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An Agrometeorological Model for Assessing the Effect of Heat Stress During the Flowering and Early Fruit Set on Avocado Yields[1]

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ABSTRACT. **An agrometeorological model was developed for assessing the effect of heat stress during flowering and early fruit set on avocado *(Persea americana* Mill) yields. This model accounted for heat stress only and was considered to occur when the daily maximum temperature was >33°C. In addition to the daily maximum temperature, the model considered the duration of such temperatures in days, as well as the timing of the occurrences of such temperatures in relation to the flowering and early fruit set of 'Fuerte' avocado. The specifications of the climatic data inputs are based on experimental results in the temperature range of 33° to 43°C extrapolated linearly. A series of weighting factors were used for the duration of heat spells in days. In the temperature range of 33° to 35° the weighting was n - 1; for the 36° to 38° range, 1.4^n; and for the 39° to 43°C range, 2.0^n. Weighting factors for the timing of the occurrence of heat spells follow closely the near-normal percentage distribution curve of open flowers. At bud burst in March, the weighting is 0.4, increasing to 1.3 at early fruit set by mid-May and decreasing rapidly to 0.3 by the end of June. The functional relationship between the model heat stress output and the yield of avocado for an irrigated, high-yielding plantation shows fairly good correlation, r^2 = 0.42 to 0.51, depending on the statistical method used. The agreement between the heat stress index and the yield of avocados is closely related only during those years when the plantation is subject to heat stress indexes greater than 10. Testing the model on independent data commenced in 1985 and includes a yield memory term.**

Avocados are relatively new to Israel. Introduced commercially at the end of the 1950s and early 1960s, plantations expanded rapidly and accounted for ≈12,000 ha. The average yield of avocado is ≈10 $t \cdot ha^{-1}$, but considerable yield fluctuations occur from year to year. The coefficient for variation of the yield is about 40% to 50%, depending on climate, cultivar, and site-specific factors. Avocados are grown with the aid of irrigation so that soil moisture is unlikely to be a serious factor limiting production.

Temperatures, on the other hand, fluctuate considerably during flowering and fruit set. It is assumed that, in addition to physiological control mechanisms, temperature

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fluctuations are responsible for the major part of the variability in yields of avocados. Under similar climatic conditions in California, Hodgson (8) considered three climatic factors to be limiting to avocado cultivation: a) frost during the winter season; b) low mean minimum temperatures during flowering and fruit setting; and c) sudden heat waves during fruit set.

Great care has been taken in Israel during the introductory period to select sites that are frost-free (11). Topoclimatological surveys on a national scale have been carried out to provide detailed information on the probability of frost occurrences and duration to avoid unsuitable sites (11, 12). Frost during the winter season therefore is not considered a major factor affecting yields.

Opinion varies regarding the negative effect of low temperatures during the flowering and fruit set. In California, it was reported that fruit set does not occur when the mean daily temperature is ≤13°C (8). Gillespie (7) stated that there was little or no fruit set if the mean night temperature was <8°. Oppenheimer (17) also observed that temperatures of at least 12° to 13° were required for successful flowering and fruit set. Other investigations indicate, however, that low temperatures only delay or retard the flowering and fruit set and are not in themselves detrimental. Tomer (25) and Sedgley (22) showed that temperatures <10° retarded flowering and fertilization, and Rotem and Leshem (19) reported that good avocado yields could be obtained even after a number of consecutive nights with a minimum temperature of 10°. Recent work by Argaman (2) clearly shows that a temperature of 7° to 8° during two consecutive nights did not affect the flowering and fruit set process. Argaman (2) and Gafni (6) concluded that the minimum temperature during the flowering and fruit set period in Israel did not usually limit avocado yields.

There is considerable evidence for the detrimental effect of high temperature on flowering and fruit set. Sedgley (22) showed a detrimental effect of 33°C day and 28° night temperatures on pollen tube growth and fruit set. This effect was confirmed by Argaman (2) under controlled climatic conditions of 32° to 35° day and 22° night temperatures. During the early stages of fruit set, there seems to be considerable sensitivity to high temperatures. Sedgley and Annells (23) reported that a high temperature of 35° during the day caused complete early fruit drop up to 10 days after fertilization. It is suggested that high temperatures during the flowering and fruit set are responsible for early abortion and low yields (3, 18). High temperatures accompanied by low relative humidity may be especially critical (10, 13). The timing of such occurrences and their duration in relation to flowering and fruit set seems especially critical in Israel (25).

