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NON-WATER-STRESSED BASELINES: A KEY TO MEASURING AND INTERPRETING PLANT WATER STRESS*

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ABSTRACT

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A plant water stress index has recently been developed which employs a radiometric measurement of foliage temperature and a psychometric measurement of the vapor pressure deficit of the air. To utilize the index, it is necessary to know the relationship that exists between foliage—air temperature differential and air vapor pressure deficit for the plant in question when it is well watered and transpiring at the potential rate This information is provided for 26 different species for clear sky conditions in the format of non-water-stressed baselines For six of these plants, including one aquatic species, such information is also included for cloudy or shaded conditions, and two grain crops have results presented for both pre-heading and post-heading growth stages.

INTRODUCTION

Plant temperatures, particularly leaf temperatures, have long been recognized as having the potential to yield information about plant water stress (Tanner, 1963). An early review of the work of many pioneers in this field, however, indicated that a number of environmental and plant factors combine to determine leaf temperature at any given time, thus rendering its interpretation extremely difficult (Idso et al., 1966). Consequently, there has been a long search for some simplifying model which would bring to fruition the oft-expressed optimism of the large number of workers in this field, namely, that plant temperature measurements could be used to assess the water status of plants and hence be applied to such practical operations as irrigation scheduling.

Perhaps the most simple approach to this problem was the development of the stress-degree-day concept by Idso et al. (1977). These investigators merely related foliage temperature T_F, as measured by an infrared thermometer, to air temperature T_A, suggesting that if $T_F - T_A$ were negative, the plants were well-watered, but that if the differential was positive, water was needed.

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This simple approach proved adequate in many subsequent studies (Ehrler et al., 1978a, b; Idso et al., 1978, 1979, 1980; Reginato et al., 1978; Walker and Hatfield, 1979). However, other experiments indicated that the foliage—air temperature differential alone was not sufficient to handle complexities introduced by significant microclimatic variations of either a temporal or spatial nature (Gardner, 1979; Walker, 1980). Thus, Idso et al. (1981a) developed a new plant water stress index that essentially normalizes the stress-degree-day parameter for environmental variability.

Since the new index has been described in detail in several other publications (Idso, 1981b, 1982; Idso et al., 1981a), including studies relating it to plant water potential (Idso et al., 1981c, 1982a), stomatal diffusio resistance and net photosynthesis (Idso et al., 1982b), and yield (Idso et al., 1981b; Idso, 1982), it will not be described again. Suffice it to note instead that utilization of the index depends upon one's knowing a crop's specific 'non-water-stressed baseline', which is defined to be the relationship that exists between the foliage air temperature differential ($T_F - T_A$) and the air vapor pressure deficit (VPD) under conditions of non-limiting soil moisture, when the plants in question are transpiring at the potential rate.

To date, such non-water-stressed baselines have been determined for only a small number of crops: alfalfa (*Medicago sativa* L.), soybeans (*Glycine max* L. Merr.), and squash (*Cucurbita pepo* L.), by Idso et al. (1981a); wheat (*Triticum durum* Desf. var Produra), by Idso et al. (1981b); cotton (*Gossypium hirsutum* L.), by Idso et al. (1982b); beans (*Phaseolus vulgaris* L.) and water lily (*Nuphar luteum* Sibht. and Sm.), by Idso (1981a). Thus to extend the usefulness of the new plant water stress index, a series of experiments were conducted to obtain non-water-stressed baselines for a much wider variety of plants, including vegetable crops and even a shrub and a tree.

MATERIALS AND METHODS

A listing of all plants studied is given in Table I; and for completeness and easy comparison, the other plants that have been analyzed in this manner are included.

