CHAPTER

10

Field Capacity, Wilting Point, Available Water, and the Nonlimiting Water Range

The amount of water available for plant uptake has been related to a soil's *water budget*. The three terms associated with the water budget are *field capacity* (FC), *wilting point* (WP), and *available water* (AW).

10.1 FIELD CAPACITY

To define FC we consider the following. In many soils, after a rain or irrigation, the water immediately starts draining deeper into the soil. After 1 or 2 days the water content in the soil will reach, with time, for many soils, a nearly constant value for a particular depth in question. This somewhat arbitrary value of water content, expressed as a percentage, is called the field capacity.

It is not known who first used the term field capacity. The term was not used by Briggs and Shantz, who developed the concept of the WP (see next section). Briggs (see Appendix, Section 10.5, for his biography) defined the "moisture equivalent", which was the amount of water held against centrifugation of soil at $3000 \times g$, where g is the acceleration due to gravity (Landa and Nimmo, 2003). The term is no longer accepted (Soil Science Society of America, 1997), but it was a precursor to the idea of FC.

Early researchers recognized that there was a point at which water moved slowly after a rain or irrigation (Taylor and Ashcroft, 1972, p. 299). They wanted to assign a value to this point, and therefore, the concept of FC developed. They recognized it as the amount of water that a well-drained soil holds against gravitational forces and when downward drainage is markedly decreased. They felt it was a true equilibrium and they felt it was the upper limit of AW for plants.

Principles of Soil and Plant Water Relations
http://dx.doi.org/10.1016/B978-0-12-420022-7.00010-0

However, as time progressed, soil scientists realized that FC was an imprecise term. They saw that it was not a unique value, because equilibrium is never reached. Soil water is dynamic; removal of water occurs due to drainage, evaporation, and transpiration and addition of water occurs with dewdrops, rainfall, and irrigation (Taylor and Ashcroft, 1972, p. 300). The movement of water downward does not cease, but continues at a reduced rate for a long time. There is no real value for FC. Therefore, a range of values (soil water contents) are associated with FC (Figure 10.1). Many factors influence FC, as follows (Hillel, 1971, pp. 162–165).

1. *Previous soil water history:* A wetting soil and a drying soil hold different amounts of water. A soil that is saturated and then dries has a higher FC than a soil that is being wetted. This is due to hysteresis (see Chapter 6).
2. *Soil texture and structure:* These change with soil horizon and influence water retention. Clayey soils retain more water, and longer, than sandy soils. The finer the texture is, the higher is the FC, the slower is its attainment, and the less distinct is its value (Hillel, 1971, p. 164).
3. *Type of clay:* The higher the content of montmorillonite is, the greater is the content of water.
4. *Organic matter:* Soil organic matter helps retain water.
5. *Temperature:* The temperature influences the amount of water held, particularly if the soil has been previously wetted. The amount of water retained at FC decreases as the soil temperature increases (Kramer, 1983, p. 71). This results in increased runoff from a watershed as soil warms.

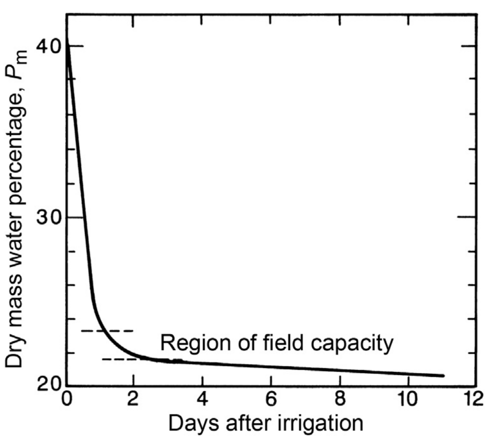

FIGURE 10.1 Diagram showing field capacity as a range of values of soil water contents. *From Taylor and Ashcroft (1972). Used with permission.*

6. *Water table:* The term "field capacity" is of doubtful value in soils with a water table near the surface. The term applies to free-draining soils.
7. *Depth of wetting:* Usually, the wetter the profile is at the outset, the greater is the depth of wetting during infiltration, the slower is the rate of redistribution, and the greater is the FC.
8. *Presence of impeding layers (e.g., clay, sand, and gravel):* The layers inhibit redistribution and increase the FC. Again, the term "field capacity" is of questionable value for soils having layers of widely differing hydraulic conductivities.
9. *Evapotranspiration:* The rate and pattern of extraction of water by plant roots from soil can affect the gradients and flow directions in the profile and modify redistribution (Hillel, 1971, p. 165).

People have suggested abandoning the concept of FC, because it has caused misleading conclusions. For example, if it is assumed that no drainage occurs, when in fact it is, drainage is included in consumptive use by plants. This leads to consumptive use values that are too large.

Until the 1984 edition of the *Glossary of Soil Science Terms* (Soil Science Society of America, various years), the term "field capacity" was labeled "obsolete". These included the glossaries published in 1971, 1975, 1978, and 1979. More current glossaries (1984, 1987, 1997, 2008) no longer call it obsolete, and the term is widely used in the literature. One is often asked to provide the FC for a soil when publishing a paper. Even though FC is not an exact value, the reason that the term has been brought back into the literature probably relates to the development of computer models. A numerical value like AW (discussed in Section 10.3; it is the difference between FC and permanent WP) is needed to put into computer models to relate water in the soil to plant growth. Along with AW, the non-limiting water range (NLWR) (see Section 10.4) now frequently is used in computer models to relate water in the soil to crop growth or yield. Crop-growth models could be developed when computers became widely available and on the desk of every scientist (late 1980s).