The flowering process is controlled by the interaction of the genetic plant material with environment factors. The two climatic factors that play by far the most important role in controlling reproductive development are temperatures and day length. It was therefore considered that the negative impact of heat stress on the reproductive processes might to some extent be predetermined by the preceding winter temperatures.

This study was designed to model the effect of high temperatures during the day on avocado yields. Some of the damaging high temperature threshold values have been taken from the recent studies by Argaman (2) and Gafni (6), and empirical values have been introduced for the duration and timing of heat spells. The resultant heat stress index obtained was correlated with 20 years of avocado yield data for a plantation with a high level of agrotechnology. It was assumed that good correlations between a modeled heat stress index and fruit yield would indicate a cause and effect relationship and permit the quantitative assessment of the effect of extreme temperatures on flowering and early fruit set. The successful application of such a model, which is a simplified representation of a complex relationship, can provide a useful tool for assessing the long-term yield potential and its variability of areas to be planted. It can also be used for irrigation practices aimed at microclimatic modifications, in order to reduce damage to yield due to heat stress (13).

Materials and Methods

In developing a heat stress model, the following temperature "components" were taken into account: a) the daily maximum temperatures ≥33°C; b) the duration of such "high temperatures"; and c) the timing of such heat spells in relation to flowering and early fruit set. The heat stress index was the weighted product of the three components.

a) MAXIMUM TEMPERATURES—THRESHOLD VALUES. The effect of maximum temperature during flowering and fruit set of the avocado is based on the experimental work of Argaman (2) and Gafni (5). The reported threshold value of critical maximum temperature was 33°C. Increasing maximum temperatures was considered to have a negative effect due to a detrimental impact on the fertilization process and the degree of pollen sterility. Maximum temperatures > 42° to 45° were considered to be catastrophic events.

These experimental threshold values were interpolated linearly, and a weighting scale was introduced for increasing daily maximum temperatures. The relative weighting factor at 33°C was 1.0 and increased to 4.5 at 43°.

b) DURATION OF HEAT SPELL. The duration of a heat spell was considered to be the number of days that the daily maximum temperature was > 33°C. It was considered that the longer the duration of the heat spell, the more harmful it would be to the reproductive process. Both increasing temperatures and the duration of these elevated temperatures can affect inflorescence sterility. Sterility may become a function of the percentage of open florets x the number of days temperatures are > 33°C, but especially > 36°C.

A negative effect of the duration of stress has been demonstrated for annual crops by Shaw (21) and Lomas and Herrera (16), although these workers considered moisture stress. Lomas and Shashoua (14), however, clearly showed that the longer the period of hot and dry days, the lower the wheat yield in Israel. Field observations also confirmed this assumption, although the quantitative value of the effect of the duration of heat spells on avocado yields is unknown. Therefore, a series of empirical weights were proposed for trial analysis by computer, increasing in value exponentially. The weightings finally chosen for the duration of heat spells were those that gave the highest correlations with yield. Thus, for the temperature range of 33° to 35°C, the relative weighting factor for spell duration was n - 1 for the 36° to 38° range, 1.4^n; and for the 39° to 43° range, 2.0^n.

C) EFFECT OF HEAT STRESS TIMING. 'Fuerte' avocados begin flowering in Israel during March and complete the flowering process in May (24). The duration of the flowering period is temperature-dependent (10, 15); thus, in the coastal plain, the flowering process is completed in about 60 to 70 days, whereas in the interior valleys it lasts about 30 to 35 days (10, 24).

The percentage distribution of open flowers of the inflorescence over time follows a near-normal distribution curve. The curve peaks some days after the halfway mark of the duration period of the flowering process, since the beginning of the flowering process starts relatively slowly due to low temperatures early in the season.

Levin (10) showed that the earlier the bud burst and the lower the temperature, the longer the duration of the flowering process. Similar results were reported by Lomas and Burd (15) for citrus in the coastal plain.

