SOIL TEMPERATURE INFLUENCE ON WATER USE AND YIELD UNDER VARIABLE IRRIGATION

JON M. WRAITH

1989
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by

Jon M. Wraith

A dissertation submitted in partial fulfillment of requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Soil Science and Biometeorology

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Logan, Utah

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Jon M. Wraith
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ABSTRACT

Soil Temperature Influence on Water Use and Yield under Variable Irrigation

by

Jon M. Wraith, Doctor of Philosophy

Utah State University, 1989

Major Professor: Dr. R.J. Hanks
Department: Soil Science and Biometeorology

The need for efficient use of water resources has increased the importance of optimum soil water usage in agricultural systems. Soil temperature has been shown to be important in influencing the early development of many plant species. Many agricultural regions have suboptimal soil temperature regimes for plant growth, and some cultural practices have been shown to reduce near-surface soil temperatures. The seasonal influence of soil temperature on soil water extraction and aboveground and belowground plant growth under variable irrigation was investigated at the USU Greenville Farm in Logan, UT. Soil surface mulches and buried heat cables were used to modify soil temperature. A line-source sprinkler system provided a gradient of water application.

During 1987 yields were mainly influenced by irrigation. During 1988 greater soil temperature differences resulted in significant plant growth and yield responses. Soil water depletion corresponded to soil temperature treatments during the early part of the growing seasons. Depth of maximum soil water depletion was about 20 cm deeper for warm
treatments. Water uptake rates of earlier-maturing plants in warm treatments were reduced later in the season, so that cumulative seasonal soil water depletion was similar for all temperature treatments. Although depth of rooting was somewhat greater under high than low irrigation during 1988, low irrigation treatments depleted soil water to greater depth. There was no interactive response of plant growth and yield or of soil water depletion to soil temperature and irrigation treatments.

Modifications were made to a computer simulation model of the soil-plant-atmosphere system in order to more mechanistically simulate plant water uptake and to include influences of soil temperature on seasonal rooting growth and soil water extraction. The model adequately simulated both the pattern and magnitude of soil temperature influences on soil water depletion, and conclusions drawn from model simulations agreed with field observations during 1987 and 1988.
INTRODUCTION

Maximum utilization of available soil water is a prerequisite for obtaining optimum crop or forage yields. Increasing demands on water resources and mounting concern over environmental consequences of over-irrigation have made the efficient utilization of water resources an important social issue as well. The reserve of water available to plants depends primarily on the volume of soil occupied by root systems. The characteristic rooting pattern of each species is genetically controlled but environmentally modified (Taylor and Klepper 1978, Richards 1986, O'Toole and Bland 1987).

Low soil temperatures have long been known to reduce the rate of early plant growth and development. Many agricultural regions at northern latitudes and/or high elevations have soil temperature regimes that are suboptimal for plant growth. Some low-input/reduced-tillage cultural practices have been shown to reduce near-surface soil temperatures (Johnson and Lowery 1985, Al-Darby and Lowery 1987). Much more is known about aboveground growth responses to soil temperature than about belowground responses. This disparity is especially true for normal field conditions; much of current knowledge has been gained from greenhouse or growth chamber studies that do not incorporate the dynamic nature of physical conditions found in the field. Most of this research has focused on the early stages of plant development.

Computer simulation models of the soil-plant-atmosphere system are being increasingly used as aids in research and management. These models should include the most important environmental variables while at the same time maintaining the highest possible degree of simplicity.
There is an increasing demand for information concerning environmental effects on root growth and soil resource utilization for use in these mathematical models (Taylor and Klepper 1975, Klepper et al. 1983). Simulation models will probably play an even more important role in studies of the rhizosphere than in aboveground research because of the difficulties associated with direct belowground measurements.

The objective of this research was to investigate the seasonal influence of soil temperature on soil water extraction and aboveground and belowground plant development under variable irrigation in an area having relatively cool growing season temperatures. Specifically addressed were field soil temperature influences on a) aboveground plant growth and yield, b) belowground plant growth, and c) soil water depletion. Also investigated was the possibility of an interactive response to soil temperature and irrigation. Modifications were made to a computer simulation model of the soil-plant-atmosphere system in order to more mechanistically simulate plant water uptake and to include influences of soil temperature on seasonal rooting growth and soil water extraction.
LITERATURE REVIEW

Introduction

Plant growth is the result of many biochemical and biophysical processes. Genetically determined growth patterns and capacities may be modified by external conditions including light, temperature, and water and nutrient status. It has been known for many years that low temperature often results in reduced growth rate. The response of biochemical reaction rates to temperature may be characterized by the Arrhenius equation, which predicts an exponential increase in reaction rate with increasing temperature. The temperature coefficients, or \( Q_{10} \), of biochemical processes are around 2 to 3, while for biophysical reactions they are about 1.1 to 1.3 (Miedema 1982). It seems likely, therefore, that reduced plant growth at low temperature is primarily the result of restricted biochemical reaction rates.

Meristematic regions are considered to be sites of temperature sensitivity in plants because cell division and elongation occur primarily at or near these zones. Because the shoot apical meristem of many graminoids remains in or near the soil for four to six weeks after emergence (Walker 1969, Watts 1972), near-surface soil temperatures exert a strong influence on early shoot development of these plants.

The concept of thermal time has been shown to be useful in predicting plant phenological development (Angus et al. 1980, Coelho and Dale 1980, Ong 1983). Wang (1960) reviewed and critiqued the heat unit approach and suggested several avenues for improvement. These
included taking temperatures at more representative locations, changing threshold temperatures according to plant age, and differentiating growth and development. Gregory (1983) reported that root axis and lateral development in pearl millet was related to the thermal time measured at the shoot meristem. He stressed that for the concept of thermal time to provide a clearer understanding of temperature effects on root development, it will be necessary to account for possible differences in the thermal response of different parts of the root system and of other environmental factors, particularly soil water status.

There is a functional equilibrium between plant shoots and roots (Nielsen 1974) such that when the supply of water and nutrients to shoots is limited, carbohydrates accumulate and root growth may be increased. This may result in the uptake of more water and nutrients and the consequent stimulation of shoot growth. The slowing of root growth processes by low root zone temperatures will reduce their capacity as sinks for carbohydrates (Nielsen 1974). Soil temperature influences on root growth and function may therefore have an indirect influence on shoot growth as well as the direct influence cited above. Several other factors may also limit the proliferation of roots into soil profiles including soil structure and strength, aeration, water and nutrient content and their distributions, soil temperature, and belowground pests and pathogens (Taylor 1983, Hamblin 1985, Masle and Passioura 1987). Even if roots are present in a soil volume, their activity may be constrained by one or more of these factors, thus reducing the rate of water and nutrient uptake. Recent evidence of
direct root-to-shoot communication concerning soil water status in the root zone (Blackman and Davies 1985, Gollan et al. 1986, Lachno and Baker 1986) has renewed attention on the role of roots in modifying aboveground plant functions.

Kramer (1940) concluded that, aside from deficient soil moisture, low soil temperature is the most important environmental factor affecting the rate of water absorption by roots. Decreased absorption of water at low root temperatures is thought to be caused by the combined effects of increased viscosity of water and decreased permeability of cytoplasmic membranes. Effects of temperature on root membrane permeability and subsequent plant water potential responses have been the object of several studies (Kaufmann 1975, Dalton and Gardner 1978, Running and Reid 1980). Lemon (1962) and Lemon and Wiegand (1962) discussed the influence of temperature on soil aeration and root respiration. They concluded that when oxygen is plentiful, chemical processes determine root respiration reaction rates. These biochemical processes are strongly sensitive to temperature. When the oxygen supply at the root surface is below a critical level, however, rate of oxygen uptake is controlled by the physical process of diffusion, which is relatively insensitive to soil temperature. Because soil aeration is not a problem under most field conditions, soil temperature will play a role in root respiration, thus influencing plant growth.

The temperature of the soil is affected by air temperature; the intensity, quality, and duration of radiant energy; precipitation amounts and patterns; the evaporative potential of the air; color and
thermal characteristics of the soil; soil surface cover; and other soil and environmental factors. Many cultural practices can affect soil thermal characteristics and/or the amount of surface residue left in cultivated fields. In addition, straw and other mulches are often used to prevent erosion and reduce evaporative soil moisture loss. Tillage-planting systems affected soil temperature on five soils in Indiana (Griffith et al. 1973). Systems that left the most surface residue had the coolest temperatures. Reduced spring soil temperatures under three conservation tillage systems as compared to conventional tillage (Johnson and Lowery 1985) were attributed to differences in thermal admittance, heat flux at depth, and total heat inputs to the soil profile.

Several authors (Böhm 1979, Klepper et al. 1983, Taylor 1983) have stressed the need in many applied botanical sciences (e.g., agriculture, horticulture, forestry and range sciences) for research on aboveground and belowground environmental effects on root growth. Root research is about two decades behind that for shoots (Klepper et al. 1983), primarily because it is much more tedious and time consuming. It is also difficult to know what parameters to measure.

Evapotranspiration studies have demonstrated that depth and amount of water extraction from the soil are affected by irrigation and/or precipitation levels (Davidoff 1982, Sorensen 1984). Generally, lower levels of added water during the growing season cause roots to extract moisture from greater depth within the soil profile. In contrast, total root growth is generally higher for the higher water levels (Abdul-Jabbar et al. 1982). Soil water content affects both the growth
pattern and the function of root systems. Water held in the soil at high potential enhances root growth both by providing low penetration resistance for root elongation and by providing a steep water potential gradient for rapid water flow into the cells of enlarging roots (Klepper et al. 1983). Consequently, roots tend to proliferate in moist zones of soil. Soil nutrient availability is governed chiefly by diffusion, mass flow, and root interception (Hunsigi 1975, Tisdale et al. 1985); these processes are each influenced by both soil moisture content and soil temperature.

Related Studies

The majority of the research on soil temperature effects on plant growth, and particularly on root growth and activity, have been conducted under controlled conditions in growth chambers or greenhouses. This allows researchers to focus on responses to only one or a few environmental variables while controlling the magnitude of others. Logsdon et al. (1987) studied the isolated effects of mechanical impedance, low temperature, oxygen stress, and water stress on root morphology of pot-grown corn seedlings in a growth chamber. They reported that low soil temperature had the most dramatic effect on the 6-day-old seedlings. Plant growth as a whole was slowed with low soil temperatures, and total root length increased exponentially with increasing temperature. Mackay and Barber (1984) studied effects of 18 and 24°C soil temperature and soil P status on root growth and P uptake by young corn plants (up to 42 days). Root growth was increased 2.6- to 5.1-fold at the 25°C temperature.
In a growth chamber experiment involving variable levels of constant soil and air temperatures (Tew et al. 1963), low soil temperature was a major factor in controlling transpiration rates of young sunflower plants. Similar results have been obtained for white clover (Cox and Boersma 1967). Lopushinsky and Kaufmann (1984) noted that transpiration rate declined linearly with soil temperature for Douglas fir seedlings. Low soil temperature (0.2°C) delayed budburst, reduced shoot growth, and completely prevented root growth of seedlings. Wallace (1970) reported that transpiration and evapotranspiration were influenced more by soil temperature than by soil moisture for Salsola kali plants grown in a greenhouse.

Brengle and Whitfield (1969) reported that wheat grew more slowly at 12.8°C than at 18.3°C and produced fewer tillers. However, at 12.8°C there were 50% more kernels per head. Wheat yields were best at root zone temperatures of about 20°C in several studies (Stewart and Whitfield 1965, Varade et al. 1970, Whitfield and Smika 1971). Optimum temperatures were affected by nutrient supply (especially P) and soil texture. Roots of soybean plants grown at constant and equal air and soil temperatures grew at steeper angles with increasing root zone temperature (Kaspar et al. 1981); similar results were obtained for corn (Mosher and Miller 1972).

Although controlled-environment conditions may greatly facilitate examination of plant responses to environmental variables, research concerning effects of soil temperature on plant growth and rooting activity conducted under these conditions may not be indicative of field responses. Ogunkunle and Beckett (1988) found no significant
correlations between yield of spring barley (*Hordeum vulgare*), growing on the same soils, for field and glasshouse conditions. Correlations between field and undisturbed soil cores and field and outdoor pot trials were significant, but correlation coefficients (r) were only 0.59 and 0.36 to 0.67 (two years), respectively. Highkin (1958) showed that peas grown at constant optimum soil temperatures did not grow as well as those grown under variable temperatures around the optimum. Temperature variation in field soils is a function of depth and time period, with larger temperature fluctuations near the soil surface.

Moody et al. (1963) reported lower field soil temperatures at 8 cm depth throughout the growing season under a wheat straw mulch. This low temperature under mulch was associated with a temporary depression of corn growth during the early growing season. Height and grain yield of mulched plants were greater than unmulched plants. Anderson and Russell (1964) noted that wheat straw significantly depressed yields of spring and winter wheat when applied at rates of 4484 and 5605 kg ha⁻¹ or more, respectively. Maturity was delayed 4 to 6 days. Each 453 kg increment of bright straw depressed the late-morning temperature in the 10-20 cm depth of soil by an average value of 0.28°C during the early growth period. The depression increased with the season to a value of 0.36°C by mid-June, then decreased again by mid-July when the crop almost completely shaded the soil surface. Black (1970) studied the influence of wheat straw residue quantity and position on soil water and temperature near the soil surface (0 to 7.6 cm) under dryland winter wheat. Both quantity and position of residue modified soil water and temperature near the plant crown during tillering.
soil temperature and early corn growth. They reported lower seed zone soil temperatures under the conservation tillage systems. Relative plant growth rate was highly correlated with soil temperature at 5 cm depth.

Several authors have utilized synthetic surface mulches in order to influence soil temperatures (Hanks et al. 1961, Watts 1973, Uppal and Cheema 1980, A.H. Ferguson 1987, personal communication). Watts (1973) studied the development of corn seedlings transplanted to field plots at the fourth-leaf stage. Black plastic, sheet glass, and perlite were used to influence field soil temperatures relative to bare soil. Soil water content was maintained near field capacity for all treatments. The rate of plant development, leaf expansion rate, and the final yield of cobs increased with increasing soil temperature. He noted that mean daily soil temperature at 5 cm depth was a good index of the "environment" for corn growth during the vegetative stage.

Increased depth of moisture utilization by corn plants growing in similar soils in Davis, California, as compared to Logan, Utah, and Fort Collins, Colorado (Stewart et al. 1977), may have been partially due to the effects of soil temperature on root growth. Soybean root simulation (Stone et al. 1983) indicated that the downward rate of root extension was limited by the progression of the annual temperature wave. Root tips tended to collect at and follow the 16 to 17°C temperature front. Fernandez and Caldwell (1975) speculated that the initiation of root growth activity for three cool semi-desert shrubs at progressively later dates with increasing depth in the soil profile may have been related to the seasonal progression of the soil profile.
warming front.

Allmaras and Nelson (1971, 1973) reported corn root dry weight and configuration were changed by tillage and straw mulch treatments, but differing results were obtained for both years of the study. Teskey and Hinckley (1981) found that root elongation rate of white oak was linearly related to changes in soil temperature and soil water potential. At temperatures less than 17°C, soil temperature was the dominant factor, but at higher temperatures soil water potential became the most important factor. However, the number of growing roots and root growth intensity increased at cold soil temperatures and at soil water potentials of -0.3 to -0.8 MPa. They concluded that root growth and development were not exclusively affected by the soil environment.

Research conducted with winter wheat in Montana (A.H. Ferguson 1987, personal communication) indicated that soil temperature had a marked effect on soil moisture depletion and aboveground growth during the season. Little or no soil water extraction occurred from soil layers until temperatures reached 10 or 11°C. Aboveground portions of plants grown in cold soils developed much more slowly than did those grown on warm soils, although by harvest there was no obvious visual difference in dry matter. No direct root parameter measurements were made during their study, so it was impossible to determine whether soil temperature affected root growth or root water uptake or both.
Monitoring Root Growth and Activity

Information concerning root growth and activity is particularly desirable on a dynamic basis rather than where measurements have been made only one or a few times during a season (Böhm 1979). Glass wall methods including rhizotrons and minirhizotrons, as well as some core techniques (e.g. core-break) have been recommended (Böhm 1979, Gregory 1979) for relatively rapid measurement of root numbers with respect to depth under field conditions. Minirhizotrons are non-destructive and are more rapid than core methods (Böhm et al. 1977). In addition they generally have a lower coefficient of variation than do core sampling techniques (Sanders and Brown 1978), which have spatial variation confounded with variation in time because measures cannot be repeated at any particular location (Gregory 1979). Installation of minirhizotron tubes at an angle from the vertical has been suggested (Bragg et al. 1983) because of the tendency of roots to grow down along vertical tubes, resulting in an overestimation of root length at deeper depths.

Böhm (1979) also considered the trench-profile method to be one of the best to use for evaluating effects of soil environmental influences on root growth for row crops. Vepraskas and Hoyt (1988) found similar results using trench-profile and core break methods, but reported that if a backhoe was used to dig trenches, the trench-profile method required about one-fifth the number of person-hours to obtain comparable data.
Soil moisture depletion has been used as an indirect method of studying root responses (Rambal 1984, Wraith et al. 1987). This method is especially appropriate if the activity and not the absolute amount of roots in a soil profile is the research aim (Böhm 1979).

