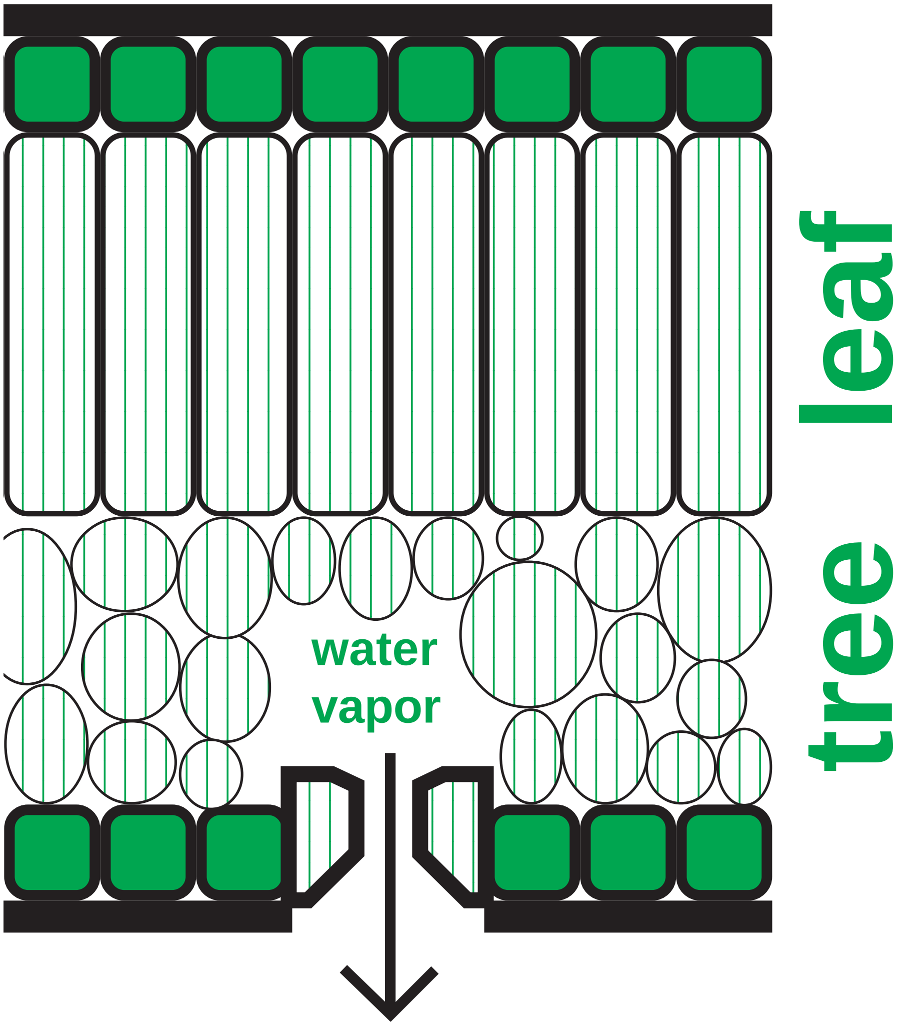
Water, Drought & Trees:

Understanding Foundation Principles for Tree Health

diagram of tree leaf cross-section with stomate



by Dr. Kim D. Coder
Professor of Community Forestry & Tree Health
Warnell School of Forestry & Natural Resources

The University of Georgia

OUTREACH
MONOGRAPH
SFNR07-6
8/2007

WARNELL
School of Forestry and Natural Resources

Water, Drought & Trees:

Understanding Foundation Principles for Tree Health

NOTICE: This manual is an educational product and a scientific literature review document. This manual is not intended to be used, and should not be used, as a landscape watering or drought standard, or part of a regulatory guideline. This manual is for developing water, drought, and watering awareness among tree health care workers. Within this manual the author and institution have in good faith examined and offered credible information within an educational framework for this subject area, and as such are not responsible for any errors and omissions, or end-user use or misuse of this information. This manual is for informational and educational purposes only.

Table of Contents

Water, Drought & Trees:

Understanding Foundation Principles for Tree Health

Water use, movement, and transpiration in trees is primarily a physical process based upon available energy (temperature) on a site. Trees living through a drought are stressed and damaged by water limitations for transport and cell health. Trees living under summer drought and large heat loads, are forced to spend any available water to survive. Drought stresses all tree life processes.

Trees act as conduits through which water passes. Instead of water evaporating at the soil surface, a tree provides an elevated surface for water evaporation. One way to view a tree and water use is to imagine a tree as a water fountain lifting and evaporating water from its leaves. At the water interface between tree and atmosphere (the leaf) is the major biological control point for water movement in a tree, and for water conservation.

Most Valuable Resource (MVR)

Water is essential to tree life as well as the most limiting resource. Trees have developed specialized organs, processes, and surfaces to carefully use and conserve water. The value of water lies with its chemical properties, physical reactions, and biological uses. Water is the single most important molecule in trees as well as the ecological systems which sustain trees. Water is the starting point for photosynthesis capturing energy from the sun, a hydraulic fluid, a transport stream, and solvent. Water comprises 80% of tree mass on average.

Within each living tree cell is a water-based solution that contains, supports and dissolves a variety of materials and molecules responsible for life. This water solution of life is called "cytoplasm." The tree is genetically programmed to maintain water contents in cytoplasm allowing food production, energy use, and protein synthesis to occur. To keep the inside of living cells bathed in water, trees horde water from the environment. Trees are a standing pipe of soil water held against gravity and the dryness of the atmosphere.

Water Everywhere?

Approximately 97% of all water on our planet is in the oceans. Ocean water contains about 35,000 parts per million (ppm) dissolved materials, comprised of at least 70 elements. Fresh water (less than 1000 ppm dissolved materials) represents the remaining 3% of water on Earth, 2/3's of which is snow and ice in glaciers and polar ice caps. Water in the atmosphere, ground water, lakes, and streams comprise the remaining 1/3 of one percent of Earth's fresh water. Liquid and solid water cover roughly three-quarters of Earth's surface area. Water vapor is a greenhouse gas, reflecting and reradiating energy.

Because of water's properties, it can absorb or release more heat than most other substances for every temperature degree of change. Water buffers extreme temperature fluctuations, acting as heat reservoirs, heat exchangers, cooling systems, and protection for life. The changing states of water (and the energy released) power thunderstorms and hurricanes. Water's changing states help dissipate sun energy and buffer rapid climatic changes across the globe. The global and continental water cycles create deserts and rainforests, depending upon ratios of evaporation and precipitation. The attributes of water make it the driving force of small scale and large scale climate.

Water is the catalyst of life. When water availability is constrained, life slows, declines, and fails. Drought forces trees to make many genetically based, resource economic decisions in order to survive. Tree health professionals must understand water and its many impacts on trees.

Many Facets of Water

Water is an unique substance. Pure water in small portions is clear and colorless with no taste or odor. The properties of water make it both unusual chemically and critical biologically. The most basic of its interactions with other water molecules, and other materials, are associated with its electronic properties. Water is a perfect platform to build and sustain life.

Water States

At a growing tree's temperature, water exists as a gas and as a liquid. As temperature changes, relative proportions of water in its two primary states change. More energy propels water molecules at a faster rate, and by definition, temperature increases. As energy is reduced in water, temperatures decline with water eventually freezing to a solid. Pure water freezes to a solid at 32^oF (0^oC) and boils to vapor at 212^oF (100^oC), under one atmosphere of air pressure. Our temperature scales are set by these properties of water.

Water in the gas phase surrounds us in the atmosphere. The most simple weather descriptions include a relative humidity measure. On a large scale, water vapor blankets the Earth and acts as a greenhouse gas, keeping heat from escaping into space. Water in its solid phase drags other water molecules to its crystal surface. These growing ice crystals can act like daggers to living cells. Depending upon its molecular energy level, it is possible to have individual water molecules in a continuous exchange between all three physical states. Figure 1.

Molecular Form

A water molecule -- the most basic unit -- is composed of three atoms covalently bonded together. These bonds involve sharing electrons between atoms. Two of the three atoms are small hydrogens, each with a single negatively charged electron surrounding a positive charged proton with various numbers of neutrons. The third atom in water is a massive oxygen which has an atomic structure that easily captures and holds up to two negatively charged electrons. These covalent bonds between atoms in a water molecule are strong.

There are many kinds of water. Water can exist in nine (9) different forms (isotope combinations). There are two (2) types of naturally occurring hydrogen available for use which vary in their nuclear components. There are three (3) naturally occurring oxygen types available. The lightest form of water is by far the most common -- H_2O molecular weight = 18. The heavier isotope combinations of naturally occurring water (molecular weights = 19-22) are extremely rare and may not be as biologically active as standard water. Table 1.

Charge Exposure

In binding with oxygen, hydrogens tend to loose their negative electrons for most of the time. The almost continuous loss of negatively charged electrons from both hydrogens partially exposes their positively charged proton centers. The capture of two extra negatively charged electrons for most of the time by oxygen, adds a partial negative charge to oxygen. The ability of oxygen to steal electrons (unequal sharing) from its hydrogen partners generate a partial charge separation within water molecules. The partial positive and negative charges balance out within one water molecule leaving no net charge.

Individual molecules of water have a slight tendency to completely ionize or disassociate. Chemically two water molecules can break apart into one H_3O^+ ion and one OH^- ion, or an average disassociation of one H+ (proton) and one OH^- (hydroxy group). A chemical balance exists between water molecules in ionized and non-ionized states, with most in a non-ionized form. At a neutral pH

Figure 1: Diagram showing states of water and names of transitions between states.

