Water use of two corn varieties, drought resistant and drought sensitive

Hanzhong Zhang

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Water use of two corn varieties: Drought resistant and drought sensitive

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Water use of two corn varieties--drought resistant and drought sensitive

by

Hanzhong Zhang

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GENERAL INTRODUCTION

Corn water use is an important issue in the corn belt of U.S. because corn yield mainly depends on soil water availability, a function of water recharge (precipitation and irrigation) and evapotranspiration. Under some circumstances, reduced water consumption will enhance yield. Reduction in water use could mean less irrigation need. Economically, reduction in water requirements and expenditures generates profits either by increasing yield or reducing irrigation costs. Drought resistant hybrid selection has been suggested as a way to conserve water but such a relationship does not necessarily follow.

Corn breeders have invested great effort to produce drought resistant varieties. However, selection of drought resistant varieties is normally on the basis of yield. The physiological, and morphological differences and the differences in water use among hybrids that confer drought resistance or susceptibility are not well defined.

To fully evaluate drought resistance of corn, it is necessary to understand all aspects of water use and drought resistance of the plants.

1. Water Use

1.1. Plant water relations

In the field, transpiration responds to diurnal and seasonal changes in atmospheric and edaphic conditions and to such factors as the development of leaf area, root growth and soil water availability. As water is lost to the atmosphere from the mesophyll and inner surfaces of the epidermal cells of the leaf, the water potential of these cells falls and a gradient in water potential is then established between plant leaves and the soil. This gradient is proportional to the rate of transpiration and to the resistance to water flow in the
soil and plant. Water movement in the vapor phase, i.e., from the evaporation sites within the leaf to the bulk air, is largely through the stomata. Stomata function as adjustable gates. The stomata respond to a range of environmental factors, notably light, humidity, carbon dioxide concentration, and temperature (Rosenthal et al., 1977; Barlow et al., 1977a; Barlow et al., 1977). They also respond to leaf turgor and closure at low turgor potentials helps to regulate the water balance.

Stomatal resistance differs among species. The gradient in potential between the soil and plant leaves can become appreciable even in fully turgid crops growing in moist soil (Turner and Begg, 1973; Turner, 1978). This may indicate that in addition to vapor phase resistance, substantial liquid phase resistance exists within the soil-plant system. Typically crop leaf water potentials can fall as low as -15 bars for plants growing in soil with a potential of around -0.1 bar. As soils dry to water potentials of around -10 bars, the leaf water potentials can reach values of -30 bars. Water moves along the potential gradient from the soil to the atmosphere through the roots, stems, and leaves of the plant.

Water moves in two distinct pathway modes during uptake by a root system. The first is the tissue mode, between the epidermal cells of the root surface and the xylem vessels within the root stele. The second is the capillary mode, between the point of absorption into the xylem and the basal parts of the shoot. The root systems of crops are usually more concentrated in the surface layers of soil which contain a high proportion of the available nutrients and are re-wetted more frequently by rainfall or irrigation. Nevertheless, roots can be induced to proliferate deeper in the soil due to prolonged drying of the surface soil (Kleppe et al., 1973; Reicosky et al., 1972). Two important features of crop root systems affect water uptake. First, high root densities can result in the rapid depletion of available water in surface soil layers. Second, deep root penetration can make available a much larger volume of soil water for plant extraction than is provided by the surface layers of soil.
1.2. Corn water use

Water consumption by corn varies greatly throughout the growing season and is affected significantly by climate. Daily changes in the weather also affect evapotranspiration. Early in the season, evapotranspiration in Iowa will average about 0.25 cm per day and will peak shortly after silking at about 1 cm per day on the average (Shaw, 1963). Daily water consumption may range from zero to more than 1 cm.

Transpiration in corn accounts for a considerable portion of water loss during peak consumption periods. Studies have shown that it can account for 50-70% of the total water lost during peak use (Peters, 1960). At the onset of drought, corn plants of all ages will wilt in the afternoon and recover turgidity at night. The stomata of corn plants exposed to severe drought for 3 or 4 days resume much of their apparent normal behavior after a 1 or 2 day recovery period. But, severe drought over longer periods of 1 week or more produces marked changes in stomatal behavior and they never again seem to be able to open fully (Glover, 1959). There are differences between crops in stomatal control. Although the rate of photosynthesis in corn is directly related to stomatal diffusive resistance at leaf water potentials between -3.5 and -10 bars, in soybeans this direct relationship occurs between -11 and -16 bars (Boyer, 1970). The lower leaves of corn close their stomata at a higher water potential than the upper leaves (Turner and Begg, 1973). This can be partly attributed to the high osmotic potential of the lower leaves at full turgor and not because of differences in the degree of turgor potential. Stomatal resistance at a particular time of the day is a function of radiation, air and leaf temperature, relative humidity, wind speed, the degree of senescence of the leaf, and the water potential of the leaf.

The relationship between leaf water potential and stomatal resistance may vary among genotypes. A genotype in which the stomata remain open at low water potentials
may have an advantage in a short period of drought stress since the diffusion of carbon
dioxide for photosynthesis can proceed with minimum interruption. Also leaf cooling by
evaporation may be a factor. However, this type of stomatal behavior would be detrimental
under extended drought as the plant would exhaust the soil water supply rapidly. There is a
change in minimum leaf water potential values as the corn plant changes from vegetative to
reproductive growth (Reicosky et al., 1975). Leaf water potential is lower after tasseling,
under the same environmental conditions, apparently because of physiological changes in the
plant. Peak water use by corn occurs about the time of silking or shortly thereafter.

2. Water Stress

2.1. Water stress

The direct consequence of water stress is dehydration which results in the loss of
water molecules that act as protective layers on membranes and other cell organs. Since
water plays a major role in plant metabolism, dehydration may cause imbalance of
biochemical processes.

One response to stress is stomatal closure which restricts gas exchange essential to
transpiration and photosynthesis. Stomatal closure is caused by a reduction in the hydration
and turgor pressure of the guard cells relative to epidermal cell turgor (Stewart and Dwyer,
1983).

2.2. Corn water stress

Water stress during vegetative development reduces expansion of leaves, stems and
roots, and ultimately affects the development of reproductive organs and potential grain
yield (Denmead and Shaw, 1960). The effect of water stress is greatest during corn's
reproductive stage. Water stress at tasseling not only hinders the plant's ability to flower and shed pollen, but also can greatly affect the viability of corn pollen, especially when the drought is accompanied by high temperatures as is usually the case.

Much research has shown that water deficits at the time of tasseling and silking also cause the greatest reduction in yield. Moderate water stress reduces grain yield by 25% when prior to silking, by 50% when occurring at silking, and by 21% after silking (Denmead and Shaw, 1960). Length of the stress period is also important. One report shows that soil water depletion to the wilting percentage for 2 days during the tasseling or pollination period can result in as much as a 22% decrease in yield, while a 6-8 day period of depletion can cause a yield reduction of about 50% (Robins and Domingo, 1953).

3. Drought Resistance

3.1. Mechanism of drought resistance

Drought resistance is the ability of a crop species or cultivar to grow and yield satisfactorily under drought. Whether a period of prolonged dry weather affects the physiological and morphological processes contributing to yield, and ultimately affects yield itself, depends on a number of factors. Not only will it depend on the timing of the dry weather in relation to the life cycle of the crop and on the water holding capacity of the soil in the root zone, but also on characteristics of the plants. Three types of drought resistance can be distinguished as: drought escape, drought avoidance and drought tolerance. Drought escape is the ability of a crop species or cultivar to complete its lifecycle before serious plant water deficits develop; drought avoidance is usually based on a mechanism whereby an internal environment is created within the plant such that its cells are not under stress, even though the external environment may be very stressful; and drought tolerance is the capacity
to endure the stress, to survive or even to function normally under internal as well as external conditions of extreme stress.

There are two characteristics that enable crop plants to escape drought and yield satisfactorily. In situations in which the probability of drought increases with the life of the crop, a shorter duration crop may result in greater yield. However, shorter maturity crops usually have lower yields in favorable years. The introduction of drought escape characteristics, particularly earliness, has undoubtedly brought the greatest advances in breeding for drought resistance to date. Nevertheless, crops in semiarid or even temperate and tropical areas (O'Toole and Chang, 1979), are subjected to random drought and therefore it would be advantageous to have some drought avoidance or tolerance characteristics.

Some crop plants can avoid periodic drought and maintain a high plant water status by either preventing water loss or by maintaining the supply of water to the plant. To prevent water loss a crop plant must reduce transpiration by stomatal closure, reduce the absorption of radiation, reduce the evaporating surface of the plant, or any combination of the three. Most crop species close their stomata as leaf water deficits increase and this reduces transpiration (Turner, 1975) and helps maintain a high plant water status, particularly if stomatal closure is complete and cuticular resistance is high. A reduction in the radiation absorbed by leaves can be achieved by active or passive leaf movements, increased pubescence, or increased waxiness. An alternative means of tolerating drought at a high plant water status is to maintain the rate of water uptake: two plant characteristics facilitating for this are a prolific and deep root system and a low resistance to water flow through the plant.

Maintenance of turgor as leaf water deficits increase should enable the maintenance of physiological functions by the plant. Turgor can be partly or fully maintained by osmotic
adjustment as leaf water potential decreases, by an increase in elasticity, or by a decrease in cell size (Turner, 1979). There is now considerable evidence that osmotic adjustment, leading to partial or full turgor maintenance, occurs in a range of crop species and cultivars. Tolerance of dehydration is clearly important in survival of plants. However, as pointed out by Turner (1979) and Fischer and Turner (1978), surviving severe stress is less important in crop species than in natural communities. However, dehydration tolerance and its contribution to crop survival can be important in situations where random droughts occur or where the probability of rainfall increase with the life of the crop. Seedling survival and survival in the vegetative phase are important in obtaining yields under drought (O'Toole and Chang, 1979), and differences in protoplasmic tolerance at both the seedling and later stages are known to exist among cultivars (O'Toole et al., 1978).

3.2. Corn drought resistance

Resistance of corn to drought follows the mechanisms described above. Corn may tolerate or avoid drought depending on the severity and duration of stress. With mild stress, corn may adjust its internal biochemical status, osmotic potential, to tolerate drought. However under the severe drought, corn may avoid the stress either by budgeting plant water use, increasing plant resistance, and decreasing total leaf area, or by shortening the life cycle and completing growth in a favorable period.

Drought resistance is limited by severity and duration of drought. Under severe and long drought, corn growth may be retarded and reproduction may aborted.
4. Water Use Efficiency

4.1. Dry matter water use efficiency

Water use efficiency may be defined as the ratio of dry matter produced to water consumed. The major environmental factor influencing the water use efficiency of a crop is atmospheric humidity. Lowering the vapor pressure of the atmosphere around a leaf will tend to increase the transpiration rate of the leaf. Photosynthesis will not be affected, however, unless the stomata close as a result of a direct effect of humidity on the stomata or an indirect effect through a lowering of the leaf water potential. Thus, unless some compensatory closure of stomata occurs, a decrease in humidity will decrease the water use efficiency of the plant. Water use efficiency is also influenced by leaf form. According to Taylor (1974), small leaves with moderate resistance exhibit greatest water-use efficiency.

