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Determination of temperature and time thresholds for BIOTIC irrigation of peanut on the Southern High Plains of Texas

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Abstract The timely application of irrigation water to a crop is essential for optimizing yield and production efficiency. The “Biologically Identified Optimal Temperature Interactive Console (BIOTIC)” is an irrigation protocol that provides irrigation scheduling based upon measurements of canopy temperatures and the temperature optimum of the crop species of interest. One of the goals of this paper is to document the gradual development of the method and its implementation. Two threshold values are required to implement BIOTIC irrigation of a crop in a given region, a species-specific temperature threshold and a species/environment-specific time threshold. The temperature threshold, an indication of the thermal optimum for the plant, is derived from the thermal dependence of its metabolism. The time threshold, which represents the average amount of time each day that the canopy temperature of the well-watered crop will exceed the temperature threshold, is calculated from weather data. Interest in the use of BIOTIC for irrigation scheduling for peanut (*Arachis hypogaea* L.) resulted in this study in which the temperature and time thresholds for peanut were determined on the Texas Southern High Plains. A temperature threshold value of 27°C was determined from the thermal dependence of the reappearance of photosystem II variable fluorescence (PSII Fv) following illumination. A time threshold of 405 min was calculated from an analysis of weather data collected over the course of the 1999 growing season. The determination of

these threshold values for peanut provides the basis for the application of the BIOTIC protocol to irrigation scheduling of peanut on the Southern High Plains of Texas.

Keywords Irrigation · Water stress · Peanut

Introduction

Irrigation management provides for the control of plant water status through the timely application of water to maintain the crop within a predetermined range of water stress (Wanjura et al. 1992). Plant water stress under irrigation can range from very mild in a fully irrigated regime to severe. Irrigation scheduling serves to ensure that water is available in sufficient quantity at the time when it is needed by the plant. Generally this is accomplished by monitoring an indicator of the availability of water for the plant. Irrigation can be scheduled on the basis of a number of indicators including: the water content of the soil, the water potential of the plant, measured and predicted rates of evapotranspiration, and the temperature of the plant (Hearne and Constable 1984). All of these methods have their advantages and disadvantages.

Irrigation scheduling based on measurement of plant temperature, an approach that utilizes the plant as an indicator of water status is the topic of this paper. Transpiration (the evaporation of water from the leaf) results in cooling of the leaf and provides the basis for determining plant water status from temperature measurements. As the soil water available to the plant declines, the transpirational cooling of the plant is reduced, which results in an increase in plant temperature. The use of plant temperature as an indicator of plant water status requires that plant temperature be defined with respect to a reference temperature. Air temperature, the temperature of a well-watered plant, and optimum plant temperature have all been used as reference

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Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.

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temperatures in irrigation management protocols (Idso et al. 1982; Fuchs 1990; Jackson et al. 1981; Wanjura et al. 1992).

The “Biologically Identified Optimal Temperature Interactive Console (BIOTIC)”, an irrigation scheduling protocol based on plant temperature, has been developed over the course of several years by researchers at the USDA/ARS in Lubbock, Texas (Upchurch et al. 1996). BIOTIC continually compares measurements of canopy temperatures to an estimate of the plant’s optimal temperature to assess the need for irrigation. The BIOTIC protocol has been used to schedule irrigation for several species including cotton, sunflower, soybeans, sorghum and millet. Irrigation has been scheduled with BIOTIC for both center pivot LEPA and drip irrigation systems (surface and subsurface) in humid and arid environments. Two distinct advantages of the BIOTIC method are its relatively low cost and the need for only minimal attention from the user. Since the BIOTIC method schedules irrigation for a field based on the canopy temperatures of the same field, it is site specific in its implementation.

The literature describing BIOTIC encompasses more than 25 published papers spanning a period of 14 years and is reflective of the gradual development of the protocol (Wanjura et al. 1990, 1995; Burke et al. 1988; Burke 1990; Mahan et al. 1990). As a result of the development of the method over a period of years, there is no single source citation defining the most up-to-date methodology concerning its implementation. The intent of this paper is threefold: first, to provide a historical narrative of the development of the BIOTIC method; second, to present the theory of BIOTIC and the preferred approaches for its implementation; and third, to describe the implementation of BIOTIC for irrigation scheduling in peanut (*Arachis hypogaea* L.) on the Southern High Plains of Texas.

