IRRIGATION MANAGEMENT SERIES

Soil, Water, and Plant Relationships

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Plant growth depends on two important natural resources — soil and water. Soil provides the mechanical support and nutrient reservoir necessary for plant growth. Water is essential for plant life processes. Effective management of these resources for crop production requires the producer to understand relationships between soil, water, and plants.

Knowledge about available soil water and soil texture can influence the decision-making process, such as determining what crops to plant and when to irrigate. This publication provides general information on the physical characteristics of soil, soil and water interactions, and how plants use water, particularly as these topics relate to irrigated agriculture. However, the information is pertinent to rain-fed agricultural production as well. More in-depth information on other related topics is available in other K-State Research and Extension publications, including MF2389 *What is ET?*; L935 *Important Agricultural Soil Properties*; and L934 *Agricultural Crop Water Use*.

The basic soil, water, and plant relationships are important to agricultural producers, but especially to irrigation users that desire to use best management practices such as irrigation scheduling. Irrigation scheduling determines when and how much water needs to be added to a crop's root zone to promote optimum yields. One climatic- or evapotranspiration (ET)-based irrigation scheduling option is the KanSched program (see reference list for program availability).

Soil's Physical Characteristics

There are many factors that determine the physical characteristics of soil. These include soil texture, soil structure, bulk density, and soil porosity. They all affect the interaction between soil, water, and air.

Soil Composition. A unit of soil is a combination of solid material, composed of mineral and organic matter, and open space, called pores. By volume, most soils are roughly 50 percent solids and 50 percent pore space.

The mineral matter makes up about 45 to 47 percent of the total soil volume. This mineral matter consists of small particles of either sand, silt, or clay.

Organic matter is made up of decaying plant and animal substances and is distributed in and among the mineral particles. Organic matter can account for up to about 5 percent of the overall soil makeup by volume, but many agricultural soils have less than 1 percent organic matter.

The pores, spaces that occur between the mineral particles, are important because they store air and water in the soil.

Figure 1 shows the approximate relationship between the substances in the soil composition, with the pore space shown split between air

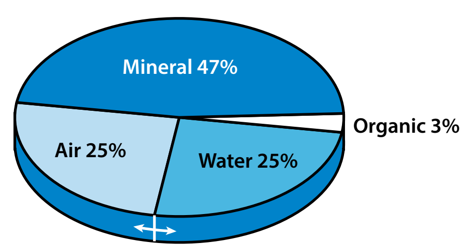

Figure 1. Typical soil composition by volume.

and water. The amount of water and air present in the pore spaces varies over time in an inverse relationship. This means that for more water to be contained in the soil, there has to be less air. The amount of water in soil pore space is essential to crop production and will be further discussed in the section on soil water content.

Soil Texture. The size of the particles that make up the soil determine soil texture. The traditional method of determining soil particle size consists of separating the particles into three convenient size ranges. These soil fractions or separates are sand, silt, and clay.

Generally, only particles smaller than 2 mm (1/12 inch) in size are categorized as soil particles. Particles larger than this are categorized as gravel, stones, cobbles, or boulders.

Sand particles range in size from 2 mm to 0.05 mm. There are subcategories assigned to this range that include coarse, medium, and fine sand.

Silt particles range in size from 0.05 mm down to 0.002 mm. The physical appearance of silt is much like sand, but the characteristics are more like clay. Clay particles are less than 0.002 mm in size.

Clay is an important soil fraction because it has the most influence on soil behavior such as water-holding capacity. Clay and silt particles cannot be seen with the naked eye.

Soil texture is determined by the mass ratios, or the percent by weight, of the three soil fractions. The soil textural triangle, Figure 2, shows the different textural classes and the percentage by weight of each soil fraction. For example, a soil containing 30 percent sand, 30 percent clay, and 40 percent silt by weight is classified as a clay loam.

Soil Structure. Soil structure is the shape and arrangement of soil particles into aggregates. Soil structure is an important characteristic used to classify soils and heavily influences agricultural productivity and other uses, such as load-bearing capacity for structures.

The principal forms of soil structure are platy, prismatic, columnar, blocky, and granular. These soil structure descriptions indicate how the particles arrange themselves into aggregates. Aggregated soil types are generally the most desirable for plant growth. Soil structure terms also are used in conjunction with descriptive words to indicate the class and grade of soil. Class refers to the size of the aggregates, while grade describes how strongly the aggregates hold together. Structureless soils can be either single-grained (individual unattached particles, such as a sand dune) or massive (individual particles adhered together without regular cleavage, such as claypans or hardpans.) Soil structure is unstable and can change with weather conditions, biological activity, and soil management practices.