The level of carbon dioxide in the atmosphere will also influence the efficiency of water use by plants. Other environmental factors that influence water use efficiency are air temperature, irradiance, and soil water availability. Air temperature usually operates through its effect on atmospheric humidity (Fischer and Turner, 1978). For maximum water use efficiency there is an optimum irradiance (Jones, 1976) which is usually less than the irradiance incident on a leaf oriented normal to the sun. Except when the mesophyll resistance is low and the boundary layer resistance is high, stomatal closure will lead to an increase in water use efficiency (Jones, 1976). Soil moisture stress, resulting in closing of stomata, might therefore be expected to increase the efficiency of water use. The effect of water deficit on the mesophyll resistance must also be considered but the current evidence suggests that, in general, water deficits increase or do not alter water use efficiency (Slatyer, 1970; Johnson et al., 1974; Johnson et al., 1975). However, evidence of a decrease in the
efficiency of water use with water stress is available particularly for C4 species (Sinclair et al., 1975).

Differences in the ratio of stomatal resistance to mesophyll resistance between plants is the major plant factor contributing to differences in the efficiency of water use. Although corn has a high water requirement, it is one of the most efficient crops in producing dry matter with the water it uses. Water use efficiencies of 0.0027, 0.0037, 0.0018 and 0.0012 for corn, sorghum, wheat, cotton and alfalfa, respectively, have been reported (Martin et al., 1976).

4.2. Yield water use efficiency

Yield water use efficiency is the amount of water used to produce yield. Yield water use efficiency is closely related to dry matter water use efficiency. Yield increases as dry matter water use efficiency increases (Timmons et al., 1966; Olson, 1971) have been reported. But the relation between dry matter and yield water use efficiencies depends on crop varieties, phenology and water availability during the growing season. For example, early maturing corn hybrids are more efficient in using water for grain production while the later maturing hybrids use water more efficiently for forage production. However, later maturing hybrids will usually produce more grain than earlier hybrids even though they may be less efficient in water use. Water stress during the pollination and grain filling would reduce grain yield more than forage yield.
5. Experiments vs. Modeling

Plant characteristics related to water use and drought resistance can be studied with laboratory and field experiments, and can be described by modeling. Since the plant water system is very complicated, modeling may be useful for interpretation of results.

Simulation models can help scientists to understand various parts of some agronomic systems. Both experiment and simulation modeling are often applied in plant water studies. Experiments provide data and validate simulation models. On the other hand, simulation helps in experiment data interpretation and in systematic analysis.


This dissertation consists of papers intended for publication. The two research papers forming the main body of this work are intended for submission to the Agronomy Journal. The experimental results are presented in the first paper. The simulation of corn transpiration is described in the second paper, which includes model development and validation. Each paper includes an abstract and introduction. This dissertation also includes the General Summary following the second paper. References cited in the General Introduction can be found in the Bibliography following the General Summary. Relevant material not intended for submission with the papers appear in the Appendices.
PAPER 1

WATER USE AND DROUGHT RESISTANCE OF TWO CORN HYBRIDS
Water use and drought resistance of two corn hybrids

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(to be submitted to Agronomy Journal)
ABSTRACT

Corn (*Zea mays* L.) hybrids are often selected for drought resistance only on basis of yield test. Water use and water use efficiency are usually unknown. However, water use is very important in areas with limited precipitation or under conditions of consecutive drought years. The objective of this study was to evaluate differences in leaf area, root system, plant water use, transpiration rate and soil water extraction for two distinct varieties and to compare these hybrids with sorghum in terms of drought resistance.

The drought resistant corn, drought sensitive corn and the sorghum used in this study were Pioneer Brands 3379 (P3379), Pioneer Brands 3343 (P3343) and Pioneer Brands 8086 (P8086). Both indoor and field experiments were conducted. Water use was measured in the greenhouse by weighing pots every day or every other day through the growing periods. Leaf areas and transpiration rates were measured approximately once a week. Two year field studies were conducted. Soil water content of the field plots was determined approximately once a month through the growing seasons. Corns were harvested at the ends of growing seasons from the field. In addition, root systems were evaluated and the permanent wilting point was identified.

In this study, P3379 had greater leaf area, more massive root system, and higher transpiration rates, but had lower permanent wilting point. These characteristics in P3379 may result in total higher water consumption (also observed in greenhouse). No significant differences in soil moisture and grain yield were observed in the field but yield of P3379 was greater than that of P3343 in the yield test by Iowa State University Cooperative Extension. Therefore, if P3379 have a higher yield than P3343, it may be due to greater water consumption. P3379 may be considered as a water spender that can resist mild drought but
not severe drought. Selection of corn hybrid in terms of drought resistance should be based on yield, plant water use and soil moisture condition and climatic condition.
INTRODUCTION

Corn (*Zea mays* L.) production is related to water availability. Selection of drought resistant hybrids is very important for areas that occasionally experience insufficient water supply. The physiological characteristics of cultivars in terms of drought resistance are often poorly identified.

Response to drought stress has been investigated with respect to several physiological and morphological characteristics including leaf water potential (O'Toole and Moya, 1978; O'Toole and Cruz, 1980), leaf osmotic potential (Jones and Rawson, 1979), leaf turgor potential (Vicent and Woolley, 1972; Johnson and Brown, 1977), stomatal activity (McCree, 1974; Turner, 1973), leaf rolling (O'Toole and Cruz, 1980), root development (Vincent and Woolley, 1972), plant growth and root length density (Lorens et al., 1987a; Lorens et al. 1987b), and the relationship between leaf turgor potential and leaf water potential (Johnson and Brown, 1977; Ackerson, 1983). Dube et al. (1974) and Skretkowicz and Thurtell (1983) examined corn genotypes that differed in their sensitivities to soil water depletion. Skretkowicz and Thurtell (1983) concluded that the drought resistant corn genotype that they evaluated maintained low stomatal resistance for longer periods of time than the susceptible genotype as a result of a lower leaf water potential threshold necessary for stomatal closure, enabling the plants to extend their period of soil water extraction.

Studies by scientists mentioned above have examined the responses of crop plants to water stress and suggested various mechanisms that may result in improved drought resistance. However, these is not a clear understanding of the morphological and physiological characteristics that are responsible for different water use rates and different responses to drought stress.
The objectives of this study were to investigate differences in leaf area development, root system, transpiration rates, and water use between two corn hybrids, as related to yields. Identification of these differences should result in a better understanding of the adaptive mechanisms that result in drought resistance.
MATERIALS AND METHODS

Two corn hybrids, Pioneer Brands 3379 (P3379) and 3343 (P3343) were used in the studies because of their different yield responses during stressful seasons. P3379 and P3343 are considered to be a drought resistant and a drought sensitive hybrid respectively. The sorghum hybrid, Pioneer Brand 8086 (P8086), Grain sorghum (Sorghum bicolor L.), which is known as drought resistant crop, was used as a control.

Our studies included greenhouse, growth chamber and field experiments. The experiments are identified according to experiment type and the date that seeds were sown. The first two letters of names indicate experiment types: GH, GC and FE for greenhouse, growth chamber and field experiments respectively, and numbers indicate sowing dates. For instance, GH0615.89 stands for a greenhouse experiment in which seeds were sown on 15 June 1989. All experiments will be referred to by experiment names in this paper.

1. Greenhouse Experiments

Five sets of greenhouse experiments were conducted in 1989 and 1991: GH0615.89, GH0724.89, GH0906.89, GH1204.89 and GH0606.91.

Corn was sown in pots with dimension of 25, 22, and 23 cm for diameter of the top, diameter of the bottom, and height, respectively. All experiments except GH1204.89 were planted in a greenhouse soil, which was composed of 25% clay loam soil, 40% perlite, 20% peat moss and 15% sand. Clay loam soil from the Agronomy farm (8 miles west of Ames, Iowa) was used in the experiment GH1204.89. The characteristic water retention curves of greenhouse soil and the clay loam soil were determined in the soil physics laboratory of the Agronomy Dept. at Iowa State University. Water potential gradient was achieved with
tension table and pressure cooker and soil moisture was determined with gravimetric method.

In all experiments, seeds were sown in plate pans and transplanted to pots two weeks after sowing. There were three replicates for each treatment (variety) and there was one plant in one pot for each replicate. All pots were covered with cotton in preventing evaporation from pot soil. Three non-plant pots covered with cotton were used as control to account for soil evaporation. The bench in the greenhouse was north-south oriented and replicates were uniformly distributed on the bench. Plants were watered once every other day, every day, or twice every day, depending on plant size and atmospheric demand, to maintain a well soil moisture condition with water potential in the range of -0.3 to -1 bar in pots. The soil water potential was determined by gravimetric soil water content with retension curve. The amount of water added to each pot was calculated with Plant water use was measured with an electronic balance at one to three days intervals, depending on environmental water demand and pot soil water condition, through whole growing periods. The actual plant water use was corrected with water loss in non-plant pots. The Leaf areas were measured approximately once a week with LI-COR LI3000 (LI-COR, Inc., Lincoln, NE) portable area meter. Transpiration rates were measured irregularly, approximately once every two weeks with LI-COI 6200 steady flow porometer. Leaf water potential measurements were conducted only in GH0606.91, using pressure chamber.

2. Growth Chamber Experiment

A growth chamber experiment (GC0620.90) was conducted to determine water use under continuous stress and moisture conditions. Planting procedure was similar to that used in experiments in the greenhouse. Seeds were sown in the greenhouse on June 20,
1990 and they were transferred to the Growth Chamber 20 days after sowing. The growth chamber micro-environment conditions were 28C/23C for day/night temperature, 8-22h/22-8h for day/night length cycle and the irradiance of approximately one fourth of photosynthetically active radiation in full sun.

There were two treatments in the GC0620.90. One was wet-dry treatment, in which plants were well watered at the beginning of the experiment and were allowed transpiration without additional water. The other treatment was wet-wet, in which pots were kept well watered through the whole experiment. Leaf areas were measured pre-experiment. Plant water use was measured every two hours in the beginning of the experiment and the measurement interval was gradually increased to 8 hours at the end of the experiment, by weighing pots. Leaf temperature, chamber air temperature, humidity and radiation were recorded hourly during the 3 days experiment.

3. Field Experiment

The plots of field experiments were located at Iowa State University Agronomy Farm, 8 miles west of ISU campus.

