COTTON WATER RELATIONS

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INTRODUCTION

Water is the most abundant substance on the Earth's surface and yet is the most limiting to maximum productivity of nearly all crop plants. Land plants, like cotton, must maintain a balance between the water supply stored in the soil system and the atmospheric evaporative demand in order to carry out growth and development processes necessary for productivity and economic yield. In order for a plant to grow, it must carry on photosynthesis, which means it must absorb radiant energy and atmospheric CO_2. In doing so, energy is available to evaporate liquid water from the cell wall to water vapor in the intercellular spaces, which can easily diffuse out of the leaf into the bulk air when the stomata are open to allow CO_2 in for photosynthesis. As water vapor escapes from the leaf, liquid water is evaporated and the tissue water potential (Ψ_w) declines creating a gradient for water to flow from the soil to the leaf. The rate of vapor transport is called transpiration, and it has a direct effect on the resultant tissue water status, which can affect metabolic activity and growth processes. The soil represents the reservoir from which the plant roots extract water. Both texture and depth affect the water holding capacity of the soil system. When the soil water supply is not adequate to meet the transpirational demands, then plant water deficit stress occurs and growth and productivity are affected negatively. Maintaining the soil water supply at non-limiting levels is dependent upon very timely rains or the use of supplemental irrigation.

POTENTIAL EVAPORATION

Weather parameters of incident radiation, air temperature, relative humidity, and wind speed can be measured hourly or daily and used to calculate the potential evaporation rate of the atmosphere. The modified-Penman equation is currently the most widely used and accurate predictive model for estimating potential evaporation from crop systems.

$$\mathbf{ET_o = c[W - R_n + (1 - w) - f(u) - (e_a - e_d)]}$$

where ET_o = potential crop evapotranspiration (mm/day), W = temperature-related weighting factor, R_n = net radiation in equivalent evaporation (mm/day), f(u) = wind related function, $(e_a - e_d)$ = vapor pressure deficit of the air at mean air temperature, and c = adjustment factor to compensate for the effect of day and night weather conditions.

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The major source of energy required to convert liquid water to vapor is solar energy, the same energy that is required to produce chemical energy for the reduction of CO_2 to organic compounds in the photosynthetic process. The heat of vaporization of water (2.43 MJ kg^{-1} or 540 cal g^{-1}) is one of the highest for liquids. During the cotton growing season, total incident radiation levels in excess of 25 MJ day^{-1} are common. If all this energy were absorbed and converted to heat and used to evaporate water, the evaporation potential would be in excess of 10 mm day^{-1} or 0.4 inches. However some of the incident radiation is reflected back into the atmosphere (albedo~25%) and some is re-radiated as long wave thermal energy (proportional to K^4), reducing the amount of energy available for evaporation.

The rate at which water vapor diffuses out of the leaf (transpiration rate) is a function of the vapor pressure deficit between the leaf mesophyll air space and the bulk air surrounding the leaf and the extent of the leaf surface conductance, which is dependent on stomatal pore size.

Transpiration Rate (mol H_2O m^{-2} s^{-1}) = (C_{wv} leaf-C_{wv} air) • stomatal conductance

where C_{wv} is the water vapor content. The vapor pressure of the air surrounding the leaf varies with changing temperature during the course of the day. The relative humidity changes as air temperature changes, declining as temperature increases. The dewpoint, which is a measure of the absolute water vapor content of the air, remains fairly constant during the course of a day. The air inside the leaf is very close to saturation (i.e., relative humidity is greater than 99%). The vapor pressure gradient between the leaf and the bulk air surrounding it steepens as the air temperature increases. Therefore the actual rate of water loss from the leaf is dependent upon the vapor pressure deficit between the air inside the leaf and the air surrounding the leaf.

CROP WATER USE

Crop water use rate (daily water loss) is a function of the daily potential evaporation rate times a crop coefficient (K_c), which is defined as the effective leaf area index of the crop (Fig. 1). The ratio of actual daily crop water use to potential evaporation increases linearly with increasing leaf area index reaching a maximum (1.0) at leaf area indices around 3. The slope of the relationship between LAI and K_c is affected by canopy structure and plant spacing.

