Soil-Plant-Water Relations and the Importance in Horticultural Crops

1. Introduction

Where temperature permits plant growth, the existence of plants is controlled chiefly by the water availability. Without water, plants cannot grow, and man and animals cannot survive. With too much water, plant growth is also rather limited due partly to oxygen deficit in root zone (Ro et al., 1995). The objective of this seminar is to discuss the most important aspects of water management in relation to crop production and environmental conservation. Water is held in soil (viz. in sponge), from which it is taken up (i.e. squeezed) by plant roots. Once in the roots, it can move through the plant, and evaporate from the leaves into the atmosphere through phase transition of water. The driving force for this transfer of water from soil through plants and into the atmosphere is the difference in the energy status between water in soil and ultimately water in the atmosphere around the plants.

Of particular importance is the soil as a reservoir for water. Rainfall and irrigation water infiltrates into a soil relatively fast, but is released by the soil quite slowly. The soil, therefore, forms a huge buffer of reservoir for water. One of the most challenging problems in agriculture is the proper management of the soil as the storage for water. Water added by rainfall or irrigation above its capacity will drain to the subsoil. When drainage is prevented, flooding and waterlogged conditions will occur, with the result that crop growth is either completely suppressed or limited to certain water-tolerant crops.

To adequately cope with plant water relations, we should know soil physical characteristics such as water retention and the capacity, and water flow and its redistribution in the soil. In addition, we should know what makes water flow and redistribute in the soil, including evaporation, water uptake by plant roots, and so on. The subject matter of this seminar can be divided in the following broad areas: a) what is soil water?; b) static water in soil at equilibrium; c) water movement in soil; d) water movement through plants; e) evaporation of water into the atmosphere; f) efficient management of the soil-plant-atmosphere-continuum (SPAC). Each of these broad subject areas will be discussed separately or interrelatedly in lieu of water management found in the literature. Let us start with the question about "What is soil water?"

2. What is soil water?

2.1. Soil as a disperse three-phase system

Systems in which at least one of the phases is subdivided into numerous minute particles, which together exhibit a very large interfacial area per unit mass, are called "disperse systems". The three phases of ordinary nature are represented in the soil as follows: the solid phase constitutes the "soil matrix", the liquid phase consists of "soil solution", and the gaseous phase is the "soil air". The solid matrix of the soil includes particles, which vary in chemical and mineralogical composition as well as in size, shape, and orientation. Therefore, the organization of the solid components of the soil determines the geometric characteristics of the pore spaces in which water and air are transmitted and retained. Hence, the soil can be regarded as a sponge system having various pore length and diameter.

2.2. Soil water under stress

We sometimes say the water is under stress. Stress, as you noticed, may be either a pull or a push, tension or compression. So, stress may be properly expressed as a pull or a push per unit area with the dimension of pressure. The term "surface tension" should not be confused with tension. Surface tension, or more specifically, the surface tension coefficient, an energy per unit area, or, equivalently, is a force per unit length; where as tension is a force per unit area. A molecule in the body of fluid is attracted equally from all sides. But a molecule at the surface undergoes a resultant inward pull, since there are no molecules outside the liquid causing attraction. Hence, molecules in the surface have a stronger tendency to move to the interior of the liquid than molecules in the interior have to move to the surface. What results is a tendency for any body of liquid to minimize its surface area. Surface tension is the energy stored in the surface area per unit increase in its area.

Surface tension can be illustrated by capillary rise in small tubes; the smaller the tube is the higher is the rise. The negative pressure of water in the capillary is the suction exerted on this confined water between soil matrix. Capillary rise is caused when the water molecules near the soil surface are attracted to the water molecules just above the water surface. This attraction along with the surface tension of the water causes the water surface in the tube to curve upward into a meniscus. This upward curvature (concave meniscus) causes the pressure just below the meniscus to drop below atmospheric pressure. Thus, water has risen in a capillary tube above free-water surface is characterized by a negative pressure, which causes water to be retained in the capillary soil pores.

