

# Use of Canopy-air Temperature Differentials as a Method for Scheduling Irrigations in Snap Beans

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**Abstract.** Two field experiments were conducted during 1981–1982 to determine the feasibility of using midday canopy temperatures, measured with an infrared radiation thermometer, for irrigation scheduling in 'Oregon 1604' and 'Galamor' snap beans (*Phaseolus vulgaris* L.). Treatments which allowed various levels of positive canopy minus air temperature differences [stress-degree-days (SDD)] to accumulate between irrigations were evaluated along with a treatment irrigated at 4 growth stages, a dry treatment, and a control treatment which was irrigated at  $-0.06$  MPa soil water potential (SWP). Diurnal measurement of canopy and air temperatures indicated that the greatest differences between canopy and air temperature occurred near solar noon. In 1981, all treatments irrigated by an accumulation of positive SDD had reduced yields compared to the control SWP treatment. In 1982, under higher rainfall and lower air saturation vapor pressure deficits (VPD) than in 1981, yields of the SDD irrigated treatments were comparable to those obtained with the SWP treatment. Accumulation of positive SDD values to schedule irrigations was adequate when midday VPD values were low. However, when high VPD occurred, SDD values were always negative. A model is presented in which SDD values can be adjusted for environmental variability to more accurately schedule irrigations. Measurements of air temperatures within the canopy were made and compared to surface canopy temperatures measured with an infrared thermometer. Regression analysis showed that canopy temperature could be predicted using the air temperature within the canopy ( $R^2 = 0.89$ ). The sum of SDD values for the season was used to estimate canning maturity pod yield ( $R^2 = 0.65$ ).

Effective irrigation scheduling is necessary to obtain optimum yields in semi-arid climates or where rainfall is un dependable or insufficient. Recently, the use of remotely sensed plant canopy temperatures has been suggested as a method for scheduling irrigations (4, 9, 10, 14).

Transpiration of water from plant leaves cools them due to the large latent heat of vaporization of water relative to the heat capacity and thermal conductivity of plant tissue and air (3). Temperature depressions for given conditions should be proportional to the transpiration rate (17, 21). In turn, transpiration rates depend on leaf-to-air vapor pressure difference and on stomatal plus boundary layer resistance. However, continued transpiration results in soil water depletion, which results in a decrease in transpiration rate and an increase in canopy temperature. This increase in canopy temperature can be used as an indicator of plant water stress (7, 15, 19) and temperature differences between unstressed and stressed plants have been reported ranging from  $1^\circ$  to  $2^\circ\text{C}$  up to  $6^\circ$  to  $7^\circ$  for many crops (2, 6, 19, 23).

Several methods have been suggested recently to utilize remotely sensed leaf temperatures for irrigation scheduling. One method associates increased leaf temperature variability in a field with an increase in plant water stress (4, 9). Aston and van Bavel (1) suggested that the onset of stress could be detected by comparing the increase in leaf temperature of a stressed plot to that of an unstressed plot. Geiser et al. (10) suggested that plants could be irrigated when canopy-air temperature differentials exceed a predetermined value based on measured net radiation and relative humidity.

A 4th method, described by Jackson et al. (14) utilizes the stress-degree-day (SDD) concept originally developed by Idso et al. (11) to predict yields. The SDD concept is defined as:

$$\text{SDD}_i = (T_c - T_a)_i$$

where  $T_c$  is the canopy temperature and  $T_a$ , the air temperature measured about one hr after solar noon on day  $i$ .

According to Idso, if the plant has adequate water,  $T_c - T_a$  will be near zero or negative; if it is water stressed,  $T_c - T_a$  will be greater than zero. The sum of the accumulated positive values of  $T_c - T_a$  can serve as an index of when to irrigate. For wheat in Phoenix, Ariz., for example, the positive SDD value is set at 10 (5, 14). In California, the positive SDD value for dry beans is 15 (18).

Using the above information, especially that described by Idso et al. (11) and Jackson et al. (14), a 2-year field study was conducted, the objectives of which were: 1) to determine if an elevation in leaf temperature, induced by water stress, can be used to schedule irrigations in snap beans, and 2) to evaluate the usefulness of canopy-air temperature differences in yield predictions as originally described by Idso et al. (11).

## Materials and Methods

Two field experiments were conducted during 1981–1982 at the Oregon State University Vegetable Research Farm on a Chelalis silty clay loam soil that had an average available water-holding capacity of 6.4 cm per 0- to 30-cm depth. At planting, the soil was at field capacity. Details of the experimental site were described previously (8, 17).