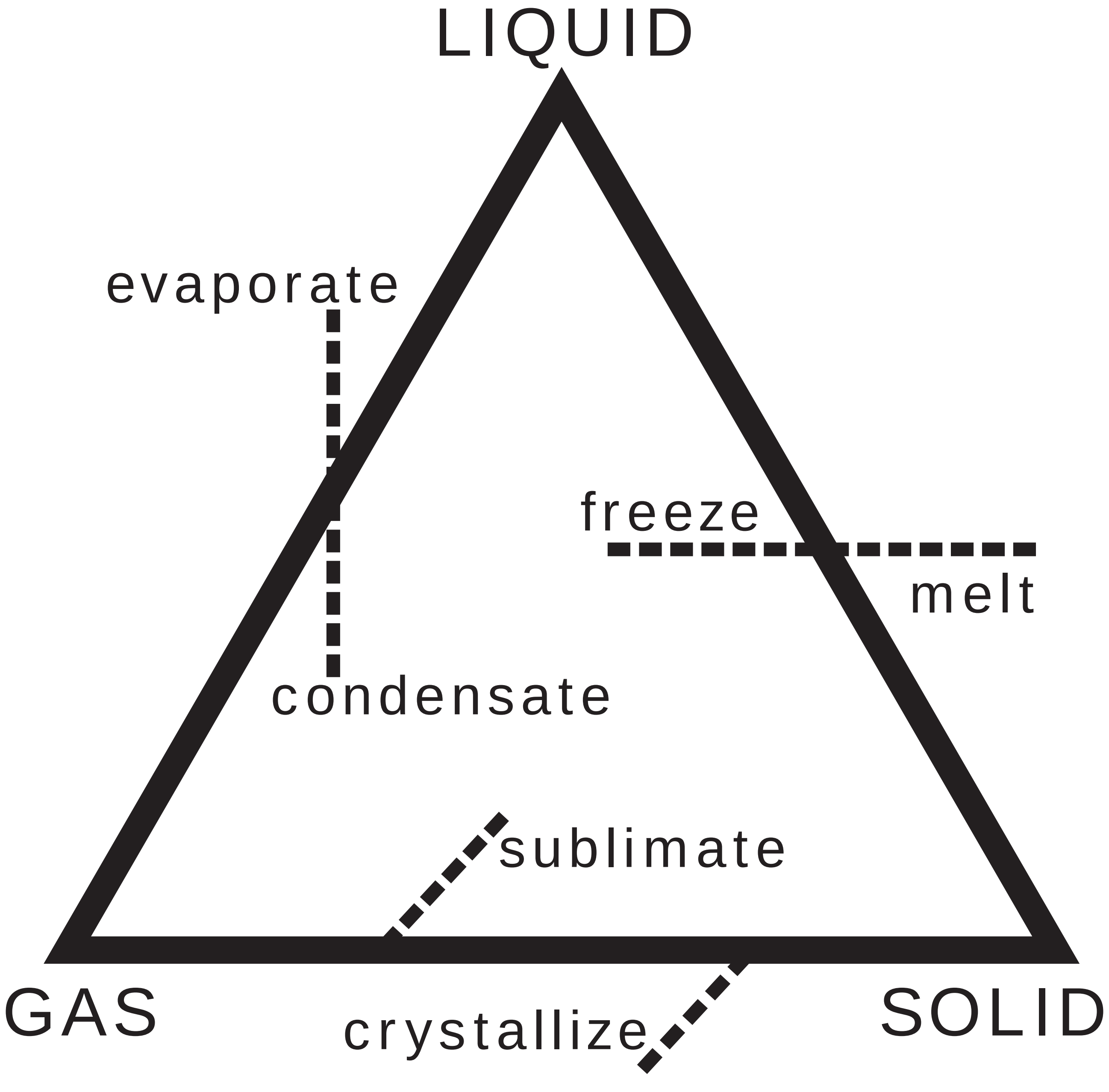


Table 1: Percent of the nine (9) naturally occurring water molecule forms in the atmosphere.

(Note percents are NOT in decimal form).

total hydrogen mass	oxygen mass	percent water form on Earth
2 (^1H,^1H)	16	99.74 %
2	17	0.04 %
2	18	0.20 %
3 (^2H,^1H)	16	0.01 %
3	17	0.000004 %
3	18	0.00002 %
4 (^2H,^2H)	16	0.000001 %
4	17	(4×10^{-10}) %
4	18	(2×10^{-9}) %
		100%

^3H is a synthesized radioactive hydrogen with a ~12.3 year half-life.
All the rest of synthesized hydrogens and oxygens have short half-lives (< few seconds).

(pH = 7), one in 10 million water molecules are ionized. As pH becomes lower (more acidic), more H^+ ions exist per liter of water. A pH of 4 means the concentration of H^+ is one in 10,000. Water molecules generally stay in one molecular piece, unequally sharing the hydrogen's electrons.

Sticky Shapes

Part of understanding partial charge attraction is examining the shape of the water molecule. There are many ways to envision three atoms in water attaching to each other. Water molecules are not straight or a 90^o L-shaped. Oxygen has four possible attachment points for hydrogens, the corners of a tetrahedron, but can only bond with two hydrogens. The two hydrogens can only be attached to a single oxygen in one way. The hydrogens are always at a $\sim 105^o$ (104.5^o) angle from each other over the surface of the much larger and massive oxygen atom. At this angle, each hydrogen presents a partial positive charge to other water molecules and materials. The oxygen presents two variable partial negative charges to other molecules. Figure 2.

The interactions between water molecules involve partial negative charges attracting partial positive charges among all other water molecules. This partial charge attraction is called "hydrogen bonding." Hydrogen bonding is not as strong as a covalent bond between atoms, but is strong enough to require some energy to break (i.e. 4.8 kilocalorie/mole). Hydrogen bonding also can occur over longer distances (1.8X longer) than the short covalent bonds between atoms in a water molecule.

H-Bonds

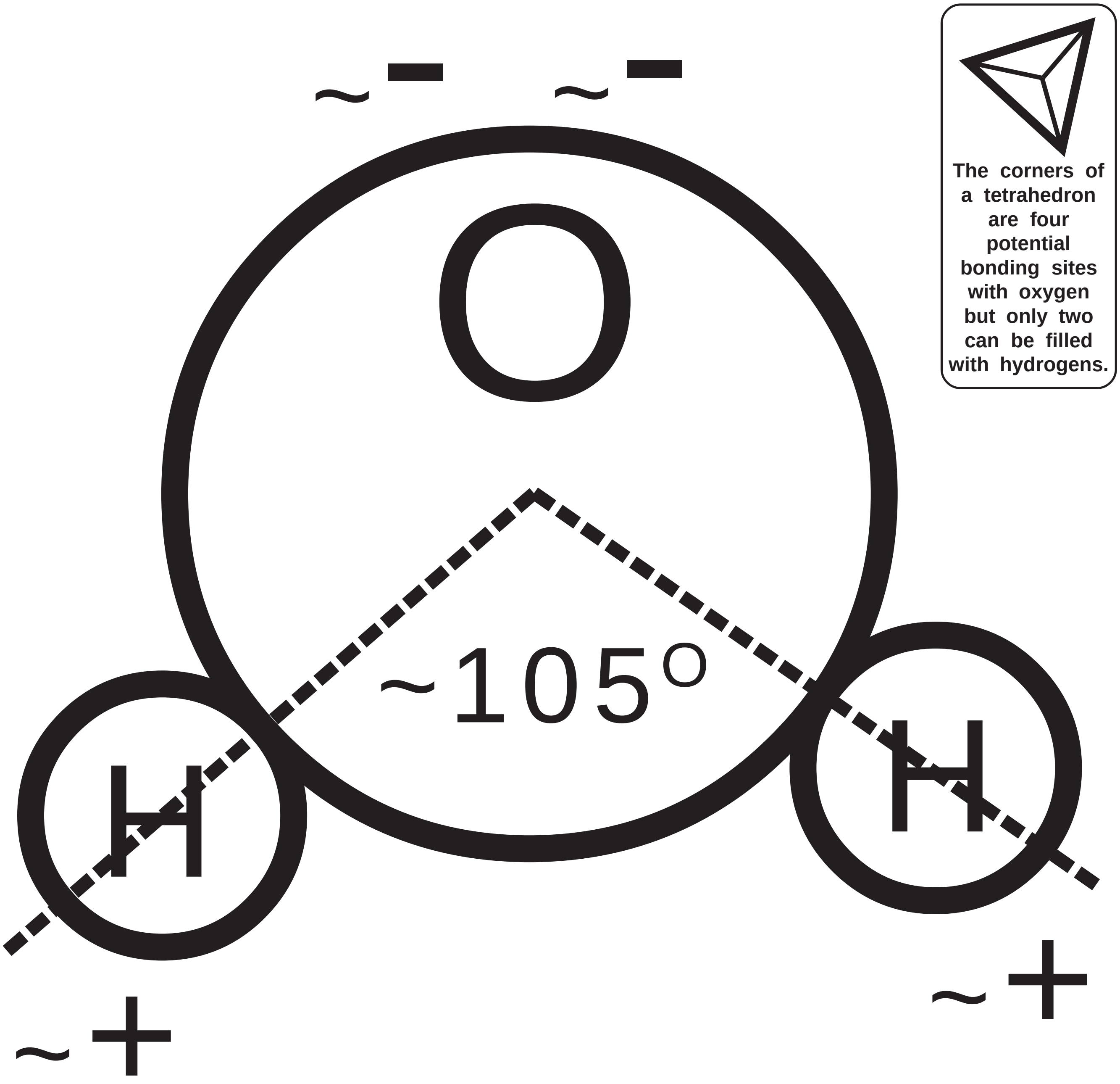
As a liquid, every water molecule is surrounded with other water molecules except those at an edge or on the surface. Within liquid water, each molecule is held within an ephemeral framework of 0-4 hydrogen bonds from all directions. The mutual attraction between water molecules is called "cohesion." Even though one hydrogen bond slips to another molecule, the average number of these bonds per water molecule remains roughly the same for each energy level. As temperatures climb, more hydrogen bonds break. At the liquid water surface, more molecules escape from liquid into a gas form. Figure 3.

Hydrogen bonding occurs when hydrogen is positioned between two strongly electronegative atoms. Oxygen, fluorine, nitrogen and chlorine can participate in compounds with hydrogen bonding. Oxygen in one water molecule can form a hydrogen bond with a hydrogen on another water molecule. Both oxygen and nitrogen form hydrogen bonds that can positively influence the shape or conformation of biological molecules. Both chlorine and fluorine pull apart and disrupt biologics.

Complex Structures

Water is simply not a host of individual molecules interacting. Because of hydrogen bonding, water develops complex structural and geometric relationships with surrounding water molecules which exist in few other materials. Remember, potential for a maximum of four hydrogen bonds coming from a single water molecule allows water to mimic a four-sided, three dimensional structure called a tetrahedron, rather than a flat, two-dimensional triangle. As these tetrahedrons stack-up, they form small areas of structure which approximate a crystalline form.

As more crystalline areas develop and line-up with each other, water can be described as having a semi-crystalline form in a liquid state. This semi-structure confers stability which makes water unique. Water is dominated by this stable semi-crystalline structure up to about 105^oF (40.5^oC). At this temperature the energy within water is great enough to prevent most large structural areas of hydrogen bonding from occurring. This stability temperature is biologically significant because water which surrounds, supports, and interfaces with many tree enzymes and molecular conformations begin to subtly change properties above this temperature.



The corners of a tetrahedron are four potential bonding sites with oxygen but only two can be filled with hydrogens.

Figure 2: Diagram of water molecule with an oxygen (O) and two hydrogen (H) atoms combined. The hydrogen atoms are always separated by ~105° (104.5°) as they glide over the oxygen perimeter, never on opposite sides. The oxygen draws electrons away from the hydrogens generating a polar molecule with partial negative charges (~-) on the oxygen side and partial positive charges (~+) on the hydrogen side.