2.3. Soil moisture regime in relation to soil aeration

Let us imagine we have "Coke"or "Pepsi" cola, or "Budweiser" or "Heineken" beer. When we are exhausted or thirst, a drink of refreshing beverage or beer makes us re-energized. As we understood, either refreshing beverage or beer was bottled with a pressurized CO_2 to give us refreshness. The reason why CO_2 is used for this purpose is that it not only provides refreshment but also is dissolved much greater than O_2. The concentration of CO_2 in the soil solution is much greater than that of O_2 due mainly to respiration by roots and cool temperature therein.

Due to root respiration, the partial pressure of CO_2 increases and hence this situation makes soil solution saturated with CO_2 and soil O_2 depleted. When the soil O_2 is depleted, it must be replaced by the atmospheric O_2 lest it should inhibit root growth and functioning in soils. The availability of O_2 to them strongly depends on the transport rate of O_2 through the soil (simply called soil aeration). In soil pores, air and water mutually replace their individual space, and this naturally simple mechanism is very important for the underground life.

3. Static water in soil at equilibrium

One asks. How much of the soil is occupied by air, and how much by water, and how are the two interrelated? How does air get into the soil and how is it circulated? How does water enter the soil? How does water move from the wetter zones to the drier zones? What laws are operative in the movement of air and water in the soil? Answers to these questions are all of interest. From the practical point of view, the interactions of air and water and their economy and the balance in the soil is related to sustainable agriculture, which sustains crop growth and yield and protects environmental quality for the generations to come.

3.1. Potential of soil water

To understand how water moves within the SPAC, it is necessary to define a few valuable terms, and discuss them. There are several methods to express the status of water in a soil. One can determine the amount of water contained in a soil, or one can determine the energy status of water in a soil. Since potential energy is a measure of the amount of work stored in a body, knowing the potential energy status of water in the soil and in the plant can help us estimate how much work the plant must expend to extract a unit amount of water. The concept of "soil water potential" is a criterion or yardstick for this energy. The energy per unit quantity of water is called the "potential". What determines the tendency of water to flow is the potential difference between two positions (not potential energy difference).

Soil water is subject to a number of force fields, which causes its potential energy to differ from that of pure, free water. Such force fields result from the attraction of the solid matrix for water, as well as from the hydrostatic pressure, the presence of solutes (electrolytes), and gravitation. Accordingly, the total potential (Ψ_{tot}) of soil water is can be thought of as the algebraic sum of the individual component potentials.

- *Gravitational potential* (Ψ_g): Probably, we found little difficulties to visualize the meaning of what this potential stands for. Just like another objects at the earth's surface, soil water has a natural tendency to be pulled downwards by gravity. The gravity force, which causes water to move from higher to lower elevations, can be expressed in terms of the gradient of the gravitational potential of water. Since the potential of soil water represents the relative levels of its energy state, we may choose the reference elevation, which is defined as zero, arbitrarily. Water will flow spontaneously from higher to lower elevation.

- *Pressure potential* (Ψ_p): Below the water table where the soil is saturated, the water is under hydrostatic pressure, whose magnitude depends on the vertical distance (depth) below the water table. Since individual component potential works in every potential calculation, it is practically necessary to introduce new terminology of "hydraulic potential", unless the concentrations of electrolytes between two solutions in question is not much different.

- *Matric potential* (Ψ_m): In unsaturated soils, the positive pressure potential is replaced by the matric potential. Matric potential is the potential originating in the solid phase: it generally has a negative value, indicating that, in an unsaturated soil, one has to apply energy to remove water from the soil. As free water enters in the capillary, it tends to rise with the expansion of volume. During expansion of water due to capillary rise, water does work to the surrounding system, thus lowering its internal potential energy. The amount of work done by this expansion is equivalent to $P(\triangle V)$. This explains the reason why the state of energy of soil water held in the capillary was lower than that of free water.