The plots were in a randomized complete-block design with irrigation treatments as main plots (6 m  $\times$  6 m) and snap bean cultivars, 'Oregon 1604' and 'Galamor', as subplots. Plant spacing was 91 cm between rows and 3.7 cm within rows so that a density of 30 plants/m<sup>2</sup> was achieved. Four replications were used and plots were separated by 15 m of bare soil so that irrigation of one treatment by overhead sprinklers, at a rate of

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9 mm/hr, would not influence another treatment. According to soil tests, fertilizer at 56 kg N, 74 kg P, and 47 kg K/ha was banded at planting.

Canopy temperatures were measured with a handheld, infrared radiation thermometer (IRT) (Telatemp Corp., Fullerton, Calif. Model AG-42). The instrument has a field of view of 5°, a sensing window of 10.5 to 12.5 μm, a resolution of 0.1°, and an accuracy of 0.5°. Ambient air temperature and air temperature within the canopy were measured using a CR-5 digital recorder fitted with A104-T temperature integrators (Campbell Scientific Inc., Logan, Utah). Copper-constantan thermocouples were placed within the canopy at a height of 15 cm from the soil surface or in a weather shelter located over bare soil. Measurements began when first trifoliolate leaves were fully expanded and continued until harvest.

Scheduling of irrigation was based on either soil water potential, as measured by gypsum electrical resistance soil moisture blocks (20), plant growth stages (GS), or accumulation of positive SDD values. Number of irrigations and amounts of water applied are shown in Table 1. Enough water was applied at each irrigation to return the soil to field capacity. Gypsum blocks were placed between plants of 'Oregon 1604' at 15-, 30-, and 45-cm depths in all plots and were read 3 times weekly. Block readings at 15 cm were used for scheduling the first one or 2 irrigations while those at 30 cm were used to schedule later irrigations. In the growth stage treatment, plants were irrigated 4 times after establishment as follows: 1) at full expansion of the first trifoliolate leaf; 2) the day before first bloom; 3) at the end of flowering and the beginning of pod fill; and 4) at about 5 days before harvest. The growth stages of 'Oregon 1604' were used to delineate the above stages for both cultivars.

Canopy temperature measurements were made in all plots soon after solar noon (1330–1430 PDT) on a daily basis. In addition, on 6 days in 1981, 7 sets of measurements were made at 2.5 hr intervals from 0430–2200 (PDT). Five measurements were made on each plot from the SE, S, SW, NW, and NE directions. Row orientation was east-west. Positive SDD values were accumulated using the equation:

$$SDD = \sum_{i=1}^N (T_c - T_a)_i$$

where  $T_c$  is the average of 20 IRT midday measurements per treatment and  $T_a$  is the ambient air temperature measured in a weather shelter within the plot area. Values of  $T_c - T_a$  less than zero are equal to zero. The index,  $i$ , is the first day after irrigation, and  $N$  is the number of days required to reach a prescribed value of positive SDD. In 1982, a treatment was added in which  $T_a$  was adjusted based on the data in Fig. 5. The procedure is discussed later. The resulting canopy-air temperature difference is referred to as the adjusted SDD value (SDDa).

A once-over hand-harvest to simulate machine harvest was made at snap bean canning maturity on a 60-plant sample from each plot. Pods from all replications of a given treatment were bulked for sieve size grading. In order to compare treatment response to differential irrigation, yields were adjusted to a common 50% sieve sizes 1–4 if the proportion of pod yield in this size range reached a value of less than 60%. The 50% value is obtained by adjusting the yield 1% for each 1% deviation from the 50% value. Specific treatments within each experiment are covered separately below.

*Expt. 1 (1981).* Six irrigation treatments were as follows: –0.06 MPa soil water potential (SWP), 10 positive SDD (10 SDD), 15 positive SDD (15 SDD), 25 positive SDD (25 SDD), a growth stage (GS), and a dry treatment. 'Oregon 1604' and 'Galamor' were seeded on June 19. Emergence was on June 25 for 'Oregon 1604' and on June 26 for 'Galamor'. All plots were irrigated on June 24 with 9 mm of water to help establish the plants. This irrigation is counted in treatment totals. Rainfall from planting to harvest was 3.5 mm. First bloom (when about 10% of the plants had open flowers) for 'Oregon 1604' was on July 29, 40 days after planting for the GS and dry treatments and on July 30, 41 days after planting for the SWP, 10 SDD, 15 SDD, and 25 SDD treatments. First bloom for 'Galamor' was on August 1, 43 days after planting for the GS and dry treatments and on August 2, 44 days after planting for the SWP,

Table 1. Number of irrigations, amount of water applied, and final pod yield of 'Oregon 1604' and 'Galamor' snap bean.