The new experiments were conducted primarily in Arizona, some at the U.S. Water Conservation Laboratory in Phoenix (barley, guayule, tomato, wheat), some at the University of Arizona's Mesa Experiment Farm (alfalfa, guayule, pea, potato, sugarbeet, tomato), some at the Agricultural Research Station of the Institute for Biospheric Research in Tempe (bean, beet, chard, corn, cowpea, cucumber, fig tree, kohlrabi, lettuce, pea, pumpkin, rutabaga, squash, tomato, turnip), some at the University of Arizona's Cotton Research Center (alfalfa, cotton), and some at a backyard pond in Phoenix (water lily). Other data were gathered at Kansas State University in Manhattan, Kansas (alfalfa, soybean, sunflower), at the University of Minnesota in St. Paul, Minnesota (alfalfa) and at North Dakota State University in Fargo, North Dakota (soybean).

At each of these locations, air wet- and dry-bulb temperature measurements were made at half-hourly intervals with a Bendix* aspirated psychrometer held about a meter and a half above the ground. Concurrently, measurements of plant foliage temperature were made with a Teletemp AG-42 infrared thermometer equipped with a 10.5—12.5 μm bandpass filter. This instrument was held so as to obliquely view the plants in such a way that only plant parts, and no underlying soil, could radiate energy to its sensor. Plants were veiwed both from the east and west, with four separate measurements from each direction being averaged together. Before and after each set of readings, the infrared thermometer was calibrated by viewing a standard blackbody reference whose temperature could be read to 0.1°C.

The only exception to this procedure involved the water lily. Due to a lack of sufficient growth to completely cover the water surface, it was necessary to view individual, exposed leaves protruding above the water. For plants that grow to a sizeable height, such as corn, chairs were used to acquire the advantage needed to view the top of the canopy; while in the case of the fig tree, which extended to a height of some four meters, tall step-ladders were employed.

All data were smoothed by a simple 3-term running averaging procedure, i.e., $X_t = (X_{t-1} + X_t + X_{t+1})/3$, where t is the time of measurement, and then plotted for visual assessment as in Figs. 1—11. Figure 1 has appeared previously in the literature, but is included here to show both the consistency of data from a number of different locations and the nature of the upper limit that prevails when transpiration is negligible. The data for tomato in Fig. 2 also demonstrate the multi-location consistency aspect, even including data obtained within the humid conditions of a greenhouse.

Linear regressions were next run on the different data sets with the resultant best-fit lines being added to the figures and the pertinent statistics being recorded in Table I.

RESULTS AND DISCUSSION

A perusal of Figs. 1—11 and Table I shows, first of all, that not all of the results can be given equal weight; some derive from very extensive data sets, while others are much more meagre. Since there is such a paucity of data of this type in the literature, however, it was decided to present all that was available. Also, some parts of the world always have very dry growing seasons, while others have only very wet ones, thus creating a real difficulty for researchers in these areas trying to establish an accurate non-water-

* Trade names and company names are included for the benefit of the reader and imply no endorsement or preferential treatment of the product(s) listed by the U.S Department of Agriculture.

TABLE I

Results of linear regression analyses of $T_F - T_A$ vs VPD data depicted in Figs. 1—11

