7-1-1983

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Principles of Water Management for Soybean Production in Mississippi

The potential for increasing soybean yields by irrigation in Mississippi is well established. Heatherly (1983) measured a 27 bu/acre increase in yield of soybeans grown on Dubbs silt loam and up to a 37 bu/acre increase in yield of soybeans grown on Sharkey clay during 1980, but that level of yield response to irrigation should not be expected each year. The yield increase was only 1.7 bu/acre and 1 bu/acre on Dubbs silt loam and Sharkey clay, respectively, in 1979, a year of near-ideal rainfall distribution at the test sites. Maximum yield levels were nearly the same, however, in both years.

Non-irrigated yields of Tracy soybeans on Sharkey clay were 53.2 and 15.5 bu/acre in 1979 and 1980, respectively. The year-to-year variation in soybean yields is great, and the variation in response of different soils to irrigation during drought years is high. These conditions cause severe variation in farm income as well as in agribusiness and related-industry income. Sound water-management practices will stabilize soybean yields on a higher level and will reduce the undesirable year-to-year income variability. In this bulletin we discuss the principles involved in soil-plant-water relations, with special emphasis on soybeans. We hope that, by using these relations, farmers and farm advisors will be better able to make wise management decisions to increase and stabilize crop yields and farm income.

Soil-Water Relations

Soil is a complex of varying proportions of four principal components----minerals, nonliving organic matter, air and water. In addition, soil usually contains numerous living organisms, such as bacteria, fungi, algae, protozoa, insects and small animals, which directly or indirectly affect soil structure and plant growth.

On a volumetric basis the mineral particles are the chief components of Mississippi soils. The mineral particles are of various sizes, with the relative mixture of particle-size groups determining the textural classification of each soil. Four mineral fractions, as defined by diameter, are listed in Table 1 along with the percent of each of these particle sizes in three common soil textural classifications.

Depending on the relative contribution of each size class in a particular soil, soils are classified as sands, loams, silts or clays. Most soils fall into various intermediate classes such as sandy loam, silt loam or clay loam.

The least complex soil is a sand, which by definition contains less than 15% silt and clay and is relatively inert chemically. Sandy soils form relatively simple capillary systems with a major portion of their volume made up of large pore spaces, and this ensures good drainage and aeration. However, because

Table 1. Classification of soil particles according to the International Society of Soil Science and the mechanical analysis of three soils.

Fraction	Particle Diameter	Soil Texture		
		Sandy Loam	Loam	Heavy Clay
	millimeter	%		
Course sand	2.0 - 0.2	66.6	27.1	0.9
Fine sand	0.20 - 0.02	17.8	30.3	7.1
Silt	0.02 - 0.002	5.6	20.2	21.4
Clay	Smaller than .002	8.5	19.3	65.8

of these large pores and the subsequent rapid drainage following addition of water, these soils hold very little water that is available for use by plants.

Clay soils are at the other textural extreme with reference to particle size and complexity, because they contain a minimum of 40% clay. The clay particles usually are aggregated in complex granules and are plate-like in shape. Because of their shape and small size, these aggregates have a much greater surface area than do cubes or spheres of similar volume. The extensive surface area of the clay particles enables clay soils to hold more water and minerals than do sandy soils. For example, a cubic sand grain 1 mm on each edge has a surface area of only 6 mm^2, but, if it is broken into clay-sized particles of 0.001 mm on each edge, the resulting total surface area is 6000 mm^2. It has been calculated that the surface area available to bind water ranges from less than 1000 cm^2/g in coarse sands to more than 1,000,000 cm^2/g in clays. Thus, the relatively small size of the particles in the clay fraction largely controls both the chemical and physical properties of soils.

Loam soils contain more or less equal amounts of sand, silt and clay; therefore, they have properties that are intermediate between those of clay and sand. Such soils are considered to be the most favorable for crop production, because they hold more readily-available water than either sand or clay, and have more nutrients than sand. They are also better aerated and easier to work than clay.

About half of the soil volume is usually occupied by air and water. For practical purposes, this pore space may be divided into two major classes—(1) large pores, which do not hold water against gravitational forces and (2) small pores, which hold water that will not drain due to gravity. Large pores drain freely and quickly after rain or irrigation and are normally filled with air. The small pores contain water that remains after most free drainage from large pores is complete. Part, but not all, of this water is available to plants. Heavy soils (those high in clay content and total pore space) allow only slow air and water adjustment because of the large total surface area of the particles. This surface area holds water by surface tension, so it resists the force of gravity.

