Pearson New International Edition

Elements of the Nature and Properties of Soils

Nyle C. Brady Raymond Weil

Third Edition

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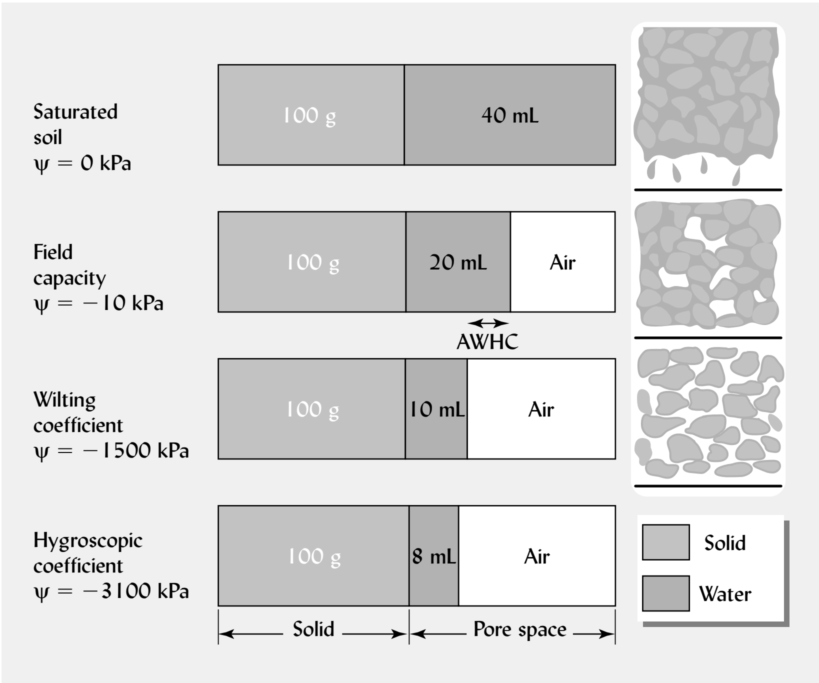

Figure 21
Volumes of water and air associated with 100 g of soil solids in a representative well-granulated silt loam. The top bar shows the situation when the soil is completely saturated with water. This situation will usually occur for short periods of time when water is being added. Water will soon drain out of the larger pores (macropores). *The soil is then said to be at* field capacity. *Plants will remove water from the soil quite rapidly until they begin to wilt. When permanent wilting of the plants occurs, the soil water content is said to be at the* wilting coefficient. *There is still considerable water in the soil, but it is held too tightly to permit its absorption by plant roots. The water lost between field capacity and wilting coefficient is considered to be the soil's plant available water-holding capacity* (AWHC). *A further reduction in water content to the* hygroscopic coefficient *is illustrated in the bottom bar. At this point the water is held very tightly, mostly by the soil colloids.*

drainage into a less-moist zone of similar porosity.[4] Water movement will continue to take place by unsaturated flow, but the rate of movement is very slow since it now is due primarily to capillary forces, which are effective only in micropores (Figure 21). The water found in pores small enough to retain it against rapid gravitational drainage, but large enough to allow capillary flow in response to matric potential gradients, is sometimes termed **capillary water**.

While all soil water is affected by gravity, the term *gravitational water* refers to the portion of soil water that readily drains away between the states of maximum retentive capacity and field capacity. Gravitational water includes much of the water

