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MODELING MAIZE (Zea mays L.) LEAF DEVELOPMENT AND APEX TEMPERATURE UNDER DIFFERENT THERMAL ENVIRONMENTS

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MODELING MAIZE (*Zea mays* L.) LEAF DEVELOPMENT AND APEX TEMPERATURE UNDER DIFFERENT THERMAL ENVIRONMENTS

By

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ABSTRACT

MODELING MAIZE (*Zea mays* L.) LEAF DEVELOPMENT AND APEX TEMPERATURE UNDER DIFFERENT THERMAL ENVIRONMENTS

By

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Accurate prediction of leaf appearance rate is required in maize (*Zea mays* L.) simulation models to estimate leaf area development, biomass and yield. Plant temperature is closely related to the development rate, but the air temperature record used to estimate plant temperature is often biased during the early stages of maize development because the growing plant parts are below the soil surface. A field study was used to compare measured soil, air and apex temperatures with maize leaf appearance rates. Seasonal variation in leaf tip appearance rates was observed for four sowing dates spaced about one month apart during 1996. Solar radiation and temperature of the air, apex and soil (0.01 m, 0.03 m and 0.05 m depths) were recorded on half-hourly intervals. Apex temperature was found to be close to the soil temperature at 0.03 m or 0.05 m when the apex was below the surface. When the apex was above the surface, its temperature was close to the air temperature. The phyllochron (degree-days between leaf appearance events) was found to be higher (52.4°C/leaf tip) than values used in most existing maize models. A functional model was developed to estimate mean daily apex temperature using inputs of daily maximum and minimum air temperatures and solar radiation. The model was tested using an independent weather data set. The resulting estimates had a root mean square error (RMSE) of 1.31°C per day and mean bias error (MBE) of -0.06°C respectively. After stem elongation pushed the apex above the soil surface, mean air temperature was close enough to the mean apex temperature to assume that they were equal.

DEDICATION

I affectionately dedicate this work to my husband, Eduardo, my son ,Pablo and my daughter, Lucía, for their love and unconditional support; to my parents for teaching me that knowledge and hard work are tools for my future; to Dr. Roberto Seiler for his encouragement and inspiration.

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INTRODUCTION

A search for an understanding of the basic relationships between plants and their environment has kept man occupied for centuries. The role of simulation in this search has attempted to bring all factors involved in the system together in order that we may evaluate various cause and effect relationships. Several crop models, with different levels of detail, have been developed to simulate crop growth and development on a daily basis (e.g., Acock *et al*, 1983; Wilkerson *et al*, 1985; Ritchie *et al*, 1985; Jones and Kiniry, 1986; Boote, *et al*, 1989; etc). Such models, due to their mechanistic or functional basis, have been used to address different types of problems. Crop models predict crop yields sown anywhere at anytime, and have proven to be useful tools for decision making by farmers, researchers and policy makers (Ritchie, 1986; Singh, 1989) at field, farm, regional, and national levels (Thornton, 1991; Thornton *et al.*, 1991).

Crop simulation models should consider plant growth and development as separate processes. Growth and development are affected by different environmental variables (Ritchie and NeSmith, 1991) and have different sensitivity to water and nitrogen deficits and excesses (Ritchie, 1991). Modeling crop development is critical in order to predict crop productivity. The ability to estimate the stage of crop development is important for planning management decisions such as timing of irrigation, fertilizer, herbicide or insecticide application; for determining the availability of machinery for cultural practices; for adjusting planting dates so that flowering happens at optimum time to facilitate cross pollination in hybrid seed production; for growing plants with varying maturity dates to ease harvesting at intervals suitable to commercial canning operations; for defining which variety can be grown commercially in a specific area (Shaykewich, 1995) and for selecting a hybrid that will have a reasonable chance of maturing before frost in the case of late planting or double cropping management systems.

According to Wang (1960), one of the first studies related to crop development was done by Reamur (1735) who suggested that the time required for plants to complete a phase of their development could be more accurately estimated from the sum of daily air temperature than from the sum of calendar days. He also stated that the sum of daily mean air temperature was nearly constant to reach a given maturity stage for any plant. Following the work of Reamur, several methods of temperature summations to predict phenological stages have been developed (Gilmore and Rogers, 1958; Cross and Zuber, 1972; Brown, 1975; Tollenaar *et al*, 1979; Coelho and Dale, 1980). Different terms have been used to address this concept: degree days (°C d), day-degrees, heat units, heat sums, thermal units, and growing degree days although thermal time has been recommended for being used in a general terminology for temperature summation methods (Gallagher, 1979).

Wang (1960) criticized thermal time methodology, partly because plants do not respond to air temperature in the same way during various development stages. Response differences are due to differences in a minimum threshold temperature for various physiological processes and differences in the location of the response within the plant.

Thus, using the same base temperature for all stages and a measured temperature that may not be the temperature of the site where developmental processes occur may result in prediction errors. Solar radiation, wind, vapor pressure deficit, rainfall, etc., also influence plant development but they are not taken into account by thermal time methodologies. In addition, these methodologies do not consider the effects of extreme day or night temperatures, inter-diurnal temperature changes (defined as the difference between the maximum temperature of one day and the minimum temperature of the following day) and the difference between day and night temperatures (Wang, 1960).

Ritchie and NeSmith (1991) described different thermal time calculations using distinct base temperatures for several phenological stages of the crop. They also explained some possible sources of errors in thermal time calculations: error due to the time of manual recording of maximum and minimum temperatures in standard weather stations, differences in the value of the mean temperature based on the method of calculation (simple average of the daily maximum and minimum or average of hourly or less than hourly mean values), and error due to the location of the weather station related to the crop and position of the instrument related to the place where development is occurring. Geiger (1971) also described the errors associated with thermal time calculations when the temperature data are taken from climatological stations near to sites of prediction. He stated that such calculations may not reflect the altered microclimate of the crop canopy caused by crop surface roughness and exposure differences between the standard climatological station grass surface and the field crop. Other studies also noted inaccuracies in the temperature data due to inconsistent time of observation of daily maximum and minimum temperatures (Mitchell, 1958; Baker, 1975; Schaal and Newman, 1976; Schaal and Dale, 1977), and systematic biases when mean temperatures are calculated from simple maximum-minimum data (Hortik and Arnold, 1965; Robertson, 1968).

Maize (*Zea mays* L) development research in recent years has been focused on understanding the primary role of temperature on development and on the improvement of the thermal time approach. Most maize phenological modeling is based on the concept of thermal time or growing degree-days (Splinter, 1974; Duncan, 1975; Coelho and Dale, 1980). Some variations of this concept have been introduced with the incorporation of photoperiod (Coligado and Brown, 1975), or by varying base temperature (Jones and Kiniry, 1986; Kiniry, 1991; Stapper and Arkin, 1980), which have improved the ability to predict development although none of the changes have eliminated thermal time. Thus temperature remains the primary factor driving maize development.

Thermal time is usually calculated from air temperature, while the specific location on the plant where temperature influences development is in the developing point, the zone where plant cell division and expansion is occurring (Ritchie, 1991). During the early growth stages of a maize plant, the zones of cell division and expansion are slightly below the soil surface. Under these conditions the development rates (leaf initiation, leaf appearance, or reproductive initiation rates) are more closely associated with temperature near the soil surface than with the air temperature (Beauchamp and Lathwell, 1967; Cooper and Law, 1978; Duburcq *et al.*, 1983; Hesketh and Dale, 1987). Models that use air temperature to predict canopy development implicitly assume that air temperature and temperature of the cell expansion zone are equal (Cellier, *et al.*, 1993). These researchers stated that the assumed air-plant temperature similarities are usually acceptable when the canopy is fully developed because a large part of solar radiation is then dissipated into latent heat, which induces low temperature differences between the air and the vegetation. However, in the early growth period, the plant is not large enough to significantly affect the energy exchanges between the soil and the atmosphere. In such cases most of the incident solar radiation is dissipated into sensible heat, resulting in a potentially large difference between air at the site of measurement and the near soil surface temperature. Temperatures at the cell expansion zone will be more extreme (Duncan et al., 1973), particularly in the daytime, so that the crop growing point can experience a significantly higher mean temperature than is recorded by the standard air temperature. This will result in an underestimation of the thermal time by a model using standard air temperatures.

Previous experiments underscore the importance of the point where temperature is measured. Beauchamp and Lathwell (1967), in greenhouse studies of the effect of the root-zone constant temperatures on the early development of maize (based on leaf appearance rates), determined that for any growth-stage interval, the number of days required to reach that stage increased with decreasing root-zone temperature. Their data also revealed that the influence of the root-zone temperature in determining interval length was relatively greater once the plants had passed the 2-leaf stage and persisted only until the 6-leaf stage. Thus root-zone temperatures regulated maize development only during the period of leaf initiation. After that, air temperature assumed increasing importance as the meristem is moving away from the root zone temperature. In another greenhouse study of the relationship between young maize stalk internal near meristem temperature (measured with a thermistor probe) and aerial and root zone temperature, Beauchamp and Torrance (1969) found a predominating influence of root zone temperature on the temperature of tissues in the apical region of maize plant shoots. They explained that when the soil temperature is lower than the air temperature, the temperature of the apical meristem located 0.02 m to 0.03 m above the soil surface tends to remain 1 °C to 3 °C higher than soil temperature. Afterwards, in a controlled environment experiment, Watts (1972) showed that when meristem temperature was modified but shoot and root temperature were kept constant, rapid changes in maize leaves extension rates occurred. Subsequently, in a field experiment with different soil covers in order to induce soil temperature differences, Watts (1973) reported a close relationship between mean daily soil temperatures at 0.05 m depth and rates of leaf expansion and leaf appearance in maize. Barlow *et al.*, (1977) noted that the rate of leaf elongation decreased with lower soil temperature due to the effect of lowering the temperature of the shoot apical meristem region in young maize plants. Coelho and Dale (1980) and Hanway (1982) concluded that soil temperatures strongly affect the rate of maize growth until the sixth leaf-stage when the growing point emerges above ground level. Cutforth and Shaykewich (1989) determined that the duration of the planting to emergence interval of maize was predominantly controlled by soil temperature (measured at 0.05 m depth) but that the duration from emergence to stem elongation was significantly related to air temperature and not to soil temperature. Although, their results were in contrast to the findings of other researchers cited above, Cutforth and Shaykewich (1989) explained the differences considering that the criterion used in their study was stem elongation and not leaf appearance rate or leaf extension.

Previous studies have demonstrated that maize leaf development responds more to soil temperature (Walker, 1969) than to air temperature until the sixth leaf-stage (Beauchamp and Lathwell, 1967; Watts, 1973). However, most models or prediction equations use air temperature as the basis for the thermal indices since it is more readily available than soil temperature. Since most of the developmental processes can be observed at the apex level and the apex can be considered as an early image of the future plant, use of the actual apex temperature is most desirable. Measurements of soil temperature are often unavailable. Thus, soil temperature models have been developed for a variety of purposes and with varying degree of complexity and data requirements. They range in approach from the more empirical and statistical models (e.g., Cruse *et al.*, 1980; Gupta *et al.*, 1981; Meikle and Treadway, 1979, 1982) to the more physical and deterministic models (e.g., Hanks, *et al.*, 1971; Shroeder *et al.*,1978; Horton and Chung, 1991). Although statistical models are simple to construct and use, they are often site specific and require a large data base for developing the empirical coefficients. On the other hand, soil temperature models based on physical processes (radiative energy balance and sensible, latent, and ground-conductive heat energy fluxes) like those from Bucham (1982), Sasamori (1970) or Schieldge *et al.*, (1982) need much input data (e.g., solar radiation, radiation balance or vapor pressure) which are generally not available at a sufficiently dense time and spatial scale. Ten Berge (1990) and Horton and Chung (1991) developed models to predict bare soil temperature which are physically based but required 30 minutes interval data of solar radiation, vapor pressure, wind speed and rainfall or daily global radiation, maximum and minimum air temperature, average wind speed and total rainfall, respectively. Luo *et al.*, (1992) constructed a model using principles of energy balance and soil heat transfer which realistically simulated soil temperature with variable crop cover and soil water content but also required many inputs. Several other models have been developed to estimate soil temperature from air temperature (e.g., Hasfurther and Burman, 1974; Toy *et al.*, 1978; Gupta *el al.*, 1983; Dwyer *et al.*, 1990).

As Potter and Williams (1994) emphasized, the desirable characteristics of soil temperature models for practical long-term simulations models should be: (i) minimal inputs, because the simulations often have only daily weather station data as input; (ii) high operational speed, because the simulations are for many years; (iii) sensitivity to management operations that may vary the crop biomass or residue on the soil surface; and (iv) reasonable robustness over a wide range of soil and climatic conditions.

The models described above represent a broad spectrum of soil temperature models that have been developed. On the other hand, to my knowledge, only one model based on physical processes (Cellier *et al.*, 1993) was designed to model maize apex temperature under field conditions when the leaf area index of the crop is lower than 0.5 and the apex is about 0.03 m above the soil surface. The model estimates the apex temperature for both day-time and night-time averages from hourly values of solar radiation, wind speed, air temperature and humidity. As the empirical coefficients obtained for the model are climate dependent, a separate calibration may be required to apply it to different environments. When Cellier *et al.*, (1993) measured meristem temperatures using thin thermocouples, they found average differences between meristem and air temperatures up to +5° C during day-light hours with higher differences on sunny days than in overcast ones (4-6°C compared with 1-2° C respectively)..

Higgins *et al.,* (1964) proposed that leaf development was a valid index for estimating plant response to environmental conditions on a short term basis. Since leaf development involves leaf differentiation and leaf growth, the rate of leaf appearance provides an easily discernible index of plant-part differentiation without plant destruction. New leaf appearance events occur many times and at a predictable rate during the plant life cycle. From the three ways in which leaf appearance has been described for maize (primordia, tip and collar), tip appearance is the simplest, nondestructive and almost linear throughout mostly of the vegetative cycle. Leaf collar appearance rates have been described as a linear function of the mean daily temperature when maize is grown at constant temperature over the 16°C to 28°C temperature range until V12 stage and in the absence of moisture or nutrient stress (Warrington and Kanemasu, 1983). However, they found a curvilinear relationship when maize is grown under differential day/night temperature regimes. Earlier work of Tollenaar *et al*, (1979) and Thiagarajah and Hunt (1979) found similar results for the rate of leaf tip appearance for a range of temperatures between 12°C and 26°C.

The inverse of the slope of the thermal time-leaf tip appearance curve is called the phyllochron. The phyllochron or rate of leaf appearance , is defined as the time between the appearance of successive leaves on a shoot and is usually expressed in units of thermal time per leaf (McMaster and Wilhelm, 1995). The phyllochron provides a convenient method to describe plant vegetative development and aids in understanding and modeling crop development.

As stated above, during the early developmental stages of maize, the apex of the plant is 0.01 or 0.02 m below the soil surface. During those times , the soil temperature should be a better indicator of the apex temperature than air temperature. It is logical to expect that if we wish to be able to simulate maize development under different soil management scenarios and different sites, we need to estimate plant responses to soil temperatures resulting from these scenarios. If we choose to use near surface soil temperatures in estimating thermal time, we need to collect the data and determine the functional relationship between soil temperature at that level, the apex temperature and air temperature. Such information is usually not available and is the main focus of this thesis.

Objectives

Maize is one of the most economically important plants grown in North America. Cool conditions after sowing due to environmental factors or different soil tillage practices may delay maize development by decreasing soil temperatures and may increase the risk of frost terminating grain filling. On the other hand, warmer conditions due to environmental or management practices that increase plant development rates could shorten the crop cycle and reduce yields. Between these two extremes, a wide variety of environmental conditions can modify maize development. Current models can not provide a precise determination of maize phenological stages mainly because of the uncertainties of the plant-air temperature differences. It is unrealistic to expect to have apex temperature data available. Soil temperature data to use as an estimate of apex temperature are not usually measured in many sites either. Most sites where plant development predictions are needed will have only air temperature data because the cost and time that soil and apex temperatures require is not available. If maize simulation models will be continue in use as management tools, in risk assessment and for predicting crop yield, a more accurate determination of the crop phenological stages is required.

Bearing the above factors in mind, the specific objectives of this research are:

1 - To determine the functional relationship between air temperature measured with standard instrumentation at screen level (1.5 m height) and apex temperature under different meteorological conditions.

2 - To determine the functional relationships between apex temperature and soil temperature at the different soil depths.

3 - To model maize leaf tip appearance rate using soil and apex temperatures and compare these results with those from air temperature.

4 - To model maize development using the functional relationships developed between air and apex temperature and / or soil and apex temperature in order to get a generalized approach to the observed data.