In sandy soils, the large pores predominate, and this results in better drainage and aeration and lower water-holding capacity than in clay soils, which have a large proportion of small pores (Figure 1). Ideal agricultural soils have about equal volumes of small and large pores. Such soils have enough large pores to permit adequate and reasonably rapid water infiltration, drainage and aeration and enough small pores to provide adequate water-holding capacity to support crop growth.

Water Retention by Soil

As water is removed from the soil during drying, air replaces the water in the pore space (Figure 1). As a result, air-water interfaces develop and form curved water surfaces between adjacent particles of soil. The surface tension acting in these curved interfaces counterbalances the forces of water removal caused by either gravity, evaporation or plant roots. This is one mechanism by which water is retained in the soil.

In shrinking soils such as Sharkey or Houston clay, another mechanism is involved in retaining water in the soil. As water is removed, the soil particles are brought closer together by the characteristic shrinkage of spaces between the particles. These particles carry a negative surface charge and act to repel one another. As the soil particles are
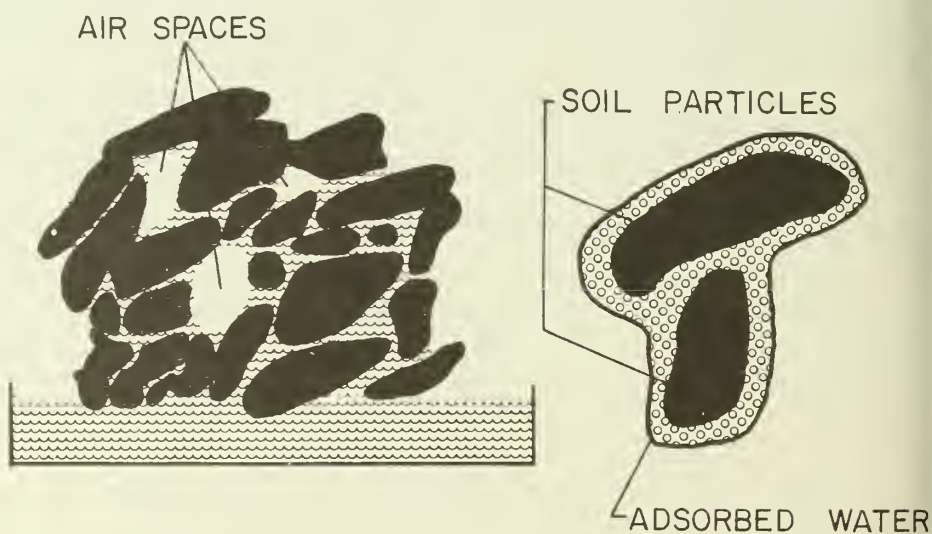

Figure 1. (Left) Diagram of soil particles with saturated zone at bottom. Drainage has allowed air to enter larger pore spaces near surface.

(Right) Enlarged sketch of soil particles after drainage is complete. The adsorbed water near the soil surface is partially available for plant use.

brought closer together by the removal of water, the repulsive forces become greater. The shrinkage and associated repulsive forces of the clay particles balance the tension caused by drying.

In some soils, high salt concentrations also decrease the availability of water to plants, thereby providing a third mechanism by which water is retained in soils, thus affecting the availability of water to plants. However, this is not an important mechanism of water retention in Delta soils, nor in most other Mississippi soils.

Water absorbed by dry soils is held very tightly by the mechanisms described above. Absorbed water is accompanied by an equally important force---the attraction of water molecules to each other. As soil water becomes more plentiful, water molecules are attracted to other water molecules and produce films around the soil particles. As these water films increase in thick-

ness, the outer surface of the water film is influenced less by the soil surfaces and becomes subject to removal by gravitational and evaporational forces. Therefore, when the soil is near saturation, it is very easy to remove the initial increments of water. However, as the soil moisture content is lowered, the water films become thinner and the force necessary to remove subsequent increments becomes progressively greater.

This dynamic manner in which water is held in soil is especially important, because it affects many aspects of management for crop production. For example, it affects the principal factors related to drainage after a saturating rain or irrigation, it affects the concept of field capacity (the moisture content of soil following removal of water by gravity), and it affects the availability of soil water to plants.

In addition to gravitational flow through large pores, as has already

been mentioned, water moves at slower rates in the small pores due to capillary action. Gradients, or differences in soil-water content from one point to another, may exist within a given volume of soil due to differences in water supply and water use. A root may extract significant quantities of small-pore water from a particular region of the soil. The area in the immediate vicinity of the root may become drier during a period of rapid use, but it will gain water from the surrounding soil during the night or during a period of low water use. The distance that significant amounts of water can move by capillary action is rather low. The rate at which it moves depends on the gradient or differences in moisture content of the soil and soil texture. More water can move by capillary action at high soil-moisture levels than under drier conditions regardless of the soil moisture gradient.