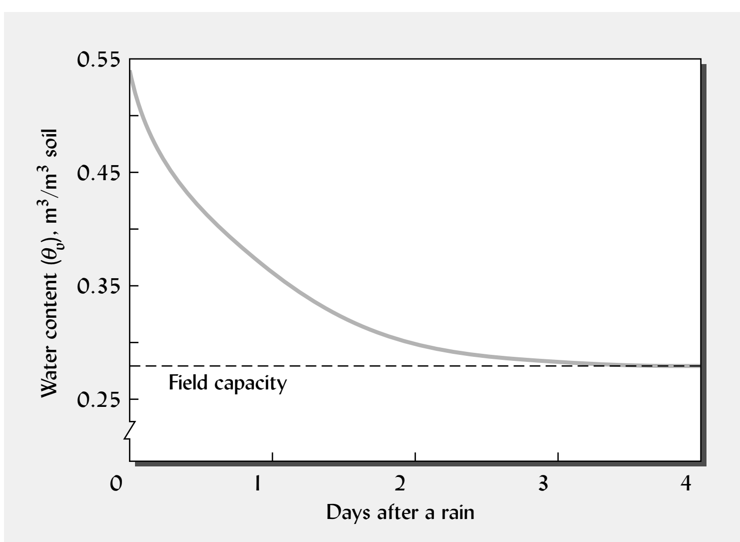

Figure 22
The water content of a soil drops quite rapidly by drainage following a period of saturation by rain or irrigation. After two or three days the rate of water drainage out of the soil is very slow and the soil is said to be at field capacity.
(Diagram courtesy of R. Weil)

[4]Note that because of the relationships pertaining to water movement in stratified soils (see Section 6), soil in a flower pot will cease drainage while much wetter than field capacity.

that transports chemicals such as nutrient ions, pesticides, and organic contaminants into the groundwater and, ultimately, into streams and rivers.

Field capacity is a very useful term because it refers to an approximate degree of soil wetness at which several important soil properties are in transition:

1. At field capacity, a soil is holding the maximal amount of water useful to plants. Additional water, while held with low energy of retention, would be of limited use to upland plants because it would remain in the soil for only a short time before draining, and, while in the soil, it would occupy the larger pores, thereby reducing soil aeration.
2. At field capacity, the soil is near its lower plastic limit—that is, the soil behaves as a crumbly semisolid at water contents below field capacity, and as a plastic putty-like material that easily turns to mud at water contents above field capacity. Therefore, field capacity approximates the optimal wetness for ease of tillage or excavation.
3. At field capacity, sufficient pore space is filled with air to allow good aeration for most aerobic microbial activity and for the growth of most plants.

Permanent Wilting Percentage, or Wilting Coefficient

Once an unvegetated soil has drained to its field capacity, further drying is quite slow, especially if the soil surface is covered to reduce evaporation. However, if plants are growing in the soil, they will remove water from their rooting zone, and the soil will continue to dry. The roots will remove water first from the largest water-filled pores, where the water potential is relatively high. As these pores are emptied, roots will draw their water from the progressively smaller pores and thinner water films in which the matric water potential is lower and the forces attracting water to the solid surfaces are greater. Hence, it will become progressively more difficult for plants to remove water from the soil at a rate sufficient to meet their needs.

As the soil dries, the rate of plant water removal may fail to keep up with plant needs, and herbaceous plant may begin to wilt during the daytime to conserve moisture. At first the plants will regain their turgor at night when water is not being lost through the leaves, and the roots can catch up with the plants' demand. Ultimately, however, an herbaceous plant will remain wilted night and day when its roots cannot generate water potentials low enough to coax the remaining water from the soil. Although they may not show wilting symtoms, most trees and other woody plants also have great difficulty obtaining any water from soil in this condition. The water content of the soil at this stage is called the **wilting coefficient**, or **permanent wilting percentage**, and by convention is taken to be the amount of water retained by the soil when the water potential is <1500 kPa (Figure 23). The soil will appear to be dusty dry, although some water remains in the smallest of the micropores and in very thin films (perhaps only 10 molecules thick) around individual soil particles (see Figure 21).

As illustrated in Figure 22, plant **available water** is considered to be that water retained in soils between the states of field capacity and wilting coefficient (between <10 to <30 kPa and <1500 kPa). The amount of capillary water remaining in the soil that is unavailable to higher plants can be substantial, especially in fine-textured soils and those high in organic matter.

