

COTTON PHYSIOLOGY TODAY

Newsletter of the Cotton Physiology Education Program -- NATIONAL COTTON COUNCIL

July 1992, Volume 3, Number 7

Plant Water Relations

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In the rainbelt, extremes of moisture availability alter plant growth in highly predictable ways. Understanding those ways allows producers to cut cost and minimize damage to yield. Where supplemental irrigation is available, understanding plant water needs is obviously essential to receiving a benefit from the investment. This issue will cover the science behind irrigation scheduling in the rainbelt. The next newsletter will continue with the strategies and methods to schedule irrigations under different rainfall levels.

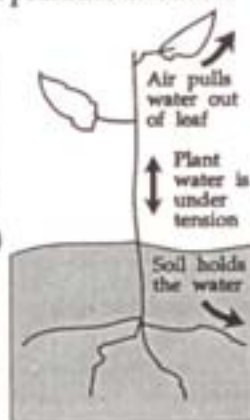
Water Supply to the Plant

Regardless of where the water originally comes from, a cloud or an irrigation well, ultimately the soil provides the water to the plant. Water storage and supply is primarily controlled by soil texture (especially the clay content). Soil water is stored against the force of gravity, in fine capillary pores and on the surface of soil particles. Since clay particles are small they have high surface areas relative to their volume. In addition, when clay particles are mixed in soil they also produce many small pores. Both of these increase the water holding capacity of soil. Water holding capacity is measured in inches of water per foot of soil, with values ranging from 0.5 for a coarse sand to 3 inches for a clay loam.

Plants must pull water from the soil. That same force that holds water in the soil against gravity must be overcome by the plant in order to extract water. Plants use the pull of dry air to overcome the soil's hold on water. Plants function as straws between the atmosphere — which has a strong pull on the water — and the soil — which holds the water. These forces that pull and hold water are measured as water potential. In soil the water potential is measured with tensiometers in centibars and in plants with a pressure chamber in bars (100 centibars = 1 bar).

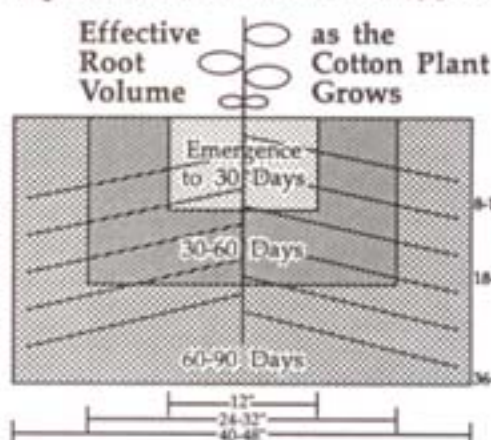
Water Potential from Soil to Air

	Humid Wet Soil	Dry Air Wet Soil	Dry Air Dry Soil
— Water Potential (bars) —			
Air	-200 (85%RH)	-1000 (45%RH)	-1000 (45%RH)
Leaves	-10	-12	-15
Roots	-1.5	-1.7	-2
Soil	-0.1	-0.1	-0.6



The table below shows the typical change or gradient in suction from the soil to the atmosphere for 3 different days: humid with wet soil, dry air with wet soil and dry air with dry soil. As the air and soil dry, plant tension increases from -10 to -12 and finally to -15 bars.

Root depth and distribution also determine the water supply. Although water can move upward large distances in soil as capillary flow, it does so slowly. Capillary rise is limited further in sandy soils, which dry much faster near the surface than in deeper layers. Increasing root depth and density thus increases the plant's ability to pull water from the soil. During periods of drought or



in regions with limited irrigation water, root depth and distribution are more important than when rainfall or irrigation are light and frequent.

Water Demand by the Atmosphere

The atmospheres pull or suction for water determines how much water is needed by the plant for maximum health. The potential evapotranspiration is the term used to describe the potential water use by a well-watered, short-growing crop. If the plant can not meet this water need, then leaves and stems undergo stress from desiccation and heat. Anyone who has dried hay in the field or clothes on the line understands the factors that increase evapotranspiration (ET): low humidity, bright sunlight, wind, and hot temperatures. These atmospheric measurements are used in various computer models (such as the Penman equation) to predict water demand by the atmosphere or the potential ET.