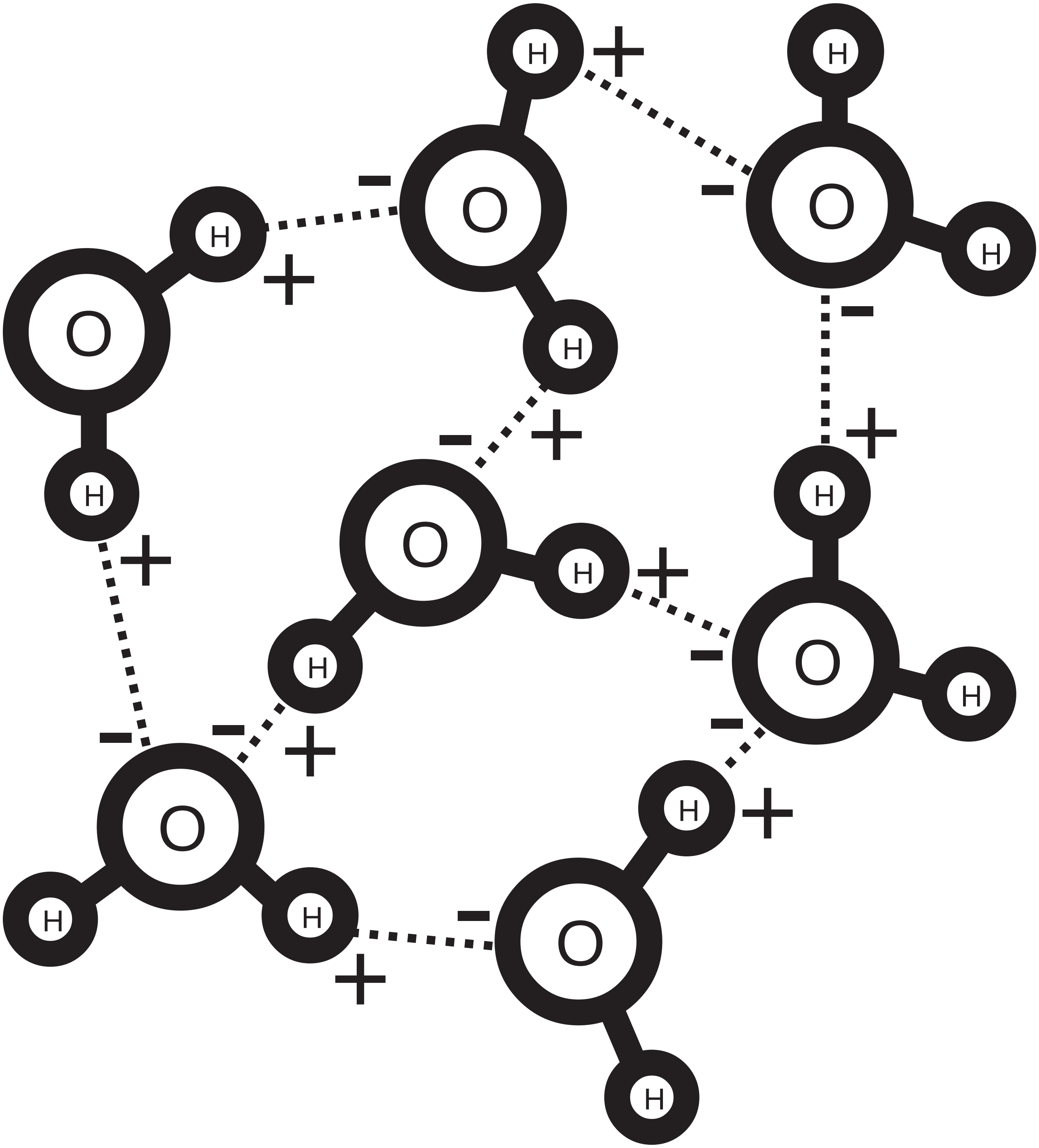


Figure 3: Diagram of seven water molecules interacting with each other due to partial electrostatic charges and the associated 0 to 4 hydrogen bonds. The dotted lines represent hydrogen bonds. Remember, this is a simple two dimensional diagram, while water molecules are in a four dimensional framework of constantly changing hydrogen bonds.

Ice Floats

As liquid water cools, more and more hydrogen bonds are formed and maintained. This increased attraction with decreasing temperature continues until 40°F (4°C) when water is at its densest. As liquid water continues to cool, the hydrogen bonding of cold water begins to reorganize into large areas of crystalline-like structures. As energy content in liquid water declines to 32°F (0°C), the hydrogen bonds set-up a liquid crystal structure made of tetrahedron shapes.

As water freezes, the tetrahedrons are set into true crystal forms. This water crystal formation is a solid which is less dense than the liquid it formed from. The four hydrogen bonds and the packing density of tetrahedron crystals formed at freezing separates the individual water molecules by more space than is present between water molecules in a liquid form. Ice floats because it is less dense than liquid water. The lower density tetrahedron structure of solid water allows ice to float, and provides the basic building blocks and shapes found in snowflakes and frost.

Being Dense

Water's greatest density is at 40°F (4°C). Water volumes nearing 40°F (4°C) will sink. Moving water temperature from 40°F (4°C) down to 32°F (0°C), water internally restructures and rises to float on the surface. Water is least dense at 32°F (0°C). Within an 8°F (4°C) temperature range, water is found at its densest and lightest. The characteristic of a solid form being less dense than a liquid form is rare. This feature allows lakes to freeze from the top downward in Winter, and completely thaw in Spring, protecting the water column and lake floor ecological systems from freezing damage. Liquid water density differences help propel water column mixing rates, as well as providing environmental stimuli to a number of water creatures.

Changes

As energy is added to liquid water, more molecular movement occurs with greater intensity, breaking more hydrogen bonds. Within liquid water, there are several energy states where water molecule interactions undergo significant changes. The molecular interconnectivities shift to maintain the lowest energy level and/or simplest structure possible.

The ice-to-liquid state change is clearly an important event for the biological use of water. Additionally, 40°F (4°C), when water is at its densest, is an important structural change point. There is also a structural phase change at approximately 105°F (40.5°C) where the lower energy semi-crystalline patchwork of water molecules grades into fields of more energetic and less interactive water molecules. Some biological materials and processes become much less efficient beyond this point because of water properties, as well as temperature effects.

Little Big Size

The most abundant form of water has the smallest molecular weight of 18 mass units with 16 mass units coming from a single oxygen. Other molecules similar to the mass and size of water molecules quickly evaporate and exist as a gas at tree growth temperatures. Because of hydrogen bonding, water molecules are "sticky," attracting each other and generating properties expected of a much different, much heavier and larger compound. Water interacts with any materials having at least small irregularities in their electronic composition. Water will adhere to many surfaces which have many forms of partial charges and ionic terminals.

Water forms a thin film around most soil and biological materials. For example, a landscape soil under drought conditions contains a relatively large concentration of water. This water content is sticking to and surrounding organic matter and clay particles, and filling small gaps or pores between particles. By placing soil in an oven at 212°F (100°C), most of the water can be driven off, although some still will remain closely bound to various surfaces and within crystal structures. Adding water to a soil allows the surface films of water to enlarge, filling ever larger soil pores. Any added water becomes part of the water matrix already in a soil which sticks together, and a portion of which can be dragged into a tree.

Electric Shells

Many elements essential to trees dissolve readily in water and form ions, either positively charged "cations" or negatively charged "anions." Ions come from the disassociation or separation of a molecule. Table salt easily ionizes into positive cation sodium ($Na+$) and negative anion chlorine ($Cl-$) when stirred into water. The full charges on the ions cause the partially charged water molecules to line-up and surround each in a hydration sphere or layer. The ions then tend to behave as larger molecules because they are blanketed with many water molecules attracted by their charge.

In soil, most essential elements are not dissolved in solution but held within organic materials or mineral compounds. There are always a small portion of these elements dissolved in water and attracted to the various charges on soil particles. The small water molecule charges, in-mass, tug at any surface materials and surround them (dissolve them). An individual water molecule is very small compared to most other materials and can be drawn into the smallest of pores or spaces. This physical property helps water dissolve many things. Water infiltrates and coats life and its resources.

Polar Blankets

Water is generally a highly stable, non-ionized, polar molecule that acts as a nearly universal solvent. Wherever water flows through soil or over tree surfaces, it dissolves and carries along valuable materials. Because of its small size and polar nature, water dissolves many materials, more than any other liquid. Water can fit into small surface faults and between molecules which helps dissolve materials. Water is considered a polar substance because of its unique hydrogen bonds caused by partial electronic charges. In terms of kitchen chemistry, polar substances like water dissolve or attract other polar materials. Water can not influence non-polar materials like oils, thus oil and water do not completely mix but separate. Adding a soap or detergent to an oil-water mixture puts a charged "handle" on the oil and then water can dissolve it away.

Materials that are ionic or polar can be pulled into water and surrounded by a shell of many water molecules hiding or covering any charge. Many acids, bases and salts ionize easily in a water solution and are immediately surrounded by a hydration layer or shell. A hydration shell of water surrounding polar or charged materials makes these materials behave as if they were larger compounds. Some relatively large (at the molecular scale), but highly charged materials like clay colloids, can be suspended in water. Large molecules with many atoms can be surrounded by water minimizing their electrostatic charges and cohesion forces, helping these large molecules dissolve in water.

Surface Tension

Water molecules within liquid water are pulled equally (on average) from all sides by hydrogen bonding. Water molecules at the surface are pulled only on one side into the water mass. Without attraction from the air above, surface water molecules are held and pulled inward toward other water molecules. "Surface tension" is the result of a force generated by hydrogen bonding pulling together water molecules. Surface tension allows small items which are more dense than water to be held on the surface of the water. "Water strider" insects use water surface tension as a means of transportation. Water has a strong surface tension force, like a cloth stretched across a drum head. The only other common liquid with a stronger surface tension is the liquid metal mercury.

Without gravity or a surface to adhere to, large groups of water molecules will be pulled by surface tension into a round ball to minimize surface area per unit volume. In gravity, tear-drop-shaped droplets are formed as water falls. Liquid water on surfaces to which it does not adhere well (i.e. a waxy surface) will “bead-up.” Water would rather stick to itself than to many surfaces. The surface tension of water allows wind to push against it, generating waves in large water bodies. Detergent helps reduce the surface tension of water (by as much as 70%) and allows water to spread out over a surface.

Capillary Movement

There are some surfaces to which water is attracted or adheres well. These wettable surfaces cause a film of water to partially pull away from other water molecules and cling to the wettable surface. As one molecule moves forward and adheres to a surface, it pulls on other water molecules behind. Over time a layer of water will be pulled out and over a wettable surface. If a small diameter tube is made of a wettable surface material, water will be pulled against gravity, and other forces, into the tube. This characteristic of water is called “capillary movement.”