Common name	Scientific name	Conditions	N^a	a_0	a_1	r	s_{yx}	s_0	s_1
Alfalfa	*Medicago sativa* L	Sunlit	229	0.51	−1.92	0.953	0.65	0.11	0.041
Barley	*Hordeum vulgare* L.	Sunlit, pre-heading	34	2.01	−2.25	0.971	0.17	0.22	0.098
		Sunlit, post-heading	72	1.72	−1.23	0.860	0.40	0.24	0.087
Bean	*Phaseolus vulgaris* L	Sunlit	265	2.91	−2.35	0.978	0.72	0.11	0.031
		Shaded	65	−1.57	−2.11	0.973	0.39	0.17	0.064
Beet	*Beta vulgaris* L	Sunlit	54	5.16	−2.30	0.982	0.46	0.16	0.060
Chard	*Beta vulgaris* L (Cicla)	Sunlit	69	2.46	−1.88	0.955	0.58	0.17	0.071
Corn	*Zea mays* L	Sunlit, no tassels	97	3.11	−1.97	0.985	0.32	0.10	0.035
Cotton	*Gossypium hirsutum* L	Sunlit	181	1.49	−2.09	0.971	0.38	0.13	0.038
Cowpea	*Vigna catjang* Walp	Sunlit	60	1.32	−1.84	0.991	0.34	0.14	0.034
Cucumber	*Cucumis sativus* L	Sunlit	109	4.88	−2.52	0.962	0.82	0.23	0.069
		Shaded	59	−1.28	−2.14	0.982	0.57	0.19	0.054
Fig tree	*Ficus carica* L	Sunlit	119	4.22	−1.77	0.924	0.66	0.21	0.068
Guayule	*Parthenium argentatum*	Sunlit	62	1.87	−1.75	0.928	0.89	0.31	0.094
Kohlrabi	*Brassica oleracea caulorapa communis* DC	Sunlit	70	2.01	−2.17	0.979	0.46	0.13	0.054
Lettuce, leaf	*Lactuca scariola* L	Sunlit	89	4.18	−2.96	0.998	0.68	0.08	0.021
Pea	*Pism sativum* L	Sunlit	85	2.74	−2.13	0.951	0.54	0.17	0.076
Potato	*Solanum tuberosum* L	Sunlit	26	1.17	−1.83	0.922	0.67	0.45	0.157
Pumpkin	*Cucurbita pepo* L	Sunlit	76	0.95	−1.93	0.978	0.46	0.22	0.048
		Shaded	89	−1.32	−2.10	0.985	0.47	0.14	0.039
Rutabaga	*Brassica napo-brassica*	Sunlit	91	3.75	−2.66	0.988	0.54	0.14	0.044
	Ruta-baga A P DC	Shaded	53	−0.50	−2.51	0.913	0.86	0.37	0.157
Soybean	*Glycine max* L Merr	Sunlit	125	1.44	−1.34	0.897	0.83	0.18	0.060
Squash, hubbard	*Cucurbita pepo* L	Sunlit	90	6.91	−3.09	0.983	0.80	0.22	0.062
		Shaded	11	2.12	−2.83	0.993	0.65	0.44	0.113
Squash, zuchinni	*Cucurbita pepo* L	Sunlit	87	2.00	−1.88	0.985	0.38	0.17	0.036
Sugar Beet	*Beta vulgaris* L	Sunlit	47	2.50	−1.92	0.898	0.78	0.40	0.140
Sunflower	*Helianthus annuus* L	Sunlit	58	0.66	−1.95	0.979	0.39	0.14	0.054
Tomato	*Lycopersicum esculentum* Mill	Sunlit	103	2.86	−1.96	0.986	0.64	0.13	0.033
Turnip	*Brassica rapa* L.	Sunlit	129	1.94	−2.26	0.979	0.68	0.14	0.042
Water lily	*Nuphar luteum* Sibth & Sm	Sunlit	36	8.99	−1.93	0.866	0.65	0.86	0.191
		Shaded	Not applicable to curvilinear relationship						
Wheat, produra	*Triticum durum* Desf	Sunlit, pre-heading	161	3.38	−3.25	0.947	0.63	0.15	0.087
		Sunlit, post-heading	56	2.88	−2.11	0.939	0.53	0.28	0.105

[a] N = number of data points, a_0 = intercept, a_1 = slope, r = correlation coefficient, s_{yx} = standard error of estimate of y on x, S_0 = standard error of the regression coefficient a_0, and $S_{0,1}$ = standard error of the regression coefficient a_1, for the linear regression equation $y = a_0 + a_1 X$, with temperatures expressed in C and vapor pressure in kPa