Computer Simulation Models

Mathematical simulation of the soil-plant-atmosphere system has become increasingly popular in the past 20 years, with the advent of relatively powerful and affordable computers. Computer simulation models are extremely valuable in synthesizing and integrating information about the various dynamic processes taking place in this system and in identifying research needs for closing gaps in our knowledge about these processes. They may also be used to extrapolate research results to different conditions and over longer time intervals than would otherwise be possible, and to evaluate management options without resorting to time-consuming and expensive field trials (or at least to help evaluate which field trials to conduct).

These models vary in their complexity, depending largely on the objectives behind their creation. Those intended for synthesis of knowledge and for detailed research about individual processes tend to have the highest levels of complexity, while more general and management-oriented models are simplified to a greater degree. A few require extremely powerful computers (i.e. Cray X-MP/48, Grant 1989a,b) while others might be capable of running on portable programmable calculators. As a general rule these models should not be any more complex than necessary (Hillel 1987). Simple models are often adequate.
for many purposes even though they treat some processes in an empirical rather than a completely mechanistic manner. Hanks and Nimah (1988) noted that simplifying assumptions must be made in modeling any natural system. They asserted that the suitability of the resultant models is determined largely by the validity of the underlying assumptions. These assumptions should be explicitly recognized, based on field experience and data, and be continually checked against field experimental results (Hanks and Nimah 1988).

Several reviews of soil-plant-atmosphere models have been conducted, including those of Molz (1981) and Whisler et al. (1986). These papers cover the theory and processes involved in modeling this system, list model applications, discuss various existing models, and address data acquisition, model validation, and sensitivity analyses.

Many current root water uptake models arose from Gardner's (1960) calculations of uptake along a hypothetical cylindrical root of infinite length. He treated this single root as line sink, with water uptake based on potential gradients and resistances between the root xylem and soil. More recent work (Hainsworth and Aylmore 1986) as well as physiological and theoretical considerations (Caldwell 1976) have shown that the assumption of uniform water uptake along the root cylinder is erroneous. However, this model remains useful as a physically-based simplification (Taylor and Klepper 1975). Because of the near-impossibility of simulating the actual geometry of root systems most root water uptake models have taken a macroscopic approach. Uptake in each layer of soil is generally assumed to correspond to the relative proportion of roots in that layer, in
accordance with water potential gradients and resistances to flow. Uptake models based more closely on the cylindrical root approach (i.e. Stockle and Campbell 1985, 1989) generally assume a uniformly distributed root system in a given soil layer, thereby avoiding estimation of actual rooting geometry. Most of these models assume that the primary resistance to water flow is in the root endodermis (root radial resistance). While this is not always true, particularly for coarse-textured soils (Herkelrath et al. 1977), it seems to hold for the upper 75% of the water content range for normal rooting conditions (Molz 1981). Because most water flow occurs at relatively high water contents, failure to include soil and/or soil-root interfacial resistances is probably a valid simplifying assumption under most circumstances. Taylor and Klepper (1975) indicated that root xylem (axial) resistance to water flow was negligible in comparison with root radial resistance.

Many of these routines have been shown to simulate plant water uptake patterns quite satisfactorily (Molz 1981). Boyer (1975), Weatherly (1982), and Passioura (1988) have reviewed aspects of water uptake by roots in detail. Their papers provide information as to the validity of many of the simplifying assumptions used in these models.

The inclusion of growing root systems presents a further difficulty. Our knowledge of root growth patterns, and environmental effects on these patterns, is limited. Several empirical approaches have been attempted. Gerwitz and Page (1974) fitted an exponential equation to data from the literature on relative root mass vs. depth for several vegetable crops, cereals, and grasses. Borg and Grimes
(1986) reviewed their own and published data and obtained a close fit of a sine function to relative root depth vs. relative time to maturity. Although more data is becoming available on maximum rooting depths and the relative proportion of roots by depth for some crops, these empirical equations have proven adequate for many purposes.

Justification

Little past research has addressed the soil temperature influence on aboveground and belowground plant responses throughout the entire growing season. Even fewer studies have examined these responses under irrigated field conditions. Although the early growth responses of plants to soil temperature have been fairly well documented, the agronomic importance of these findings is unclear.

Computer simulation models are being increasingly utilized for management purposes as well as for research. If these models are to be of maximum utility they must include the most important environmental variables affecting the system(s) being simulated. If low soil temperatures are found to play an important role in crop growth and water use, their affects should be accounted for in these models.
METHODS

Study Site

Field research was conducted at the Utah State University Greenville Farm, 3 km north of the university, in North Logan, UT (41° 46' N, 111° 49' W, 1425 m a.s.l.). Soils at this site are Millville silt loams (coarse-silty, carbonatic, mesic Typic Haploxerolls) with 2 to 4 percent slopes. These soils are moderately to well drained and have moderate permeability; runoff is slow. Available water holding capacity to a depth of 1.5 m in the root zone is 20 to 25 cm. Mean annual precipitation is 38 to 43 cm, mean annual temperature is 8.3 to 9.4°C, and the frost-free season is 140 to 160 days (USDA-SCS 1974).

Field Design

Winter wheat (*Triticum aestivum* (L.) em. Thell cv. Ute) and corn (*Zea mays* L. cv. PX606) were grown during the 1987 season. Corn only was grown during 1988. Fields were fertilized prior to planting with 100 kg ha\(^{-1}\) N and 14 kg ha\(^{-1}\) P on 6 March 1987, and with 112 kg ha\(^{-1}\) N on 1 April 1988 in accordance with typical agronomic practices at the experimental farm.

A line-source sprinkler system (Hanks et al. 1976) provided a gradient of water application. Three irrigation levels were utilized during 1987; two levels were employed during 1988.

A neutron moisture meter (503DR, Campbell Pacific Nuclear, Inc.) was used to estimate soil water content. The meter was field-
calibrated. The coefficient of determination ($r^2$) for the resulting calibration was 0.97. The following water balance equation was used to calculate evapotranspiration within treatments:

$$\text{Et} = P + I - Ro - Dr + \Delta S$$  \[1\]

where $\text{Et}$ is evapotranspiration, $P$ is precipitation, $I$ is irrigation, $Ro$ is surface runoff, $Dr$ is drainage beyond the root zone, and $\Delta S$ is change in soil water storage. Precipitation was measured at a U.S. Weather Bureau station about 40 m north of the plots. Runoff was assumed to be insignificant based on field observations. Drainage was estimated based on changes in water content of soil layers below the root zone, and was also assumed to be near zero. The validity of these assumptions was reinforced by computer simulation of field conditions which indicated that runoff and drainage were negligible.

Soil temperature was monitored with copper-constantan (EXPP-T-20, Omega Engineering, Inc.) thermocouples. Junctions were twisted, soldered, and insulated with a commercial silicon sealant (Silicone II, General Electric Co.). Thermocouples were connected to datalogging equipment (CR7, 21X, AM32; Campbell Scientific, Inc.) which were programmed to measure soil temperature every 15 minutes and record 2-hour and daily means.

Winter Wheat

Winter wheat was planted 10 Oct. 1986 in an area that was fallowed during 1985 and 1986. Wheat rows were planted east to west and were spaced 15 cm apart.
Four replications of three soil temperature treatments and three irrigation levels were established during March 1987. Treatments included control, 2.5 t ha\(^{-1}\) barley straw mulch between wheat rows, and heat cables (Soil-Heat, Cox and Co.) buried approximately 20 cm deep. Heat cable treatments were installed by cutting small channels into the soil with a chainsaw, inserting the cable, then backfilling. These cables were used only on high and low water levels. Plots were 3 by 5 m, with 2-m buffer strips between adjacent soil temperature treatments.

One access tube for neutron moisture meter readings was installed to a depth of approximately 2.5 m near the center of each plot during mid-October 1986. Measurements were made at 20-cm increments to 2.4 m. Irrigation was measured with catchment cans placed near the access tubes.

Thermocouples were installed in each plot at depths of 2, 10, 50, and 100 cm. Due to a limited number of datalogger channels, thermocouples within each of 2 replications were alternately monitored for several consecutive days in rotation throughout the season, while those in the remaining 2 replications were monitored continuously.

One extruded polybutyrate minirhizotron observation tube (3 m x 38 mm OD x 35 mm ID) was installed at a 20\(^{\circ}\) angle from the vertical within each plot during 16 to 22 April. Excavations were made using soil augers having the same outside diameter as the tubes. Approximately 15 cm of observation tube extended above the soil surface. The portion of these tubes from slightly below ground level to their upper tips were covered with an opaque tape, a rubber cork was inserted in the open end, and an inverted can placed over the top to exclude light and
Two 5-m rows within each plot were harvested by hand at maturity during 20 to 23 July. After oven drying these were threshed and measurements made of grain and total aboveground dry matter yield.

**Corn**

Corn was planted on 1 June 1987, northeast of and adjacent to the wheat plots. Rows were oriented north to south using a 76-cm row spacing and approximately 15 cm between plants within rows.

Three replications of two soil temperature treatments and three irrigation levels were installed during 11 to 16 June. Plot size was 4 by 4.5 m. The sprinkler line was oriented at right angles to the corn rows. Temperature treatments included a 0.15-mm (6-mil) transparent polyethylene surface mulch, and transparent polyethylene mulch covered with about 6.4 t ha\(^{-1}\) barley straw. Holes approximately 5 cm diameter were cut in the polyethylene around each corn seedling, and numerous small punctures (approximately 5- to 10-mm dia.) were made to aid in infiltration of water.

Two neutron access tubes were installed about 1 m apart near the center of each plot. Readings were taken at 20-cm increments to 2.4 m. Irrigation was measured with catchment cans in each plot, which were maintained at canopy height as the crop matured.

Thermocouples were buried at 10, 50, and 100 cm in each plot. These were all connected to a single (CR7) datalogger, monitored continuously, and sampled on the same schedule as reported above for wheat.
Two pyrex minirhizotron observation tubes (1.22 m x 38 mm OD x 32 mm ID, Corning Glass Works) were installed at approximately 20° from the vertical near the access tubes. A soil auger having slightly smaller diameter than observation tubes was used to excavate holes, and a cylindric wire brush was passed through the cavity several times to remove any compacted soil from the walls before insertion of tubes. The aboveground portions of these tubes were prepared as described above.

Three-meter segments from two rows within each plot were harvested by hand on 16 September. These were weighed in the field, then 3 plants per plot were separately weighed and oven dried to get aboveground dry matter yields.

Four replications of three temperature treatments and two water levels were utilized during 1988. Field plots were 6 by 6 m.

Transparent polyethylene sheets were spread over all plots on 11 April. Approximately 6.5 t ha\(^{-1}\) barley and wheat straw was placed over the polyethylene on two thirds of temperature treatment plots during 11 and 12 April. Small punctures were again made to aid in the infiltration of water.

Two neutron access tubes were installed 2 m apart near the center of each plot on 7 April. Readings were taken at 20-cm increments to 2.0 m. Soil water content measurements were made immediately prior to and about 48 hours after each irrigation.

Four thermocouples were installed near each set of access tubes in two replications during 27 April to 9 May. These were at depths of 2, 10, 50, and 100 cm. Additional thermocouples were installed at 30, 75,
and 150 cm in six plots to provide supplemental data on soil temperature profiles. All soil thermocouples were monitored as for corn during 1987. Shaded thermocouples were also installed to monitor air temperatures at 5 cm above ground level, to investigate whether the treatments caused significantly different temperatures above ground.

Corn was planted by hand on 16 May. Rows were oriented north to south, spaced 76 cm apart, and plants were spaced approximately 20 cm apart within rows. Immediately prior to planting, straw was removed from one half the plots where it had been previously applied. Temperature treatments consequently included 1) polyethylene mulch ("plastic"), 2) polyethylene mulch plus straw mulch ("straw"), and 3) polyethylene mulch with straw removed prior to planting ("straw-plastic"). The area surrounding the plots was planted the same day using conventional equipment. Row orientation and spacing were similar to the hand-planted areas. The line-source sprinkler was again positioned perpendicular to the corn rows.

Crop growth data were collected five times during the season. The number of fully expanded leaves and the maximum distance from the ground to the tip of manually-extended leaves were measured for 6 to 10 plants per plot on 7 and 23 June. Three plants per plot were harvested, oven dried, and weighed on 20 July, 22 August, and 19 September. Grain was removed from the dry cobs and weighed separately for the 19 September harvest, giving both grain and total aboveground dry matter yields.

Rooting development with respect to depth was measured during 12 to 18 July and 23 to 29 August. A pit approximately 1 by 1 m, centered
within a corn row, was excavated in each plot within one replication. These were dug to 1.5 m during the July sample and to 2.1 m during the August sample. One pit wall was then hand-smoothed with a small trowel and a 10-cm grid was centered on the row and secured to the wall. The grid extended 40 cm on either side, slightly greater than half the distance across the interrow space. A gentle water spray was used to wash about 2 mm of soil from the pit wall within one horizontal row of grids at a time and the number of roots visible within each grid was recorded. This procedure was then repeated for the opposite wall.

Because of the serious plot disturbance which resulted from this method of data collection and the time necessary for its completion (approximately 7 hours per pit), data were collected from treatment plots in only one replication. Although this sampling scheme precluded statistical analyses of root data, it also resulted in the loss of this replication for soil water, soil temperature, and aboveground dry matter yield subsequent to the second root excavation. Böhm (1979) notes, however, that this method has been shown to provide very good estimates of root distribution with few or no replications.

Data Analysis

Analysis of variance was used to compare treatment means for soil water depletion, plant growth and yield of corn during both 1987 and 1988, with significant differences determined at the five percent level using Fisher's LSD. Because heat cables were not installed for the medium irrigation treatments analysis of variance was not used for the winter wheat data. Rather, standard errors of the difference between
means were utilized to compare treatments for this crop. No valid probability level may be assigned to the main effect of irrigation because irrigation levels are applied in a systematic manner by the line-source sprinkler (Hanks et al. 1980).

Modifications to the Computer Simulation Model

A soil water balance - climate model (SOWATET, Hanks In press) was modified in order to more mechanistically simulate plant water extraction. Soil temperature effects on plant growth and water use were also incorporated into the model.

The SOWATET model uses a numerical solution to the general equation for vertical flow,

\[
\frac{\delta \psi_m}{\delta z} = \frac{\delta}{\delta z} \left[ K(\theta) \frac{\delta \psi_m}{\delta z} + K(\theta) \right] + A(z) \tag{2}
\]

where \( \psi_m \) is soil matric potential, \( K(\theta) \) is hydraulic conductivity, \( z \) is depth, and \( A(z) \) is a plant root water extraction term. The numerical approximation of the root extraction term is

\[
A(z) = \frac{(HROOT + 1.05 \cdot z - \psi_m(z)) \cdot RDF(z) \cdot K(z)}{\Delta x \Delta z} \tag{3}
\]

where HROOT is the "effective" water potential in the root at the soil surface, 1.05\( \cdot z \) adjusts the extraction for various depths (effectively a gravitational potential plus axial resistance to flow in the root xylem), \( \psi_m(z) \) is the soil matric potential at depth \( z \), RDF(z) is the relative proportion of active root mass in the depth increment \( \Delta z \), \( K(z) \) is hydraulic conductivity, and \( \Delta x \) is the distance from the root xylem to the point in the bulk soil where matric potential is equal to \( \psi_m \).
The value of $\Delta x$ is assumed to be one cm. Flux of water is allowed into the root but not out. The value of $H_{\text{ROOT}}$ is solved for under the constraints: 1) $\Sigma A(z) = T_p$ if $H_{\text{ROOT}} > H_{\text{LOW}}$; 2) otherwise $H_{\text{ROOT}}$ is set equal to $H_{\text{LOW}}$, and $\Sigma A(z)$ is calculated by Eq. [3]. No hysteresis is assumed in the model, giving matric potential as a single-valued function of water content.

Input data needed to run the model include: 1) soil properties including water content-matric potential and water content-hydraulic conductivity relations, values for saturated and air dry water content, and values for saturated, "wilting", and air dry matric potential; 2) plant properties including relative root mass as a function of time and depth, time when active plant growth starts and when full cover is reached, and the "wilting" soil water potential; 3) boundary and climatic properties including the initial values of water content vs. depth, and precipitation and potential evapotranspiration as functions of time (top boundary conditions). The bottom boundary may be set to a constant water content (thus allowing upward and/or downward flux), or a no flux condition at the bottom boundary may be specified.

The model first reads the constants and the initial and boundary conditions from a data file. Several other parameters are then computed and initialized from this information. Potential evapotranspiration ($ET_p$) is partitioned into potential soil evaporation ($E_{\text{sp}}$) and potential transpiration ($T_p$) based on evaporation and transpiration coefficients (related to crop growth). Diurnal values of $ET_p$ are assigned using a sinusoidal pattern during the first 12 hours of each day, with the area under the curve equal to daily $ET_p$. A root
growth routine calculates the current rooting depth and relative root mass by depth. Depth of rooting is calculated by an exponential function of time between the day root growth starts and the day maximum root distribution is achieved. Hydraulic conductivities and water capacities are then calculated as a function of depth, including an approximate top boundary hydraulic conductivity in order to meet the imposed top boundary flux condition. Root water uptake by depth \( A(z) \) is determined based on this information. A tridiagonal matrix is then solved for water flow by calculating new matric potentials by depth. Fluxes are cumulated, new soil water contents are estimated as functions of the new matric potentials, and the time is updated. The model determines whether to end the simulation by comparing time expired with the cumulative completion time from the input file. If the simulation is not yet over, the boundary conditions are updated and another iteration begins.