3.1. 1990

A 3 x 3 Latin square experiment design with defoliation treatment on P3379 and P3343 was used in FE0503.90. Defoliation was intended to use as leaf area treatment but it was not analyzed. The three levels of treatment were: non-defoliation, two leaf defoliation and four leaf defoliation from bottom of plant. Defoliation was conducted on August 5, 1990. There were three replicates in each level of the treatment. The two hybrids were planted adjacent to each other in each square on May 3, 1990. Each square had four rows,
with row length of 7.6 m, for each hybrid. Each row was 0.77 cm wide and ran in a north-south direction. Four rows of sorghum (P8086) as reference were planted east of the Latin square on June 3, 1990.

Because of a large number of plots, soil was only sampled in three layers from soil surface with layer depth of 30 cm for moisture determination. The samplings were conducted on June 25, July 23, August 31 and September 27, 1990 with JMC Environmentalist's sub-soil probes and weighing method was used to obtain gravimetric soil water content. Leaf areas and transpiration rates were measured once a month. The yields were harvested from middle two rows with a length of five meters of each plot at the end of growing season (October). Grains were dried in the oven for four days with oven's temperature of 60 C.

3.2. 1991

The field experiment in 1991 was three replicate plots for each variety with four rows for each one. Plot size was three times larger than that of 1990. Sorghum was planted in the same position as in 1990. The defoliation treatment was discontinued. Five layers (30 cm per layer) of soil were sampled for moisture determination, approximately once a month (June 30, July 16, August 14, and October 7). Transpiration rates, leaf areas and leaf water potentials were measured in the early and late growing season using the same method as used in greenhouse experiments.

Three plants in each replicate were dug early (June 19) and middle (July 18) season to determine root/leaf area ratio. Roots were washed, and dried in oven. Root/leaf ratio was determined by the ratio of dry weight of seminal and second branching adventitious roots to total plant leaf area. Yields were harvested from middle two rows with a length of 10 m at the end of season. Grain was dried in the same method as in 1990.
The t-test of mean was used for soil moisture and yield and the paired t-test was used root/leaf ratio between P3343 and P3379.
RESULTS

1. Morphology

1.1. Plant height and leaf area

Development rates for plant leaf area and plant height are presented in Fig. 1. Both leaf area and plant height of maize (P3343 and P3379) reached maximum about 80 days after sowing (DAS). Total leaf area of P3379 was greater than P3343 through the whole growing period (Fig. 1a). On the other hand, P3343 was taller than P3379 (Fig. 1b). Sorghum behaved differently from maize. Its leaf area developed beyond 80 DAS (Fig. 1a) but its height reached maximum at 65 DAS (Fig. 1b). Measurements of plant height and leaf area were not only conducted in greenhouse studies but also in field experiments.

Leaf areas and plant height of both greenhouse and field experiments are summarized in Table 1. Significance of differences was evaluated by the t-test of means. Leaf areas of P3379 were significantly greater than those of P3343 in the field studies (FE0503.90 and FE0513.91) in both earlier and mature stages. Significance in t-test was only shown in GH0908.89 for the greenhouse studies. Heights of P3343 were significantly greater than those of P3379 at 33 DAS in GH1204.89 and 62 DAS for FE0513.91.

1.2. Root

Table 2 presents ratio of weight of dry branching roots to leaf area of FE0513.91. P3379 had greater root/leaf ratio in both early and mature stages with significance of 0.1 and 0.2, respectively, with the t-test of means.
2. Water Use and Transpiration Rates

P3343 and P3379 responded differently in water use (Fig. 2). P3379 used more water than P3343 in early stages from 25 DAS to 55 DAS (Fig. 2a). Water use was very close at the later stages, after 60 DAS. As a result of greater daily water consumption, P3379 used more water in overall growth than P3343 (Fig. 2b). However, unit leaf area daily (UADWU) water use was similar for P3343, P3379 and P8086, with greatest magnitude in the early stages, decreasing during the first 60 DAS and the UADWU of P3379 was smaller than that of P3343 afterward (Fig. 2c).

Fig. 3 shows water use rates of P3379 and P3343 for two treatments, wet-dry and wet-wet. Under the wet-wet condition, water use rate of P3379 was lower than that of P3343 in the beginning of the experiment (0 to 7 hours after initial setup) but the former was greater than the latter 7 hours after initial setup, and remained so for the 30 hour experiment. However, under the wet-dry condition, the water use rate of P3379 was much greater than P3343 in the early period then it dropped off linearly at hour 11. On the other hand, P3343 had a lower water use rate from the beginning of the test and remained relatively constant water use rate longer than P3379 before its water use rate decreased.

Field measurements showed that the transpiration rates of P3343, P3379 and P8086 were 1.62, 2.22 and 3.34 mmol m\(^{-2}\) s\(^{-1}\), respectively under similar light conditions and leaf water potential (Table 3). Table 4 shows the transpiration measurements in the greenhouse. Transpiration rates of P3343 were greater than P3379 in moist soil but those of P3379 exceeded P3343 in dry soil.

There were some difference in response of leaf resistance to irradiance between P3343 and P3343 (Fig. 4) in the field. The difference was more profound in the region of
low irradiance (from 0 to 200 w m\(^{-2}\)) in which leaf resistance of P3343 was greater than that of P3379 under the same irradiance.

3. Soil Moisture, Wilting Points and Silking Date

The permanent wilting points were 0.083, 0.073 and 0.063 (gravimetric soil water content) for P3343, P3379 and P8086, respectively from the greenhouse studies.

Soil moisture in field studies was summarized in Table 5. There were no statistically significant differences in soil moisture between the two varieties. However, there were different patterns of soil moisture change for P3343, P3379 and P8086 (sorghum) in the growing seasons (Fig. 5). Fig. 5 shows mean soil moisture (gravimetric water content) and precipitation during the field experiments of 1990 and 1991. In the early season (June 30) of 1991, the soil moisture in P3343 plot was lower than that of P3379 (Fig. 5a). The difference decreased during the season (July 16), and the soil moisture of P3343 was greater than that of P3379 by Aug. 14. The difference increased by the end of season (Oct. 7) by 0.01 (equivalent to 3.81 cm water in the 150 cm soil profile). Soil moisture of P8086 (sorghum) steadily decreased and remained lower than both P3379 and P3343 (corn), throughout the growing season and did not recover as did soil moisture in the replicated plots. The P8086 appeared to be actively developing while P3343 and P3379 appeared senescent late in the study.

A different soil moisture change pattern was observed in 1990 (Fig. 5b). Soil moisture for P3379 was greater than that of P3343 from mid season to the end of the season. A gradual decrease of soil moisture was observed for P8086. Fig. 5c indicates that the year 1990 was wetter than 1991 in the early half of the season. The soil moisture content during 1990 never fell as low as the maximum value observed in 1991. During the
season of plentiful moisture (1990) P3343 appeared to use the greater moisture, but had relatively reduced consumption under drier conditions (1991).

Silking dates for P3343 and P3379 were July 18 and July 15 in FE0513.91, respectively.

4. Yields

No significant differences in yield between these two varieties were observed in field studies. (Table 6). However, yield test data provided by Iowa State University Cooperative Extension (Zigler et al., 1988, 1989, 1990) showed that P3379 has a greater yield than P3343 in five of ten tests (Table 7). The differences in yield of these two varieties were smaller in the wetter year (1990), greatest in the moderately dry year (1989) and intermediate for the very dry year (1988). This pattern was shown in Fig. 6, in which yield ratio of P3343 to P3379 were plotted for each test district according to observed rain fall in growing season (May to Sept.). A ratio of one indicates the two varieties had the same yield and the ratio of greater, or smaller than one means the yield of P3343 was greater, or smaller than that of P3379, respectively. The yields of P3379 and P3343 were similar in low and high precipitation sites. The yield of P3379 was greater than P3343 when precipitation totaled from 18 to 25 inches.
DISCUSSION

1. Morphology

The greater total leaf area of P3379 (Fig. 1a and Table 1) may increase its photosynthetic products. However, this advantage may be limited if planting density is allowed to vary. Light interception is determined by leaf area index (LAI) and leaf orientation. A greater LAI with horizontal orientation may decrease light penetration into the canopy and reduce light interception by lower leaves (Gates, 1980; Norman, 1979). A greater leaf area increases transpiration and evapotranspiration ratio, i.e., the evapotranspiration is contributed more by transpiration than by evaporation (Howell, 1979).

The long period of leaf development for sorghum (Fig. 1a) may account for the steady increase of water use observed (Fig. 2a, b) throughout the study period.

Root weight/leaf area ratio may indicate the capability for plant water extraction from the soil. Higher root weight/leaf area ratio may mean that there would be a potential to extract more water from soil which could result in a higher transpiration rate. Higher root weight/leaf area ratio for P3379 (Table 2) may contribute to its greater transpiration rates and use water (Table 3, 4, Fig. 2a, and 3).

2. Water Use and Transpiration Rates

Plant water use is a function of transpiration rate, leaf area and atmospheric demand. The periodical change of daily water use in Fig. 2a was due to transpiration rate and leaf area while the daily fluctuation was caused by changes in atmospheric demand. The leaf area was the dominant effect in the periodical change. The peak daily water use for both P3343
and P3379 were around 80 DAS (Fig. 1a) when plants had maximum total leaf area (Fig. 2a). Though leaf transpiration rate may be greater pre-peak daily water use, its effect was blocked by increasing in leaf area. Decrease of daily water use post the peak may be due to decreasing leaf transpiration rates and atmospheric demand.

A greater daily water use of P3379 led to a greater cumulative water use (Fig. 2b). Unit area daily water use (UADWU) was calculated by dividing daily water use with total leaf area. The drop of UADWU in the early growing period (Fig. 2c) was probably due to the decreasing portion of water loss by evaporation from the soil. In the early stage, when daily transpiration was small, pot evaporation significantly influenced the UADWU. The UADWU gradually decreased after 85 DAS due to leaf aging. The lower UADWU of P3379 than that of P3343 after 60 DAS may be due to the shortage of water supply from pot since P3379 had a greater total leaf area and a greater use rate (Fig. 3) and pot soil water of P3379 would be used up sooner than that of P3343.

P3379 used more soil water in the dry year (Fig. 5a) and it may be because it had a greater leaf area and root system, and a lower permanent wilting point. Root development might be reduced in the wet year, especially, if wet in the early growing season (1990). The greater soil moisture consumption by P3343 in 1990 (Fig. 5b) may be due to the greater precipitation and fewer layers of soil sampled (3 layer). Roots of P3343 may be located in the area near soil surface and it would consume more water if there are more precipitation events since precipitation recharges the top soil first.

The greater transpiration rate for P3379 under dry conditions in the greenhouse (Table 4) was probably due to the bigger root system (Table 2) and possibly to a lower permanent wilting point. High transpiration rates at low leaf water potential in the field for all plants (Table 3), compared to low transpiration rates with high leaf water potential (Table 4) in the greenhouse, may be due to high light intensity and to a bigger root system in the
field. A higher leaf resistance of P3343 in response to the same irradiance may result in a lower transpiration rate in P3343. Also the nature of the osmotic adjustment by the plant was not known nor studied.