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Chapter 2

AIR, SOIL AND APEX TEMPERATURES INFLUENCES ON MAIZE (*Zea mays* L.) LEAF DEVELOPMENT

ABSTRACT

Accurate prediction of leaf appearance rate is required in maize (*Zea mays* L.) simulation models to estimate canopy development, and ultimately maize yield. Most maize simulation models use air temperature for thermal time calculations to predict leaf appearance rate although nearby soil temperature is more closely related to the growing apex temperature than air temperature during early stages of development. A field experiment was conducted in 1996 at East Lansing, Michigan, on a Capac loam soil, to determine the effect of soil, air and apex temperatures on maize development and to evaluate their utility in the improvement of leaf developmental predictions. Maize leaf tip and leaf number were observed on four different sowing dates. Solar radiation and temperature of the air, apex and soil (0.01 m, 0.03 m and 0.05 m depths) were recorded on half-hourly intervals. Measured apex temperature was close to the soil temperature at 0.03 m or 0.05 m when the apex was below the surface or slightly above, otherwise the apex temperature was more related to the air temperature. An average bias of about 1.6 °Cd (degree-days) was found when air thermal time was used instead of apex thermal time. The phyllochron was found to be higher (52.4°Cd/leaf tip) that values actually used in most maize models, a possible reason of over-prediction of leaf development rates.

Introduction

Crop simulation models should consider plant growth and development as separate processes. Growth and development are affected by different environmental variables (Ritchie and NeSmith, 1991) and have different sensitivity to water and nitrogen deficits and excesses (Ritchie, 1991).

Most maize phenological modeling is based on the concept of thermal time (TT) or growing degree-days (GDD) (Splinter, 1974; Duncan, 1975; Coelho and Dale, 1980). Some variations of this concept have been introduced with the incorporation of photoperiod (Coligado and Brown, 1975) or by varying base temperature (Jones and Kiniry, 1986; Kiniry, 1991; Stapper and Arkin, 1980), which have improved the ability to predict development although none of the changes have eliminated thermal time. Thus, temperature remains the primary factor driving maize development.

Wang (1960) criticized thermal time methodology, partly because plants do not respond to air temperature in the same way during various development stages. Response differences are due to the differences in minimum threshold temperatures for various physiological processes and to differences in the location of the response within the plant. Thus, using the same base temperature for all stages and a measured temperature that may not be the temperature of the site where developmental processes occur may result in prediction errors. Solar radiation, wind, vapor pressure deficit, rainfall, etc., also influence plant development but they are not taken into account by thermal time methodologies. In addition, these methodologies do not consider the effects of extreme day or night temperatures, inter-diurnal temperature changes (defined as the difference between the maximum temperature of one day and the minimum temperature of the following day) and the difference between day and night temperatures (Wang, 1960).

For thermal time to be appropriate as a predictor of plant development, there should be a linear relationship between the development rate and plant temperature over a well-defined range of temperatures; the daily temperature should not fall below the base temperature or exceed an upper threshold temperature for a significant part of the day; and the developing plant portion should have the same mean temperature as the temperature being used in the summation (Ritchie and NeSmith, 1991).

Thermal time is usually calculated from air temperature, while the specific location on the plant where temperature influences development is in the developing point, the zone where plant cell division and expansion is occurring (Ritchie, 1991). During the early growth stages of a maize plant, the zones of cell division and expansion are slightly below the soil surface. Under these conditions the development rates (leaf initiation, leaf appearance, or reproductive initiation rates) are more closely associated with temperature near the soil surface than with the air temperature (Beauchamp and Lathwell, 1967; Cooper and Law, 1978; Duburcq *et al.*, 1983; Hesketh and Dale, 1987). Models that use air temperature to predict canopy development implicitly assume that air temperature and temperature of the cell expansion zone are equal (Cellier, *et al.*, 1993). These researchers stated that the assumed air-plant temperature similarities are usually acceptable when the canopy is fully developed because a large part of solar radiation is then dissipated into latent heat, which induces low temperature differences between the air and the vegetation. However, in the early growth period, the plant is not large enough to significantly affect the energy exchanges between the soil and the atmosphere. In such cases most of the incident solar radiation is dissipated into sensible heat, resulting in a potentially large difference between air at the site of measurement and the near soil surface temperature. Temperatures at the cell expansion zone will be more extreme (Duncan et al., 1973), particularly in the daytime, so that the crop growing point can experience a significantly higher mean temperature than is recorded by the standard air temperature. This will result in an underestimation of the thermal time by a model using standard air temperatures. On the other hand, during periods when soils are cooler than air temperatures, as often is the case during the early spring, the estimated thermal time required for development based on air temperatures would be greater than that based on soil or apex temperatures (Hesketh and Warrington, 1989).

Cellier *et al.*, (1993) found day-light average differences between air and apex temperature up to +5 ° C, with higher differences on sunny days than in overcast ones (4-6°C compared with 1-2°C respectively) during the early stages of development of maize plants. They measured maize apex temperature by inserting thin thermocouples in the plant at two heights (0 and 0.03 m) above the soil surface. Cellier *et al.*, (1993) designed a model based on physical processes, to estimate the apex temperature for both day-time and night time averages from hourly data of solar radiation, wind speed, air temperature and humidity. As the empirical coefficients obtained for the model are climate dependent, a separate calibration may be required to apply it to different environments. Jeppson and Crookston (1986) found that apex temperature was closely associated to soil temperature. They suggested that plants were able to dissipate all the plant-intercepted heat from the sun and that any apex heating came indirectly from the soil. The differences found between air and meristem temperature support the evidence of biases when air temperature is used in thermal time calculations instead of apex or near surface temperatures.

Higgins *et al.*, (1964) proposed that leaf development was a valid index for estimating plant response to environmental conditions on a short term basis. Since leaf development involves leaf differentiation and leaf growth, the rate of leaf appearance provides an easily discernible index of plant-part differentiation without plant destruction. New leaf appearance events occur many times and at a predictable rate during the plant life cycle. From the three ways in which leaf appearance has been described for maize (primordia, tip and collar), leaf tip appearance is the simplest, nondestructive and almost linear throughout mostly of the vegetative cycle. Leaf-collar appearance rates have been described as a linear function of the mean daily temperature when maize is grown at constant temperature over the 16°C to 28°C temperature range until V12 stage and in the absence of moisture or nutrient stress (Warrington and Kanemasu, 1983). However, they found a curvilinear relationship when maize are grown under differential day/night temperature regimes. Earlier work of Tollenaar *et al*, (1979) and Thiagarajah and Hunt (1979) found similar results for the rate of leaf tip appearance for a range of temperatures between 12°C and 26°C. Dwyer and Stewart (1986) showed a high correlation of leaf stages (collar visible) with three different thermal indices: GDD, Maize Heat Unit Index and Night Temperature Index. They suggested that air temperature alone could adequately account for variability in the time of appearance of each mature leaf as soil type and year did not contribute significantly to that variability.

The slope of the curve of leaf tip appearance versus thermal time for the data of Tollenar *et al.* (1979) was approximately 0.0265 leaves/°Cd (leaves per degree-day) between

8°C and 34°C (Ritchie and NeSmith, 1991). The inverse of the slope of the thermal time-leaf tip appearance curve is called the phyllochron. The phyllochron or rate of leaf appearance, is defined as the time between the appearance of successive leaves on a shoot and is usually expressed in units of thermal time per leaf (McMaster and Wilhelm, 1995). The phyllochron provides a convenient method to describe plant vegetative development and aids in understanding and modeling crop development. Ritchie and NeSmith (1991) stated that measurements of the phyllochron were in the narrow range of 38° to 45°Cd/leaf tip appearance when a base temperature of 8°C was used in the thermal time calculation. In other environmental studies, the thermal requirement per tip varied from 33 to 42° Cd and the base temperature from 6 to 9°C (Zur *et al.*, 1989; Tollenaar *et al.*, 1979). Field studies at different elevations in Kenya resulted in 41°Cd per leaf tip and a 9°C temperature base (Cooper, 1979). Picard *et al.*,(1985) reported 35 to 43°Cd per tip using a base temperature of 6°C. Assuming a base temperature of 8°C, the thermal requirement varied from 37 to 42°Cd per leaf in three field studies involving numerous hybrids at Urbana from 1985 to 1987 (J.D. Hesketh, unpublished data, cited in Hesketh and Warrington, 1989). In all these fields studies estimates were not corrected for soil temperature effects.

During the early developmental stages of maize, the apex of the plant is 0.01 or 0.02 m below the soil surface. During those times, soil temperature should be a better indicator of the apex temperature than air temperature. Although previous studies (Cellier *et al.*, 1993; Ben-Haj Salah and Tardieu, 1996) showed a difference between apex and air temperatures during short periods of the maize life cycle, the effect on maize development was not explained. Based on the utility of the leaf tip appearance rate and temperature relationship to predict maize development, it is logical to expect that if we want to simulate maize development under different soil management scenarios and different sites, we need to estimate plant responses to soil temperatures resulting from these scenarios. An experiment therefore was designed to determine the effect of soil, air and apex temperatures on maize (*Zea mays* L.) development and to evaluate their utility in the improvement of maize phenology prediction.

Materials and Methods

A field experiment was conducted in 1996 at the Michigan State University Research Farm, East Lansing, Michigan (42° 78' N, 84° 60' W), on a Capac loam soil (Fine-loamy, Mixed, Mesic, Aeric Ochraqualf). More details of the soil description are given in the Appendix).

Maize (hybrid 'Pioneer 3572') was manually planted at a plant density of 6.5 plants m^{-2} and at 0.05 m depth on four different dates: 29 May, 30 June, 2 August and 29 August. The seeds were sowed approximately one month apart to expose the crop to different thermal environments. Each adjacent experimental unit was 45 m^2, with five rows 15 m in length and 0.75 m apart except for the fourth sowing which had only one row 15 m in length.

All plots were moldboard plowed in the fall and received secondary tillage prior to planting in the spring. Plots were raked before planting to level the surface. Starter fertilizer was applied at sowing at a rate of 45-45-45 kg ha^{-1} (N-P-K). Weed plants were hand removed during the growing season. An irrigation of 25 mm was applied on 24 July.

Soil temperatures were measured for each sowing date, at depths of 0.01 m, 0.03 m and 0.05 m every five seconds and half hourly average values were stored in a LI-COR 1000 data logger (LI-COR, Inc, Lincoln, NE). Air temperature at screen level (1.5 m height) and solar radiation were recorded on each plot at the same frequency. A second data logger, Campbell CR 10 (Campbell Scientific, Inc, Logan, Utah) was used to complement the first one when measurements in the different sowing were overlapped. Temperature in the region around the apex (called from now apex temperature) was measured using thin copper-constantan thermocouples needles of 0.008" diameter (Omega HYP-0-33-1-T-G-120-SMP-M, Mini Hypodermic thermocouple probe, Omega Engineering, Stamford, CT). Each needle was thermally insulated with silicone and covered with shrinkable tubing, leaving only 0.005 m uncovered at its end where the thermocouple junction was placed. Data were recorded every 5 seconds and averaged every 30 minutes. They were stored in a data logger (Campbell CR 10 or LI-COR 1000, with 1000-10 Thermocouple Terminal Block). The temperature sensor was changed to a new plant almost daily to avoid error in temperature values due to the possible effect of damaged tissue where the sensor was inserted. Maximum and minimum soil, air, and apex temperatures were recorded at the same frequency. Rainfall data were collected at the nearest weather station (MSU Horticultural Research Station, East Lansing). Data were aggregated over the day, and the daily maximum, minimum, and average values were calculated from the half hourly maximum, minimum and average readings.

Ten consecutive plants away from the plots' borders were marked at the beginning of the growing season. The date when 50% of the plants reached the different stages of development as defined by Ritchie and Hanway, (1982) was observed. Vegetative plant development was studied using appearance rate of leaf tips. Fully expanded leaves (FL) were recorded when the collar appeared and total number of leaves (TLN) was determined when the tip appeared. The number of tips on each plant was observed three times per week.

Thermal time (TT) was calculated using soil temperature at each measured depth, apex temperature and air temperature for each of the four sowing from emergence until the last tip appeared. Thermal time was defined as:

$$TT = \sum_{i=1}^{n} (\bar{T} - T_b)$$

where: $\bar{T}$ is daily mean air, soil or apex temperature and T_b is the base temperature at which development stops. The base temperature used was 8°C (Ritchie and NeSmith, 1991). The daily mean was calculated by averaging half hourly mean temperature values for the different variables. When the daily average temperature was below T_b, no value was added to the summation. Thermal time calculated with the different temperatures was compared to determine which provided the best estimation of tip appearance rate and vegetative development. The phyllochron (thermal time required for each tip to appear) was calculated for each one of thermal time-leaf tip relationships determined using air, soil and apex temperatures.

Because needle thermocouples were not available until the second sowing, apex temperature was not measured for the first sowing. Some failures in the recording of the apex temperature at the beginning of the third sowing provided an incomplete record. The missing data of the third sowing were estimated using regression formula developed with the available apex and soil temperature data for that sowing.

Results and Discussion

Thermal time calculation from daily average air, apex and soil temperatures at the different depths, for each sowing and from crop emergence are presented in Figures 1 to 4 for the four sowing dates. Accumulation of thermal time was faster for soil or apex temperatures than air temperatures for all the sowing dates because of higher average temperatures in the soil and apex. Apex thermal time was closer to soil thermal time calculated using soil temperatures at 0.03 m or 0.05 m depths for the second and third sowing, and to soil temperature at 0.01 m depth for the fourth sowing. These results demonstrate that apex temperature is closer to the temperature of the soil at the depth where the growing point is situated until the apex emerged above the soil surface when it becomes to be more affected by air temperature.

The apical meristem remained below ground until V5 stage (Ritchie and Hanway, 1982) and reached the soil surface a few days prior to V6 stage when the total number of leaf tips was 9 for the first three sowing dates. No data for this stage were available for the fourth sowing because plants were killed by a frost at V4 stage and with 6 leaf tip. The second and third sowing reached V6 stage at about the same amount of thermal time and days (25 days) while the first sowing required more days (27 days) and more thermal time (Table 1).

Differences in the thermal time required to reach different development stages are due to variations in the patterns of soil, apex and air temperatures observed during the four sowing. Soil and air temperatures did not differ consistently until June 23 (Day of the year 175) during the first sowing probably because of wet weather and high soil water content which decreased soil temperatures (Figure 5). Daily average differences between apex and air temperature of up to +5°C on sunny days and up to +2°C on overcast days were found for the last three sowing when the apex was below the soil surface or slightly above (Figures 6, 7 and 8). Smaller fluctuations between air and apex temperatures were found when stem elongation moved the apex above the soil surface, thus making it more affected by the air temperature. These results supported previous similar findings by Cellier *et al*, (1993). Soil and apex temperatures followed the same pattern and had similar values while the apex was below the soil surface (Figures 6, 7 and 8) which also agreed with Duncan *et al.*, (1973) conclusions.

Table 1: Accumulated thermal time (°Cd) using apex, air and soil temperatures from emergence until the ninth leaf-tip appeared for three different sowing dates. S 1, S 3 and S 5 mean soil thermal time calculated using soil temperatures at 0.01, 0.03 and 0.05 m depths, respectively.

Sowing	Air	S 1	S 3	S 5	Apex
First	373.7	447.7	441.3	432.1	
Second	327.2	433.6	425.6	418.9	411.8
Third	335.4	430.2	414.3	406.9	407.1

Hourly series of all measured temperatures are shown in Figure 9 for a sunny and a cloudy day for the crop sowed on the second date. Higher differences between apex and air temperatures are evident after sunrise, increasing during the day with a maximum around noon (almost 10°C difference) and decreasing in the late afternoon (Figure 9 a). A similar pattern was observed for soil temperature at 0.01 m depth while a delay in the time of occurrence of maximum and minimum temperatures was shown by the other two soil depths due to the soil buffering effect (Table 2). Smaller differences between all temperatures are evident on overcast days (Figure 9 b) because of the decreased amount of soil heating associated with less direct solar radiation on the soil surface. Even on cloudy days however, the apex and soil temperatures were slightly higher than air temperatures (Table 2).