**Modification of Plant Water Uptake Algorithm**

The method of Stockle and Campbell (1985) for simulating plant water uptake was adapted for use in the SOWATET model. This approach is based on the "cylindrical root model" developed by Gardner (1960), Cowan (1965), and others.

If cylindrical plant roots are assumed to be equally spaced in the soil, each root may be considered to have sole access to the water in a cylinder of soil surrounding it. The differential equation for water uptake by a single root may then be written as

\[ q/A = -K(d\psi_m/dr) \]  \[4\]
where \( q \) is flux of water, \( A \) is area for water flow into the root (equal to \( 2\pi rl \) where \( l \) is root length), \( K \) is soil hydraulic conductivity, and \( r \) is radial distance from the root xylem. Integrating Eq. [4] from the root surface to a distance which represents one half the mean distance between roots gives

\[
(q/2\pi l)\ln(r_s/r_r) = (K_s\psi_s - K_r\psi_r)
\]

where "r" and "s" subscripts refer to the root surface and to the location in the soil midway between adjacent roots, respectively. One half the mean distance between roots is

\[
r_s = (\pi RLD)^{-1/2}
\]

where RLD is root length density.

The uptake of water from a given length of root is related to the root length density, soil depth, and extraction rate by

\[
q/1 = E_i/RLD_i \Delta z_i
\]

where \( E_i \) is water extraction rate in layer \( i \), and \( \Delta z_i \) is soil depth in this layer.

Uptake of water from the soil is a function of the potential gradient between the soil and the root xylem, and of the resistances to water flow in the soil and across the root endodermis. Water uptake from a given soil layer is then

\[
E_i = \frac{(K_r\psi_r - K_s\psi_s)(\Delta z_i)}{\ln(2\pi r^2 RLD_i)} \left(\Delta z_i\right)
\]

Total water uptake is the sum of uptake from each soil layer,
where $\psi_s$ is soil water potential and $\psi_g$ is gravitational potential in layer $i$, $\psi_x$ is xylem water potential, $R_s$ is soil resistance and $R_r$ is root resistance in layer $i$. Root resistances are calculated assuming that root resistance to uptake in any layer is proportional to the total root resistance, and inversely proportional to the relative root length density in the layer

$$R_{r_i} = R_r(L_{LD_i}/R_{LD_i})$$

where $R_r$ is total root resistance for the entire root system. Total root resistance may be estimated from measurements of soil and xylem water potentials and transpiration rate as

$$R_r = (\psi_s - \sum \psi_{g_i} - \psi_x)/E$$

if $\psi_s$ is uniform throughout the entire rooting volume and axial resistances are neglected. $\sum \psi_{g_i}$ represents the gravitational potential summed over depths in the root zone.

Soil resistance in layer $i$ ($R_{s_i}$) is equal to $(\psi_s - \psi_{r_i})/E$. Calculation of $(\psi_s - \psi_{r_i})$ is difficult because $\psi_r$ is a nonlinear function of rooting density, soil water potential, and transpiration rate. This may be done iteratively, but because the resistance to flow between soil and root is generally a small proportion of the total resistance to water flow (Campbell 1985), an approximate soil resistance may be calculated assuming $\psi_r = \psi_s$. Using Eq. [8],

$$R_{s_i} = \ln(2\pi \tau_i^2 R_{LD_i})/K_i(4\pi R_{LD_i} \Delta z_i)$$
This approach assumes negligible interfacial resistance between soil and root surface, an assumption which will probably not be valid in coarse-textured soils. Caldwell (1976) discussed the implications of actual root water uptake failing to conform to one of the inherent assumptions of the cylindrical root model: that water uptake is uniform along the entire root length. He calculated that significant resistances to flow could develop between the bulk soil and the root surface, even at relatively high water contents, if water uptake was confined largely to root tips and to occasional breaks in the suberized lining along mature portions of active roots. Physiological considerations and microscale studies indicate that the highest rates of water uptake are indeed at the tips of actively growing roots. However, actual data on the number and location of root tips for growing root systems in the field are extremely scarce, and the mathematical modeling of root tip dynamics is complicated and not well developed.

If axial resistance to flow in the xylem is considered negligible compared to the soil and root radial resistances, Eq. [9] may be solved for \( \psi_x \)

\[
\psi_x = \frac{\Sigma[\psi_{s_i}/(R_{s_i} + R_{r_i})]}{\Sigma[1/(R_{s_i} + R_{r_i})]} - E
\]

[13]

Flow of water from the roots to the atmosphere is governed by the potential gradient between root xylem and plant leaf, and the resistance to flow between these two points. Assuming axial resistances to flow are negligible in comparison to leaf resistance,

\[
E = (\psi_x - \psi_l)/R_l
\]

[14]
so that leaf water potential may be estimated by

$$\psi_l = \psi_x - E \cdot R_l$$  \[15\]


$$\psi_l = \bar{\psi} - E(R_l + R_{sr})$$  \[16\]

where $\bar{\psi}$ is a mean weighted soil water potential,

$$\bar{\psi} = \Sigma[\psi_s/(R_s + R_{rl})]/\Sigma[1/(R_s + R_{rl})]$$  \[17\]

and $R_{sr}$ is the combined soil-root resistance for the entire root volume,

$$R_{sr} = 1/\Sigma[1/(R_s + R_{rl})]$$  \[18\]

In the simulation of plant water uptake using this approach, values for total root system resistance ($R_r$) and root length densities ($R_{LD_i}$) are used to calculate root resistances for each soil layer ($R_{rl}$) by Eq. [10]. Soil resistances for each layer, the mean weighted soil water potential, and the combined profile soil-root resistance are calculated using Eqs. [12], [17], and [18]. For conditions where high resistances or low water potentials limit transpiration rate, a function relating transpiration to leaf water potential

$$\psi_l = E_p/[1 + (\psi_l/\psi_c)^{a}]$$  \[19\]

is employed, where $E_p$ is potential transpiration, $\psi_c$ is the water potential at which $E = E_p/2$, and $a$ is a species-dependent constant with a value of about 10 (Campbell 1985). This function simulates stomatal
regulation of transpiration rate as leaf water potential declines. A first approximation of leaf water potential is calculated using Eq. [16], and a Newton-Raphson iteration is used to solve for \( \psi_1 \) by combining Eqs. [16] and [19]. Once \( \psi_1 \) is known, \( \psi_x \) is found by Eq. [15], and rate of water uptake by depth is estimated using Eq. [9]. The maximum time step for the model should not exceed about two hours, in order that the daily peak in calculated potential evapotranspiration (Fig. 1) not be missed.

Critical assumptions of this approach are: 1) that the cylindrical root model (Gardner 1960, Cowan 1965), which assumes uniform water uptake along the length of uniformly-distributed roots, adequately describes actual root water uptake; 2) that root resistance to water flow in a given soil layer is inversely proportional to the relative root length density in the layer; 3) that the decrease in water potential from the bulk soil to the root surface is much less than that from the root surface to the root xylem; and 4) that resistance to axial flow in the plant xylem is negligible compared to soil, root radial, and leaf resistances.

**Incorporation of Soil Temperature Influences**

To incorporate the influences of soil temperature on aboveground and belowground plant growth and soil water extraction into the modified SOWATET model, a relative plant growth function was defined (Allmaras et al. 1964, Cooper 1973, Jones et al. In press). The instantaneous value of the relative growth parameter is given by

\[
GR_{1j} = 0.5 + 0.5 \cdot \sin[\pi(STEMP_j - 2 \cdot TMIN)/(TOPT - TMIN)]
\]  [20]
where $GR_{l_j}$ is the value of the relative growth parameter ($0 \leq GR_{l} \leq 1$) at time "j", $STEMP_j$ is mean daily 10 cm soil temperature ($^\circ C$) during the same time interval, TMIN is the minimum temperature for growth, and TOPT is optimal growth temperature (Fig. 2). A time-weighted mean of the instantaneous parameter is used to modify aboveground and belowground plant growth. This is calculated as

$$GR = \int GR_{l} \, dt / \int dt$$  \hspace{1cm} [21]$$

Variable names from the computer simulation program are used in these equations to facilitate comparison with the printout of the program code in Appendix A.

Even though plant apical meristems are generally quite near the soil surface during early growth and vegetative development, a depth of 10 cm has been chosen because daily mean temperatures at this depth are much less variable than nearer the soil surface and are often available from experiment stations or similar climatic data collection sites. Differences in soil temperature at meristem depth and at 10 cm may be taken into consideration in assigning values for TMIN and TOPT. The amount of time (in days) soil temperature exerts this regulatory
Fig. 1. Calculated potential evapotranspiration (cm h\(^{-1}\)) as a function of hour of day. Calculations were made assuming a mean daily potential evapotranspiration rate of 0.029 cm h\(^{-1}\).

Fig. 2. Relative plant growth as a function of 10 cm soil temperature. Calculations were made assuming values for TOPT and TMIN of 27 and 9°C respectively.
influence on relative plant growth is specified by the parameter STDAY. Indications are that this period is about 4 to 6 weeks for many species (Walker 1969, Hanway 1971).

The seasonal partitioning of potential ET between soil evaporation and transpiration is also modified by the soil temperature effect on plant growth. Potential soil evaporation is given by

\[
V_{1j} = \frac{TET_j \cdot AK1}{1 + \exp[6 - AK3(TIME_j - 24 \cdot ESTART)]}
\]

for \( TIME/24 \leq STDAY \), and

\[
V_{1j} = \frac{TET_j - TET_j \cdot AK1}{1 + \exp[6 - AK3A(TIME_j - 24 \cdot ESTART)]}
\]

for \( TIME/24 > STDAY \), where "j" subscripts refer to time, \( V_1 \) is potential soil evaporation, \( TET \) is potential evapotranspiration, \( TIME \) is current time (h) in the simulation, \( ESTART \) is the day plant cover developed to the point that transpiration became significant relative to soil evaporation, \( AK1 \) is ratio of \( T/ET \) at maturity, \( ESTOP \) is time (d) after which plant cover development does not significantly change the partitioning of radiant energy between transpiration and evaporation, \( AK3 \) is \( .5/(ESTOP - ESTART) \), \( AK3A \) is \( .5/((ESTOP + PT/24) - ESTART) \), and \( PT \) is the amount of time (h) that plant development has been delayed relative to optimal soil temperature conditions.

Potential transpiration is then \( (1 - V_1) \) (Fig. 3). Ten cm soil temperature on day \( ESTART \) is assumed to be \( \geq TMIN \), in order for plant growth to begin. The value of \( V_1 \) is updated periodically, and each time the top boundary condition changes. The mean potential rates of \( E \) and \( Et \) are distributed sinusoidally during each 24-hour period by
\[ \text{EOR} = 2.5(24 \cdot Vl)(0.025 + \sin(2\pi/48 \cdot \text{STIME})^4)/24 \]  
\[ \text{ET} = 2.5(24 \cdot \text{TET})(0.025 + \sin(2\pi/48 \cdot \text{STIME})^4)/24 \]  

(Fig. 1), where EOR and ET are potential Es and ET (cm h\(^{-1}\)) respectively, and STIME is the hour of day at the middle of the time period (h) for which these values apply. STIME is calculated as

\[ \text{STIME} = [(\text{TIME}/24) - \text{INT}(\text{TIME}/24)] \cdot 24 + \text{DELT}/2 \]

where DELT (delta-time) is the amount of time (h) covered by the current calculations.

The soil temperature effect on GR also modifies belowground plant growth. Calculation of rooting depth is based on the empirical relation between relative rooting depth and relative time to maturity found by Borg and Grimes (1986). The time-dependent depth of rooting is

\[ \text{DROOT} = G R J \cdot \text{RDMAX}[0.5 + 0.5 \sin(3.03 \frac{\text{TIME}/24 - \text{RSTART}}{\text{RDFDAY} - \text{RSTART}} - 1.47)] \]  

for \( \text{TIME}/24 \leq \text{STDAY} \), and

\[ \text{DROOT} = \text{RDMAX}[0.5 + 0.5 \sin(3.03 \frac{\text{TIME} - \text{DT} - 24 - \text{RSTART}}{\text{RDFDAY} - \text{RSTART}} - 1.47)] \]

for \( \text{TIME}/24 > \text{STDAY} \) (Fig. 4), where DROOT is current rooting depth, RDMAX is maximum potential rooting depth, RSTART is day significant root development begins, RDFDAY is the day roots reach maximum extent under optimal soil temperature conditions, and DT is the amount of time (h) that root depth development has been delayed relative to optimal soil temperature conditions.
Fig. 3. Ratio of potential transpiration to potential evapotranspiration as a function of temperature and relative time to plant maturity. Calculations were made for soil temperatures of 27 (TOPT), 20, 17, and 12°C; STDAY = 0.4.

Fig. 4. Calculated rooting depth (DROOT) as a function of time and soil temperature. Calculations were made assuming constant 10 cm soil temperatures of 27 (TOPT), 22, 17, and 12°C, RDMAX = 150 cm, RSTART = 10 d, RDFDAY = 100 d, and STDAY = 40 d.
Proliferation of roots in a given soil layer is governed by a logistic function,

$$RD_i = GR_i \cdot RLD_i / \left[1 + AK4 \cdot \exp\left(-\frac{AK5_i(TIME - RSTART_i)}{RDFDAY}/24\right)\right]$$  \hspace{1cm} [29]

for \( TIME/24 \leq STDAY \), and

$$RD_i = RLD_i / \left[1 + AK4 \cdot \exp\left(-\frac{AK5_i((TIME - DT_i) - RSTART_i)}{RDFDAY}/24\right)\right]$$  \hspace{1cm} [30]

for \( TIME/24 > STDAY \) (Fig. 5), where \( RD_i \) is current root length density in layer "i", \( RLD_i \) is the corresponding potential root length density, \( AK4 \) is 49.64, \( AK5_i \) is \( 8.5/(RDFDAY - RSTART_i)/24 \), \( RSTART_i \) is time (h) when \( DROOT \) initially reached the depth midpoint of layer "i", and \( DT_i \) is the amount of time (h) that root proliferation in the layer has been delayed relative to optimal soil temperature conditions. Note that simulated growth differences due to soil temperature occur during the early stages of plant development (Figs. 3, 4, 5). This is consistent with the literature and is in agreement with results from the field experiments presented herein. Time of maximum plant canopy, rooting depth, and root length density development are delayed by an amount of time equal to \( PT \), \( DT \), and \( DT_i \) respectively (Figs. 3, 4, 5). This implies that air temperature, which controls the rate of temperature-mediated physiological development after meristem elevation, is not significantly different than at \( PT \), \( DT \), and \( DT_i \) hours previously and that no compensatory plant growth mechanisms occur.

In order to preserve compatibility with previous versions of SOWATET, supplemental data required to operate the current model, designated "SOWATMP", are placed at the end of the standard SOWATET
Fig. 5. Calculated root length density as a function of time and soil temperature. Calculations were made assuming constant 10 cm soil temperatures of 27 (TOPT) 22, 17, and 12°C, RLD = 4.0, RSTART = 0 d, RDFDAY = 100 d, and STDAY = 40 d.

To determine whether the revised plant water uptake algorithms produced results similar to those in the original model, simulations were made with both models using the same input data and predicted values for seasonal transpiration, soil evaporation, and cumulative change in soil water content were compared. The sensitivity of the model to some of the most influential soil temperature-plant growth input parameters was also investigated.

Simulations of field conditions during 1984 were used to assess the general performance of the SWATMP soil-plant-atmosphere model. No comparisons were made for 1987 because reliable climatic data were not available. Comparisons between measured and predicted soil water depletion were made for the straw and plastic mulch treatments under high and low irrigation because these soil surface treatments provided the maximum field responses under which to test the model.
data file. These data include 1) an array of 10 cm depth soil temperature (STEMP array) corresponding to time increments in the top boundary array, 2) the day root development begins (RSTART), and the maximum rooting depth (RDMAX), 3) optimal (TOPT) and minimum (TMIN) values of 10 cm soil temperature for plant growth, 4) the number of days soil temperature exerts a direct influence on plant development (STDAY), 5) total root (RR) and leaf (RL) resistances, 6) mean root radius (RL), 7) the potential for stomatal closure (PC), and the exponent (SP) from the stomatal closure function (Eq. [19]). Values for root length density by depth are substituted for the values of relative root mass required by SOWATET at the same location within the data file.

To determine whether the revised plant water uptake algorithms produced results similar to those in the original model, simulations were made with both models using the same input data and predicted values for seasonal transpiration, soil evaporation, and cumulative change in soil water content were compared. The sensitivity of the model to some of the most influential soil temperature-plant growth input parameters was also investigated.