Soil Bulk Density and Porosity. Soil bulk density expresses the ratio of the mass weight of dry soil to its total volume. The total volume includes both the solids and the pore spaces. Soil bulk density is important because it is an indicator of the soil's porosity. The porosity of a soil is defined as the volume of pores in a soil. A compacted soil has low porosity and thus a greater bulk density. A loose soil has a greater porosity and a lower bulk density. Like soil structure, a soil's bulk

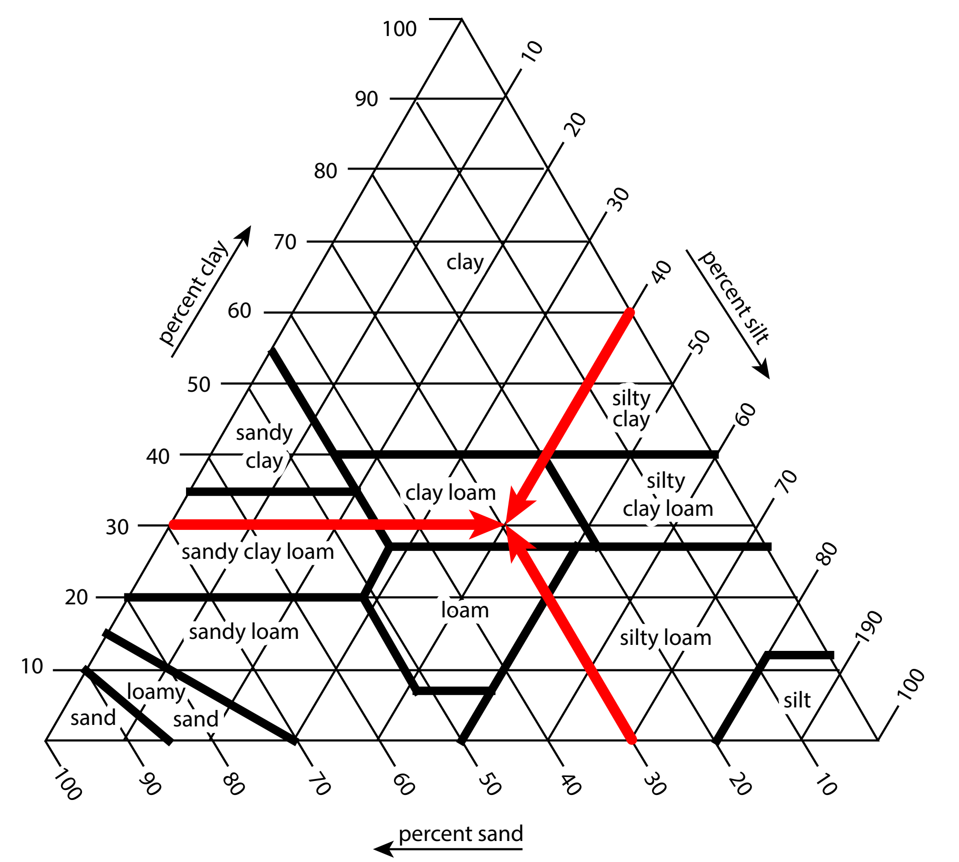

Figure 2. A soil textural classification triangle, showing a clay loam soil composed of 30 percent sand, 30 percent clay, and 40 percent silt.

Table 1. Average water-holding capacity for Kansas soils, depths greater than 12 inches (NRCS National Engineering Handbook Part 652 Irrigation Guide).