Capillary movement involves three primary forces generated in liquid water by hydrogen bonding -- adhesion, cohesion, and surface tension. Adhesion is the attraction of water for a wettable surface. Cohesion is the attraction of one water molecule for another water molecule. Surface tension minimizes surface area. Inside a small diameter tube, water is attracted along the walls by adhesive forces. As water is pulled along the tube surface by adhesive forces, surface tension and cohesion drag more water molecules along behind. When the cohesive forces of the water, tube size resistance to movement, and gravity become too great, (or surface tension is reduced) water movement in a capillary stops.

Tubular Water

One way to envision water pulled into and up a capillary tube is to use a suspension bridge model. A column of water is suspended against gravity by adhering to tube walls (bridge uprights). Adhesive forces on the tube walls allow cohesion forces in the rest of the water molecules to be pulled up and supported like spanning cables between bridge uprights carrying the weight. Cohesive forces keep all the water molecules together, reaching the minimum surface area for the diameter of the tube (distance between bridge uprights).

Capillary movement components can be seen where liquid water touches the side of a glass. The water surface is not flat or evenly suspended across the tube, but is drawn slightly up the sides of the glass. This raised rim is called a “meniscus.” A meniscus is the visible sign of adhesive forces between the glass and water, as water is being pulled up the side of the glass. The smaller the diameter of tube, the greater the adhesive / cohesive forces pulling-up on the water column for the same mass suspended behind. Extremely small diameter tubes, soil pores, or intercellular spaces can attract water, allowing it to move a relatively long way (many inches).

Capillary movement is responsible for some within- and between-cell water movement in trees, and small pore space movements in soils. Cell wall spaces are extremely small (interfibral) and can slowly “wick-up” water. Water conducting tissues of trees (xylem), does NOT utilize capillary movement for water transport. If xylem were open at its top, a maximum capillary rise of 2-3 feet could be obtained. Xylem transport is by mass movement of water not capillary action. Capillary movement is a matter of inches, not dragging water to the top of a 300 feet tall tree.

Specific Heat

As energy is added to water, the molecules tend to increase vibration and movement. The more movement, the more hydrogen bonds broken. Many hydrogen bonds must be broken before the average movement of an individual molecule is affected (i.e. water temperature increases). Because of the massive number of hydrogen bonds in water, it requires a lot of energy to record even a small change in water temperature. Water can absorb a great deal of energy tied up in breaking hydrogen bonds but does not lead to measurable temperature increases.

The property of absorbing significant energy before showing temperature change is a measure called "specific heat." Having a high specific heat means water is well suited for cooling machines and buffering temperature changes. A high specific heat also means as water finally does change states, a lot of energy is involved. For example, in a moist soil system, water present can absorb more than five times the amount of energy (heat) compared with the soil materials present, for the same change in temperature.

Evaporation

As water temperature is raised to near boiling, more and more hydrogen bonds are broken. From the surface, as select water molecules are untethered from all hydrogen bonds, they escape into the atmosphere as water vapor. This process occurs at all temperatures, but is maximized at near boiling when almost all hydrogen bonds are broken and water vaporizes (changes states). The amount of energy required for changing liquid water into a gas (boiling or vaporization) is large for such a small molecule because of the cohesion (hydrogen bonding) between molecules.

Throughout liquid water, the average attractive forces between molecules is dependent upon temperature. But each separate molecule can have a higher or lower energy level than average. Water molecules with higher than average energy levels can overcome the shifting hydrogen bonds and break away. This is called evaporation when a water molecule from a liquid mass escapes into a gas phase. Because the escaping molecule had a higher than average energy level, it leaves the liquid cooler (lower average energy) upon evaporation, which is called evaporative cooling or heat dissipation. As temperature of the water increases, evaporation becomes faster.

At tree growth temperatures, energy required to evaporate water is the highest for any liquid. Most of this energy is used to break hydrogen bonds. Biologically, the significance of this high heat of vaporization means when water evaporates from the leaf, a large amount of heat is needed and a large amount of evaporative cooling takes place. In addition, water buffers rapid changes in temperature through its resistance to temperature change.

Vapor Pressure

Humidity is the amount of water vapor in the air. At a given atmospheric pressure, there is only a specific amount of water vapor which can be a constituent of air (partial gas pressure). Water molecules under saturated conditions comprise a maximum of from less than 1% (at 40^oF) up to 9% (at 112^oF) of the air. Oxygen (O_2) and nitrogen (N_2) comprise the bulk of the atmosphere.

The maximum amount of water vapor which could be in air is called the "saturated vapor pressure." Rarely is the water vapor in air at saturation. Any amount of water vapor less than saturation can be represented by a percent of full saturation or relative humidity. At any relative humidity less than 100% (saturation), water molecules at the liquid surface would be evaporating faster than being captured. The lower the relative humidity (farther from saturation vapor pressure), the faster the evaporation from the water surface. This can be thought of as a vapor pressure deficit or "dryness" of the atmosphere.

For example from Figure 4, saturated vapor pressure of water (100% relative humidity) is given. Also shown are 90% and 70% relative humidity (RH). These relative humidity values less than 100% represent a vapor pressure deficit in the air of -142 bars and -482 bars of water potential tension respectfully.

Drying Force

The rate of water molecules evaporating for each temperature is a unique "vapor pressure." When the vapor pressure of liquid water equals the air pressure over it, water boils. The standard boiling temperature of pure water is considered 212^oF (100^oC) at one atmosphere of pressure (or ~1 bar or ~1,000 millibars). Changing air pressure will change the boiling temperature (equilibrium

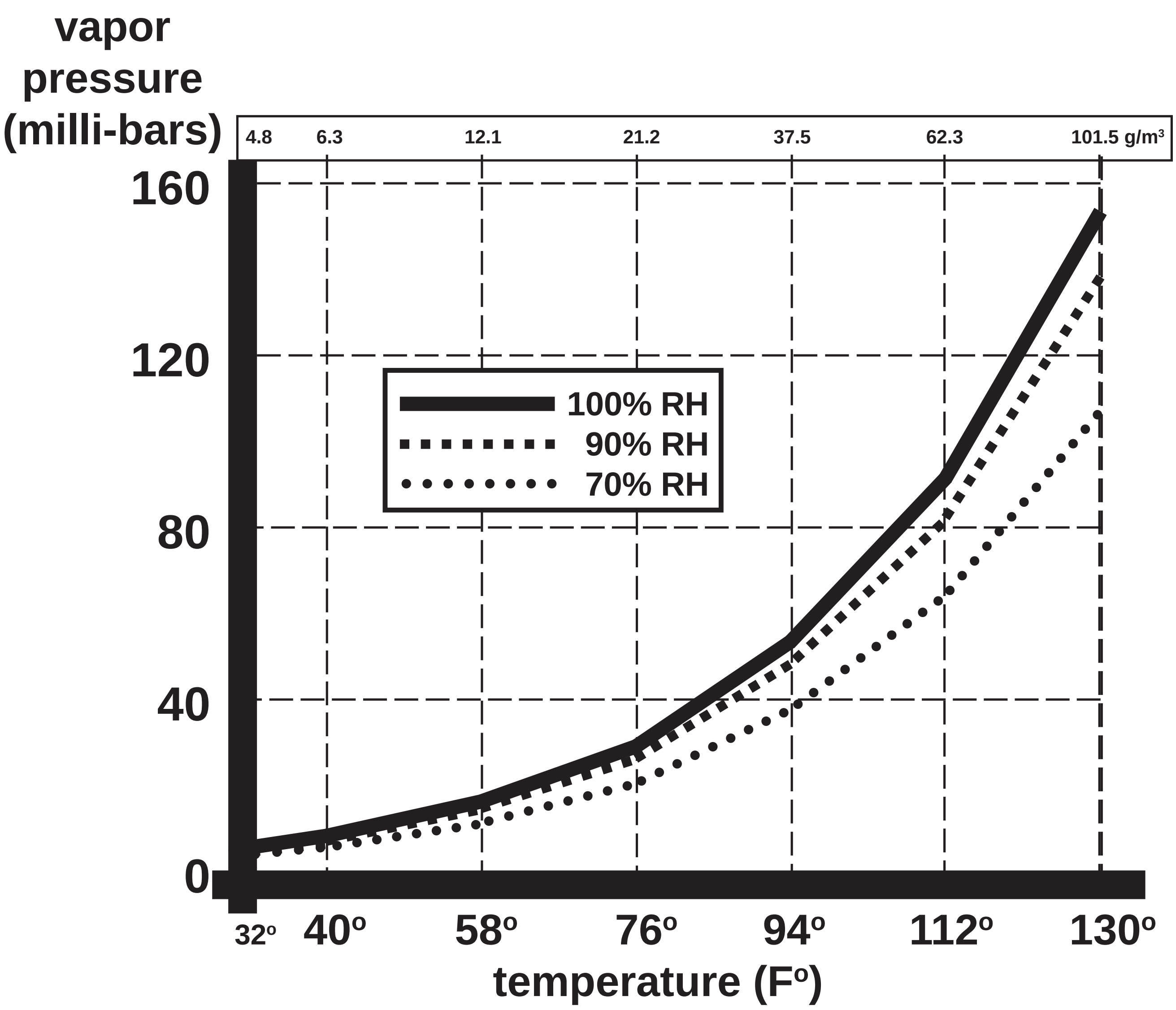


Figure 4: Saturated vapor pressure of water in atmosphere (100% relative humidity), the most water vapor normally found in air above liquid water. Also shown are 90% and 70% relative humidity (RH). The box over the graph contains the amount of water (vapor density in grams per cubic meter) in air for each temperature. (value approximations derived from Tabata, 1973)

between vapor pressure and air pressure). Temperature and air pressure are key components governing evaporation and boiling.

Water moves from areas of high concentrations to areas of low concentrations -- from more moist to less moist. In a tree, water evaporates from the moist inner leaf surfaces, and escapes from the stomates and tree surfaces into the dry air. Even at very high relative humidity levels in the atmosphere, trees lose water because the atmosphere is chemically dry. For example, air at 98% relative humidity has a water potential which is more than 100 times drier than the internal leaf surface. Except under fog conditions (100% relative humidity), trees are always losing water to a dry atmosphere. Table 2. As temperatures increase during the day, relative humidity plummets making the drying force of the atmosphere much greater. Figure 5.

Tensile Strength

Water is strong under tension (not to be confused with surface tension!). The force needed to pull water apart is substantial (theoretically pure water can sustain -300 bars of tension). Water in small tubes can sustain tension forces approaching 8% the tensile strength of aluminum or copper wire. Maximum tensile forces applied to water show up to 30% of the hydrogen bonds are positioned and participate in tension loading. Unfortunately, many things negatively impact the tensile strength of water.