Simulations of field conditions during 1988 were used to assess the general performance of the SOWATMP soil-plant-atmosphere model. No comparisons were made for 1987 because reliable climatic data were not available. Comparisons between measured and predicted soil water depletion were made for the straw and plastic mulch treatments under high and low irrigation because these soil surface treatments provided the maximum field responses under which to test the model.
RESULTS AND DISCUSSION

Soil Temperature

Winter Wheat

Maximum differences observed in mean daily soil temperature under the wheat in 1987 were about 5.8, 6.1, 4.2, and 2.6°C at 2, 10, 50, and 100 cm respectively (Figs. 6, 7, 8, 9). Measured soil temperature differences were greatest at 10 cm depth rather than nearer the soil surface because heat cables were buried at about 20 cm. Thermocouples at 2-cm depth were raised aboveground on day-of-year 133, as apical meristems elevated above ground level. Attempts were made to maintain these thermocouples at about meristematic height, but these were observed to have fallen from their supports numerous times. This data is therefore reliable only until day 133.

The spring of 1987 was uncharacteristically warm in Logan. Soil temperatures in all plots exceeded 10 to 11°C, identified as a critical lower temperature range for water extraction in winter wheat (A.H. Ferguson, 1986, personal communication), to a considerable depth rather early in the development of the wheat plants.

The characteristic amplitude damping and time lag with depth exhibited by these field soil temperature data are extremely difficult to duplicate under the controlled-environment (i.e. growth chamber) conditions commonly used in soil temperature research. The effects of these diurnal and annual temperature fluctuations on plant responses is poorly documented and needs to be investigated further in order to
Fig. 6. Mean daily soil temperature (°C) at 2 cm depth under winter wheat.

Fig. 7. Mean daily soil temperature (°C) at 10 cm depth under winter wheat.
Fig. 8. Mean daily soil temperature (°C) at 50 cm depth under winter wheat.

Fig. 9. Mean daily soil temperature (°C) at 100 cm depth under winter wheat.
determine the validity of utilizing constant or day-night temperature regimes.

**Corn**

Maximum soil temperature differences observed in the corn plots during 1987 were about 4.3, 3.6, and 2.2°C at 10, 50, and 100 cm respectively (Figs. 10, 11, 12). These differences built up rather rapidly after the surface mulches were applied shortly after seedling emergence, but decreased thereafter as the vegetative canopy developed and shaded the soil surface. Note that soil temperatures steadily increased during the growing season for wheat, but decreased for corn. This is due primarily to the timing of the respective crop growing seasons with respect to the annual sinusoidal soil temperature wave. The relation was also influenced by the history of conditions at the soil surface. There were considerably lower temperatures at a given depth under the full wheat canopy during calendar days 180 to 190 compared to the sparse corn canopy.

During 1988 the earlier mulch treatments were quite effective in influencing soil temperature. Maximum differences observed in mean daily soil temperature between polyethylene ("warm") and straw ("cool") plots were about 13, 10, 8.5, and 6°C at 2, 10, 50 and 100 cm respectively (Figs. 13, 14, 15, 16). Temperature differences built up during the pre-planting period to a maximum shortly after planting, then gradually decreased as the corn canopy developed and shaded the ground surface. After the straw mulch was removed from the straw-plastic treatment at planting, soil temperatures increased to levels similar to the polyethylene treatments within a few weeks. Soil
Fig. 10. Mean daily soil temperature (°C) at 10 cm depth under corn during 1987.

Fig. 11. Mean daily soil temperature (°C) at 50 cm depth under corn during 1987.
Fig. 12. Mean daily soil temperature (°C) at 100 cm depth under corn during 1987.

Fig. 13. Mean daily soil temperature (°C) at 2 cm depth under corn during 1988.
Fig. 14. Mean daily soil temperature (°C) at 10 cm depth under corn during 1988.

Fig. 15. Mean daily soil temperature (°C) at 50 cm depth under corn during 1988.
temperatures, particularly near the surface, dropped several degrees during and immediately after irrigation events (days 160, 182, 205, 230). This was due to evaporative cooling of the soil surface.

Mean daily air temperatures at 5-cm height were very similar between treatments (Fig. 17), indicating that the aboveground temperature environment was not significantly altered by the soil surface treatments. This agrees with the results of Hanks et al. (1961) who reported that although soil temperatures were affected, air temperatures over bare soil, clear plastic, straw mulch and aluminum-painted gravel were about the same. Differential crop responses were therefore due solely to soil temperature differences.

Crop Growth and Yield

**Winter Wheat**

Wheat aboveground dry matter yields in 1987 responded to increased irrigation but not to soil temperature (Fig. 18). Results for grain were generally similar but grain yields for heat cable plots under high irrigation were higher than for straw mulch, and under low irrigation were higher than for control plots (Fig. 19). The surface soil under the low irrigation straw mulch remained visually wetter than for the bare surfaces of both other treatments due to decreased soil evaporation. Apparently this additional water partially compensated for higher soil temperatures in the two unmulched treatments under limited water availability (Figs. 18, 19). Unger (1978) reported that cooler soil temperatures in dryland sorghum plots mulched with 8, and especially 12 Mg ha\(^{-1}\) wheat straw resulted in a 2- to 5-day delay in
Fig. 16. Mean daily soil temperature (°C) at 100 cm depth under corn during 1988.

Fig. 17. Mean daily air temperature (°C) at 5 cm height during 1988.
Fig. 18. Wheat aboveground dry matter yield (Mg ha\(^{-1}\)) during 1987. Treatments having the same letter above bars are not significantly different (p < 0.05).

Fig. 19. Wheat grain yield (Mg ha\(^{-1}\)) during 1987. Treatments having the same letter above bars are not significantly different (p < 0.05).
emergence and slower early plant growth. However, yields were not reduced in these treatments because the mulches resulted in increased stored soil water at planting, following a fallow period. This increase in stored soil water resulted in greater yields than for treatments with little or no surface mulch.

The mean ratio of grain yield to aboveground dry matter yield for all treatments was about 0.42 (Fig. 20), which is similar to those noted by other researchers (Hanks and Sorensen 1984, de Wit 1958). Hanks and Sorensen (1984) concluded that there was no clear indication of any influence of water stress on this ratio, sometimes termed "harvest index". (Letters denoting statistical significance are not used in Figs. where nonsignificant F-tests were obtained using analysis of variance, or where no valid probabilities may be assigned.)

Wheat aboveground dry matter and grain yields increased with increased water application (Figs. 21, 22). The difference was greater at low irrigation levels. There were no significant differences in dry matter or grain yields due to soil temperature treatments.

**Corn**

The influence of irrigation level on corn aboveground dry matter yield during 1987 was similar to that for wheat (Fig. 23). Yields increased with increasing irrigation water application. Because surface mulches were applied about two weeks after the corn was planted during 1987, soil temperature differences were nonexistent or relatively minor during the critical early growth stages (data in Fig. 10 begins about 20 days after treatments were applied). Although plants in warm soil plots were about two days ahead of those in straw
Fig. 20. Ratio of grain yield to aboveground dry matter yield for wheat during 1987.

Fig. 21. Wheat aboveground dry matter yield (Mg ha$^{-1}$) during 1987, as a function of irrigation level.
Fig. 22. Wheat grain yield (Mg ha\textsuperscript{-1}) during 1987, as a function of irrigation level.

Fig. 23. Corn aboveground dry matter yield (Mg ha\textsuperscript{-1}) during 1987, as a function of irrigation level.
plots in development (based on visual observation), aboveground dry matter yields at final harvest were nearly identical (Fig. 24). There was no temperature by water level interaction with respect to aboveground dry matter yield (Fig. 25).

Because surface treatments were installed earlier and thus had a greater effect on soil temperature and early plant development during 1988, crop growth was affected by soil temperature treatments throughout the 1988 season. Emergence was delayed by about one day for plants in straw and straw-plastic treatments. Corn plants in the cool (straw) plots had fewer fully emerged leaves than did those in plastic and straw-plastic treatments three and five weeks after planting (Fig 26). Maximum extended height of plants corresponded to increasing soil temperature on 7 June, three weeks after planting (Fig. 27). At five weeks (23 June) maximum height was greater for both plastic and straw-plastic treatments than for the cooler straw treatment. Watts (1972) showed that corn leaf extension was more highly correlated with temperature changes of the shoot meristem than of the shoot or root medium. Grobbelaar (1963, cited by Allmaras and Nelson 1973) observed that the shoot primordia of corn had not emerged from the soil surface until after the sixth leaf emerged from the whorl. This probably occurred somewhat before 7 June for straw-plastic and plastic treatments, and about 23 June for the straw treatment (Fig. 26).

Aboveground dry matter yield was greater for plastic and straw-plastic treatments on 20 July, nine weeks after planting (Fig. 28). After 14 weeks aboveground dry matter yield increased in the order: straw, straw-plastic, and plastic. By final harvest (17 weeks),
Fig. 24. Corn aboveground dry matter yield (Mg ha⁻¹) during 1987, as a function of soil temperature treatment.

Fig. 25. Corn aboveground dry matter yield (Mg ha⁻¹) during 1987, as a function of irrigation level and soil temperature treatment.
Fig. 26. Mean number of fully expanded leaves on 7 and 23 June 1988, as a function of soil temperature treatment. Treatments having the same letter above bars are not significantly different (p < 0.05).

Fig. 27. Mean maximum plant height (m) on 7 and 23 June 1988, as a function of soil temperature treatment. Treatments having the same letter above bars are not significantly different (p < 0.05).
aboveground dry matter yield for plastic treatments remained greater than for straw treatments while that of straw-plastic treatments was not different from straw or plastic treatments. Grain yield at final harvest was different for all treatments and corresponded to early-season soil temperature (Fig. 29).

Aboveground dry matter yields from high irrigation plots were qualitatively higher than those from low irrigation plots during each of the three harvests (Fig. 30), although no valid significance level may be assigned. Grain yield at harvest was also qualitatively higher for the higher water level. There was no interactive response to soil temperature treatments and irrigation level for aboveground dry matter (Fig. 31) or grain yield (Fig. 32). The ratio of grain to aboveground dry matter yields was about 0.4 for each soil temperature treatment under low irrigation (Fig. 33). Under high irrigation this ratio was somewhat lower (0.34) for the straw treatment and higher (0.45) for the straw-plastic and plastic plots, although these values were not significantly different.

Root Depth Distribution

The minirhizotrons which were installed for root observations in both crops during 1987 proved to be unsatisfactory due to the presence of gaps at the interface between the soil and minirhizotron surface which allowed roots to proliferate and to grow down along the tubes. Root numbers with respect to depth are thus available only for 1988, when a trench profile method was used.

Root distribution data for 12 to 20 July, 1988 are presented in Figs. 34 to 39. The most obvious feature of these data is that plants
Fig. 28. Aboveground dry matter (g plant$^{-1}$) for corn during 1988, as a function of soil temperature treatment. Treatments having the same letter above bars are not significantly different (p < 0.05).

Fig. 29. Grain yield (g plant$^{-1}$) for corn during 1988, as a function of soil temperature treatment. Treatments having the same letter above bars are not significantly different (p < 0.05).
Fig. 30. Aboveground dry matter (g plant\(^{-1}\)) for corn during 1988, as a function of irrigation level.

Fig. 31. Corn aboveground dry matter yield (g plant\(^{-1}\)) during 1988, as a function of irrigation level and soil temperature treatment.
Fig. 32. Corn grain yield (g plant\(^{-1}\)) during 1988, as a function of irrigation level and soil temperature treatment.

Fig. 33. Ratio of grain yield to aboveground dry matter yield for corn during 1988.
Fig. 34. Proportion of total number of roots by depth during 12 to 20 July 1988, for straw mulch high irrigation treatment.

Fig. 35. Proportion of total number of roots by depth during 12 to 20 July 1988, for straw mulch low irrigation treatment.
Fig. 36. Proportion of total number of roots by depth during 12 to 20 July 1988, for straw-plastic mulch high irrigation treatment.

Fig. 37. Proportion of total number of roots by depth during 12 to 20 July 1988, for straw-plastic mulch low irrigation treatment.
Fig. 38. Proportion of total number of roots by depth during 12 to 20 July 1988, for plastic mulch high irrigation treatment.

Fig. 39. Proportion of total number of roots by depth during 12 to 20 July 1988, for plastic mulch low irrigation treatment.
under high irrigation generally had a larger proportion of roots at greater depth than did those under low irrigation in the same temperature treatment. Under low irrigation there was a much higher number of roots in the upper part of the soil profile for the straw treatment than in straw-plastic and plastic treatments. Root distributions were similar under high irrigation, with the proportion of deep roots increasing slightly in the order: plastic, straw-plastic, and straw.

During 23 to 31 August maximum rooting densities were again somewhat deeper under high than low irrigation (Figs. 40 to 45). For low irrigation the proportion of deep roots increased in the order: straw, straw-plastic, and plastic. Under high irrigation the deepest visible roots were in the plastic treatment, followed by straw and straw-plastic. Maximum rooting densities occurred at nearly 1 m depth during this interval, as compared to about 50 to 70 cm for the July sample.

The higher proportion of visible roots at depth under high irrigation during both sampling intervals supports the premise (Klepper et al. 1983) that root growth is enhanced by high soil water potentials, which are thought to provide low penetration resistances for root elongation and steep water potential gradients for rapid water flow into the cells of enlarging roots.

A consistent influence of soil temperature on rooting depth was apparent only under limited irrigation. This may be due to the timing of root distribution sampling, as soil temperature differences were dissipating by the time these samples were conducted (days 193 to 201...
Fig. 40. Proportion of total number of roots by depth during 23 to 31 August 1988, for straw mulch high irrigation treatment.

Fig. 41. Proportion of total number of roots by depth during 23 to 31 August 1988, for straw mulch low irrigation treatment.
Fig. 42. Proportion of total number of roots by depth during 23 to 31 August 1988, for straw-plastic mulch high irrigation treatment.

Fig. 43. Proportion of total number of roots by depth during 23 to 31 August 1988, for straw-plastic mulch low irrigation treatment.
Fig. 44. Proportion of total number of roots by depth during 23 to 31 August 1988, for plastic mulch high irrigation treatment.

Fig. 45. Proportion of total number of roots by depth during 23 to 31 August 1988, for plastic mulch low irrigation treatment.
and 235 to 243) (Figs. 13 to 16). Indeed, most of the observed differences in cumulative soil water depletion corresponding to soil temperature had occurred by about the time of the first root sampling session (see below). Soil temperature may also (or alternatively) have a secondary (to soil water status) influence on root growth, with a compensatory response evident only under limited soil water conditions.

Soil Water Use

Winter Wheat

Cumulative soil water depletion by 21 April, prior to the first irrigation, generally paralleled the soil temperature treatments (Fig. 46). The majority of soil water depletion during this period was above 60 cm depth (Fig. 47). By 8 June substantial depletion of soil water had progressed to nearly 2 m (Fig. 48). Cumulative depletion near the soil surface was less than that slightly deeper in the profile due to application of water by several irrigation events in the interim. Depletion of water still corresponded to soil temperature (Figs. 49, 50), with more depletion occurring under low irrigation (Figs. 49, 51). Cumulative evapotranspiration, as contrasted with soil water depletion, was greater under high irrigation, as more irrigation water was applied. Wheat plants in the lowest irrigation level headed out during late May; plants in these plots matured earlier than those in medium and high irrigation plots due to limited water availability. Plants in warmer plots were several days ahead of those in cooler plots in physiological development. As vegetative growth subsequently decreased
Fig. 46. Cumulative soil water depletion (cm) during 31 March to 21 April 1987, as a function of soil temperature treatment and irrigation level. Treatments having the same letter above bars are not significantly different (p < 0.05).

Fig. 47. Cumulative soil water depletion (cm) by depth during 31 March to 21 April 1987, as a function of soil temperature treatment.
Fig. 48. Cumulative soil water depletion (cm) by depth during 31 March to 8 June 1987, as a function of soil temperature treatment.

Fig. 49. Cumulative soil water depletion (cm) during 31 March to 8 June 1987, as a function of soil temperature treatment and irrigation level. Treatments having the same letter above bars are not significantly different (p < 0.05).
Fig. 50. Cumulative soil water depletion (cm) under winter wheat during 1987, as a function of soil temperature treatment. Treatments having the same letter above bars are not significantly different (p < 0.05).

Fig. 51. Cumulative soil water depletion (cm) under winter wheat during 1987, as a function of irrigation level.
in favor of grain filling, soil water use declined. Plants in the
cooler straw plots, and to a slightly lesser extent in control plots,
thus continued using soil water at a higher rate during mid- and late-
June than those in heat cable plots. By 30 June the relationship
between temperature treatments had changed for the low irrigation
level, with the straw plots having the highest cumulative water
depletion (Fig. 52), followed by heat cable, then control plots. The
relationship for the other two irrigation levels remained about the
same, as physiological maturity was delayed relative to the low water
plots. When summed over irrigation levels, cumulative depletion by 30
June still corresponded to increasing soil temperature (Fig. 50). The
lower irrigation plots again had higher cumulative water depletion by
this date than for medium and high water applications (Fig. 51), when
summed over temperature treatments.

As plants in medium and high irrigation treatments matured, the
same pattern developed as for the low irrigation plots. By final
harvest on 27 July the slower-developing plants in the coolest plots
had continued to use water longer than plants in warmer plots. As a
result of this the medium irrigation straw treatment overtook the
control treatment (Fig. 53) and plants in the high irrigation straw
treatment nearly caught up with those in control and heat cable plots,
which had similar cumulative water depletion. When averaged over the
irrigation treatments, plants in the cable and straw plots depleted
more soil water than those in control plots over the season (Fig. 50),
although this difference was quite small. As expected, seasonal soil
water depletion decreased with increasing irrigation (Fig. 51).
Fig. 52. Cumulative soil water depletion (cm) during 31 March to 30 June 1987, as a function of soil temperature treatment and irrigation level. Treatments having the same letter above bars are not significantly different (p < 0.05).