Soil Texture	Bulk Density	Percentage by Mass			Fraction by Volume		
		Field Capacity	Wilting Point	Available Water Capacity	Field Capacity	Wilting Point	Available Water Capacity
Sand	1.70	7.0	3.0	4.0	0.12	0.05	0.07
Loamy Sand	1.70	10.0	4.2	5.8	0.17	0.07	0.10
Sandy Loam	1.65	13.4	5.6	7.8	0.22	0.09	0.13
Fine Sandy Loam	1.60	18.2	8.0	10.2	0.29	0.13	0.16
Loam	1.55	22.6	10.3	12.3	0.35	0.16	0.19
Silt Loam	1.50	26.8	12.9	13.9	0.40	0.19	0.21
Silty Clay Loam	1.45	27.6	14.5	13.1	0.40	0.21	0.19
Sandy Clay Loam	1.50	26.0	14.8	11.2	0.39	0.22	0.17
Clay Loam	1.50	26.3	16.3	10.0	0.39	0.24	0.15
Silty Clay	1.40	27.9	18.8	9.1	0.39	0.26	0.13
Clay	1.35	28.8	20.8	8.0	0.39	0.28	0.11

density and porosity can be affected by weather-related factors, biological activities, and soil management practices. Table 1 lists typical bulk densities for Kansas soils.

Soil and Water Interactions

Soil acts like a reservoir that holds water and nutrients plants need to grow. Some soils are large reservoirs with more holding capacity that release water and nutrients easily to plants, while other soils have limited reservoirs. The following discussion focuses on soil water as it relates to plant availability and applying irrigation water.

Soil Water Content. Soil water content is the amount of water stored in the soil at a given time. The most commonly defined soil water content values are saturation, field capacity, wilting point, and oven dried. At saturation, which usually occurs immediately after a heavy rainfall or an irrigation application, all pore spaces in the soil are filled with water. When the soil is at or near saturation, some of the water is free to drain or percolate due to the force of gravity. This excess water is referred to as gravitational water. Since this percolation takes time, some of this extra water could be used by plants or lost to evaporation. Field capacity is defined as the amount of water remaining in the soil after rapid percolation has occurred. This is not a definite soil water point; therefore, field capacity often is defined as approximately one-third atmosphere tension. Tension is defined in a following section.

Wilting point is defined as the soil water content at which the potential or ability of the plant root to absorb water is balanced by the water potential of the soil. Most crops show significant signs of stress, such as wilting to the extent of dying, if soil water reaches the wilting point, especially for extended periods of time. Wilting point is usually approximated by a value of 0.15 atmospheres (bars).

Soil that has been oven dried is used as a reference point for determining soil water content. When the soil is oven dried, all soil water has been removed from the soil. The amount of water at any soil-water content varies by soil type. Specific water-holding capacities can be obtained from various sources; however, NRCS County Soil Surveys are probably the most extensive and readily accessible. Figure 3 illustrates typical amounts of water held at the defined soil water content for sand, loam, and silty clay loam soils. The reasons for the differences between soil types is explained in the next sections.

Water content can be expressed as inches of available water or as a percentage. Typical values of both expressions are shown in Table 1 for soils at depths greater than 12 inches. Typically the top soil layer has slightly higher available water-holding capacity (see L935, *Important Agricultural Soil Properties* for more information).

How Soil Holds Water. Soil holds water in two ways: (1) as a thin film on individual soil particles and (2) as water stored in the pores of the soil. Water stored as a thin film on individual soil particles is held in place by adsorption forces. Adsorption involves complex chemical and physical reactions but in simple terms, a thin film of water adheres to the outside layers of soil particle molecules. Water stored in the pores of the soil is stored by capillary forces. An example of the capillary force phenomenon would be to place one end of a glass capillary tube in a pan of water. Water in the tube will rise to a certain height, which depends on the diameter of the capillary tube (Figure 4). This phenomenon can act in any direction and is the key to water being stored in soil pores, as illustrated in Figure 5.

Soil Water Tension. The ease by which water can be extracted from the soil depends on the soil water tension, also known as the soil water potential. These are equivalent values, except for the sign (negative vs. positive), which might be thought of as either a push or a pull on the water.

Water being held in pores by the capillary storage is held in the soil at a certain tension. The same is true for water held with the adsorption phenomenon. As the soil dries, these tensions become larger. It is easier for a plant to extract water being held at lower tensions.

