Plant Available Soil Water

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INTRODUCTION

The soil stores the water used by plants to sustain life. The amount of soil water that can be used by the plant varies, due to characteristics of the soil (e.g., texture) and of the plant (e.g., root distribution and depth). Knowledge of the amount of water available to the plant, or plant available water (PAW), is needed to determine the agricultural or ecological potential of soils and is used in many agronomic applications, such as irrigation scheduling programs or crop production models. It helps define the water content limits beyond which plant growth is affected because of insufficient or excessive amounts of water, or beyond which water is lost out of the root zone due to deep percolation. The water content is typically expressed on a weight ($g\,m^{-3}$) or volume ($m^3\,m^{-3}$) basis.

Another term associated with PAW is the nonlimiting water range, which is defined as the region bounded by the upper and lower soil water content over which water, oxygen, and mechanical resistance are not limiting to plant growth.[1] The two soil water content boundaries that help determine PAW are the upper or "full" boundary, which is referred to as field capacity (FC), and the lower or "dry" boundary, or the permanent wilting point (PWP). Field capacity has been defined as the water remaining in the soil two to three days after having been wetted with water and after free drainage is negligible.[1] Permanent wilting point has been defined as the largest water content of a soil at which indicator plants, growing in that soil, wilt and fail to recover when placed in a humid chamber.[1] Both boundaries are not "sufficiently precise or general to be much more than a rough index," according to an uncited quotation in Ref. [2]. In the field, determining when drainage is "negligible" is extremely difficult; soils often have complex horizons with different water-holding characteristics; and plants may root differently from their genetically predetermined pattern due to soil physical and chemical characteristics or environmental conditions. Also, soil water determined as "available water" is not necessarily the portion of water that can be absorbed by all plants, but can be plant specific.[1] Richards[3] stated that "availability" involved both the "ability of the plant root to absorb and use the water with which it is in contact," and the "readiness with which the soil water moves in to replace that which has been used by the plant."

Water moves through the soil and plant in response to gradients in the potential energy of the water, going from regions of higher water potential to those with lower water potential. Water potential (ψ) is the measure of the free energy status of water and its ability to do work, which can be changed by the presence of solutes (osmotic potential), pressure (pressure potential), gravity (gravitational potential), and components which bind with water molecules (matric potential). For water to be available to a plant, the plant's roots first must be present; water must move through the soil to the root, pass into the root, and travel from the root to the leaf surface; and the rate of water supply must be able to meet transpiration requirements and maintain cellular functions. At high evaporation rates, the soil may be unable to transport enough water to meet transpiration demands and the plant may go into water stress at higher soil water contents than it would at lower evaporation rates.

CROP ROOTING CHARACTERISTICS

The characteristics of a root system depend upon heredity, but may be modified by environmental factors such as soil texture, depth, moisture content, mineralogy, chemistry, aeration, and solute concentration.[4] Monocots develop fibrous root systems, while dicots tend to have taproot systems (Fig. 1) that can take many different forms.[5] A species may always be deep rooted, or always shallow rooted, while still others develop different types of root systems in different types of soils. The age of the plant also determines rooting patterns and water uptake as well. As a plant grows, its roots extend downward and outward at varying rates. Kaigama et al.[6] reported rates of root extension for grain sorghum (*Sorghum bicolor* Moench.) of one to two centimeters a day. The rate of exploration by roots is controlled primarily by plant vigor and by soil environmental conditions, especially temperature, moisture, and strength.[5] Warm, moist soil encourages root development while increased soil strength can severely restrict it. As a plant matures, many roots die or lose much

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Fig. 1 The fibrous root system (left) of witchgrass (*Panicum capillare* L.) and the taproot (right) of cotton (*Gossypium hirsutum* L.).

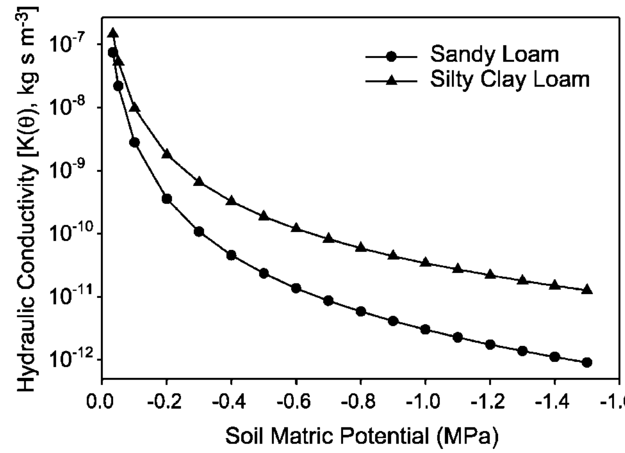

Fig. 2 Approximate hydraulic conductivity of a sandy loam and a silty clay loam in a range of soil matric potentials within plant available water (-0.033 to -1.5 MPa) as determined by the pressure outflow apparatus.