Fig. 53. Cumulative soil water depletion (cm) during 31 March to 27 July 1987, as a function of soil temperature treatment and irrigation level. Treatments having the same letter above bars are not significantly different (p < 0.05).
Depth of maximum soil water depletion, based on neutron moisture meter readings, increased during the season. For low irrigation treatments this depth ranged from 20 cm in early April to 140 or 160 cm by the end of July (Fig. 54), with maximum depletion from cable plots occurring somewhat deeper in the profile than for straw and control plots during much of this time. Depth of maximum depletion increased from 20 to 100 or 120 cm under medium irrigation (Fig. 55), with plants in straw treatments having slightly deeper values than for those in control plots. Maximum depletion under high irrigation progressed from 20 to 80 or 100 cm during the season (Fig. 56). Depletion was mostly similar between treatments until early June, after which time control and heat cable treatments had a maximum extraction depth about 20 cm deeper than for the straw treatment.

An approximately linear relation was evident between aboveground dry matter yield and evapotranspiration, and grain yield and evapotranspiration (Figs. 57, 58). This commonly observed relationship between yield and water use has been reviewed by Hanks (1983). He and several others have utilized this relationship for crop growth modeling.

**Corn**

Cumulative soil water depletion by corn during 1987 followed a pattern similar to that of the wheat crop. By 16 July cumulative depletion was higher for the warmer plastic treatment at all irrigation levels (Fig. 59); the difference between soil temperature treatments was greater under lower irrigation. This relation was also found by 4 August (Fig. 60). During mid-August reproductive growth began, causing
Fig. 54. Depth (cm) of maximum soil water depletion by winter wheat during 1987, under low irrigation, as a function of soil temperature treatment.

Fig. 55. Depth (cm) of maximum soil water depletion by winter wheat during 1987, under medium irrigation, as a function of soil temperature treatment.
Fig. 56. Depth (cm) of maximum soil water depletion by winter wheat during 1987, under high irrigation, as a function of soil temperature treatment.

Fig. 57. Relationship of aboveground dry matter yield (Mg ha\(^{-1}\)) to cumulative evapotranspiration (cm) for winter wheat during 1987, as a function of soil temperature treatment and irrigation level.
Fig. 58. Relationship of grain yield (Mg ha\(^{-1}\)) to cumulative evapotranspiration (cm) for winter wheat during 1987, as a function of soil temperature treatment and irrigation level.
Fig. 59. Cumulative soil water depletion (cm) during 5 to 16 July 1987, as a function of soil temperature treatment and irrigation level.

Fig. 60. Cumulative soil water depletion (cm) during 5 July to 4 August 1987, as a function of soil temperature treatment and irrigation level.
soil water use to decline. Plants in warm early-season soil treatments were several days ahead of those in cooler treatments. During the latter part of the season soil water use was higher in straw mulched treatments, particularly for medium and high irrigation. By 19 August cumulative soil water depletion was about equal under these higher irrigation levels (Fig. 61), and by 15 September was slightly higher for the straw treatments (Fig. 62). However, cumulative soil water depletion remained higher for the plastic treatment throughout the season under low irrigation.

When averaged over the three irrigation levels cumulative soil water depletion during 1987 was somewhat greater for warm (plastic-covered) plots by 16 July, 4 August, and 19 August (Fig. 63), although these differences were not significant. The two treatments were nearly equivalent in cumulative soil water depletion by 15 September.

Plants under high irrigation used more soil water than those receiving low and medium levels by 16 July (Fig. 64). This is probably due to more rapid initial growth under the most favorable soil water regime. By 4 August, however, corn in the low irrigation treatments had depleted more water than in medium and high. During the remainder of the season cumulative soil water depletion was highest under low irrigation, followed by medium, then high.

Cumulative soil water depletion was greater at depth for the warm soil treatment during the entire growing season (Figs. 65, 66, 67, 68), when averaged over all irrigation levels. This difference was greatest under low irrigation and decreased with increasing water application, as illustrated by Fig. 69. By 15 September little difference in
Fig. 61. Cumulative soil water depletion (cm) during 5 July to 19 August 1987, as a function of soil temperature treatment and irrigation level.

Fig. 62. Cumulative soil water depletion (cm) during 5 July to 15 September 1987, as a function of soil temperature treatment and irrigation level.
Fig. 63. Cumulative soil water depletion (cm) under corn during 1987, as a function of soil temperature treatment.

Fig. 64. Cumulative soil water depletion (cm) under corn during 1987, as a function of irrigation level.
Fig. 65. Cumulative soil water depletion (cm) by depth during 5 to 16 July 1987, as a function of soil temperature treatment.

Fig. 66. Cumulative soil water depletion (cm) by depth during 5 July to 4 August 1987, as a function of soil temperature treatment.
Fig. 67. Cumulative soil water depletion (cm) by depth during 5 July to 19 August 1987, as a function of soil temperature treatment.

Fig. 68. Cumulative soil water depletion (cm) by depth during 5 July to 15 September 1987, as a function of soil temperature treatment.
Fig. 69. Cumulative soil water depletion (cm) by depth during 5 July to 4 August 1987, as a function of soil temperature treatment and irrigation level.

Fig. 70. Cumulative soil water depletion (cm) by depth during 5 July to 15 September 1987, as a function of soil temperature treatment and irrigation level.
depletion with depth remained between temperature treatments under medium and high irrigation (Fig. 70), although water uptake at depth remained noticeably greater for plants in the warm plots under low irrigation. Depletion at depth was also greater under lower water application levels (Fig. 70), as plants were forced to utilize stored water deeper in the profile.

Depth of maximum soil water depletion (excluding nearest the soil surface following irrigations) was about 20 cm deeper for the warmer soil treatment under all irrigation levels during most of the season (Fig. 71). The depth of maximum soil water depletion increased during the season, from about 20 or 40 cm by 16 July to 120 cm by 15 September under low and medium irrigation, and from 20 or 40 cm on 16 July to 40 or 80 cm by 15 September under high irrigation.

The relation between aboveground dry matter yield and water use was approximately linear for this crop (Fig. 72), as noted above for wheat.

The substantial soil temperature differences during the early 1988 growing season that caused plants growing in warmer soil to develop and mature more rapidly than those in cool treatments resulted in more rapid use of soil water for these plants. Cumulative soil water depletion by 29 June (Fig. 73) corresponded closely to the number of fully developed leaves on 23 June (see Fig. 26), with plastic and straw-plastic treatments having greater depletion than for straw. Most of this water was removed from above about 1 m (Fig. 74), with the warmer soil treatments using notably more water from this part of the profile. There was no difference between the two irrigation levels in
Fig. 71. Depth (cm) of maximum soil water depletion by corn during 1987, as a function of soil temperature treatment and irrigation level. Values for straw low and straw medium are identical, as are those for plastic low and plastic medium.

Fig. 72. Relationship of aboveground dry matter yield (Mg ha⁻¹) to cumulative evapotranspiration (cm) for corn during 1987, as a function of soil temperature treatment and irrigation level.
Fig. 73. Cumulative soil water depletion (cm) during 1988, as a function of soil temperature treatment. Treatments having the same letter above bars are not significantly different (p < 0.05).

Fig. 74. Cumulative soil water depletion (cm) by depth during 20 to 29 June 1988, as a function of soil temperature treatment.
ater use by the soil temperature treatments during this period (Fig. 5). Warm soil treatments continued to use more water through 22 July (Fig. 73), depleting more water from the mid-profile (Fig. 76) than plants in straw plots. There was little difference in depletion by depth between irrigation levels by this date (Fig. 77). As plants approached maturity soil water use decreased. By 15 August there was no longer any difference in cumulative depletion (Fig. 73), and by 6 September the slower-developing plants in the straw treatment had overtaken those in warmer treatments, which were using little soil water by this time; this difference was not significant, however. The decrease in cumulative depletion values for plastic and straw-plastic treatments between 15 August and 6 September is due to irrigation exceeding evapotranspiration during this interval. This difference in water use by the end of the growing season was primarily under low irrigation (Fig. 78). There was little difference between temperature treatments in soil water depletion with depth by 6 September (Fig. 79), but low irrigation treatments depleted considerably more water at all depths to 2 m than for high irrigation (Fig. 80). Much of this difference in the top 80 cm or so is undoubtedly due to greater replenishment of water under high irrigation. Differences in depletion at greater depths, however, are a result of insufficient water nearer the top of the profile under low irrigation.

Although there was a higher proportion of visible roots at depth under high irrigation during both root sampling intervals (12 to 20 July, 23 to 31 August), plant water uptake was greater at depth under low irrigation. Root growth and water uptake therefore were not
Fig. 75. Cumulative soil water depletion (cm) during 20 to 29 June 1988, as a function of soil temperature treatment and irrigation level.

Fig. 76. Cumulative soil water depletion (cm) by depth during 20 June to 22 July 1988, as a function of soil temperature treatment.
Fig. 77. Cumulative soil water depletion (cm) by depth during 20 June to 22 July 1988, as a function of irrigation level.

Fig. 78. Cumulative soil water depletion (cm) during 20 June to 6 September 1988, as a function of soil temperature treatment and irrigation level.
Cumulative soil water depletion (cm) by depth during 20 June to 6 September 1988, as a function of soil temperature treatment.

Cumulative soil water depletion by depth during 20 June to 6 September 1988, as a function of irrigation level.

Fig. 79. Cumulative soil water depletion (cm) by depth during 20 June to 6 September 1988, as a function of soil temperature treatment.

Fig. 80. Cumulative soil water depletion (cm) by depth during 20 June to 6 September 1988, as a function of irrigation level.
directly related under these conditions, because irrigation water applied to the upper soil layers was preferentially utilized over water stored deeper in the soil. Taylor and Klepper (1975) found that roots at all depths were equally effective when compared at equivalent soil water contents and plant water potentials.

Cumulative soil water depletion under the two irrigation levels was very similar to that observed for wheat (Fig. 51) and corn during 1987 (Fig. 66). Depletion was greater under low irrigation by 22 July (Fig. 81), and remained so for the duration of the growing season.

Depth of maximum soil water depletion was 20 to 40 cm deeper for the warmer plastic and straw-plastic plots during most of the 1988 season under both irrigation levels (Fig. 82). Depth of maximum depletion increased during the season, from about 20 or 40 cm to 40 or 80 cm during late July, then back up to 40 cm by 6 September under high irrigation, and from 20 or 40 cm to 100 or 140 cm by mid-August for low irrigation. The abrupt decrease in this depth for low irrigation plots between mid-August and early September is due to a sizable irrigation during this interval. Other than this peak near the top of the profile, maximum soil water depletion during this interval was from 120 cm for the low irrigation straw treatment, and 200 cm for the corresponding straw-plastic and plastic treatments.

An incremental increase with time in the depth at which maximum water uptake occurs has been noted during drying cycles under non-irrigated conditions (Fernandez and Caldwell 1975), but is often not evident where water in the upper soil layers is periodically replenished by surface irrigation. Although depth of maximum soil
Fig. 81. Cumulative soil water depletion (cm) during 1988, as a function of irrigation level.

Fig. 82. Depth (cm) of maximum soil water depletion by corn during 1988, as a function of soil temperature treatment and irrigation level. Values for straw-plastic and plastic are identical at both irrigation levels.
water depletion increased during the season for these crops, maximum water uptake was probably greater near the soil surface during most of the season. Still, these data illustrate the same phenomenon. The modification of this downward progression by periodic surface water application is evident in the differences observed between the high irrigation level, particularly for the coolest soil treatment, and the low (and medium) water application treatment(s).

The relationships between aboveground dry matter yield and seasonal evapotranspiration (Fig. 83), and between grain yield and seasonal evapotranspiration (Fig. 84) were approximately linear, as for winter wheat and corn during 1987.

Computer Simulation Model

Calculated soil evaporation, transpiration, and cumulative changes in soil water content during a simulated growing season were similar for the SOWATET and SOWATMP models. When input data corresponding to the high irrigation straw mulch treatment during 1988 were used, cumulative transpiration was about 2 cm higher for the SOWATET model, while cumulative soil evaporation was lower by about the same amount (Fig. 85). Significant transpiration began somewhat earlier with SOWATET. This is probably due to differences in the root growth algorithms. The time-dependent functions used for calculating rooting depth are similar for both models. The SOWATMP model characterizes the time-dependent increase of root length density in each layer by a sigmoid function (Eqs. [29] and [30], Fig. 5), while the SOWATET model assigns relative root mass by depth proportionally to the RDFSAV array
Fig. 83. Relationship of aboveground dry matter yield (g plant$^{-1}$) to cumulative evapotranspiration (cm) for corn during 1988, as a function of soil temperature treatment and irrigation level.

Fig. 84. Relationship of grain yield (g plant$^{-1}$) to cumulative evapotranspiration (cm) for corn during 1988, as a function of soil temperature treatment and irrigation level.
as soon as rooting depth reaches each layer. This results in a lag between the time rooting depth reaches a given soil layer and the time significant root length density development begins in that layer in SOWATMP compared to SOWATET. Cumulative change in soil water content for SOWATMP also lagged slightly behind that predicted by SOWATET during the early season (Fig. 86), although this relation became reversed by the end of the season. Results were similar for simulated straw mulch low irrigation conditions (Fig. 87).

The SOWATMP model, unlike SOWATET, does not specify water flow into roots only. This results in calculated efflux of water from roots into dry soil layers under some conditions, in accordance with water potential gradients, hydraulic conductivities, and root radial resistance to water flow. Because the top soil layer is allowed to dry down to air dry in both models, some simulated root exudation occurs into this layer with the SOWATMP model. This additional water is then available for direct evaporation from the soil surface, resulting in somewhat higher values for Es (Fig. 85). This phenomenon has been demonstrated for both crop and native plant species (Baker and van Bavel 1986, 1988; Richards and Caldwell 1987), but its magnitude under normal conditions is thought to be fairly minor. No roots are allowed in the top soil layer in either model because it is the top boundary in the numerical procedure for calculating water flow, and is subject to instantaneous changes. A small depth increment is therefore generally used for the uppermost layer, with subsequent layers being substantially larger. When simulations were initially run using a 0.5 cm top depth increment, calculated values for soil evaporation for
Tr SOWATET
Tr SOWATMP
Es SOWATET
Es SOWATMP

Fig. 85. Cumulative evaporation and transpiration as predicted by models SOWATET and SOWATMP for the high irrigation, straw mulch treatment.

Fig. 86. Cumulative change in soil water content as predicted by models SOWATET and SOWATMP for the high irrigation, straw mulch treatment.
SOWATMP were found to be too high. This is because the small top soil layer quickly dried down to air dry, generating very large water potential gradients between it and deeper relatively moist soil layers. Although hydraulic conductivities at near-air dry water contents are very low, only a relatively small amount of water flow into this narrow layer was enough to significantly raise its volumetric water content and hence conductivity to additional water influx. Changing the depth of the top layer to about 2 or 3 cm resolved the problem and generated results closer to those of the original model.

The plant water uptake algorithm used in the modified computer model is more process-oriented than is the approach used in the original SOWATET model. The SOWATMP model also calculates plant leaf water potential, which may be useful in routines for estimating growth reduction due to plant water stress. A potential disadvantage is that the additional input data required are less readily available. It is generally easier to provide good estimates of relative root mass by depth than actual root length densities, although representative values of the latter parameter are becoming more available for many crops (Mengel and Barber 1974, McGowan et al. 1984, Belford et al. 1987). Estimates of leaf (RL) and total root (RR) resistances will probably come from the literature also, although the procedure and instrumentation for obtaining these values is available in many plant and soils laboratories. Total root resistance is probably one of the most difficult parameters to obtain with reasonable certainty. The value of RR used in these simulations was similar to, though slightly higher than, that given by Campbell (1985). Fortunately, the model
Fig. 87. Cumulative evaporation and transpiration as predicted by models SOWATET and SOWATMP for the low irrigation, straw mulch treatment.

Fig. 88. Cumulative transpiration as a function of different values for root resistance (RR), as predicted by model SOWATMP. Simulated conditions were for the low irrigation, straw mulch treatment, using values for RR of 80, 100, and 120 thousand (h).
does not appear to be particularly sensitive to the value of this parameter (Fig. 88).

An approximately linear relative growth function was initially chosen during development and testing of the soil temperature-plant growth algorithms. This relation was found not to have sufficient influence on early season soil water uptake due to the sigmoid or sinusoidal nature of aboveground and belowground plant growth parameters. A sinusoidal relative growth function was then adopted (Fig. 2). In addition to being more satisfactory relative to physiological considerations, this function provided results closer to those found in the field. Because of this shape, however, the relative growth function is fairly sensitive to the interval between values chosen for TOPT and TMIN. The inhibiting influence of the relative growth parameter at a given soil temperature becomes stronger as the spread between these parameters is narrowed. Fig. 89 illustrates the effect on simulated cumulative transpiration brought about by changing the value of TMIN while maintaining TOPT constant at 28°C. Values of 9 and 28°C for TMIN and TOPT, respectively were found to be satisfactory in simulations of field conditions. These agree closely with those calculated by Allmaras et al. (1964) for corn in the Northern Corn Belt of the United States.