In trees, cell wall materials, the diameter of the xylem water column, the amount and types of dissolved materials present, and discontinuities in the semi-crystalline structure of the water around H+ and OH- groups will all lower tensile strength in a water column. Water from the soil will have dissolved materials which will affect tensile strength. Dissolved gases, when put under a negative pressure (tension in a water column), can come out of solution and form a bubble. Once a bubble is formed, it can expand and contract eliminating tensile strength of the water column.

Tiny Bubbles

Gas bubble formation in tree xylem water columns is called cavitation. As temperatures rise and tension in the water column increases, more gases will fall out of solution and form small bubbles. These tiny bubbles may gather and coalesce, “snapping” the water column in two. As temperatures decrease, water can hold more dissolved gasses until it freezes. Freezing allows gases to escape, potentially cavitating water conducting tissue when thawed. Trees do have some limited means to reduce these cavitation faults.

Energy Changes

The “heat of fusion” is the energy required to change an amount of solid water into liquid water at its melting point. Water’s heat of fusion is 80 calories per gram. This energy does not change the temperature of the water but breaks approximately 15% of the hydrogen bonds in the crystalline ice which then melts into liquid water. The transition from ice at 32^oF (0^oC) to liquid at 32^oF (0^oC) requires the addition of 80 calories of heat and initiates a decrease in volume and an increase in density of about 9%.

The “heat of vaporization” is the energy required to change an amount of liquid water into a gas at its boiling point. Water’s heat of vaporization is 540 calories per gram (5.4 times the energy needed to raise water temperature from 32^oF to 212^oF (0^oC to 100^oC)). There is no change in water temperature as this vaporization energy is absorbed because it is overcoming the hydrogen bonding in liquid water to generate vapor (steam). At 212^oF (100^oC), water in both liquid and gas phases exist. Steam is more reactive and energetic than liquid water because of the additional energy (5.4X more energy) accumulated by the molecules for vaporization.

Water is very stable as it is heated past its boiling temperature. The bonds between atoms in pure water remain intact beyond $3,630^oF$ ($2,000^oC$). Water can be decomposed into its component

Table 2: Estimated water potential (bars) of the air for various relative humidity values (percent) and temperatures (F^{o}) .

relative humidity (%)	air temperature (F^{o})				
	50^{o}	60^{o}	70^{o}	80^{o}	90^{o}
100	0	0	0	0	0
99	-13	-13	-14	-14	-14
98	-26	-27	-27	-28	-28
95	-67	-68	-70	-71	-72
90	-138	-140	-143	-145	-148
70	-466	-475	-483	-492	-500
50	-905	-922	-939	-956	-971
30	-1,572	-1,602	-1,631	-1,660	-1.687
10	-3,006	-3,064	-3,119	-3,175	-3,226

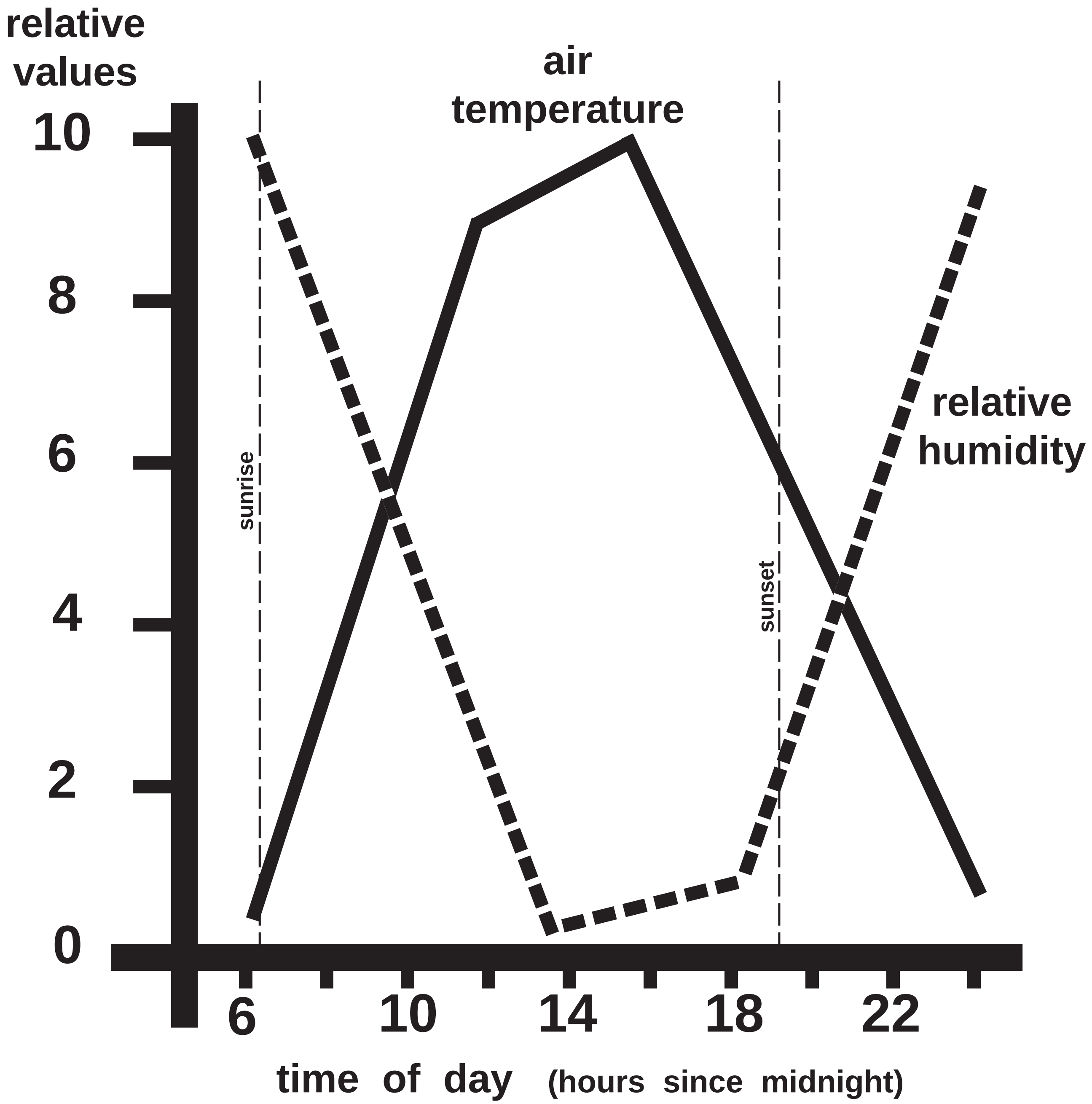


Figure 5: Relative value or measurement throughout a day for relative humidity and air temperature. Note the inverse relationship between temperature and relative humidity.

gases by adding small amounts of acid (H+) or base (OH-), and then running an electric current through the liquid. Pure water at a neutral pH (pH = 7) does not conduct electricity significantly.

On The Move

Water movement and its transportation of materials is essential to tree life. The three major forms of water transport are driven by diffusion, mass flow, and osmosis forces:

Diffusion – Diffusion operates over cell distances. Diffusion is the movement of dissolved materials from high concentration areas to low concentration areas. Diffusion can move a dissolved molecule in water across a cell in a few seconds. Diffusion does not operate biologically over larger distances. It would take decades to diffuse a molecule across a distance of one yard.

Mass Flow – Most water movements we visualize are due to mass flow caused by pressure differences. Wind, gravity, and transpiration forces initiate and sustain small differences in water pressure. These small differences drive water and its dissolved load of materials in many different directions. Because pressure is the driving force in mass flow, (not concentration differences as in diffusion), the size of the conduit is critical to flow rates. If the radius of the conduit is doubled, volume flow increases to the fourth power (X^4) of the size increase. For example, if the conduit radius doubles, the flow rate increases by 16 times.

Osmosis – Osmosis is the movement of water across a membrane. Membranes in living tree cells separate and protect different processes and cellular parts. Membranes act as selective filters, preventing materials with large hydration spheres or layers from passing through. Small, uncharged materials may pass freely. The driving force to move materials in osmosis is a combination of pressure and concentration forces.

Biology

Water provides a solution and climate for specific biochemical reactions to occur. The structure or configuration of enzymes depend upon water’s structural support. In addition, many reactions and their associated biological catalysts are temperature sensitive. Water provides a constant temperature bath and a stable environment for life-functions. Water is also a component or product of some biological reactions.

For example, the photosynthetic system in a tree depends upon oxidation of water to provide electron resources needed for capturing light energy. The oxygens in O_2 gas released in photosynthesis are derived from water. The hydrogens from water are used as a source for chemical reduction of CO_2 captured from the air. Water provides electrons, hydrogens, and oxygen to capture light energy, make tree food, and produce oxygen!

Pump-Up Cells

Water is a good hydraulic fluid. It is non-compressible and low viscosity. Water is used to expand and hold tree cells rigid and erect (turgor pressure). Cell divisions generate individual units for expansion. Water pressure generated through osmotic changes in cells is used to push against the cell wall and expand cell dimensions (growth). Water expands and holds the cell at its new dimensions until cell wall fibers and lignification constrain expansion. The visible wilting and petiole drooping in trees during drought periods are derived from loss of cellular pressure because of water loss.

(Tree life is water and water is tree life!)

Soil / Water Environment

Trees are always undergoing dehydration-hydration (drying / wetting) cycles because the rate of absorption of soil water by roots lags behind the rate of transpiration from tree crowns. Trees dehydrate during the day, particularly on hot, sunny days. Trees will refill with water during the night. Trees obtain almost all of their water from the soil. Under some conditions other sources of atmospheric moisture in the form of dew or fog may prevent or postpone dehydration of tree crowns.

The rate of absorption of water by roots is impeded by: A) low soil moisture content; B) small or slow-growing root system; C) poor soil aeration; D) low soil temperature; E) poor soil-tree root contact; F) high concentration of materials in the soil solution (salts); and, G) combinations and/or interactions of A-F above. The water in soil consists of: (Figure 6)

1. **Gravitational water** = occupies large soil pores and drains away under the influence of gravity. It is available to trees but usually drains away too fast to be important.

2. **Capillary water** = the most important source of water for trees, is held in films around soil particles and in small pores between soil particles.

3. **Hygroscopic water** = water still remaining in air-dry soils held so tightly by soil particles that it moves only as vapor and is generally unavailable to trees.

4. **Water vapor** = water in the soil atmosphere as humidity which is not used directly by trees.

After a rain, the rate of water drainage through a soil decreases rapidly with time until it stops. When water drainage out of a saturated soil stops, the soil is traditionally considered to be at "field capacity." At field capacity, which is considered the upper limit of tree-usable soil water, capillary movement of water is slow. The lower limit of tree-usable soil water is traditionally considered to be the "permanent wilting point." The wilting point is the soil water content below which trees cannot extract enough water for survival. Note tree foliage can wilt for a number of internal and external reasons before the soil reaches the permanent wilting point.