3. Drought Resistance and Water Use Efficiency

Yield responses of P3379 and P3343 to different water conditions (Table 7 and Fig. 6) may result from their differences in morphological and physiological characteristics. This study has identified some features that may influence drought resistance.

Greater leaf area, bigger root system, higher transpiration rate, and greater total water use appear to benefit P3379 under conditions of sufficient soil water. Because water and CO$_2$ share the same pathway between the atmosphere and the leaf cell, greater transpiration may mean a greater leaf conductance for CO$_2$.

Low permanent wilting point leads to a greater availability of soil water. With low permanent wilting point and bigger root systems, P3379 could have some advantage under moderate drought stress.

However, under prolonged drought the greater water demand of P3379 would not be an advantage. Under severe drought, limited available water would be quickly used up and the plant with high water demand like P3379 would suffer from further drought.

Because of greater water consumption, water use efficiency of P3379 may be lower than that of P3343. Additional studies of osmotic adjustment, stomate response to moisture stress, mechanic for polination under water stress and aborted grain under stress should be considered in the identification of drought resistant plant characteristics.

From the ecological point of view, P3379 is a water spender in term of drought resistance and such that it uses water quickly in the available conditions. P3379 may have
higher yield than P3343 under no and mild drought conditions. However, it may likely suffer as much as P3343 under severe drought. Because of the greater consumption of water, P3379 could result in a greater reduction of soil water under condition of limited water recharge.

A consideration of variety selection for a crop needs to be made on the basis of soil water condition and long term precipitation forecasting. Under a short term drought stress, a part of season drought or a single year drought, P3379 would have a better yield. Long term drought (years) might reduce the yield of P3379. Climate analysis to assess the severity and duration of drought periods together with biological understanding of drought tolerance could be used to optimise variety selection and management.
REFERENCES


Figure 1. Total plant leaf area (GH0908.89) and plant height (GH1204.89) of corn and sorghum in greenhouse
Figure 2. Water use in the greenhouse (GH0908.89)
Figure 3. Water use in wet and continuous dry conditions in the growth chamber (GC0620.90)
Figure 4. Response of leaf resistance to irradiance gradient measured on July 31 in FE0513.91, the probability of the coefficient differences being real is \( P=0.2113 \), a: P3343; b: P3379
Figure 5. Soil moisture and precipitation in the field experiments: a. soil moisture in 1991, b. soil moisture in 1990, c. precipitation.
Figure 6. Precipitation (May to September) vs. yield ratio of P3343 to P3379 (yield data from 1988-1991 Iowa corn yield test reports by Cooperative Extension Service, Iowa State University)
Table 1. Plant height and area of P3343 vs. P3379

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<th>P3379 avg</th>
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•**, ** significant of P3379 over P3343 at 0.05 and 0.01, respectively, in the t-test of means
•* significant of P3343 over P3379 at 0.05 in the t-test of means
height (ht) and area of plant in cm and cm², respectively
Table 2. Ratio$^1$ of branching root weight to leaf area (FE0513.91)

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1. ratio in mg cm$^{-2}$
2. mean difference significant at P=0.0127, with paired t-test
3. mean difference significant at P=0.1272, with paired t-test

Table 3. Transpiration rate vs. leaf water potential
8/19/91, FE0513.91

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PPFD, photosynthetic photon flux density in µmole m$^{-2}$ s$^{-1}$
trsp, transpiration rate in mmol m$^{-2}$ s$^{-1}$
potential, in bars
Table 4. Transpiration rates and leaf water potential in wet and dry dry soil condition (GE0606.91)

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PPFD, photosynthetic photon flux density in µmole m\(^{-2}\) s\(^{-1}\)
trp, transpiration rate in µmole m\(^{-2}\) s\(^{-1}\)
potential, in bars
soil moisture, in g g\(^{-1}\)
Table 5. Soil moisture of field experiments

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1, two side-significance level of the t-test of means

Table 6. Yields\(^1\) in FE0503.90 and FE0513.91

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1, yield in bushels acre\(^{-1}\)
2, two-sided significance level of the t-test of means
Table 7. Yield test\(^1\) and precipitation

<table>
<thead>
<tr>
<th></th>
<th>P3343 yield(^2)</th>
<th>P3379 yield</th>
<th>ratio of P3343/P3379</th>
<th>precip(^3)</th>
<th>sig.(^4)</th>
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<td>-D5</td>
<td>103</td>
<td>110</td>
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1, data from 1988, 1989, and 1990 Iowa corn yield test report by Cooperative Extension Service, Iowa State University
2, corrected dry yield in bushels acre\(^{-1}\)
3, cumulative precipitation from May to October in inches
4, least significant difference of P3379 over P3343
PAPER 2

EVALUATION OF CORN HYBRID WATER USE WITH A COMPUTERIZED MODEL
Evaluation of corn hybrid water use with a computerized modeling

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(to be submitted to Agronomy Journal)
ABSTRACT

A computerized model of corn (*Zea mays* L.) transpiration was developed and verified. The model includes computation of temperature and vapor profiles in a corn canopy, radiation penetration in the canopy, and developments of leaf area index and plant height. Experimental data for greenhouse and field studies using Pioneer hybrids 3343 (P3343) and 3379 (P3379) were used to verify the model. The study indicated that the computed plant water use and leaf area development agree well with measurements. Sensitivity study showed that plant total leaf area significantly influenced plant water use, especially when leaf area index was low. Increase of leaf area with a fixed planting density would increase plant water use in a growing season. The effect of silking date on plant water use was not as significant as leaf area, although silking date is an indicator of plant water use. The model is applicable in evaluation of phenological, morphological and physiological differences that influence transpiration.
INTRODUCTION

Studies of corn water use of Pioneer hybrids 3343 (P3343) and 3379 (P3379) (Zhang and Taylor, 1992) indicate that the differences in physiological, morphological and phenological characteristics in corn (*Zea mays*) hybrids are primarily responsible for differential water use. Descriptive modeling was used to understand and quantify these effects.

In some plant physiological models, stomatal conductance is either estimated from water transport in the plant (e.g., Running, et al. 1975) or by using a residual method (de Wit, 1978; Ng and Loomis, 1984). These approaches have limitations as they require extensive instrumentation to measure water transport in the plant. Therefore, the estimation might be inconvenient or inaccurate. The mechanistic approach is limited by the assumption that a plant's stomatal conductance is independent of varieties and species. On the other hand, existing climatic models of evapotranspiration are both complicated and often too coarse for estimating plant transpiration. For example, CERES-MAIZE (A simulation model of maize growth and development) requires extensive information of soil physical properties, soil fertility, plant genetic characteristics and weather for input. The basic model is not configured to evaluate leaf transpiration based on morphological, physiological and phenological differences.

This paper describes a model for estimating corn transpiration developed for this project. The purposes of this model are 1) to evaluate physiological, morphological, and phenological effects on water use, 2) to estimate water use efficiency of corn hybrids, 3) to estimate effects on total crop water use and yield. The model is descriptive and may ultimately be used to modify a version of CERES-MAIZE for plant process evaluation of the traits being investigated in this study.
MODEL DEVELOPMENT

The main assumption of the model is that the leaf resistance is the main biological factor controlling corn plant transpiration. Since the purpose of this model is to evaluate effects of leaf area, leaf resistance and silking date on transpiration, we assume corn is not under soil moisture stress in this simulation.

1. Plant Transpiration

Overall plant transpiration is determined by transpiration rate, leaf area and time interval. Therefore, plant transpiration \( m \) can be defined as

\[
TR = \sum_{i=1}^{n} (LAI_iE_i) T
\]

where \( i \) is layers in a corn canopy from 1 to \( n \), \( LAI_i \) and \( E_i \) are leaf area index and transpiration rate \( (m \text{ s}^{-1}) \) at layer \( i \), respectively and \( T \ (s) \) is time interval.

Transpiration rate is influenced by atmospheric water demand, soil water condition and plant physiological characteristics. Transpiration rate \( (m \text{ s}^{-1}) \) is described by the method of bulk vapor transfer (Deardorff, 1978):

\[
E = \frac{\rho_a q_l - q_a}{\rho_v (r_l + r_a)}
\]

where \( \rho_a \) and \( \rho_v \) are densities of air and vapor in kg m\(^{-3}\) · q and \( r \) are specific humidity (kg kg\(^{-1}\)) and resistance \( (s \text{ m}^{-1}) \), respectively and subscripts, \( l \) and \( a \), stand for leaf and air, respectively.
Specific humidity ($q$) is related to vapor pressure $e$ (KPa) by (Rosenberg et al., 1983):

$$q = 0.622 \frac{e}{P}$$  

where $P$ is standard atmospheric pressure (KPa).

Substituting (3) into (2) and transpiration rate becomes:

$$E = \frac{0.622 \rho_a e_l - e_a}{P \rho_v r_l + r_a}$$  

The $P$, $\rho_a$ and $\rho_v$ are assumed to be constants. The transpiration ($E$) is function of leaf and air vapor pressure gradient ($e_l - e_a$) and total resistance of leaf and air ($r_l + r_a$). Leaf transpiration rate is proportional to vapor pressure gradient and inversely proportional to the total resistance.

Leaf vapor pressure is considered to be a saturated vapor pressure (Gates, 1980) and saturated vapor pressure has been related to temperature as follows (Rosenberg et al., 1983):

$$e_{sat} = 0.61078 \exp\left(\frac{17.269 T}{237.3 + T}\right)$$  

Therefore, the vapor pressure gradient can be determined by leaf temperature and air vapor pressure. Leaf temperature and air vapor pressure vary along a plant canopy profile since they are functions of air temperature in the canopy.
2. Temperature and Vapor Profile

2.1. Temperature profile

According to Norman (1979), the temperature profile within a canopy can be expressed as:

$$T_{a(z)} - T(H) = \frac{H}{\rho_a C_p K_s} \left[ \sum_j \frac{H_{c,j}}{2} \left( 1 - \frac{z^2}{H^2} \right)^2 + H_{soil} \left( 1 - \frac{z}{H} \right) \right]$$

where $z$ is a level in the canopy, $H$ is the height of the canopy, $T_{a(z)}$ is the air temperature at $z$ level of the canopy, which is in layer $j$, $T(H)$ is the air temperature at the top of canopy (assumed same as air temperature outside canopy), $H_{c,j}$ is canopy heat flux (w m$^{-2}$) in layer $j$ of the canopy, which is a function of the leaf to air temperature gradient and of the leaf boundary resistance, $H_{soil}$ is heat flux from soil (w m$^{-2}$), and $\rho_a$, $C_p$ and $K_s$ are constants of air density (1.18 kg m$^{-3}$), specific heat of air at constant pressure (1004 J C$^{-1}$ kg$^{-1}$) and the turbulent exchange coefficient for sensible heat (0.186 m$^2$s$^{-1}$), respectively.