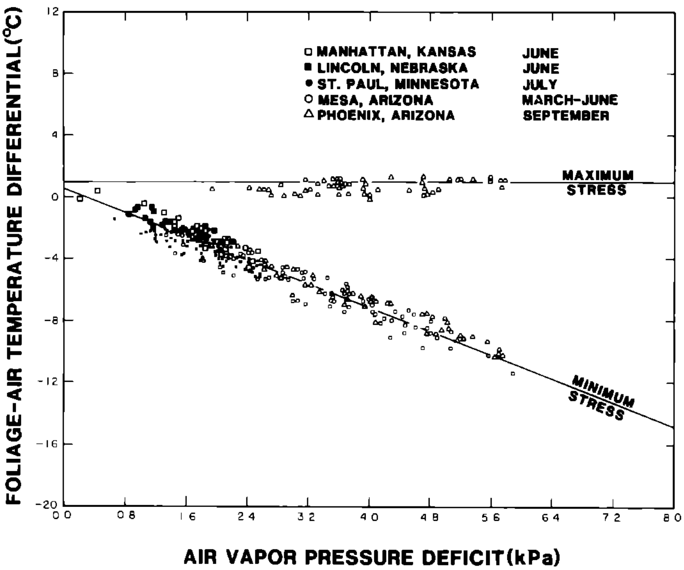

Fig. 1. $T_F - T_A$ vs. VPD for well-watered and maximally stressed alfalfa at a variety of sites across the United States. From Idso et al. (1981c).

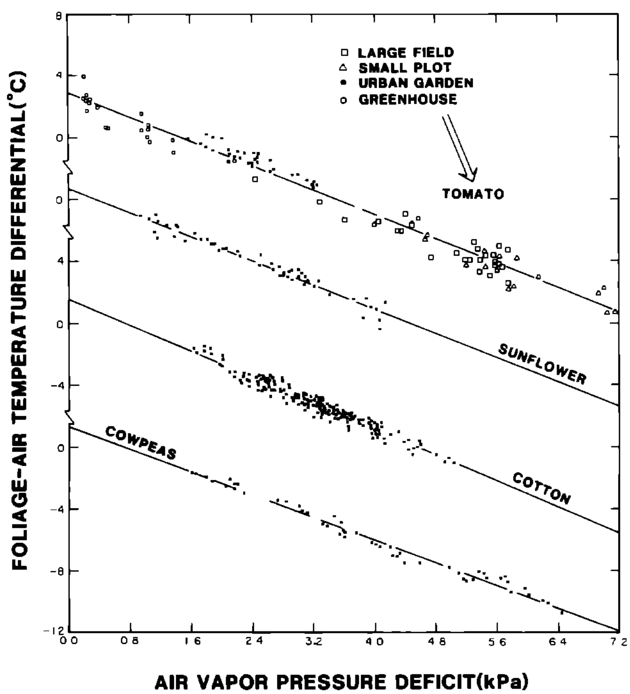

Fig. 2 $T_F - T_A$ vs. VPD for well-watered tomato, sunflower, cotton, and cowpeas.

