

SOIL-PLANT-ATMOSPHERE DYNAMICS

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Contents

1. Introduction
 2. Soil-Water Status
 - 2.1. Soil-Water Content
 - 2.2. Soil-Water Potential
 3. Plant-Water Status
 - 3.1. Plant-Water Content
 - 3.2. Plant-Water Potential
 4. Soil-Plant-Atmosphere Continuum (SPAC)
 - 4.1. Definitions
 - 4.2. Flow of Water in SPAC
 - 4.3. Flow of Water in Soil
 - 4.4. Water Uptake by Roots
 - 4.5. Water Flow inside Roots
 - 4.6. Water Flow from Roots to Leaves
 - 4.7. Evapotranspiration and Consumptive Use
 - 4.8. Order of Magnitude of Water Potentials in SPAC
 5. Drought Stress and Plant Productivity
 - 5.1. Effects of Drought Stress
 - 5.2. Water Use Efficiency or Crop Water Productivity
 - 5.3. Yield Response
 6. Conclusions
- Glossary
Bibliography
Biographical Sketches

Summary

A good understanding of soil-plant-atmosphere dynamics is important for sustainable soil-water management. This chapter describes some basic concepts about water content and water potential in soils and plants, and how they affect water flow within the soil-

plant-atmosphere continuum. This chapter highlights the water flow within soils and the forces driving this process, from soil to roots, leaves and atmosphere. Attention is given to root-water uptake as affected by salinity and water stress and to the concept of field capacity and wilting point. The effect of drought stress and its relation to crop yield is discussed, as well as some aspects related to water use efficiency and crop productivity, as well as and the strategies to increase it.

1. Introduction

Water is one of the most common and most important resources on earth. It is essential for the existence of life, and the kinds and amounts of vegetation that can be found depend more on the quantity of water available than on any other single environmental factor (Kramer and Boyer, 1995). It is crucial to the physiology of plants, because of the important role that water plays in all physiological processes and because of the large quantities that are required. Water acts as a solvent and transport medium at cellular level (for metabolites) and at whole plant level (for carbohydrates and nutrients). It keeps turgor in the plant's tissue, which is a prerequisite for growth. Water is also used in the photosynthesis process and it serves as cooling medium during transpiration.

One of the most important sources of water to plants is the soil, the pedosphere – typically a few meters thick – which forms the interface with the atmosphere (air), the biosphere (living organisms), the hydrosphere (surface water and groundwater) and the geosphere (earth). Soil has the amazing property that it can retain water for substantial periods of time, and then release it afterwards. However, though renewable, water is also a scarce resource. Moreover its retention and availability to plants are a function of soil texture and structure, amount and kind of solutes, and cultural practices. A better understanding of soil-plant-atmospheric dynamics is therefore important for sustainable soil-water management.

2. Soil-Water Status

The water status in soils can be defined in terms of (1) the amount of water in a given soil (on a mass or a volume basis), i.e. gravimetric or volumetric soil-water content, and (2) the forces acting on water in the matrix, i.e. soil-water potential. Many processes in the soil-plant-atmosphere continuum are influenced by the amount of water, including gas exchange with the atmosphere, diffusion of air and nutrients to plant roots, soil temperature and hence the activity of microorganisms, and the rate at which dissolved (agro)chemicals are transported through the root zone.

The forces exerted on water by the soil matrix affect e.g. the efficiency of water absorption by plant roots, the amount of drainage due to gravity, and the extent of upward movement of water and solutes.

The soil-water content tells little about the amount of water available to plants. A sandy soil may be saturated at a water content that is near wilting point for a loamy soil. Soil-water content is also not sufficient to explain the movement of water in soils. When a sandy soil is brought in contact with a loamy soil of equal water content, water will move from the sand to the loam.

2.1. Soil-Water Content

Soil-water content or soil-moisture content can be expressed in various ways. The *gravimetric soil-water content* w (kg kg^{-1}) is expressed relative to the mass of oven-dry soil according to:

$$w = \frac{M_w}{M_s} \quad (1)$$

where M_w is the mass of water (kg) and M_s is the mass of the solids, i.e. the mass of the oven-dry soil (kg). By convention, oven-dryness is reached after drying a sample at 105 °C till constant weight.

It is often desirable to express soil-water content on a volume basis. The *volumetric soil-water content* θ ($\text{m}^3 \text{m}^{-3}$) is the volume of water per bulk volume of oven-dry soil:

$$\theta = \frac{V_w}{V} \quad (2)$$

where V_w is the volume of water (m^3) and V is the bulk volume of oven-dry soil (m^3). If bulk density ρ_b (Mg m^{-3}) is known, θ can be calculated as:

$$\theta = \frac{\rho_b}{\rho_w} w \quad (3)$$

where ρ_w is the density of water (Mg m^{-3}).

Other related definitions include *degree of saturation* or *water-filled pore space*, where the volume of water is expressed relative to the volume of pores (or volumetric water content over porosity), the *moisture ratio*, which is the volume of water over volume of solids and often used in case of soil subjected to swelling and shrinkage, and *soil-water storage* or *equivalent water depth*, which is the volumetric water content times the soil depth increment having that water content.

Soil-water content can be measured directly in a gravimetric way with oven or microwave oven drying, or indirectly with a variety of methods, the most important ones being neutron scattering methods, electrical resistance methods, Time Domain Reflectometry (TDR), and capacitance and Frequency Domain (FD) methods.