The effect of heat stress on sterility becomes a function of the percentage of florets open at the time of the occurrence of heat stress. It was therefore considered necessary to introduce a weighting factor that would account for the distribution curve of open avocado flowers. Since fruit drop was reported to occur also during the beginning of June (24), the weightings proposed cover a period from March to June. During this period, the flowering and early fruit period is of some 80 days in duration. Thus, a total weighting factor of 8.1 was apportioned to follow closely the near-normal percentage distribution curve of open flowering. At bud swelling and bud burst during the month of March, its weighting factors increase gradually from 0.1 to 0.4, and are 0.9 at the end of April, as the percentage of open flowers is nearly at its peak. The weighting factors are at their highest by mid-May, 1.3, when early fruit set occurs. Thereafter, the weighting factors decrease rapidly to 0.3 at the end of June.

DATA BASE. The crop yield data ($t \cdot ha^{-1}$) was obtained from a plantation of 0.8 ha in the communal settlement of Kabri, Western Galilee, located ≈5 km inland from the coast (long. 35°09', lat. 33°01', 100 m elevation).

The plantation was planted in 1960 with 'Fuerte'. Detailed records of yield are available from 1965 to 1984, a period of 20 years (with the exception of 1967). The long-term average yield of 14.750 $t \cdot ha^{-1}$ is ≈50% above the national average, indicating both a relatively high yield potential as well as good management practices. Yield variability from year to year was considerable; cv 38%.

The phenology of the flowering process was pooled from a number of sources. Shnir (24) reported on the flowering process for 2 years in the coastal plain, and Levin (10) and Adato et al. (1) collected phenological data for a 5-year period from the Hulah valley. I also obtained detailed phenological data from the Jordan valley for a 5-year period, from Jordan valley introduction experimental station, all for 'Fuerte'. All observations clearly showed a near-normal distribution curve of open flowers, except during spring periods with temperatures well below average, when the flowering process is delayed.

The climatic data used were from the agrometeorological station of Gan Shomron (long. 32°27', lat. 35°00', 50 m elevation), ≈ 6 km inland. Although the station was ≈60 km from the avocado plantation, observation consistency over 20 years was considered more important than records from a station nearer the plantation but without homogeneous meteorological observations, especially since the treatments are between years. During *sharav* conditions, distance from the sea is one of the major factors determining the intensity of the heat waves. This factor is shown by climatic maps of the mean maximum temperatures from March to June (S. Rubin and L. Klebaner, personal communication). Further, homogeneity of data is critical in a long- term agroclimatic analysis (16), and the plantation of Kabri and the meteorological station at Gan Shomron fulfill this requirement.

CONCEPTUAL AGROMETEOROLOGICAL MODEL. The climatic data-driven agrometeorological model consists of the calculated heat stress index (HSI). This index is based on the product of three components: the daily maximum temperature, the duration of heat spells, and their timing in relation to the phenology of the flowering process. The crop environment thus obtained was related to the crop performance using established statistical techniques, being fully aware that such a simplified model attempts to account for a most complex relationship.

Both quadratic and cubic regressions were used. This took the form of:

$$Y = a + bI + cI^2 \qquad [1]$$

$$Y = a + bI + cI^2 + dI^2 \qquad [2]$$

Avocado producers claimed that the possible effect of heat spells during flowering and early fruit set was, to some extent, predetermined by winter temperatures preceding the flowering period. Winter (December to February) mean minimum temperatures therefore were included in the analysis as an additional variable.

Having obtained the response of the avocado yields to the HIS, the mean minimum temperature was included in a multiple regression of the form:

$$Y = a + bI - cI^2 + dT - eT^2 \qquad [3]$$

Where Y = the expected yield of avocado, I = the weighted HIS, and T = the mean minimum temperature (December to February).

The objective of the model was to provide a numerical relationship between excessively high temperatures during the flowering and early fruit set period and the yield of avocado. The yield data obtained from a well-managed plantation over a period of 20 years adequately sampled the variations off weather between years and assured representation of conditions other than environmental. Although yield is the summation of all pre- ceding processes, it was assumed that in the case of an irrigated and well-managed avocado plantation, heat stress during flowering and early fruit set could be one climatic factor likely to dominate all others.