FC is not the upper limit of AW to plants because all water that is not held tightly by soil can be used by plants while it is in contact with roots, even if water is rushing by during rapid drainage. What limits uptake is soil aeration, and, as we shall see (Chapter 12), the air-filled pore space must be at least 10% by volume for most roots to survive (Wesseling and van Wijk, 1957).

Note that FC does not apply to pots in a greenhouse. FC refers only to field conditions. Greenhouse pots do not have underlying soil that pulls water down deep into the soil profile by capillarity. However, one can talk of "pot capacity", which is the amount of water remaining in a pot after irrigation and visible drainage has ceased.

One should always try to measure FC in the field for each soil. The matric potential associated with FC can be as high as −0.0005 MPa in a highly stratified soil or as low as −0.06 MPa in a deep, dryland soil (Baver et al., 1972, p. 382). If one cannot measure FC in the field, it is often estimated to be the soil water content at a soil matric potential of −0.033 MPa or −33 kPA (one-third bar).

10.2 WILTING POINT

The WP, also called the *permanent wilting point*, may be defined as the amount of water per unit weight or per unit bulk volume in the soil, expressed in percentage, that is held so tightly by the soil matrix that roots cannot absorb this water and a plant will wilt.

Unlike FC, the term wilting point is associated with known scientists, Briggs and Shantz (1912). They defined the "wilting coefficient" (WP) as "the moisture content of the soil (expressed as a percentage of the dry weight) at the time when the leaves of the plant growing in that soil first undergo a permanent reduction in their moisture content as the result of a deficiency in the soil-moisture supply" (Briggs and Shantz, 1912, p. 9). As with FC, early workers felt that WP was a precise value.

The method of determining permanent WP is as follows (Taylor and Ashcroft, 1972, p. 303). An indicator plant, usually sunflower (*Helianthus annuus*), is put in 500 g of soil in a metal can. The plant grows and is given adequate moisture until the third pair of true leaves is formed. Then the top of the can is sealed with wax. The sunflower grows in a greenhouse or outdoors until it wilts. Then it is transferred to a dark, humid chamber for recovery. If the plant recovers, it is put out again. The procedure is repeated until the plant remains wilted overnight (24 h) in the humid chamber. The soil water content then is at the permanent WP.

For plants that have leaves that do not wilt, like cacti, Briggs and Shantz (1912) developed special procedures to determine the WP. For example, they put a plant with water-storage tissue in a glass container with soil. They glued a knitting needle to one side of the glass. They put the glass with knitting needle in a horizontal position by propping it between two other containers sitting on a table. The needle was free to move up and down a scale. As the cactus used water in the soil, the needle moved in one direction. Then the motion along the scale was gradually reversed, as the cactus shoot itself started to lose water. The WP was the point of reversal of needle movement (Briggs and Shantz, 1912, pp. 47–53).

As with FC, later researchers realized that the WP is not a unique value. It is dynamic, like FC. There are a range of values at which the rate of water supply to a plant is not sufficient to prevent wilting, depending on the soil profile (soil texture, compaction, and stratification); the amounts of water in the soil at different depths, which affect root distribution; the transpiration rate of a plant; and the temperature (Table 10.1). One should use a water bath to determine the WP, to control the temperature. Also, leaves wilt differently. Usually the basal leaves wilt first (Taylor and Ashcroft, 1972, p. 303), so one can refer to the "first permanent wilting point,", at which the basal leaves do not recover, and the "ultimate permanent wilting point,", at which the apical leaves do not recover. The permanent WP depends upon plant osmotic adjustment. Therefore, we recognize that there is a range of values for permanent WP, and it is not a unique value (Figure 10.2).

If one cannot measure the permanent WP, it is usually estimated to be the water content at a soil matric potential of −1.5 MPa or −1500 kPa (−15 bars). However, plants can absorb water from soil at potentials much lower than this; creosote bush (*Larrea divaricata*) can absorb water to −6.0 MPa (Salisbury and Ross, 1978, p. 389). But the amount of water actually held by the soil between −1.5 MPa and −6.0 MPa is small.

The point at which the water content at the soil−root interface reaches the WP is of interest mathematically for root models (Philip, 1957; Gardner, 1960). In the models, the WP is dependent not only on the soil water content at wilting, but also on the diffusivity of the soil, the radius of the root, and the transpiration rate. In his 1957 model of water uptake by plant roots, Philip pointed out that uncritical use of the WP as an invariant index of the lower limit of the availability of soil moisture to plants can be misleading (Philip, 1957; Raats et al., 2002, p. 18).

However, the permanent WP still needs to be determined to calculate AW, which we shall discuss in the next section. As noted above, computer models are now commonplace. A widely used equation in models of soil

TABLE 10.1 Influence of Temperature on the Soil Water Percentage at Which Sunflowers will Wilt Permanently

	Permanent Wilting Percentage for Three Soils		
Temperature (°C)	**Millville Silt Loam**	**Benjamin Silty Clay Loam**	**Yolo Fine Sandy Loam**
5	…	…	9.0 ± 0.11
12.8	…	…	8.5 ± 0.03
15	8.38 ± 0.13	11.63 ± 0.23	…
25	7.34 ± 0.17	10.46 ± 0.26	…
35	6.66 ± 0.16	…	…

From Taylor, S.A., Ashcroft, G.L., 1972. Physical Edaphology: The Physics of Irrigated and Nonirrigated Soils. W.H. Freeman and Company, p. 303. Used with permission.