The tensions that correspond to the soil-water equilibrium points discussed above is a good example of water tensions affecting plant water use. At saturation, the soil water tension is approximately 0.001 bar. One bar tension is equivalent to 1 atmosphere of pressure (14.7 psi). Thus, from the above discussion, it would be easy for a plant to extract water from a saturated soil. Saturation only

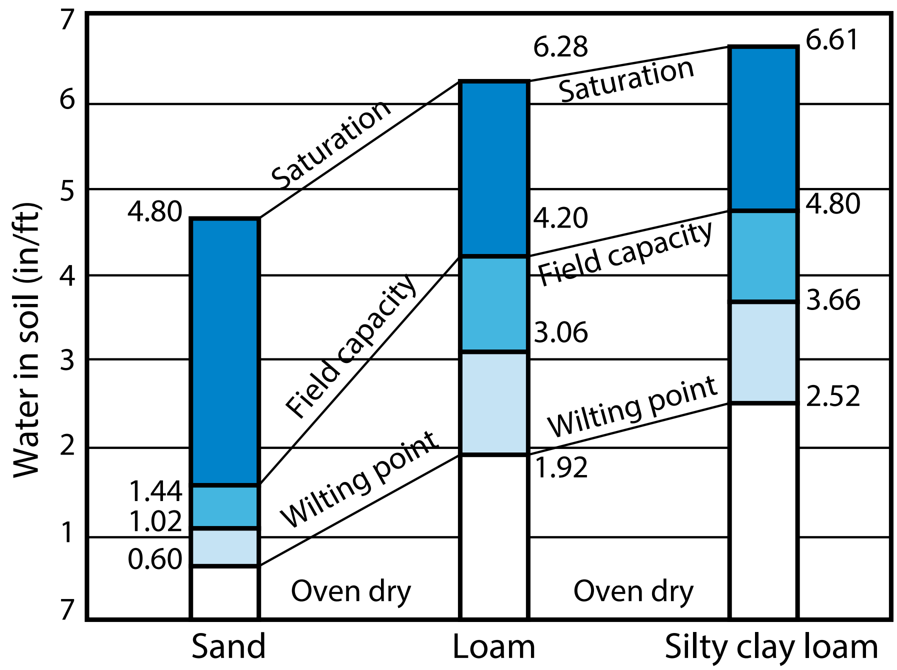

Figure 3. Typical soil water content within three soil textures.

lasts a short time, so plants extract only a small portion of the water above field capacity. Field capacity is defined to be at approximately one-third atmosphere pressure or approximately 0.3 bar. At this content, it is still easy for the plant to extract water from the soil.

The wilting point occurs when the potential of the plant root is balanced by the soil water potential; thus, plants are unable to absorb water beyond this tension (approximately 15 bars). As soil water approaches the wilting point, plants will exhibit increasing symptoms of water stress, such as wilting and leaf senescence. Prolonged exposure will result in plant death. As a reference, the soil water tension in an oven-dried soil sample is approximately 10,000 bars.

A soil water retention or soil water characteristic curve illustrates the tension relationship (Figure 6). These curves are slightly different for different types of soils due to different soil textures and structures. Water between the field

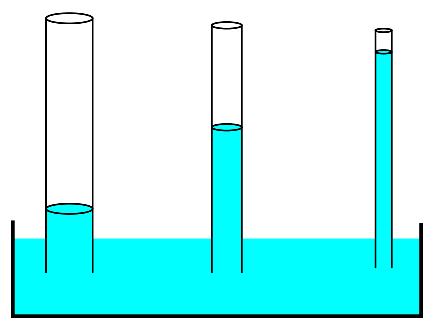

Figure 4. Capillary forces illustrated by how far water rises in tubes of various sizes.

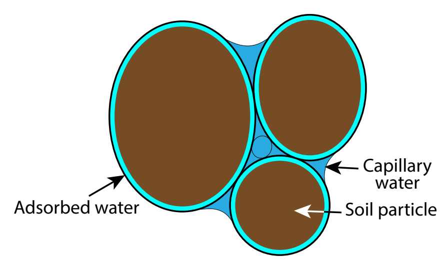

Figure 5. How soil holds water.

capacity and the wilting point is water available to the plant. Best plant growth and yield for most field crops occur when the soil water content remains in the upper half of the plant available soil water range, which is sometimes referred to as readily available soil water.

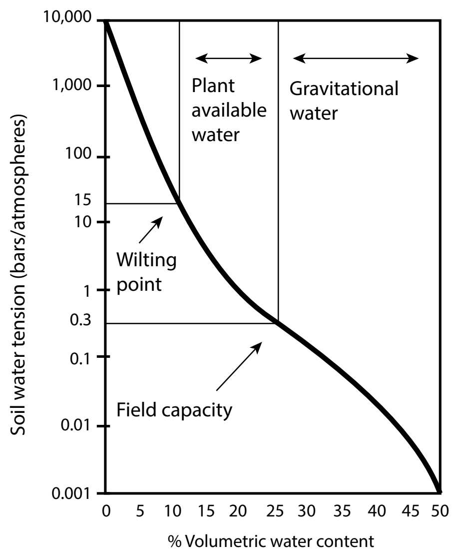

Figure 6. The relationship between soil water content and soil water tension for a loam soil type.