Historical development of BIOTIC

The BIOTIC method uses canopy temperatures in excess of the temperature threshold as an indicator of water stress. The use of canopy temperature as an indicator of plant water stress was well established during the late 1970s and early 1980s (Idso et al. 1977; Jackson et al. 1981; Idso 1982). In an effort to develop indicators of the early onset of water and temperature stress, scientists with the ARS in Lubbock defined optimal plant temperatures with respect to the thermal dependence of the Michaelis constant of an enzyme (K_M). They described this thermal dependence in terms of a thermal kinetic window (TKW), a range of temperatures conducive to optimal metabolic activity (Burke et al. 1988; Mahan and Upchurch 1988; Upchurch and Mahan 1988). Burke et al. (1988) reported that plant performance was positively correlated on a seasonal basis with the amount of time that plant temperatures were within the TKW. This finding resulted in an effort to develop a method for

scheduling irrigation by comparing canopy temperature to a biologically-based optimum temperature and irrigating in response to canopy temperatures in excess of this temperature threshold. The use of a biologically-based estimate of thermal optimality as a reference temperature provided a departure from previous irrigation scheduling methods based on canopy temperature.

A field study in 1988 was the first evaluation of irrigation scheduling with real-time measurements of canopy temperature and a TKW- based temperature threshold. In an effort to investigate the relevance of the biologically-identified temperature threshold of 28°C for cotton, threshold temperatures of 30 and 32°C and a weekly soil water replacement treatment were included in the study (Wanjura et al. 1990). The threshold temperature treatments applied irrigation for 15 min whenever the average canopy temperature for the previous 15-min period exceeded the threshold temperature. This study demonstrated the feasibility of scheduling irrigation using a drip system and that the use of different temperature thresholds to activate irrigation did indeed result in the application of different quantities of water. Temperature threshold studies continued for two more years on cotton with the range of temperatures expanded from 26 to 32°C in 2° increments (Wanjura et al. 1992). Over all 3 years, lint yield was highest for the 28°C threshold temperature and decreased for higher or lower temperature thresholds. It was concluded that a 28°C threshold would provide maximum yield where water and season length were not limiting.

In the initial studies that used 15-min decision intervals for control, this short interval provided for very rapid alleviation of water deficits and thus precise control of the plant’s water status. A modification of the approach was required when the method was expanded to include irrigation systems with longer irrigation intervals. In the transition from a drip system that could meet demand within 15 min to center pivot systems that required 3–7 days to complete an irrigation event, it was necessary to incorporate a means of integrating temperatures in excess of the temperature threshold over the time interval between irrigations. The inclusion of a “time threshold” in the scheduling decision process served to adapt the BIOTIC to longer decision intervals.

A 1991 study with cotton (Wanjura et al. 1992) used a temperature threshold of 28°C in combination with daily time thresholds which varied between 2.5 to 7.0 h of accumulated time above 28°C. The number of irrigations applied during the irrigation season decreased linearly as the time threshold was increased. Total irrigation amounts increased from 27 to 41 cm for time thresholds between 7.0 and 2.5 h. These results demonstrated the feasibility of using both a crop specific temperature threshold with a daily time threshold calibrated to local environmental conditions to control scheduling of daily or longer interval irrigation events. The application of temperature thresholds and time thresholds for controlling irrigation scheduling was also demonstrated on cotton at Mississippi State, at Lubbock, and at

Shafter, California (Wanjura and Upchurch 1996). Irrigation was successfully scheduled during 1994 in environments that ranged from humid to arid.

Evelt et al. (2000) carried out an automated irrigation scheduling study that employed crop specific temperature thresholds in combination with different time thresholds with corn and soybeans to make daily irrigation scheduling decisions to achieve either maximum yield or maximum water use efficiency. These treatments were compared with a manual weekly irrigation treatment that was replenished to 100% of field capacity as measured by a neutron probe. The automated treatments were more stable across 2 years and produced either higher yield or greater water use efficiency than the manual treatment in corn, but not in soybeans. Thus the potential exists for regulating the application of water to crops that satisfy different production system objectives, using plant temperature as the primary control.