2.2. Vapor profile

The equation analogous to (6) can be written for the water vapor profile as follows

$$e_{a(z)} - e(H) = \frac{H P}{0.622 \rho_a K_v} \left[ \sum_j \frac{E_{c,j}}{2} \left( 1 - \frac{z^2}{H^2} \right)^2 + E_{soil} \left( 1 - \frac{z}{H} \right) \right]$$

where $e_{a(z)}$ is the air vapor pressure (KPa) at $z$ level of the canopy, $e(H)$ is the air vapor pressure (KPa) at the top of canopy (assumed as air vapor pressure outside canopy), $E_{c,j}$ is vapor flux (kg m$^{-2}$ s$^{-1}$) in layer $j$ of the canopy, which is a function of the leaf and air vapor pressure gradient and the total leaf resistance, $E_{soil}$ is the vapor flux (kg m$^{-2}$ s$^{-1}$) from soil and $\rho_a$, $P$ and $K_v$ are constants of air density (kg m$^{-3}$), standard air pressure (KPa) and the
turbulent exchange coefficient for vapor, respectively. \( K_v \) is close to \( K_s \) under stable conditions (Rosenburg et al., 1983).

In order to simplify the model, \( \Sigma H_{c,i} \), \( H_{soil} \), \( \Sigma E_{c,i} \) and \( E_{soil} \) in (6) and (7) are assumed to be constants. Their effects on transpiration are evaluated in sensitivity test.

2.3. Leaf temperature

The energy balance for a crop canopy can be written as (Jackson 1982):

\[
R_n = G + H + \lambda E
\]  \hspace{1cm} (8)

where \( R_n \) is the net radiation (\( \text{w m}^{-2} \)), \( G \) is heat flux below the canopy (\( \text{w m}^{-2} \)), \( H \) is the sensible heat flux (\( \text{w m}^{-2} \)), and \( \lambda \) is the latent heat of vaporization. In their simplest forms, \( H \) and \( E \) can be expressed as:

\[
H = \rho C_p (T_c - T_a)/r_a
\]  \hspace{1cm} (9)

\[
\lambda E = \rho C_p (e_{c,sat} - e_a)/[\gamma (r_a + r_c)]
\]  \hspace{1cm} (10)

where \( C_p \) is the heat capacity of air (\( \text{J kg}^{-1} \text{C}^{-1} \)), \( T_c \) is canopy temperature, \( T_a \) is the air temperature (\( \text{C} \)), \( e_{c,sat} \) is the saturated vapor pressure (\( \text{Pa} \)) at \( T_c \), \( e_a \) is the vapor pressure of the air (\( \text{Pa} \)), \( \gamma \) is the psychrometric constant (\( \text{Pa C}^{-1} \)), \( r_a \) is the air resistance (\( \text{s m}^{-1} \)), and \( r_c \) is the canopy resistance (\( \text{s m}^{-1} \)) to vapor transport.

Combining (8)-(10), assuming that \( G \) is negligible, we obtain:

\[
T_c - T_a = \frac{r_a R_n}{\rho C_p \Delta + \gamma (1 + r_c/r_a)} \left( \frac{e_{a,sat} - e_{c,sat}}{\Delta + \gamma (1 + r_c/r_a)} \right)
\]  \hspace{1cm} (11)
where $\Delta$ is:

$$\Delta = \frac{e_{a, sat} - e_a}{T_c - T_a} \quad (12)$$

3. Resistance

3.1. Boundary air resistance

The boundary air resistance for a leaf is defined by Gates (1980) as:

$$r_a = k_2 \left( \frac{W^{0.2}D^{0.3}}{V^{0.5}} \right) \quad (13)$$

where $k_2$ is a constant ($200 \text{ s}^{-0.5} \text{ m}^{-1}$), $W$ and $D$ are leaf width and dimension (m), and $V$ is wind speed (m s$^{-1}$).

3.2. Leaf resistance

Total leaf resistance is mainly controlled by stomatal opening, which is sensitive to irradiance. The ability of stomatal opening changes with leaf age. Therefore, leaf resistance is a function of light intensity and leaf age.

The functional relationship between leaf resistance and irradiance for a single leaf has been suggested to approximately be a hyperbolic function (Turner and Begg, 1973) and has a general form of:

$$r = aR^b \quad (14)$$

where $R$ is the irradiance in W m$^{-2}$, and $a$ and $b$ are empirical constants in which $b$ is negative. According to Dwyer and Stewart (1986), leaf resistance at fully sun light is related with leaf age as:
\[ r_f = r_{f, r} + 18.8A_l \]  \hspace{1cm} (15)

where \( r_f \) is leaf resistance at near full sunlight, \( r_{f, r} \) is \( r_f \) at full expansion of leaf, and \( A_l \) is the date relative to leaf full expansion in term of week.

It is assumed here that the leaf aging effect on leaf resistance is the same for sunny leaf and shady leaf. Therefore, (15) becomes:

\[ r = aR^b + 18.8A_l \]  \hspace{1cm} (16)

The leaf resistance \( r \) is used to calculate transpiration in the plant canopy.

4. Wind profile

Wind profile is described by Norman (1979) as:

\[
V_z = \begin{cases} 
V_H [1 + M(1 - \frac{z}{H})]^2 & \text{for } H/5 \leq z < H \\
\frac{\ln(z/z_{0,5})}{\ln(H/5z_{0,5})} & \text{for } z < H/5
\end{cases}
\]  \hspace{1cm} (17)

where \( M \) is a constant that may vary with canopy characteristics (assuming 2 for maize), \( z \) is a level within canopy (m), \( H \) is the height of a canopy, \( z_{0,5} \) is the thin layer above soil (5 mm), the \( V_z \) is the wind speed at level \( z \) (m s\(^{-1}\)), \( V_H \) and \( V_{H/5} \) are wind speeds (m s\(^{-1}\)) at the top of canopy and one fifth height of canopy, respectively. The wind speed is used to calculate air resistance in (13).
5. Leaf Area Index (LAI)

5.1. LAI model

LAI model developed by Flesh and Dale, 1987 is used. In this model, maize leaf growth is divided into three periods. The first period is from planting to silking and its equation is:

$$LA_{\text{NC}} = \frac{L_{\text{Amax}} \times \text{POP}/10}{1 + 100L_{\text{Amax}} \times \exp(-20.21NC^2 \times HYB_1 NC)}$$  \hspace{1cm} (18)

where NC is normalized thermal calendar, $LA_{\text{NC}}$ is the LAI at NC (normalized thermal calendar), $L_{\text{Amax}}$ is the maximum leaf area ($m^2$), POP is the population density (thousand plants per hectare), and HYB$_1$ is a hybrid constant (assumed as 5.86 for Pioneer hybrids).

The second period is from silking to the NC of 0.87 and its equation is:

$$LA_{\text{NC}} = LA_1[1-(NC-0.5)(0.86-HYB_2)]+0.37(NC-0.5)$$ \hspace{1cm} (19)

where $LA_1$ is the actual maximum LAI (occurs at silking date), HYB$_2$ is another hybrid constant (assumed as 0.67).

The third period occurs after the date of NC greater than 0.87 and it is defined as:

$$LA_{\text{NC}} = LA_2 - 0.15D$$ \hspace{1cm} (20)

where $LA_2$ is the LAI value at the end of the second period, and D is the number of days past the date on which NC equals to 0.9. LAI falls rapidly to zero during the third period.

LAI is used to calculate leaf transpiration in (1).
5.2. Normalized thermal crop calendar

The NC was calculated for each LAI (Flesch and Dale 1987) as:

\[
NC_t = \begin{cases} 
\frac{\Sigma FT_t}{\Sigma FT_s} & \text{before silking} \\
0.5 + 0.5 \frac{\Sigma FT_t - \Sigma FT_s}{\Sigma FT_m - \Sigma FT_s} & \text{after silking}
\end{cases}
\]  

(21)

where \( NC_t \) is the NC at day \( t \), \( \Sigma FT_t \), \( \Sigma FT_m \) and \( \Sigma FT_s \) are the accumulated temperature function from planting to day \( t \), from planting to maturity and from planting to silking, respectively.

The temperature function is defined as (Coelho and Dale, 1980):

\[
FT = \begin{cases} 
0.027T - 0.162 & ; \text{6 C} \leq T < 21 \text{ C}, \\
0.086T - 1.41 & ; \text{21 C} \leq T < 28 \text{ C}, \\
1.0 & ; \text{28 C} \leq T < 32 \text{ C}, \\
-0.083T + 3.67 & ; \text{32 C} \leq T < 44 \text{ C}, \\
0 & ; \text{6 C} > T \text{ or} \geq 44 \text{ C}.
\end{cases}
\]  

(22)

where \( T \) is the air temperature.

The crop thermal calendar is used to prediction LAI in a growing season in (18)-(20).

5.3. LAI profile

\( \text{LAI} \) in canopy profile is define as:

\[
\text{LAI}_{\text{NC}_{i}} = \frac{\text{LAI}_{\text{NC}}}{n}
\]  

(23)

where \( \text{LAI}_{\text{NC}_{i}} \) is \( \text{LAI}_{\text{NC}} \) at layer \( i \), \( n \) is the number of layers in a canopy and is 10 at and after silking date and is defined:
\[ n = \begin{cases} 10 & \text{at and after silking} \\ 10 - \text{PSW} & \text{pre-silking} \end{cases} \] (24)

where PSW is the number of weeks before silking date.

6. Shortwave Radiation Penetration

Irradiance on each layer of canopy is used in determining leaf and air temperature, and resistance in canopy profile. The penetration of radiation into canopy for spherical orientation (assumed corn has this orientation) is defined as (Norman, 1979):

\[ R = R_0 \exp\left(-\frac{\mu s}{2}\right) \] (25)

where \(R_0\) is the radiation at the top of canopy, \(\mu\) is the leaf area density (m\(^2\) of one-sided leaf area per m\(^3\) of canopy), \(s\) is the distance radiation traveled. Since the leaf area is assumed to be evenly distributed along the canopy. The leaf area density can be define as:

\[ \mu = \frac{LAI}{H} \] (26)

where \(H\) is the height of canopy.

The distance radiation travels is:

\[ s = H(1 - \frac{i}{n}) \] (27)

where \(n\) is the number layers the canopy is divided, \(i\) is a layer in the canopy (layer is counted from ground to the top of canopy).

These functions are used to calculate irradiance in the canopy.
7. Plant Height and Leaf Dimension

The development of plant height (m) is defined as:

\[
H = \begin{cases} 
H_{\text{max}} \frac{D-D_p-10}{H_{\text{max}}D_s-D_p-10} & \text{at and after silking} \\
0 & \text{pre-silking}
\end{cases}
\]

where \( H_{\text{max}} \) is the maximum leaf plant height (m), \( D \) is the days after planting (sowing), \( D_p \) and \( D_s \) are planting and silking dates, respectively. Emergence of corn seed is assumed at 10 days after planting. \( H \) linearly increases with \( D \) before silking date.

