Stress Day Index to Characterize Effects of Water Stress on Crop Yields

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As water supplies diminish, optimization of water use in food production becomes more and more imperative. The major use of our dwindling water supply in food production is the irrigation of agricultural crops. Thus, it follows that optimum use of water in crop production is necessary. One aspect of irrigation which must be improved if optimum water use is to be realized is irrigation scheduling. A concept which is useful in optimizing irrigation scheduling as well as in other areas is stress day index. The purposes of this paper are to define this concept, suggest ways for characterizing its components and discuss how the concept may be useful in optimizing water use in irrigated agricultural food production.

The stress day index (SDI) concept provides a quantitative means for determining the stress imposed on a crop during its growing season. This concept is applicable to characterization of both irrigation and drainage requirements of crops, i.e. to evaluating water and oxygen stresses. Quantitative characterization of animal stresses with this concept seems plausible also, as mentioned in a previous paper (Hiler, 1969). This paper concerns only the characterization of water stress in crops.

The stress day index is determined from a stress day factor and a crop susceptibility factor. The stress day factor (SD) is a measure of the degree and duration of plant water deficit. The crop susceptibility factor (CS) depends on the species and stage of development of the given crop and indicates the plant susceptibility to a given water deficit. The stress day index can be written as follows:

$$SDI = \sum_{i=1}^{n} (SD_i \times CS_i) \quad \ldots\ldots [1]$$

where n represents the number of growth periods considered. A discussion of possible alternative approaches for quantitative characterization of SD and CS follows.

STRESS DAY FACTOR, SD

The stress day factor is an indication of the crop water deficiency caused by the aerial and subsurface environments. In order to gain insight into the proper characterization of the stress day factor, it is helpful to describe in an approximate manner the flow of water from the bulk soil mass through the plant to the atmosphere. The works of Van den Honert (1948), Cowan (1965), Newman (1969), and Gardner (1960) provide some background for this statement.

For steady state conditions, the flow of water from the bulk soil mass to the leaf in the liquid phase can be described as follows:

$$E = \frac{\psi_s - \psi}{R_s + R_p} \quad \ldots\ldots\ldots\ldots [2]$$

where E is transpiration rate, ψ is leaf water potential, ψ_s is soil water potential, R_s is soil resistance to flow and R_p is plant resistance which is the sum of root, xylem and mesophyll resistances. Work by Ehlig and Gardner (1964) and more recently by Kanemasu and Tanner (1969) indicates pronounced stomatal closure due to water stress occurs within a rather narrow range of leaf water potential which varies for different species. Let ψ_w be this critical leaf water potential. Then a supply function, E_w, can be defined as

$$E_w = \frac{\psi_s - \psi_w}{R_s + R_p} \quad \ldots\ldots\ldots\ldots [3]$$

which is the maximum rate of water supply from the soil reservoir.

Two steady state flow situations are now possible. The symbol E_d represents atmospheric evaporative demand on the crop or 'potential evaporation.'

I. When $E_d \leq E_w$, then $E = E_d$ and $\frac{E}{E_d} = 1$

This occurs when the leaf diffusion resistance, r_s, is minimal with stomates wide open.

II. When $E_d > E_w$, then $E = E_w$ and $\frac{E}{E_d} = \frac{E_w}{E_d}$ which is less than unity.

It should be emphasized at this point that this is a steady state flow analysis and as such is only approximate. More exact analyses must await the perfection of dynamic models of plant growth and production. For steady flow to occur in the soil-plant-atmosphere system, the rate of change of the leaf diffusion resistance, r_s, must be zero. It is recognized that there is a period of nonsteady flow between Cases I and II. During this period, the rate of change of leaf diffusion resistance with time exceeds zero and $E > E_w$. It is assumed that the stomates regulate flow to the point where $E = E_w$; when this is accomplished, the slope of r_s versus time again becomes zero and Case II holds. Experimental evidence by van Bavel (1967) indirectly supports this assumption.