of their ability to absorb water. The success of cultivated plants subjected to drought may depend on the development of deep, profusely branched root systems that absorb water from a large volume of soil.[4]

WATER MOVEMENT THROUGH THE SOIL

Most of the water flow through the soil can be described by Darcy's law, given as

$$J_w = -K(\psi)(d\psi/dz) \quad (1)$$

where J_w is the water flux density (kg m^{-2} sec^{-1}) in a soil with hydraulic conductivity $K(\psi)$ (kg sec m^{-3}), and water potential gradient $d\psi/dz$ (J kg^{-1} m^{-1} or m sec^{-2}) with the components of water potential most responsible for flow being the matric and gravitational potentials.[7] Water flow through the soil in the range of PAW is determined by its unsaturated hydraulic conductivity, which can be approximated by Campbell and Norman[7]

$$K(\psi) = K_s(\psi_e/\psi)^{2+3/b} \quad (2)$$

where ψ_e is air entry water potential and K_s is the saturated conductivity of the soil. The parameter b is the exponent of the moisture release equation which, along with ψ_e and K_s, depends on soil physical characteristics such as texture. As the size of the pore space in a soil decreases (coarse textured to fine textured), the air entry potential decreases and b increases, resulting in unsaturated conductivity that is higher for finer-textured soils than coarse-textured ones (Fig. 2).

WATER MOVEMENT THROUGH THE PLANT

The ultimate destination for most of the soil water moving into a plant is the leaf surface, where it is lost as vapor through the stomatal pore. The driving gradient to move the liquid water from the root to the leaf is the water potential gradient between them. The resistances to flow through this system has been compared to a resistor network in an electric circuit, where water and current flow are analogous and can be described using Ohm's law in the form of[7]

$$U = (\psi_s - \psi_L)/(R_R + R_L) \quad (3)$$

where U is the rate of water uptake, ψ_S is the soil water potential, ψ_L is the leaf water potential, R_R is the root resistance, and R_L is the leaf resistance. The root resistance varies with the permeability of the root due to age or distance from the root apex, and changes due to dehydration, temperature, rate of water flow, or time of day.[4] Leaf resistance is affected by the location, size, shape, and abundance of stomata; environmental conditions affecting stomatal activity; and the size of the boundary layer surrounding the leaf, which is determined by the size and

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shape of the leaf and wind speed. At the leaf's surface, the sun's energy converts the water from a liquid to vapor state in the substomatal cavity. A vapor pressure gradient must then move the water vapor through the stomatal pore and boundary layer into the atmosphere surrounding the leaf. As the vapor pressure deficit between leaf and air increases, the demand for water flow through the soil and the plant also increases, with the rate of vapor loss also being controlled in part by the size of the stomatal opening.

MEASUREMENT OF PAW

The upper and lower boundaries that help determine PAW are FC and PWP. No simple, accurate method exists for either field or laboratory determinations. Numerous methods are available to approximate these boundaries, with procedures and limitations to the results outlined in Ref. [8]. A commonly used procedure is laboratory measurements using a pressure outflow apparatus. In this method, a soil sample is placed on a porous ceramic plate or permeable membrane in a chamber and saturated with water. Pressure is applied to the samples until equilibrium soil water contents at matric potentials of − 1.5 MPa for PWP and − 0.033 MPa for FC are achieved.[8] Among the many other methods developed to determine these boundaries are ones based on soil texture and bulk density;[9] bulk density, particle density, and particle-size distribution curve,[10] and electrical conductivity.[11]

Ideally, PAW should be measured in the field for each crop and soil combination. Field capacity is primarily a function of soil properties, while PWP is a function of a combination of soil, plant, and environmental factors. Fig. 3 shows the differences between measured lower limits of water use (θ_{LL}), or approximate PWP, for corn (*Zea mays* L.), grain sorghum, and wheat (*Triticum aestivum* L.) and soil water contents measured at − 1.5 MPa matric potential ($\theta_{-1.5}$) using the pressure outflow apparatus procedures. The crops were grown in lysimeters containing a monolithic soil core of Ulysses silt loam (fine-silty, mixed, superactive, mesic Aridic Haplustoll), which is a deep, uniform soil formed in calcareous loess. Soil water content data were collected at harvest using neutron scattering. The vertical, dashed line represents the "zero" point of $\theta_{-1.5}$ such that values to the left of the dashed line represent the field-measured water contents less than $\theta_{-1.5}$ and those to the right the field-measured water contents greater than $\theta_{-1.5}$. Volumetric water contents were converted to mm by multiplying it by the measurement depth. Summed for the 2.2-m profile, grain sorghum used 46 mm and wheat 65 mm more than that summed for $\theta_{-1.5}$, while corn was similar to $\theta_{-1.5}$ levels. All crops showed a distinct decline in soil water use at the 0.9-m depth, possibly associated with the abrupt increase in bulk density in that layer compared with the layers above and below (data not shown). Fig. 3 shows the variability in lower limit of water availability among crops and the difference from $\theta_{-1.5}$. The figure suggests that PWP determined by laboratory methods is similar to