Treatment	Oregon 1604			Galamor		
	No. irrigations	Water applied (mm)	Yield (MT/ha)	No. irrigations	Water applied (mm)	Yield (MT/ha)
			<i>1981</i>			
SWP	8	209	18.4 a <sup>2</sup>	9	245	18.3 a
10 SDD	4	98	12.9 b	5	148	11.3 b
15 SDD	4	111	11.5 b	4	111	9.8 bc
25 SDD	2	62	9.8 b	2	62	5.7 cd
GS	5	160	11.9 b	5	160	11.2 b
Dry	1	9	4.1 c	1	9	2.8 d
			<i>1982</i>			
SWP	7	160	20.6 ab	8	187	19.6 a
10 SDD	4	125	17.9 b	4	125	16.4 a
5 SDD	4	98	18.9 ab	5	133	17.0 a
5/1 SDD	5	138	23.9 a	6	174	20.8 a
GS	5	151	21.1 ab	5	151	19.8 a
Dry	1	9	11.2 c	1	9	10.6 b
10/2 SDDa	5	138	24.7 a	6	174	19.2 a

<sup>2</sup>Mean separation between cultivar and within year by Duncan's multiple range test, 5% level.

10 SDD, 15 SDD, and 25 SDD treatments. Harvest for 'Oregon 1604' was on August 20, 62 days after planting. 'Galamor' was harvested on August 26, 68 days after planting. A summary of environmental data is shown in Table 2.

*Expt. 2 (1982).* Seven irrigation treatments were as follows: SWP, 10 SDD, 5 positive SDD (5 SDD), 5/1 positive SDD (5/1 SDD), and 10/2 positive adjusted SDD (10/2 SDDa). The 5/1 SDD and the 10/2 SDDa treatments each had 2 levels of either SDD or SDDa accumulation, the upper number for the vegetative stage and the lower number for the reproductive stage. First bloom for 'Oregon 1604' was considered to be the beginning of the reproductive stage for both cultivars. Plots were seeded on June 8 and emergence was on June 16 for 'Oregon 1604' and on June 17 for 'Galamor'. All plots were irrigated on June 19 with 9 mm of water to help establish the plants. Rainfall from planting to harvest was 51 mm. First bloom was on July 20 for 'Oregon 1604', 42 days after planting and on July 24 for 'Galamor', 46 days after planting. Harvest for 'Oregon 1604' was on August 12, 65 days after planting. 'Galamor' was harvested on August 19, 72 days after planting. A summary of environmental data is shown in Table 2.

### Results and Discussion

*Diurnal changes in canopy temperature.* Since the canopy temperature differences measured between cultivars were within the accuracy range of the IRT, canopy temperature measurements for the 2 cultivars were combined. Canopy temperatures reached a daily maximum value earlier than did ambient air temperature (e.g., August 17, 1981, in Fig. 1). All canopy temperatures were lower than air temperature at predawn and in the late afternoon. The canopy temperature of the SWP treatment remained lower than air temperature throughout the day while the canopy temperature in the dry treatment was higher than air temperature from midmorning to late afternoon. Leaf canopy temperature reached a maximum value at solar noon when incoming solar radiation was at its peak. Since the air temperature maximum lagged behind the irradiance maximum, the SDD value of a stressed plant had its maximum daily value near solar noon. These data are in agreement with the results of Ehrlar et al. (7) and Palmer (19). On days when the VPD level was very high, however, the stressed plants had canopy temperatures which were lower than air temperature for the entire day.

Irradiance level, as influenced by cloud cover, also had an effect on leaf temperature. If the irradiance level was rapidly decreased by a passing cloud, leaf temperatures dropped by as

Table 2. Summary of environmental data from planting to harvest.