The aforementioned analysis indicates that some function of (E/E_d) may be a good indicator of SD. The proposed form is

$$SD = 1 - \frac{E}{E_d} \quad \ldots\ldots\ldots\ldots [4]$$

The values of E and E_d as given here would be integrated values over a specified time period, preferably but not necessarily one day. When no transpiration occurred, SD would take on a maximum value of one; SD would be zero when transpiration occurred at the potential rate. The value of E could be determined in many ways; possibly a soil moisture accounting procedure similar to that proposed by Nix and Fitzpatrick (1964) would work best in the field. The evaporative demand, E_d, would be best characterized by the combination method (see references 20, 25, 26) if necessary data were available.

The form of SD proposed in equation [4] implies that no crop water

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deficit occurs until partial stomatal closure occurs and transpiration decreases below evaporative demand ($E < E_d$). Water stress in crops is exerted in essentially three ways, in the following order as water stress increases: (a) reduction in cell turgor as this affects cell elongation and possibly carbohydrate and nitrogen metabolism; (b) reduction in CO_2 intake rate as this affects photosynthetic rate; and (c) increase in leaf temperature as this affects metabolism (Kramer, 1969). Experiments by Jordan (1970) indicate that cell elongation ceases in cotton long before stomatal action causes reduction in transpiration below the evaporative demand level. Thus, although the form of SD in equation [4] appears to characterize advanced crop water stress well, it may not be sensitive to early signals of crop water stress.

Another possible characterization of the stress day factor which seems justified from the aforementioned analysis of water flow in the soil-plant-atmosphere continuum is as follows:

$$SD = |\psi| \quad \ldots\ldots\ldots\ldots \quad [5]$$

where the vertical lines denote the absolute value. Here, as with the previous case, this value should be an integrated value over a given time period. If this cannot be achieved, then an early morning value or some combination of an early morning and a mid-afternoon value should be used. As an environmental factor, SD is a function of the aerial and soil environments, i.e. a function of the atmospheric evaporative demand and the soil water potential among other things such as rooting density and distribution. The plant integrates the demand and the supply; the leaf water potential is an indication of how the plant performs this integration. Thus, the leaf water potential would appear to be a good characterization of SD.

For the aforementioned Case I, the leaf water potential would be written following equation [2] as follows:

$$\psi = \psi_s - E(R_s + R_p) \quad \ldots\ldots \quad [6]$$

For Case II, the leaf water potential would be

$$\psi = \psi_w \quad \ldots\ldots\ldots\ldots\ldots \quad [7]$$

since when pronounced stomatal closure occurs, the leaf water potential does not decrease below the critical value.

Equations [6] and [7] indicate that $|\psi|$ is a good characterization of SD up until the time that pronounced stomatal closure occurs. It may not be a good indicator of advanced crop water stress, i.e. stress which occurs as a result of significant increases in leaf temperature. For the application of irrigation scheduling, this shortcoming would not seem to be a great problem because in that case, sensitivity to initial stress would be more important than characterization of advanced stress. Through proper irrigation scheduling, one would not let the plant get to the advanced stress stage. Thus, for optimum irrigation scheduling, $|\psi|$ would seem to be a better characterization of SD than $1 - E/E_d$. For applications related to dryland agriculture or conditions of very limited irrigation where advanced stress cannot be avoided, the opposite would likely be true.

Values of leaf water potential could be predicted from equations [6] and [7] if each of the terms on the right side of the equation could be determined. The present state of knowledge makes this an extremely difficult task. Perhaps a better alternative is to measure $|\psi|$ by some available technique (Barrs, 1968). The authors are using the Scholander pressure bomb method and the leaf chamber psychrometer. A method suggested by Spomer (1968) offers promise if the sensor can be miniaturized sufficiently for use in field crops. The freezing point method developed recently by Cary (1970) also appears promising.

Another approach to estimating $|\psi|$ is through measurement of other plant indicators. Some of these include leaf diffusion resistance, leaf temperature and stem diameter. Experiments are underway to evaluate this approach.