Hygroscopic Coefficient

Although plant roots do not generally dry the soil much beyond the permanent wilting percentage, if the soil is exposed to the air, water will continue to be lost by evaporation. When soil moisture is lowered below the wilting point, the water molecules that

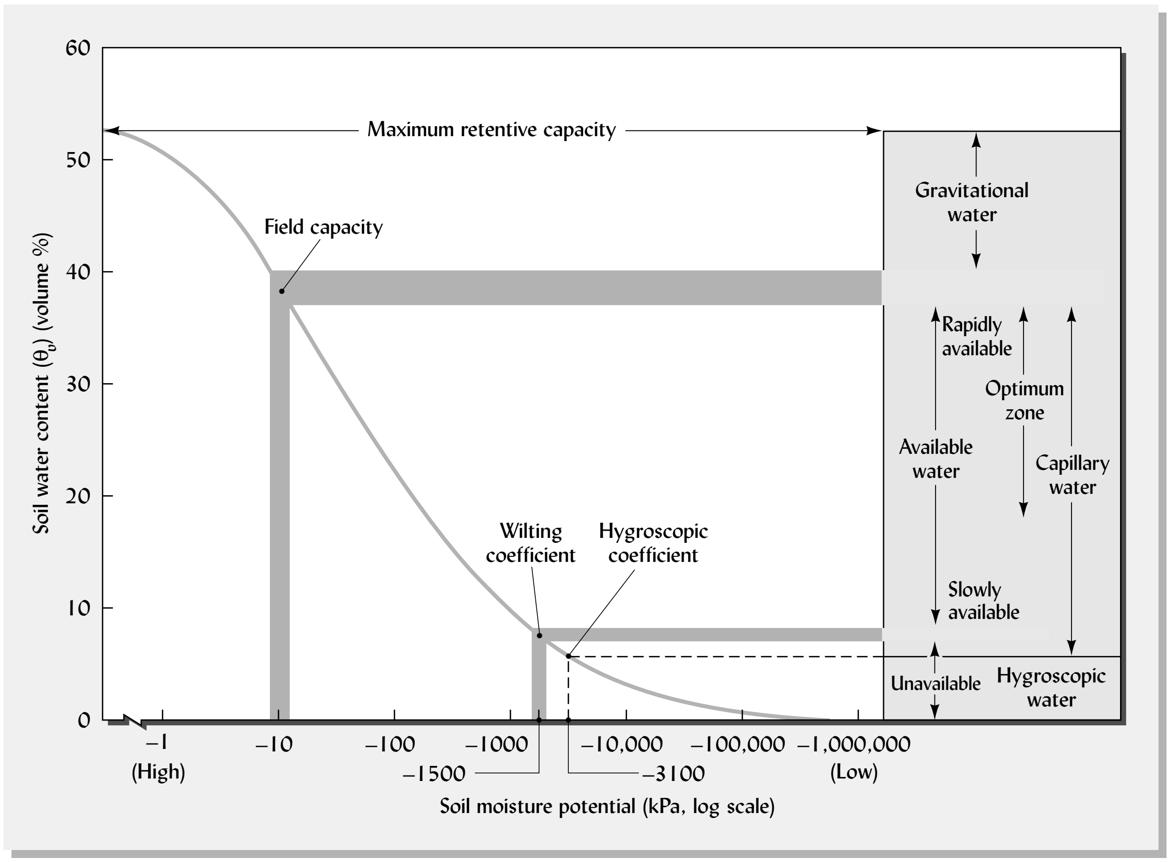

Figure 23
Water content–matric potential curve of a loam soil as related to different terms used to describe water in soils. The shaded bars in the diagram to the right suggest that measurements such as field capacity are only approximations. The gradual change in potential with soil moisture change discourages the concept of different "forms" of water in soils. At the same time, such terms as gravitational *and* available *assist in the qualitative description of moisture utilization in soils.*

remain are very tightly held, mostly being adsorbed by colloidal soil surfaces. This state is approximated when the atmosphere above a soil sample is essentially saturated with water vapor (98% relative humidity) and equilibrium is established at a water potential of <3100 kPa. The water is thought to be in films only 4 or 5 molecules thick and is held so rigidly that much of it is considered nonliquid and can move only in the vapor phase. The moisture content of the soil at this point is termed the **hygroscopic coefficient**.