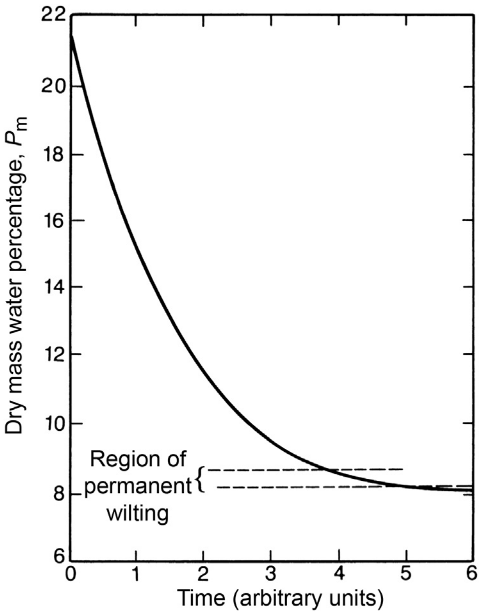

FIGURE 10.2 Average water percentage in the top foot of soil in which alfalfa is rooted to a depth of 3 m. The permanent wilting percentage is a range of values of soil water contents over which the removal rate is slow. *From Taylor and Ashcroft (1972). Used with permission.*

physicists is the van Genuchten equation (van Genuchten, 1980; see Eqn (21) in his paper). The equation relates soil water content to pressure head (or what we call matric potential in this book). It is used to get hydraulic conductivity in unsaturated soils. It is a key equation, because soils are usually unsaturated. The Darcy equation can be used only in saturated soils (see Chapter 7, Eqn (7.1)). (The title of van Genuchten's paper uses the term "closed form". In an e-mail to me dated March 12, 2004, Dr Brent E. Clothier, Plant and Food Research, Palmerston North, New Zealand, defined the term. He said it is closed form because the parameters used to describe the water characteristic and the conductivity are functionally linked, so that they are closed in the sense that they are related and not just independently fitted parameters. See Chapter 6, for the definition of the soil water characteristic, and Figure 6.8.) In the van Genuchten equation, one must determine the residual water content. The residual water content in the van Genuchten equation is represented by θ_r. The question arises, "What is the relation between the residual water content and the wilting point?"

The residual water content is not defined in the *Glossary of Soil Science Terms 2008* (Soil Science Society of America, 2008) or any previous glossaries. In an e-mail dated January 20, 2006, Dr van Genuchten (formerly of the US Salinity Laboratory, Riverside, California; now in the Department of Mechanical Engineering, Federal University of Rio de Janeiro, Brazil) defines residual water as follows: "The residual water content is the water content where no liquid flow occurs any more, and hence where water moves (or can be removed) only by vapor flow. The wilting point is an excellent approximation of the residual water content of very coarse-textured (sandy) soils. However, the wilting point at pF = 4.2 likely over-estimates the residual water content of fine-textured (clay) soils where still lots of bound water may be present that collectively (because of the large surface area) may still yield a reasonable liquid flow rate. Remember that those pressure plate approaches for water content measurements require very long times for equilibrium to develop, and that the water content can still go down significantly for pF much larger than 4 or 5." Bound water is not defined in the *Glossary of Soil Science Terms 2008* (Soil Science Society of America, 2008) or any previous editions. However, when we defined matric potential (Chapter 4, Section II, Part 1), we noted that it was due to both water held directly on particle surfaces as well as water held by capillarity in soil pores. So the definition of bound water could be "water held directly on particle surfaces". The dictionary (Webster's New World Dictionary of the American Language and Publishing, 1959) defines "bound" as meaning "closely connected". When we define mobile water content (Chapter 13, Section IX), we shall see that one reason water is immobilized is due to the fact that is it bound to the surfaces of soil particles. Residual water is considered in detail by Dexter et al. (2012).

Dr van Genuchten uses the term "pF". The *Glossary of Soil Science* lists pF as "obsolete" in the 1971 edition (first one I have), 1975 edition, 1978 edition, and 1979 edition, and it does not appear in the 1984 edition or since then. In the editions where the pF appears, it is defined as "(Obsolete) The logarithm of the soil moisture tension expressed in centimeters height of a column of water".

So for pF = 4.2 (see Dr van Genuchten's value above)
Antilogarithm: 15,849 cm
Divide by 1020 cm/bar:
15.5 bars (close enough to −15 bars or −1.5 MPa for the permanent WP)
1 bar = 0.987 atm; divide by 1033 cm/atm; 15.3 atm.
For pF = 4; antilog = 10,000 cm or 9.8 bars or 0.98 MPa. For pF = 5; antilog = 100,000 cm or 98 bars or 9.8 MPa.

Daniel Hillel has published textbooks on soil physics since 1971 (Hillel, 1971). His most recent ones are Hillel (2004, 2008). However, only his first textbook defines pF. In this book he states (Hillel, 1971, p. 60), "In attempting to express the negative pressure potential of soil water in terms of an equivalent hydraulic head, we must contend with the fact that this head may be as much as −10,000 or even −100,000 cm of water. To avoid the use of such cumbersomely large numbers, Schofield (1935) suggested the use of 'pF' (by analogy with the pH acidity scale) which he defined as the logarithm of the negative pressure (tension, or suction) head in centimeters of water. A pF of 1 is, thus, a tension head of 10 cm H_2O, a pF of 3 is a tension head of 1000 cm H_2O; and so forth." Note that pF should not be used in the scientific literature, because it is an obsolete term. It does, however, still appear in publications. The matric potential should be expressed in pascals. Heads can be expressed in centimeters, as discussed in Chapter 4, Section III.