Another possible method of SD characterization is simply to consider the evaporative demand minus the supply. From equation [2], the formulation would be as follows:

$$SD = E_d - \frac{\psi_s - \psi}{R_s + R_p} \quad \ldots\ldots \quad [8]$$

Estimations of E_d and E could be made by the combination method and a soil moisture accounting model, as previously discussed. Precise determination of the second term on the right side of equation [8] is diffucult at present.

Finally, since SD is a function of atmospheric evaporative demand and soil water potential in the root zone among other things, an empirical approximation of SD would be

$$SD = E_d \times |\psi_s| \quad \ldots\ldots\ldots \quad [9]$$

where $|\psi_s|$ is the absolute value of the integrated soil water potential in the root zone measured in early morning and E_d is the daily evaporative demand. This formulation is utilized in the results presented later. Equations [8] and [9] are indices of the leaf water potential.

The one of these four formulations of SD which should be used depends on the application to which the concept is being put and the availability of the necessary measurements. Following is a discussion of the other component of the stress day index concept, the crop susceptibility factor.

CROP SUSCEPTIBILITY FACTOR, CS

This factor is a function of the species and stage of growth of the crop. It indicates the susceptibility of a crop to given magnitudes of SD. Essentially, two methods for CS determination will be discussed.

One approach to the characterization of CS is to subject the crop to a specified critical SD value at different physiological growth stages. The critical SD value would be different for different species and would have to be determined in a preliminary experiment. The primary experiment for determinations of CS would be as follows:

	Treatment	Yield
I –	Stress at Growth Stage I, no stress during rest of season	i
II –	Stress at Growth Stage II, no stress during rest of season	ii
⋮		
M –	Stress at Growth Stage M, no stress during rest of season	m
C –	No stress during season	x

Then, the crop susceptibilities during each of the M growth stages would be

$$CS_I = \frac{x - i}{x}, \qquad CS_{II} = \frac{x - ii}{x} \quad \ldots\ldots\ldots \quad [10] \qquad \vdots \qquad CS_M = \frac{x - m}{x}$$

This is an experimental approach to determining CS and is best adapted to field experiments where the soil water variable can be at least partially controlled. One method for water control is to put a plastic barrier under the rows with flaps extending above ground so that the crop root zone can be covered and hence protected from rainfall or irrigation during the stress period. Field experiments are desirable so that the natural environment will be simulated as closely as possible. Experiments with soybeans, Southern peas and peanuts are currently underway to evaluate CS in this manner. A more sophisticated approach to CS determination which is similar to this one is to relate carbon accumulation per day or photosynthetic rate to SD.

A second method for CS characterization is to plot the crop yield (abscissa) versus cumulative SD for a given growth period (ordinate). Then the value of CS for each period is the slope of the plot related to that period, i.e.

$$CS_i = \frac{\Delta SD_i}{\Delta \text{ Yield}} \quad . . . . [11]$$

where i denotes the growth period. It should be noted that by this method CS is not determined independently of SD. Also the SD-value is only an incremental value while the yield is a total value for the growing season. Both of these methods for CS determination force SDI to be inversely proportional to crop yield.

Thus, there are several alternatives for the calculation of SD and CS. Having chosen the suitable approach for calculating each factor, it is possible to calculate values of SDI on a daily basis, on a growth stage period basis, or for the entire growing season as desired.

RESULTS

Irrigation experiments were conducted during the 1968 and 1969 growing seasons at College Station and Stephenville, Texas. The results of these experiments are useful in illustrating the SDI concept.

Grain sorghum (variety, RS–671) was grown at College Station, Texas in a sheltered lysimeter installation which has been previously described (Hiler, 1969). It should be noted here that the influence of rainfall was eliminated from the experiment by a movable shelter which automatically covered the lysimeter area when rainfall occurred. Also, the undisturbed soil cores in the lysimeters consist of Travis fine sandy loam soil which has an 18-in. A-horizon of fine sandy loam and a B-horizon of red sandy clay.