The BIOTIC method has been tested in private farming operations for several years in semi-arid regions. These studies in production agriculture settings allowed the assessment of producer preferences and perceptions in terms of instrument design, installation, configuration, and user interfaces.

In its current form, BIOTIC provides a departure from traditional approaches to irrigation scheduling using canopy temperatures. It has been tested in both research and production environments and provided irrigation management that was competitive with that provided by other management protocols. The instrumentation and implementation have been demonstrated to be sufficiently robust for use in production environments.

Theoretical basis of BIOTIC

The BIOTIC protocol is based on the observation that elevated canopy temperatures are often coincident with plant water deficits (Aston and van Bavel 1972; Jackson et al. 1981). There are a variety of irrigation scheduling methods that utilize canopy temperatures to detect water deficits (Idso et al. 1977; Jackson et al. 1981; Idso 1982; Moran et al. 1994). BIOTIC differs from other temperature-based irrigation scheduling methods in that it compares canopy temperature with a biologically-based estimate of the optimum temperature of the plant. This "temperature threshold" is based on the observation of the thermal dependence of plant metabolic activity (Terri and Peet 1978; Peeler and Naylor 1988; Mahan 2000). Implementation of BIOTIC with irrigation systems that cannot apply water on short intervals (e.g. furrow and large pivot irrigation systems) requires the inclusion of a time threshold in the decision process. The time threshold defines the daily amount of time that the temperature of the canopy, in a well-watered state, can exceed the temperature threshold in the absence of a water deficit

(Wanjura et al. 1995). Irrigation is considered appropriate when the temperature of the canopy exceeds the temperature threshold for a time period in excess of the time threshold.

Under certain conditions relative humidity can limit transpirational cooling of the plant canopy to an extent that the canopy temperature of even well watered plants will exceed the temperature threshold. This potential limitation is controlled in the BIOTIC protocol by the calculation of a "limiting relative humidity" threshold and excluding elevated temperatures under such conditions from the decision process.

In the following sections the theory and methods used in the determination of the three required thresholds will be discussed. Additionally, the method of choice for each determination will be identified.

Temperature threshold

The temperature threshold, an estimate of the thermal optimum of the metabolism of the plant, is determined from the temperature dependence of a selected metabolic indicator. There are three methods that have been developed to determine the temperature threshold for a plant: enzyme kinetic analysis, chlorophyll development in etiolated seedlings, and recovery of variable fluorescence.

In the initial stages of the development of BIOTIC, temperature thresholds were determined on the basis of the thermal dependence of the apparent Michaelis constant (K_M) of enzymes from the species of interest. The use of the minimum K_M as an indicator of the optimum temperature for the plant was based on the concept of a thermal kinetic window which posits that the minimum and stable K_M value is an indicator of the thermal optimum for enzyme function and by extension for the organism as a whole (Burke et al. 1988; Mahan et al. 1990). The utility of the enzyme kinetic method for temperature threshold determination was somewhat limited since it involves numerous enzyme assays under temperature controlled conditions.

The temperature optimum for the accumulation of the chlorophyll a/b light harvesting complex of photosystem II (LHCP II), its mRNA and the mRNA of the small subunit of RuBISCO in cucumber (*Cucumis sativus* L. cv. Ashley) were evaluated as a measure of the thermal dependence of metabolism (Burke and Oliver 1993). The TKW for cucumber is between 23.5 to 39°C, with the minimum apparent K_M occurring at 32.5°C. The photosystem II variable fluorescence reappearance following illumination was maximal between 30 and 35°C. Maximum synthesis of the LHCP II occurred at 30°C. Their study provided new information about the relationship between TKWs and cellular responses to temperature. In addition, the results suggested that the temperature range outside of which plants experience temperature stress is narrower than traditionally supposed.