The energy concept of soil retention

Space here does not permit a discussion of the details of measuring soil water-retention characteristics. Briefly, however, a force applied to soil will expel water from the soil, and the water expelled at a particular force can be measured. In practice, this is accomplished by beginning with a saturated soil and applying a small force, usually about equal to that of gravity, and a certain amount of water will be expelled, depending on the retention ability of the particular soil. The soil is then said to be at or near field capacity. The force generally used to accomplish this effect is about 0.3 bar of pressure or suction. (A tensiometer in equilibrium with a saturated soil will read about zero. At field capacity the tensiometer will read about 0.3 bar or 30 centibars.) One bar is equivalent to about one atmosphere of pressure (14.7

lbs/inch^2 or 29.5 inches of mercury under standard conditions). By adding additional pressure (force) to the soil sample, additional water is expelled. This process can be continued until essentially all of the water available to plants is removed. Data from such treatments can be used to determine the amount of water available in a particular soil at different pressures or tensions. Additionally, one can estimate the relative availability of water at any soil moisture content. Table 2 shows typical soil moisture retention relationships of selected soils.

Some investigators have grown different plant species until they reached the permanent wilting point (that point at which a plant will not recover from wilt until water is added to soil). They found this to occur at about 15 bars of soil-water

tension. The water content at 15 bars may be subtracted from the water content at field capacity to determine the amount of water available to plants between field capacity and the permanent wilting point. Sharkey clay has about 11%, and Dubbs silt loam has about 20% plant-available water. In practice, however, if irrigation facilities are available, a crop should not be allowed to become so dry that it becomes permanently wilted. A more practical definition of plant-available water might be the water available between field capacity or 0.3 and 1.0 bar. The soil moisture available between 1.0 and 15.0 bars tension apparently requires the plant to be under tensions high enough that plant injury occurs during the water extraction process. Therefore, we prefer to call the soil water held between 0.3 and 1.0 bar

Table 2. Volumetric water content of soils equilibrated at different pressures.

Soil Water tension	Estimated relationships	Soil Type		
		Sharkey clay*	Dubbs silt loam*	Bosket very fine sandy loam
bars		-----------------------%-----------------------		
0.3	Field capacity	36.8	27.5	24.2
0.7	Limit of Tensiometers	34.1	21.0	16.1
1.0		32.8	18.4	13.6
3.0		30.0	13.0	8.9
5.0		28.4	11.2	8.0
10.0		27.0	9.0	7.3
15.0	Permanent Wilting Point	26.0	8.0	6.9

*Data from Heatherly, L. G., and W. J. Russell, Field Crops Research 2:135-143. 1979.

readily available plant water. The amount of *readily available plant water*, found by subtracting the percent water at 1.0 bar from the percent water at 0.3 bar (36.8% - 32.8%) is 4% for Sharkey clay (Table 2). By multiplying 4% by 50 inches of soil depth (a reasonable estimate of effective rooting depth), one can see that Sharkey clay has only 2 inches of *readily available plant water*. The 4% estimate calculated above, however, may be conservative because field capacity in clay soils probably occurs at tensions near 0.1 bar; however, the 0.3 bar is a more reasonable estimate of water tension at field capacity in most coarser-textured soils.

Plant Responses to Water Deficit

The leaves of plants are ideally suited for the exchange of gases (carbon dioxide, water vapor, etc.) and the trapping of energy from the sun. The surfaces of leaves are coated with a waxy substance called cutin, which protects the leaves from excessive water loss. This waxy surface is interspersed with literally millions of tiny pores, called stomata. These stomata are formed by specialized cells that are capable of expanding and contracting, thereby causing opening or closing of the pores. This mechanism allows the plant to control the movement of air and moisture to and from the interior of the leaf, depending on the plant's internal water condition and the external environment (temperature, relative humidity, etc.). Generally, the stomata are open during the day and closed during the night. If the environment around the plant is such that the plant's internal water status becomes too stressed, however, the stomata will close to limit water loss.

Under conditions of adequate water, the stomata will open in the early morning in response to the sun's rays. Water vapor is lost through the open stomata of the leaf by the evaporation of water from the moist interior cell surfaces, and carbon dioxide from the atmosphere diffuses into internal areas of the leaves through the same stomata. Once inside the leaf, carbon dioxide is adsorbed onto the wet cell surfaces. It then diffuses into the cells where it is converted (via photosynthesis) into sugar, the primary energy source that drives

all plant growth and development. Also, sugar ultimately provides the building blocks for structural materials (cell walls, proteins, chlorophyll, lipids, etc.).