Peanuts, (variety, Starr) were grown at the Texas A&M–Tarleton Experiment Station, Stephenville, Texas in a field plot installation. The soil at this site was Duffau fine sandy loam which has an A-horizon consisting of fine sandy loam and a B-horizon of red sandy clay. The rainfall variable could not be controlled here.

The irrigation treatments in the aforementioned experiments follow.

I. Irrigate when tensiometer readings in the crop root zone equal 40 centibars in the amount of 1.1 times the water losses from I.

II. Irrigate when tensiometer readings in the crop root zone equal 70 centibars in the amount of 1.1 times the water losses from II.

III. Irrigate when I is irrigated in the amount of 0.7 times the water losses from III.

IV. Irrigate when II is irrigated in the amount of 0.7 times the water losses from IV.

The water losses were determined at College Station by soil moisture measurements with the neutron method and at Stephenville by calculation of actual evapotranspiration from climatological and crop measurements using the van Bavel method (1966, 1967). Details of this latter calculation are presented elsewhere (Hiler, Tackett and Clark, 1970).

Relationships between SDI and yield are presented for grain sorghum and peanuts in Fig. 1 and 2, respectively. The values of SD were determined from equation [9] while CS values were determined from equation [11]. Potential evapotranspiration in centimeters per day was determined using the van Bavel method (1966, 1967) with the value of the surface roughness, Z_o, equal to two centimeters. The units of soil water potential were centibars. The three lines in Fig. 1 were determined by calculating CS using Treatments I and III only, Treatments II and IV only, and Treatments I, II, III and IV. The y-intercept for each of the lines is an indication of the potential crop yield if no crop water stress had occurred, for the given conditions of soil fertility, insect damage, etc. It must be emphasized at this point that the SDI concept does not account for interactions between crop water stress and soil fertility. Theoretically this potential yield should be the same for all three lines if the SDI concept is valid. The maximum difference between the y-intercept values in Fig. 1 is less than five percent. The two lines shown in Fig. 2 also have similar y-intercept values. These lines indicate that sprinkler irrigation may be more desirable than furrow irrigation for peanuts. Most of the difference in return resulted from differences in peanut quality rather than quantity of yield.

The CS values as determined from equation [11] are shown in Table 1. Two observations concerning these data warrant comment. First it appears that peanuts are more susceptible to crop water deficiency than is grain sorghum. However, this is not necessarily true because sorghum yields were expressed in pounds per acre while peanut yields were expressed in dollars per acre. This approach was used for peanuts because

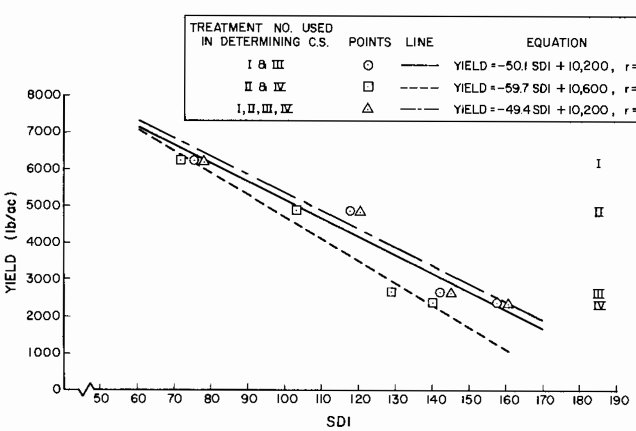

FIG. 1 Stress day index versus grain sorghum yield–College Station, Texas, 1969.