10.3 AVAILABLE WATER

Plant AW may be defined as the difference between FC and WP. The formula is

$$AW = FC - WP. \tag{10.1}$$

The FC might be measured as 5% of water per unit volume of bulk soil for sand, which we shall label A, and might be measured as 50% per unit volume of bulk soil for heavy clay, which we shall call B. The WP might be 2% water per unit volume for the sand A, and it might be 20% per unit volume for the heavy clay B. Using the numerical values of FC and WP for the sand A and heavy clay B, we find AW as

$$\text{(Sand A) } AW = 5\% - 2\% = 3\%$$

$$\text{(Heavy clay B) } AW = 50\% - 20\% = 30\%.$$

The above two AWs are in percentages referred to a volume of bulk soil. These AWs may be considered to mean that, in 100 cm of the sand A profile, there is 3 cm of equivalent surface water in the plant available form; and in 100 cm of heavy clay B, there is 30 cm of equivalent surface water in plant available form. The clay soil B stores (30−3) = 27 cm more of equivalent surface water per meter depth of soil profile than does the sand A. From this example, we see that soil texture can have a large effect on soil water availability.

As noted in the preceding section, the terms field capacity and wilting point should be used with caution. FC should be based on moisture measurements made in the field to a depth of interest, say 100−150 cm, and not on laboratory measurements. Equation (10.1) implies to some agronomists that water can be taken up by plant roots with equal ease, from FC to the WP. This view was promulgated by F.J. Veihmeyer and A.H. Hendrickson at the University of California in Davis, who collaborated for many years starting in the 1920s. For some plants this may be true, because for them the energy of getting water from the soil into the plant will be small compared to the energy required to get the water through the plant and through the stomata on leaves, and then into an

TABLE 10.2 Yield (metric ton/ha) of Alfalfa, Potatoes, and Sugar Beets at Different Soil Moisture Contents

	Moisture Content in Centimeters of Water Per 100 cm of Soil Depth at Time of Irrigation			
Crop	**30**	**18**	**15**	**5**
Alfalfa	14.3	14.3	13.4	10.3
Potatoes	33.8	35.7	32.2	7.8
Sugar beets	43.2	42.3	40.5	28.9

Data obtained from Taylor, 1952.

evaporated form into the atmosphere. For such plants, one would not worry if the soil were to approach fairly close to the WP before rainfall or irrigation water was supplied. For most crops, however, yields are reduced if the water in the soil approaches the WP before water is supplied. This is illustrated in Table 10.2, where yields of alfalfa, potatoes, and sugar beets are shown when irrigation water was applied at four different moisture levels: 30, 18, 15, and 5% (30, 18, 15, and 5 cm of equivalent surface water per 100 cm of soil profile). The WP of this soil was 3% and FC was about 30%. Yields were reduced before the permanent WP was reached, showing that water is not equally available between FC and WP (Taylor, 1952).

10.4 NONLIMITING WATER RANGE

In 1985, John Letey, a soil physicist at the University of California in Riverside, developed a concept called the NLWR, which acknowledges that water may not be equally available to plants between FC and the permanent WP. The interaction between water and other physical factors that affect plant growth must be considered. Bulk density and pore size distribution affect the relationship between water and both aeration and mechanical resistance. The relationship between water and aeration is opposite to that between water and mechanical resistance. Increasing water content decreases aeration, which is undesirable, but decreases mechanical resistance, which is desirable. The NLWR may be affected by aeration and/or mechanical resistance (Figure 10.3). The NLWR becomes narrower as bulk density and aeration limit plant growth. On one end of the scale, oxygen limits root growth and on the other end of the scale, mechanical resistance restricts root growth. The restriction may occur at a water content higher than the value that would be considered limiting to plants on the basis of plant AW.

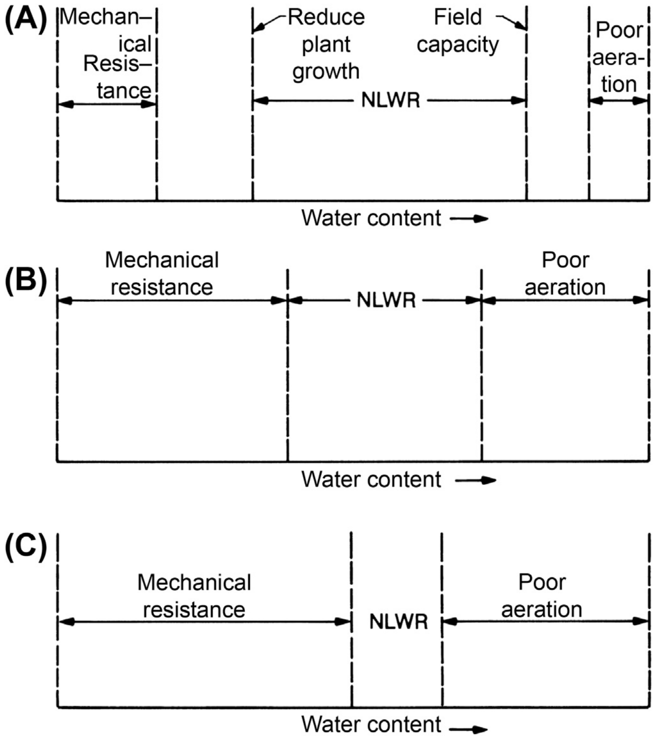

FIGURE 10.3 Generalized relationships between soil water content and restricting factors for plant growth in soils with increasing bulk density and decreasing structure in going from case A to C. The nonlimiting water range is abbreviated NLWR. *From Letey (1985). This figure is used by permission of Springer-Verlag and John Letey.*

To determine the NLWR, one must determine the matric potential at which the oxygen diffusion rate (ODR) limits root growth. The oxygen diffusion ratemeter is used to determine this value (see Chapter 12). Then one needs to determine the matric potential at which root growth is inhibited due to too high a resistance. This is done with a penetrometer (see Chapter 11). For example, in a coastal plain soil in South Carolina, researchers found that corn roots stopped growing at a matric potential of −0.08 bar, as determined using the ODR method, and at a matric potential of −0.4 bar due to too high a resistance (Letey, 1985). One needs to use a soil moisture release curve to find the soil water contents associated with these matric potentials. The NLWR is the difference between the two water contents: the larger soil water content minus the lower soil water content.