9 FACTORS AFFECTING THE AMOUNT OF PLANT-AVAILABLE SOIL WATER

What is available water holding capacity? http://soils.usda.gov/sqi/publications/files/avwater.pdf

As illustrated in Figure 23, there is a relationship between the water potential of a given soil and the amount of water held at field capacity and at permanent wilting percentage, the two boundary properties determining the available water-holding capacity. This energy-controlling concept should be kept in mind as we consider the various soil properties that affect the amount of water a soil can hold for plant use.

The general influence of texture on field capacity, wilting coefficient, and **available water-holding capacity** is shown in Figure 24. Note that as fineness of texture increases, there is a general increase in available moisture storage from sands to

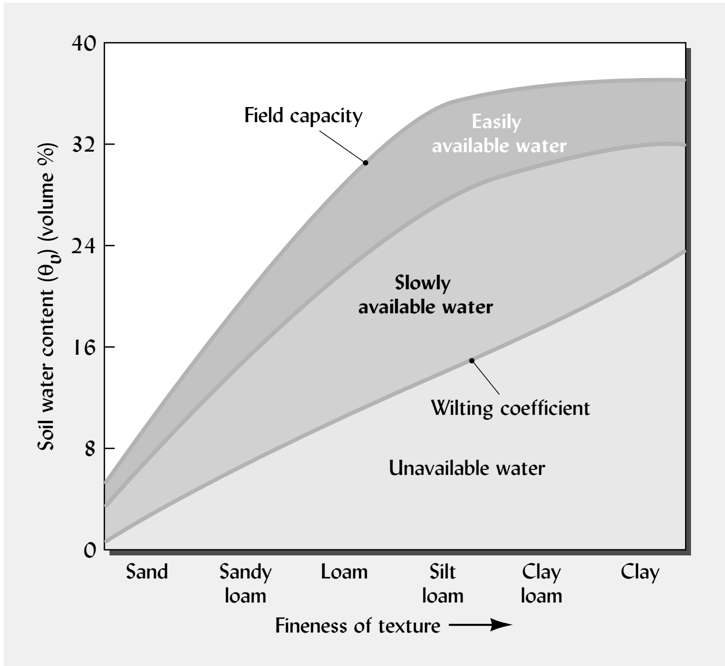

Figure 24
General relationship between soil water characteristics and soil texture. Note that the wilting coefficient increases as the texture becomes finer. The field capacity increases until we reach the silt loams, then levels off. Remember these are representative curves; individual soils would probably have values different from those shown.

loams and silt loams. Plants growing on sandy soils are more apt to suffer from drought than are those growing on a silt loam in the same area (see Plate 45). However, clay soils frequently provide less available water than do well-granulated silt loams since the clays tend to have a high wilting coefficient.

The influence of organic matter deserves special attention. The available water-holding capacity of a well-drained mineral soil containing 5% organic matter is generally higher than that of a comparable soil with 3% organic matter. Evidence suggests that soil organic matter exerts both direct and indirect influences on soil water availability.

The direct effects are due to the very high water-holding capacity of organic matter, which, when the soil is at the field capacity, is much higher than that of an equal volume of mineral matter. Even though the water held by organic matter at the wilting point is also somewhat higher than that held by mineral matter, the amount of water available for plant uptake is still greater from the organic fraction (Figure 25).