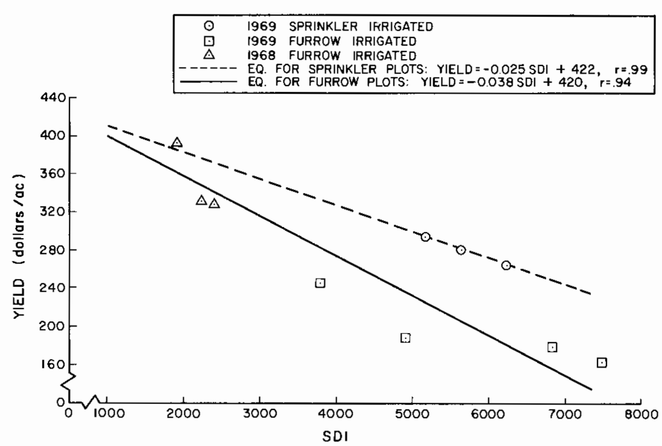

FIG. 2 Stress day index versus peanut yield with sprinkler and furrow irrigation–Stephenville, Texas, 1968–1969.

TABLE 1. CROP SUSCEPTIBILITY VALUES FOR GRAIN SORGHUM AND PEANUTS DETERMINED FROM EQUATION [11]

Crop	Growth stage	CS-I and III	CS-II and IV	CS—All treatments
Grain sorghum	Vegetative 0-25 cm height	0	0	0
Grain sorghum	Vegetative 25-60 cm height	2.0×10^{-2}	1.0×10^{-2}	2.5×10^{-2}
Grain sorghum	60 cm – boot	4.6×10^{-2}	4.1×10^{-2}	4.2×10^{-2}
Grain sorghum	boot – bloom	6.2×10^{-2}	8.2×10^{-2}	6.7×10^{-2}
Grain sorghum	soft dough-harvest	11.0×10^{-2}	8.0×10^{-2}	11.1×10^{-2}
Peanuts	Anthesis			3.5
Peanuts	Peak flowering and early pegging			3.7
Peanuts	Peak pegging			1.7
Peanuts	Early nut development			2.8
Peanuts	Intermediate nut development			2.2
Peanuts	Late nut development			0.7

NOTE: Values for peanuts were determined from yields expressed in dollars per acre while those for grain sorghum were from yields in pounds per acre. This is the reason for the large differences in magnitudes between the values for peanuts and grain sorghum. This was done because peanut quality is extremely important in determining gross return.

peanut quality is extremely important in determining gross return. The important consideration in Table 1 is to compare the relative magnitudes of the CS values within each crop for different growth stages, rather than the absolute magnitudes. Second there is considerable difference between the calculated CS values for grain sorghum when Treatments I and III only were considered as compared to when Treatments II and IV only were considered. It can be noted from the definition of the treatments that Treatments II and IV were subjected to a greater combined potential stress than were Treatments I and III. This points out the importance of having CS values determined from an independent experiment where the crop is subjected to a critical SD value at specific growth stages. Hence, it appears that CS will be determined more reliably using equation [10] than if equation [11] is used.

Data are available in the literature which will permit CS determinations by equation [10] (see references 1, 2, 6, 7, 8, 9, 12, 22, 23). The CS values calculated from the results of these experiments are given in Table 2. These data indicate that for many crops the most critical growth stage occurs near the onset of anthesis. Various studies on crop responses to water at different growth stages is reviewed and summarized by Salter and Goode (1967).

DISCUSSION . . .UTILITY OF SDI CONCEPT

The stress day index concept is useful in irrigation scheduling, in interpreting results of irrigation experiments and in predicting yields for given crop water stress conditions. Each of these applications will be discussed briefly.

Most irrigation scheduling today is done either through past experience based on visual observations or through measurements of the soil water status. It is a well known fact that crop growth and yield are determined directly by the plant water stress and only indirectly and partially by the soil water status (Kramer, 1969). This suggests that irrigation scheduling should be based on plant water stress which incorporates soil water deficit, atmospheric evaporative demand, rooting density and distribution, crop susceptibility, etc. rather than on soil water status alone. Plant water stress is determined with the stress day index concept, as the product of the plant water deficit (SD) and the crop susceptibility at a given growth stage to that deficit (CS).