- *Osmotic potential* (Ψ_o): The presence of solutes in soil water affects its thermodynamic properties and lowers its potential. In particular, solutes lower the vapor pressure of soil water. While this phenomenon may not affect liquid water flow in the soil significantly, it does come into play whenever a membrane or diffusion barrier is present which transmits water more readily than salts. In general, where solute concentrations are relatively uniform, osmotic potential is not important as a driving force for water flow in most soils. However, whenever we thought of soil-plant continuum for water flow, it should be taken into account, because the solute concentration in plant roots is considerably higher than in the soil. Thus, the difference in solute potential within roots and in the soil solution is extremely important for water uptake by plants.

3.2. Soil water content

Soil water content, which is the fractional water contained in soil, can be expressed in terms of either mass or volume ratios. On a mass basis, it is the ratio of mass of water to unit dry mass of soil, and this is called "gravimetric water content (Θ_m)". On a volume basis, on the other hand, it is the volume of water occupied in the unit volume of bulk soil, and this is called "volumetric water content (Θ_v)". Both were interrelated by means of the bulk density and the density of water. To explain this, we need to define another new term "bulk density" of soil. The bulk density expresses the ratio of the mass of oven-dried soil to its total bulk volume. If the pores constitute half the volume, it is half of particle density, which is the ratio of the mass of oven-dried solid soil to the volume of solids. For your knowledge, the particle density of most mineral soils is about 2.6-2.7 Mg m^{-3}, and this is thus close to the density of quartz. There are several direct and indirect methods to measure water status in soil. Only the most frequently methods, covering leading edge technologies, will be discussed here: soil sampling and drying, tensiometry, electrical resistance, neutron scattering, methods based on dielectric constant measurement.

3.3. Soil water retention

The amount of water held by a soil can be defined as a function of soil matric potential and this relationship is often called soil water retention curve or soil water characteristic curve. Note that the water content reaches a maximum when all of the pore space within a soil is filled with water and thereafter, maintains a plateau. This point is called air entry potential. The water content of the coarse sand decreases quickly in response to the application of only slightly negative matric potential. The clay, on the other hand, retains high soil water content even at matric potential as low as 1600 kPa, about the permanent wilting point. The high water content even at the wilting point illustrates the fact that even though the clay soil holds more water, it is not necessary available for use by plants.

3.4. Hydraulic conductivity

The rate of water flow, just as the rate of heat flow, depends not only on the potential gradients, but also on the conductivity of the medium. In case we have two points in question, the hydraulic gradient over which is extremely large and the medium between them has zero hydraulic conductivity, no water flow will take place.

The heat conductivity of most materials is essentially constant with temperature, so the rate of heat flow is proportional to the temperature gradient. In contrast, the hydraulic conductivity of soil is not constant, but varies greatly with soil water content. This occurs liquid water can flow only through liquid-filled pores. As a consequence, the hydraulic conductivity of soil decreases drastically (as much as million-fold!) as the soil water content decreases from saturation to dryness (wilting point of plants).

4. Plant water potential

Water is an essential constituent forming 80-90% of the fresh weight of actively growing tissues, the solvent in which gas, salts, and other solutes move, a reagent in many metabolic reactions, and essential for maintenance of turgidity of cells and tissues. Hence, an understanding of plant water relations requires consideration of both soil moisture and atmospheric moisture. Plant water relations involve the absorption of soil water, ascent of sap, loss of water by transpiration, and the internal water balance of the tree. To deal with water balance of plants within their surroundings, a concept of "water potential" should be addressed, too.

Chemical potential is related to free energy of a component of a system and refers to its capacity to do work. Just like soil water, measuring the absolute chemical potential of water is difficult, but it is rather easy to measure the difference in potential between a reference and water under consideration. In plant water relations, the chemical potential of water in converted to water potential by dividing chemical potential by the partial molal volume of water. The units for chemical potential are in energy terms ($J\ mol^{-1}$), and the water potential may be expressed as in pressure ($N\ m^{-2} = Pa$).

As water molecule is subject to various force fields, several separable component potentials can contribute water potential: osmotic or solute potential, turgor or pressure potential, and gravitational potential. The osmotic contribution arises from dissolved solutes and lowered activity of water near charged surfaces. Just like soil water, it is sometimes useful to separate from a matric potential associated with surface effect. The turgor potential derives from xylem tension and positive pressure inside cells as water presses against the walls. Gravitational component varies with plant height at a rate of 0.1 MPa per 10 m vertical displacement. Values of osmotic and matric potential is negative, while those of pressure potential may be positive, as in turgid cells, or negative as it frequently is in xylem sap under tension.