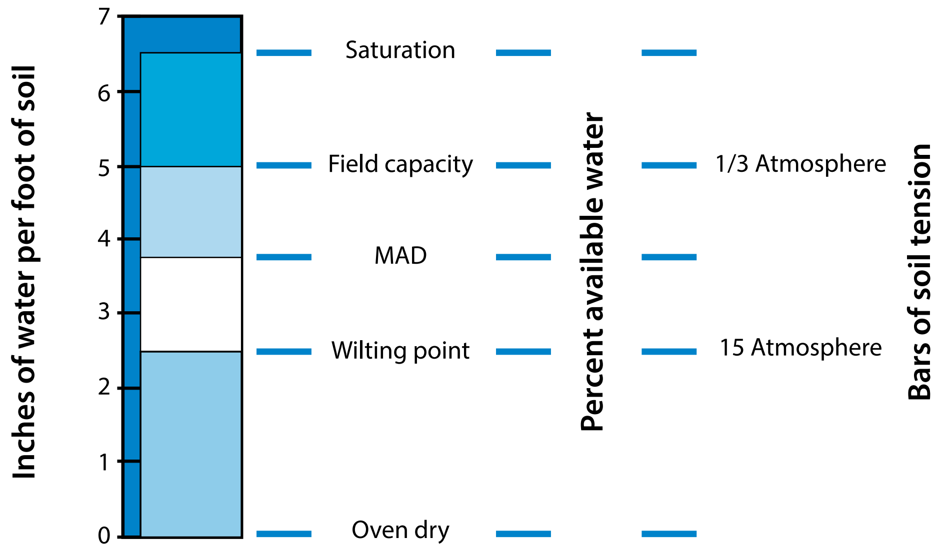

Figure 7. Illustration of the relationship of soil water content terms, values, percent available soil water, and soil tension for a silty clay loam soil type.

The dividing point between available soil water content and readily available soil water content is named the maximum allowable depletion, or MAD soil water content. For most field crops, the MAD level is usually defined as about 50 percent available water. In some water-sensitive crops, such as vegetables and flowers, the MAD level may be less, such as 30 percent available water. The relationship between the soil water content value, percent available soil water, and soil tension for a silty clay loam soil is illustrated in Figure 7.

Soil water potential is a measure of the energy status of the soil water. Water flows from a greater potential area to an area of less potential. The units of measurement are normally either bars or atmospheres. What can be confusing is that soil water potentials are negative pressures that are also expressed as tension or suction. In this case, water flows from greater (less negative) potential to a lesser (more negative) potential. Plants develop the tension, or potential, to move water from the soil into the roots and distribute the water through the plant by adjusting the water potential, or tension, within their plant cells. Water potential is made up of several components, but one of particular importance is the osmotic or solute potential. Solute potential is due to the presence of dissolved solutes, such as sugars and amino acids, in the plant cell.

For water to move from soil, into roots, into stems, into leaves, and finally into air, the water potential must always be decreasing. This is illustrated in Figure 8, moving from the greater water potential soil (less negative) to the lower water potential air (more negative). The water potential in air is always low as compared to plants, so water movement is toward the air through the plants. However, plants are limited in the amount of adjustment they can make.

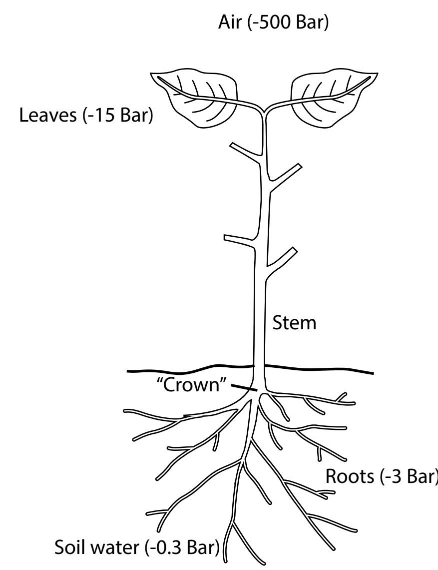

Figure 8. Illustration of decreasing water potential to move water from the soil to the atmosphere through a plant. Water movement is from higher water potential (less negative pressure reading, expressed in bars of pressure) to lower water potential (more negative pressure reading). Air is usually at lower water potential than a plant.