Tree Available

Tree survival and continued success are dependent upon soil pore spaces holding a good mix of air and water. Appreciating how much water a soil can hold, and providing an adequate supply for a tree, is essential for good tree health care. Trees pull water from soil pore spaces. Soil texture is one of the many items impacting pore space and tree-usable water. Soil texture, the mix of different basic particle sizes in a soil, can be summarized by the percent clay, sand and silt present. Figure 7 provides a description of soil textures by name and composition. Note only clay and sand are shown here because silt would be the remainder. Figure 8 simplifies soil texture further by showing how each particle size classification dominates soil water relations. Note clay contents greatly impact soil water holding pore space.

In each soil, soil texture helps determine how many water holding pores (micro-pores) are present. Figure 9 provides the percent of water holding pores, at field capacity in uncompacted soils, are present compared with total soil pore space. Some soil pore spaces hold water more tightly than trees can exert force to remove the water. Figure 10 shows the amount of unavailable water held by soils with various textures. This water can not be pulled from the soil and into the tree through transpiration.

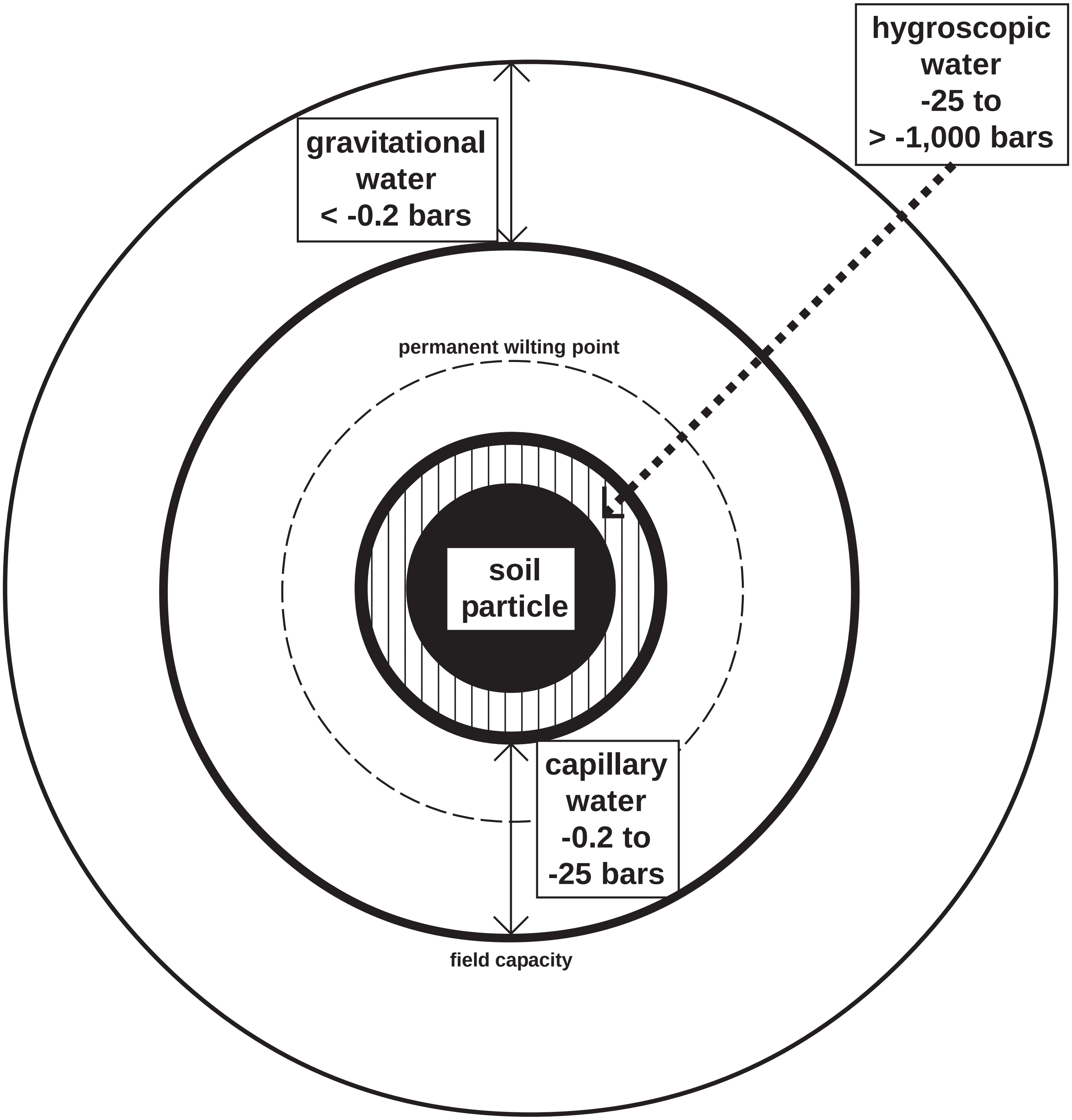


Figure 6: Idealized view of water layers surrounding a single soil particle. Tree available water is held loosely in the outer (low energy) areas as far inward as the wilting point level (dotted circle). Water closer than the wilting point cannot be extracted by a tree. (after Brady, 1974)

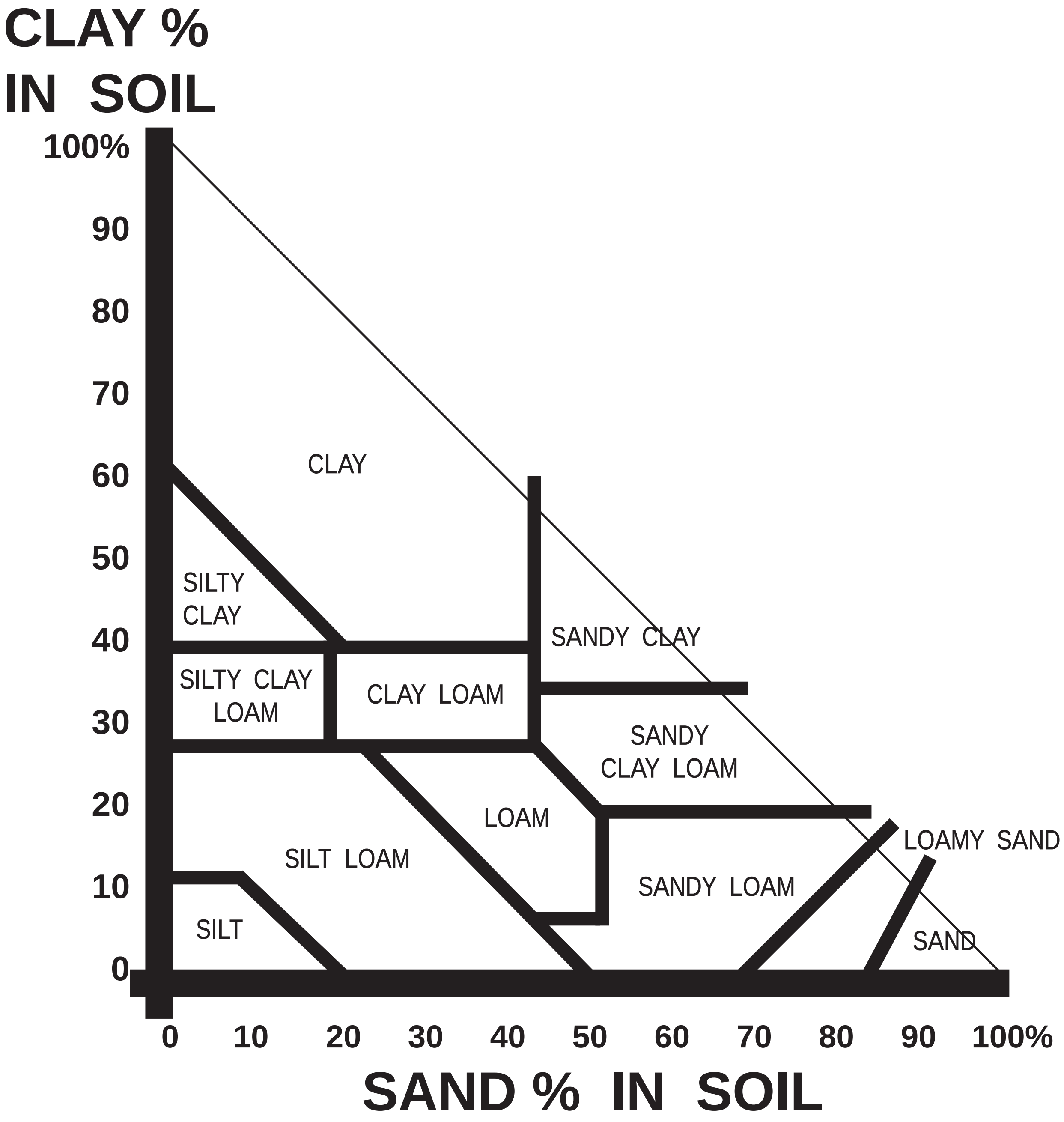


Figure 7: Soil texture types and associated particle size percentages of sand (large / coarse) and clay (small / fine). Silt is a mid-sized particle.