Simulated cumulative change in soil water content under straw and plastic mulches, for high irrigation, agreed well with field observations (Fig. 90). The magnitude of the difference due to soil temperature treatments was realistic, as were the actual values during much of the simulation. The match became poorer near the end of the
Fig. 89. Cumulative transpiration as a function of different values for TMIN (°C), as predicted by model SOWATMP. Simulated conditions were for the low irrigation, straw mulch treatment, with TOPT held constant at 28°C.

Fig. 90. Comparison of field measurements and model SOWATMP predictions of cumulative change in soil water content, for high irrigation, straw and plastic mulch treatments. F and M are field and model, respectively, and Pl and St indicate plastic and straw mulch.
simulation, because errors and uncertainties accumulated. Results were similar under low irrigation (Fig. 91). The model did not predict the crossover in field measurements at about 2000 h. This may be because the model does not explicitly simulate plant responses to water stress, although the actual reason is not known.

One practical aspect of using computer simulation models which is often overlooked is that when predictions and actual measurements do not agree, one is obliged to examine the possible reasons. Aside from being a valuable intellectual exercise this may occasionally bring previously overlooked attributes of the measurements under scrutiny. When differences in measured and simulated cumulative changes in water content were initially compared it became apparent that there were substantial differences in measured versus predicted soil water recharge between plastic and straw mulch treatments following many irrigation events. This was particularly true for the low irrigation level. It was concluded that the straw mulch may have acted as a "sponge", absorbing a portion of the applied water before becoming saturated. This would have had a relatively greater influence under low irrigation, where less water was applied each time. After adjustments were made to account for these differences, a better fit was obtained with the simulations. Although this adjustment is speculative, the underlying assumption would serve to bring the ratios of both aboveground dry matter and grain yields to evapotranspiration, for the straw mulch-low irrigation treatment, closer in line with those of the other treatments (Figs. 83 and 84).
Fig. 91. Comparison of field measurements and model SOWATMP predictions of cumulative change in soil water content, for low irrigation, straw and plastic mulch treatments. F and M are field and model, respectively, and Pl and St indicate plastic and straw mulch.

Fig. 92. Comparison of measured and predicted volumetric soil water content at 20 and 40 cm. Simulated conditions were for the low irrigation, plastic mulch treatment. F and M are field and model, respectively, and numbers refer to soil depth.
Fig. 93. Comparison of measured and predicted volumetric soil water content at 60 and 80 cm. Simulated conditions were for the low irrigation, plastic mulch treatment. F and M are field and model, respectively, and numbers refer to soil depth.

Fig. 94. Comparison of measured and predicted volumetric soil water content at 100 and 120 cm. Simulated conditions were for the low irrigation, plastic mulch treatment. F and M are field and model, respectively, and numbers refer to soil depth.
Simulated and measured water content by depth as a function of time agreed reasonably well (Figs. 92, 93, 94). The fit between simulated and measured values was poorest at high water contents, including measurements made following irrigation events. This may be due to any combination of several factors. Some of the most likely sources of error are in the assumed beginning soil water contents, irrigation and rainfall amounts, and in the water content-water potential relation near "field capacity". Simulations using smaller depth increments might also reduce these discrepancies. Soil layer boundary depths of 0, 3, 10, 20, 40, 60, ... cm were used for these comparisons.

Because of the simplifying assumptions used in computer simulation models, the complicated interrelationships between the various component processes, and the uncertainty in values provided for input, undue levels of precision should not be attributed to simulation results. Several factors contributed to decreased precision in the simulations conducted as part of this investigation. Irrigation and precipitation amounts varied spatially, and the amount of applied water that infiltrated into the soil through the surface mulches at each location is not known. The models assume that the soil profile is homogeneous; specifically that the water content-water potential and water content-hydraulic conductivity relations apply to the entire soil volume. This is not the case at the field site, particularly where a lens of relatively coarse soil occurs below about 1.4 m. Values used for potential evapotranspiration were 5-day means of daily values calculated by a Penman combination equation (Penman 1963). The values
for plant growth parameters (i.e. ESTART, ESTOP, RSTART, RDFDAY) were estimates based on field observations. Soil water content by depth at planting (when the simulations begin) were estimated rather than measured. All these factors contribute to uncertainty in the model outputs. Both models contain enough "judgement variables" that almost all discrepancies between observed and simulated responses can be minimized or eliminated through continuous "tweaking". This is a dubious practice if carried too far, however, as one can not be certain of the accuracy of the changes so made. Rather than comparing the absolute values of differences in simulated and field data, the pattern and relative magnitude of changes in model output in response to varied input conditions were taken as indicative of their efficacy.

If the modified soil-plant-atmosphere model may be considered to adequately account for 10 cm soil temperature influences on early plant growth, predictions can be made of responses to hypothetical soil temperature conditions. Although field soil temperatures are dynamic, assuming constant temperatures permits greater clarity of interpretation. Simulations were made for straw mulch low irrigation conditions using the same values for the various plant and soil parameters as assumed in the previous simulations, with different constant 10 cm soil temperatures. Predicted cumulative transpiration decreased with decreasing soil temperature (Fig. 95), in accordance with the severity of the inhibition of the relative growth parameter. This response was more pronounced as soil temperatures approached TMIN. A similar response was noted in predicted cumulative change in soil water content (Fig. 96).
Fig. 95. Cumulative transpiration as predicted by model SOWATMP for different levels of constant 10 cm soil temperature. Simulated conditions were for the low irrigation, straw mulch treatment.

Fig. 96. Cumulative change in soil water content as predicted by model SOWATMP for different levels of constant 10 cm soil temperature. Simulated conditions were for the low irrigation, straw mulch treatment.
The SOWATMP model appears to adequately simulate both the pattern and magnitude of soil-plant-atmosphere water dynamics in response to 10 cm soil temperature. Simulations using the model indicated that changes in plant water uptake were relatively minor unless soil temperature differences were fairly large, or until soil temperatures approached the minimum value for plant growth. These conclusions agree with measured field data. Because of the apparently linear relation between cumulative soil water use and plant dry matter yield (de Wit 1958, Hanks 1983), similar interpretations may be made for plant growth and yield, which is in further agreement with results of the field investigations conducted during 1987 and 1988.

Although the revised model was written and tested in a compiled BASIC language (QuickBASIC, Microsoft Corp.), line numbers have been retained and advanced functions not available in standard GWBASIC have not been utilized. This should enable the model to be run on any IBM-compatible PC-class or higher computer. Time of execution, which varies with the number of soil layers, the number of top boundary changes, and with several other factors, has not been significantly increased by inclusion of the soil temperature-related algorithms.

Summary

Because of the high thermal mass of soil, altering field soil temperature regimes was found to be difficult. Although heat cables were able to increase soil temperatures somewhat, surface mulches were more effective. Even so, unless these treatments were applied several weeks prior to planting the temperature differences observed were not
very great. A disadvantage of the surface mulches, which relied on solar radiation for their effectiveness, was that their influence declined as crops matured and shaded the (mulched) soil surface. This allowed soil temperatures at a given depth to converge to similar values within a few weeks. Irrigation events also resulted in soil cooling and helped equilibrate temperatures between treatments.

During 1987 crop yields were mainly influenced by irrigation level, although there were some differences due to soil temperature within irrigation levels for the winter wheat. The warmest soil treatment had the higher yields where significant differences did occur. Yields of both crops responded to increased irrigation. During 1988 surface mulches were applied about five weeks prior to planting. Greater soil temperature differences were achieved, and significant differences in crop growth were noted between temperature treatments throughout the season. Differences in aboveground dry matter and grain yields due to irrigation were also evident during 1988. Yields were higher for the high water application level.

Depth of visible roots during 1988 was somewhat greater under high than low irrigation. Maximum number of roots was at about 50 to 70 cm during 12 to 20 July, and about 1 m during 23 to 31 August.

Soil water extraction corresponded to soil temperature treatments for all crops during the early part of the growing seasons, with more water depleted in warmer plots. Plants in warm soils matured earlier, as did those under the lowest of three irrigation levels during 1987. Water uptake rates of earlier-maturing plants were reduced during the latter part of the growing season. Cumulative water depletion by
plants in the coolest plots, which continued to use water longer, equalled that of warmer plots by the end of the season. Soil water depletion was highest by the end of the season for all crops under low, then medium (where applicable) irrigation.

Extraction of stored soil water during the growing season was influenced by irrigation level, with extraction occurring to deeper depths under lower levels of water application. This was more apparent during 1987 when greater differences in water application were used. The depth at which maximum soil water uptake occurred was generally somewhat deeper for plants in warmer soils during most of the growing season, for both winter wheat and corn.

The crop yield and water use relations during both years were consistent with the approximately linear relationship that has been noted by other researchers.

Modifications were made to the SOWATET soil-plant-atmosphere model to include soil temperature influences on plant water use. Simulation results were consistent with field observations.
CONCLUSIONS

The early growth responses to differences in soil temperature observed in these experiments were consistent with those found previously under both controlled-environment and field conditions. Based on the conditions in these investigations, final aboveground dry matter and grain yields will not be decreased for winter wheat and corn plants whose early growth is delayed by low soil temperatures unless soil temperature differences are relatively large. This may not be true in areas with shorter growing seasons or where planting has been delayed.

Depletion of soil water was lower for plants growing in cooler soils. Depth of maximum water extraction was about 20 cm deeper in warmer soils during most of the growing season. This response should be taken into account when estimating the volume of the active rooting zone for irrigation planning or other purposes.

The relationship between cumulative evapotranspiration and yield of winter wheat and corn was approximately linear for all treatment combinations. This indicates a simple plant growth response to soil temperature, with no significant alteration of water use efficiency.

Because no interactive response of soil water depletion or plant growth and yield to soil temperature and irrigation levels was observed, the above conclusions should be valid over a fairly wide range of soil temperature and water application levels. The extent of these conditions should include as a minimum the ranges of soil
temperatures and water application which were utilized during these field experiments.

Problems were encountered with the minirhizotron method of monitoring root growth. The trench-profile method used during 1988 was time-consuming and destructive to treatment plots. This limited the number of occasions during the season when rooting data could be obtained. Advances in knowledge of plant root responses to their environment based on field observations will continue to be limited until more suitable methods are found for continuous and non-destructive belowground monitoring.

The SOWATMP model adequately simulated both the pattern and magnitude of soil-plant-atmosphere water dynamics in response to 10 cm soil temperature. The simulated responses were consistent with field observations and measurements during 1987 and 1988. This model should be useful for predicting soil water depletion by plants in situations where near-surface soil temperatures limit plant growth.
REFERENCES


APPENDICES

Model Listing with Sample Input
Appendix A

Model Listing With Sample Input
REM SOWATMP.BAS MODEL
JOT-< M. WRAITH

SOWATET.BAS SOIL WATER FLOW MODEL (R. J. HANKS), WITH MODIFIED ROOT WATER UPTAKE, AND SOIL TEMPERATURE-DEPENDENT PLANT GROWTH.

FORMAT OF INPUT FILE

First line: LABEL$

Next line: K, IER, NB, ND,KI, KCPMAX

Next line(s): V array (pot. surface flux)

Next line(s): DD array (depth of soil layer boundaries)

Next line(s): P array (matric head)

Next line(s): E array (hydraulic conductivity)

Next line(s): W array (beg. water content)

Next line: DETT, CONO, TAA, TIME, TT, CUMT

Next line(s): V array (potential surface flux)

Next line(s): DO array (depth of soil layer boundaries)

Next line(s): P array (matric head)

Next line(s): E array (hydraulic conductivity)

Next line: W array (beginning water content)

Next line: DETT, CONO, TAA, TIME, TT, CUMT

Next line(s): V array (potential surface flux)

Next line(s): DO array (depth of soil layer boundaries)

Next line(s): P array (matric head)

Next line(s): E array (hydraulic conductivity)

Next line(s): W array (beginning water content)

Next line: DE TETT, CONO, TAA, TIME, TT, CUMT

Next line(s): V array (potential surface flux)

Next line(s): DO array (depth of soil layer boundaries)

Next line(s): P array (matric head)

Next line(s): E array (hydraulic conductivity)

Next line(s): W array (beginning water content)