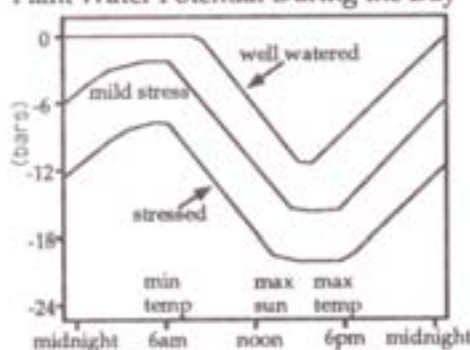
The potential ET indicates how much energy is flowing into a field, energy that is used to evaporate water or heat up the soil and plant. Sunlight and hot air are obvious sources of energy. Although dry air and wind do not directly provide energy for evaporation, they speed the process by allowing quick transfer of water vapor near the leaf to the air a couple of feet above the plant. If water is not available for evaporation (either from the leaves or soil surface), or the transfer of water vapor away from the plant is slow, then the incoming energy heats up the plant and soil. Overheating occurs when cotton suffers either drought or the weather is humid, calm, yet sunny.

The actual water used by the crop (cotton ET) is influenced by plant size, soil water availability and health of the plant, in addition to the potential ET. When plants are small, they have only a limited leaf area to evaporate or transpire water. Likewise, if the conducting system in the stem and roots is blocked by a vascular wilt such *Verticillium* or *Fusarium*, cotton ET is reduced. Dry soil obviously limits cotton ET because less water is available to the plant. ET is used extensively to schedule irrigations in methods referred to as the Water Budget or ET scheduling.

Plant Water Status

The straw between the air and soil is the plant system of roots, stems, branches and leaves. Since the water status of the plant — not the soil or air — directly determines how healthy the plant is, some irrigation scheduling methods rely on direct measures of plant water status, either plant temperature or plant water potential. Plant temperature is sensed by infrared detectors and when combined with air temperature indicates the degree of evaporative cooling. Plant water potential or the tension inside the plant integrates both the atmospheric demand and soil water supply. If either the air pulls harder (low humidity) or the soil holds tighter (dries) then the plant will be under more tension or stress. Plant water potential

Plant Water Potential During the Day



changes during the day as the atmosphere changes and the soil near the roots dries. The following figure illustrates the diurnal change in plant water potential for a Lubbock July day.

Water Movement from Soil to Air

Water moves from the soil to air under two different routes, evaporation directly off the soil and transpiration through the plant. These two routes are combined in evapotranspiration (ET) because energy coming into the system can cause water to flow in either or both pathways, depending on resistances to water flow. When the soil surface is wet, the resistance for evaporation is very low and most of the water flow is from the surface soil, but as the soil surface dries, resistance to evaporative water flow increases and plant transpiration becomes the dominant route.

The transpiration process relies on absorption of water by the roots, movement of water as liquid through the stem, branches, and leaves, and vaporization of water from the leaves into the air, primarily through the stomates. The driving force for the transpiration process is water potential gradients in the soil, roots, stems, leaves and air. Water moves down a gradient of decreasing water potential.

Resistances in the soil, roots, leaves and air keep the water flow under control. The greatest resistance to water flow occurs in the leaf, where the stomates and aerodynamics retard the movement of water vapor out of the leaf boundary layer and into the bulk air. This resistance is overcome by the greatest change or gradient in water potential from -10 in the leaf to -1000 bars in the air. This combination of high resistance and high gradient allows the stomates to regulate the flow of water from soil to air.

Resistances in other parts of the system can become critical under certain circumstances. For example, plants with vascular wilts suffer a blockage to water movement in the roots and stems that results in leaves rapidly desiccating, wilting and eventually dying from heat injury. If the soil dries, resistance to water movement also becomes great. Resistance to water movement in soils with low clay contents skyrockets as the soil nearest to the root dries. On hot sunny afternoons, cotton plants can wilt in sandy soil that appears moist, because the soil immediately adjacent to the roots has dried and lost its ability to conduct water to the roots. Only during the night, when stomates close, does the water redistribute and bridge the gap with the roots.