Table 2: Minimum (Min), maximum (Max) and average air, apex and soil temperatures at three depths on July 18 1996 (Solar radiation 10.01 MJ m^{-2}) and July 20 1996 (Solar radiation 29.79 MJ m^{-2}). S 1, S 3 and S 5 mean soil temperature at 0.01, 0.03 and 0.05 m depths, respectively

Day	**July 18**			**July 20**		
Temperature	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**
Air	29.5	19.3	23.2	25.1	9.7	17.2
Apex	31.4	20.1	24.1	34.8	12.5	22.7
S 1	31.7	20.3	24.2	37.5	13.1	23.9
S 3	28.8	21.0	24.0	33.5	14.9	23.4
S 5	28.1	21.2	24.0	33.1	15.7	23.6

Differences in air and apex temperature patterns affected thermal time calculations and suggested that apex temperature should be used instead of air temperature in the determination of maize leaf development. When apex temperature is not available, soil temperature at 0.03 m or 0.05 m depths appear to be adequate substitutes.

To characterize maize leaf development, the relationship between total number of leaf tips and thermal time calculated with the different temperatures was studied. Figures 10,11, 12 and 13 show these relationships for the different sowing dates from emergence of the third leaf tip. The third tip was chosen as the lowest one because the first and second tips appeared at a considerably faster rate. Leaf development was highly correlated to thermal time calculated with the measured air, soil and apex temperatures for all sowing dates (Table 3). The number of leaf tips considered in the analysis was different for each sowing making comparisons of the results between the different sowing dates difficult. For the first and fourth sowing, the number of tips was nine and six respectively. The second and third sowing tips number were sixteen and fifteen, respectively. Differences in thermal time calculated using soil and air temperatures were determined during the first stages of crop development (Figures 2 and 3) when soil and air temperatures showed larger differences (Figures 6 and 7) and were maintained for the remainder of the growing season. Smaller differences between soil and air temperatures characterized the first and fourth sowing (Figure 5 and 8). Lower correlation of apex thermal time for the third sowing could be related to the use of estimated values of apex temperature at the beginning of that sowing due to failure of the recording system. Fortin and Pierce (1991) and Dadoun (1993) suggested the use of soil temperature in thermal time calculations when the apex is below the surface and air temperature afterwards although their research was carried out with different types of mulch applied to the soil surface.

Although correlation coefficients between leaf tip number and thermal time calculated with the air, apex or soil temperatures recorded in each plot were higher in all cases, differences arise when the phyllochron is considered. The second and third sowing, within the third to sixteen or fifteen leaf tips respectively, showed a phyllochron calculated with air thermal time between the ranges found by previous researchers with the same base temperature (Ritchie and NeSmith, 1991; J.D. Hesketh, unpublished data, cited in Hesketh and Warrington, 1989). The first and fourth sowing, with fewer leaf tips (from the third to the ninth or sixth leaf tips respectively) indicated higher phyllochron. Cooler temperatures characterized the beginning of the first sowing and most of the fourth sowing, which may have affected maize leaf development through delaying leaf tip appearance rate. Landi and Crosbie (1982) found that short periods of cold stress prior to full emergence of the fifth leaf reduced leaf emergence in some hybrids. Symptoms of cold stress may be also expected at temperatures of 10 - 12° C (Taylor and Rowley, 1971). Signs of cold stress were evident at the end of the third and fourth sowing when air and apex temperatures were around 15 °C or lower.

An error in the prediction of maize leaf development of about 7° Cd per phyllochron is evident if air thermal time is used instead of apex thermal time. Thus, models that estimate maize leaf development based on air thermal time are likely to over-predict the number of leaf tips. For the second and third sowing, the difference between the measured number of leaf tips and the predicted using air thermal time instead of apex thermal time is almost 2 leaf tips.

When all data are aggregated (Figure 14) using apex thermal time for the last three sowing dates and soil thermal time calculated with S 5 for the first sowing, the average phyllochron is 52.4 degree-days for all but the first two tips. Although a linear relationship between leaf tip appearance and thermal time is shown, a deviation from the linear pattern is observed during some portions of the second and third sowing from the point where the number of tips is around nine or above. At that time the apex is beginning to move above the soil surface level due to rapid shoot elongation. After that a closer relationship to air temperature was observed. A slight water stress which occurred from the seven to the eight tip could have affected the rate of leaf tip appearance in the second sowing and induced this change in the rate pattern. Irrigation was applied when the second sowing had 8 tips.

Muchow and Carberry (1989) found that a reduction in the rate of leaf-collar appearance occurred when the crop experienced water stress during the early growth stages (approximately from tassel initiation to anthesis). Re-watering corrected the situation and the rate was increased for the leaf collar appearance as compared to the non-stressed plots (Muchow and Carberry, 1989). For the third sowing, a period of air temperatures around 15°C or less began when the crop had approximately 11 leaf tips (Figure 7). The effect of low temperatures on leaf development was described earlier which may explain the decrease in the leaf tip appearance rate. There was no apparent reason for the increase in the rate of leaf tip appearance for leaves 14 and above observed for the second and third sowing although it may be related to the stage of development as the final leaf tips are appearing for the third sowing.

When the combined data analysis was carried out with soil thermal time (S 1, S 3 and S 5) (Figure 15, 16 and 17 respectively) or air (Figure 18) instead of apex thermal time, the average phyllochrons have different values which support the necessity of choosing the right temperature to accurate predict leaf development.

Conclusions

This experiment demonstrated that there was a consistent bias between apex temperature and air temperature during early growth stages of maize crop development under different thermal environments. These findings are in agreement with previous studies of Cellier *et al.*, (1993) and Ben-Haj Salah and Tardieu, (1996). Soil temperature at 0.03 m or 0.05 m depths proved to be a better indicator of the temperature that is affecting early developmental processes than air temperature because soil temperatures were quite close to the apex temperature when the apex was near the soil surface. When the crop had more than six full developed leaves or nine leaf tips and the apex was above the soil surface, apex temperatures were closer to air temperatures. This study demonstrated that the temperature measured in air, apex or soil, when accumulated through most of the season had a high correlation with leaf development. The apex temperature was more consistently correlated between the sowing dates. As a result, crop models which use air temperature in thermal time calculation are over-predicting the total number of leaf tips and maize leaf development. A higher phyllochron than used in most maize crop models was identified, indicating the necessity of changing its value from about 40°Cd per phyllochron to about 52°Cd in order to adequate predict maize leaf development based on the bias in thermal time found in this study.

Table 3: Correlation coefficients (**r**),slope (**b**), phyllochron (**Phyl**) (° Cd/leaf-tip) and standard error of the slope (leaf-tips/° Cd) (**STD**), for leaf-tip number predictions from the third leaf-tip calculated using thermal time (**TT**) obtained from air, apex and soil temperatures at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths for four different sowing

Sowing	TT	b	Phyl	r	STD
First (until leaf-tip 17	Air	0.0191	52.36	0.999	0.0002
until leaf-tip 9)	Air	0.0195	51.28	0.999	0.0004
	S 1	0.0162	61.73	0.997	0.0005
	S 3	0.0164	60.98	0.998	0.0004
	S 5	0.0167	59.88	0.998	0.0004
Second (until leaf-tip 16)	Air	0.0218	45.87	0.998	0.0003
	S 1	0.0185	54.05	0.998	0.0003
	S 3	0.0187	53.42	0.998	0.0003
	S 5	0.0188	53.16	0.998	0.0003
	Apex	0.0198	50.53	0.997	0.0003
Third (until leaf-tip 15)	Air	0.0219	45.57	0.995	0.0005
	S 1	0.0172	58.14	0.994	0.0004
	S 3	0.0178	56.07	0.995	0.0004
	S 5	0.0178	56.07	0.996	0.0003
	Apex	0.0190	52.60	0.992	0.0005
Fourth (until leaf-tip 6)	Air	0.0201	49.75	0.997	0.0006
	S 1	0.0162	61.73	0.996	0.0006
	S 3	0.0156	64.10	0.996	0.0006
	S 5	0.0147	68.03	0.996	0.0005
	Apex	0.0180	55.56	0.997	0.0006

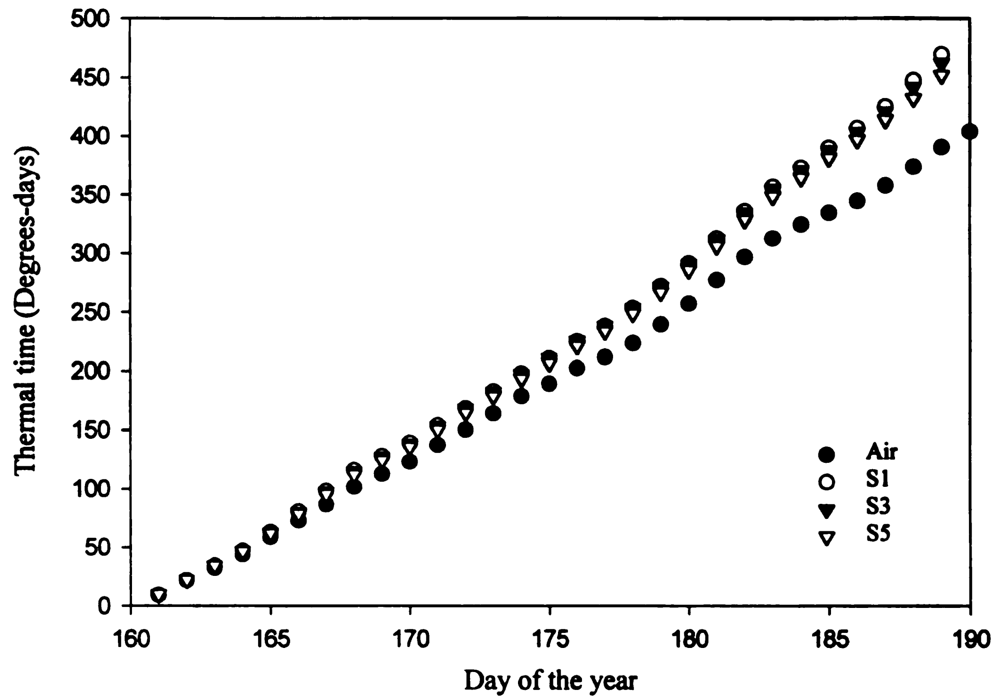

Figure 1: Seasonal variation in thermal time accumulation from emergence until the appearance of the ninth leaf tip for the first sowing using air and soil temperatures with a base temperature of 8 °C. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively.

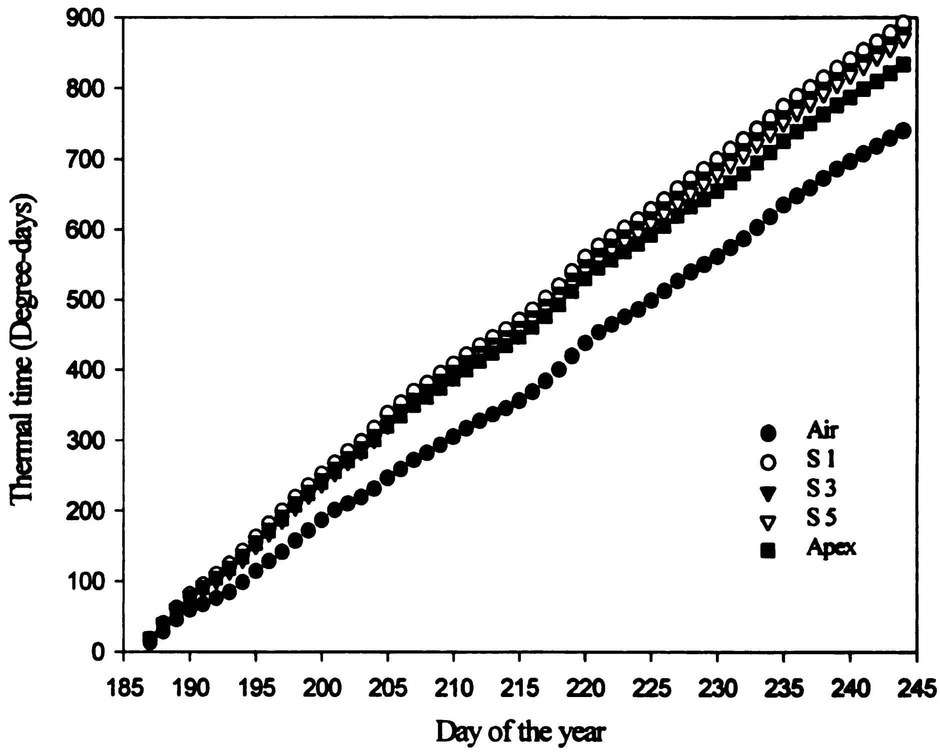

Figure 2: Seasonal variation in thermal time accumulation from emergence until the last leaf tip emerged for the second sowing using air, soil and apex temperatures with a base temperature of 8°C. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively.

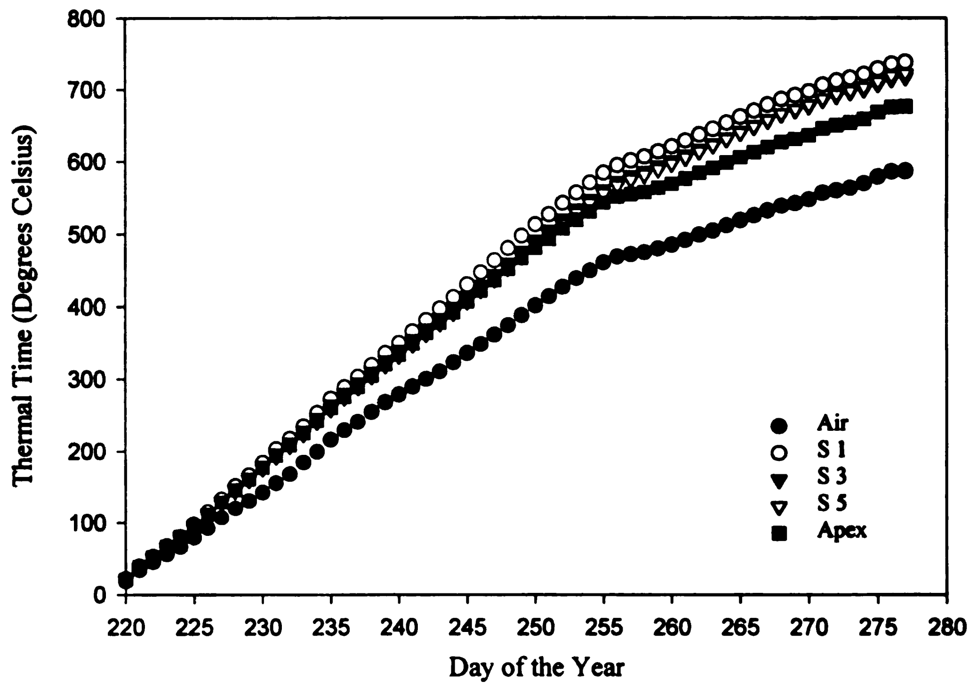

Figure 3: Seasonal variation in thermal time accumulation from emergence until the last leaf tip emerged for the third sowing using air, soil and apex temperatures with a base temperature of 8°C. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively.

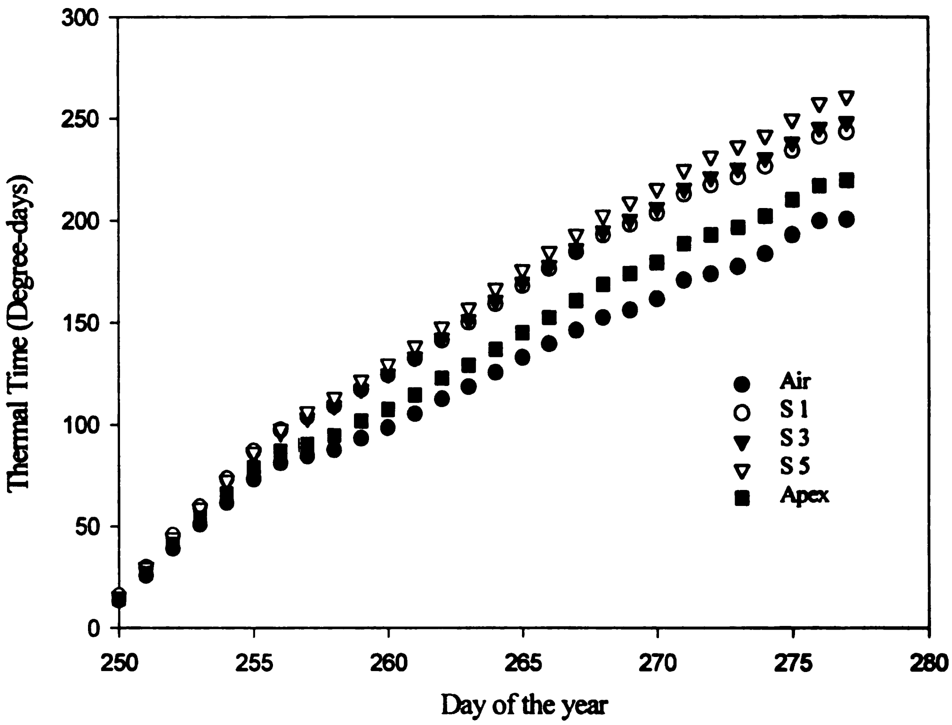

Figure 4: Seasonal variation in thermal time accumulation from emergence until the last leaf tip emerged for the fourth sowing using air, soil and apex temperatures with a base temperature of 8°C. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively.