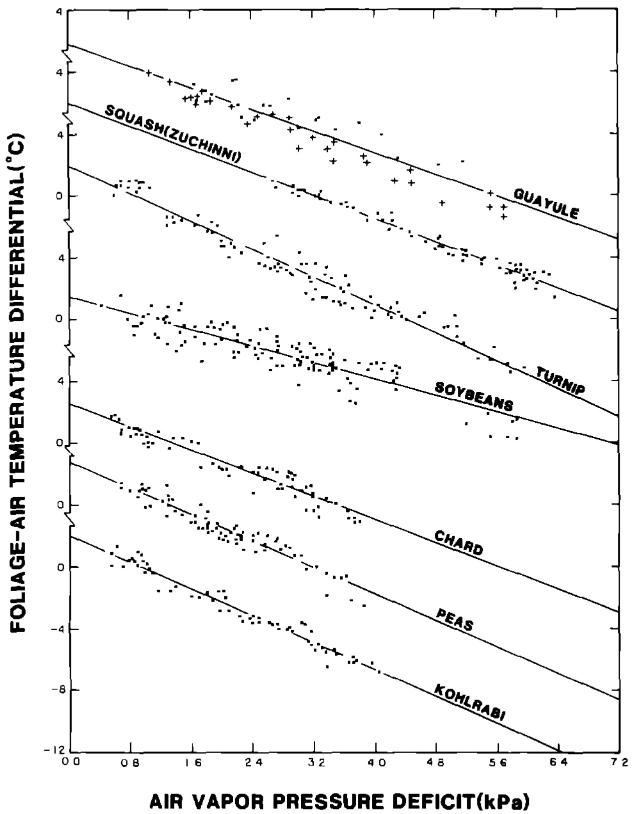

Fig 3 $T_F - T_A$ vs. VPD for well-watered guayule, zuchinni squash, turnip, soybeans, chard, peas and kohlrabi.

stressed baseline for a particular crop, due to the need to have the widest possible VPD range that can be obtained. For such workers, the actual numbers of the data sets depicted here will be made available upon request.

Another reason for the inequality of different data sets arises from their different degrees of scatter. Some of this divergence comes from the natural spatial variability of field crops. For instance, several large fields of alfalfa were studied to obtain the data of Fig. 1 (S_{yx} = 0.65°C); and probably no two measurements were ever made from exactly the same place. However, in the case of corn (S_{yx} = 0.32°C), a single small plot was investigated, and almost all of the data points were obtained from viewing the crop from the same eight standard positions. Thus, other researchers may not obtain quite the same results as those displayed here, for the same reason.

The data of Figs. 1—11 and Table I reveal several basic facts not previously described in the literature. The first of the new observations is that the baselines of some crops may shift significantly as they move from a vegetative to reproductive growth stage. Figure 5 displays this phenomenon in wheat and barley, where the less steep slopes of the post-heading stage

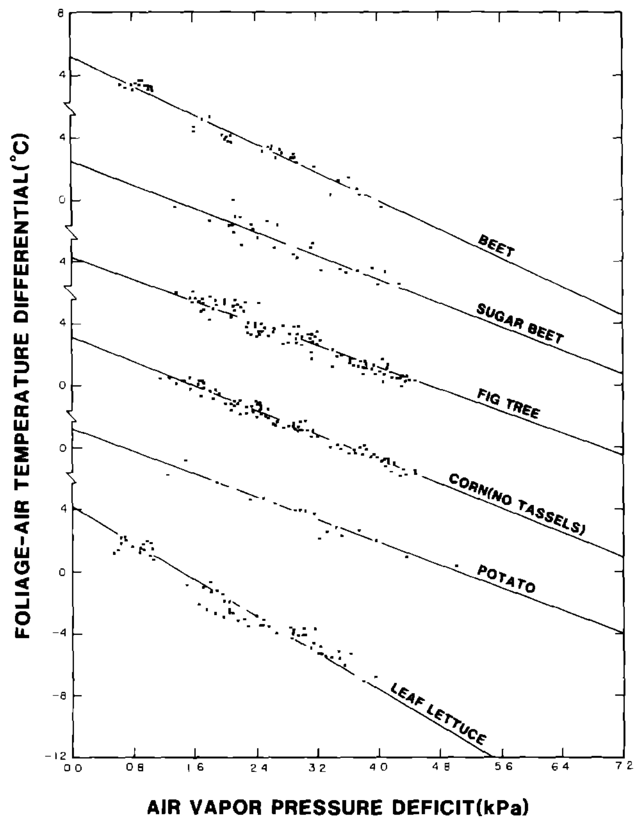

Fig. 4 $T_F - T_A$ vs VPD for well-watered garden beet, sugar beet, corn, potato, leaf lettuce and a fig tree.