Results and Discussion

The climate of the central plain is typically Mediterranean. The spring season (March to May) is a period with considerable climatic variability. At the end of the rainy season and the beginning of the dry season, changes in the local synoptic circulation are responsible for the relatively large fluctuations in temperature and relative humidity. The average climatic data for the coastal plain are presented in Table 1.

The relatively mild climatic conditions due to the influence of the sea and the frost-free sites make the area particularly suitable for avocado plantations. The simultaneous occurrences of high temperatures and low relative humidities are not highly correlated. During the month of March this correlation was only r^2 = 0.20, increasing gradually to r^2 = 0.25 in June. The frequency distribution of both maximum daily temperatures and the minimum relative humidity at Bet Dagan are shown in Fig. 1.

Table 1. Average climatic values for the coastal plain (Bet Dagan) of photoperiods (hours and minutes), global radiation ($kJ \cdot m^{-2}$), maximum (tx) and minimum (tm) temperatures (°C), and rainfall (mm) at Kabri, Israel.

Month	Photoperiod (hours:Min., day/night)	Radiation ($kJ \cdot m^{-2}$)	Temp (°C) Tx	Temp (°C) Tm	Rainfall (mm)
January	10:16/13:44	10.800	17.9	6.6	145
February	11:02/12:58	13.939	19.2	6.8	98
March	11:55/12:05	17.706	21.5	8.6	59
April	12:56/11:04	22.269	24.6	11.0	19
May	13:46/10:14	26.162	26.7	13.0	7
June	14:15/ 9:45	28.297	29.3	17.1	---
July	14:05/ 9:55	27.627	30.6	19.3	---
August	13:38/10:38	25.409	30.9	19.6	---
September	12:24/11:36	21.349	29.9	18.1	3
October	11:27/12:33	16.284	28.0	14.8	22
November	10:32/13:28	12.181	24.2	11.2	75
December	10:05/13:55	9.586	19.4	8.2	106

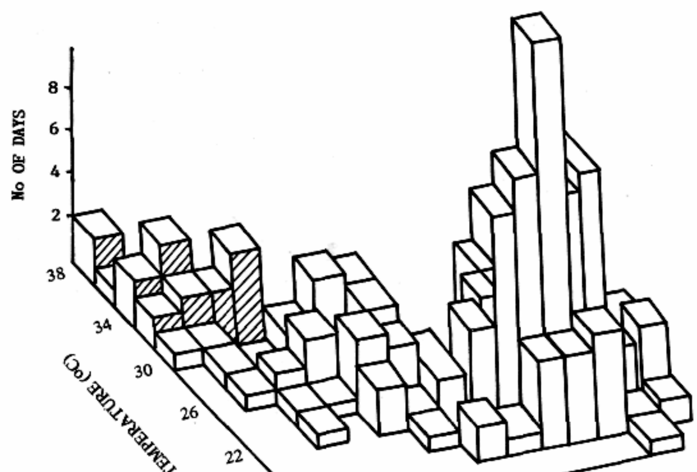

Fig. 1. Frequency distribution of maximum temperature and the minimum relative humidity (lowest humidity observed at one of the three daily observations) at Bet Dagan during Apr. and May 1973–1983. Shaded sections indicate heat stress conditions.

Although it is generally true that the higher temperatures are associated with the lower relative humidities during the day, the range of humidity for any temperature level is fairly large. Extreme conditions of both high temperatures (≥39°C) and low relative humidities (≤15%) are fortunately very infrequent.

The long-term average national yield in Israel is ≈ 10 $t \cdot ha^{-1}$. The average yield of the settlement of Kabri for ≈13 ha is 9.77 ± 3.89 $t \cdot ha^{-1}$, indicating that the avocado yields are fairly typical of the production of the coastal plain. The plot chosen for model development was one giving higher yields, 13.76 ± 5.2 $t \cdot ha^{-1}$, so that soil or plant material would not be serious factors limiting avocado yields. The coefficient of variation for the whole settlement was 40% and that of the model development plot was 38%.