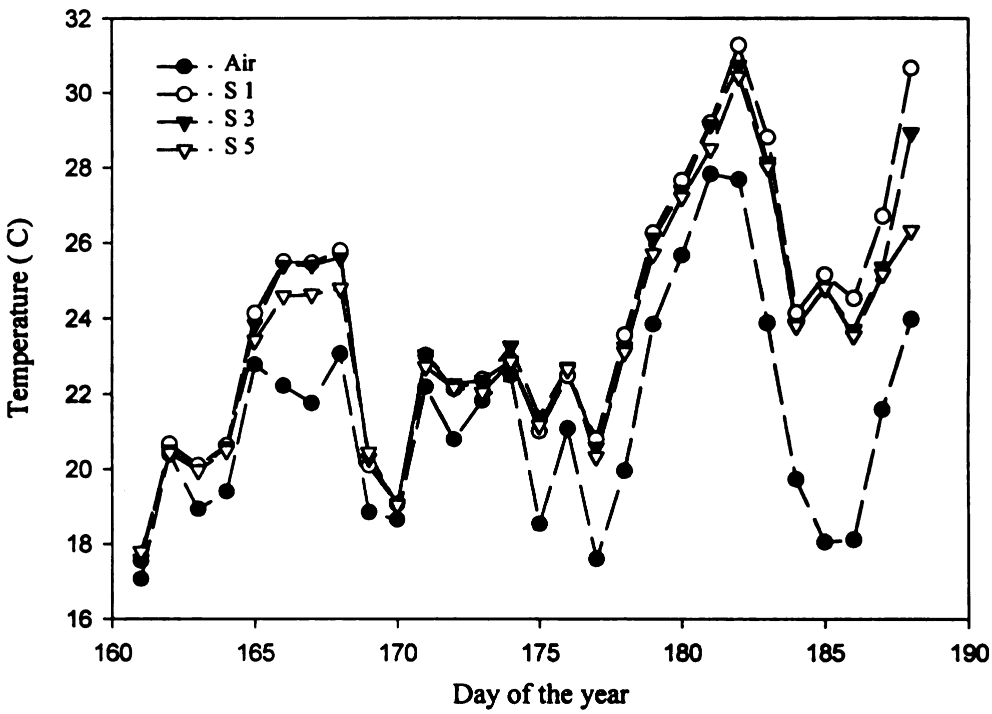

Figure 5: Seasonal variation in daily average air and soil temperatures from emergence until the ninth leaf tip appeared for the first sowing. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively.

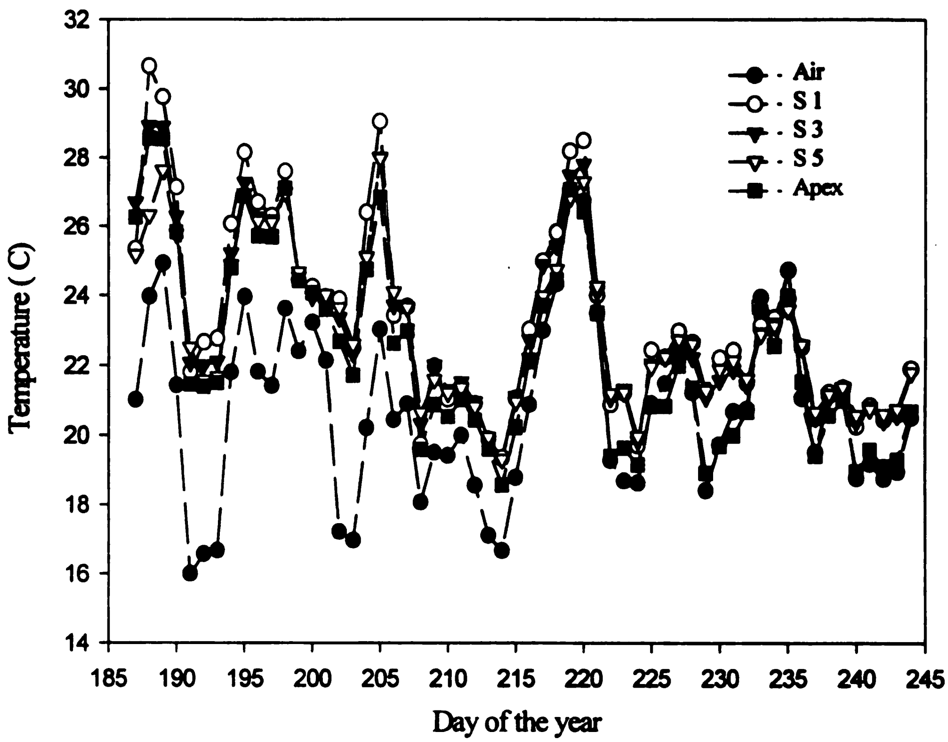

Figure 6: Seasonal variation in daily average air, soil and apex temperatures from emergence until the final leaf tip appeared for the second sowing. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively.

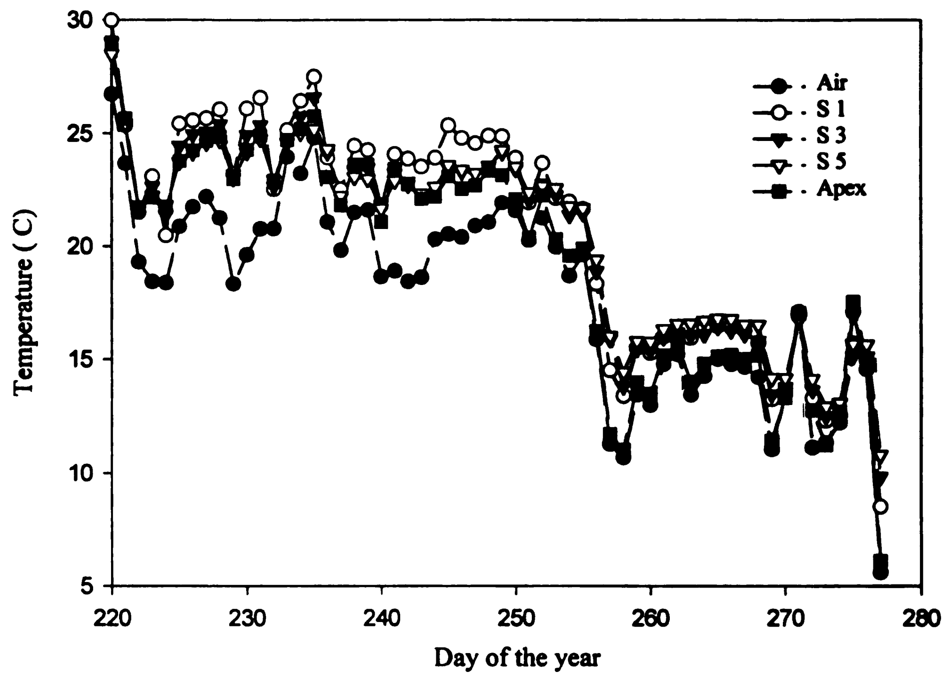

Figure 7: Seasonal variation in daily average air, soil and apex temperatures from emergence until the last leaf tip appeared for the third sowing. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively.

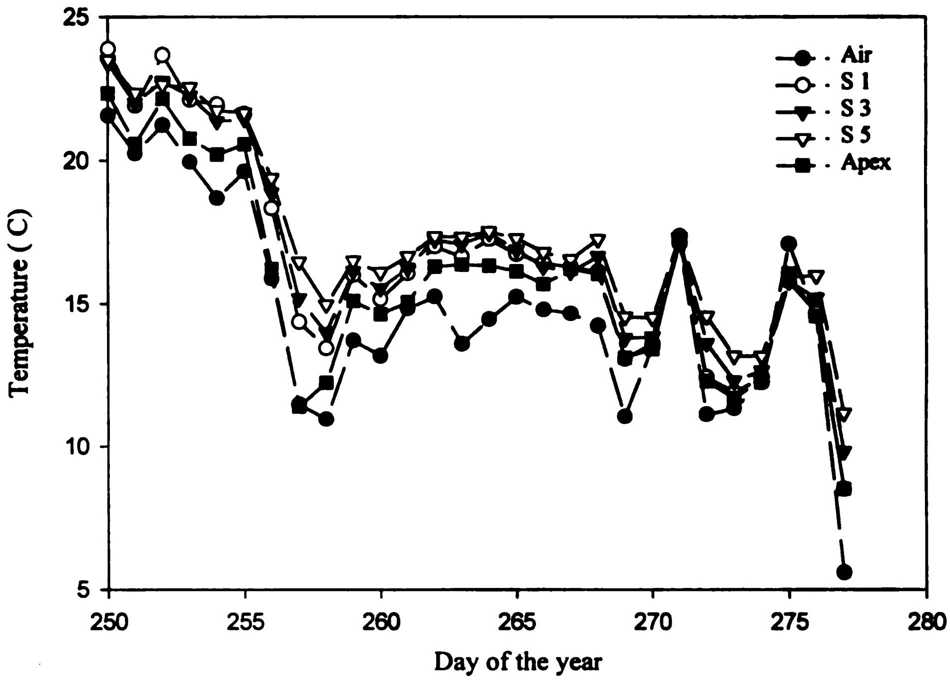

Figure 8: Seasonal variation in daily average air, soil and apex temperatures from emergence until the sixth leaf tip appeared for the fourth sowing. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively.

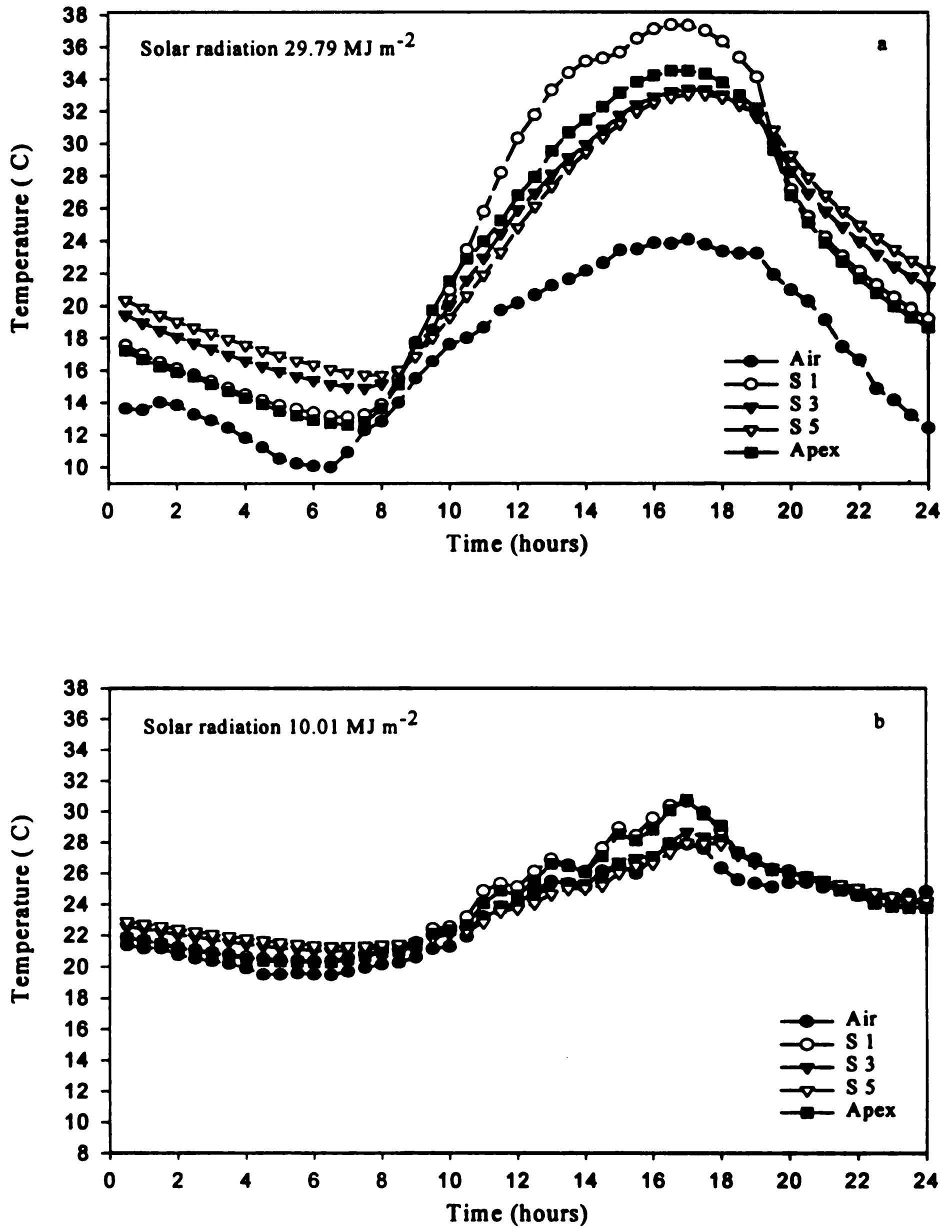

Figure 9: Half-hourly variation of apex, soil and air temperatures for a sunny (July 20, 1996) (a) and a cloudy (July 18, 1996) (b) day during the second sowing. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively.

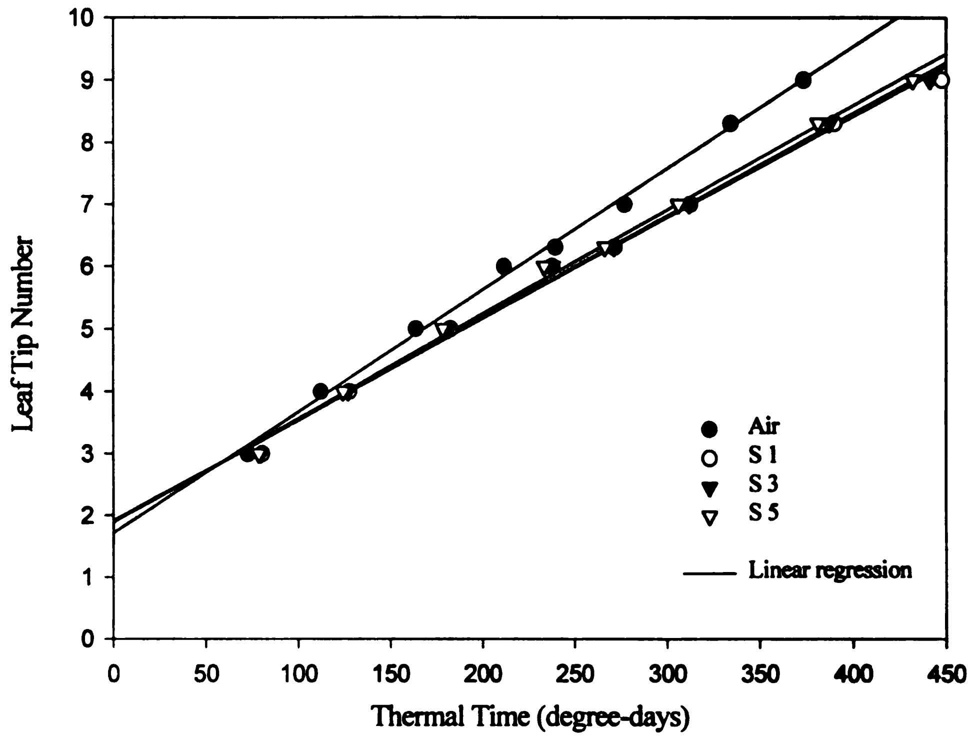

Figure 10: Total number of leaf tips as a function of thermal time calculated using air and soil temperatures from the third leaf-tip and for the first sowing. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively. Each point is the mean of observations done in 10 plants.