Several advantages have led to wide acceptance of water potential measurements. Most important was the fact that water movement occurs along gradients of decreasing free energy. We have some knowledge on the static status of water, i.e., its content and potential, and the driving force, which causes water to flow. Furthermore, we are also equipped with knowledge on how to calculate the potential difference in question. So, the direction of water flow and gradient driving flows are easily inferred. The osmotic and turgor potentials have inherent physiological meaning, indicating, respectively, the level of solute accumulation and turgor in plant tissues.

If the difference in potential under consideration is produced by some external agent, such as pressure or gravity, the movement is termed as "mass flow", while if that results from random motion of molecules caused by their own kinetic energy, as in evaporation, the process is called "diffusion", which is sometimes facilitated by the advective flow. Diffusion rates of substances in liquid water are adequate to support rapid transport across the distance at the cellular level. However, the much greater importance is cast on the mass flow in long distance transport through the xylem conduits. In fact, solutes and the water carried with them my move many meters per hour by mass flow in the xylem, while solute molecules in aqueous solution would require 8 or more years to diffuse even a distance of 1 m based on the estimation. Water flow through soil is more complicated than that in plant, so it is nearly impossible to introduce every aspect of soil water flow and its redistribution processes. However, it will be discussed in part elsewhere in this seminar.

5. The soil-plant-atmosphere continuum

One important contribution to plant and soil water relations is the treatment of water movement through the soil, into roots, through the plant, and out into the air as a series of closely interrelated processes. This idea, sometimes called the SPAC (Philip, 1966), is useful in emphasizing the necessity of considering all aspects of water relations in studying the water balance of plants. This unified field concept leads to treatment of water movement in the SPAC system as analogous to the flow of electricity in a conducting system, and it therefore can be described by an analog of Ohm's law.

The continuum concept provides a useful, unifying theory in which water movement through soil, roots, stems, and leaves, and its evaporation into the air, can be studied in terms of the driving forces. The concept is also useful in analyzing the manner in which various plant and environmental factors affect water transport by influencing either the driving forces or the resistance, or sometimes both. For detailed reviews of water transport in the SPAC system, refer to Boyer (1985).

5.1. Absorption of soil water

- Soil moisture regime

In moist soils, the rate of water absorption is controlled primarily by two factors: the rate of transpiration and the efficiency of root absorbing system. As soil dries, the availability of water begins to be limited by decreasing water potential and soil hydraulic conductivity. Soil aeration, soil temperature, and the concentration and composition of the soil solution also affect absorption of water. The readily available water is traditionally defined as that between field capacity and the permanent wilting percentage. Soil moisture content at field capacity is the amount of water retained in soil after gravitational water flow nearly ceased, while that of permanent wilting percentage is the amount of water with which plants remain wilted unless the soil is re-wetted. In general, the permanent wilting moisture percentage is said to occur at about -1.5 MPa. In reality, plants will continue to absorb water from a soil until the bulk soil water potential reaches the osmotic potential of the plant, so this makes the permanent wilting percentage to be obsolete.

It is well known that the conductivity of water flow in soil decreases rapidly as soil dries from field capacity to permanent wilting percentage. In addition, there is evidence that soil-root air gaps may develop in drying soil as both roots and soil shrink (Taylor and Willatt, 1983). The mode of water transport across this gap is restricted to diffusion, which is much slower than advective transport of liquid water. Furthermore, it must be noted that soil texture is greatly influential to hydraulic properties of the soil and the geometry of soil-root interface. However, this seminar will not further discuss the problems and knowledge related to dynamic water flow in soils, because it needs lots of time and higher knowledge level.