Measurement	1981	1982
Avg max air temp (°C)	27.3	25.7
Avg min air temp (°C)	10.9	11.1
No. days max air temp > 32°C	10	3
Avg irradiance at solar noon ( $\mu\text{Es}^{-1}\text{m}^{-2}$ )	1635	1512
No. days solar noon irradiance < 1500 $\mu\text{s}^{-1}\text{m}^{-2}$	10	17
Total rainfall (mm)	3.5	51
Avg min relative humidity (%)	37.7	39.5
Avg air vapor deficit at solar noon (mb)	26.8	16.4
Total pan evaporation (mm)	427	400
Avg pan evaporation per day (mm)	6.1	5.5

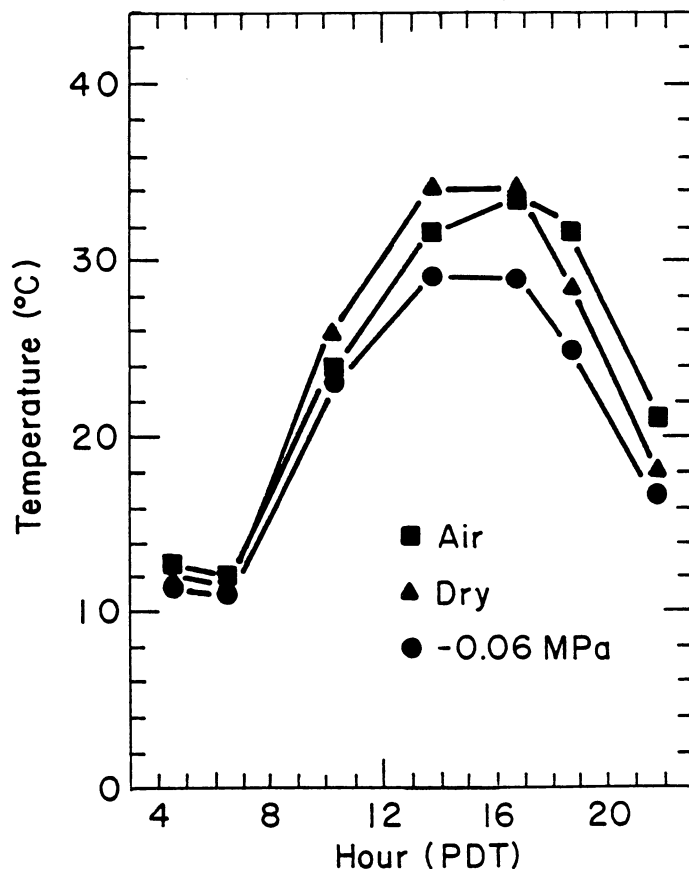


Fig. 1. Diurnal fluctuation of snap bean canopy temperatures in the dry treatment and the treatment irrigated at  $-0.06$  MPa soil water potential, as compared to ambient air temperature on August 17, 1981 (59 days after planting).

much as  $4^{\circ}$  to  $5^{\circ}\text{C}$  within 60 sec. After the cloud passed, leaf temperatures returned to their original values just as quickly. Air temperature response, as a result of fluctuations in irradiance level, was not as rapid. On days when a complete cloud cover persisted until during or just before midday temperature measurements, SDD values were exaggerated. Conversely, if irradiance was reduced by clouds just before or during the measurement period, then SDD values were lower than would be expected.

*Yields.* In 1981, the SWP treatment produced yields that were significantly higher than any other treatment. It also received almost twice as much water as the 10 or 15 SDD treatments (Table 1). In 1982, under cooler and wetter conditions than in 1981 (Table 2), only the dry treatment yielded significantly less than the SWP treatment (Table 1). Also in 1982, there was less difference in the total amount of water applied between the SWP and SDD irrigated treatments. The 10 SDD treatment, for 'Oregon 1604' had reduced yields compared to the 10/2 SDDa and 5/1 SDD treatments. The lower yield of the SWP treatment as compared to the 10/2 SDDa or 5/1 SDD treatments may have been due to excessive irrigation, resulting in early lodging of the plants and the subsequent occurrence of white mold.

*SDD accumulation.* During 1981, temperature extremes near  $40^{\circ}\text{C}$  occurred between 48 and 55 days after planting (Fig. 2). These extreme temperatures did not occur during the 1982 growing season (Fig. 3). During this extreme temperature period, positive SDD accumulation was very slow, due to canopy temperature being cooler than air temperatures (Fig. 4). On days when maximum temperatures were between  $20^{\circ}$  and  $30^{\circ}$ , positive