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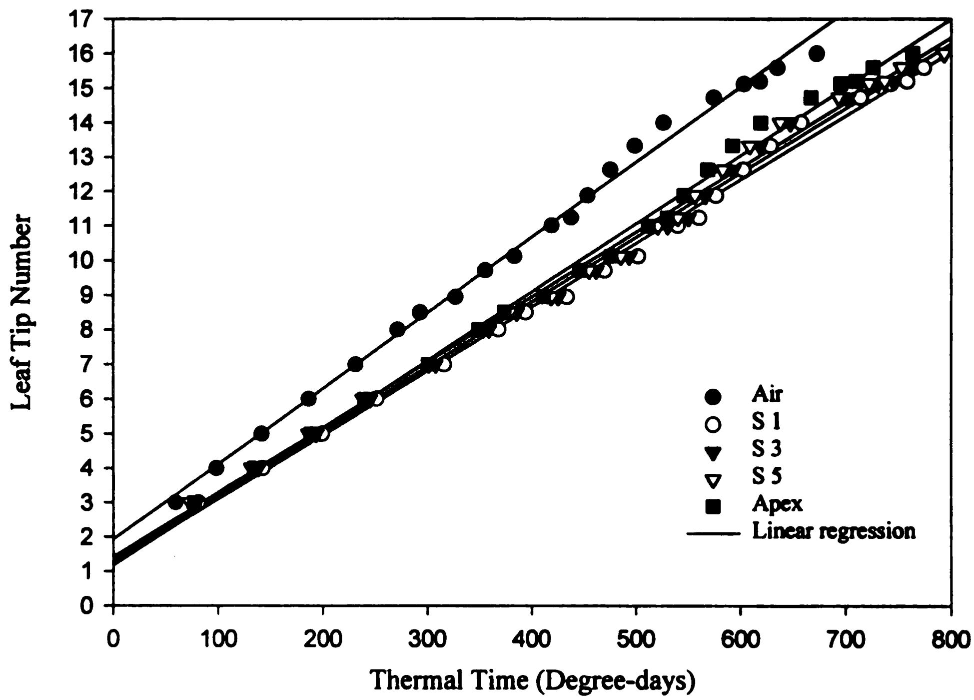

Figure 11: Total number of leaf tips as a function of thermal time calculated using soil, air and apex temperatures from the third leaf tip and for the second sowing. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively. Each point is the mean of observations done in 10 plants.

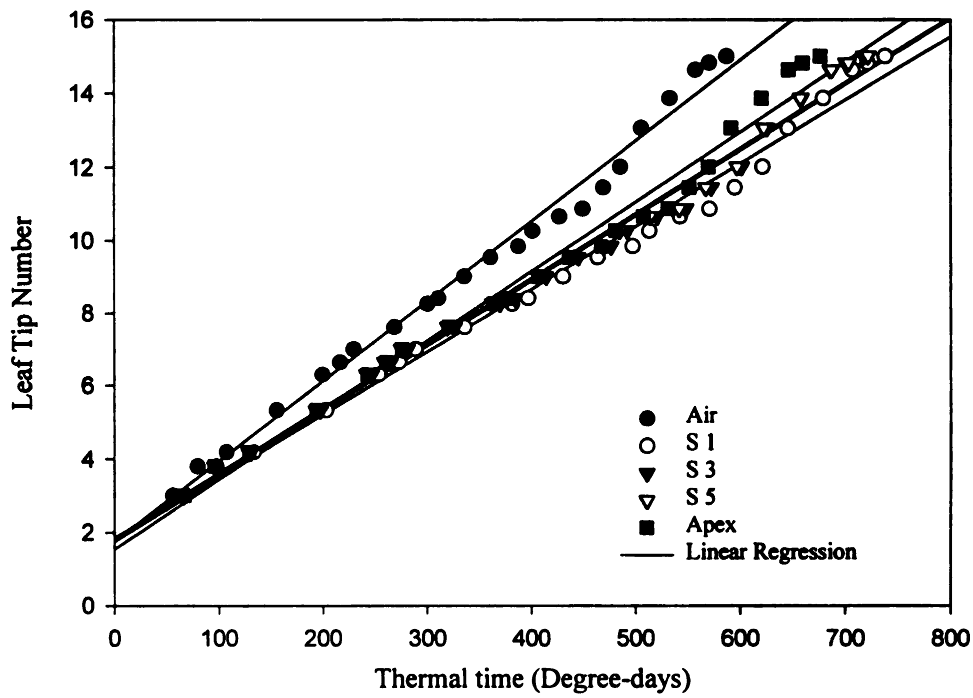

Figure 12: Total number of leaf tips as a function of thermal time calculated using soil, apex and air temperatures, from the third leaf tip and for the third sowing. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively. Each point is the mean of observations done in 10 plants.

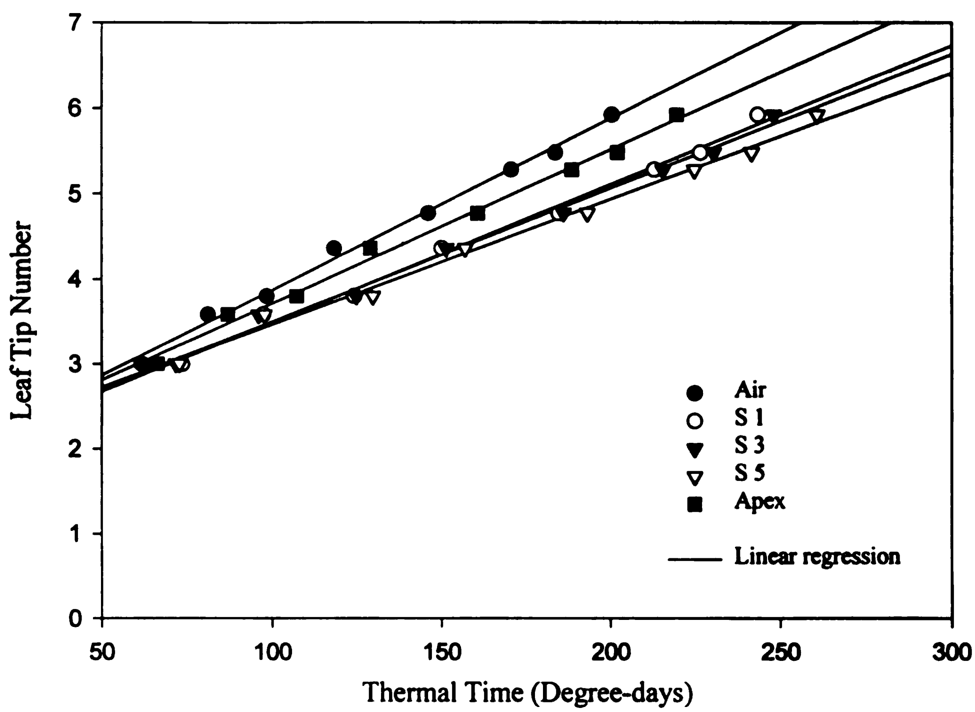

Figure 13: Total number of leaf tips as a function of thermal time calculated using soil., apex and air temperatures from the third leaf tip and for the fourth sowing. Soil temperatures are at 0.01 m (S 1), 0.03 m (S 3) and 0.05 m (S 5) depths, respectively. Each point is the mean of observations done in 10 plants.

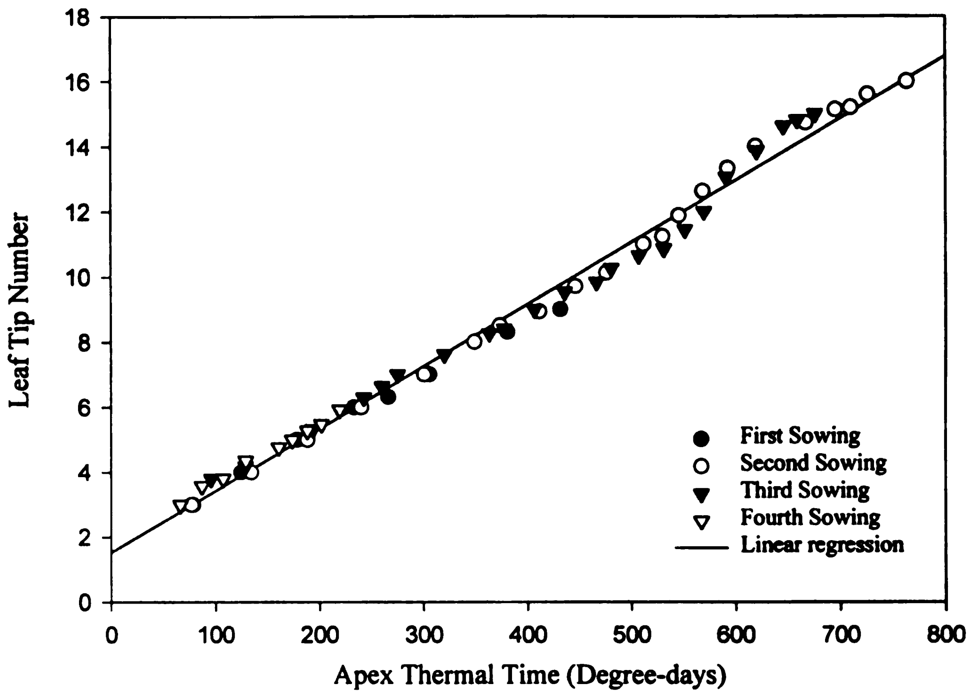

Figure 14: Total number of leaf tips as a function of thermal time calculated using soil temperature at 0.05 m depth (First sowing) and apex temperature for the other three sowing. Slope = 0.01907 leaves/degree-day, Phyllochron = 52.4 degree-days/leaf tip, r = 0.996

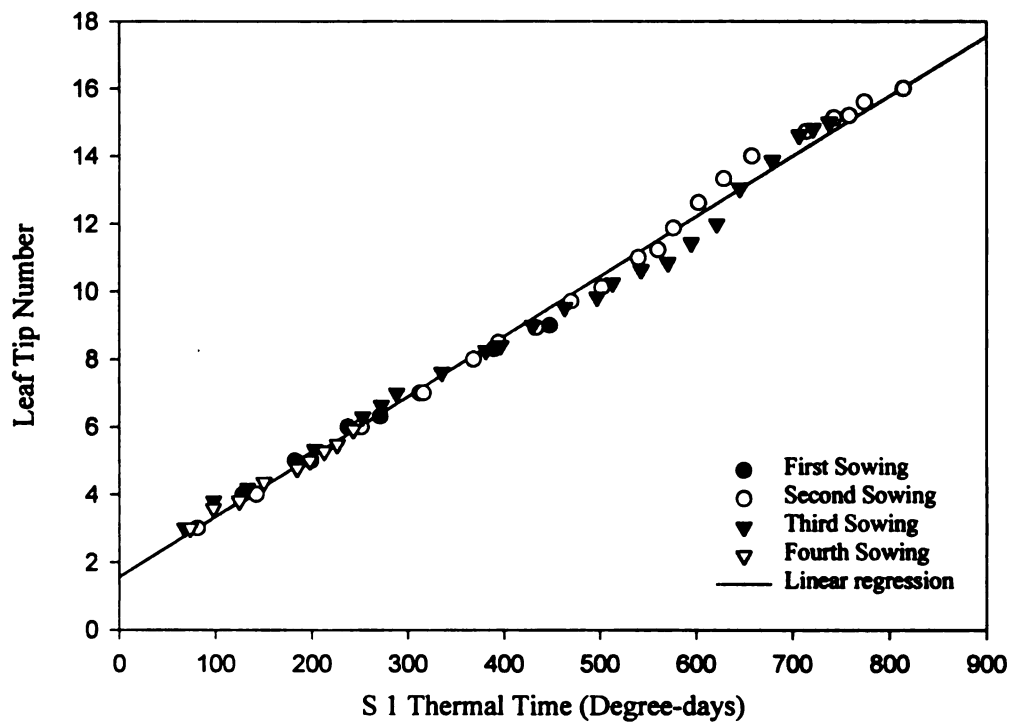

Figure 15: Total number of leaf tips as a function of thermal time calculated using soil temperature at 0.01 m depth. Slope = 0.01776 leaves/ degree-day, Phyllochron = 56.3 degree-days/leaf tip, r=0.996

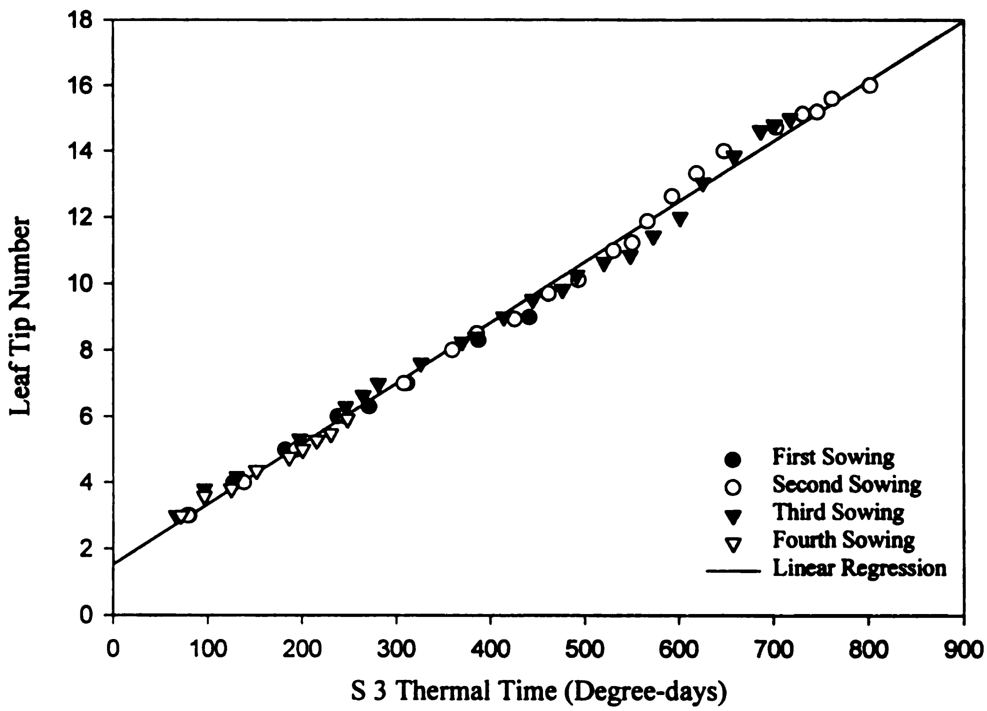

Figure 16: Total number of leaf tips as a function of thermal time calculated using soil temperature at 0.03 m depth. Slope = 0.01827 leaves/ degree-day, Phyllochron = 54.7 degree-days/leaf tip, r=0.997

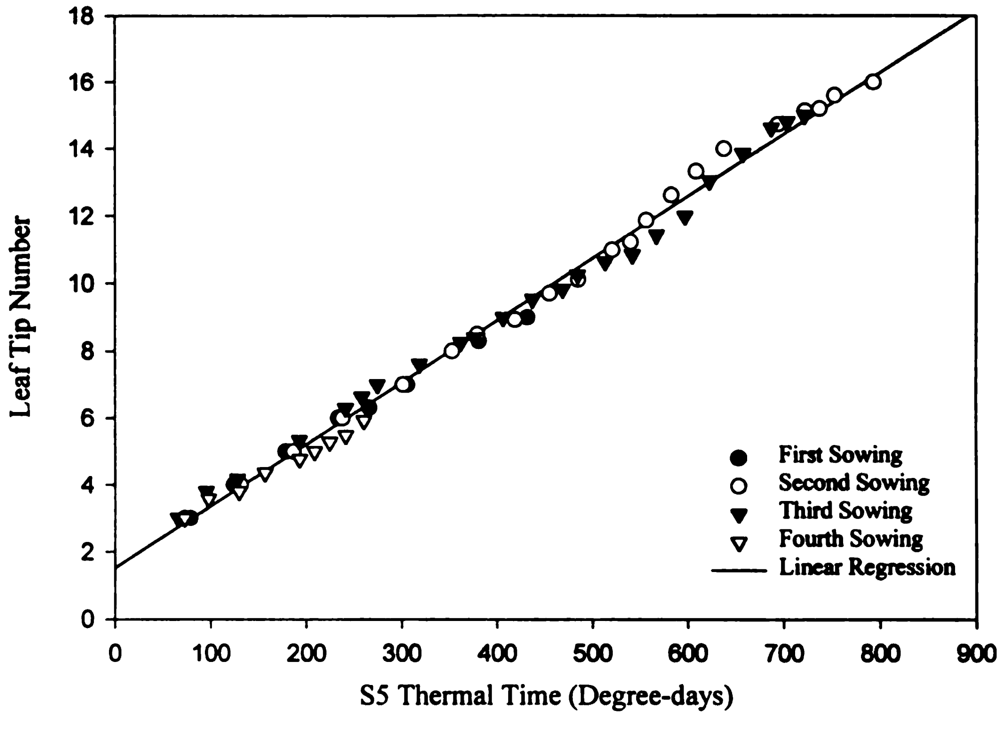

Figure 17: Total number of leaf tips as a function of thermal time calculated using soil temperature at 0.05 m depth. Slope = 0.01846 leaves/ degree-day, Phyllochron = 54.2 degree-days/leaf tip, r=0.997