- Absorption through roots

Root systems of plants consist of roots in all stage of development. Furthermore, the absorbing surface of roots are often modified by the presence of mycorrhizal fungi, thus resulting in wide variations in permeability of roots to water and solutes. Therefore, the pathway of radial water transport in roots has long been a subject of debate and remains so to date. The relative importance of the pathways debated so far depends on both the comparative hydraulic conductivities and cross-sectional areas of cell membranes and cell walls. Some studies suggest that water flow through roots may be primarily symplastic (Boyer, 1985). Hansol et al. (1985) demonstrated that apoplastic flow into the root xylem was low unless the O_2 is depleted from the roots. However, the issue remains unsettled. Passioura (1988) reviewed water flow into and through roots. Discussion at a tissue level is beyond the scope of this seminar, so further explanation is excluded.

- Water absorption processes

It is well known that water absorption occurs along gradients in water potential from the medium in which the roots are growing to the root xylem. Two absorption processes can be identified in the literature: osmotically driven absorption and passive absorption. The former is common in slowly transpiring plants, while the latter predominates in actively transpiring plants and is responsible for most of water absorption by woody plants.

The roots of plants growing in warm, well-aerated, moist soil function as osmometers, when the plants are transpiring slowly because accumulation of solutes in the xylem sap lowers the osmotic potential and consequently the total plant water potential below that of the soil. The resulting inward movement of water produces the root pressure that is responsible for guttation and the exudation from wounds observed in some plant species. Whether osmotically driven water movement is by diffusion or advective flow is not certain, but Boyer (1985) argued that sufficient tension could be developed within membrane channels to support advective flow. In recent years, Kramer and Boyer (1995) further discussed the process of osmotically driven water absorption.

On the other hand, as the rate of transpiration increases and tension develops in the xylem sap, the gradient for water uptake switches from dominance of osmotic potential to pressure potential gradients. The greater water volume flux under these conditions sweeps out accumulated solutes in the root xylem sap and decreases the amount of osmotically driven absorption. The roots became passive absorbing organs through which water is pulled in by mass flow generated in the transpiring shoots. It seems likely that practically all water absorption by transpiring plants, both woody and herbaceous, occurs passively.

- Field water balance

Water use of crops by irrigation or rainfall is established to replace evapotranspired water at a sufficiently frequent interval to avoid serious plant water stress. For sandy soils with low water-holding capacity (retentivity), this may require even daily irrigation during the peak water-use period. The important factors that must be considered, in addition to water-holding capacity, are the evapotranspiration rate, the uniformity and frequency of irrigation, soil water status, and so forth. The above statement may suggest that adequate irrigation all over the filed is hardly attainable. Recent technology, however, made it possible to attain soil water status to a desired level at farmers' fingertips using in-situ soil moisture sensor connected to data-loggers to facilitate automated irrigation scheduling based on the chosen irrigation level by continuously monitoring soil water status (Ro, 2001).

Deficit irrigation at selected times is an important strategy not only to prevent nutrient leaching during the growing season and but also to save water, reduce shoot growth (prevent outgrowing) in favor of fruit growth and thus improve fruit quality without reducing yield (Behboudian et al., 1998). If irrigation is sufficiently frequent, and the deficit is small, crops experience no water stress. Especially where water tables are shallow, however, care must be taken to assure an overall downward flux of water without deteriorating water quality.

- Supply of water and nutrients by the soil

As you already noticed, soil moisture influences the rate of nutrient uptake mainly because it affects the rate of nutrient supply by the soil and the rate of root extension. In general, the ability of a root surface to absorb nutrients is usually not limiting. However, the density of fruit trees in soil is lower than that of other crops, since they may be more sensitive to moisture-related interruption of nutrient availability from the soil (a kind of my speculation). On the other hand, fruit tree root systems tend to extend deeper into subsoil where nutrients may continue to be available even if the topsoil dries out.

Nutrients in the soil are supplied to roots by three mechanisms: root interception, mass flow, and diffusion. Root interception is the absorption of nutrients directly encountered by root surfaces as roots grow through soil. Root interception is believed to account for a very small portion of total nutrient uptake by most crops (<1%). However, it may be more important for fruit trees because the lower density of fruit tree roots in soil reduces the ability of mass flow and diffusion to deliver nutrients to root surfaces.