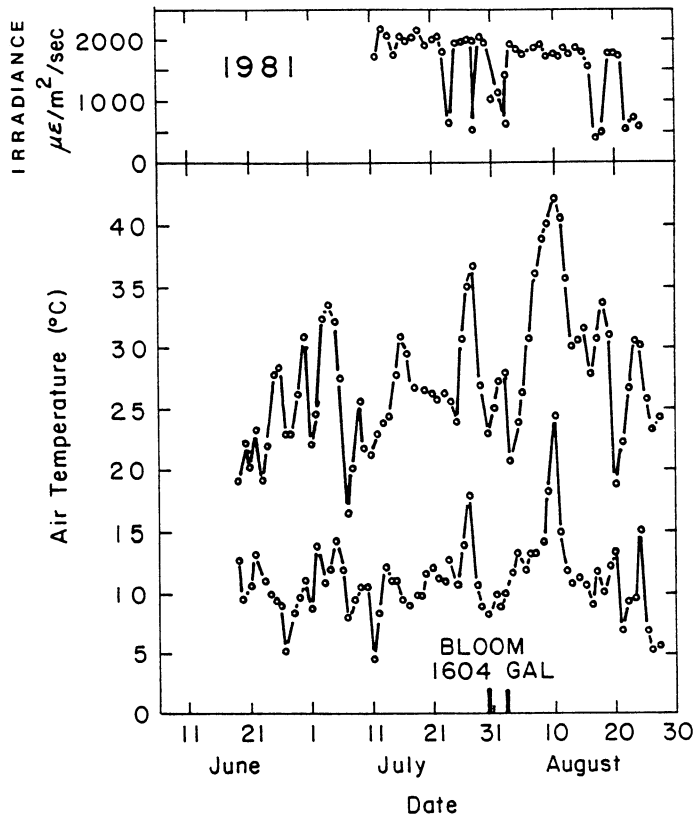


Fig. 2. Daily maximum and minimum air temperatures and incoming solar radiation at (irradiance) midday in 1981.

SDD accumulation was more rapid. To analyze this phenomenon, SDD values of the SWP treatment within 3 days of each irrigation were plotted against air vapor pressure deficit (VPD) (Fig. 5, curve A). As VPD levels increased, canopy temperatures

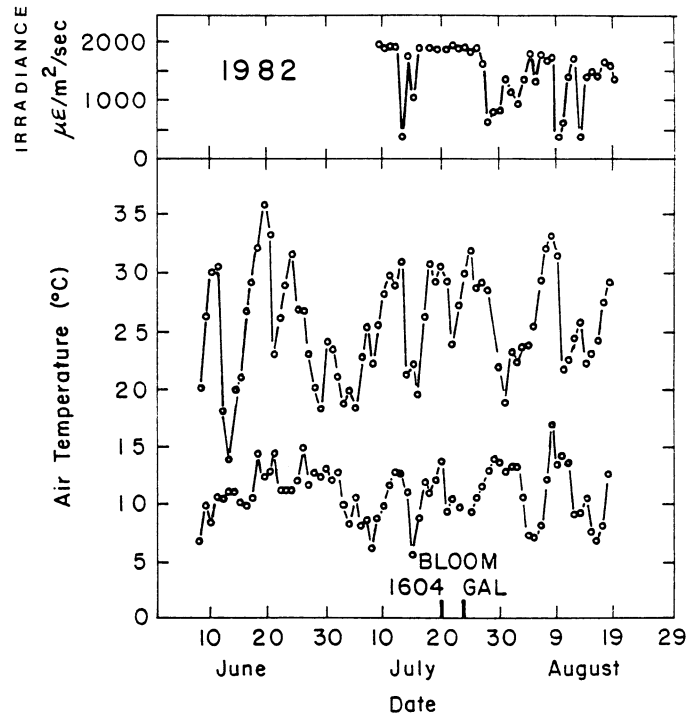


Fig. 3. Daily maximum and minimum air temperatures and incoming solar radiation (irradiance) at midday in 1982.

