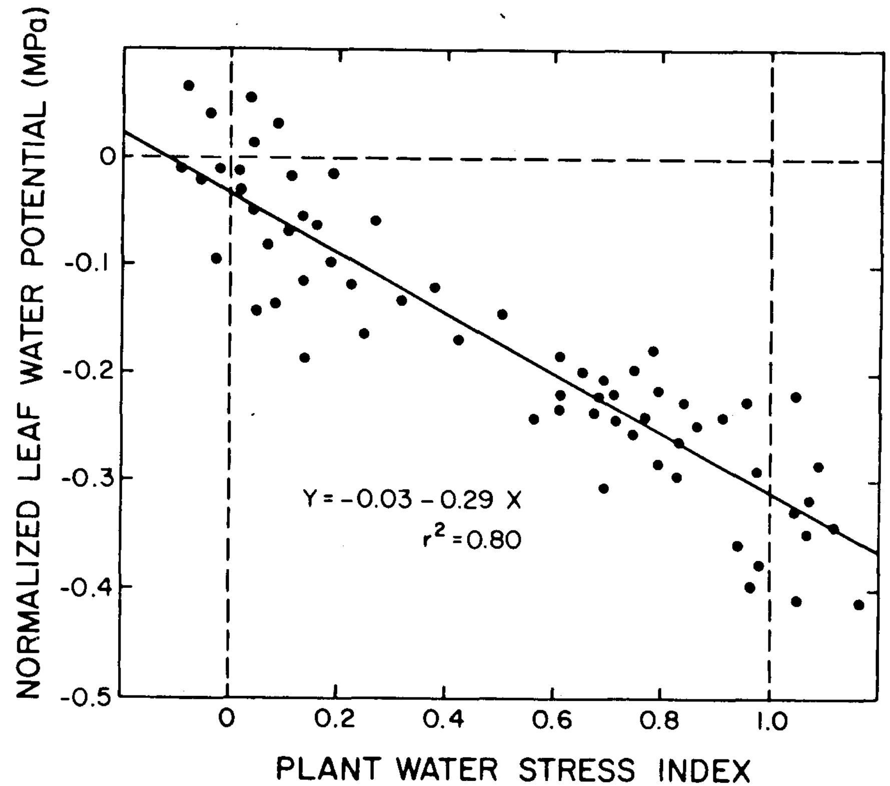

FIG. 6. Relationship between PWSI and normalized potato ψ_{leaf}.

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