Plant height is used to calculate the distance radiation travels in (26) and temperature and vapor profiles in (6) and (7).

The average leaf width (m) is defined as:

\[
W = \begin{cases} 
0.08 + 0.02 + 0.06 & \text{at and after silking} \\
0.02 + 0.06 & \text{pre-silking}
\end{cases}
\]

The leaf dimension (length) (m) is defined as:

\[
L = \begin{cases} 
0.8 & \text{at and after silking} \\
0.15 + 0.65 & \text{pre-silking}
\end{cases}
\]

Average leaf width and dimension are assumed to be 0.02 and 0.15 (m), respectively when a corn seed emerges, and they linearly increase until the plant silks. The leaf width and dimension are assumed to remain constant after silking.

The leaf width and dimension were used to calculate air resistance in (13).
8. Numerical Solution

The model is coded in C language. The whole program consists of 11 functions which are contained in four files. Constants and macros of the program are contained in a header file. The whole program is modular. The equation (11) of the energy budget is solved by an iterative method.

The inputs for the model include daily and hourly weather data, maximum plant leaf area, planting date, silking date, maturity date, and planting density. Outputs are daily transpiration, daily plant water use, cumulative water use, total plant area and leaf area index.

The model enables the evaluation of the contribution of leaf resistance coefficient (with light), phenology (silking date), plant height, and maximum LAI to corn water use under conditions of sufficient soil moisture. The effects of plant water potential and root to leaf ratio are not modeled.
RESULTS AND DISCUSSION

The data used in running of this model were from greenhouse and field studies reported by Zhang and Taylor (1992). The experiments are identified according to experiment type and the date that seed were sown. The first two letters of names indicate experiment type: GH, GC and FE for greenhouse, growth chamber and field experiments respectively, and numbers indicate sowing dates. For instance, GH0615.89 stands for a greenhouse experiment in which seeds were sown on 15 June 1989. Biological data used in model validation are summarized in Table 1. Leaf resistance coefficients were obtained by hyperbolic curves fitting of data from FE0513.91 (Fig. 1).

Weather data for FE0503.90 and FE0513.91 were obtained from an automatic weather station near the experiment plots (60 m) and weather data for GH1204.89 were gathered specifically for the experiment.

1. Model Verification

1.1. Water use

The model was tested with the greenhouse (GH1204.89) and field (FE0513.89) experiments. Measurements of leaf water use and leaf resistance were made for the adaxial side only. Our measurements indicated that adaxial transpiration accounted for 75% of the total plant transpiration. The model assumed that leaves had one surface only and might have been expected to underestimate total water use by 25%. Figures 2 and 3 compare water use between measured and calculated results for GH1204.89. The computed results agreed well with the measured data for P3343 (Fig. 2a and Fig. 3a). The calculated daily
water use followed the same pattern as the measured one (Fig. 2a). However, the computed water use was much greater than the measured for P3379 (Fig. 2b and Fig. 3b). The calculated daily water use was approximately twice that of the measured after 60 DAS and the calculated total water use was greater than the measured one by 30% at the end of the growing period.

The deviation between the calculated and measured data was most likely due to the leaf resistant coefficients. The calculated and measured values for P3379 in GH1204.89 would agree well if the leaf resistant coefficient of P3343 was used which can be seen in the dotted lines in Fig. 2b and Fig. 3b. This may indicate that there are different responses of corn hybrids to field environment and greenhouse environment. There may be an acclimation effect in the greenhouse so that the difference in the field may be reduced. Also the resistance response coefficient for P3343 may be more representative of both cultivars.

Computation of water use for FE0315.89 (Fig. 4) showed that total water use of P3343 and P3343 would be approximately 60 and 73 kg per plant, respectively, by the end of season. These are equivalent to 16.5 and 20.1 inches of water in soil.

1.2. Leaf area

The estimation of leaf area is based on a normalized crop thermal calendar (NC) and silking date, in which NC determines leaf area growth rate and silking date determines the time that maximum leaf area is reached (Eq. 20). Different silking dates result in different time of maximum leaf area. Comparisons of calculated and measured leaf area are presented in Fig. 5 and Fig. 6. Fig. 5 shows the calculated and measured leaf area of GH1204.89. The calculated values underestimated but generally fitted the time relationship in this experiment. The deviation in leaf expanding stage may be from both NC and silking date. Figure 6 shows leaf area for the whole growing season for both P3343 and P3379 in
the field (FE503.90). Leaf area developed rapidly before silking date, and stabilized or slightly decreased after silking and before maturity, and decreased rapidly after maturity. The calculated data agreed well with the limited number of observations.
2. Sensitivity Tests

2.1. Silking date

The influence of silking date on total plant water use is represented in Fig. 7. Annual plant water use was greatest for silking dates near 195 Julian days. Silking date does not contribute substantially to plant water use from this model. This is because the effects of silking date are canceled by maturity. An early silking date would result in a plant reaching maximum leaf area and great leaf conductance early and this would increase plant water use. However, early silking dates are associated with early maturity which would decrease total plant water use, but silking date does shift the peak of plant water use. If there is lower atmospheric demand in early season, then an early silking date can reduce water use by moving up the peak of leaf area and leaf conductance. In practice, a hybrid with early silking (early maturity) may have low leaf area (Cross, 1990). This would result in low water use.

2.2. Leaf area and plant height

Maximum plant leaf area has a great effect on plant water use (Fig. 8). Increasing total leaf area of 0.2 m² may result in an increase of total plant water use approximately by 10% at a planting density of 2800 acre⁻¹. The effect of total plant leaf area on water use becomes less as the leaf area increases since the less shortwave radiation would transmit through the canopy with an increase of LAI (Eq. 25 and 26). There is a limit of plant water use for increasing of leaf area. The difference in water use between P3343 and P3379 in Fig. 8 is mainly due to leaf resistance coefficients.

Water use diminishes with increased plant height (Fig. 9). The effect of plant height is to reduce wind speed (Eq. 17) and vapor pressure change (Eq. 7) in corn canopy.
2.3. Canopy heat flux and vapor flux

Plant water use increases with an increase of canopy sensible heat flux (Fig. 10). This effect is resulted from increasing water demand in plant canopy. A rise of canopy vapor flux decreases plant water use (Fig. 11). This is because an increase of canopy vapor flux leads to increase in vapor pressure in canopy and the vapor pressure gradient between leaf and canopy is decreased. The increase of canopy vapor flux is mostly due to an increase of surface soil moisture.

Effects of soil heat flux and vapor flux were not tested but they are similar to heat and vapor flux for the canopy. Canopy heat and vapor flux is not normally significant to model results. Less than two kilograms of total plant water use would increase for an increase of canopy heat flux from 50 to 500 \( \text{w m}^{-2} \) and increase of canopy vapor flux of ten times would result in a total water use reduction of five kilograms in a growing season.
CONCLUSION

The model described corn water use and leaf area development through the growing season as showed in validation tests. It can be used to evaluate plant water use in terms of morphological, physiological and phenological differences. Therefore, the model can be useful in describing corn hybrid features related to water use and drought resistance.

Leaf resistance is the most significant biological factor in plant water use. Total plant leaf area is the secondary factor of plant water use. An increase of total plant leaf area by 0.2 m$^2$ with a planting density of 2800 acre$^{-1}$ will result in an increase of water use by 5 kilograms (1.37 inches). Plant height and silking date are not critical factors of plant water use. Wilting point effects were not modeled.

In terms of plant water use, a drought resistant hybrid should have characteristics of lower permanent wilting point, greater leaf resistance and relative small leaf area with a relatively high yield. However, yield is usually associated with a lower leaf resistance coefficient and greater total leaf area. Therefore, the selection of an agriculturally meaningful drought resistant hybrid should be based on yield, plant characteristics, soil and climatic conditions.

Model improvement could include leaf orientation, permanent wilting point and soil moisture such that the model could evaluate their effect and better estimate soil moisture status.
REFERENCES


Ng, E., and R. S. Loomis. 1984. Simulation of growth and yield of the potato crop. PUDOC, Wageningen, the Netherlands.


Figure 1. Correlation between leaf irradiance and leaf resistance on July 31, 1991, the probability of the coefficient difference is $P=0.2113$, a: P3343; b: P3379 (Zhang and Taylor, 1992)
Figure 2. Comparison of measured and calculated daily water use of GH1204.89 using resistance coefficients from FE0513, a: P3343; b: P3379 with two computations, one using coefficient for P3379 and the other using coefficient for P3343.
Figure 3. Comparison of measured and calculated cumulative water use of GH1204.89 using resistance coefficients from FE0513, a: P3343; b: P3379 with two computations, one using coefficient for P3379 and the other using coefficient for P3343.
Figure 4. Computation of cumulative water use in the field of 1991 (FE0513.91) for both P3343 and P3379
Figure 5. Comparison of measured and calculated total plant leaf area of P3343 vs. P3379 for GH1204.89

Figure 6. Comparison of measured and calculated total plant leaf area of P3343 vs. P3379 for FE0503.90
Figure 7. Effect of silking date on total plant water use

Figure 8. Effect of maximum plant leaf area on total plant water use
Figure 9. Effect of plant height on total plant water use

Figure 10. Effect of canopy sensible heat flux on total plant water use
Figure 11. Effect of canopy vapor flux on total plant water use
Table 1. Summary of biological input data used in model validation and sensitivity testing

<table>
<thead>
<tr>
<th></th>
<th>P3343</th>
<th>P3379</th>
</tr>
</thead>
<tbody>
<tr>
<td>FE0513.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>leaf resistance coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>constant a</td>
<td>5299</td>
<td>-0.504</td>
</tr>
<tr>
<td>constant b</td>
<td>2047</td>
<td>-0.353</td>
</tr>
<tr>
<td>max. total leaf area (m²)</td>
<td>0.75</td>
<td>0.79</td>
</tr>
<tr>
<td>leaf height (m)</td>
<td>2.52</td>
<td>2.42</td>
</tr>
<tr>
<td>planting density (1000/A)</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>planting (sowing) date (julian days)</td>
<td>133</td>
<td>133</td>
</tr>
<tr>
<td>silking date (julian days)</td>
<td>196</td>
<td>199</td>
</tr>
<tr>
<td>GH1204.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>max. total leaf area (m²)</td>
<td>0.80</td>
<td>0.84</td>
</tr>
<tr>
<td>leaf height (m)</td>
<td>2.02</td>
<td>1.85</td>
</tr>
</tbody>
</table>
GENERAL SUMMARY

Water use and drought resistance of two corn hybrid P3343 and P3379 were studied in greenhouse and field conditions for three years (1989-1991). Transpiration rate, leaf resistance, daily water use, leaf area, plant height, root weight, and soil moisture were measured in the study. A mechanistic model of corn transpiration was developed and tested.