The leaf surface is covered with a cuticle of water impervious substances such as waxes and oils. The stomata offer the only path for water vapor to escape the leaf interior. Stomata exist on both the upper and lower leaf surfaces of cotton. The average stomatal density is approximately 10,000 cm^{-2}. Stomatal conductance is highly variable and responds to radiation level, CO_2 concentration, atmospheric humidity, and leaf water status. The controls of stomatal activity consist of both physical and biochemical components. When the soil water supply is non-limiting, stomatal conductance is at its maximum dependent upon the physical conditions. When soil water supply becomes limiting, stomatal conductance declines to restrict water loss.

As liquid water is converted to water vapor inside the leaf and it moves out of the leaf, the liquid water concentration declines in the cellular tissue, establishing a water potential gradient within the entire plant-to-soil liquid water continuum. Water potential (Ψ_w) is a measure of the free energy status of water in solution and is the driving force for water movement from a region of high free energy (Ψ_w close to 0) to a region of low free energy (Ψ_w = negative). The water potential of the leaf tissue is dynamic and reflects the changes in evaporative demand and soil water supply on a daily basis (Fig. 2). When soil water potential is high (close to field capacity), the leaf water potential reaches a minimum value dependent upon the cellular osmotic potential (Ψ_π). In most cotton plants this minimum Ψ_w is around –1.3 MPa. When the soil water potential (Ψ_s) becomes limiting (approximately –0.2 MPa) then as evaporative demand increases, either the leaf water potential must continue to decline (Ψ_w declines) or stomatal conductance must decrease to reduce water loss to maintain a favorable tissue water status.

SOIL WATER SUPPLY

Soil water supply is dependent on soil texture and depth. The texture determines the water holding capacity per unit depth. As clay content increases, the water holding capacity increases due to increased surface area per unit volume of soil and due to the surface electrical charge associated with clay particles. Cardinal water contents have been established for each soil texture and consist of field capacity and permanent wilting point values (Table 1). The extractable soil water between field capacity and permanent wilting point is defined as plant available water.

PLANT RESPONSE TO SOIL WATER DEFICITS

Plants begin to suffer tissue water stress long before the soil water content reaches permanent wilting point. The quantity of water a plant can extract from a given soil before suffering stress depends on root length density and evaporative demand conditions. Plants with high root length densities (cm roots cm^{-3} soil) or plants experiencing relatively low evaporative demand conditions can extract a greater amount of the plant available water before suffering stress than plants with lower root length density or that exist in higher evaporative demand conditions. Cotton has a relatively low root length density when compared with other crop species. Therefore cotton plants begin to suffer water stress at considerably higher soil water potentials than do other crop species. Under very high evaporative demand conditions, cotton plants can suffer short-term water stresses on a daily basis even though the soil water supply is close to field capacity. When tissue water stress is experienced, either stomatal closure must occur to restrict water loss or the tissue must adjust either cell size or cellular osmotic potential to allow the cell water potential to decline to maintain the flow of liquid water. Stomatal conductance reductions to limit water loss also can represent limitations to CO_2 diffusion into the leaf to support photosynthetic activity. Stomatal conductance and CO_2 assimilation rate change in parallel with decreasing leaf water potential resulting in reduced growth rates.

Research from the Texas High Plains suggests that the period from square initiation to first flower represents the most critical developmental period in terms of water supply affecting yield components (Table 2). Both boll number (per plant) and boll size have fairly strong positive correlations with water supply during this period of development. Water supply from first flower to peak bloom also affects boll number. However, it appears that the production of fruiting sites rather than retention of young fruit is more critical to yield and responsive to water supply under our short growing season environment.

Over 85% of the yield variability in cotton is due to boll number changes rather than boll size. Water stress prior to flowering reduces fruiting site number due to inhibition of site initiation rather than due to square shed. Stress after flowering affects young fruit abortion. Both the supply of reduced carbon and nitrogen as well as a hormonal imbalance in the young fruit are responsible for fruit abortion. It appears the young fruit less than 10 days of age are most vulnerable to abortion.

Maintaining a non-stressed condition from the onset of squaring through the peak bloom period is essential to maximize yield within the limits of the other environmental constraints.

IRRIGATION WATER SUPPLY

When rainfall is not adequate to maintain the soil water supply above the level where plant stress begins to occur, then irrigation can be successfully used to supplement the rain. Two considerations must exist for successful irrigation application to occur. The rate of crop water use must be known and the replacement capacity of the irrigation system must be known. The rate of crop water use has been discussed above and consists of knowing the potential evaporation rate of the atmosphere and multiplying that by the crop coefficient at that time. The best measure of irrigation capacity is gallons per minute per acre (GPMA). Each GPMA is equivalent to 0.052 acre in. per day of replacement capacity. If the cotton crop is using 0.25 in. per day ($PET \times K_c$) then an irrigation capacity of 5 GPMA is required to provide the daily water use (Fig. 3).