Use of Water by Plants

A plant's root system must provide a negative tension (pressure) to extract water from the ground. This tension must be equivalent to the tension that holds the water in the soil. For example, if the water in the soil is at 0.3 bars (around field capacity), the plant must provide at least 0.3 bars of negative tension to pull the water from the ground. At the wilting point, the maximum negative tension that a plant can provide is balanced by the soil water tension. At this point, the plant can no longer extract water from the soil and will be under severe stress to the point of death. There are several factors that determine when and where a plant uses water, and how much water a plant will use. These factors include daily plant water need as influenced by climatic conditions and stage of growth, plant root depth, and soil and water quality.

Plant Water Need. A plant has different water needs at different stages of growth. While a plant is young, it requires less water than when it is in the reproductive stage. As a plant approaches maturity, its water needs drops. Curves have been developed that show the daily water needs for most types of crops. Figure 9 shows a typical crop water curve. Perennial crops, such as alfalfa, have crop water-use curves similar to those in Figure 9, except that the crop water use is altered when the crop is cut or harvested. The water use would drop dramatically at cutting and recover with regrowth, making the water-use curve appear in a sawtooth-shaped pattern.

Plant Root Depth. A plant's root depth determines the depth to which soil water can be extracted. A young plant with only shallow roots will not have access to soil water deeper than its rooting depth. Plants typically extract about 40 percent of their water needs from the top quarter of their root zone, then 30 percent from the next quarter, 20 percent from the third quarter, and taking only 10 percent from the deepest quarter, as illustrated in Figure 10. Therefore, plants will extract about 70 percent of their water from the top half of their total root penetration. Table 2 shows the depth of root penetration and 70 percent water extraction for several common field crops. Deeper portions of the root zone can supply a higher percentage of the crop's water needs if the upper portion is largely depleted. However, reliance on use of deeper water reduces optimum plant growth. For irrigation scheduling purposes, the total potential plant root zone is not used. Instead a managed root zone depth of no more than 4 feet is recommended. Applying water to deeper depths subjects the irrigation to higher potential for deep percolation

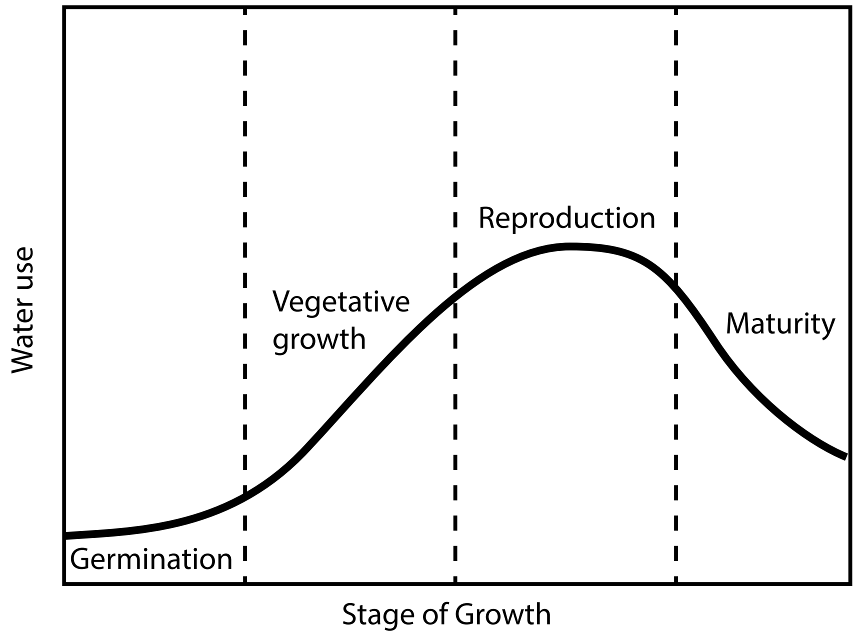

Figure 9. Typical plant water-use curve by stage of growth.