Organic matter indirectly affects the amount of water available to plants because it helps stabilize soil structure and increase the total volume as well as the size of pores. This results in an increase in water infiltration and water-holding capacity with a simultaneous increase in the amount of water held at the wilting coefficient. Recognizing the beneficial effects of organic matter on plant-available water is essential for wise soil management.

Compaction Effects on Matric Potential, Aeration, and Root Growth

Soil compaction generally reduces the amount of water that plants can take up. First, as the clay particles are forced closer together, soil strength may increase beyond about 2000 kPa, the level considered to limit root penetration. Second, compaction decreases the total pore space, which generally means that less water is retained at field capacity. Third, reduction in macropore size and numbers generally means less air pore space when the soil is near field capacity. Fourth, the creation of more very fine micropores will increase the permanent wilting coefficient and so decrease the available water content.

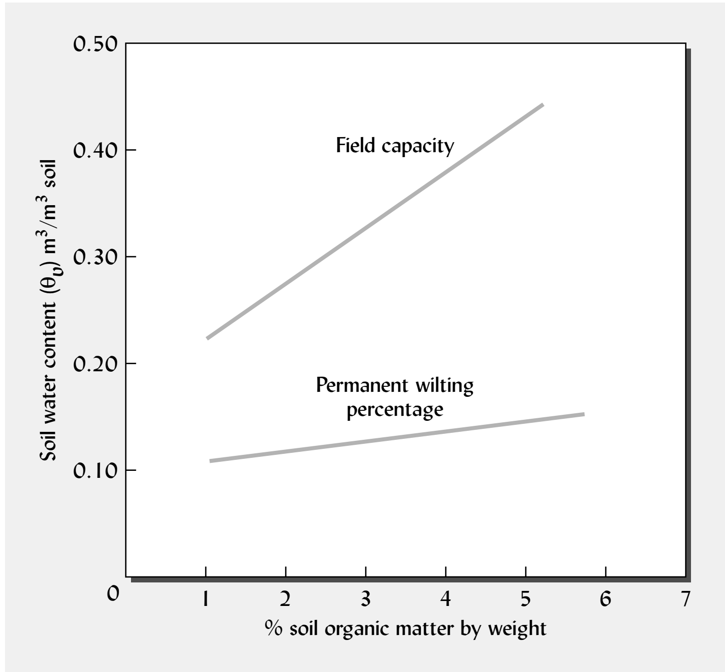

Figure 25
The effects of organic matter content on the field capacity and permanent wilting percentage of a number of silt loam soils. The differences between the two lines shown is the available soil moisture content, which was obviously greater in the soils with higher organic matter levels. [Redrawn from Hudson (1994); used with permission of the Soil & Water Conservation Society]

Least Limiting Water Range We have already defined **plant-available water** as that held with matric potentials between field capacity (<10 to <30 kPa) and the permanent wilting point (<1500 kPa). Thus, plant-available water is that which is not held too tightly for roots to take up and yet is not held so loosely that it freely drains away by gravity. The **least limiting water range** is that range of water contents for which soil conditions do not severely restrict root growth. According to the least limiting water range concept, soils are too *wet* for normal root growth when so much of the soil pore space is filled with water that less than about 10% remains filled with air. At this water content, lack of oxygen for respiration limits root growth. In loose, well-aggregated soils, this water content corresponds quite closely to field capacity. However, in a compacted soil with very few large pores, oxygen supply may become limiting at lower water contents (and potentials) because some of the smaller pores will be needed for air.

The least limiting water range concept tells us that soils are too *dry* for normal root growth when the soil strength (measured as the pressure required to push a pointed rod through the soil) exceeds about 2000 kPa. This level of soil strength occurs at water contents near the wilting point in loose, well-aggregated soils, but may occur at considerably higher water contents if the soil is compacted (see Figure 26). To summarize, the least limiting water range concept suggests that root growth is limited by lack of oxygen at the wet end of the range and by the inability of roots to physically push through the soil at the dry end. Thus, compaction effects on root growth are most pronounced in dry soils (Figure 27).