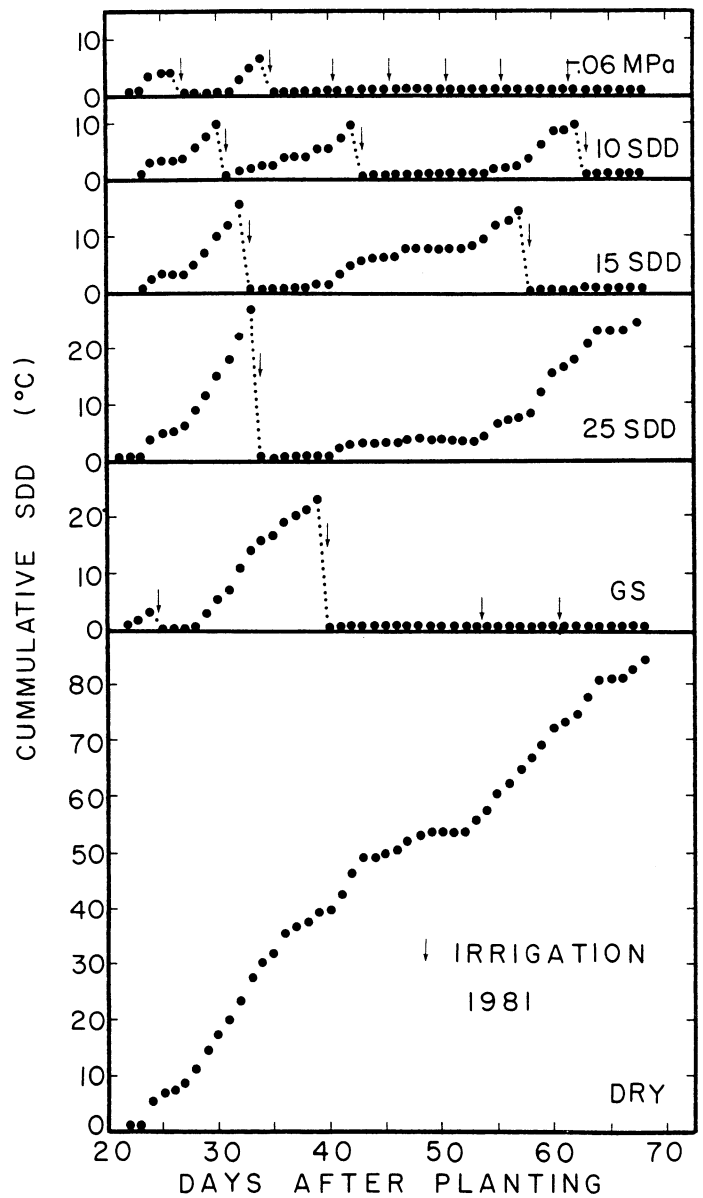


Fig. 4. Accumulation of positive canopy-air temperature differences (SDD) between irrigations of snap beans in 1981.

of the SWP treatment became cooler compared to ambient air temperature (i.e., SDD values became more negative).

Also plotted in Fig. 5 are SDD values vs. VPD for the dry treatment (curve B). As indicated, at high VPD even the most water-stressed plants had leaf temperatures which were lower than ambient air. Hence, even though the greatest stress levels may have occurred at high VPD, positive SDD values did not accumulate. The relationship between SDD and VPD is similar to that suggested by Idso et al. (12, 13); however, it differs in 2 ways. First, our data include values only from midday measurements while that used by Idso includes values from 2 to 3 hr after sunrise to 2 to 3 hr before sunset. Since it was determined by Idso et al. (12, 13) that midday measurements of leaf and air temperatures are best for determination of SDD values, it would follow that only midday values should be used. Secondly, the line representing maximum SDD accumulation (curve B), is not a horizontal line, as Idso suggested, but rather can best be fitted by an inverse quadratic function.

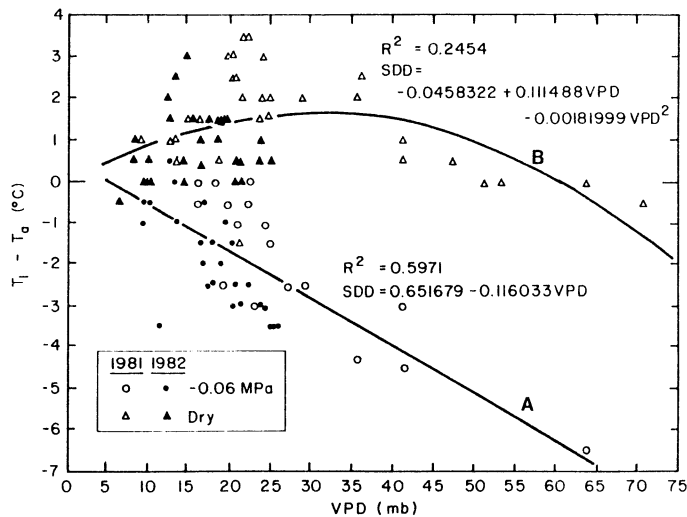


Fig. 5. Effect of increasing air vapor deficit (VPD) on midday canopy-air temperature differences (SDD) in the  $-0.06$  MPa soil water potential (curve A) and dry (curve B) treatments of snap beans in 1981 and 1982.

In one case, as many as 6.5 positive SDD values accumulated between 2 irrigations during the vegetative period in the SWP treatment (from 27–35 days after planting); however, no positive values were measured during the reproductive stage (Fig. 4). This indicates that high yields can be obtained even if more positive SDD values accumulate during the vegetative stage than during the reproductive stage.