imply a greater effective canopy diffusion resistance relative to that which prevails in the pre-heading stage. Thus, for a given icremental increase in the air VPD, more transpirational cooling occurs in the pre-heading stage than in the post-heading stage. Fritschen and van Bavel (1964) reported a complementary relationship between actual lysimetric evaporation measurements conducted on headed and non-headed sudangrass (*Sorghum sudanense* (Piper) Stapf). They postulated that the lower evapotranspiration rate from the headed crop was not caused by physiological maturity but "due to the fact that the seedheads absorbed the radiant energy, converted it into sensible heat, and also provided a very effective aerodynamic barrier against the transfer of sensible heat to the transpiring surfaces". This same reasoning would also seem to apply to wheat and barley.

Figures 6—11 reveal a second new aspect of this work — the relationship between the baselines of crops under sunlit and shaded conditions. In all cases, the shaded-crop baseline is located well below the sunlit-crop baseline. For terrestrial plants, this depression averages 3.8°C at the midpoint of the air VPD range, i.e., at 3.6kPa.

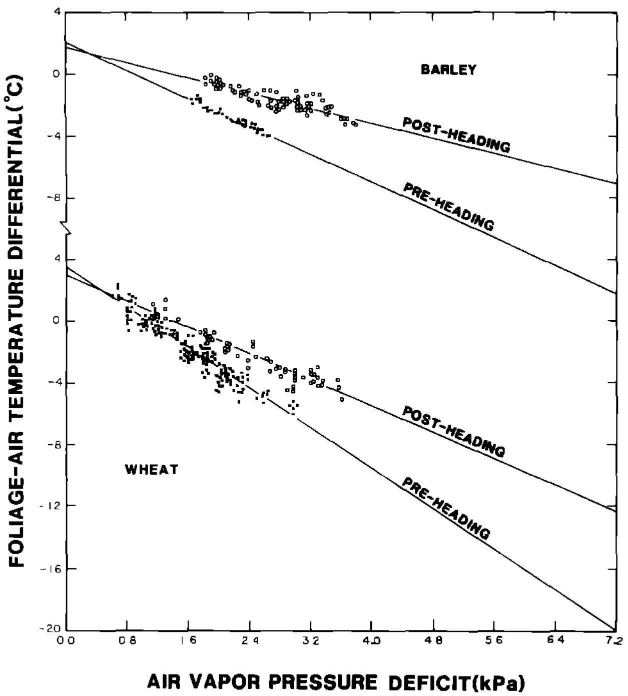

Fig. 5 $T_F - T_A$ vs VPD for well-watered pre-heading and post-heading barley and wheat.

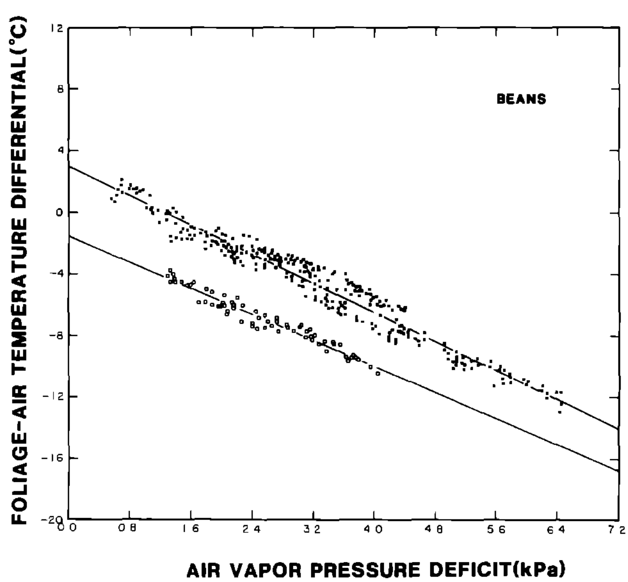

Fig 6 $T_F - T_A$ vs. VPD for well-watered sunlit ( ) and shaded (°) garden beans.