Water Stress: From Wet to Dry

Because water is utilized many different ways by the plant, changes in water content and availability result in a multitude of different effects on the plant, some beneficial and some detrimental. Understanding these allows us to identify optimum water levels for different plant stages and predict the effect of various water stresses on plant growth. For example, if we could predict whether excess moisture will stunt or promote plant growth we could use Pix more timely. To understand the impact of varying water levels on cotton, first look at some of the roles water plays in the plant.

- **Expansive growth.** Water provides the turgor pressure inside cells keeping them turgid and expanding (if the cell wall is still young). With reduced water availability, expansive growth of leaves and stems slows.
- **Cooling.** With evaporation and transpiration, a tremendous amount of heat energy is withdrawn from the soil and plant. This evaporative cooling, or perspiration, allows the plant to absorb sunlight for photosynthesis without overheating.
- **Nutrient transport.** Nitrate, and to a lesser degree other nutrients, are primarily swept into the plant by the flow of water to the roots (driven by transpiration). If water flow is reduced in a certain soil layer, nutrient uptake from that layer also will be reduced.
- **Chemical broth.** Water provides the background fluid which stabilizes large molecular structures and allows chemicals to react. Most molecules are stable and chemical reactions can proceed at very low water contents. Thus, this role of water normally does not limit plant growth in the field.
- **Source of hydrogen and oxygen.** Water is a common reactant in many chemical exchanges. This role of water never limits plant growth.

Too Wet: Anaerobic Desiccation

Roots require a constant supply of oxygen for survival and activity. Oxygen can only be replenished by diffusion from the atmosphere because other organisms in soil also consume — not produce — oxygen. When the supply of oxygen is cut off by water blockage of large soil pores, roots stop absorbing water and eventually die. Cotton plants standing in water logged soil can wilt and desiccate. To avoid anaerobic (lack of oxygen) desiccation, do not let water stand longer than 36 hours, especially when the temperature is hot or the soil has high organic matter — the decomposition of which also uses oxygen.

Too Wet: Nutrient Availability Due to Oxidation-Reduction of Soils

Soil aeration alters the mobility and plant availability of iron, through oxidation-reduction reactions. In soils with high pH, reducing (water logged) conditions for 24 hours can decrease the availability of iron, resulting in symptoms of iron deficiency throughout the plant. Iron deficiency looks similar to nitrogen deficiency but occurs more rapidly after flooding and only in high pH soil. Upper leaves in iron deficient plants are bright yellow with lower leaves yellow to pale green. Nitrogen deficiency develops slower, and in all soil types, with upper leaves that are greener than lower leaves. As a water logged soil dries, allowing oxygen to enter, iron becomes more available. Plants recover their deeper green color, often without any measurable effect on plant growth or yield from the temporary iron deficiency.

Too Wet: Stunted Growth

Young cotton appears to be highly sensitive to excess rainfall or irrigation. Although it is known that excess water in the spring cools the soil, reduces soil oxygen supply, and aggravates seedling diseases, we can not fully explain the greater sensitivity of seedling cotton to excess moisture. Perhaps the larger plant, by utilizing more soil moisture, is able to "drain off" the excess water faster thus allowing oxygen replenishment, warming and disease suppression. Excess moisture causes seedling cotton to develop smaller leaves and internodes, resulting in stunted and retarded growth.

Too Wet: Nitrogen Loss and Uptake Restrictions

When soil is flooded for brief time periods, plants still take up water. However, nitrate uptake is slowed due to leaching and denitrification loss of existing nitrate and poor production of new nitrate from organic matter and ammonium. Short term nitrogen deficiencies can result if N demand by the plant is high and plant storage marginal. Under these conditions, use of nitrate containing fertilizer or foliar urea can maintain a supply of nitrogen during brief periods of soil saturation. As a general rule — if the water supply increases, the applied N rate also should increase, because more N is lost and more is needed for the added growth and yield potential.

Too Wet: Root Growth Limitations

Roots will proliferate in the soil layer most optimum for growth. Typically, this is the surface soil, because it is warmer and more enriched with oxygen. If rainfall or irrigation is frequent during the spring/early-summer when the root system is developing, the resulting low subsoil oxygen level will limit root growth to within the surface soil. These fields will then be prone to drought later in the season.