Peeler and Naylor (1988) reported that the recovery of variable fluorescence in leaves was thermally dependent and Burke (1990) and Ferguson and Burke (1991) used this method to determine the thermal optima of various plant species. Chlorophyll fluorescence functions as a natural indicator of in vivo temperature characteristics of the plant. An example is the minimum apparent K_M for NADH for hydroxypyruvate reductase from Norgold M potatoes which occurred at 20°C, with the thermal kinetic window falling between 15 and 25°C (Ferguson and Burke 1991). The optimum temperature for variable fluorescence (Fv) reappearance (expressed as the ratio Fv/Fo where Fo is the initial fluorescence) is defined as the temperature providing the maximum Fv/Fo ratio and the minimum time in darkness required to reach this ratio. The optimal temperature identified from the fluorescence reappearance is also 20°C for the Norgold M potato. Similar correlations between the temperatures of the TKW and the temperatures providing maximum fluorescence reappearance have been reported for cucumber, wheat, cotton, soybean, tomato, petunia, and bell pepper (Burke 1990; Ferguson and Burke 1991; Burke and Oliver 1993).

The three methods described above provide a variety of approaches to the determination of the temperature threshold. Though each has some utility, in practice, one may be preferred over another. Burke and Oliver (1993) compared three methods for the determination of the thermal dependence of plant metabolism. In their study of the temperature optimum of cucumber cotyledons, they monitored the thermal dependence of three metabolic indicators: (1) enzyme kinetics as described by Burke et al. (1988) and Mahan et al. (1990) using the apparent K_M for NADH of hydroxypyruvate reductase, (2) the reappearance of photosystem II variable fluorescence (PSII Fv) following illumination as described by Peeler and Naylor (1988), and (3) chlorophyll accumulation in etiolated seedlings exposed to light as described by Burke (1990). They found similar thermal dependencies for each process and concluded that each of the three methods was adequate for defining a BIOTIC temperature threshold describing the thermal dependence of metabolism in the plant. Based primarily on the simplicity of the procedure and the ease of implementation, they recommended use of the thermal dependence of the reappearance of PSII Fv as a means of determining the BIOTIC temperature threshold for a given plant.

Time threshold

Wanjura et al. (1995) described three methods for the determination of time thresholds: (1) empirical field-testing of multiple time thresholds for irrigation and the selection of the threshold that optimized crop performance, (2) empirical analysis of historical crop canopy temperatures for a crop grown under well-watered conditions, and (3) theoretical determination of well-

watered crop canopy temperatures using an energy balance analysis.

The empirical analysis is based on field testing with multiple time thresholds for watering and the selection of the time threshold that optimized crop performance or yield. The empirical method is conceptually simple and straightforward. This approach does require a substantial investment in terms of field management and instrument monitoring over multiple growing seasons and is relatively costly in both time and economic terms.

Analysis of canopy temperature data to determine the daily time that the canopy of a well-watered crop is above the temperature threshold is simple in concept. In those instances where such data has been previously collected this method is an effective means of acquiring a time threshold for a crop. In the case where historic canopy temperature data is unavailable, the time and monetary investment required to collect such data over multiple growing seasons can be substantial and reduces the utility of the approach.

Through the use of an energy balance, the canopy temperatures that occur in a well-watered, non-stressed plant can be calculated from weather data collected over the growing season for the crop in an environment of interest. The time threshold is then the arithmetic mean of the length of time per day that the *calculated* temperature of a well-watered crop canopy is in excess of the threshold temperature of the crop of interest.

In its general form (Monteith 1973), the energy balance of a crop canopy can be expressed as follows:

$$R_n = G + H + \lambda E \quad (1)$$

where R_n is net radiation, G is the heat flux below the canopy, H is sensible heat flux from the canopy, and E is the latent heat flux to the air. Applying the fundamental equations describing G , H and λE and rearranging, the following equation can be obtained.

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \frac{\gamma^*}{\Delta + \gamma^*} - \frac{e_A^* - e_A}{\Delta + \gamma^*} \quad (2)$$

where T_c is the canopy temperature in °C, T_A is the air temperature in °C, r_a is the aerodynamic resistance in $s.m^{-1}$, R_n is the net radiation in $W.m^{-2}$, ρ is the density of air in $kg.m^{-3}$, c_p is the heat capacity of the air in $J.kg^{-1}$, Δ is the slope of the saturation vapor pressure-temperature curve $Pa.^{\circ}C^{-1}$, $e_A^* - e_A$ is the vapor pressure deficit of the air in kPa, and γ^* is the apparent psychrometric constant expressed in $Pa.^{\circ}C^{-1}$.