The *least limiting water range* (LLWR) was introduced by da Silva et al. (1994). They said that the response of plants to variation in water content must be considered using ranges for AW, soil aeration, and mechanical resistance. Inside the range, growth is least limited, and outside of the range, growth is most limited. Consequently, they used the term LLWR rather than NLWR to describe the concept introduced by Letey (1985). Values fall either "in" or "out" of a range (da Silva and Kay, 1996). da Silva et al. (1994) arbitrarily set limits for the growth of plants in response to AW, soil aeration, and mechanical resistance based on data in the literature. The critical values for crop growth that they chose, associated with matric water potential, air-filled porosity (the measure of soil aeration), and soil resistance, were FC at −0.01 MPa (Haise et al., 1955), WP at −1.5 MPa (Richards and Weaver, 1943), air-filled porosity at 10% (Grable and Siemer, 1968), and soil resistance at 2 MPa (Taylor et al., 1966). da Silva and Kay (1996) calculated the air-filled porosity at 10% as $\theta_{sat}-0.10$ where $\theta_{sat}=1$—bulk density/particle density, and θ_{sat} is the water content in the soil at saturation. (See Chapter 7 and Eqn (7.2) for the calculation of porosity.) As noted above for FC, most roots need at least 10% by volume air space in the soil to survive, and we shall present the scientific data for this conclusion in Chapter 12, Section 1. In determining the LLWR, researchers measure penetration resistance with penetrometers to determine if the soil is within the least limiting range for soil strength. (We discuss penetrometer measurements in Chapter 11.) However, the researchers do not measure the ODR of the soil, as originally proposed by Letey in describing his NLWR (Letey, 1985, p. 284). If values from the literature are used, this eliminates the need for extensive field experiments to determine the water content at which root growth is limited by mechanical strength and oxygen diffusion. However, these values should be measured in each experiment, because the limits for different crops and cultivars will vary. Mohammadi et al. (2010) recommended that oxygen status of the soil should be measured in determining the upper limit of the LLWR, but in the modeling work reported in their paper, they did not measure it. They obtained ODRs from the literature (Stępniewski et al., 2005). Feng et al. (2002) said that the ODR method, which mimics the oxygen supply to the root surface, was the best one to evaluate the aeration status of the soil and other measures like air-filled porosity should not be used.

The LLWR and the NLWR, which is often used synonymously with the LLWR (Verma and Sharma, 2008), have been determined subsequently by many researchers (da Silva and Kay, 1997a,b; Betz et al., 1998; Zou et al., 2000; Groenevelt et al., 2001; Asgarzadeh et al., 2010, 2011). It is used to determine not only the soil physical factors limiting crop growth but also soil quality (Lapen et al., 2004; Verma and Sharma, 2008). The concept of the NLWR or LLWR is useful provided one realizes that it depends on circumstances such as the type of crop, its growth stage, and potential evaporation. The concept of the NLWR is appealing because it can be related to the empirical descriptions of the water uptake term in root models, such as the model of Feddes et al. (1974); see also Feddes and Raats (2004) (P.A.C. Raats, personal communication, January 25, 2006).

The LLWR is becoming popular due to the fact that it can be used not only in root models but also in other models to characterize water availability (Asgarzadeh et al., 2011). In fact, researchers now refer to it as a type of pedotransfer function (Chen et al., 2014). Pedotransfer function is not defined in the *Glossary of Soil Science Terms 2008* (Soil Science Society of America, 2008). Pedotransfer functions have been used to understand hydraulic characteristics of soil since 1989, when Bouma (1989) proposed their use. He suggested that key measures of the soil's characteristics could be used to infer other traits that are more difficult to measure directly. For this process, he defined "pedotransfer functions", which allow existing knowledge to be transferred to deduce something that is unknown or difficult to determine (Clothier et al., 2004). More specifically, pedotransfer functions are regression equations that are used to predict difficult-to-obtain parameters from more easily measured soil properties (Perfect, 2003). They have been widely used to predict input parameters for soil hydrological models from basic soil physical properties such as particle size distribution and bulk density (Pachepsky and Rawls, 2004). Pedotransfer functions were used to estimate reliably FC at −33 kPa and permanent WP at −1500 kPa by knowing soil texture and bulk density (Pollacco, 2008).

10.5 BIOGRAPHIES OF BRIGGS AND SHANTZ

Dr Lyman James Briggs (1874−1963), a physicist, was born on May 7, 1874, in Assyria, Michigan, the son of Chauncey L. Briggs and Isabella (McKelvey) Briggs. He got his B.S. degree at Michigan State College in 1893, his M.S. degree at the University of Michigan in 1895, and his Ph.D. at Johns Hopkins in 1901 (Cattell, 1944). He received a Doctor of Science (Sc.D.) degree from Michigan State in 1932; a Doctor of Engineering degree from the South Dakota School of Mines in 1935; a Doctor of Laws (LL.D.) degree from the University of Michigan in 1936; a Sc.D. from George Washington University in 1937; a Sc.D. from Georgetown University in 1939; and a Sc.D. from Columbia University in 1944 (Debus, 1968).