As evaporation from the leaf continues, the loss of water creates a tension in the cells. This tension pulls water from the adjacent vascular system, which transmits the tension down the stem to the root system. As the tension in the root system is increased, water from the surrounding soil is absorbed by the root. The water tension inside the root competes with the soil particles for available water. If the soil water is in relatively good supply, the root moisture deficit need not be very low to pull the water away from the soil; however, if the soil-water supply is relatively low and the water film on soil particles is thinner, the soil particles hold the available water more tightly. In cases of low water supply, the root tension must be fairly high to remove the limited water from the soil.

The moisture tension in a plant is therefore controlled by (1) the soil moisture supply and (2) the evaporative demand of the atmosphere. Figure 2 illustrates how these two factors interact to cause wilting. Under wet soil conditions (36% soil water), transpiration (loss of water from plant leaves to the atmosphere) was limited by the environmental conditions until water loss exceeded about 0.28 inch/day. At 25% soil moisture, however, the plants were able to use only about 0.06 inch/day because of the limited soil-water supply. If the atmospheric demand had been greater, the plants would have wilted. On a cloudy, overcast day, the evaporative demand was low; and the plants did not wilt, even in this relatively dry soil. Thus, differences in atmospheric demand interact with differences in the soil water supply to cause varying patterns of plant response.

In sandy soils, the portion of the plant-available water available at low soil moisture tensions increases as the soils become drier, but rela-

tively little reserve moisture is available. An examination of Table 2 shows that Bosket very fine sandy loam has about 61% (5.3 inches in the surface 50 inches) of its plant-available water between field capacity and 1.0 bar, while Sharkey clay has only 37% (2.0 inches in surface 50 inches) of its plant-available water in the *readily available soil moisture* range.

The available soil moisture may be expressed as a continuous curve, with decreasing quantities of water remaining in the soil after extraction at increasing tensions, and one may question whether the comparison at 1.0 bar is justified. We have found that controlling soil moisture so that it never gets above 1.0 bar tension produces higher yields than if the soil is allowed to become drier before irrigation is applied. Therefore, the value of 1.0 bar appears to have some validity.
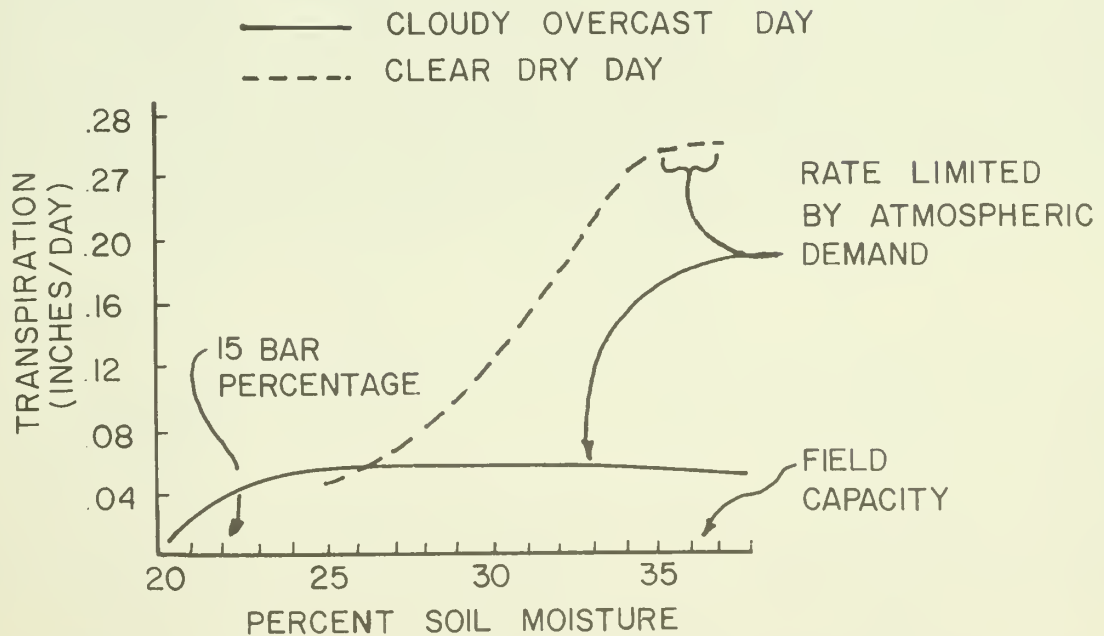

Figure 2. The effect of decreasing soil water content on rate of transpiration during days of high and low potential transpiration (after Denmead and Shaw).