It is proposed that the daily SDI value (daily SD times daily CS) be used in scheduling of irrigations. By this approach, irrigation is started simply when the daily SDI value reaches a predetermined critical level, SDI_o. This level would be the same throughout the growing season. This method is more desirable than present rational irrigation scheduling methods because it is based on plant water stress (incorporating all the aforementioned factors and possibly others) and not just on soil water status alone.

The SDI concept is valuable also in interpreting results of irrigation experiments. The concept permits one to

TABLE 2. CROP SUSCEPTIBILITY VALUES FOR VARIOUS CROPS DETERMINED FROM EQUATION [10]

Crop	Growth Stage	CS
Barley (1)*	Vegetative	0.07
Barley	Anthesis	0.37
Barley	Grain-swell	0.34
Corn (2)	Tassel emergence	0.06
Corn	Silking-pollination	0.73
Corn	Blister kernels	0.48
Corn (9)	Vegetative	0.25
Corn	Silking	0.50
Corn	Ear	0.21
Cotton (12)	Early flowering	0.21
Cotton	Peak flowering	0.32
Cotton	Late flowering	0.20
Onions (8)	Seedling	0.04
Onions	Beginning of bulb formation	0.41
Onions	1/3 of bulb's maximum weight	0.29
Onions	1/2 of bulb's maximum weight	0.19
Potatoes (7)	Seeding to sprouting	0
Potatoes	Sprouting to appearance of stolens	0.38
Potatoes	Appearance of stolens to beginning of tuberization	0.43
Potatoes	Beginning of tuberization to 1/3 of tuber's maximum weight	0.21
Potatoes	1/3 to 2/3 of tuber's maximum weight	0.25
Potatoes	2/3 of tuber's maximum weight to maturity	0.10
Wheat (6)	Jointing	0.48
Wheat	Flowering	0.43
Wheat	Dough	0.37
Grain Sorghum (22)	6 to 8 leaf stage	0.12
Grain Sorghum	Mid to late boot	0.36
Grain Sorghum	Heading and flowering	0.45
Soybeans (23)	Bloom	0.47
Soybeans	Early fruit	0.22
Soybeans	Late fruit	0.27

*Numbers in parenthesis refer to appended references.

analyze crop yield results directly in terms of crop water stress rather than indirectly in terms of frequency or amount of applied irrigation water. Given that all factors other than crop water stress which affect yield do not change significantly, relationships similar to those presented in Fig. 1 and 2 can be used to predict crop yields for known crop water stress conditions.

SUMMARY

The stress day index concept (SDI) provides a quantitative means for determining the stress imposed on a crop during its growing season. This paper concerns quantitative characterization of water stress in crops with SDI and its effect on crop yields. The stress day index is determined from a stress day factor (SD) and a crop susceptibility factor (CS) as given in equation [1]. The stress day factor is a measure of the degree and duration of plant water deficit. The crop susceptibility factor indicates the plant's susceptibility to water deficit at different growth stages.

Alternative approaches to determination of SD and CS are given. The SD alternatives are based on physical theory of flow of water in the soil-plant-atmosphere continuum and are given in equations [4], [5], [8], and [9]. Two alternative approaches to the characterization of CS are given in equations [10] and [11].

Relationships between SDI and yield are determined from results of grain sorghum and peanut irrigation experiments. These results indicate the desirability of utilizing equation [10] over equation [11] for determining CS. Values of CS obtained by utilizing equation [10] are presented. These values are based on results of irrigation experiments given in the literature.

Finally various applications of the SDI concept are discussed briefly. These include irrigation scheduling, prediction of yields for given crop water stress conditions, and interpretation of irrigation experiments.

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List of Symbols

SDI	–	stress day index
CS	–	crop susceptibility factor
SD	–	stress day factor
E	–	transpiration rate
ψ	–	leaf water potential
ψ_s	–	soil water potential
R_p	–	plant impedance to water flow
R_s	–	soil impedance to water flow
ψ_w	–	critical leaf water potential
E_w	–	maximum rate of water supply from soil to plant
E_d	–	atmospheric evaporative demand
r_s	–	surface diffusion resistance of crop canopy