For a well-watered crop transpiring at its potential rate:

$$\gamma^* = \gamma(1 + r_{cp}/r_a) \quad (3)$$

In this relationship r_{cp} is the resistance of a well-watered crop. The canopy temperature of a well-watered or non-stressed plant can be calculated using the crop water stress index (CWSI) defined by Jackson et al. (1981) as:

$$\text{CWSI} = 1 - E/E_p = \frac{\gamma(1 + r_c/r_a) - \gamma^*}{\Delta + \gamma(1 + r_c/r_a)} \quad (4)$$

The value of the CWSI ranges from 0 to 1 with a non-stressed plant having a value near zero. In this equation r_c replaces r_{cp} and represents the actual canopy resistance. The ratio r_c/r_a can be defined by substituting Eq. 3 into Eq. 2 and rearranging.

$$\frac{r_c}{r_a} = \frac{\gamma r_a R_n / (\rho c_p) - (T_c - T_a)(\Delta + \gamma) - (e_A^* - e_A)}{\gamma [(T_c - T_a) - r_a R_n / (\rho c_p)]} \quad (5)$$

All parameters in Eq. 5 are measured and/or derived with the exception of T_c . The goal is to determine the value of T_c that results in a CWSI that is close to zero. This value is obtained by solving Eq. 5 using air temperature as the initial estimate of T_c and applying that solution to Eq. 4 to determine if that value of T_c yields a CWSI between 0 and 0.05. If the CWSI is outside the range of 0 to 0.05, T_c is incrementally modified and the process repeated. This iterative process results in the calculation of the temperature of a non-stressed plant canopy (a CWSI between 0 and 0.05). This analysis is further filtered to include only the time when the air temperature is greater than the biological threshold temperature, the net radiation is positive and the relative humidity is not limiting. This filtering process limits the analysis to times when there is sufficient energy to raise the canopy temperature to the biological threshold and the environment permits cooling.

Limiting relative humidity

High humidity can limit transpirational cooling of the canopy to the point that canopy temperatures cannot cool below the temperature threshold even under well-watered conditions. Thus, under such conditions, elevated canopy temperature is not a reliable indicator of plant water deficits and the temperature of the canopy will not respond to water application and thus must be corrected for by comparisons of canopy temperature values with relative humidity measurements.

Implementation of BIOTIC for peanuts

Multiple methods exist for determination of the temperature and time thresholds required for implementation of BIOTIC in a crop. The following section describes the preferred methods for BIOTIC implementation in reference to peanuts on the Southern High Plains of Texas.

Materials and methods

The peanut variety AT-120 was grown in a greenhouse under hydroponic conditions and used as plant material

for temperature threshold determination. Seeds were planted into rock wool pads (Hummert International, Earth City, Mo.) that had been saturated with a complete nutrient solution. The seedlings received water daily and additional nutrients every 2 days by applying nutrient solution to the pads through an automated drip system. The seedlings were grown from 30 to 90 days after planting and fully-expanded leaflets were harvested for fluorescence analysis.

The peanut variety Vineyard that was planted on 14 May 1999 at the Texas Tech "Erskine Farm" in Lubbock County was used for time threshold determination. Normal culture practices were followed with respect to tillage, weed and insect control during the season. Plants were irrigated with a center pivot irrigation system. A total of seven irrigations of 2 cm each were applied during the growing period.