The total water supply to the crop (stored soil water + rain + irrigation) must be maintained at adequate levels to reduce the risk of plant water stress occurring from the onset of squaring until the last harvestable fruit is 10-12 days old. Then water supply must be managed to allow plant stress to develop to reduce the retention of fruit that have little chance of being harvested and to allow maturation of retained fruit.

How irrigation water is applied has a major influence on both the application efficiency (percent of delivered water that actually can be used by the crop) and the distribution efficiency (unifiormity of application across the area). Flood irrigation has the poorest distribution efficiency. Sprinkler irrigation has better distribution efficiency than flood methods, but has low application efficiency due to wetting the entire soil surface allowing for a relatively high percentage of the applied water to be lost to evaporation from the bare soil surface. LEPA (Low Energy Precision Application) is a system that uses a center pivot adapted to drop the liquid water on the soil surface (eliminating evaporation from the nozzle to the ground). Circular rows are required for maximum efficiency. Water is delivered to alternate rows, wetting less than 50% of the soil surface and increasing the percent applied water stored for crop usage to over 90%. This application system is most effective when the water supply is not adequate to meet the evaporative demand of the crop. Not only is the delivery system important, but also how frequently can water be applied. Using the LEPA system, a 3-5 day frequency produces the highest yields compared to longer irrigation intervals (Fig. 4). Caution must be used at very low application volumes to reduce the evaporation percentage. We recommend that no less than 0.5 in. be applied at a time. The disadvantage of the LEPA system is the very high application rates per unit of land area. The outside irrigation spans are applying water at rates that greatly exceed the infiltration rate of even the sandiest soils. In order to reduce runoff, furrow dikes are strongly encouraged.

LEPA technology allows us to use this system for more than just applying water. We have developed the nitrogen requirement per unit of water to maximize cotton productivity on the Texas High Plains. Each inch of total water available to the cotton crop requires 5 lb of nitrogen to maximize yield and water use efficiency. We apply the nitrogen through the irrigation water at a rate of 8-12 lb N/in. of applied water to supplement the rain (Fig. 5).

Most recently, we have evaluated phosphorus and sulfur applications in conjunction with nitrogen using fertigation. Our results have clearly demonstrated the fertigation of phosphorus is as good, or even superior to, applying phosphorus in a band under the row. Fertigation provides flexibility to manage the nutrient inputs based on yield potential as it develops during the growing season, rather than guessing prior to planting. Since fertigation can be used to apply phosphorus effectively, does it also affect the efficiency of use? We tested $N:P_2O_5$ ratios and found that the highest yields were achieved in our soil systems (high pH and calcareous) with a $N:P_2O_5$ ratio of 5:1 (Fig. 6). Boll size was increased by higher $N:P_2O_5$ ratios up to 5:3. The increased lint per boll was the result of increased micronaire. Fiber and seed maturity were enhanced in fruit in the top half of the plant. Our top fruit are affected by cool night temperatures in September reducing growth rates. Supplementing the phosphorus by fertigation allows faster boll and fiber growth under cool temperature conditions.

SUMMARY

Cotton has tremendous yield potential. Rarely do we harvest more than 25-30% of the fruit that the crop produced. Water stress is the single greatest environmental limitation to achieving higher percentages of the inherent yield potential. Water management through irrigation and nutrient supply management offer us great opportunities to increase yields. Proper understanding of the interaction of the plant with the water supply (soil system) and the aerial environment dictating water use is essential to proper water management.

Table 1. Relationship between soil texture and initial soil water supply characteristics.

Textural Class	Field Capacity	Permanent Wilting Point	Plant Available Water	Initiation of Stress
Clay loam	4.8[z]	2.4	2.4	1.3
Loam	4.2	2.1	2.1	1.1
Sandy loam	3.6	1.8	1.8	0.9
Loamy sand	2.4	1.2	1.2	0.8

[z] Inches of water per foot of soil depth.

Table 2. Correlation coefficients (r) for yield components and growing season water supply for cotton at various growth stages.