He was in charge of the Physics Laboratory Division (now Bureau of Soils) for the US Department of Agriculture (USDA), 1896−1906. He was physicist in charge of the Biophysical Laboratory, Bureau of Plant Industry, 1906−1912, and from 1912 to 1920, he was in charge of biophysical investigations. He was detailed to the Bureau of Standards by executive order in 1917–1919. He was chief of Division of Mechanics and Sound, Bureau of Standards from 1920 to 1933 and its assistant director of research and testing from 1926 to 1933. He was director of the Bureau of Standards from 1933 to 1945, and was director emeritus from 1945 until his death in 1963. He was a member of the National Advisory Committee for Aeronautics (1933–1945), and was its vice chairman from 1942 to 1945. He was chairman of the subcommittee on aircraft structures, 1937–1945; a member of the aerodynamics subcommittee, 1922–1930; chairman of the Federal Specifications Board, 1932–1940, and of the Federal Fire Council, 1933–1939; president of the National Conference on Weights and Measures, 1935–1945; member of the International Ice Patrol Board, 1933–1945; chairman of the Washington Biophysical Institute Council, 1933–1939; on the board of directors of the American Standards Association, 1933–1945; member of the US National Committee for the International Geophysical Year; on the executive committee of the engineering division of the National Research Council, 1945–1950, and on its Committee of Fundamental Physical Constants; and director of the scientific program for stratospheric balloon flights. He was a trustee of George Washington University from 1945 until his death (Debus, 1968).

He shared the Magellan medal with Paul R. Heyl in 1922, received the Medal of Merit in 1948, and the Gold Medal of the US Department of Commerce for exceptional service. He was an honorary Fellow of the American College of Dentists; a Fellow of the American Association for the Advancement of Science; a Fellow of the American Physical Society (and its vice president in 1937 and president in 1938). He was a member of the National Academy of Sciences; American Society of Mechanical Engineers; Washington Academy of Science (its president in 1917); Philosophical Society of Washington (its president in 1916); American Philosophical Society; American Academy of Arts and Sciences; Institute of Aeronautical Science; Newcomen Society (engineering society); Washington Academy of Medicine (its president, 1945–1946); and an honorary member of the Physical Society of Engineering. He was a member of Tau Beta Pi, Sigma Xi, and Sigma Pi Sigma (Debus, 1968).

His areas of research interest were aerodynamic characteristics of projectiles, bombs, and aerofoils in a high-speed windstream; acceleration of gravity at sea; gyroscopic stabilization; soil analysis; properties of liquids under negative pressures; and defense projects. He collaborated with Paul R. Heyl on the development of an earth inductor compass (Debus, 1968).

Briggs married Katherine E. Cook on December 23, 1896, and they had two children: Mrs Isabel Myers and Albert Cook (deceased) (Debus, 1968). Lyman Briggs died on March 25, 1963. His scientific contributions have been detailed by Landa and Nimmo (2003). A biographical memoir has been cowritten by his grandson, Peter Briggs Myers (Myers and Sengers, 1999).

Dr Homer LeRoy Shantz (1876–1958), a botanist, was born in Kent County, Michigan, on January 24, 1876, the son of Abraham K. Shantz and Mary E. (Ankney) Shantz. He got his B.S. degree at Colorado College, Colorado Springs, in 1901, and his Ph.D. at the University of Nebraska in 1905. In 1926, he received a Sc.D. from Colorado College (Debus, 1968).

He was an instructor of botany and zoology at Colorado College, 1901–1902; of botany at the School of Agriculture in Nebraska, 1903–1904; and in Missouri, 1905–1906. He was professor of botany and bacteriology at the University of Louisiana in 1907. He worked for the Bureau of Plant Industries, USDA, first as an expert in alkali and drought-resistant plant breeding investigations (1908–1909); then as a plant physiologist (1910–1920); and then was in charge of plant geography and plant physiology (1920–1926). He was special lecturer on plant geography in the Graduate School of Geography, Clark University, 1922–1926. Between 1926 and 1928, he was professor of botany and head of the department at Illinois. He was president of the University of Arizona, 1928–1936. He was Chief of the Division of Wildlife Management, US Forest Service, 1936–1944 (Cattell, 1944), and was annuitant collaborator with the USDA from 1945 until his death in 1958. In 1956, he was a professor of botany at the University of Arizona, and in 1956–1957, he was principal investigator for the Arizona African Expedition (Debus, 1968).

He was a Fellow of the American Society of Agronomy and of the Royal Society of Arts. He was a member of the Phytographic Society of Sweden and honorary president of the 7th International Botanical Congress in Stockholm in 1950, and in Paris in 1954. He was a member of the Botanical Society; Washington Association of American Geographers; the American Society of Plant Physiologists (he received its Charles Reid Barnes life membership); Ecological Society; Wildlife Society; the Society pro Fauna et Flora Fennica; International Society for Protection of Nature; the International Institution of African Languages and Cultures; Sigma Xi; and Phi Beta Kappa (Cattell, 1944; Debus, 1968).

He was involved with many special projects. In 1918, he was part of the plant resources "Inquiry" in Africa and Latin America, formed to determine natural plant resources and crop-producing possibilities of large portions of Africa and Latin America for use by the American Commission to Negotiate Peace, 1918–1919. In 1924, he was on the Education Committee of East Africa. In 1931–1934, he was a USDA member of the National Land Use Planning Committee of the US Geological Survey, and was an explorer in the Smithsonian Institution expedition to Africa in 1919–1920. He was a member of the Educational Commission to East Africa under the auspices of the Phelps Stokes Fund and the International Education Board in 1924 (Debus, 1968).

His research interests included the vegetation of the Great Plains and the Great Basin; the indicator value of natural vegetation; the physiology of drought resistance; biological study of the lakes in the Pike's Peak region; North American Branchinecta and their habitats; plant geography of Africa and Latin America; plant geography and plant industry; agriculture of the African natives; wildlife management; and agricultural geography of Africa (Cattell, 1944; Debus, 1968).

He married Lucia Moore Soper on December 25, 1901, and they had two children: Homer LeRoy and Benjamin Soper. He died on June 23, 1958 (Debus, 1968).