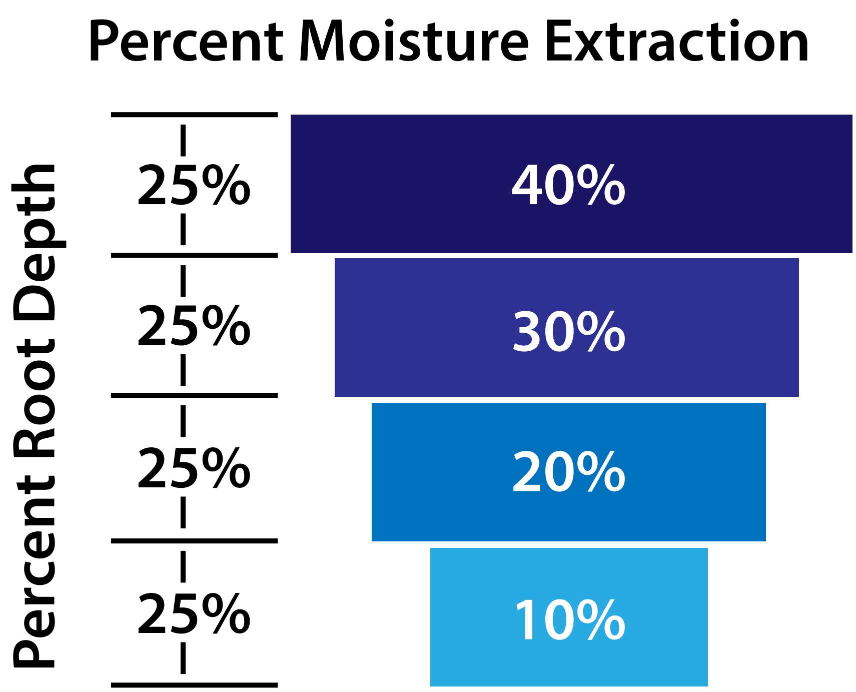

Figure 10. Generalized crop water extraction by depth of root zone for a non-layered and unrestricted soil profile.

Table 2. Depth of root penetration and 70 percent of their water extraction for several common field crops.

Crop	Depth of Root Penetration (Feet)	70% of their Water Extraction (Feet)
Corn	4 – 6	2 – 3
Grain Sorghum	4. 5 – 6	2 – 3
Alfalfa	6 – 10	3 – 4
Soybeans	5 – 6	2 – 3
Wheat	4 – 6	3
Sugar Beets	5 – 6	3

losses. The managed root depth may be much less than 4 feet if soils have restrictive layers that prevent root penetration. Some sands also result in restricted root penetration.

Soil and Water Quality. Another factor on the amount of soil water available to the plant is the soil and water quality. For good plant growth, a soil must have adequate room for water and air movement, and for root growth. A soil's structure can be altered by certain soil management practices. For example, excessive tillage can break apart aggregated soil and excessive traffic can cause compaction. Both of these practices reduce the amount of pore space in the soil, reducing the availability of water and air, and reducing the room for root development.

The quality of the water is also important to plant development. Irrigation water with a high content of soluble salt is not as available to the plant, so greater soil water content must be maintained in order to have water available to the plant. Increasing salt content of the water reduces the potential to move water from the soil into the roots. Some additional water would also be needed to leach the salt below the crop root zone to prevent salt build-up in the soil. Poor quality water can affect soil structure. Most Kansas crops are considered intermediate in terms of their salt tolerance.

Summary

Basic knowledge of soil-plant-water relationships makes it possible to better manage and conserve irrigation water.

Some of the important factors to remember include:

1. Soil water-holding capacity varies with soil texture. It is high for medium- and fine-textured soils but low for sandy soils.
2. Plant roots can use only available soil water, the stored water between field capacity and permanent wilting point. However, as a general rule, plant growth and yields can be reduced if soil water in the root zone remains below 50 percent of the water holding capacity for a long period of time, especially during critical stages of growth.
3. Although plant roots may grow to deep depths, most of the water and nutrients are taken from the upper half of the root zone. Plant stress and yield loss can occur even with adequate water in the lower half of the root zone.
4. Poor irrigation water quality can reduce the plant's ability to take up water and can affect soil structure.

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KSRE Websites:

General Irrigation
www.ksre.ksu.edu/irrigate

Mobile Irrigation Lab
www.bae.ksu.edu/mobileirrigationlab

Subsurface Drip Irrigation
www.ksre.ksu.edu/sdi

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