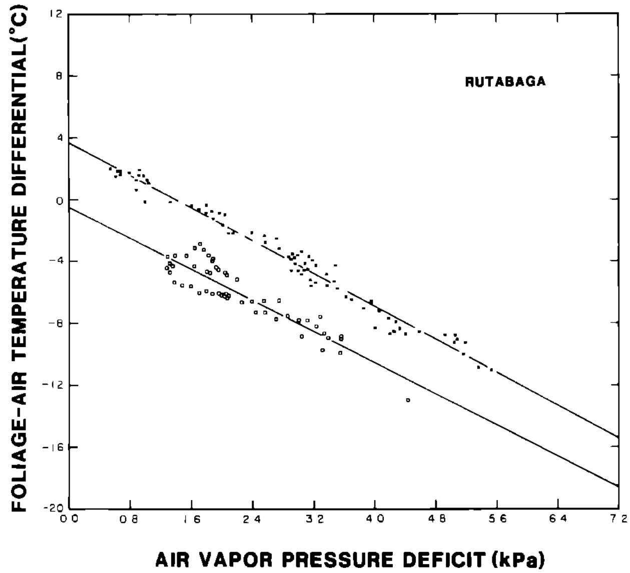

Fig. 7. $T_F - T_A$ vs. VPD for well-watered sunlit ( ) and shaded (◦) rutabaga.

The one aquatic plant studied (water lily) proved to be truly anomolous, displaying a curvilinear baseline when shaded. The analysis of Jackson et al. (1981) indicates that such curved baselines may occur if the plant stomatal diffusion resistance is a constant. Linear relationships, on the other hand, imply a variable stomatal diffusion resistance that is an inverse function of the daily course of solar radiation. For terrestrial plants that must conserve

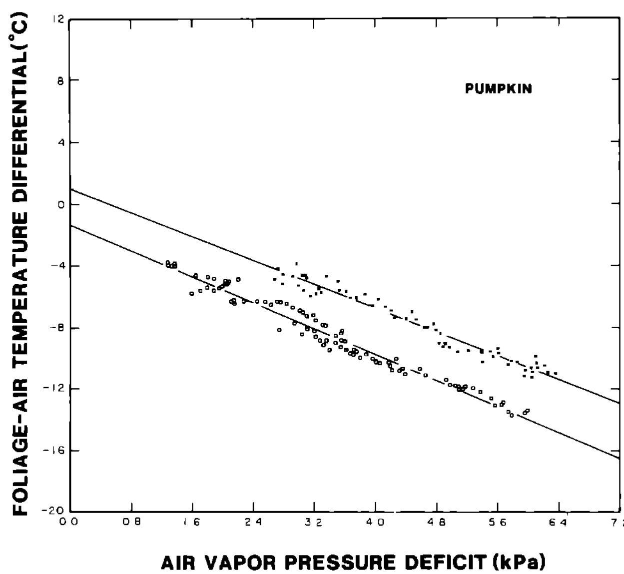

Fig. 8. $T_F - T_A$ vs VPD for well-watered sunlit ( ) and shaded (◦) pumpkins

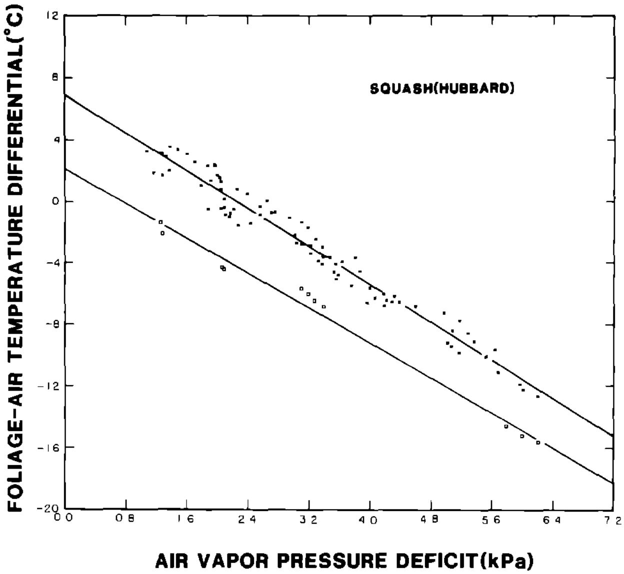

Fig. 9. $T_F - T_A$ vs. VPD for well-watered sunlit ( ) and shaded (◦) hubbard squash