Temperature threshold determination

The temperature threshold was determined using chlorophyll fluorescence measurements (Burke 1990). The temperature threshold was determined on detached leaflets from greenhouse grown peanut seedlings over a range of temperatures from 10 to 45°C. To achieve the desired temperatures, leaflets were placed on moist filter paper on the temperature blocks of an electronically controlled eight-position thermal plate system (Burke and Mahan 1993). The leaflets were covered with Glad Cling Wrap (First Brands, Danbury, Conn.) to prevent drying while still allowing gas exchange and illuminated for 15 min with full-spectrum light from a Para-Lite II light fixture (Full Spectrum Solutions, Jackson, Mich.). This fixture produces up to 10,000 lux of light at its maximum setting. The temperature blocks were adjusted to specific temperatures from 10 to 45 °C, the light was turned off, and chlorophyll fluorescence measured immediately (initial fluorescence) with a Hansatech Plant Efficiency Analyzer. Chlorophyll fluorescence was then measured every 5 min (variable fluorescence) over a 30-min evaluation period. Fv (variable fluorescence) to Fo (initial fluorescence) ratios were determined and plotted. Following a minimum of three replications, a range of temperatures showing the highest Fv/Fo ratios and most rapid rise times were selected for additional analysis. The procedure was then repeated but with 2°C increments across the selected range, thereby providing a more accurate identification of the optimal temperature. An optimum temperature of 27°C was identified for the peanut variety AT-120.

Time threshold determination

An instrument station was established in a production peanut field in Lubbock on 12 May 1999 and was removed on 2 October 1999. Field data collection was automated with a data logger/controller (Campbell

Scientific 21X, Logan, Utah). All instruments were monitored at 6 s intervals (10 observations per minute). The data were averaged over 15-min intervals and these averages were used in subsequent analyses.

Parameters measured included net radiation (Q^* 6.7.1 Net Radiometer Radiation Energy Balance Systems, Bellvue, Wash.), air temperature (type K thermocouple), relative humidity (HyCal CT-829, HyCal Sensing Products), wind speed (R.M. Young, Model 12102 3-Cup Anemometer), and precipitation (Texas Electronics TR-525 M). All sensors were positioned over the canopy and 2 m above ground level. Canopy height was measured weekly at 10 locations randomly chosen within a 5 m radius of the instrument station. The time threshold value was calculated by the method of Wanjura et al. (1995). The application of the energy balance procedure for determining time thresholds is outlined in Fig. 1. The relevant equations have been addressed in the introduction and procedures for deriving the terms in Eq. 4 and Eq. 5 are well defined in the literature (Jackson et al. 1981).

A step-by-step description for calculation of a time threshold follows:

1. Weather data consisting of air temperature, net radiation, relative humidity and wind speed were measured and averaged at 15-min intervals over the course of the season encompassing the irrigation period of the crop
2. A value of 20 s.m^{-1} was used for the r_{cp} of peanut (Jackson et al. 1981; O'Toole and Real 1986). The value of r_a was calculated for each time step of the weather data from continuously measured 2 m wind speed and canopy height interpolated from weekly measurements
3. Canopy temperature that result in a CWSI near zero (between 0 and 0.05) were calculated for each time step of the weather data when the air temperature is

above the biological threshold, net radiation is positive, and relative humidity is not limiting

4. For each day of available weather data the amount of time the calculated canopy temperature (step 3) was above the crop specific temperature threshold (27°C in this example) was determined.
5. The time threshold is the arithmetic mean of the daily values that exceeded zero from step 4

Calculation of limiting relative humidity value

The lower temperature limit for an evaporating surface will approach that of a wet bulb thermometer but generally cannot reach that temperature. It has been estimated that a peanut canopy is only capable of cooling to about 2°C above the ambient wet bulb temperature (Wanjura et al. 1995). Thus the "limiting relative humidity" value for any point in time is equal to the relative humidity that is calculated using air temperature at that time and a wet bulb temperature that is 2°C below the temperature threshold of the crop. The limiting relative humidity value is calculated as a function of air temperature for any temperature threshold using standard psychrometric relationships (Brooker 1967; Wilhelm 1976). A limiting relative humidity curve for a 25°C wet bulb temperature that would be used for peanut which has a 27°C temperature threshold is shown in Fig. 2.