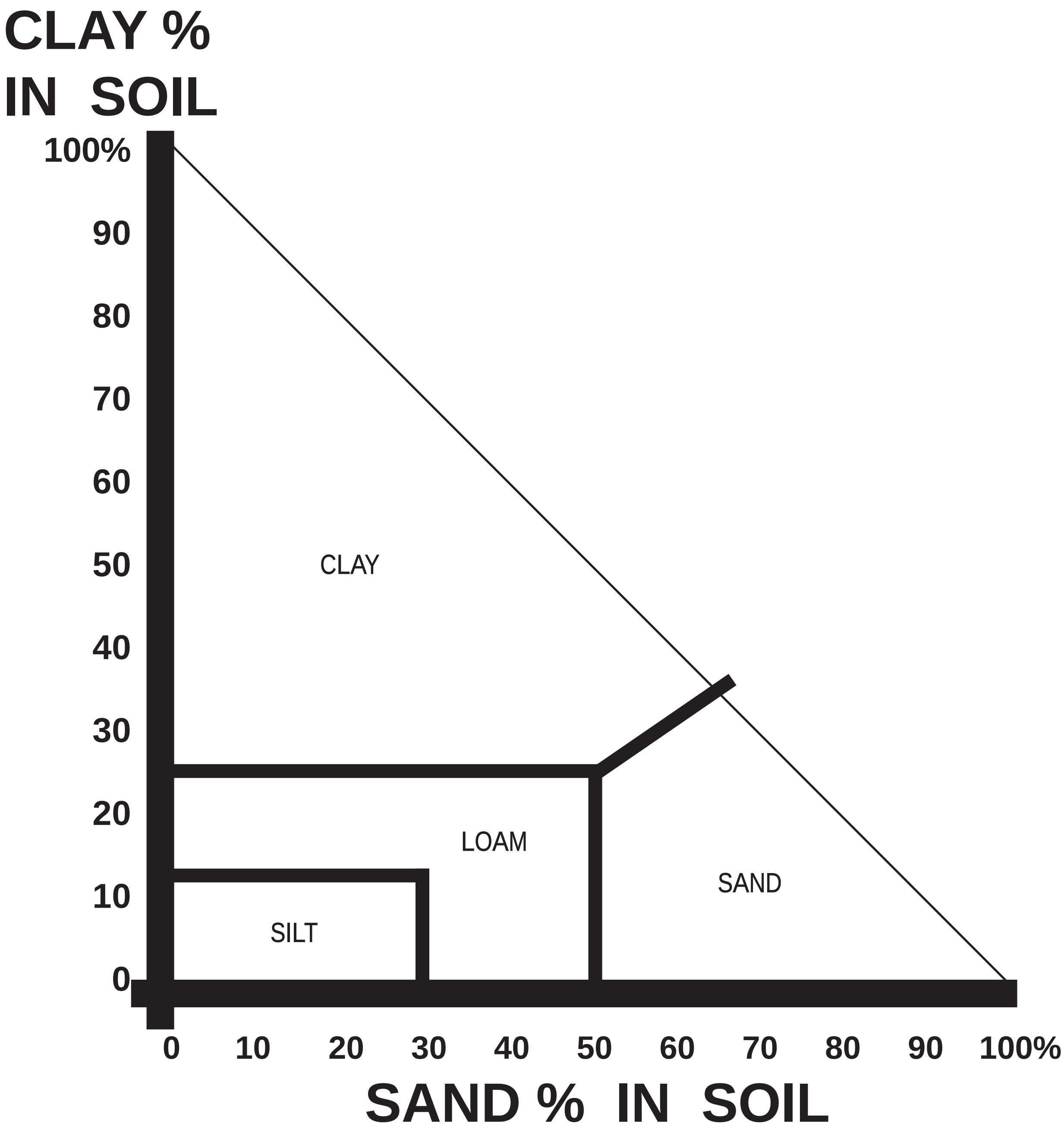


Figure 8: Dominance of chemical and physical water related attributes for soils with different particle sizes (textures).

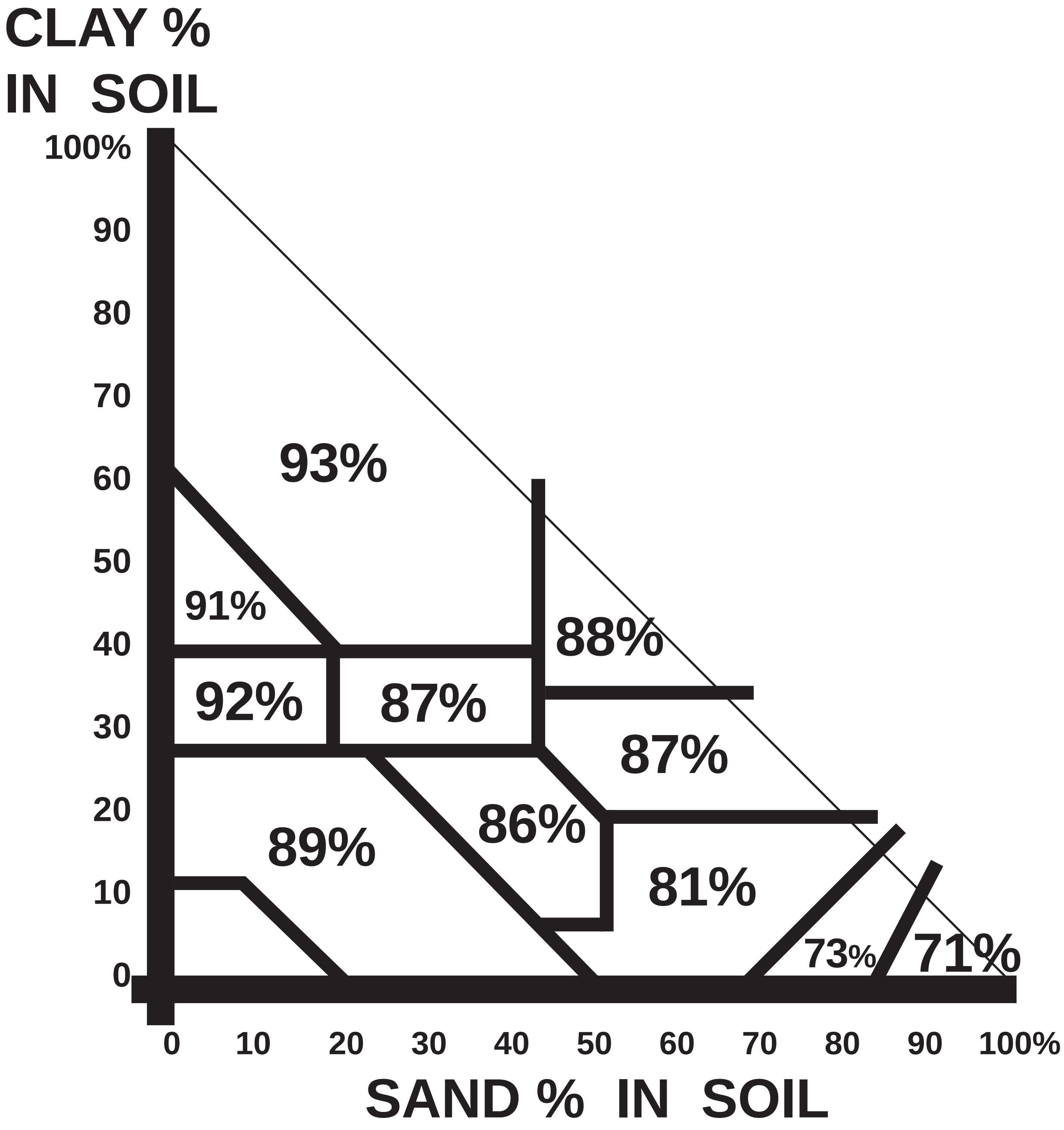


Figure 9: Approximate percent of water containing pore space (micropore) compared to all pore space in uncompacted soils of various textures at field capacity.

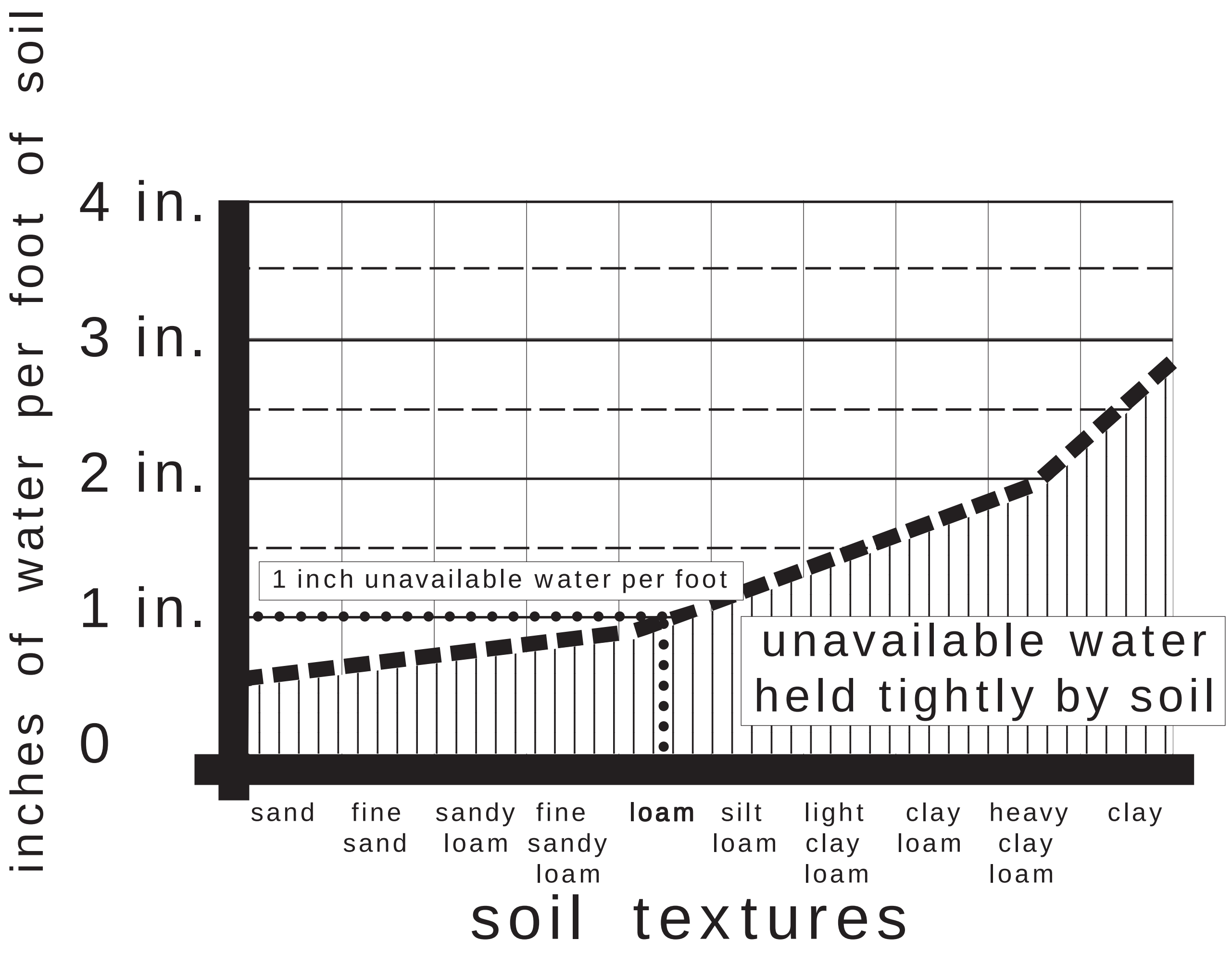


Figure 10: Unavailable water per foot in soils of various textures. The large dotted line represents the permanent wilting point. (Small dotted lines are an example from text.)

Figure 11 shows the total amount of water which could be held against gravity in a soil (saturation not flooded). This concentration of soil water is the most water a soil can hold without any water draining away. The soil is said to be at field capacity. Figure 12 shows the total amount of tree-available water present in soils of various textures. Subtracting Figure 10 from Figure11 produces Figure 12. In Figure 12, the top line on the graph is the total water in a soil. The bottom line on the graph is the amount of water unavailable to a tree due to soil surfaces and pore spaces holding water too tightly, and to trees not being able to generate enough force to remove water from the soil.