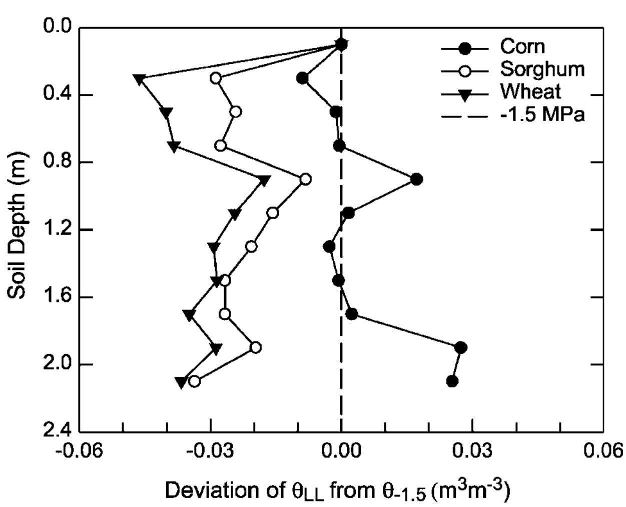

Fig. 3 The deviation of the lower limit of water extraction by corn, grain sorghum, and wheat (θ_{LL}) from the soil water content measured at 1.5 MPa ($\theta_{-1.5}$) by the pressure flow apparatus in a lysimeter containing a monolithic core of Ulysses silt loam. Data points to the left of the vertical dashed line indicate that the crop used more water than that at $\theta_{-1.5}$ and to the right it used less than $\theta_{-1.5}$.

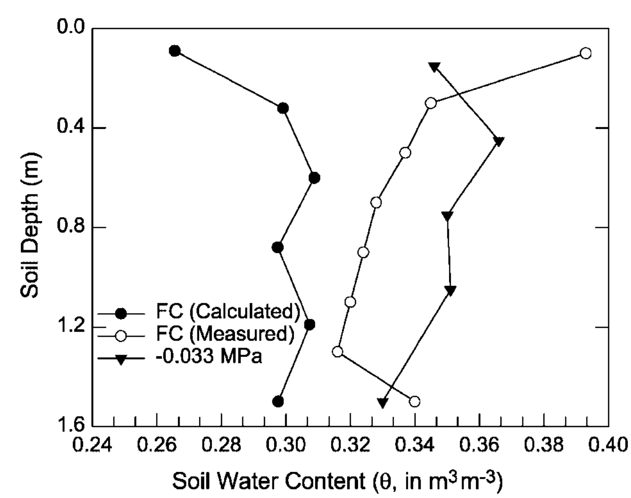

Fig. 4 Field capacity (FC) by depth of a monolithic soil containing Pullman clay loam measured by neutron scattering after the core was saturated and allowed to drain (open circles), calculated from equations of Ritchie et al.[9] using measured bulk density and percentages of sand and clay for the soil horizons (closed circles), and measured by the pressure outflow apparatus at 0.033 MPa pressure (triangles).

field-measured PWP of short season corn, but not necessarily to that of grain sorghum or wheat.

Measurement of FC can be equally as problematic. Cassel and Nielsen[8] stated that "personal experiences suggest that the uncertainty in FC is greater than that for PWP" with "no good alternative for measuring FC other than the in situ field method." Fig. 4 shows FC measured by neutron scattering in a lysimeter (same dimensions as above) containing a monolithic soil core of Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll). Also shown is water contents measured at 0.033 MPa by the pressure outflow apparatus and FC calculated using procedures outlined by Ritchie et al.[9] The calculated FC required textural analysis for the clay and sand proportions as well as bulk density, which was determined from samples taken at the lysimeter monolith collection site. Converted from volumetric water contents and summed for the 1.5-m depth, the measured FC was 507 mm, the calculated was 447 mm, and the laboratory method was 523 mm.

CONCLUSION

Knowledge of PAW is important for determining the agricultural and ecological potentials of a soil and the best management practices that maximize crop productivity and minimize water losses. Laboratory determination of both FC and PWP is usually adequate for most applications, but the user must be aware of its limitations (Figs. 3 and 4). Soil texture, structure, layering, and chemistry along with crop type, rooting characteristics, stage of development, as well as environment are just some of the many factors that can impact PAW. The procedures for more accurate determination of PAW are often complicated, requiring specialized equipment and an extensive number of measurements, because it is a function of the interactions between the plant, the soil, and the environment.

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