BEGIN MODEL

DIM A(30), B(30), C(30), F(60), DD(30), V(120), P(55), E(55), W(30), D(60)
DIM T(55), H(30), L(30), ND(30), STEMP(60), RR(30), RO(30), RS(30)
DIM UPRATE(30), BZ(30), UPR(30), RSTART(30), DEP(30), DROPT(450)
DIM DTIME(450), T2(30), RDOPT(30, 450), RTIME(30, 450), DT(30), DT(30)
DIM V1OPT(450), V1TIME(450), AK5(30)
DEFINT I-N
CLS
INPUT "ENTER DATAFILE NAME (NO EXTENSION)"; INFIL$
INFIL1$ = INFIL$ + " DAT": OPEN INFIL1$ FOR INPUT AS #1
OUTFIL2$ = INFIL$ + " WC": OPEN OUTFIL2$ FOR OUTPUT AS #2
OUTFIL3$ = INFIL$ + " FLX": OPEN OUTFIL3$ FOR OUTPUT AS #3
CLS
GO TO 1000
1000 REM *********************************************************************
1010 REM ****************** READ DATA AND INITIALIZING VARIABLES **************
1020 REM
1030 REM LINE INPUT #1, LABEL$
1040 REM" ENTER DATAFILE NAME (NO EXTENSION)"; INFIL$
1050 REM INFIL1$ = INFIL$ + " DAT": OPEN INFIL1$ FOR INPUT AS #1
1060 REM OUTFIL2$ = INFIL$ + " WC": OPEN OUTFIL2$ FOR OUTPUT AS #2
1070 REM OUTFIL3$ = INFIL$ + " FLX": OPEN OUTFIL3$ FOR OUTPUT AS #3
1080 REM
1090 REM *********************************************************************
1100 REM ****************** CHECKING DATA AND INITIALIZING VARIABLES *************
1110 REM
1120 REM
1130 REM FOR I = 1 TO IER: INPUT #1, V(I): NEXT I
1140 REM FOR I = 1 TO KK: INPUT #1, DD(I): NEXT I
1150 REM FOR I = 1 TO ND: INPUT #1, P(I): NEXT I
1160 REM FOR I = 1 TO ND: INPUT #1, E(I): NEXT I
1170 REM
1100 FOR I = 1 TO KK: INPUT #1, W(I): NEXT I
1110 INPUT #1, DETT, CONQ, TAA, TIME, TT, CUMT
1120 IF TAA < 1 THEN ITAA = 0
1130 IF TAA >= 1 THEN ITAA = 1
1140 INPUT #1, HDRY, HMET, WATL, WATH, HLOW, DELW
1150 INPUT #1, RDFDAY, RDFDEL, ESTART, ESTOP, AK1, AK2, RRES, HH1
1160 FOR I = 1 TO KK: INPUT #1, RLD(I): NEXT I
1170 FOR I = 1 TO IER / 2: INPUT #1, STEP(I): NEXT I
1180 INPUT #1, RSTART, RMMAX, TMIN, TOPT, STDAY, RR, RL, R1, RC, SP
1190 CLOSE #1
1200 DD(0) = 0
1210 AK4 = (1 - .99) / .99 * EXP(8.5)
1220 D(I) = (E(I) * (P(2) - P(1)))
1230 T(I) = 0
1240 FOR I = 2 TO ND
1250 D(I) = E(I) * (P(I) - P(I - 1)) + D(I - 1) 'Summed diffusivity by depth (K * matric head)
1260 T(I) = DELW + T(I - 1) 'Water content by depth (cm)
1270 NEXT I
1280 KC = 1: RC = 1: LL = 1: PI = 3.14159
1290 PLXDEL = .01
1300 RDDEL = RDFDEL
1310 HRDRT = HLOW: CWFLX = 0: DELT = DETT
1320 TM = 1 - TT: TBB = 1 - TAA: YMAX = WATH
1330 RUNOF = 0: CUMS = 0: MYTIME = 0: RP1 = 0: CUMB = 0
1340 CUMB = 0: IRDF = 0: EVAP = 0: SIR = 0: CTRAN = 0
1350 FOR I = 1 TO K: RSTART(I) = 0: NEXT I
1360 ESTOP(0) = ESTOP
1370 J = INT((W(I) - T(I)) / DELW) + 1
1380 H(I) = (P(J + 1) - P(J)) * (W(I) - T(J)) / DELW + P(J)
1390 G(I) = H(I)
1400 C(I) = DELW / (P(J + 1) - P(J))
1410 FOR I = 2 TO KK
1420 J = INT((W(I) - T(I)) / DELW) + 1
1430 H(I) = (P(J + 1) - P(J)) * (W(I) - T(J)) / DELW + P(J) 'Beg. matric head profile
1440 C(I) = DELW / (P(J + 1) - P(J)) 'Water capacity profile
1450 G(I) = H(I)
1460 NEXT I
1470 PII = 0
1480 FOR I = 2 TO K
1490 PII = PII + (W(I) * (DD(I + 1) - DD(I - 1)) / 2) 'Calculate water depth in profile
1500 NEXT I
1510 RETURN
2000 REM ***************************************************
2010 REM ** PRINT OUT INPUT DATA AND CALCULATED VARIABLES **
2020 REM
2030 'PRINT #2, LABELS, DATES, TIMES
2040 'PRINT #2, " K IER NB ND KCMAX"
2050 'PRINT #2, USING "###"; K; IER; NB; ND; KCMAX
2060 'PRINT #2, "WAT CONT MAT HEAD CONDUCT; DIFFUSIV WAT CONT MAT HEAD CONDUCT; DIFFUSIV"
2070 'NE = ND / 2
2080 FOR I = 1 TO NE
2090 I = NE + I
2100 'PRINT #2, USING "######"; T(I); P(I); E(I); D(I); T(J); P(J); E(J); D(J)
2110 NEXT I
2120 'PRINT #2, " DEPTH W_CAP W-DEPTH H-DEPTH"
2130 FOR I = 1 TO KK
2140 IF I = 1 THEN 2160
2150 'PRINT #2, USING "#########"; DD(I); C(I); W(I); H(I)
2160 Y(I) = W(I)
2170 NEXT I
2180 'PRINT #2, " TIME FLUX" 
2190 FOR I = 2 TO IER STEP 2
2200 'PRINT #2, USING "######"; V(I), V(I - 1)
2210 NEXT I
2220 WFD = V(1)
2230 EOR = V(1)
2240 'PRINT #2, " DETT CONQ TAA TIME TT CUMT DELW"
2250 'PRINT #2, USING "###.###.###"; DETT; CONQ; TAA; TIME; TT; CUMT; DELW
2260 'PRINT #2, " HDRT WATL WATH ATW LLOW HH1"
2270 'PRINT #2, USING "###.###.###"; HDRT; WATL; WATH; ATW; LLOW; HH1
2280 'PRINT #2, " RDFDAY RDFDEL ESTAR ESTOP AK1 AK2"
2290 'PRINT #2, USING "###.###.###"; RDFDAY; RDFDEL; ESTAR; ESTOP; AK1; AK2
2300 CIC = 1
2310 HROR = G(2)
2320 'PRINT #2, " TIME SINK ETPL TRAN EVAP PSI-LEAF CFW "
2330 'PRINT " TIME WATBA WATU ETPL TRAN EVAP PSI-LEAF CFW "
2340 VIEW PRINT 3 TO 25
2350 RETURN
3000 REM **************************** PLANT COVER GROWTH LOOP *************************
3010 REM **************************** PLANT COVER GROWTH LOOP *************************
3020 ' 
3030 IF TIME < PLXDEL AND TBCHANGE <> 0 THEN RETURN 'if not time to update
3040 FOR I = 2 TO IER STEP 2 'Find correct position in V array
3050 IF V(I) > TIME THEN 3070
3060 NEXT I
3070 IF V(I) / 2
3080 GR1 = .5 * SIN(P) / (TOPT - TMIN) * (STEMP(IR) - 2 * TMIN) 'Rel. growth
3090 GR = ((GR * TIME) + (GR * DELT)) / (TIME + DELT) 'Weighted mean rel growth
3100 PLXDEL = PLXDEL + RDFDEL
3110 IF TIME < ESTAR AND TBCHANGE <> 0 THEN RETURN 'if not yet ESTAR
3120 IF V(I - 1) < 0 THEN 3160 'If pot. ET at top boundary
3130 IF V(I) = 0: V1 = V(I - 1) 'If infiltration at top: ETp = 0,
3140 IF V(I) > TIME THEN 3170 'If hardly any roots yet, ETp = Ep
3160 GOTO 3380
3170 IF TIME / 24 < ESTAR THEN 3370 'if plant growth not yet started
3180 IF DROOT + DD(2) THEN 3370 'if hardly any roots yet, ETp = Ep
3190 IF V(I) = 0 THEN 3170 'if hardly any roots yet, ETp = Ep
3200 IF TIME / 24 > STDAY THEN 3260 'If infiltration at top: ETp = 0,
3210 IF TP = TP / 2
3220 'time counter for V1 and V1OPT()
3230 V1 = TET - GR * TET * AK1 / (1 + EXP(6 - AK3 * (TIME - ESTAR * 24)))
3240 V1OPT(TP) = TET - TET * AK1 / (1 + EXP(6 - AK3 * (TIME - ESTAR * 24)))
3250 VTIME(TP) = TIME
3260 GOTO 3380
3270 IF PT1 = 1 THEN 3340 'if PT has already been calculated
3280 NLO = 1: NWI = TP
3290 WHILE NWI - NLO > 1 'find correct position in V1OPT() by bisection
3300 N = INT(NHWI) + NLO / 2
3310 IF V1OPT(N) > V1 THEN NWI = N ELSE NLO = N
3320 WEND
3330 PT = TIME - VTIME(NLO) 'time "lost" due to suboptimal soil temperature
3340 N = 1
3350 IF V1OPT(N) > V1 THEN NWI = N ELSE NLO = N
3360 GOTO 3380
3370 V1 = TET 'Pot. E = Pot. ET
3380 RETURN
4000 REM **************************** ROOT GROWTH LOOP *****************************
4010 REM **************************** ROOT GROWTH LOOP *****************************
4020 IF RDMA = 1 THEN RETURN 'if roots already mature
4030 IF TIME / 24 < RSTART THEN RETURN 'if root growth has not started.
4040 RDSSUM = 0
4050 IF ABS(RDFDEL) < .000001 THEN 4650 'sets roots at max immediately.
4060 IF TIME < RDFDEL THEN RETURN 'if not time to update yet.
4070 RDFDEL = RDFDEL + RDFDEL
4080 IF TIME / 24 > STDAY THEN 4160 ' 
4090 '****** Rooting Depth Algorithm *****
4100 TD = TD + 1 'time counter for DROOT() and DTIME()
4110 'GR = SIN(PI / 2 * (STEMP(IR) - TMIN) / (TOPT - TMIN)) 'Relative growth function
4120 DROOT = GR * RDMA * (.5 * .5 * SIN(3.03 * ((TIME / 24 - RSTART) / (RDFDAY - RSTART)))) -
1.47)

4130 DROPT(DT) = RDMAX * (.5 + .5 * SIN(3.03 * ((TIME / 24 - RSTART) / (RDFDAY - RSTART)) - 1.47))

4140 DTIME(DT) = TIME

4160 IF DT1 = 1 THEN 4240 'if already calculated DT, skip

4170 NLO = 1: NHI = TD

4180 WHILE NHI - NLO > 1 'find correct position in DROPT() by bisection

4190 N = INT((NHI + NLO) / 2)

4200 IF DROPT(N) > DROOT THEN NHI = N ELSE NLO = N

4210 WEND

4220 DT = TIME - DTIME(NHI) 'time "lost" due to suboptimal soil temperature

4230 DT1 = 1

4240 IF TIME > 24 * RDFDAY + DT THEN 4270 'skip if DROOT already = RDMAX

4250 DROOT = RDMAX * (.5 + .5 * SIN(3.03 * ((TIME - DT) / 24 - RSTART) / (ROFOAY - RSTART) - 1.47))

4260 **** Root Length Density Algorithm ****

4270 FOR I = 1 TO K

4290 IF RLO(I) = 0 THEN 4490 'skip if no roots in layer.

4300 IF RSTART(I) <> 0 THEN 4490

4310 IF DROOT >= DD(I) THEN RSTART(I) = TIME ELSE 4490 'if calculated RSTART previously.

4320 AK5(I) = 8.5 / (ROFOAY - RSTART(I))

4330 IF TIME / 24 > STDAY THEN 4390 'time root growth starts

4340 T2(I) = T2(I) + 1 'time counter for DROPT() and RDTIME()

4350 RD(I) = GR * RLO(I) / (1 + AK4 * EXP(-(AK5(I) * (TIME - RSTART(I)) / 24))

4360 RDOPT(I, T2(I)) = RLO(I) / (1 + AK4 * EXP(-(AK5(I) * (TIME - RSTART(I)) / 24))

4370 RDTIME(I, T2(I)) = TIME

4380 GOTO 4490

4390 IF DT1(I) = 1 THEN 4480 'if already calculated DT(), skip

4400 NLO = 1: NHI = T2(I) 'calculate DT()

4410 WHILE NHI - NLO > 1 'find correct position in DROPT() by bisection

4420 N = INT((NHI + NLO) / 2)

4430 IF DROPT(N, N) > RD(I) THEN NHI = N ELSE NLO = N

4440 WEND

4450 DT(I) = TIME - RDTIME(I, NHI) 'time "lost" due to suboptimal soil temperature

4460 IF NHI < 3 THEN DT(I) = DT(I - 1): GOTO 4470 'if RROOT reaches DD(I) after STDAY

4470 DT1(I) = 1

4480 RD(I) = RLO(I) / (1 + AK4 * EXP(-(AK5(I) * (TIME - DT(I) - RSTART(I)) / 24))

4490 NEXT I

4500 '**** Calculation of Root Resistances and Root Density Factors ****

4520 FOR I = 1 TO K: RDSUM = RDSUM + RD(I): NEXT

4530 FOR I = 1 TO K

4540 IF RLD(I) = 0 THEN 4600 'sets RD() to RLD() immediately

4550 IF RSTART(I) = 0 THEN 4600

4560 IF RD(I) < 5E-10 THEN 4600

4570 RR(I) = RR * RDSUM / RD(I)

4580 BZ(I) = -1 * LOG(PI * R1 * R1 * RD(I)) / (2 * PI * RD(I) * (DD(I + 1) - DD(I - 1)))

4590 GOTO 4620

4600 RR(I) = 2.793E+18

4610 BZ(I) = 0

4620 NEXT I

4630 RETURN

4640 FOR case of non-growing roots ("instantly" at maximum development) ****

4650 FOR I = 1 TO K: RDSUM = RDSUM + RLD(I): NEXT

4660 FOR I = 1 TO K

4670 RD(I) = RLD(I)

4680 IF RLD(I) = 0 THEN GOTO 4720

4690 RR(I) = RR * RDSUM / RD(I)

4700 BZ(I) = -1 * LOG(PI * R1 * R1 * RD(I)) / (2 * PI * RD(I) * (DD(I + 1) - DD(I - 1)))

4710 GOTO 4740

4720 RR(I) = 2.793E+18

4730 BZ(I) = 0

4740 NEXT I

4750 RMAT = 1 'set root maturity pointer so don't need to recalc RD()
4760 RETURN

5000 REM ******************************************
5010 REM ********** COMPUTATION OF CONDUCTIVITY (B) AND WATER CAPACITY (C) *****
5020 BOT = WATL
5030 TOP = WATH
5040 HKP = HI
5050 WP = W(J)
5060 IF EOR > 0 THEN 5100
5070 W(J) = WATL
5080 H(J) = HDY
5090 GOTO 5120
5100 W(J) = WATL
5110 H(J) = HWET
5120 TWW = (W(J) + Y(J)) * .5
5130 IF (TWW > WATH) THEN TWW = WATH
5140 J = INT((TWW - T(J)) / DELW) + 1
5150 BB = (TWW - T(J)) / DELW
5160 DIFFB = (D(J) - D(J)) * BB + D(J)
5170 HI = (P(J + 1) - P(J)) * BB + P(J)
5180 FOR I = 1 TO K
5190 TW = (W(I) + Y(I)) * .5
5200 J = INT((TW - T(J)) / DELW) + 1
5210 BB = (TW - T(J)) / DELW
5220 DIFFB = (D(J) - D(J)) * BB + D(J)
5230 GI = (P(J + 1) - P(J)) * BB + P(J)
5240 IF ABS(HI - GI) < .0001 THEN 5590
5250 B(I) = (DIFFB - DIFFB) / (HI - GI)
5260 IF I > 1 THEN 5610
5270 ER = (B(I) * (H(I) - TT - H(I)) * TT - G(I) * TM + G(I) * TM + DD(2)) / DD(2)
5280 IF ABS(ER) > ABS(EOR) THEN 5300
5290 IF H(I) = HWET OR H(I) = HDY THEN 5610
5300 IF ABS(1 * EOR - ER) - ABS(1 * EOR) = 0 THEN 5530
5310 IF KCK = 1 THEN 5370
5320 IF KCK < 12 THEN 5410
5330 H(I) = (EOR - DD (2)) / B(I) + H(I) * (TT - G(I) * TM + G(I) * TM + DD (2)) / TT
5340 IF H(I) > HDY THEN H(I) = HDY
5350 IF H(I) > HWET THEN H(I) = HWET
5360 GOTO 5610
5370 H(I) = HKP
5380 W(I) = WP
5390 KCK = KCK + 1
5400 GOTO 5120
5410 KCK = KCK + 1
5420 IF ER = EOR THEN 5610 ELSE IF ER > EOR THEN 5470
5430 IF W(I) = WATH THEN 5610
5440 BOT = W(I)
5450 W(I) = (W(I) + TOP) * .5
5460 GOTO 5500
5470 IF W(I) = WATL THEN 5610
5480 TOP = W(I)
5490 W(I) = (W(I) + BOT) * .5
5500 J = INT((W(I) - T(J)) / DELW) + 1
5510 BB = (W(I) - T(J)) / DELW
5520 H(I) = (P(J + 1) - P(J)) * BB + P(J)
5530 TWW = (W(I) + Y(I)) * .5
5540 J = INT((TWW - T(J)) / DELW) + 1
5550 BB = (TWW - T(J)) / DELW
5560 DIFFB = (D(J) + Y - D(J)) * BB + D(J)
5570 HI = (P(J + 1) - P(J)) * BB + P(J)
5580 GOTO 5240
5590 B(I) = (D(J) + Y - D(J)) / (P(J + 1) - P(J)) * new hydraulic conductivity
5600 IF I = 1 THEN 5270
5610 TWW = TW
5620 H(I) = GI
5630 DIFFB = DIFFB
5640 TW = (W(I) + Y(I + 1)) * .5
5650   J = INT((TW - T(1)) / DELW) + 1
5660   C(I + 1) = DELW / (P(J + 1) - P(J))
5670   NEXT I
5680   KCK = 1; KCP = 0
5690   RETURN
6000   REM ****************** COMPUTE ROOT WATER UPTAKE BY DEPTHS **************
6010   REM ********************************** COMPUTE ROOT WATER UPTAKE BY DEPTHS **************
6020   ETPL = ET
6030   IF ET >= 0 THEN 6160  'if infiltration occurring, skip uptake routine
6040   IF TIME / 24 < ESTART THEN 6160  'if plant growth hasn't started, skip
6050   IF ABS(WFDD) > ABS(EOR) THEN WFDD = EOR
6060   IF ABS(WFDD - EOR) < .001 THEN 6130
6070   ETALT = (ET - EOR) * (1 + (AK2 / AK1 - 1) * (EOR - WFDD) / EOR)
6080   IF WFDD < (ET - ETALT) THEN 6110
6090   ETPL = ETALT
6100   GO TO 6210
6110   ETPL = ET - WFDD
6120   GO TO 6210
6130   ETPL = ET - EOR
6140   IF ABS(ETPL) < .0001 THEN 6160
6150   GO TO 6210
6200   RETURN
6210   ' ********** PLANT WATER UPTAKE SUBROUTINE **********
6220   IF DROOT < DD(2) THEN RETURN  'avoid overflow problems
6230   PB = 0: RB = 0
6240   TPOT = -1 * ETPL
6250   FOR I = 1 TO K
6260   RS(I) = BZ(I) / B(I)  'soil resistance based on root density
6270   PB = PB + (H(I) - DD(I)) / (RR(I) + RS(I))
6280   RB = RB + 1 / (RR(I) + RS(I))
6290   NEXT I
6300   PB = PB / RB
6310   RB = 1 / RB
6320   IF PL > PB THEN PL = PB - TPOT * (RL + RB)
6330   XP = (PL / PC) * SP
6340   SL = TPOT * (RL + RB) * SP / (PL * (1 + XP) * (1 + XP)) - 1.05
6350   F = PB - PL - TPOT * (RL + RB) / (1 + XP)  'Newton-Raphson iteration to
6360   PL = PL - (F / SL)  'find leaf water potential.
6370   IF ABS(F) > 5 THEN 6330
6380   TR = TPOT / (1 + XP)  'Transp. as function of stomatal closure
6390   SINK = 0
6400   FOR I = 1 TO K
6410   UPRATE(I) = -1 * (H(I) - DD(I) - PL - RL * TR) / (RR(I) + RS(I))
6420   IF RD(I) = 0 THEN UPRATE(I) = 0  'if no roots, no uptake (avoid roundoff)
6430   SINK = SINK + UPRATE(I)
6440   A(I) = UPRATE(I) * 2 / (DD(I + 1) - DD(I - 1))
6450   NEXT I
6460   R
6470   RETURN
7000   REM ****************** SOLUTION OF TRIDIAGONAL MATRIX FOR WATER FLOW *************
7010   REM ****************** SOLUTION OF TRIDIAGONAL MATRIX FOR WATER FLOW *************
7020   FOR I = 2 TO K
7030   POT = (DD(I + 1) - DD(I - 1)) / (2 * DELT)
7040   DLXA = (DD(I) - DD(I - 1))
7050   DLXB = (DD(I + 1) - DD(I))
7060   AA = B(I - 1) / DLXA
7070   CC = B(I) / DLXB
7080   BB = C(I) * POT / TT + CC + AA
7090   DA = (C(I) * POT * G(I) + CC * (TM * (G(I - 1) - G(I)) - DLXB) + AA * (TM * (G(I) - G(I + 1)) + DLXA) + A(I) * (DD(I + 1) - DD(I - 1)) * .5) / TT
7100   IF I > 2 THEN 7170
7110   IF H(1) >= HWET OR H(1) <= HDRY THEN DA = DA + AA * H(1): GO TO 7140
DA = DA - (AA * (TM * (G(I - 1) - G(I)) + DLXA)) / TT + EOR / TT