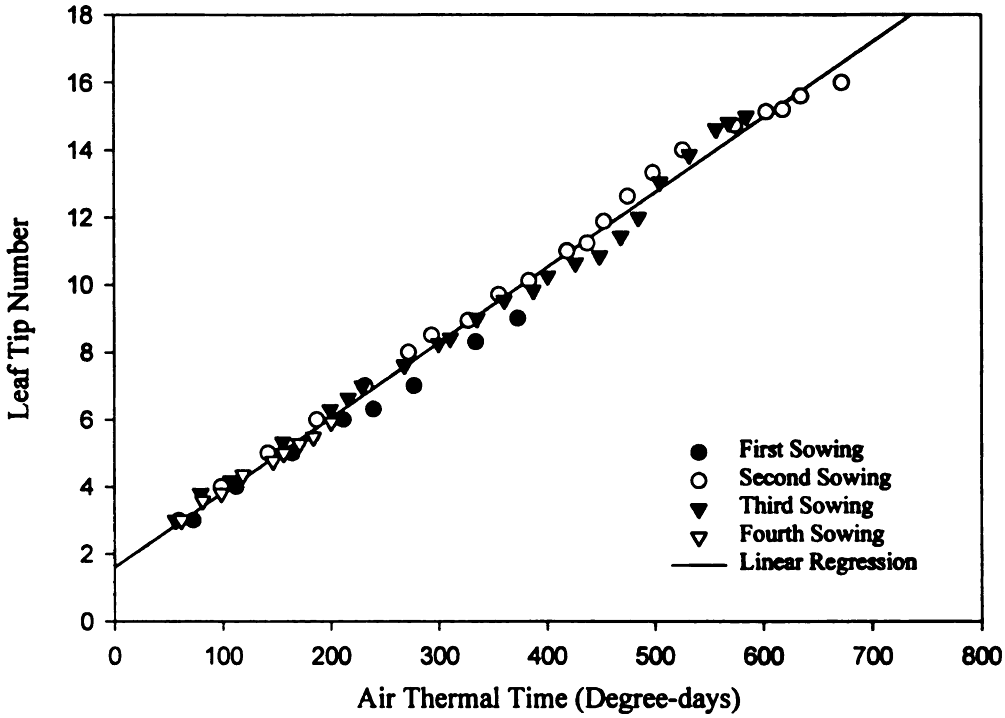

Figure 18: Total number of leaf tips as a function of thermal time calculated using air temperature. Slope = 0.02226 leaves/ degree-day, Phyllochron = 44.9 degree-days/leaf tip, r=0.996

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Chapter 3

ESTIMATION OF MAIZE (*Zea mays* L.) APEX TEMPERATURE

ABSTRACT

The importance of apex temperature in the determination of maize (*Zea mays* L.) leaf development during early development stages has been demonstrated in several studies. Thus, there is a need for a simple and efficient model for estimation of apex temperature that uses readily available meteorological information. A functional model requiring inputs of daily minimum and maximum air temperatures and solar radiation was developed to estimate mean daily apex temperature from seedling emergence until vegetative stage V7, the time when the apex is below the soil surface or slightly above. To develop the model, half-hourly meteorological and apex temperature data were taken from a field experiment conducted in 1996 at East Lansing, Michigan. A wide range in temperatures was obtained by using four different sowing dates spaced about one month apart. The model is based on individual differences between apex daylight and apex night time temperatures and maximum and minimum air temperatures. Solar radiation is used only during the daylight period. Independent data used to test the model showed that the root mean square error (RMSE) and mean bias error (MBE) for the daily mean apex temperature were 1.31°C and -0.06 °C respectively. After the V7 stage of development, mean air temperature was close enough to the mean apex temperature to assume that they were equal. Although the relationships developed in this model should be applicable elsewhere, they should be confirmed under different soil and climatic conditions.

Introduction

During the early growth stages of a maize (*Zea mays* L.) plant, the zones of cell division and expansion are slightly below the soil surface. In these conditions the development rates (leaf initiation, leaf appearance, or floral initiation rates) are more closely associated with temperature near the soil surface than with the air temperature (Beauchamp and Lathwell, 1967; Cooper and Law, 1978; Duburcq *et al.*, 1983; Hesketh and Dale, 1987; Walker, 1969). In accordance with these findings, it was demonstrated in Chapter 2 of this thesis that differences between air and apex temperatures patterns affected thermal time calculations and suggested that apex temperature should be used instead of air temperature in the determination of maize leaf development based on leaf tip appearance. Soil temperature at 0.03 m or 0.05 m depths proved to be a better indicator of the temperature affecting early developmental processes than air temperature because soil temperatures were quite close to the apex temperature when the apex was near the soil surface. When the maize crop had more than six full developed leaf or nine leaf tips and the apex was above the soil surface, apex temperatures were closer to air temperatures.

Although these previous studies indicated that near soil surface temperatures are more closely related to the apex temperature than air temperatures when the apex is near the soil surface, most models or prediction equations use air temperature as the basis for the thermal indices since it is much more available than soil temperature. Lack of soil temperature measurements has led to the development of a broad spectrum of soil temperature models, for a variety of purposes and with varying degree of complexity and data requirements. They range in approach from the more empirical and statistical models (e.g., Cruse *et al.*, 1980;

Gupta *et al.*, 1981; Meikle and Treadway, 1979, 1982) to the more physical and deterministic models (e.g., Hanks, *et al.*, 1971; Shroeder *et al.*,1978; Horton and Chung, 1991). Although statistical models are simple to construct and use, they are often site specific and require a large data base for developing the empirical coefficients. On the other hand, soil temperature models based on physical processes (radiative energy balance and sensible, latent, and ground-conductive heat energy fluxes) like those from Bucham (1982), Sasamori (1970) or Schieldge *et al.*, (1982) need much input data (e.g., solar radiation, radiation balance or vapor pressure) which are generally not available at a sufficiently dense time and spatial scale. The physically based models usually require inputs of the upper boundary temperatures to predict soil temperatures with depth and time. Soil surface temperature is usually difficult to obtain and varies considerably within the daylight period. Ten Berge (1990) and Horton and Chung (1991) developed such physically based models to predict bare soil temperature that require 30 minutes interval data of solar radiation, vapor pressure, wind speed and rainfall or daily global radiation, maximum and minimum air temperature, average wind speed and total rainfall, respectively. Luo *et al.*, (1992) constructed a model using principles of energy balance and soil heat transfer which realistically simulated soil temperature with variable crop cover and soil water content but also required many inputs. Several other models have been developed to estimate soil temperature from air temperature (e.g., Hasfurther and Burman, 1974; Toy *et al.*, 1978; Gupta *el al.*, 1983; Dwyer *et al.*, 1990) which also include correction terms involving cloudiness and thermal inertia of the soil (Langholz, 1989; MacLean and Ayres, 1985) to account for differences in soil temperatures during a sudden warming or cooling period.

As Potter and Williams (1994) emphasized, the desirable characteristics of soil temperature models for practical long-term simulations models should be: (i) minimal inputs, because the simulations often have only daily weather station data as input; (ii) high operational speed, because the simulations are for many years; (iii) sensitivity to management operations that may vary the crop biomass or residue on the soil surface; and (iv) reasonable robustness over a wide range of soil and climatic conditions. To facilitate the transfer of technology contained in the model to other sites and years, Ritchie (1991) stated that if the rational empiricism contained in functional models is sufficiently general, the models should make reasonable predictions for other soil, weather or crop management conditions.

The models described above represent a wide spectrum of soil temperature models that have been developed. On the other hand, to my knowledge, only one model based on physical processes (Cellier *et al.*, 1993) was designed to model maize apex temperature under field conditions when the leaf area index of the crop is lower than 0.5 and the apex is about 0.03 m above the soil surface. The model estimates the apex temperature for both day-time and night-time averages from hourly values of solar radiation, wind speed, air temperature and humidity. Since the empirical coefficients obtained for the model are climate dependent, a separate calibration may be required to apply it to different environments.

Soil temperature should be a better indicator of the apex temperature than air temperature during early vegetative stages. However, most sites where plant development predictions are needed have only air temperature data available because of cost and time constraints. To accurately simulate maize development under different soil management scenarios and at different sites, measurement of near surface temperature data are needed. As an alternative, a model to estimate the apex temperature could be used but it should use only readily available weather. The objective of this study was to develop and test a functional model to predict apex temperature for use in crop simulation models in order to provide a more accurate determination of maize leaf development rates.

Materials and Methods

Model description

An empirical model using daily maximum and minimum air temperatures and solar radiation as inputs to predict daily mean apex temperature was developed. A daily time step was chosen in order to incorporate this model into a maize simulation model which also operates on a daily basis. The meteorological variables included in the model are usually available at most sites.

The model estimates mean daily apex temperature (***TM***) based on the prediction of daylight apex temperature (***TD***) and night time apex temperature (***TN***) which are functions of the air maximum (T_{mx}) and minimum temperatures (T_{mn}) and solar radiation (R_s) as follows:

$$TD = A_1 * T_{mx} + B_1 * T_{mn} \qquad (1)$$

$$TN = A_2 * T_{mx} + B_2 * T_{mn} \qquad (2)$$

$$TM = TD * \frac{d_d}{24} + TN * \frac{d_n}{24} \qquad (3)$$

Where A_1 , B_1 , A_2 and B_2 are coefficient defined as:

$A_1 + B_1 = 1 \quad A_2 + B_2 = 1$ thus,

$$A_1 = \frac{TD - T_{mn}}{T_{mx} - T_{mn}} \qquad A_2 = \frac{TN - T_{mn}}{T_{mx} - T_{mn}}$$

The duration of the day (d_d) and the time of sunrise and sunset were determined following equations described by Grebet (1993) which only required the latitude and longitude of the site. The duration of the night (d_n) was the difference between twenty four hours minus d_d .

This model is proposed for use when the apex is below the surface and until V7 crop stage (Ritchie and Hanway, 1982). After that air temperature was found to be sufficiently close to the apex temperature to be used without modification.

Experimental data

The data used to determine the different coefficients were obtained from half hourly values of apex, air maximum and minimum temperatures and solar radiation recorded during 1996 with four different sowing dates. For the first sowing, apex temperature data were not available so soil temperature data measured at 0.05 m depth were used as a substitute. Complete description of the experiment is provided in Chapter 2 of this thesis.

The observed meteorological and apex temperature data were separated into two parts. One part was used to derive the empirical coefficients for the model (Set 1) and the second part was used to independently test the model performance (Set 2).

In order to evaluate the ability of the model to predict mean daily apex temperature, the root mean square error (RMSE), the total percentage of error (% Error) and the mean bias Error (MBE) were calculated. The RMSE is essentially a variance estimate calculated by comparing differences between the observed and predicted mean daily apex temperatures values. The % Error is the difference between the mean value of predicted and estimated values divided by the mean observed value. The MBE describe the bias between observed and estimated value related to the number of values included in the analysis(Willmott, 1982). Equations to calculate these parameters are presented elsewhere in the literature. Linear regression analysis were used to evaluate the quality of the predictions.

Results and Discussion

The daily values of the coefficient A_1 estimated from Set 1 were related to the corresponding values of R_s for that data set and a regression equation was obtained (Figure 19). This regression equation was used to estimate A_1 for the independent data set (Set 2) using the corresponding independent values of R_s. The daily values of the coefficient A_2 estimated from the first data set had little relation either to air temperatures (maximum or minimum) nor to solar radiation. Thus, the mean value of this coefficient was used to predict TN for Set 2.

Using equations (1), (2) and (3), ***TD***, ***TN***, and ***TM*** were estimated for the independent data set.

$$TD=A_1*T_{mx}+(1-A_1)*T_{mn} \qquad \text{with} \qquad A_1=0.01061*R_s+0.5902$$

$$TN=0.36354*T_{mx}+0.63646*T_{mn}$$

$$TM=TD*\frac{d_d}{24}+TN*\frac{d_n}{24}$$

Figures 20, 21 and 22 depict the linear regression relationship determined between observed and predicted values of ***TD***, ***TN***, and ***TM*** respectively for the independent data set. Their regression coefficients, descriptive statistical parameters and measures of model performances are presented in Table 4. The model slightly underestimated ***TD***, ***TN*** and ***TM*** with ***TN*** having a higher % Err, RMSE and MBE and a lower r^2. The y-axis intercept (a) had a lower value for ***TM*** and a higher value for ***TN*** indicating the bias of this variable. The slope (b) was in all cases near 1 indicating good agreement between estimated and measured values for the three temperatures for all ranges of temperatures. Overall, the model provides a good estimation of the mean daily apex temperature when the apex is near the soil surface with a % Err of -0.3% and a MBE of -0.06 °C. The Cellier ***et al*** (1993) apex temperature model had an average absolute error 0.7 °C and required more complex calculations and hourly meteorological data. A statistical approach described by the Cellier ***et al*** (1993) showed similar errors. The fitted coefficients they reported probably would be site specific.

Usually the mean daily air temperature is calculated as the average of the daily maximum and minimum temperatures and used in this form to determine thermal time. The differences between the estimated mean daily apex temperature and the mean air temperature were accumulated for each of the four sowing from seedling emergence until V7 stage. Cumulative differences resulted in a variable pattern of biases between times of the season (Figure 23). The MBE for each sowing date was 1.96 °C, 1.94 °C, 1.39 °C and 0.55 °C for the first, second, third and fourth sowing respectively.

When the differences between mean daily air temperature and mean daily apex temperature are accumulated from V7 stage to the last tip appeared for the second and third sowing, the mean accumulated difference was 0.018 °C and -0.42 °C respectively. This demonstrates that after V7 air temperature is an adequate predictor of apex temperature for use in thermal time calculations for crop models.

Table 4: Summary of linear regressions, descriptive statistical parameters and measures of model performance between observed and predicted apex daylight (***TD***),apex night time (*TN*) and mean daily apex temperatures (*TM)* for year 1996, at East Lansing, MI. **RMSE** (root mean square error), **% Err** (percentage of error), **MBE** (mean bias error), **Ē** (estimated mean), **Ō** (observed mean), **a** (y-axis intercept), **b** (slope), **N** (number of observations), and r^2 (coefficient of determination). **RMSE, MBE, Ē** and **Ō** are in °C.

	Ē	Ō	% Err	N	r^2	a	b	RMSE	MBE
TD	23.97	24.09	-0.5	56	0.916	-0.48	1.015	1.41	-0.12
TN	18.06	18.26	-1.1	56	0.813	1.52	0.906	1.81	-0.2
TM	21.49	21.55	-0.3	56	0.918	0.08	0.993	1.31	-0.06

Conclusions

During the early stages of maize development, the apex is near the soil surface. To predict maize leaf development, the temperature near the developing point should be used instead of air temperature. Apex temperature data and soil temperature data are often unavailable due to the cost and time that both measurements require. A functional model which required daily maximum and minimum air temperatures and solar radiation proved to adequately predict mean daily apex temperature for four different growing period until the maize plant reaches V7 stage. After that stage the apex moves rapidly above the soil surface and air temperature becomes a good predictor of mean daily apex temperature. The model was tested with an independent data set and estimated mean apex temperature with a MBE of -0.06 °C. The statistical values obtained from the model were mostly superior to the more complex model reported by Cellier *et al* (1993) which required more meteorological data. It is not possible to assure that the functions developed for the model could be applicable to other locations as the coefficients could be sensible to local conditions and also affected by different experimental circumstances.