Wet: Rank Growth

If water supply is slightly excessive, the main deleterious effect will be rank growth. The mainstem grows rapidly just after an irrigation or soaking rain, up to 1 inch per day, resulting in internodes of 3 to 4 inches (a new node and internode is added to the plant every 3 to 4 days during late squaring and early bloom). Rank growing cotton is more attractive to insects, suffers poor light distribution to the lower leaves, and is less efficient to harvest.

Optimum Rainfall or Irrigation

Optimum water input depends on the plant stage and soil texture. In the deep clay loam soils of the San Joaquin Valley, 3 to 3.5 bales per acre are produced with 3 post-plant irrigations. The irrigations are scheduled to minimize cooling in the spring, provide ample moisture during bloom, and a gradual drying in the late summer/fall. The following table lists the optimum rain or irrigation amount at different crop stages along with plant sensitivity to drought or excess water.

	Preplant	Seedling	Squaring	Bloom	Opening
Optimum rainfall amount	Heavy	None	Medium	Heavy	None
Sensitivity to drought	-	Low	High	Highest	Lowest
Sensitivity to frequent rain or excess irrigation	-	Severe	Low	Medium*	Severe

* Frequent rain is accompanied by cloudy weather that decreases boll set.

Dry: Stunted Growth

Plant growth, as measured by plant height, is directly related to water availability. From the maximum growth rate of 1 inch per day, growth rate slowly declines to zero when water stress causes mid-day wilting (approximately -25 bars water potential). Cell division and elongation in leaves also are highly sensitive to water stress; water stressed leaves are smaller due to fewer and smaller cells. Node development on the other hand, is much less sensitive to drought; droughted plants have nearly the same number of nodes, just spaced closer together.

Too Dry: Root Growth Limitations

Roots fail to grow in dry soil. The expanding root tip of cotton must push aside soil particles. In coarse textured soils — during the summer — roots only can grow for a few days after a rain or irrigation before the drying soil strength exceeds that of root tips. Fine tex-

tured soils remain plastic for a longer time period allowing continued root growth.

Too Dry: Photosynthetic Disruption

Photosynthesis, the process where light energy is converted to sugars, is sensitive to drought. Even during a moderate drought when stomates close, photosynthesis decreases. However, severe water stress, to the level of wilting, can permanently cut the photosynthetic capacity of existing leaves in half and shorten their useful life.

Prolonged water stress (30 or more days with leaf water potentials less than -18 to -20 bars) permanently damages the photosynthetic machinery of existing leaves and prevents plant recovery by interrupting the formation of new leaves. Even after a rain, recovery is often nil or extremely delayed, because the plant must rely on the older damaged leaves to intercept sunlight and produce sugars for the formation of new leaves.

Too Dry: Square and Boll Shed

When water stress exceeds -19 bars (just past the timing for optimum bloom irrigations in the San Joaquin Valley), small boll retention starts to decline. When plants reach the mid-day wilt stage (-25 bars), boll shed is severe. This severe stress also will cause small squares to shed, resulting in a severe loss of total fruit and yield potential. The combined fruit and leaf sensitivity to drought results in a plant that is most sensitive during bloom, less sensitive during seeding

stage and least sensitive during boll opening.

Too Dry: Fiber Quality Effects

Surprising is the lack of sensitivity of fiber quality to water stress. Only when water stress reaches levels that leaves are wilted during boll development and yields are cut by 20 to 50% (-24 bars), does strength and micronaire quality suffer. Fiber length is shorter under dryland-drought conditions (approximately 1/16 of an inch). The extreme sensitivity of young boll retention to water stress allows the plant to adjust downward its boll load to a level that the few remaining bolls can mature (often with excessive fiber thickening and high micronaire).

Wrap-Up

Optimum timing of cotton irrigation depends on the producer's ability to coordinate the application of water with the plant's needs; either measured directly or estimated from the many factors involved in water supply and demand (soil moisture profile, plant moisture and growth stage, ET and the weather forecast). To decide if an irrigation will do more damage than good to a field with variable soil and plants also requires knowledge of the relative damage from excess or insufficient moisture. This is why producers out West say that irrigation is more art than science. By "art" they really mean personal knowledge and experience with water movement and plant response in a particular field — "Plant Water Relations" for short.

The Cotton Physiology Education Program is supported by a grant to The Cotton Foundation from BASF Agricultural Products, and brought to you as a program of the National Cotton Council in cooperation with the State Extension Service.

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