2.2. Soil-Water Potential

Soil water, like other bodies in nature, can contain energy in different quantities and forms. Classical physics recognizes two principal forms of energy, kinetic and potential. Since the movement of water in the soil is quite slow, its kinetic energy, which is proportional to the velocity squared, is generally considered to be negligible. On the other hand, the potential energy, which is due to position or internal condition, is of

primary importance in determining the state and movement of water in the soil under isothermal conditions.

Soil water is subject to several tension fields the net effect of which results in a deviation in potential energy relative to that of a reference state. Since there is no absolute scale of energy, soil-water potential is defined relative to such reference or standard state. The latter is conventionally defined as the state of pure (no solutes), free (no external forces other than gravity) water at a reference pressure, reference temperature and reference elevation and is arbitrarily given the value of zero (Bolt, 1976). The potential energy due to the several tension fields expressed per unit quantity of soil water, relative to that of the standard state, is called the *total soil-water potential* (ψ_s). Quantity of water can be expressed as a mass, a volume or a weight, and accordingly soil-water potential can be expressed in units of J kg^{-1} (and then called chemical potential used exclusively in chemical thermodynamics), Pa (soil-water potential) or m (soil-water potential head).

The primary forces acting on water held within a soil are:

- Matric forces resulting from interaction of the solid phase with the liquid and gaseous phase, including binding to soil solids and interfacial curvature;
- Osmotic forces owing to differences in chemical composition of the soil solution;
- Forces induced by gravitation, air pressure and hydrostatic pressure; and
- Mechanical forces exerted by unsupported solid material on the soil water in case of swelling soils.

These different forces allow us to partition total soil-water potential ψ_s into different components:

$$\psi_s = \psi_{sz} + \psi_{ss} + \psi_{sm} + \psi_{sp} + \psi_{sa} \quad (4)$$

where ψ_{sz} is the gravitational potential, ψ_{ss} the osmotic potential, ψ_{sm} the matrix potential, ψ_{sp} the hydrostatic or pressure potential, and ψ_{sa} the air pressure potential. The first subscript s denotes soil, in order to make a distinction between soil-water potential and plant-water potential. The components of the total water potential can have a positive and/or a negative value, depending on the type of physical or chemical forces which interfere with the mobility of water molecules in the system.

The *gravitational potential* ψ_{sz} is determined solely by the elevation of the point of interest relative to some arbitrary reference point (e.g. the soil surface). It is the energy per unit volume of water needed to raise a body against the gravitational pull from a reference level to the point of interest. Above the reference point, it has a positive value, and below the reference, it is negative.

The *solute or osmotic potential* ψ_{ss} is determined by the presence of solutes in soil water, which lower its potential energy and its vapor pressure. Given that the pressure potential at a water level free of solutes is zero, it is always negative. It is the energy per unit volume of water when solutes identical in composition to the soil solution at the

point of interest in the soil are added to pure, free water at the elevation of the soil. The effects of solute potentials are negligible unless diffusion barriers, like soil-plant root interfaces and soil-water-air interfaces – when water evaporates, salts are left behind – exist.

The *matric potential* ψ_{sm} results from the combined effects of adsorptive forces and capillarity within the soil matrix. It is the energy per unit volume of soil needed to transfer an infinitesimal quantity of water from a reference pool of soil water at the elevation of the soil to the point of interest in the soil at reference air pressure. The dominating mechanisms determining the matric potential include (1) adhesion of water molecules to solid surfaces due to short-range London-van der Waals forces and extension of these effects by cohesion through H bonds formed in the liquid, (2) ion hydration and binding of water in diffuse double layers (osmotic effect), (3) capillarity caused by liquid-gas and liquid-solid-gas interfaces interacting with the irregular geometry of soil pores. In an unsaturated soil, the matric potential is always negative and as the matric potential is decreasing, so is soil-water content. The negative of matric potential is suction or tension, which hence obtains a positive value.

The *hydrostatic pressure potential* ψ_p is defined as the water pressure exerted by the overlying unsupported water (i.e. saturating the soil) on the point of interest in the soil. It is positive below a water table and zero at or above the water table.

The *air pressure potential* ψ_a is defined as the change in potential energy per unit volume of water when the soil air pressure is changed from the pressure of the reference state to the pressure of the soil. For most practical cases, the air pressure potential is negligible small.

In swelling soils, the matric potential ψ_m is divided into an *overburden* or *envelope pressure potential* ψ_b due to weight of overlying unsupported solids, and the *wetness potential* ψ_w , which is the matric potential at zero external air pressure and zero envelope pressure.

Since the effects of all forces other than gravity and solutes interact with each other, the soil physics committee of the International Soil Science Society (ISSS) grouped all components except ψ_z and ψ_s into the *tensiometer pressure potential* ψ_ϕ (Bolt, 1976). *Soil-water potential* is the total potential minus the gravitational potential and is thus the result of inherent properties of the soil-water itself. It is typically measured with devices as piezometers, tensiometers and soil psychrometers.

3. Plant-Water Status

Similarly to soils, the status of water in plants can be described in two ways. The first one is based on measures of the plant water content, whereas the second has a thermodynamic background and includes the chemical potential of water in the tissue (Boyer, 1995).

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Biographical Sketches

Dr. Wim M. Cornelis is Associate Professor in Soil Physics at Ghent University, Belgium. He is a member of the European Geoscience Union, the Belgian Soil Science Society, the International Soil Science Society, the World Association for Soil and Water Conservation and council member and treasurer of the European Society for Soil Conservation. His main expertise is in hydro-physical characterization of soils at various temporal and spatial scales, modeling of water and solute transport in soils, soil-water management and conservation of water, conservation, restoration and amelioration of physical soil quality, rainwater harvesting, and erosion by wind and water. He is active in various related research projects in all continents, with a specific focus on developing countries.

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