	Lint Yield	Boll	Boll	Lint	Lint
	m^{-2}	m^{-2}	$plant^{-1}$	$boll^{-1}$	$plant^{-1}$
Total water supply	0.34	0.35	0.37	0.12	0.36
WS P–SI[z]	–0.32	–0.18	–0.08	–0.24	–0.22
WS SI–FF	0.73	0.58	0.54	0.65	0.68
WS FF–PB	0.32	0.55	0.23	0.04	0.13
WS PB–Maturity	–0.43	–0.45	–0.23	–0.56	–0.27

[z] P = planting, SI = square initiation, FF = first flower, and PB = peak boll.

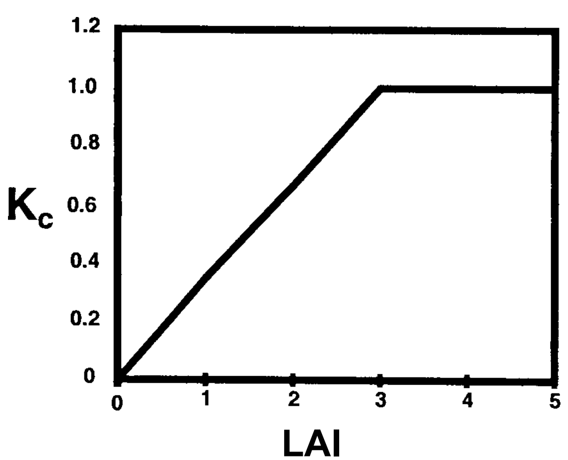

Figure 1. Crop coefficient as a function of leaf area index.

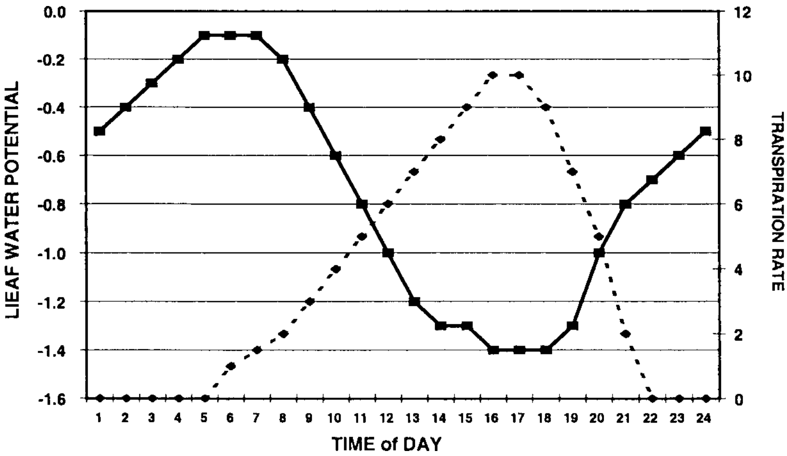

Figure 2. Diurnal pattern of leaf water potential and relative transpiration rate for cotton.

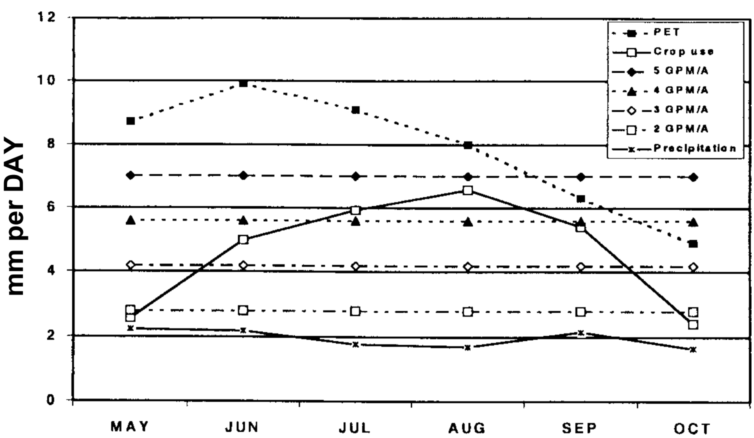

Figure 3. Relationship between growing season cotton water use rate, average precipitation, potential evaporation, and irrigation water supply capture for West Texas.