Drought Stress

The moisture status of leaves is a function of both soil water supply and evaporative demand of the atmosphere. In the field, significant water deficits develop even in well-watered plants. As water evaporates from the leaves, the tensions that develop increase the rate of water uptake. If roots cannot absorb water rapidly enough, the leaf water status will come under increasingly higher tensions. On sunny days the leaves of soybean plants normally will reach tensions of 12 or 14 bars (equilivant to 175 to 200 pounds/inch²).

Figure 3 illustrates a typical daily time course of leaf water-tension values. Near midday, clouds often develop and provide brief periods of lower solar radiation which reduces leaf water tensions and plant stress. As darkness approaches, the rate of evaporation decreases and leaf tension becomes less as water from the soil is transported from the absorbing roots to the leaves. In well-watered soils the leaf water tension will return to values near zero very quickly after darkness, but in drier soils the leaf water tension will recover much more slowly and will very gradually approach the soil-water potential. Leaf water tension is at its lowest point just before dawn, and the difference between these values and the soil-water potential values at this time is directly proportional to the dryness of the soil.

Leaf growth is very sensitive to leaf water tensions (Figure 4). As the leaf water tension becomes greater than 4 bars, the rate of leaf expansion nearly ceases. By the time the leaves reach values as high as 12 bars, growth is completely stopped. Boyer (1968) found that leaf enlargement was reduced to 25% of that of the well-watered controls by a tension of 4 bars. This level of tension normally occurs in the field by 9 or 10 o'clock in the morning; therefore, daytime leaf growth is greatly reduced even on well-watered soils. If the plants are exposed to reasonably good moisture conditions, they will recover overnight and growth will proceed. Nearly all leaf expansion
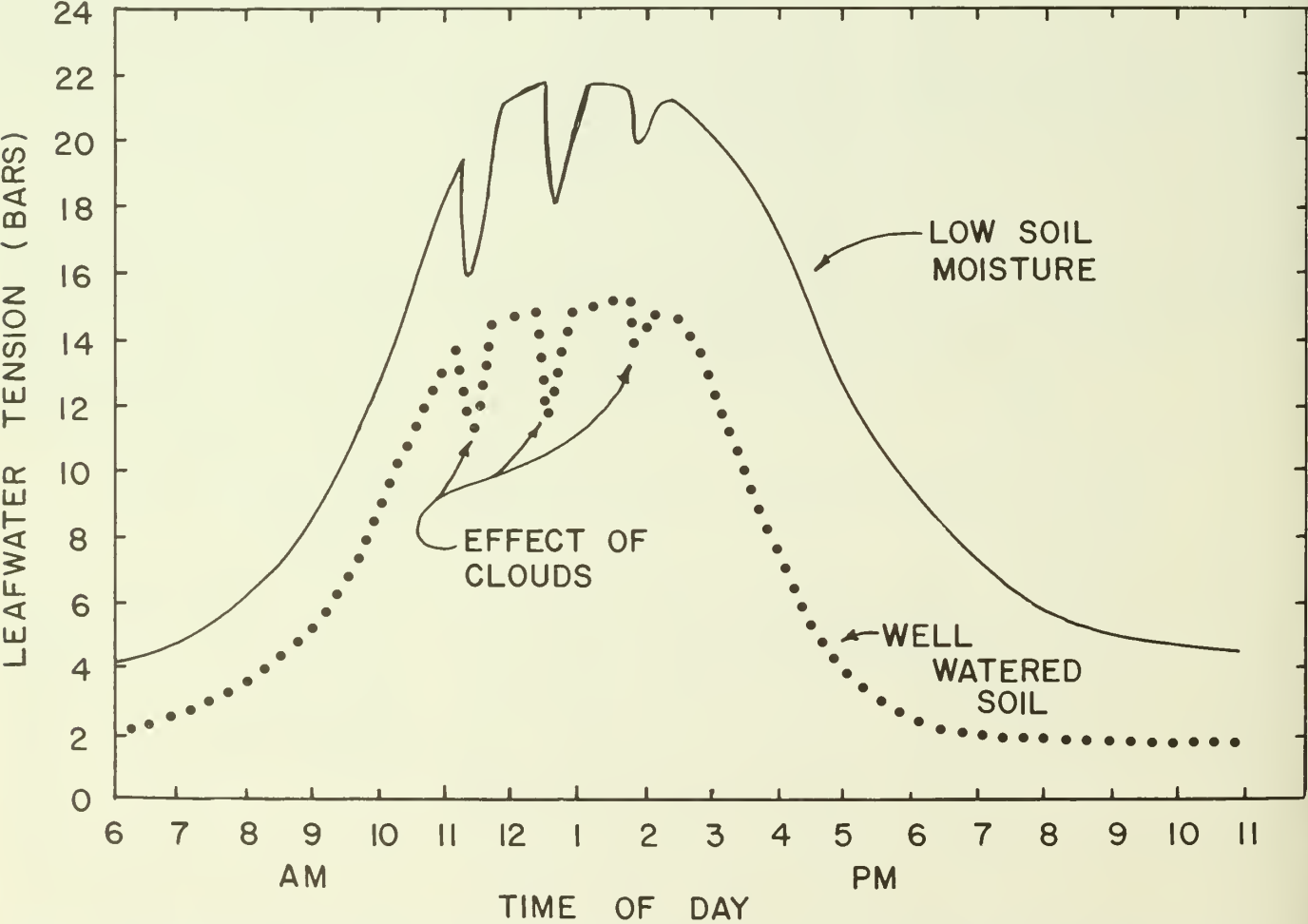