Avocado yields of the settlement of Kabri are shown in Fig. 2. There was no agrotechnology trend during the 20-year period. The agrometeorological model described is basically a simulation model using deterministic data. The specifications of the threshold values of maximum daily temperature of the model are based on experimental results (2, 6). In spite of the fact that the mechanisms through which temperatures affect inflorescence development are unclear, it seems that temperatures ≥34°C for several hours adversely affected the viability of mature pollen (6). It was for this reason that 33° was chosen as the threshold value from which heat stress was calculated. Pollen exposed to 39° to 40° lost its capacity to reach the embryo sac.

Higher maximum temperatures were thus considered more detrimental and weighted nearly linearly. High temperatures of 32° to 35° were also detrimental to fruit set (2). Temperatures of 38° to 39° severely damaged the fruit set process (6). It was for this reason that the heat stress model was extended to the early stages of fruit set, which, in the coastal plain, takes place during the months of May and June.

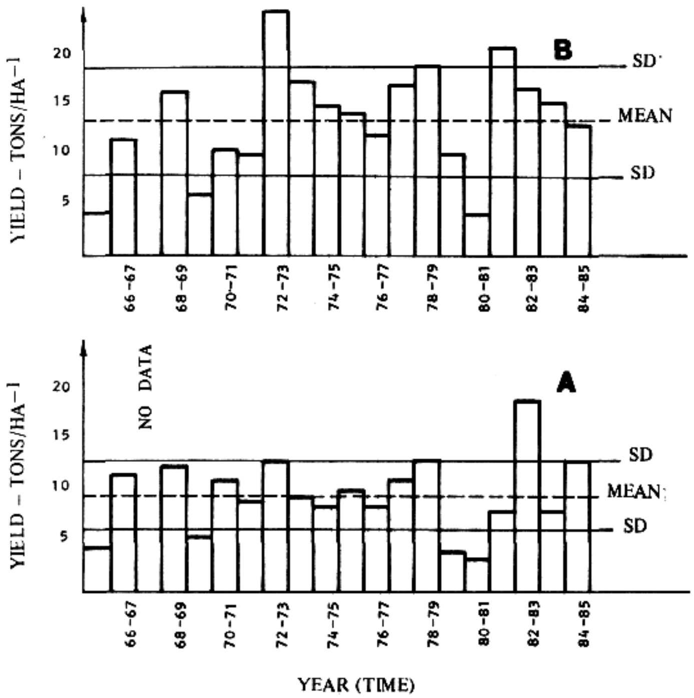

Fig. 2. The yield of the avocado 'Fuerte' at the settlement of Kabri. (**A**) all plantations; (**B**) plantation of 0.8 ha used in model construction.

No experimental data were found in the literature regarding the quantitative effect of the duration or timing of heat stress on the flowering process and ultimate yield, although Gafni found (6) that the closer the high temperature stress is to the time of pollination, the more severe is its effect.

In an effort to account for the negative effects of a) increasingly higher temperatures, b) the duration of high temperatures, and c) the timing of high temperatures in relation to the percentage open flower distribution and the period of early fruit set, an empirical procedure was adopted. The logical justification for the empirical values chosen is based on the fact that the functional relationship between the calculated heat stress index and avocado yields over a period of 20 years shows fairly good agreement.

The predisposition of avocado trees to heat stress in a well-managed and irrigated plantation may be affected by many factors. The two climatic factors most likely to influence predisposition are temperatures during the winter season and rainfall (soil moisture). However, soil moisture, due to rainfall variability during the winter season, will be supplemented by irrigation; thus, it is unlikely to influence the predisposition of the avocado trees. Temperature therefore seems to be the most important single factor likely to affect predisposition of the plantation to heat stress. With 0.8 to