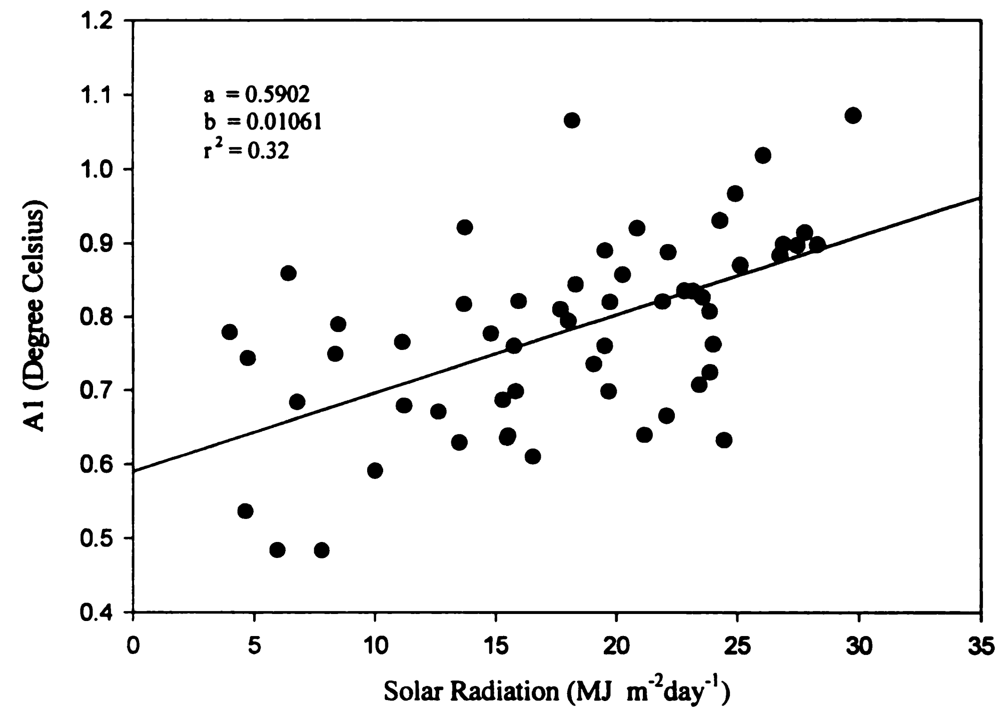

Figure 19: Linear regression analysis between A_1 (°C) coefficient and Solar Radiation (MJ m^{-2} day^{-1}) for the data used in developed the model (Set 1). Data are from East Lansing, MI, 1996.

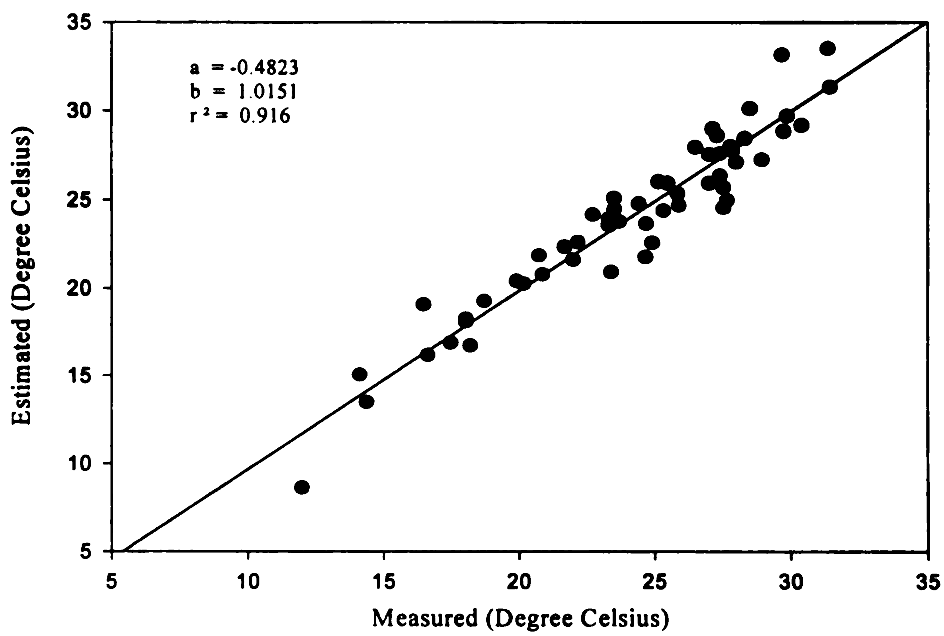

Figure 20: Linear regression analysis between estimated and measured mean daylight apex temperatures for the independent data set (Set 2) with data from East Lansing, MI, 1996.

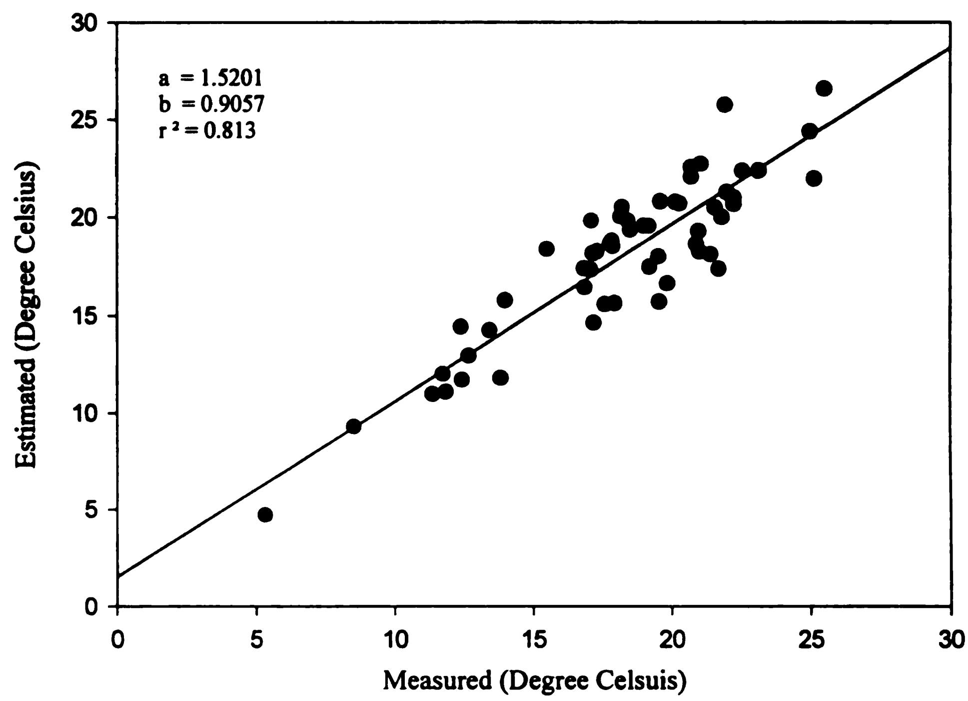

Figure 21: Linear regression analysis between estimated and measured mean night apex temperatures for the independent data set (Set 2) with data from East Lansing, MI, 1996.

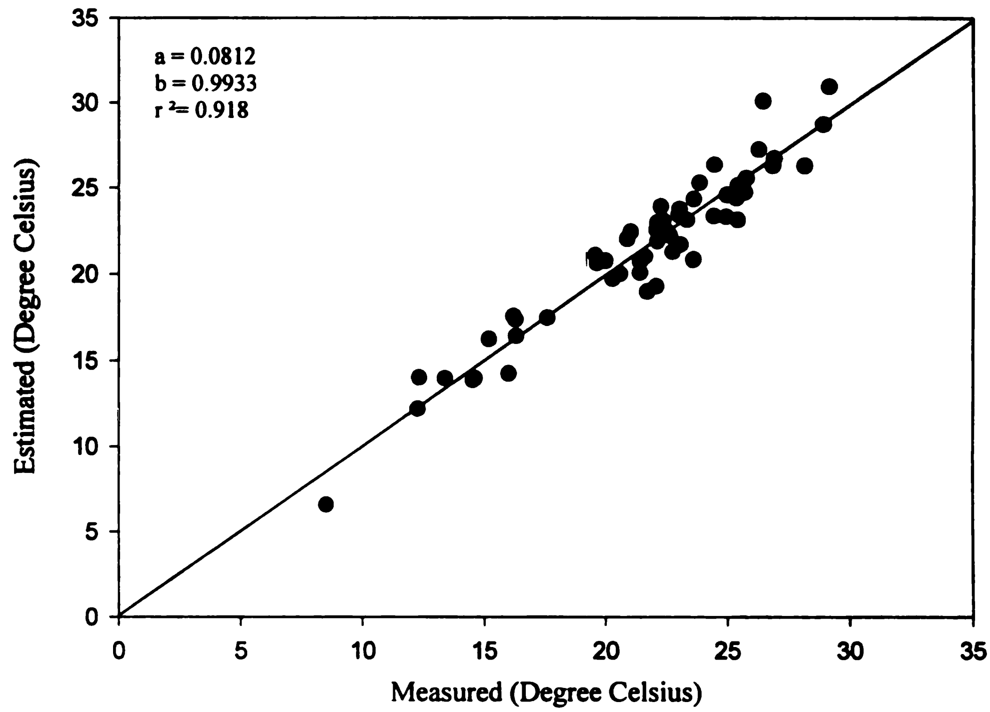

Figure 22: Linear regression analysis between estimated and measured mean daily apex temperatures for the independent data set (Set 2) with data from East Lansing, MI, 1996.

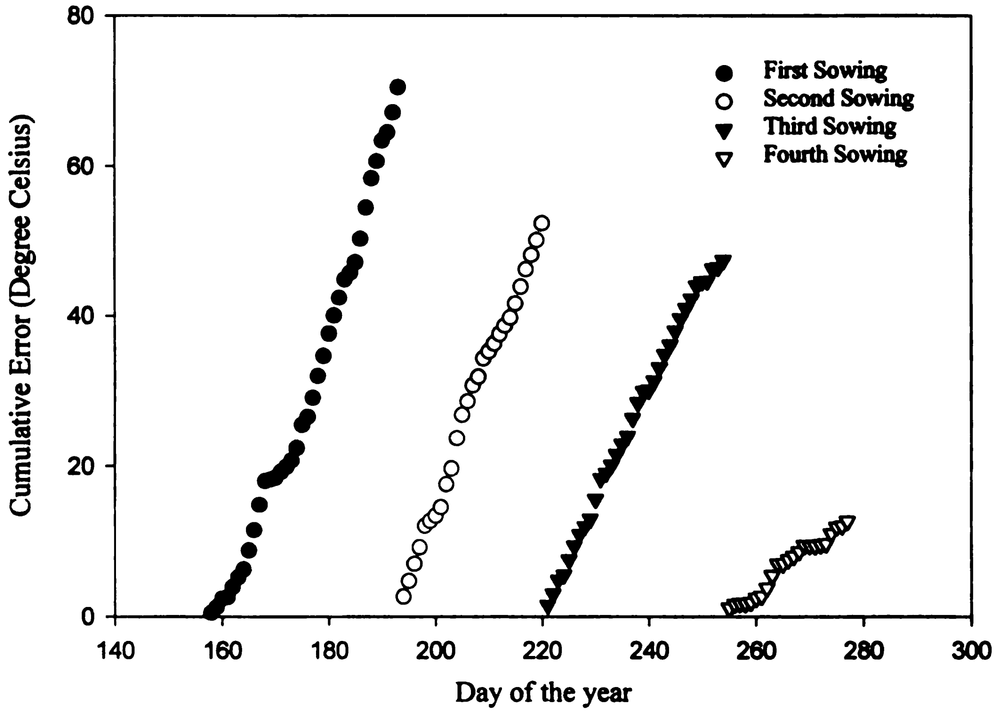

Figure 23: Cumulative differences between mean daily estimated apex temperature and mean daily air temperature (calculated as the average of the daily minimum and maximum air temperature) as a function of the day of the year, until the maize crop reach V7 stage, for East Lansing, MI, 1996.

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APPENDIX

Description of the soil

Capac Series[1]

The Capac series consists of somewhat poorly drained, moderately and moderately slowly permeable soils on till plains and moraines. These soils formed in medium and moderately fine textured deposits. Slopes are 0 to 4 percent.

Capac soils are commonly adjacent to Aubbeenaubbee, Brookston, and Marlette soils. Aubbeenaubbee soils have more sand in the upper part of the subsoil. Brookston soils are more gray in the subsoil, have a molic epipedon, and are more poorly drained. Marlette soils do not have grayish mottles in the upper part of the subsoil and are better drained.

Typical pedon of Capac loam, 0 to 3 percent slopes, 880 feet north and 190 feet west of southeast corner sec.26, T.1., R. 1 E.

Ap - 0 to 9 inches; very dark grayish brown (10YR 3/2) loam, light brownish gray (10YR 6/2) dry, weak medium granular structure; friable; few very fine roots; neutral; abrupt smooth boundary.

B&A - 9 to 11 inches; light olive brown (2.5YR 5/4) loam (B2); brown (10YR 5/3) coatings on vertical faces of peds (A2); few fine distinct yellowish brown (10YR 5/6) and few fine faint grayish brown (10YR 5/2) mottles; weak medium granular structure; friable; few thin discontinuous dark grayish brown (10YR 4/2) clay films on vertical faces of peds; medium acid; clear wavy boundary.

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[1] Soil Survey of Ingham County, Michigan. United States Department of Agriculture, Soil Conservation Service in cooperation with Michigan Agricultural Experiment Station. August 1979.

B21t - 11 to 15 inches; brown (10YR 5/3) loam; common fine distinct yellowish brown (10YR 5/6) and common fine faint grayish brown (10YR 5/2) mottles; moderate medium angular blocky structure; firm; light brownish gray (10YR 6/2) fine sandy loam coatings on vertical faces of peds; thin discontinuous dark grayish brown (10YR 4/2) clay films on faces of peds; slightly acid; gradual wavy boundary.

B22tg - 15 to 28 inches; grayish brown (10YR 5/2) clay loam; common fine distinct yellowish brown (10YR 5/6) mottles; moderate medium angular blocky structure; firm; thick continuous dark grayish brown (10YR 4/2) clay films on faces of peds; neutral; gradual wavy boundary.

B23t - 28 to 32 inches; brown (10YR 5/3) loam; common medium distinct yellowish brown (10YR 5/6) and common fine faint light brownish gray blocky structure; firm; thick dark garyish brown (10YR 4/2) clay films on faces of peds; mildly alkaline; abrupt wavy boundary.

Cg - 32 to 60 inches; grayish brown (10YR 5/2) loam; common fine faint olive gray (5Y 5/2) and common medium distinct light olive brown (2.5Y 5/4) mottles; weak medium subangular blocky structure in upper part and massive in lower part; friable; slight effervescence; moderately alkaline.

Thickness of the solum and depth to effervescent material range from 26 to 40 inches. Reaction ranges from medium acid to mildly alkaline in the solum. Coarse fragments range from less than 1 percent to 10 percent throughout the pedon.

The **Ap** horizon has hue of 10YR, value of 3 or 4, and chroma of 2 or 3 moist. It has value of 6 or more dry. The texture is dominantly loam, but the range includes sandy loam or fine sandy loam. In some pedons an **A2** horizon is present. In uncultivated areas an **A1** horizon is present.

The **Bt** horizon has hue of 10YR or 2.5Y, value of 5 or 6, and chroma of 1 to 3. It averages 18 to 35 percent clay.

The **C** horizon has hue of 10YR or 2.5Y, value of 5 or 6, and chroma of 2 or 3. It is loam or clay loam.