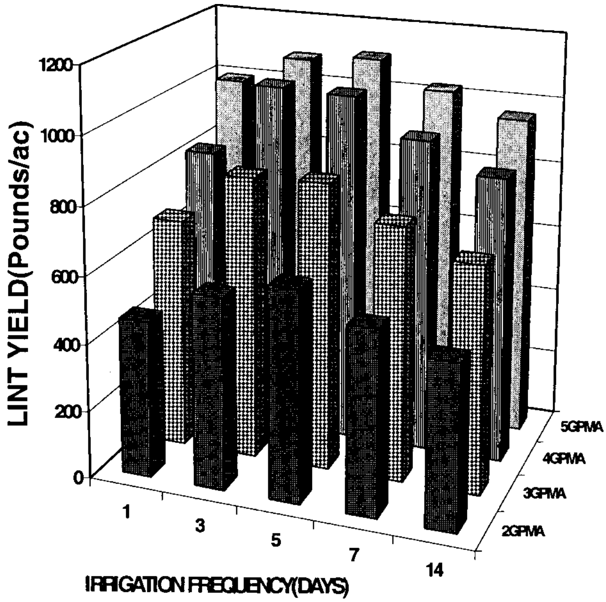

Figure 4. Cotton lint yield response to irrigation supply and frequency of application for West Texas production.

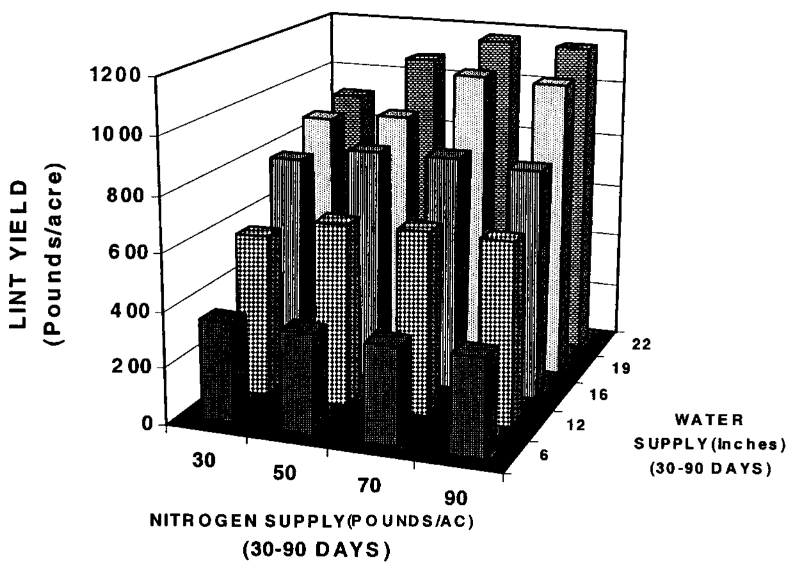

Figure 5. Cotton lint yield response to water and nitrogen supplies during the growing season.

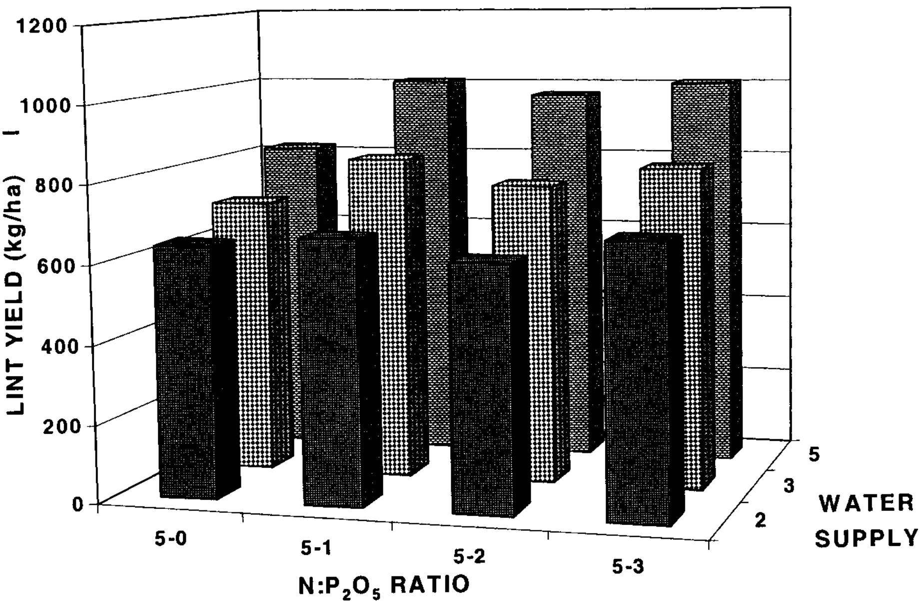

Figure 6. Cotton lint yield response to nitrogen-phosphorus ratios as a function of irrigation water supply.