Our study showed that P3379, compared with P3343, had greater total leaf area, greater plant height, lower leaf resistance, greater water use, lower permanent wilting point, and earlier silking date. These characteristics may indicate that P3379 is a water user in terms of drought resistance, i.e., it uses as much available water as it can to increase its growth and reproduction in order to avoid drought stress. Therefore, P3379 could tolerate mild drought stress with a good yield.

The model described corn water use and leaf area development during a growing season. According to computed results, leaf resistance is the most significant biological factor and total plant leaf area is the second factor in plant water use. Silking date can shift the peak plant water use in a growing season. The computerized model could help agronomists understand how physiological, physiological and phenological factors influence overall corn water use and help to quantify their effects.

In conclusion, the study of these two hybrids (P3343 and P3379) delineated the relationship of plant water use to morphological, physiological and phenological characteristics. To describe the effects of leaf orientation or display, plant water status, and soil moisture, leaf orientation and soil moisture elements should be added to the simulation model.
BIBLIOGRAPHY


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Special gratitude goes to my mother and my mother in-laws for their tremendous support in coming from China to take care of our son.

The last, but not the least, thanks go to my wife for her help, support and encouragement.
APPENDIX A

/* This is "def.h" file and it defines macros and constants */
/* for transpiration simulation program */

#define AD 1.18 /* air density at 20 C kg m^-3 */
#define HC 1004 /* heat capacity of water, J C^-1 kg^-1 */
#define D 0.7 /* leaf dimension, m */
#define W 0.1 /* leaf width, m */
#define ThreshR 20 /* threshold for radiation under which no transpiration occurs, W m^-2 */
#define Rv 461 /* vapor gas constant */
#define LN log /* natural log */
#define K1 9.14 /* constant for air resistance, J m^-2 s^-0.5 C^-1 */
#define K2 180 /* constant for s^-0.5 m^-1 */
#define SB 5.67 /* Stefan-Boltzmann constant W m^-2 K^-4 */
#define HYB1 5.86 /* hybrid factor 1 */
#define HYB2 0.67 /* hybrid factor 2 */
#define TECH 0.186 /* turbulent exchange coefficient */
#define TECV 0.186 /* turbulent exchange coeff. for vapor */
#define LHV 2454000 /* latent heat of vaporization, J kg^-1 */
#define P 100 /* atmospheric pressure, KPa */
#define Hc 200 /* canopy sensible heat flux, W m^-2 */
#define Hs 40 /* soil sensible heat flux, W m^-2 */
#define Ec 0.001240 /* vapor flux Kg m^-1 s^-1 */
#define Es 0.000134 /* vapor flux from soil */
#define G 0.66 /* Gamma, Psychrometric constant KPa C^-1 */

#define e(x) 6.1078*exp(17.269*x/(237.3+x)) /* saturated vapor function */
/* This is "main.c file" and it contains four functions, main(), descrpt(), *
* input_data(), and total_transp(). *
*******************************************************************************/

/* This is main() of the program and it sets some global *
* variable and starts the program *
*******************************************************************************/

* set: a flag for lai function
* d09: date on which nc is 0.9
* lai1: global for lai function
* lai2: global for lai function
*/

#include <stdio.h>
#include <stdlib.h>

int set, d09;
float lai1, lai2;
extern void descrpt();
extern void input_data();
extern void ncal();
extern void total_transp();

main()
{
    set = 0;
    lai1 = 0;
    lai2 = 100;
    descrpt();
    input_data();
    ncal();
    total_transp();
}
void descrpt()
{
    printf("CORN TRANSPIRATION SIMULATION MODEL
");
    printf("DEVELOPED BY HANZHONG ZHANG
");
    printf("CODED IN C
");
    printf("August 1992
");
    printf("Dept. of Agronomy
");
    printf("Iowa State University
");
    printf("DATA REQUIREMENTS
");
    printf("Weather data:
");
    printf("hourly air temperature C
");
    printf("hourly soil temperature C
");
    printf("hourly solar radiation W/m2
");
    printf("hourly relative humidity
");
    printf("hourly wind speed m/s
");
    printf("Plant data:
");
    printf("leaf resistant coeff.
");
    printf("variety
");
    printf("maximum leaf area
");
    printf("maximum plant height
");
    printf("Management data:
");
    printf("planting date
");
    printf("silking date
");
    printf("maturity date
");
    printf("planting density
");
}
/**
 * This is input_data() and it prompts for inputs of file names and input data
 */

* fnamel: file name for hourly weather data
* famee2: file name for daily temperature data
* fiiame3: file name for normalized thermal crop calendar
* fname4: file name for outputs
* coeff1, coeff2: leaf resistant coefficients, 
  \( r=coeff1 \times R^{\coefficient2} \), at silking date
* la1: maximum leaf area
* pop: planting density
* initdate: planting date in julian days
* silkdate: silking date
* matdate: maturity date
* h: maximum plant height
*/

char fnamel[20], fname2[20], fname3[20], fname4[20];
int var, initdate, lastdate, silkdate, matdate;
float pop, h, la1;

void input_data()
{
    char tmp[20];
    printf("Enter hourly weather data file name: \n");
    gets(fnamel);
    printf("Enter daily temperature file name: \n");
    gets(fname2);
    printf("Enter NC file name: \n");
    gets(fname3);
    printf("Enter output file name: \n");
    gets(fname4);
    printf("Enter coefficient 1 for leaf resistance: \n");
    gets(tmp);
    coeff1 = atof(tmp);
    printf("Enter coefficient 2 for leaf resistance: \n");
    gets(tmp);
    coeff2 = atof(tmp);
    printf("Enter maximum leaf area: \n");
    gets(tmp);
    la1 = atof(tmp);
}
printf("Enter maximum plant height: \n");
gets(tmp);
h = atof(tmp);
printf("Enter planting date in Julian day: \n");
gets(tmp);
initdate = atoi(tmp);
printf("Enter terminating date in Julian day: \n");
gets(tmp);
lastdate = atoi(tmp);
printf("Enter silking date in Julian day: \n");
gets(tmp);
silkdate = atoi(tmp);
printf("Enter maturity date in Julian day: \n");
gets(tmp);
matdate = atoi(tmp);
printf("Enter population density in thousands per hectar: \n");
gets(tmp);
pop = atof(tmp);
#include <stdio.h>
#include <stdlib.h>
extern char fname2[];
extern char fname3[];
extern int initdate;
extern int silkdate;
extern int lastdate;
extern int matdate;

int ftsilk, ftmat;
void ftemp()
{
    char buffer[80];
    int d, sset, mset;
    float t1, t2, ft1, ft2, ft, ftsum;
    FILE *fptr1, *fptr2;
    fptr1 = fopen(fname2,"r");
    fptr2 = fopen("ft.s","w");
    sset = 0;
    mset = 0;
    do
    {
        fgets(buffer,80,fptr1);
        sscanf(buffer,"%d %f %f",&d,&t1,&t2);
    }
while(d!=(initdate-1));
ftsum = 0;
do
{
fgets(buffer,80,fptr1);
sscanf(buffer,"%d %f %f",&d,&t1,&t2);
if(t1<6 || t1>=44)
    ft1 = 0;
if(t1>=6 && t1<21)
    ft1 = 0.027*t1-0.162;
if(t1>=21 && t1<28)
    ft1 = 0.086*t1-1.41;
if(t1>=28 && t1<32)
    ft1 = 1;
if(t1>=32 && t1<44)
    ft1 = -0.083*t1+3.67;
if(t2<6 || t2>=44)
    ft2 = 0;
if(t2>=6 && t2<21)
    ft2 = 0.027*t1-0.162;
if(t2>=21 && t2<28)
    ft2 = 0.086*t1-1.41;
if(t2>=28 && t2<32)
    ft2 = 1;
if(t2>=32 && t2<44)
    ft2 = -0.083*t1+3.67;
ft = (ft1+ft2)/2;
ftsum = ftsum+ft;
if(d==silkdate)
    {
    sset = 1;
    ftsilk = ftsum;
    }
if(d==matdate && mset==0)
    {
    mset = 1;
    ftmat = ftsum;
    }
fprintf(fptr2,"%d %fn",d,ftsum);
}
while((feof(fptr1)==0) && (d<(lastdate)));
close(fptr1);
fclose(fptr2);
}

/*********************
* This is ncal() and it computes normalized crop thermal *
* calendar
**************************
* ft: functional temperature
* nc: normalized crop thermal calendar
*/

void ncal()
{
char buffer[80];
int d;
float ft, nc;
FILE *fptr1, *fptr2;
ftemp();
fptr1 = fopen("ft.s","r");
fptr2 = fopen(fname3,"w");
do
{
fgets(buffer,80,fptr1);
sscanf(buffer,"%d %f",&d,&ft);
if(d<silkdate)
    nc = 0.5*(ft/ftsilk);
else
    nc = 0.5+0.5*(ft-ftsilk)/(ftmat-ftsilk);
fprintf(fptr2,"%d %f\n",d,nc);
}
while((feof(fptr1)==0) && (d<(lastdate)));
fclose(fptr1);
fclose(fptr2);
/** This is "transp.c" and it contains total_transp(). the total_transp() 
* and it computes daily and total transpiration with hourly input data. *
*outputs are stored in a file 
*******************************************************************************

* i, n: layer number of total number of layer
* d, day: temperary variables for day
* hr: hour
* ta: air temperature in C
* rh: relative humidity of air
* ts: soil temperature in C
* rad: radiation in W m^-2
* v: velocity of wind in m s^-1
* lai: leaf area index
* tr: transpiration rate in m s^-1
* str: sum of transpiration rate over a profile
* suml, sum: termoporation variables for str
* ThreshR: threshold of radiation below which no 
* calculation of transpiration will be made
* ec: a variable with ENVCND type
* s1, s2: summations of temp. and vapor differences in profile
* w1 and w2: daily and cumulative plant water use
* in g and kg, respectively
*/

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include "def.h"

extern char fname1[];
extern char fname2[];
extern char fname3[];
extern char fname4[];
extern int initdate, lastdate, silkdate;
extern float h;
extern void ncal();
extern float laif();
extern float transp_rate();
typedef struct env {

int d;
int i;
int n;
float ta;
float ts;
float rh;
float rad;
float v;

} ENVCND, *ENVPTR;

float lai, s1, s2;

void total_transp()
{

} FILE *fptrl;
FILE *fpstr2;
FILE *fpstr3;
char buffer1[80];
char buffer2[80];
int day, d, d1, hr, i, n;
float ta, rh, ts, rad, v, str, sum1, sum, wu1, wu2, nc, ht;