Results and discussion

Temperature threshold

The results of the monitoring of the thermal dependence of the fluorescence recovery from 10 to 45°C are shown in Fig. 3a. The optimum temperature is identified by a

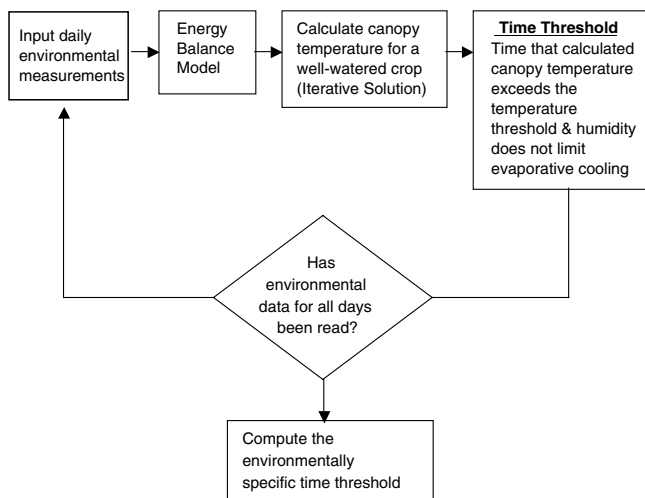


Fig. 1 Diagram of the steps used in the calculation of the time threshold with an energy balance method

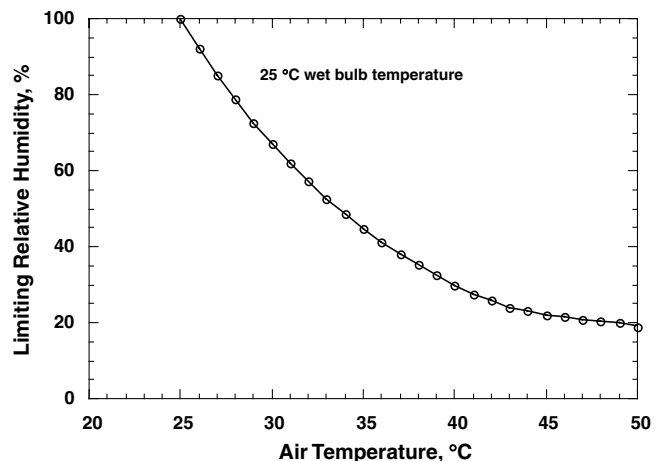


Fig. 2 Relationship between air temperature and limiting relative humidity for a 25°C wet bulb temperature based on the 27°C temperature threshold for peanut

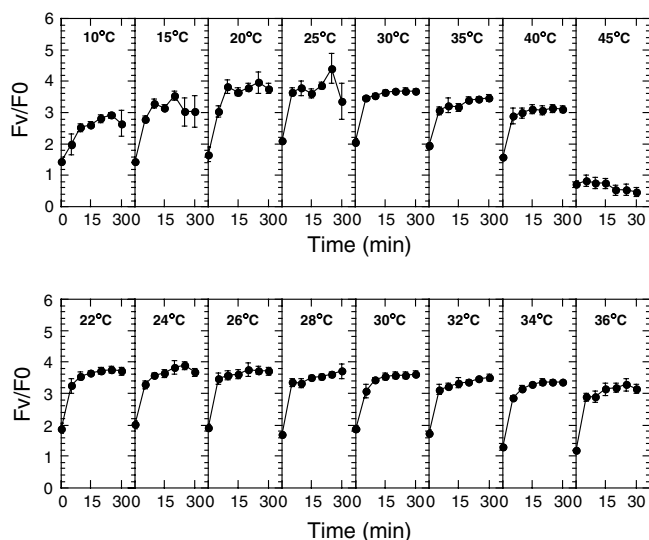


Fig. 3 Temperature response curve for the reappearance of leaf F_v in the dark following illumination for the peanut variety AT-120 (*Arachis hypogaea* L.). The optimum plant temperature for the recovery of PSII fluorescence is characterized by a combination of the maximum F_v/F_0 ratio and the minimum time in darkness required to reach the maximum F_v/F_0 ratio. **a** Temperature response curve at 5°C increments. **b** Temperature response curve at 2°C temperature increments

combination of the magnitude of the F_v/F_0 and the rate of rise at a given temperature. The F_v/F_0 value was maximal between 20 and 30°C. The thermal dependence was further refined when the experiment was repeated from 22 to 36°C at intervals of 2°C (Fig. 3b). In this series of temperatures the value of F_v/F_0 was maximal between 22 and 30°C. The rate of rise in F_v/F_0 reaches a maximum at 26°C and begins to decline by 28°C indicating an optimum of near 27°C. The thermal optimum for several peanut processes was reported to be between 27 and 30°C (Fortanier 1957). Bhagsari (1974) reported a temperature optimum near 30°C for photosynthesis in several peanut genotypes. Cox (1979) reported optimal growth in peanut with a day/night temperature regime of 30/25°C.