Figure 3. Typical soybean leaf water tensions during the course of a day on well-watered and relatively dry soils.
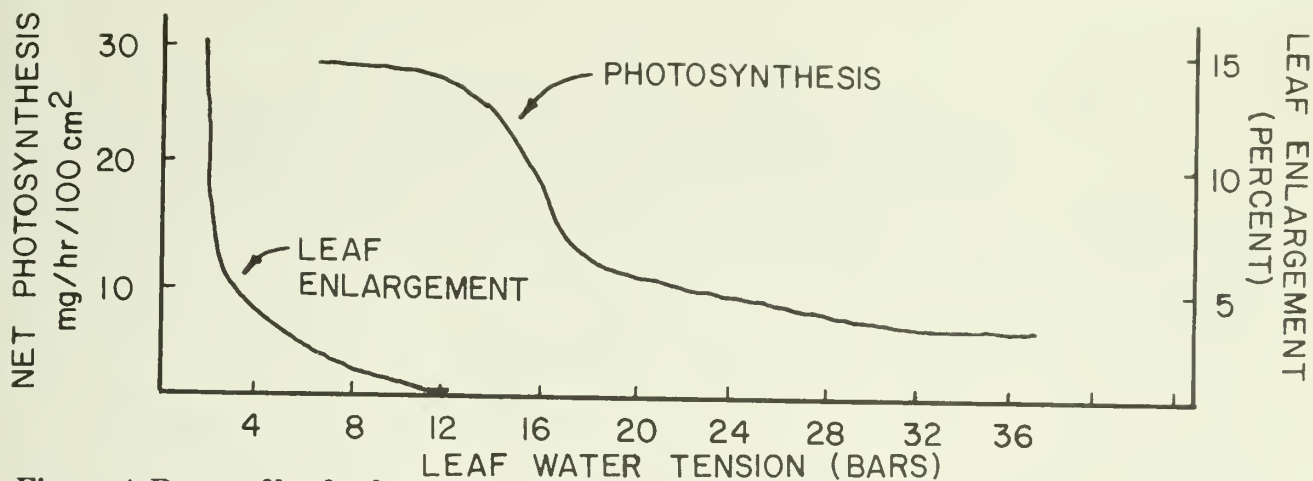
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Figure 4. Rates of leaf enlargement and net photosynthesis of soybeans at various leaf-water potentials (after Boyer).

and stem elongation occurs at night when water conditions in the plant are most favorable, and there is negligible loss of water from the leaves to the atmosphere.

If, however, the soil is relatively dry, the daytime leaf water tension may reach values of 18 to 22 bars. The overnight recovery from such high tension is slower and less complete. If such steadily increasing tensions are allowed to reoccur for several consecutive days, non-reversible damage occurs. The extent of damage depends on the longevity of the drought, while the type of damage to the plant depends on the growth stage. If prolonged moisture stress occurs during the vegetative stage, the leaves in the terminals of the main stems and branches of stressed plants will essentially stop growing and turn dark green. If and when the stress is relieved, these leaves will once again start growing, but they will not reach the size of the leaves that developed during non-stress conditions. Internode length is affected in essentially the same manner; therefore, both leaf area and plant height will be reduced by stress.