Daily Weather Data for East Lansing, MI, 1996
SOLR: Solar radiation (MJ m^{-2} day^{-1})
AirMx: Air Maximum Temperature (°C)
AirMn: Air Minimum Temperature (°C)
Rain : Rainfall (mm)
DOY: Day of the year

DOY	SOLR	AirMx	AirMn	Rain
150	29.98	16.67	6.67	0.00
151	30.04	21.11	-0.56	0.00
152	29.50	24.44	3.33	0.00
153	23.16	26.67	7.78	4.57
154	17.22	23.89	12.20	2.29
155	19.78	22.78	12.22	0.00
156	12.53	18.33	10.00	5.08
157	19.51	22.22	8.33	4.32
158	7.80	22.27	13.44	8.89
159	11.93	24.39	15.38	0.00
160	20.86	21.59	13.83	7.87
161	5.55	20.11	14.34	3.05
162	21.18	25.35	16.33	0.00
163	19.20	24.33	14.63	0.00
164	15.52	25.38	15.74	2.79
165	25.31	30.00	15.56	0.00
166	26.89	29.44	15.00	0.00
167	29.79	29.98	13.61	0.00
168	24.01	32.68	13.99	0.00
169	4.02	22.75	16.30	72.64
170	4.64	22.30	16.11	18.03
171	15.35	26.50	19.53	4.06
172	13.51	25.58	18.43	0.00
173	11.29	27.55	16.90	0.25
174	24.29	25.57	15.92	0.00
175	28.57	25.40	9.94	6.60
176	13.70	26.59	15.59	0.00
177	27.09	24.25	10.68	0.00
178	26.77	27.34	11.73	0.00
179	23.03	32.85	16.38	0.00
180	23.44	34.90	16.61	0.00
181	25.29	35.51	21.50	0.00
182	27.48	34.02	21.49	0.00
183	25.10	30.86	16.87	0.00
184	10.76	26.22	14.23	0.00
185	22.40	23.06	14.23	0.00
186	26.09	26.07	8.45	0.00

187	29.02	30.76	9.73	0.00
188	27.79	33.84	13.23	0.00
189	21.37	34.15	18.79	0.00
190	22.82	31.38	13.77	0.00
191	13.62	23.93	12.48	0.51
192	24.93	24.98	9.50	0.00
193	23.55	29.04	8.08	0.00
194	22.16	30.02	12.26	0.00
195	21.29	31.81	17.52	0.00
196	19.53	31.39	14.13	5.08
197	23.66	29.43	15.72	0.25
198	25.13	33.27	16.33	0.00
199	9.42	27.91	17.49	1.02
200	10.01	29.50	19.30	0.76
201	14.43	25.56	13.86	0.00
202	29.79	25.09	9.73	0.00
203	18.81	25.28	8.53	0.00
204	28.31	30.96	9.34	0.00
205	28.73	31.43	15.03	0.00
206	19.69	28.46	14.33	0.00
207	25.43	27.73	14.88	0.00
208	15.76	23.76	12.51	0.00
209	23.01	27.78	11.46	0.00
210	12.64	26.28	14.70	0.76
211	13.98	27.15	15.66	12.19
212	15.84	26.40	13.87	8.89
213	13.98	25.65	12.95	0.25
214	14.09	25.65	12.95	0.00
215	19.72	27.16	12.17	0.00
216	22.77	28.71	12.71	0.00
217	23.88	30.88	15.28	0.00
218	22.77	31.31	17.53	0.00
219	22.09	34.70	20.17	0.00
220	24.22	35.50	20.18	27.94
221	23.18	29.05	18.15	0.00
222	16.51	27.07	12.00	0.00
223	24.47	25.73	13.29	0.00
224	11.73	24.50	14.29	0.00
225	21.92	30.09	14.39	0.00
226	18.27	31.26	14.34	0.00
227	18.02	30.09	15.57	0.25
228	18.11	27.20	16.94	0.00
229	13.74	25.70	13.04	0.00
230	25.53	29.59	11.81	0.00
231	23.57	31.41	11.10	0.00

232	12.28	26.98	16.03	11.43
233	16.55	31.33	19.61	0.00
234	19.93	30.57	17.70	0.00
235	19.07	32.07	19.37	6.60
236	18.63	25.82	15.55	0.00
237	23.87	29.13	11.01	0.00
238	23.94	30.29	14.19	0.00
239	17.69	30.09	13.87	0.00
240	6.36	21.60	16.69	0.00
241	18.19	26.56	13.91	0.00
242	21.52	27.43	11.55	0.00
243	18.32	29.08	10.61	0.00
244	15.77	29.37	12.76	0.00
245	20.27	30.24	12.44	0.00
246	18.33	29.86	11.64	0.00
247	15.96	29.66	12.57	0.00
248	15.75	30.66	12.94	0.00
249	19.52	31.73	13.78	0.00
250	11.27	27.65	16.41	5.84
251	6.43	21.69	17.50	0.51
252	19.43	31.21	13.32	6.10
253	8.36	23.53	17.03	2.03
254	16.02	26.70	13.61	0.00
255	15.30	29.88	12.99	2.29
256	14.18	21.63	12.42	0.51
257	5.96	15.37	9.38	0.25
258	3.16	12.12	9.11	7.87
259	8.48	17.70	11.43	0.00
260	11.34	19.86	7.05	0.00
261	11.21	19.29	12.34	0.00
262	18.39	23.18	9.42	0.00
263	19.74	24.67	4.96	0.00
264	17.77	25.42	4.36	0.00
265	4.73	19.69	12.06	6.60
266	13.46	21.10	10.33	0.00
267	11.14	22.03	8.92	6.35
268	13.59	20.23	6.99	0.00
269	14.81	19.35	4.40	0.00
270	4.50	17.85	10.12	12.45
271	3.99	20.92	10.03	1.27
272	8.17	16.07	8.07	0.00
273	6.78	19.81	3.70	0.00
274	15.81	25.04	0.30	0.00
275	15.48	25.37	9.03	0.00
276	7.19	23.25	4.14	0.25

277	15.88	11.91	0.61	0.00

Daily Weather Data - First Sowing Date
SOLR: Solar radiation (MJ m^{-2} day^{-1})
S1Md : Mean soil temperature at 0.01 m depth (°C)
S3Md : Mean soil temperature at 0.03 m depth (°C)
S5Md : Mean soil temperature at 0.05 m depth (°C)
AirMd : Mean air temperature (°C)
DOY: Day of the year

DOY	SOLR	S1Md	S3Md	S5Md	AirMd
161	5.55	17.56	17.60	17.80	17.07
162	21.18	20.67	20.51	20.42	20.40
163	19.20	20.10	19.99	19.95	18.93
164	15.52	20.63	20.59	20.49	19.40
165	25.31	24.14	23.84	23.42	22.78
166	26.89	25.50	25.40	24.60	22.22
167	29.79	25.47	25.41	24.63	21.76
168	24.01	25.79	25.60	24.79	23.06
169	4.02	20.10	20.28	20.45	18.84
170	4.64	19.06	19.06	19.04	18.64
171	15.35	23.03	23.02	22.72	22.19
172	13.51	22.13	22.28	22.16	20.79
173	11.29	22.38	22.36	22.04	21.82
174	24.29	22.88	23.26	22.86	22.50
175	28.57	21.01	21.41	21.16	18.53
176	13.70	22.48	22.71	22.65	21.08
177	27.09	20.80	20.59	20.33	17.60
178	26.77	23.55	23.23	23.11	19.95
179	23.03	26.26	26.12	25.70	23.85
180	23.44	27.66	27.40	27.21	25.67
181	25.29	29.20	29.15	28.50	27.83
182	27.48	31.28	30.75	30.44	27.68
183	25.10	28.81	28.14	28.01	23.87
184	10.76	24.15	23.85	23.80	19.73
185	22.40	25.15	24.80	24.80	18.06
186	26.09	24.53	23.70	23.54	18.12
187	29.02	26.70	25.35	25.17	21.58
188	27.79	30.66	28.92	26.32	23.97

Daily Weather Data - Second Sowing Date

SOLR: Solar radiation (MJ m^{-2} day^{-1})
ApMd: Mean apex temperature (°C)
S1Md : Mean soil temperature at 0.01 m depth (°C)
S3Md : Mean soil temperature at 0.03 m depth (°C)
S5Md : Mean soil temperature at 0.05 m depth (°C)
AirMd : Mean air temperature (°C)
DOY: Day of the year

DOY	SOLR	ApMd	S1Md	S3Md	S5Md	AirMd
187	29.02	26.26	25.35	26.70	25.17	21.01
188	27.79	28.56	30.66	28.92	26.32	23.97
189	21.37	28.53	29.76	28.90	27.62	24.92
190	22.82	25.83	27.13	26.29	25.76	21.43
191	13.62	21.46	21.81	22.07	22.51	16.00
192	24.93	21.40	22.66	22.01	21.57	16.57
193	23.55	21.50	22.77	22.11	21.67	16.67
194	22.16	24.79	26.07	25.23	24.88	21.81
195	21.29	26.88	28.15	27.28	26.94	23.96
196	19.53	25.71	26.69	26.27	26.15	21.82
197	23.66	25.69	26.30	26.18	26.11	21.42
198	25.13	27.10	27.59	26.99	26.96	23.63
199	9.42	24.42	24.44	24.54	24.66	22.41
200	10.01	24.07	24.24	23.97	23.95	23.23
201	14.43	23.60	23.95	23.83	24.01	22.15
202	29.79	22.68	23.89	23.36	23.64	17.21
203	18.81	21.71	22.52	22.35	22.60	16.96
204	28.31	24.74	26.40	25.11	25.09	20.21
205	28.73	26.84	29.04	28.00	27.96	23.02
206	19.69	22.63	23.43	23.72	24.09	20.44
207	25.43	22.98	23.68	23.64	23.65	20.89
208	15.76	19.59	19.74	20.32	20.64	18.07
209	23.01	20.87	21.98	22.00	21.59	19.50
210	12.64	20.53	21.03	21.30	21.21	19.41
211	13.98	21.02	21.42	21.52	21.35	19.99
212	15.84	20.43	20.90	20.96	20.81	18.56
213	13.98	19.59	19.88	19.85	19.94	17.10
214	13.98	18.56	19.34	19.30	19.30	16.66
215	19.72	20.23	21.05	21.10	20.95	18.78
216	22.77	22.11	23.03	22.74	22.20	20.88
217	23.88	23.72	24.99	24.89	23.98	23.00
218	22.77	24.45	25.82	25.43	24.75	24.33
219	22.09	27.06	28.18	27.48	26.83	27.07
220	24.22	26.43	28.48	27.80	27.28	26.73
221	23.18	23.50	24.01	24.13	24.26	23.49

222	16.51	19.38	20.87	21.08	21.18	19.27
223	24.47	19.63	21.22	21.31	21.22	18.68
224	11.73	19.14	19.69	19.84	19.96	18.63
225	21.92	20.82	22.44	22.04	21.97	20.91
226	18.27	20.83	22.23	22.24	22.23	21.49
227	18.02	22.00	22.98	22.70	22.73	22.22
228	18.11	21.36	22.65	22.22	22.62	21.23
229	13.74	18.91	21.28	21.09	21.28	18.40
230	25.53	19.68	22.21	21.57	21.89	19.72
231	23.57	19.99	22.43	21.88	22.13	20.68
232	12.28	20.68	21.49	21.47	21.61	20.74
233	16.55	23.55	23.15	22.93	22.89	23.96
234	19.93	22.56	23.36	23.20	23.13	23.24
235	19.07	23.98	23.93	23.77	23.60	24.73
236	18.63	21.53	22.52	22.51	22.59	21.08
237	23.87	19.41	20.49	20.51	20.66	19.49
238	23.94	20.56	21.22	21.08	21.17	21.14
239	17.69	20.99	21.35	21.30	21.37	21.32
240	6.36	18.96	20.25	20.40	20.56	18.76
241	18.19	19.56	20.84	20.81	20.75	19.18
242	21.52	19.10	20.44	20.42	20.60	18.74
243	18.32	19.28	20.61	20.57	20.74	18.94
244	15.77	20.68	21.90	21.78	21.80	20.50

Daily Weather Data - Third Sowing Date
SOLR: Solar radiation (MJ m^{-2} day^{-1})
ApMd: Mean apex temperature (°C)
S1Md : Mean soil temperature at 0.01 m depth (°C)
S3Md : Mean soil temperature at 0.03 m depth (°C)
S5Md : Mean soil temperature at 0.05 m depth (°C)
AirMd : Mean air temperature (°C)
DOY: Day of the year

DOY	SOLR	ApMd	S1Md	S3Md	S5Md	AirMd
220	24.22	28.99	29.98	29.00	28.48	26.73
221	23.18	25.66	25.36	25.37	25.44	23.66
222	16.51	21.66	21.50	21.60	21.80	19.30
223	24.47	22.16	23.09	22.65	22.25	18.44
224	11.73	21.70	20.48	21.40	21.83	18.38
225	21.92	23.77	25.43	24.45	23.72	20.87
226	18.27	24.23	25.56	24.96	24.14	21.73
227	18.02	24.69	25.67	25.07	24.56	22.20
228	18.11	24.84	26.05	25.40	24.70	21.25
229	13.74	22.98	23.19	23.18	23.00	18.33

230	25.53	24.26	26.09	24.93	24.17	19.61
231	23.57	24.91	26.57	25.37	24.76	20.76
232	12.28	22.90	22.53	22.64	22.93	20.78
233	16.55	24.71	25.15	24.60	24.58	23.96
234	19.93	25.19	26.43	25.75	25.02	23.22
235	19.07	25.76	27.50	26.59	25.18	24.80
236	18.63	23.06	23.91	24.13	24.29	21.07
237	23.87	21.82	22.51	22.14	22.23	19.82
238	23.94	23.61	24.44	23.37	23.06	21.49
239	17.69	23.61	24.25	23.47	22.97	21.60
240	6.36	21.07	21.79	21.85	21.66	18.64
241	18.19	23.41	24.07	23.21	22.89	18.90
242	21.52	22.74	23.86	22.85	22.71	18.44
243	18.32	22.08	23.51	22.30	22.33	18.62
244	15.77	22.18	23.90	22.60	22.61	20.30
245	20.27	23.08	25.34	23.45	23.57	20.53
246	18.33	22.54	24.78	23.28	23.36	20.39
247	15.96	22.68	24.55	23.22	23.22	20.89
248	15.75	23.33	24.89	23.54	23.55	21.05
249	19.52	23.13	24.86	24.14	24.24	21.91
250	11.27	22.07	23.88	23.40	23.50	21.57
251	6.43	20.36	21.91	22.01	22.36	20.25
252	19.43	22.25	23.67	22.76	22.64	21.24
253	8.36	20.30	22.11	22.25	22.55	19.96
254	16.02	19.56	21.96	21.37	21.74	18.69
255	15.30	19.88	21.63	21.45	21.66	19.62
256	14.18	16.24	18.33	18.88	19.38	15.87
257	5.96	11.72	14.51	15.88	16.02	11.27
258	3.16	11.01	13.39	13.80	14.44	10.68
259	8.48	13.97	15.49	15.43	15.79	13.42
260	11.34	13.49	15.27	15.38	15.77	13.00
261	11.21	15.18	15.99	15.95	16.32	14.78
262	18.39	15.62	16.16	16.18	16.56	15.21
263	19.74	14.00	15.93	16.06	16.57	13.43
264	17.77	14.81	16.38	16.10	16.69	14.26
265	4.73	15.12	16.46	16.42	16.80	15.01
266	13.46	15.20	16.41	16.27	16.77	14.78
267	11.14	15.02	16.26	16.10	16.53	14.64
268	13.59	15.17	15.73	15.81	16.51	14.21
269	14.81	11.41	13.25	13.46	14.17	11.04
270	4.50	13.32	13.69	13.77	14.16	13.49
271	3.99	17.03	17.09	16.76	16.83	17.10
272	8.17	12.77	13.29	13.65	14.11	11.11
273	6.78	11.24	12.30	12.50	12.92	11.33
274	15.81	12.69	12.60	12.32	13.07	12.23

275	15.48	17.52	15.69	15.15	15.66	17.08
276	7.19	15.01	14.94	15.12	15.64	14.56
277	15.88	6.10	8.50	9.82	10.78	5.60

Daily Weather Data - Fourth Sowing Date

SOLR: Solar radiation (MJ m^{-2} day^{-1})
ApMd: Mean apex temperature (°C)
S1Md : Mean soil temperature at 0.01 m depth (°C)
S3Md : Mean soil temperature at 0.03 m depth (°C)
S5Md : Mean soil temperature at 0.05 m depth (°C)
AirMd : Mean air temperature (°C)
DOY: Day of the year

DOY	SOLR	ApMd	S1Md	S3Md	S5Md	AirMd
250	11.27	22.34	23.88	23.40	23.50	21.57
251	6.43	20.58	21.91	22.01	22.36	20.25
252	19.43	22.15	23.67	22.76	22.64	21.24
253	8.36	20.76	22.11	22.25	22.55	19.96
254	16.02	20.21	21.96	21.37	21.74	18.69
255	15.30	20.57	21.63	21.45	21.66	19.62
256	14.18	16.21	18.33	18.88	19.38	15.87
257	5.96	11.39	14.35	15.18	16.46	11.47
258	3.16	12.23	13.44	13.99	14.96	10.95
259	8.48	15.09	16.00	16.13	16.49	13.70
260	11.34	14.62	15.16	15.53	16.09	13.16
261	11.21	15.05	16.05	16.24	16.63	14.82
262	18.39	16.29	16.98	17.22	17.34	15.24
263	19.74	16.36	16.62	17.06	17.32	13.58
264	17.77	16.32	17.24	17.45	17.51	14.44
265	4.73	16.11	16.72	16.86	17.26	15.22
266	10.76	15.67	16.41	16.27	16.77	14.78
267	11.14	16.20	16.26	16.10	16.53	14.64
268	13.59	16.02	16.11	16.63	17.23	14.21
269	14.81	13.09	13.06	13.77	14.52	11.04
270	4.50	13.40	13.59	13.83	14.49	13.49
271	3.99	17.18	17.34	17.21	17.32	17.10
272	8.17	12.28	12.41	13.60	14.54	11.11
273	6.78	11.68	11.87	12.29	13.15	11.33
274	15.81	12.34	12.40	12.64	13.14	12.23
275	15.48	16.03	15.78	15.77	15.93	17.08
276	7.19	14.55	14.68	15.18	15.97	14.56
277	15.88	8.51	8.50	9.82	11.16	5.60

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