Based on the 1981 data presented in Fig. 4 and 5, the following conclusions were made: 1) when VPD are low, positive SDD values do accumulate; however, 10 positive SDD values are probably too many to allow to accumulate between irrigations; 2) more positive SDD values could be allowed to accumulate between irrigations during the vegetative stage than during the reproductive stage and not influence yield; and 3) when high VPD occur, the method of calculating SDD values would have to be modified to allow positive SDD accumulation.

As a result, during the 1982 season, 3 SDD treatments were included which allowed fewer positive SDD values to accumulate between irrigations. Since temperature extremes during the 1981 season were above normal, it was felt that during a more normal season lower values of positive SDD accumulation might be sufficient to obtain yields as high as the SWP treatment. In addition, a treatment (10/2 SDDa) was added in which the SDD equation was modified in the following way.  $T_a$  in the equation was lowered or raised depending on the distance of curve A from the zero line in Fig. 5. If the air temperature was  $25^\circ\text{C}$  at a VPD of 30 mb, then the  $T_a$  would be lowered by  $3^\circ$ , resulting in an adjusted  $T_a$  value of  $22^\circ$ . The measured canopy temperature would then be compared to  $22^\circ$  instead of  $25^\circ$ . This method ensures positive SDD accumulation under any environmental condition. Fig. 6 shows the positive SDD and SDDa accumulation in 1982. As indicated, positive SDDa values accumulated faster than did positive SDD values. In the 10 SDD treatment, for example, 10 SDDa values accumulated 13 days sooner than did 10 SDD values.

*Within canopy air temperature.* Measurements of air temperature within the plant canopy were used successfully to estimate canopy temperature (Fig. 7). If taken by an automatic temperature recorder, they could prove to be a useful tool on days when actual measurement of canopy temperature with an IRT is not possible.

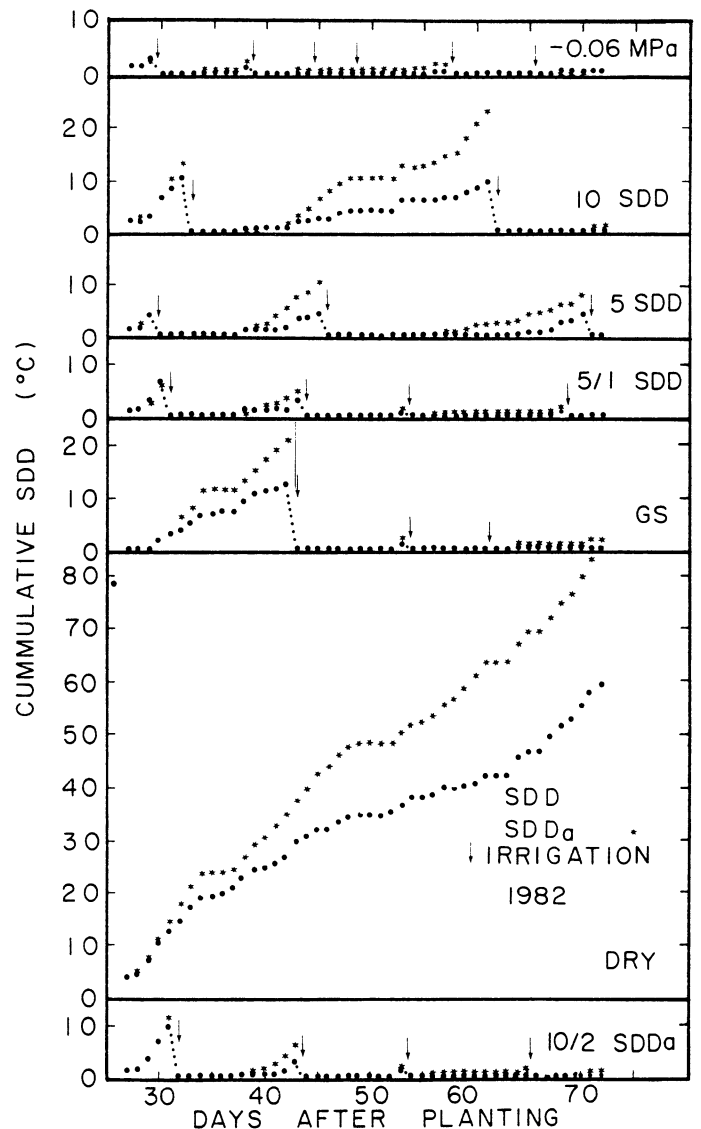


Fig. 6. Accumulation of positive canopy-air temperature differences (SDD) and environmentally adjusted SDD (SDDa) values between irrigations in snap beans in 1982.