The amount of nutrient movement by mass flow is related to the amount of water absorbed and the nutrient concentration of that water. The rate of nutrient movement to the root by mass flow depends on the rate of water uptake, which in turn is affected by climate and soil water content. Meteorological factors that enhance transpiration, such as high temperatures and low relative humidity increase nutrient movement by mass flow because of increased water absorption by roots. However, the moment the uptake rate falls below transpiration, the plant itself must begin to lose moisture. Again, mass flow of water is the same phenomenon as the movement of massive air according to the pressure difference.

When root interception and mass flow do not supply the root with sufficient quantities of a particular nutrient, continued uptake reduces the concentration of available nutrients in the soil at the root surface. This in turn causes a concentration gradient perpendicular to the root surface (low at root, high in bulk soil), with nutrients subsequently diffusing along the gradient toward the root surface. The distance for diffusive nutrient movement through the soil is usually in the range 0.1 to 15 mm. Only nutrients within this zone contribute to diffusive nutrient supply to the root. It is known that plants receive most of their phosphorus, potassium, and part of their nitrogen by diffusion. The rate of nutrient diffusion decreases with decreasing soil moisture and temperature, and with increasing soil bulk density. Diffusion process may be visualized when we think of a drop of black ink in pure water and a pungent smell of gasoline in a clean air environment when we fill up the fuel tank of automobile.

5.2. Ascent of sap

The existence of tall plants became possible only after plants evolved a vascular system that permitted rapid movement of water to the transpiring shoots, because water movement from cell to cell by diffusion is much too slow to prevent the tops of transpiring plants from being dehydrated. It is well known that loss of water by transpiration produces the pull causing the ascent of sap. Thus, as aforementioned, in transpiring plants water absorption is controlled directly by the rate of transpiration. To transport water upward against gravity, a pull of -0.01 MPa per meter is required, plus whatever pull is needed to overcome frictional resistance to upward flow in the xylem. The continuous water column extending from leaves to roots provide the feedback mechanism by which changes in the rates of water loss and absorption control one another. This mechanism is known to be essential for the survival of transpiring plants.

Rupture of stressed water columns followed by air embolism in the conducting xylem elements often decreases water conductivity. Embolism is commonly induced by drought, excessive transpiration, and winter freezing. Once air enters a vessel, it disrupts the cohesion of the water molecules, and the water column breaks and retracts, filling the element first with water vapor. Eventually, as air comes out of solution from the surrounding water, the vessel completely fills with water. The adjacent elements do not embolize as long as the pressure difference does not exceed the surface tension of the air-water interface in pores connecting the embolized and filled elements. Embolism should occur with freezing of xylem sap because air that dissolved in water is not soluble in ice.

5.3. Transpiration

Transpiration is the loss of water vapor from plants. It is a dominant factor in plant water relations because evaporation of water produces the energy gradient that causes movement of water through plants. It therefore controls the rate of absorption and the ascent of sap and causes almost daily leaf water deficits. Rapidly transpiring plants lose so much water on sunny days that the cells of young twigs and leaves may lose turgor and wilt, stomata close reducing photosynthesis, and growth declines or ceases unless adequate water supply is available. In contrast, transpiration provides beneficial cooling of plants from physioengineering viewpoint (Ro, 2000).

Transpiration is basically a process of evaporation that is controlled by physical factors. However, it is also a physiological process, and as such it is affected by plant factors such as leaf structure and exposure and the responses of stomata. It usually occurs in two stages: evaporation of water from cell walls into intercellular spaces and diffusion of water vapor into the atmosphere.

- Transpiration as a physical process

The rate of evaporation of water from any surface depends on (1) the energy supply available to vaporize water, (2) the vapor concentration gradient that constitutes the driving force for movement of water vapor, and (3) the resistances in the diffusion pathway. Solar radiation serves as the primary source of energy for evaporation of water (energy balance).

- Factors affecting transpiration

Although the rate of transpiration is basically controlled by physical factors, it is influenced by several plant factors that affect both driving forces and resistances. The important environmental factors affecting transpiration are net solar radiation, vapor concentration gradient, temperature, wind, and soil water supply. Plant factors include leaf area and exposure, canopy structure, stomatal behavior, and the effectiveness of roots as absorbing surfaces. There are complex interactions among these various controlling factors, but excluded in this essay. Instead, some relevant examples were introduced.