Time threshold determination

The instrument station collected weather data for 144 days (3,456 h). Data were collected for 100% of the monitoring period with no instrument failures. Over the course of the monitoring period there were 22 precipitation events totaling 309 mm and 8 irrigation events totaling 213 mm. Canopy coverage reached a maximum of 85% (90 days after planting) and a maximum plant height of 34 cm (108 days after planting). Iterative solutions of the energy balance resulted in predicted canopy temperature for a well-watered peanut canopy. The daily time that predicted canopy temperatures exceeded the 27°C temperature threshold is displayed in Fig. 4. This data was used to calculate the time thresh-

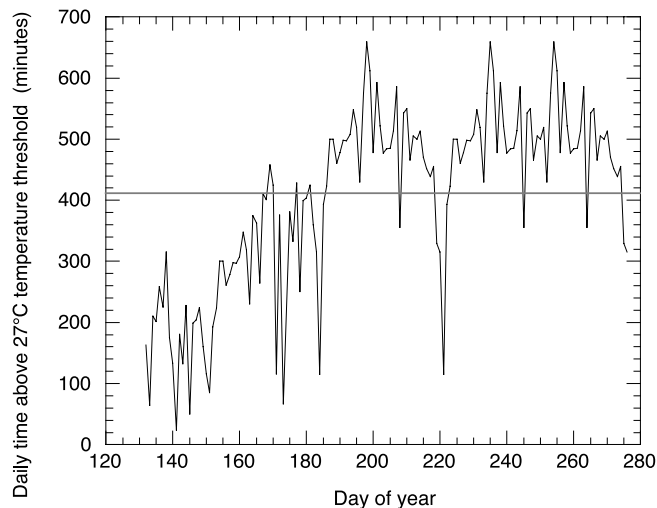


Fig. 4 Daily distribution of time that predicted canopy temperature was above the 27°C temperature threshold for peanuts. Canopy temperature was calculated on a 15-min interval from weather data at Lubbock for the period of 12 May 1999 to 2 October 1999. A horizontal line indicates the time threshold value of 405 min based on the mean daily time of canopy temperature in excess of the temperature threshold

old of 405 min which represents the daily time that a well-watered peanut canopy can be expected to exceed the biologically determined optimum of 27°C (80°F). This value is reasonable in comparison to that of 330 min previously calculated for cotton (28°C optimal temperature) in Lubbock. The time threshold in conjunction with the biological optimal temperature provides the basis for the irrigation of peanut with the BIOTIC protocol.

Summary and conclusions

The intent of this paper was threefold: (1) to provide a historical narrative of the development of the BIOTIC method, (2) to discuss the current status of the method and the preferred approaches for its implementation, and (3) to describe the approach used in our laboratory to implement BIOTIC irrigation scheduling in peanuts.

The BIOTIC protocol has been demonstrated to be an effective irrigation scheduling method for several crop species. The method has been proven in both semi-arid and humid environments of Texas, Mississippi and California. Irrigation intervals ranging from 15 min to 7 days have been demonstrated to be compatible with the BIOTIC protocol. In each instance BIOTIC has provided irrigation scheduling equivalent to that achieved by soil water balance or evapotranspiration methods.

A variety of methods have been developed for the determination of the time and temperature thresholds required for BIOTIC. While each method has its advantages and disadvantages, in many instances, variable fluorescence recovery and an energy balance model will be the preferred methods for the determination of

temperature and time thresholds respectively. The relative humidity coincident with canopy temperature was used to calculate the relative humidity threshold for that measurement interval.

With respect to peanuts on the Southern High Plains of Texas, a temperature threshold of 27°C was obtained from fluorescence recovery measurements and a time threshold of 405 min was calculated by an energy balance analysis of historic weather data. The determination of these threshold values for peanut provides the basis for the application of the BIOTIC protocol to irrigation scheduling of peanut on the Southern High Plains of Texas.

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