Osmotic Potential

The presence of soluble salts, either from applied fertilizers or as naturally occurring compounds, can influence plant uptake of soil water. For soils high in salts, the osmotic potential tends to reduce available moisture because more water is retained in the soil at the permanent wilting coefficient than would be the case due to matric potential alone. In most humid region soils, these osmotic potential effects are insignificant, but they become of considerable importance for certain soils in dry regions that may accumulate soluble salts through irrigation or natural processes.

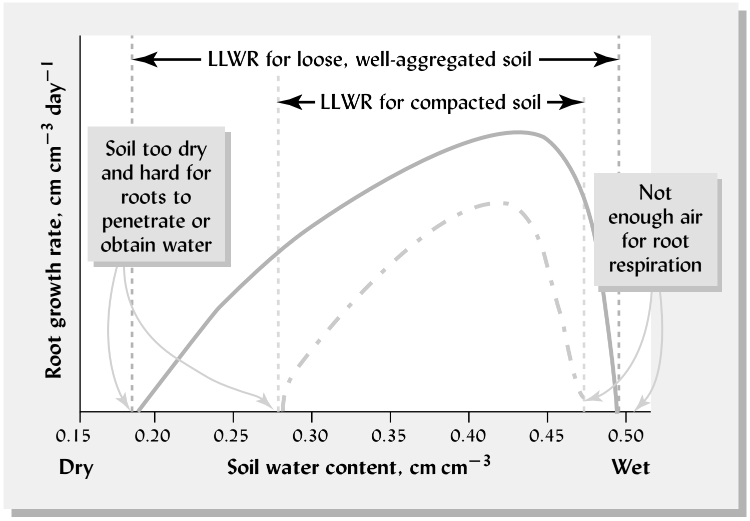

Figure 26
Compaction reduces the range of soil water contents suitable for plant growth (the least limiting water range, [LLWR]*). Near the wet end of the soil water content scale (*right*), root growth* (curved line) *is limited by lack of air for root respiration. Once the soil dries a little, the largest pores drain and fill with air. Neither water nor air is then limiting and root growth rate becomes maximal. With further drying, low water potentials make it more difficult for roots to obtain moisture, and the soil increases its mechanical resistance to root penetration. Root growth declines until the soil is so dry that roots cannot grow at all (*left*). The lower (*dashed*) curve depicts the reduced rate of root growth that would pertain if the soil were compacted. Because compaction compresses the largest pores, it takes somewhat less water than before to create an oxygen-limited condition that reduces root growth. Toward the dry end of the scale, higher soil strength brings root growth to a halt at a water content that would still support considerable growth in an uncompacted soil.* (Diagram courtesy of R. Weil, concepts from Da Silva and Kay, 1997)

Soil Depth and Layering

The total volume of available water will depend on the total volume of soil explored by plant roots (see Plate 85). This volume may be governed by the total depth of soil above root-restricting layers (see Figure 28), by the greatest rooting depth characteristic of a particular plant species, or even by the size of a flower pot chosen for containerized plants.

The capacity of soils to store available water determines to a great extent their usefulness for plant growth. To estimate the water-holding capacity of a soil, each soil horizon to which roots have access may be considered separately and then summed to give a total water-holding capacity for the profile (see Box 3).

Figure 27
Root growth of lodgepole pine tree seedlings in response to increased compaction at three soil water levels. Compaction affected root growth only when soil water was low, probably because root growth was limited by high soil strength. The tree seedlings were grown for 12 weeks in pots of mineral soil collected during timber harvest in British Columbia, Canada. The soil was compacted to three bulk density levels. Water was added as required to maintain volumetric water contents of 0.10–0.15 (low), 0.20–0.30 (medium), and 0.30–0.35 (high) cm^3/cm^3. [Drawn from data in Blouin et al. (2004)]