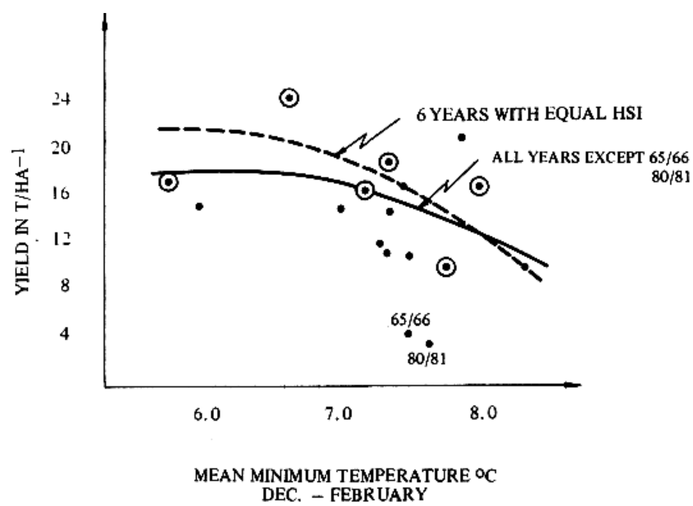

Fig. 3. Mean minimum temperature (°C) during December to February and the yield of avocado for all years (except 65/66 and 80/81 – $r^2 = 0.13$) and for six years only with more or less equal heat stress index values ($r^2 = 0.45$).

1.5 million flowers per adult tree (9), the number of flowers is not likely to limit plantation yields (17, 25). However, the mean minimum temperature during the winter season will affect the timing and duration of the flowering process (15). Changes in the timing and duration of exposure of the sensitive reproductive stage will affect not only the stage at which fruitlets are exposed to heat stress, but the number of fruitlets so exposed.

From the whole period of 20 years, six years were selected with more or less the same intensities of heat stress in order to examine the effect of winter temperatures on yield. For such a small sample size the results were not significant (r^2 = 0.45) and are presented in Fig. 3. As expected for all the years, the results were poor (r^2 = 0.13). The addition of winter mean minimum temperatures to the HSI in a multiple correlation slightly improved the correlation coefficient, but not significantly.

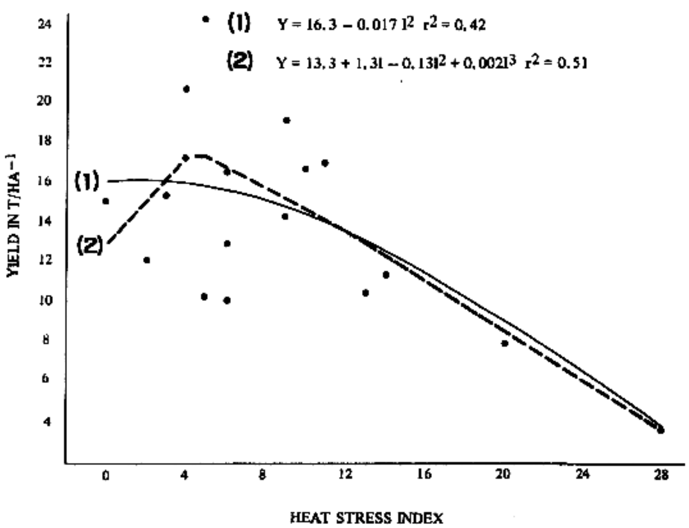

Fig. 4. Quadratic (1) and cubic (2) regressions between the calculated heat stress index and the yield of avocado at Kabri during 1963–1983.

The calculated HSI related fairly well with 20 years of historical avocado yield data (r^2 = 0.42). The numerical relationship is presented in Fig. 4. There were no significant differences between the quadratic and cubic relationship, except during years with little heat stress. Opinions vary as to the possible advantageous effect on plantation yields of mild heat stress (4 to 8 HSI), leading to some material thinning of excessive fruitlet populations. In such a case, highest plantation yields would be obtained during years with some heat stress.

There is a considerable scatter of individual points (annual yields) for heat stress index valued up to 10. It may well be that during years with mild spring temperature conditions, factors other than heat stress will be responsible for the level of avocado yields. The HSI and the yield of avocados were closely related in those years when the plantation was subject to heat stress indexes > 10.

The final test, however, if fundamentally sound relationships have been quantified, will be seen only once the model output is validated on independent data. In order to do that and in order to avoid interactions with different soil and genetic material, an additional 10 to 12-year period is necessary. Testing of the model output is now entering its third year. The model includes a plantation "memory" factor accounting for the yield of the previous year.

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