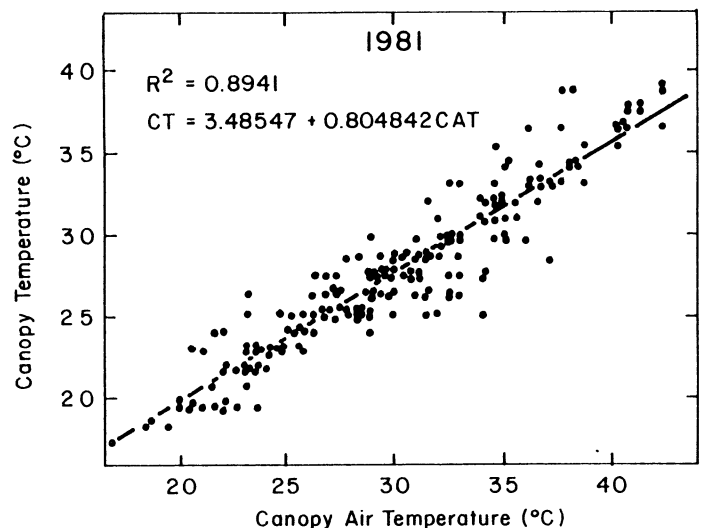


Fig. 7. Air temperature measurements within a snap bean canopy (CAT) vs. canopy surface temperature (CT), both measured at midday in 1981.

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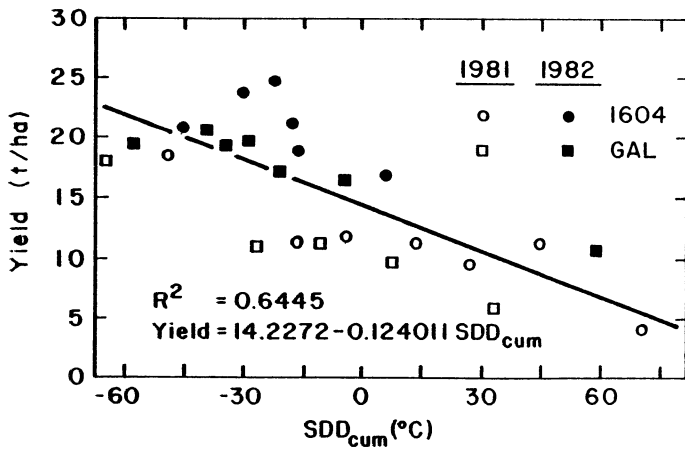


Fig. 8. Cumulative canopy-air temperature differences (SDDcum) vs. yield of 2 snap bean cultivars, 'Oregon 1604' and 'Galamor', as influenced by differential irrigation in 1981 and 1982.

**Yield predictions.** Yields are plotted against a sum of SDD (SDDcum) (Fig. 8). The data indicate that SDDcum values can be used to predict yields of snap beans using only IRT measurements ( $R^2 = 0.65$ ). This technique was suggested originally by Idso et al. (11) working with wheat. However, in the present study, the highest levels of significance were achieved when each cultivar and year was regressed individually. For example, in 1981, the  $R^2$  value for the regression of SDDcum vs. yield for 'Oregon 1604' was 0.92. Also, the relationship was improved significantly (0.80 vs. 0.90 for 'Oregon 1604' and 'Galamor' combined in 1981) when data from full expansion of the first trifoliolate leaf through harvest were used rather than by using only data from the reproductive stage. This is contrary to that proposed by Idso et al. (11) in studies with wheat, and Walker and Hatfield (22) in studies with red kidney beans. However, because of the period required to fill the seeds in wheat and red kidney beans, the reproductive stage is much longer than for snap beans. This observation illustrates the importance of crop water status during the vegetative stage of growth in determining final yield in snap beans, and may hold true for other fresh crops.

## Conclusions

The SDD method has been used successfully to schedule irrigations in areas with low environmental variability. However, in areas with high day-to-day variability in temperature and VPD, this system is not adequate.

A model is presented in which SDD values can be adjusted for environmental variability using air VPD measurements. With this modification, irrigations can be scheduled successfully and maximum yields can be obtained using only remotely sensed plant canopy temperatures, ambient air temperatures, and relative humidity measurements.

SDDcum values can be used successfully to estimate final pod yield. Because of the short reproductive period in snap bean culture, SDD values should be accumulated from full expansion of the first trifoliolate leaf until harvest, rather than during the reproductive stage only, as suggested for dry seed crops.

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