Photosynthesis and Dry Matter Accumulation

The photosynthetic process is less sensitive to moisture stress than is leaf expansion or stem growth. Soybean leaves continue to produce dry matter with no apparent reduction in rate until they reach about 12 bars of tension (equivalent to 176 lbs/inch^2). They continue producing at about 30% of their maximum rate even after they reach tensions as high as 20 bars (equivalent to 280 lbs/inch^2). In addition to a direct reduction in growth rate that occurs due to lower dry matter production per leaf (photosynthesis), drought also affects the time that leaves are functional. Thus, a result of severe drought stress is the early or premature death of the leaves, with lower leaves dying first. This results in an irreversible loss of capacity of the plant to intercept light and produce dry matter.

Flowering and Seed Set

Flowering also may be delayed by drought stress. Drought during early flowering causes abortion of flowers and reduces numbers of pods set, but additional flowers may be produced if the stress is relieved. Drought stress that occurs during late blooming causes the loss of young pods and an irreversible loss in yield. Drought stress during the beginning of podfill can result in fewer seed per pod, while stress during mid- to late-pod filling results in smaller seed and may hasten apparent maturity by causing leaves to drop early. Overall, drought stress severe enough to reduce yield does so mainly by reducing numbers of seed/acre.

In an experiment to evaluate the susceptibility of soybeans to stress at different stages of development, we found about equal sensitivity at all reproductive growth stages. There was a nearly linear loss in yield (expressed as percent of the non-stressed plots) vs numbers of days of wilting. Yield was reduced from 100% at zero days of wilting to about 60% of that of the well-watered control by 14 days of continuous wilting (Figure 5). Yield reduction continued, but at a decreased rate, when the plants were exposed to additional wilting conditions after the initial 14-day period.
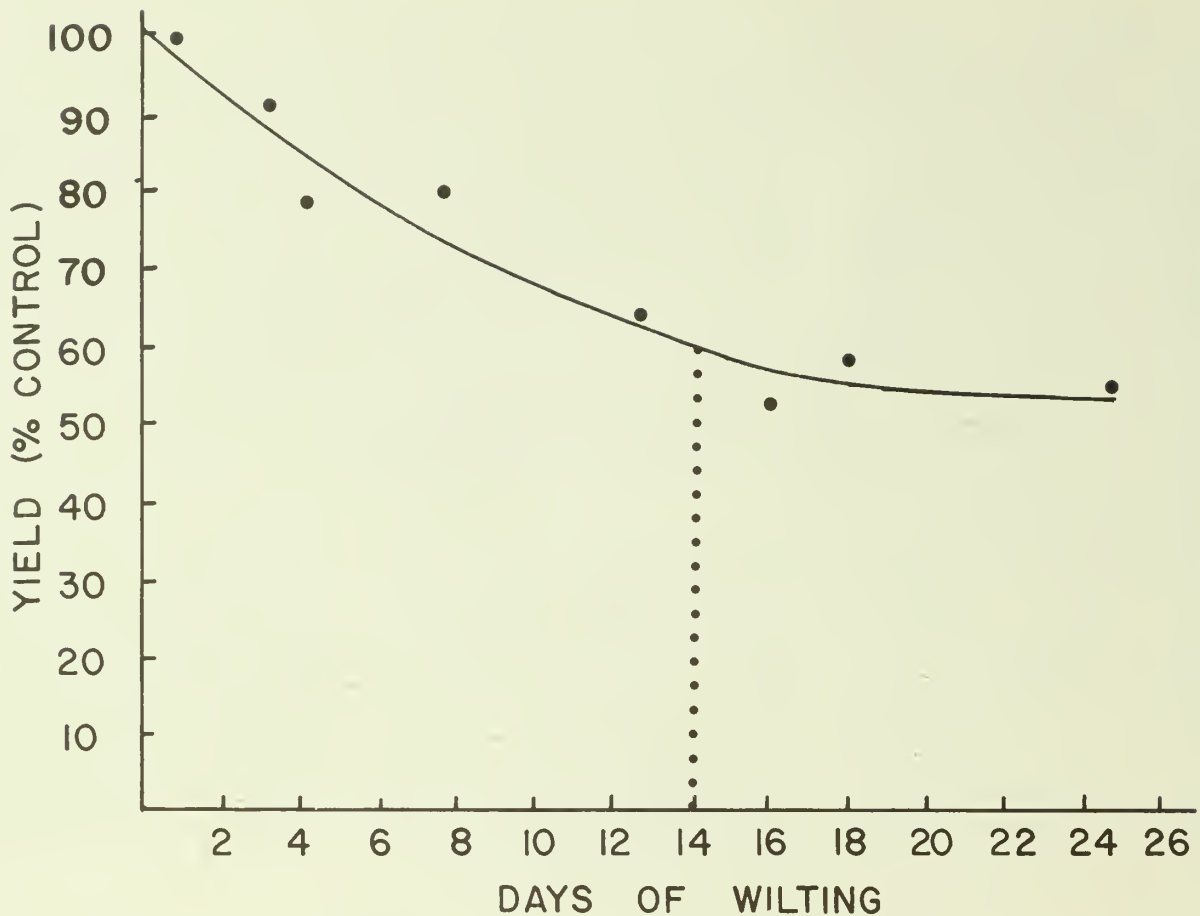
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Figure 5. Effect of days of wilting on soybean yields.