The supply of water to the roots also affects transpiration because a deficient water supply causes dehydration and stomatal closure. In moist soil, water tansport to the roots is rapid and the transpiration is controlled largely by atmospheric demand. As the soil water content decreases, however, the supply of water to the roots becomes a limiting factor and the rate of transpiration decreases and the evaporation from soil surface is diffusion-controlled (Ro, 1989). Low soil moisture reduced the transpiration of trees so much that the trees transpired more during the wet season than during the dry season, although atmospheric conditions were more favorable for transpiration during the dry season.

5.4. Plant water balance

The growth of both woody and herbaceous plants is reduced more often by water deficits than by any other environmental factors. It is well known that the degree of water stress in plants is controlled not only by the potential of soil water with which the root system is in contact but also by the relative rates of water absorption and water loss. Hence, water deficits can be caused by low soil water potential, slow absorption, rapid water loss, or most often by a combination of the three. Thus, the study of factors affecting water absorption and water loss is of importance because it contributes to an understanding of the internal water balance of plants, which in turn affects the physiological processes such as photosynthesis and conditions controlling the quantity and quality of growth. By plant water stress, we infer a condition in which the cells are less than fully turgid and the water potential is substantially less than zero.

In general, light, temperature, nitrogen and water are major environmental factors affecting the productivity of crops. Crop producers manage light by various manipulation of the canopy; temperature by site selection, frost protection and evaporative cooling; nitrogen by fertilizer applications; and water by irrigation. As one travels west from temperate Far East Asia where four seasons are distinct, and crosses the humid, subtropical Indo-Chinese peninsula where abundant tropical monsoon rainfalls dense forest, a semi-arid or arid region with seasonal or consistent drought is entered.

Drought is defined as a meteorological event that is combination of restricted water supply caused by insufficient precipitation and enhanced rates of water loss because of high evaporative demand, resulting in limited soil moisture and reduced productivity. As stated earlier, improved understanding of the water needs of crops and programmable irrigation controlling system have made possible scientific irrigation scheduling that can significantly improve the efficiency of water use (Ro and Park, 2000). Unfortunately, a large portion of our water use is still grounded in the past.

As stated elsewhere, water in horticultural crops is in continuity with water in the soil and water vapor in the atmosphere. Soil water is absorbed by roots, transported through the tree via the xylem vessels, then lost to the atmosphere as water vapor through transpiration from the leaves, and finally returned to the soil as irrigation or rainfall. It is the hydrological cycle of agricultural water. Analogous to soil water potential, if plant is turgid; pressure potential is positive, if plant is flaccid; pressure potential is zero or sometimes negative. Osmotic potential is always negative and is important in a plants ability to tolerate water stress (Morgan, 1984).

6. Importance of water relations in horticultural crops

So far we have discussed the general properties of water and how to characterize static and dynamic water status in soil, and briefly touched its relation to plant water status. All things we have discussed are obviously important, but practically less meaningful. In the field, soil influences and interacts with many substances, thus rendering a more complicated soil environment. Among various phenomena associated with soil water, I would like to emphasize the importance of soil air, particularly for O_2 (Ro et al., 1995; Ro, 2000), soil temperature (Park and Ro, 1996; Park et al., 2001), and soil nutrient concentration, which further interacts with the root systems of plants. For this, I will show the effect of nitrogen concentration of soil solution on the growth of apple trees (Ro and Park, 2000). Additional slides show the experimental results which I and my colleague have done so far. In closing this essay, even though limited time is allowed for us, I wish to think we are to some extent exposed to the soil-water relations and their importance in agriculture. As a closing remark, as elevated atmospheric temperature and CO_2 concentration are expected to be part of our future climate (Burroughs, 2001; Ro et al., 2001), the water relations in SPAC should be reexamined in relation to increased partial CO_2 pressure and higher temperature regimes in soil.

7. Literature cited

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