ENVPTR ec;
ht = h;
fptrl = fopen(fnamel, "r"); /* open file to read */
printf("after the first open\n");
fpstr2 = fopen(fname3, "r"); /* open file to read */
fpstr3 = fopen(fname4, "w"); /* open file to write */
do
{
    fgets(buffer1, 80, fptrl);
    sscanf(buffer1, "%d %d %f %f %f %f %f", &d, &hr, &ta, &rh, &ts, &rad, &v);
}
while(d!=(initdate+14) && feof(fptrl)==0);
if(feof(fptrl)!=0)
{
    printf("Error message: check the file - %s\n", fnamel);
    printf(" and run the program again.\n");
    exit;
}
do
{
    fgets(buffer2, 80, fpstr2);
sscanf(buffer2,"%d %f", &d1,&nc);
}
while(d1!=(initdate+14));
if(feof(fptr2)!==0)
{
    printf("Error message: check the file - %s\n", fname2);
    printf(" and run the program again.\n");
    exit;
}
fprintf(fptr3, "");
fprintf(fptr3, "****** OUTPUTS OF SIMULATION DATA ******* \n");
fprintf(fptr3, "JD DAS tr(cm) g/plt AWU(kg)\n");
fprintf(fptr3, "LAI A(cm2)\n");
fprintf(fptr3, "\n");
day = d;
sum1 = 0;
sum = 0;
ec = (ENVCND *)malloc(sizeof(ENVCND));
lai = laif(d,nc);
if(d<silkdate)
    h = (d-initdate-10)*ht/(silkdate-initdate-10);
    n = 1;
    do
    {
        if(rad>=ThreshR)
        {
            ec->d = d;
            ec->ta = ta;
            ec->ts = ts;
            ec->rh = rh;
            ec->v = v;
            s1 = 0;
            s2 = 0;
            str = 0;
            for (i=1; i<=n; i++)
            {
                /* calculate canopy radiation */
                ec->i = i;
                ec->n = n;
                ec->rad = rad*exp(-0.5*lai*i/n);
            }
str = str+transp_rate(ec);
}
suml = sum1+str*lai*3600/n;
if (day!=d)
{
    if(d>=silkdate)
        h = ht;
    else
        h = (d-initdate-10)*ht/(silkdate-initdate-10);

    n = 10*h/ht+1;
    sum = sum1+sum;
    wu1 = sum1*142857;
    wu2 = sum*142.857;
    suml = sum1*100;
    fprintf(fptr3, " %d %d %8.3f",day,day-initdate,suml);
    fprintf(fptr3, " %9.2f %10.5f",wu1,wu2);
    fprintf(fptr3, " %6.3f %10.3f",lai,lai*10000/7);
    fgets(buffer2, 80, fptr2);
    sscanf(buffer2, "%d %f", &d1, &nc);
    lai = laif(d1,nc);
    day = d;
    suml = 0;
}
    fgets(bufferl, 80, fptrl);
    sscanf(bufferl, "%d %d %f%f%f%f%f", &d, &hr, &ta, &rh, &ts, &rad, &v);
}
else
{
    fgets(bufferl, 80, fptrl);
    sscanf(bufferl, "%d %d %f%f%f%f%f", &d, &hr, &ta, &rh, &ts, &rad, &v);
}
}
while((feof(fptrl)==0) && (d!=lastdate));
sum = sum+sum1;
wu1 = sum1*142857;
wu2 = sum*142.857;
suml = sum1*100;
fprintf(fptr3, " %d %d %8.3f",day,day-initdate,suml);
fprintf(fptr3, " %9.2f %10.5f",wu1,wu2);
fprintf(fptr3, " %6.3f %10.3f",lai,lai*10000/7);
close(fptr1);
close(fptr2);
fclose(fptr3);
}

==============
* This is "profile.c" and it contains six files: transp_rate(), *
*wind(), leaf_resist(), air_resist(), laif(), and profile(). *
==============

#include <stdio.h>
#include <ieeefp.h>
#include <float.h>
#include <math.h>
#include "def.h"

typedef struct env
{
  int d;    /* day */
  int i;    /* layer in the canopy */
  int n;    /* number of layers in the canopy */
  float ta; /* air temperature */
  float ts; /* soil temperture */
  float rh; /* relative humidity */
  float rad; /* radiation */
  float v;  /* wind speed */
} ENVCND, *ENVPTR;

typedef struct prof
{
  float ta;
  float tl;
  float ea;
  float el;
} PV, *PVPTR;

extern int set, d09;
extern float lai, lai1, lai2;
extern int var, initdate, silkdate;
extern float pop, h, la1;
extern float s1, s2;
/*******************************************************************************
* This is transp_rate() and it computes leaf transpiration rate at specific layer
* and specific time and return a which would be called by total_transp() *
*******************************************************************************
* Rv: gas constant for vapor *
* ta: air temperature *
* tl: leaf temperature *
* ea: vapor pressure of air in pascal *
* el: vapor pressure of leaf in pascal *
* vda: vapor density of air in kg/m3 *
* vdl: vapor density of leaf in kg/m3 *
* ec: variable with ENVCND type *
* ra: air resistance in m/s *
* rl: leaf resistance in m/s *
* tr: transpiration rate m/s *
*******************************************************************************

extern float wind();
extern float leaf_resist();
extern float air_resist();
extern PVPTR (profile());

float transp_rate(ec)
ENVPTR ec;
{
    PVPTR tp;
    float vw, vdl, vda, rl, ra, tr;
    vw = wind(ec->i,ec->n,ec->v);
    rl = leaf_resist(ec->d,ec->rad);
    ra = air_resist(vw,ec->d);
    ec->v = vw;
    tp = profile(rl,ra,ec);
    vdl = tp->el/(Rv*(tp->tl+273));
    vda = tp->ea/(Rv*(tp->ta+273));
    tr = (vdl-vda)/((rl+ra)*1000);
    return(tr);
}
/*******************************************************************************
* This is wind() and it computes wind velocity within canopy profile        *
*******************************************************************************
* v: velocity of wind m/s
* vi: velocity at layer i
*/

float wind(i, n, v)
int i, n;
float v;
{
float vi;
    if((h*i/n) >= (h/5))
        vi = v*(1+pow(2*(1-i/n),-2));
    else
        vi = v*(1+pow(1.6,-2))*LN(h*(n+0.005))/(LN(h*(5*0.005)));
    return(vi);
}

/*******************************************************************************
* This is leaf_resist() and it computes leaf resistance at different layers and ages         *
*******************************************************************************
* lai: leaf area index
* Id: leaf area density
* h: canopy height
* d: distance light travelled
* af: leaf age factor
*/

float leaf_resist(day, rad)
float rad;
int day;
{
float af, rl;
    if(day<silkdate)
        af = 18.6*(day-silkdate)/14;
    else
        af = 18.6*(day-silkdate)/7;
    if(var==43)
```c
{
   rl = coeff1*pow(rad,coeff2)+af;
   if(rl<3)
      rl = 3;
}
if(var==79)
{
   rl = 6771*pow(rad,-0.504)+af;
   if(rl<3)
      rl = 3;
}
return(rl);

/**************************************************
* This is air_resist() and it computes air resistance  *
**************************************************
* K2: a constant, defined in "def.h"
* W: leaf width, defined in "def.h"
* D: leaf dimension, defined in "def.h"
* v: windspeed
*/

float air_resist(v)
float v;
{
   float ra;
   ra = K2*(pow(W,0.2)*pow(D,0.35))/pow(v,0.55);
   return(ra);
}

/**************************************************
* This computes leaf area index based on normalized *
* crop thermal calendar *
**************************************************
* nc: normalized thermal calendar
* b: factor
* lai: leaf area index
* la1: maximum plant leaf area in m2
* lai1: maximum lai at period 1
* pop: population density in thousand plants per hectar
* dec: leaf area decline factor
```
* HYB1: a hybrid factor
* HYB2: a hybrid factor
* lai2: the minimum lai at period 2
* d: number of days past the date on which nc is 0.9
*/

float laif(d, nc)
int d;
float nc;
{
  float b, dec;
  /* period 1 */
  if((nc>0.89)&&(set==0))
    {
      d09 = d;
      set = 1;
    }
  if(d<=silkdate)
    {
      b = 20.21*nc+HYB1;
      lai = la1*(pop/10)/(1+(la1/0.01)*exp(-b*nc));
      if(lai>lai1)
        lai1 = lai;
    }
  /* period 2 */
  if((nc<0.89) && (d>silkdate))
    {
      dec = lai1*(0.88-HYB2)-0.37/5;
      lai = lai1-dec*(nc-0.5);
      if(lai<lai2)
        lai2 = lai;
    }
  /* period 3 */
  if(nc>=0.89)
    {
      lai = lai2-0.15*(d-d09);
      if(lai<0)
        lai = 0;
    }
  return(lai);
}
/***************
* This is profile() and it computes air temperature and *
* and vapor profile and leaf temperature *
***************
* ta: temperature of air
* h: height of canopy
* SB: Stephan-Boltzmann constant, defined in "def.h"
* va: vapor pressure of air
* vl: vapor pressure of leaf
* ra: resistance of air
* da: density of air, constant
* dtdz: temperature gradient
* K1: a constant, defined in "def.h"
* TECH: turbulent exchange coefficient of heat, defined in "def.h"
* TECV: turbulent exchange coefficient of vapor, defined in "def.h"
* LHV: latent heat of vaporization, defined in "def.h"
* i: layer no.
* t1-t7: temporary variables
*/

PVPTR (profile(rl, ra, ec))
float rl, ra;
ENVPTR ec;
{
    float tl, ta, tr, r, ea, eh, es, el, diff;
    float t1, t2, t3, t4, t5, t6, t7, p;
    int i;
    PVPTR profvar;
    r = rl+ra;
    t1 = 1-ec->i/ec->n;
    t2 = 1-ec->i*ec->i/(ec->n*ec->n);
    t3 = AD*HC;
    t4 = sqrt(D/ec->v)/Kl;
    ta = ec->ta+h*(Hc*t2/2+Hs*tl/2)/t3;
    eh = e(ec->ta)*ec->rh/100;
    ea = eh+10*h*P*(Ec*t2/2+Es*tl/2)/(0.622*AD);
    t5 = ra*ec->rad/(AD*HC);
    t6 = G*(1+rl/ra);
    tl = ta+5;
    do
        /* printf("in the dead loop, ta: %f, tr: %f, tl: \%f\n",ta,tr,tl), */
        
    
}
tr = tl;
t7 = (e(tl)-e(ta))/(tl-ta);
 tl = ta+t5*t6/(t7+t6)-(e(ta)-ea)/(t7+t6);
}
while(((tl-tr)>0.01) || ((tl-tr)<(-0.01)));
profvar = (PV *)malloc(sizeof(PV));
profvar->ta = ta;
profvar->tl = tl;
profvar->ea = ea*100;
profvar->el = e(tl)*100;
return(profvar);
APPENDIX B

(Portion of hourly weather data for FE0513.91)

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<th>Hour</th>
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<th>RH</th>
<th>Soil T</th>
<th>Rad. W m⁻²</th>
<th>Wind m s⁻¹</th>
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(portion of daily weather data for FE0513.89)

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### APPENDIX C

(Outputs of simulation for P3343 of FE0513.91)

***** OUTPUTS OF SIMULATION DATA *****

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