We conclude, then, that the key to water management for soybeans is to initiate irrigation at or near bloom and to continue on a consistent and timely basis until seed are fully developed. This allows all phases of soybean reproductive development to occur in well-watered conditions. If water is applied during early reproductive development (bloom, early podset) but is withheld thereafter, the excellent pod load established by the early watering cannot be maintained by the plant. Therefore, numbers of seed per pod and/or seed size will be reduced, and potential yield will not be realized. On the other hand, if irrigation is delayed until later stages of reproductive development (late podset or beginning of seed filling), the potential pod load may not have been realized, and potential yield will not be achieved. In this case, seed per pod and seed size will both be near the maximum, but yield will be reduced because of lower-than-maximum numbers of pods. If drought occurs early or if *readily available soil water* is lacking due to double cropping, it is beneficial to irrigate to get a uniform stand and to develop plants of sufficient vegetative stature to produce a good seed crop.

Drought stress at any time results in reduced growth and reduced yield. Heatherly (1983) found that soil-water management throughout the season produced the highest crop yield. Full-season irrigation requires detection of moisture stress by frequent and routine soil-moisture monitoring and the application of irrigation or rain before serious stress develops. Recent work in Israel with trickle irrigation has shown that watering cotton and vegetable crops throughout the growing season has resulted in the highest yield response. Proper management of trickle irrigation requires frequent application of very small amounts of water. This degree of management intensity is not feasible under our conditions and with a relatively low-value crop, but the principle of frequent and small applications of water should provide a meaningful lesson.

Adaptation

It is widely thought that crops adapt to drought stress and become capable of withstanding drought. There is little evidence to support this view, when it is considered on the basis of producing an economic yield. The limited adaptation that does occur only increases the plant's ability to survive. Under prolonged drought, the plants increase their sugar concentration in cells, effectively allowing the plants to develop greater tensions. Therefore, the crop will be slightly more effective in extracting soil water and retaining water against atmospheric demand. This process, however, is one that occurs primarily as a survival mechanism, and a crop found to respond in this manner already has been damaged and will not reach its yield potential. Upon rewatering, these plants will lose the adaptation to drought within about a week, yet will still show rather serious yield reductions because of the effects on yield components described above. Each time this process is repeated, further reductions in yield occur, thus greatly reducing the value of the crop.

Under management that is directed at maintaining excellent growing conditions (irrigation when the soil-water tension reaches 1 bar at one foot depth), there is some concern about producing excessive vegetative growth, which might induce some lodging. This problem is not of serious concern for soybeans grown on clay soils; however, it may be avoided on coarser textured soils by reducing seeding rates to lower plant populations.

Summary

Soil texture has a profound effect on the manner in which water is retained in the soil. Coarse-textured, sandy soils have an abundance of large pores that readily fill with water but drain rapidly due to gravity. Relatively little water is retained in the small pores of sandy soils. Fine-textured, clay soils have a large percentage of their total volume occupied by very small pores. These pores exchange gas and water slowly. The water in small pores is bound to the clay particles and resists extraction by gravity and by plants. The water in small pores is available to plants only when the tension in the plants exceeds the tension with which the soil binds the water. Therefore, clay soils hold a large amount of water, but that water is bound tightly by the soil particles, and only a small portion is available to plants at rates required for good crop production. Therefore, maximum yields on clay soils require frequent applications of water. Plants are very sensitive to water availability.

In marginal water supply vs. atmospheric evaporative-demand conditions, the stomata open and close to maintain a turgid, functional leaf in-so-far as possible. When the water supply-demand conditions become too far out of balance, the plant loses its turgidity and wilts. Several physiological processes are quite sensitive to water stress and respond to tension before wilting occurs. For example, leaf and stem growth are the developmental processes most sensitive to drought stress. Drought will quickly reduce leaf and stem growth, but flowering, seed set, seed growth and photosynthesis also are affected by water deficits. Yield is often lowered by reducing numbers of seed produced per acre due to drought during the flowering and seed-set period of development. Droughts occurring late in the season often result in reduced seed size. This is caused by lower photosynthetic rates and premature leaf death.

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