their limited water supplies, the latter phenomenon is to be expected; while for aquatic plants that have no need to do so, it is not surprising to find the other response, particularly under the non-stressful condition of reduced heat load that accompanies shading.

Although many such interesting questions are posed by the results of this

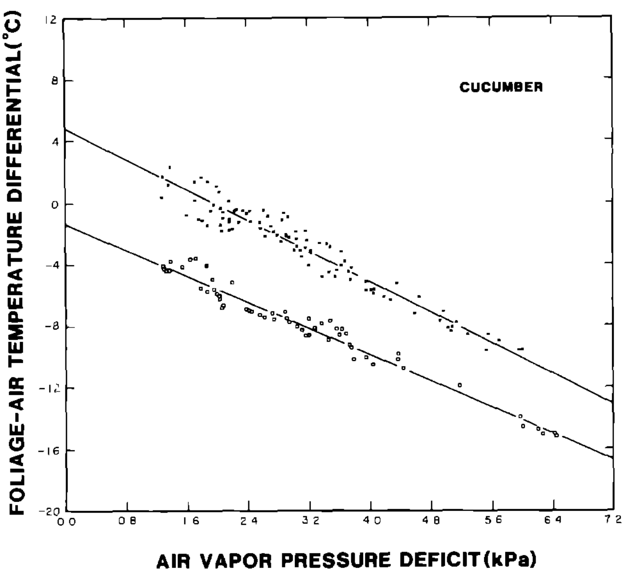

Fig. 10. $T_F - T_A$ vs. VPD for well-watered sunlit ( ) and shaded (◦) cucumber.

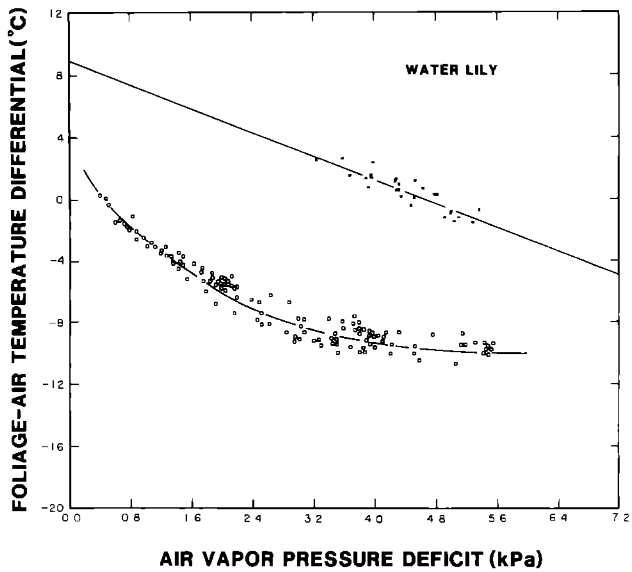

Fig. 11. $T_F - T_A$ vs. VPD for well-watered sunlit ( ) and shaded (◦) water lily.

study, its primary purpose was to obtain the results of Table I for utilization in connection with the new plant water stress index, which has been shown to be a very reliable measure of plant water stress and to be directly related to most current methodologies used to assess plant physiological responses to the environment. Thus, with the publication of the data of Table I, this new, non-contact, rapid, and area-integrating technique for measuring and interpreting plant water stress has the potential to become a practical research and management option for all concerned with the movement of water through the soil—plant—atmosphere system.

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