10.5.1 Importance of Briggs and Shantz

Both Briggs and Shantz are cited in a book listing the most important scientists from antiquity to the present (Debus, 1968). In the seventh edition of *American Men of Science* (Cattell, 1944), they had stars by their names. (A star was prefixed to 1000 biographical entries out of about 34,000 names listed.) The areas of science were broken down into 12 disciplines, and the number of people ranked in each discipline, of the 1000 men ranked, was as follows:

Chemistry, 175
Physics, 150
Zoology, 150
Botany, 100
Geology, 100
Mathematics, 80
Pathology, 60
Astronomy, 50
Psychology, 50
Physiology, 40
Anatomy, 25
Anthropology, 20

In each of the 12 principal sciences, the names were arranged in the order of merit by 10 leading scientists of the discipline, and the position of each scientist then was ranked in his specialty. Briggs was ranked first in physics, and Shantz was ranked third in Botany. (Briggs was ranked even above I.I. Rabi, who was ranked sixth in physics. Rabi won a Nobel Prize in Physics in 1944 for his resonance method, using molecular beams, for recording the magnetic properties of atomic nuclei. Rabi's work laid the basis for nuclear magnetic resonance, now routinely used in medical diagnosis.) The biographies make clear the importance of Briggs and Shantz, who were two of the most important scientists in the United States.

References

Asgarzadeh, H., Mosaddeghi, M.R., Mahboubi, A.A., Nosrati, A., Dexter, A.R., 2010. Soil water availability for plants as quantified by conventional available water, least limiting water range and integral water capacity. Plant Soil 335, 229−244. http://dx.doi.org/10.1007/s11104-010-0410-6.

Asgarzadeh, H., Mosaddeghi, M.R., Mahboubi, A.A., Nosrati, A., Dexter, A.R., 2011. Integral energy of conventional available water, least limiting water range and integral water capacity for better characterization of water availability and soil physical quality. Geoderma 166, 34−42. http://dx.doi.org/10.1016/j.geoderma.2011.06.009.

Baver, L.D., Gardner, W.H., Gardner, W.R., 1972. Soil Physics, fourth ed. Wiley, New York.

Betz, C.L., Allmaras, R.R., Copeland, S.M., Randall, G.W., 1998. Least limiting water range: traffic and long-term influences in a Webster soil. Soil Sci. Soc. Am. J. 62, 1384−1393.

Bouma, J., 1989. Using soil survey data for quantitative land evalution. Adv. Soil Sci. 9, 177−213.

Briggs, L.J., Shantz, H.L., 1912. The wilting coefficient for different plants and its indirect determination. USDA Bur. Plant Ind. Bull. No. 230. U.S. Dept. Agr: Washington, DC.

Cattell, J. (Ed.), 1944. American Men of Science. A Biographical Directory, seventh ed. Science Press, Lancaster, Pennsylvania.

Chen, G., Weil, R.R., Hill, R.L., 2014. Effects of compaction and cover crops on soil least limiting water range and air permeability. Soil Tillage Res. 136, 61−69.

Clothier, B.E., Green, S.R., Vogeler, I., Robinson, B.H., Mills, T.M., Duwig, C., Roygard, J.K.F., Walter, M., van den Dijssel, C.W., Scotter, D.R., 2004. Contaminants in the soil of the root zone: transport, uptake and remediation. In: Juhasz, A.L., Magesan, G., Naidu, R. (Eds.), Waste Management. Science Publishers, Inc., Enfield, New Hampshire, pp. 3−34.

da Silva, A.P., Kay, B.D., Perfect, E., 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Am. J. 58, 1775−1781.

da Silva, A.P., Kay, B.D., 1996. The sensitivity of shoot growth of corn to the least limiting water range of soils. Plant Soil 184, 323−330.

da Silva, A.P., Kay, B.D., 1997a. Estimating the least limiting water range of soils from properties and management. Soil Sci. Soc. Am. J. 61, 877−883.

da Silva, A.P., Kay, B.D., 1997b. Effect of soil water content variation on the least limiting water range. Soil Sci. Soc. Am. J. 61, 884−888.

Debus, A.G. (Ed.), 1968. World Who's Who in Science. From Antiquity to the Present. Marquis-Who's Who, Chicago, Illinois.

Dexter, A.R., Czyż, E.W., Richard, G., 2012. Equilibrium, non-equilibrium and residual water: consequences for soil water retention. Geoderma 177−178, 63−71.

Feddes, R.A., Raats, P.A.C., 2004. Parameterising the soil-water-plant-root system. In: Feddes, R.A., Rooj, G.H. de, Dam, J.C. van (Eds.), Unsaturated Zone Modelling: Progress, Challenges and Applications, Wageningen UR Frontis Series, vol. 6. Wageningen Universiteit en Researchcentrum (Wageningen University and Research Centre), The Netherlands, pp. 95−141.

Feddes, R.A., Bresler, E., Newman, S.P., 1974. Field test of a modified numerical model for water uptake by root systems. Water Resour. Res. 10, 1199−1206.

Feng, G., Wu, L., Letey, J., 2002. Evaluating aeration criteria by simultaneous measurement of oxygen diffusion rate and soil-water regime. Soil Sci. 167, 495−503.

Gardner, W.R., 1960. Dynamic aspects of water availability to plants. Soil Sci. 89, 63−73.

Grable, A.R., Siemer, E.G., 1968. Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potentials, and elongation of corn roots. Soil Sci. Soc. Am. Proc. 32, 180−186.

Groenevelt, P.H., Grant, C.D., Semetsa, S., 2001. A new procedure to determine soil water availability. Aust. J. Soil Res. 39, 577−598.