BB = BB - AA

F(I) = DA / BB

E(I) = CC / BB

GOTO 7200

IF I >= K THEN 7210

E(I) = CC / (BB - AA * E(I - 1))

F(I) = (DA + AA * F(I - 1)) / (BB - AA * E(I - 1))

7200 NEXT I

IF ITAA = 0 THEN DA = DA + CC * H(KK)

IF ITAA = 1 THEN BB = BB - CC

7230 IF ITAA = 1 THEN DA = DA + CC * ((G(I) - G(I + 1)) * TM + DLXB) / TT

7240 H(I) = (DA + AA * F(I - 1)) / (BB - AA * E(I - 1))

I = I + 1

7260 H(I) = E(I) * H(I + 1) + F(I)

7270 IF I > 2 THEN 7250

7280 IF ITAA = 0 THEN 7310

7290 H(KK) = H(K) + DD(KK) - DD(K)

7300 G(KK) = G(K) + DD(KK) - DD(K)

7310 IF ITAA = 2 AND H(KK) >= HWET THEN ITAA = 0

7320 FOR I = 2 TO K

7330 IF H(I) > HWET THEN 7460

7340 NEXT I

7350 REM ******** COMPUTE NEW WATER CONTENTS AS A FUNCTION OF MATRIC HEADS ******

7360 REM

7370 IF H(I) <= HDRY OR H(I) > = HWET THEN 7400

7380 WFD = EOR

7390 GOTO 7440

7400 WFD = (B(1) * H(I) * TT - H(2) * TT - G(2) * TM + G(1) * TM + DD(2))) / DD(2)

7410 IF H(I) >= HWET THEN W(I) = WAT

7420 IF H(I) < HDRY THEN W(I) = WATL

7430 GOTO 7730

7440 H(I) = (EOR * DD(2) / B(1) + H(2) * TT - G(2) * TM + G(1) * TM - DD(2)) / TT

7450 IF H(I) > HDRY AND H(I) < HWET THEN 7540

7460 IF KCP >= KCP MAX THEN 7500

7470 KCP = KCP + 1

7480 DELT = DELT * .5

7490 GOTO 7020

7500 IF H(I) < HDRY THEN H(I) = HDRY

7510 IF H(I) > HWET THEN H(I) = HWET

7520 WFD = (B(1) * H(I) * TT - H(2) * TT - G(2) * TM + G(1) * TM + DD(2))) / DD(2)

7530 GOTO 7410

7540 H(I) = H(I)

7550 I = I + 1

7560 IF ABS(H(I) - G(I)) < .0001 THEN 7720

7570 NH1 = ND

7580 NLO = 1

7590 J = INT(ND / 2)

7600 IF H(I) = P(J) THEN 7690 ELSE IF H(I) > P(J) THEN 7630

7610 NH1 = J

7620 GOTO 7640

7630 NLO = J

7640 JT = J

7650 J = INT(NH1 - NLO) / 2 + NLO

7660 IF J <= JT THEN 7660

7670 IF H(I) >= P(J) THEN 7690

7680 J = J - 1

7690 WAT = (H(I) - P(J)) * DELW / (P(J + 1) - P(J)) + T(J)

7700 W(I) = WAT

7710 GOTO 7730

7720 W(I) = Y(I)

7730 FOR I = 2 TO KK

7740 W(I) = C(I) * (H(I) - G(I)) + Y(I)

7750 IF W(I) > WAT THEN W(I) = WAT

7760 IF W(I) < WATL THEN W(I) = WATL

7770 GOTO 7120

7780 BB = BB - AA

7790 F(I) = DA / BB

7800 E(I) = CC / BB

7810 GOTO 7200

7820 IF I >= K THEN 7210

7830 E(I) = CC / (BB - AA * E(I - 1))

7840 F(I) = (DA + AA * F(I - 1)) / (BB - AA * E(I - 1))
7770 NEXT I
7780 SUM3 = 0; SUM2 = 0; SUM1 = 0
7790 FOR I = 2 TO K
7800 SUM1 = W(I) + SUM1
7810 SUM2 = Y(I) + SUM2
7820 IF ABS(SUM1 - SUM2) <= ABS(SUM3) THEN 7840
7830 SUM3 = SUM1 - SUM2
7840 NEXT I
7850 IF ABS(SUM3) <= ABS(CONQ) THEN 7890
7860 IF DELT = DELT * .1 THEN 7890 'If delt <= (.1 * delt) then go on with
7870 DELT = .5 * DELT 'model, else decrease delt by half and
7880 GOTO 7020 'go thru tridiagonal matrix again.
7890 SUM1 = 0; SUM2 = 0
7900 WUU = B(NB) * ((H(NB) - H(NB + 1)) * TT + (G(NB) - G(NB + 1)) * TM + DD(NB + 1) - DD(NB)) / (DD(NB + 1) - DD(NB))
7910 FOR I = 2 TO K
7920 SUM1 = W(I) * (DD(I + 1) - DD(I - 1)) / 2 + SUM1
7930 SUM2 = Y(I) * (DD(I + 1) - DD(I - 1)) / 2 + SUM2
7940 NEXT I
7950 CFV = SUM1 - PIT
7960 WFDD = (SUM1 - SUM2) / DELT
7970 CUMS = WFDD * DELT + CUMS
7980 IF EOR > 0 THEN SIR = EOR * DELT + SIR
7990 IF EOR < 0 THEN EVAP = WFDD * DELT + EVAP
8000 IF EOR > 0 THEN RPI = RPI + WFDD * DELT
8010 IF EOR > 0 THEN RUNOF = (EOR - WFDD) * DELT + RUNOF
8020 CUMB = CUMB + WUU * DELT
8030 CUMET = CUMET + ET * DELT
8040 HFLUX = WUU
8050 SUMA = SUMA + SINK * DELT
8060 CTAN = CTAN + ETPL * DELT
8070 CFVFLX = (SUM1 - SUM2)
8080 KB = K - 1
8090 TIME = TIME + DELT 'Update actual time in run
8100 WATB = SIR + EVAP - RUNOF - CUMB - CFV + SUMA
8110 PRINT USING "###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### #" ; TIME; WATB; WUU; ETPL; SUMA; EVAP; PL / 1000; CFV
8120 'Change screen headings at bottom of "plant cover growth..." routine
8130 IF TIME >= PRINTIME + 8 THEN PRINTIME = TIME ELSE 8180 'print to files every "X" hrs.
8140 PRINT #2, USING "###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### ###.### #" ; TIME; SUMA; EVAP; CFV; PL / 1000; SIR; RUNOF; CUMB 'see also lines 9080-90 for print #2
8150 PRINT #3, USING "###.### " ; TIME;
8160 FOR I = 1 TO KK; PRINT #3, USING "###.### " ; W(I); : NEXT I
8170 PRINT #3,
8180 IF ABS(SUM3 - 0) > .0001 THEN 8220
8190 REM ------- CHANGE DELT HERE -------
8200 DELT = 3 * DELT
8210 RETURN
8220 TW = ABS(CONQ * DELT / SUM3)
8230 IF TW >= .1 * DELT THEN 8260
8240 TW = .1 * DELT
8250 GOTO 8280
8260 IF TW <= 1000 * DELT THEN 8280
8270 TW = 1000 * DELT
8280 IF TW <= 2 * DELT THEN 8200
8290 DELT = TW
8300 RETURN
8310 REM RE--------------- CHECK TO SEE IF EVAP OR RAIN ETC. HAS CHANGED -------------------
8320 REM IF IDELT = 1 THEN DELT = DELT1
8330 IF IDELT = 0
8340 IF DELT < DELT THEN DELT = DELT
8350 IF DELT > 2 THEN DELT = 2
8360 IF TIME - V(KC + 1) < 0 THEN 9240 'still time left till top boundary change
8370 WATB = SIR + EVAP - RUNOF - CUMB - CFV + SUMA
Following printouts occur at each top boundary change

PRINT #2, " TIME CWF IRR+RAIN TRAN DRAINAGE EVAP WATBAL
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Sample input file:

C88HIPL.DAT: 1988 CORN HI IRRIGATION PLASTIC MULCH

Input:

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-0.61, 1.112, -0.0274, 1.200, -0.0300, 1.200, -0.0286, 1.440, -0.0294, 1.560, -0.0287, 1.641, -0.67, 1.647
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-968.75, -671.633, -485.276, -361.444, -275.279, -212.997, -166.493, -130.765, -102.59
-79.81, -60.918, -44.797, -30.5198, -17.04708, 0, 10000
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1.514E-17, 2.7075E-15, 1.4704E-15, 7.9865E-12, 4.3374E-10, 2.001E-6, 2.498E-6, 7.00E-6, 2.619E-5, 7.715E-5, 1.993E-4, 4.652E-4, 1.005E-3, 2.033E-3, 3.916E-3, 7.427E-3
1.300E-2, 3.200E-2, 2.941E-2, 6.782E-2, 2.1178E-1, 2.118E-1, 4.195E-1, 2.5, 2.5
-0.10, 14.26, 26, 26, 26, 26, 26, 24, 207, 203, 196, 19.19
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-2.3556, 0.02, 48, -135E, 0.02
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0.3, 7, 3.5, 2.8, 1.8, 1.3, 1.0, 0.7, 0.6, 0.5, 0.3, 1.0, 0.8
19.8, 20.9, 20.0
3, 220, 9, 28.4, 100000, 70000, 0.075, -170000, 10
Table 1. Mean volumetric soil water contents for wheat during 1987

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Appendix B

Soil Water Contents During 1987 and 1988
Table 1. Mean volumetric soil water contents for wheat during 1987.

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| PLLo      | .133 | .118 | .119 | .118 | .113 | .125 | .162 | .155 | .169 | .173 | .207 | .180 |
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| P1Hi      | .185 | .159 | .168 | .182 | .188 | .206 | .213 | .202 | .209 | .224 | .217 | .176 |
Table 3. Mean volumetric soil water contents for corn during 1988.

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### Table 5. Mean irrigation water application (cm) by date for corn during 1987

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### Appendix C

**Irrigation Water Applied During 1987 and 1988**
Table 4. Mean irrigation water application (cm) by date for wheat during 1987.

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Table 5. Mean irrigation water application (cm) by date for corn during 1987.

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<thead>
<tr>
<th></th>
<th>6-18</th>
<th>7-03</th>
<th>7-17</th>
<th>7-20</th>
<th>8-06</th>
<th>8-21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw Low</td>
<td>.161</td>
<td>.000</td>
<td>.922</td>
<td>.922</td>
<td>.402</td>
<td>.774</td>
</tr>
<tr>
<td>Straw Med</td>
<td>2.499</td>
<td>1.045</td>
<td>1.067</td>
<td>2.811</td>
<td>3.053</td>
<td>7.458</td>
</tr>
<tr>
<td>Straw Hi</td>
<td>4.747</td>
<td>1.900</td>
<td>1.489</td>
<td>4.478</td>
<td>5.173</td>
<td>11.165</td>
</tr>
<tr>
<td>Plastic Low</td>
<td>.096</td>
<td>.000</td>
<td>.311</td>
<td>.533</td>
<td>.179</td>
<td>.458</td>
</tr>
<tr>
<td>Plastic Med</td>
<td>2.711</td>
<td>.933</td>
<td>.756</td>
<td>2.456</td>
<td>2.895</td>
<td>6.923</td>
</tr>
<tr>
<td>Plastic Hi</td>
<td>4.748</td>
<td>1.778</td>
<td>1.545</td>
<td>2.278</td>
<td>4.877</td>
<td>9.638</td>
</tr>
</tbody>
</table>

Table 6. Mean estimated irrigation water application (cm) by date for corn during 1988.

<table>
<thead>
<tr>
<th></th>
<th>6-9</th>
<th>6-15</th>
<th>6-30</th>
<th>7-1</th>
<th>7-23</th>
<th>7-25</th>
<th>7-26</th>
<th>8-15</th>
<th>8-17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw Low</td>
<td>3.50</td>
<td>2.75</td>
<td>1.42</td>
<td>2.90</td>
<td>2.28</td>
<td>1.40</td>
<td>3.15</td>
<td>4.94</td>
<td>3.00</td>
</tr>
<tr>
<td>Straw Hi</td>
<td>4.30</td>
<td>3.30</td>
<td>2.14</td>
<td>4.27</td>
<td>4.30</td>
<td>2.85</td>
<td>6.40</td>
<td>7.13</td>
<td>6.40</td>
</tr>
<tr>
<td>Plastic Low</td>
<td>3.50</td>
<td>2.75</td>
<td>1.42</td>
<td>2.90</td>
<td>2.28</td>
<td>1.40</td>
<td>3.15</td>
<td>4.94</td>
<td>3.00</td>
</tr>
<tr>
<td>Plastic Hi</td>
<td>4.30</td>
<td>3.30</td>
<td>2.14</td>
<td>4.27</td>
<td>4.30</td>
<td>2.85</td>
<td>6.40</td>
<td>7.13</td>
<td>6.00</td>
</tr>
</tbody>
</table>
Appendix D

Crop Yields During 1987 and 1988

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dry Matter 20 July (g/plant)</th>
<th>Dry Matter 23 Aug (g/plant)</th>
<th>Dry Matter 19 Sept (g/plant)</th>
<th>Grain (g/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw Low</td>
<td>137.40</td>
<td>240.38</td>
<td>254.17</td>
<td>142.07</td>
</tr>
<tr>
<td>Straw-Plastic Low</td>
<td>153.19</td>
<td>277.62</td>
<td>277.62</td>
<td>158.33</td>
</tr>
<tr>
<td>Plastic Low</td>
<td>199.08</td>
<td>353.61</td>
<td>473.76</td>
<td>194.59</td>
</tr>
<tr>
<td>Straw Hi</td>
<td>159.96</td>
<td>274.84</td>
<td>384.60</td>
<td>130.87</td>
</tr>
<tr>
<td>Straw-Plastic Hi</td>
<td>223.01</td>
<td>347.37</td>
<td>465.34</td>
<td>201.38</td>
</tr>
<tr>
<td>Plastic Hi</td>
<td>288.32</td>
<td>386.07</td>
<td>521.38</td>
<td>252.67</td>
</tr>
</tbody>
</table>
Table 7. Mean yields for wheat and corn during 1987.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Winter Wheat</th>
<th>Corn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Matter</td>
<td>Grain</td>
</tr>
<tr>
<td></td>
<td>(Mg/ha)</td>
<td>(Mg/ha)</td>
</tr>
<tr>
<td>Straw Low</td>
<td>16.59</td>
<td>6.73</td>
</tr>
<tr>
<td>Control Low</td>
<td>14.64</td>
<td>5.46</td>
</tr>
<tr>
<td>Cable Low</td>
<td>16.40</td>
<td>6.78</td>
</tr>
<tr>
<td>Control Med</td>
<td>21.07</td>
<td>9.38</td>
</tr>
<tr>
<td>Straw Hi</td>
<td>21.89</td>
<td>9.10</td>
</tr>
<tr>
<td>Control Hi</td>
<td>23.92</td>
<td>10.13</td>
</tr>
<tr>
<td>Cable Hi</td>
<td>24.48</td>
<td>10.60</td>
</tr>
</tbody>
</table>

Table 8. Mean yields for corn during 1988.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>20 July Dry Matter (g/plant)</th>
<th>22 Aug Dry Matter (g/plant)</th>
<th>19 Sept Dry Matter (g/plant)</th>
<th>Grain (g/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw Low</td>
<td>153.46</td>
<td>240.74</td>
<td>354.47</td>
<td>142.07</td>
</tr>
<tr>
<td>Straw-Plastic Low</td>
<td>195.19</td>
<td>277.30</td>
<td>397.62</td>
<td>158.33</td>
</tr>
<tr>
<td>Plastic Low</td>
<td>209.03</td>
<td>333.61</td>
<td>473.76</td>
<td>194.59</td>
</tr>
<tr>
<td>Straw Hi</td>
<td>165.96</td>
<td>274.66</td>
<td>384.60</td>
<td>130.53</td>
</tr>
<tr>
<td>Straw-Plastic Hi</td>
<td>223.61</td>
<td>343.87</td>
<td>445.74</td>
<td>201.39</td>
</tr>
<tr>
<td>Plastic Hi</td>
<td>268.32</td>
<td>388.72</td>
<td>511.58</td>
<td>232.67</td>
</tr>
</tbody>
</table>
VITA
Jon Michael Wraith
Candidate for the Degree of
Doctor of Philosophy

Dissertation: Soil Temperature Influence on Water Use and Yield under Variable Irrigation

Major Field: Soil Science and Biometeorology (Soil Physics)

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Research Assistant, Soil Science, Utah State Univ. 1986-89.