Haise, H.R., Haas, H.J., Jensen, L.R., 1955. Soil moisture studies of some great plains soils: II. Field capacity as related to 1/3-atmosphere percentage, and "minimum point" as related to 15- and 26-atmosphere percentages. Soil Sci. Soc. Am. Proc. 19, 20–25.

Hillel, D., 1971. Soil and Water. Physical Principles and Processes. Academic Press, New York.

Hillel, D., 2004. Introduction to Environmental Soil Physics. Elsevier, Amsterdam.

Hillel, D., 2008. Soil in the Environment. Crucible of Terrestrial Life. Elsevier, Amsterdam.

Kramer, P.J., 1983. Water Relations of Plants. Academic Press, New York, 489 pp.

Landa, E.R., Nimmo, J.R., 2003. The life and scientific contributions of Lyman J. Briggs. Soil Sci. Soc. Am. J. 67, 681–693.

Lapen, D.R., Topp, G.C., Gregorich, E.G., Curnoe, W.E., 2004. Least limiting water range indicators of soil quality and corn production, eastern Ontario, Canada. Soil Tillage Res. 78, 151–170.

Letey, J., 1985. Relationship between soil physical properties and crop production. Adv. Soil Sci. 1, 277–294.

Mohammadi, M.S., Asadzadegh, F., Vanclooster, M., 2010. Refining and unifying the upper limits of the least limiting water range using soil and plant properties. Plant Soil 334, 221–234. http://dx.doi.org/10.1007/s11104-010-0377-3.

Myers, P.B., Sengers, J.M.H.L., 1999. Lyman James Briggs 1874–1963. In: Biogr Mem., vol. 77. National Academy Press, Washington, D.C, pp. 3–18.

Pachepsky, Y.A., Rawls, W.J. (Eds.), 2004. Development of Pedotransfer Functions in Soil Hydrology. Elsevier, Amsterdam.

Perfect, E., 2003. A pedotransfer function for predicting solute dispersitivity: model testing and upscaling. In: Pachepsky, Y., Radcliffe, D.E., Selim, H.M. (Eds.), Scaling Methods in Soil Physics. CRC Press, Boca Raton, Florida, pp. 89–96.

Philip, J.R., 1957. The physical principles of soil water movement during the irrigation cycle. In: Proc Congr Int Comm Irrigation Drainage, Third, San Francisco, vol. 8, pp. 125–153.

Pollacco, J.A.P., 2008. A generally applicable pedotransfer function that estimates field capacity and permanent wilting point from soil texture and bulk density. Can J. Soil Sci. 88, 761–774.

Raats, P.A.C., Smiles, D.E., Warrick, A.W., 2002. Contributions to environmental mechanics: introduction. In: Raats, P.A.C., Smiles, D.E., Warrick, A.W. (Eds.), Environmental Mechanics: Water, Mass and Energy Transfer in the Biosphere, Geophys. Monogr, vol. 129. American Geophysical Union, Washington, DC, pp. 1–28.

Richards, L.A., Weaver, L.R., 1943. Fifteen-atmosphere percentage as related to the permanent wilting percentage. Soil Sci. 56, 331–339.

Salisbury, F.B., Ross, C.W., 1978. Plant Physiology, second ed. Wadsworth Pub, Belmont, California.

Schofield, R.K., 1935. The pF of the water in soil. Trans. Intern. Congr Soil Sci. Third 2, 37–48.

Soil Science Society of America, 1971. Glossary of Soil Science Terms. Soil Science Society of America, Madison, Wisconsin.

Soil Science Society of America, 1975. Glossary of Soil Science Terms. Soil Science Society of America, Madison, Wisconsin.

Soil Science Society of America, 1978. Glossary of Soil Science Terms. Soil Science Society of America, Madison, Wisconsin.

Soil Science Society of America, 1979. Glossary of Soil Science Terms. Soil Science Society of America, Madison, Wisconsin.

Soil Science Society of America, 1984. Glossary of Soil Science Terms. Soil Science Society of America, Madison, Wisconsin.

Soil Science Society of America, 1987. Glossary of Soil Science Terms. Soil Science Society of America, Madison, Wisconsin.

Soil Science Society of America, 1997. Glossary of Soil Science Terms. Soil Science Society of America, Madison, Wisconsin.

Soil Science Society of America, 2008. Glossary of Soil Science Terms. Soil Science Society of America, Madison, Wisconsin.

Stępniewski, W., Stępniewska, Z., Bennicelli, P.R., Gliński, J., 2005. Oxygenology in Outline. EU Fifth Framework Program, QLAM-2001–00428. Institute of Agrophysics, Lublin, Poland.

Taylor, H.M., Roberson, G.M., Parker Jr, J.J., 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. 102, 18–22.

Taylor, S.A., 1952. Use of mean soil moisture tension to evaluate the effect of soil moisture on crop yields. Soil Sci. 74, 217–226.

Taylor, S.A., Ashcroft, G.L., 1972. Physical Edaphology: The Physics of Irrigated and Nonirrigated Soils. W.H. Freeman, San Francisco.

van Genuchten, M. Th, 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Verma, S., Sharma, P.K., 2008. Long-term effects of organics, fertilizers and cropping systems on soil physical productivity evaluated using a single value index (NLWR). Soil Tillage Res. 98, 1–10.

Webster's New World Dictionary of the American Language, 1959. College ed. World Publishing, Cleveland and New York.

Wesseling, J., van Wijk, W.R., 1957. Soil physical conditions in relation to drain depth. In: Luthin, J.N. (Ed.), Drainage of Agricultural Lands. American Society of Agronomy, Madison, Wisconsin, pp. 461–504 (See especially Figure 4, p. 468).

Zou, C., Sands, R., Buchan, G., Hudson, I., 2000. Least limiting water range: a potential indicator of physical quality of forest soils. Aust. J. Soil Res. 38, 947–958.