Drops To Drink

For example, a tree's roots occupy an area of loam soil three feet deep. Use Figure 10 to determine the total unavailable water in loam soil which is given as 1 inch of tree unavailable water per foot of soil depth, or 3 inches of water are unavailable for tree use in the whole three feet deep loam soil. Use Figure 11 to determine the total amount of water per foot in a loam soil which is 3.1 inches of water, or 9.3 inches of total water in loam soil three feet deep. The shaded area of Figure 12 shows the inches of water available for tree use per foot of soil.

In this example, Figure 12 = Figure 11 minus Figure 10, providing the answer of 2.1 inches of tree-available water per foot of soil, or 6.3 inches of tree-available water in loam soil three feet deep (2.1 inches X 3 feet soil depth). If evapotranspiration from a site is estimated to be 1/3 inch of water per day, 18.9 days (~19 days) of tree-available water would be present in a loam soil three feet deep with 1/3 inch of water loss per day from evapotranspiration.

Soil Water Movement

When a soil is wet, the rate of water movement and absorption by tree roots can be great, if the soil is well oxygenated. Resistance of wet soil to water movement is low because only small forces are necessary to pull water through water-filled pores. As soil dries the resistance to water movement increases in the soil and in the tree. Water movement becomes a problem because soil-root contact is lost from root shrinkage while resistance to water movement increases due to root suberization and compartmentalization. Pathways for water movement in the soil become thin and convoluted, with many water connections narrow and broken. Soil hydraulic conductivity (inverse of resistance) falls as the amount of fine texture particles in soil increase. Table 3.

Water in the portion of the soil that is not permeated by roots is largely unavailable for absorption. Capillary movement of soil water from more wet to dry regions in soil with a moisture content below field capacity is slow. Soil immediately surrounding tree absorbing roots dries rapidly. Continuous root extension into zones of moist soil is critical for sufficient absorption of water to replace water lost by transpiration.

A small portion of the tree-available essential elements are present as ions dissolved in the soil water solution. Most of the cations are near the surfaces of clay and humus / organic material particles because of electronic charge attraction. Anions like nitrate, bicarbonate, phosphate, sulfate, and molybdate, can be found near organic materials having anion exchange sites. Phosphorus and potassium do not move far in a soil. Tree roots must continue to "mine" the soil.

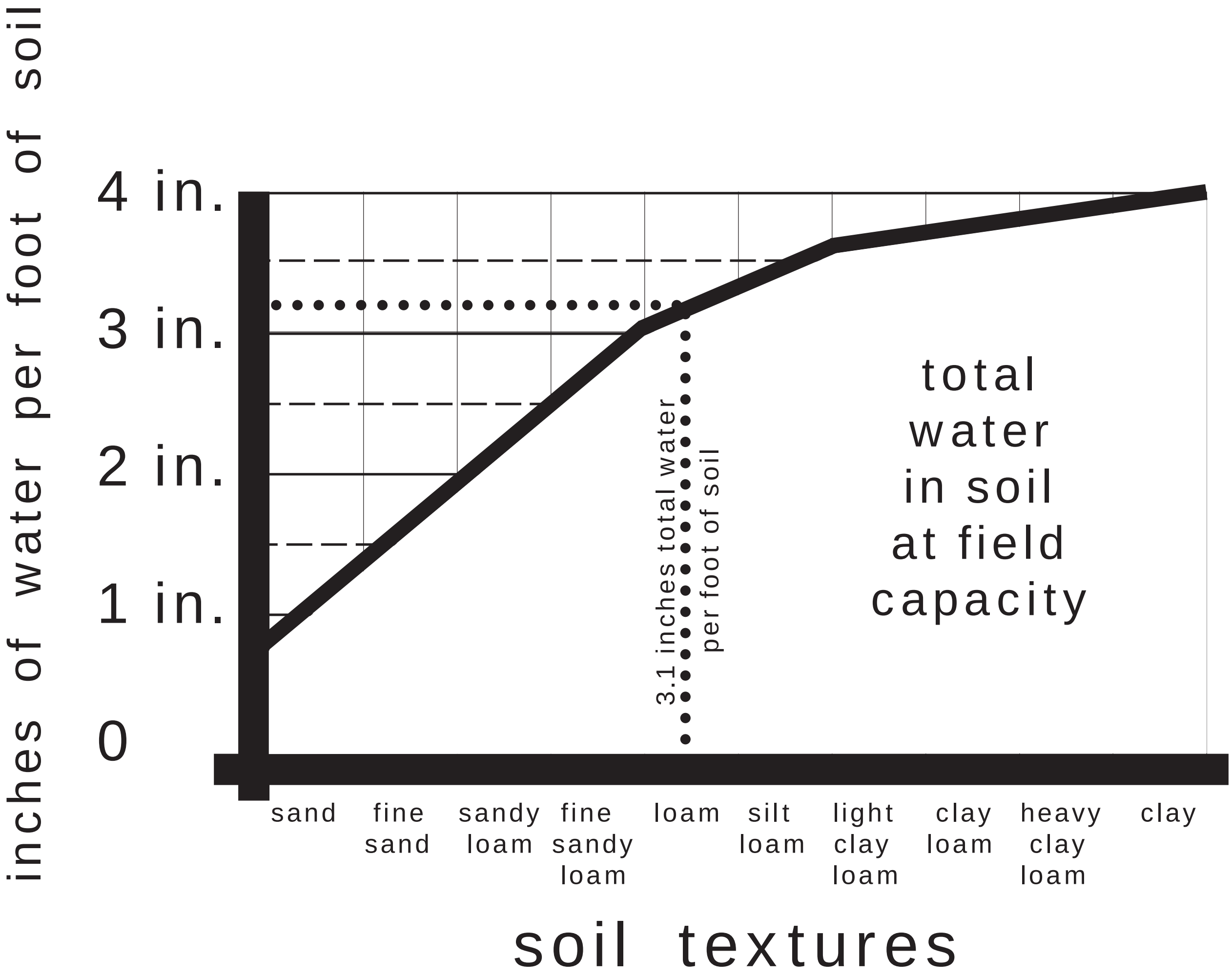


Figure 11. Total water held in soil against the pull of gravity (field capacity) for various soil textures. (Small dotted lines are an example from text.)

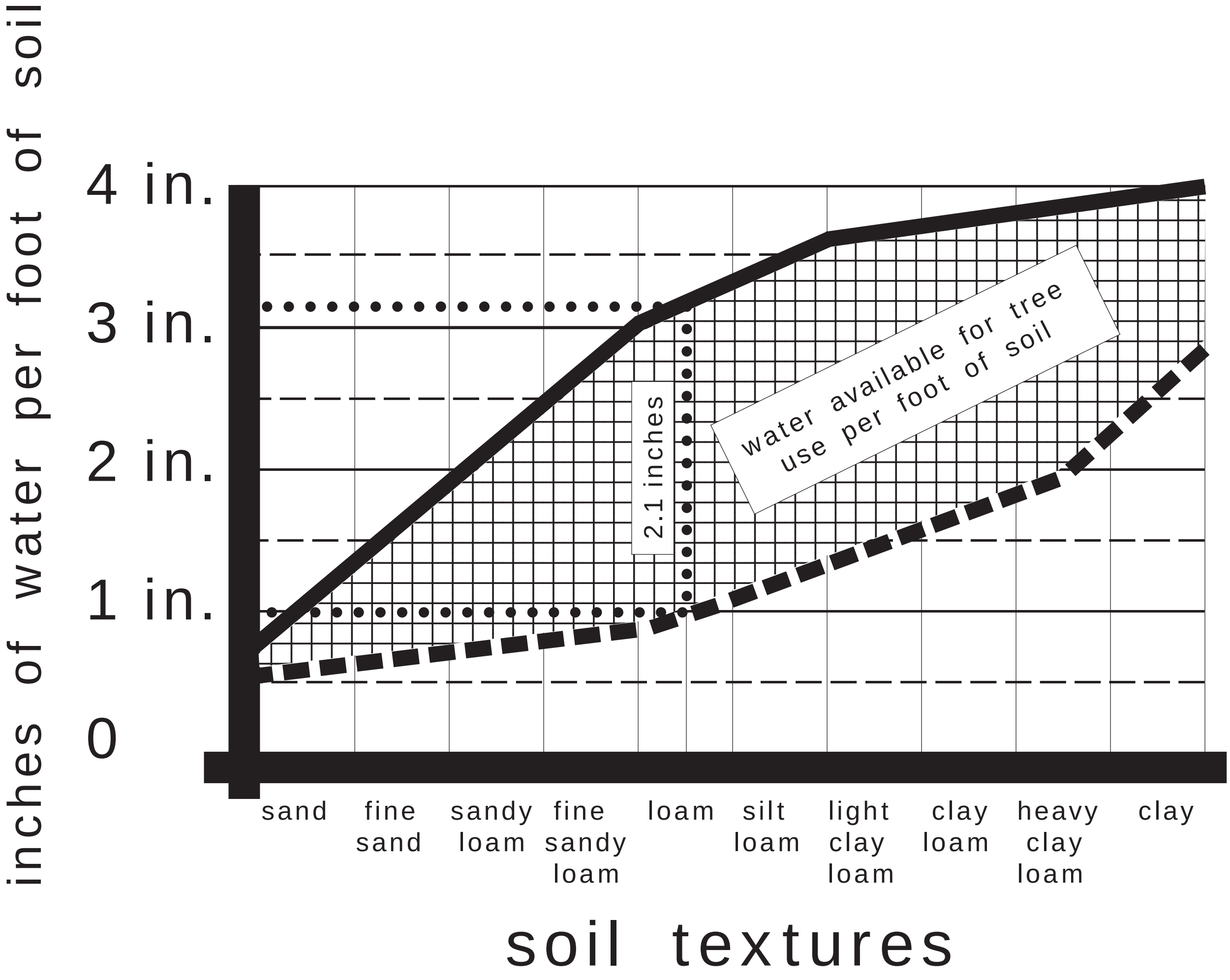


Figure 12. Difference between total water at field capacity and unavailable water held by soil. (Figure 10 subtracted from Figure 11). (Small dotted lines are an example from text.)

Table 3: Saturated hydraulic conductivity of soils with various textures. Note soil structure plays a strong role in aeration and water conductivity in soil but is not considered here.

soil texture	hydraulic conductivity (inches per hour)
sand	8.3 in/hour
loamy sand	2.4
sandy loam	1.0
loam	0.52
silt loam	0.27
sandy clay loam	0.17
clay loam	0.09
silty clay loam	0.06
sandy clay	0.05
silty clay	0.04
clay	0.02

Water Use

A tree allocates life-energy to survive and thrive in an environment which never has optimal resources. What essential resources are present are usually present in too low, too high, or unavailable concentrations. Trees continue to react to environmental changes with internal adjustments selected for efficient use of tree food and water, while minimizing energy loss to the environment.

The more limiting essential resources become, (i.e. the larger tree energy costs), the greater the stress. Trees only have a limited set of responses to any stressful situation as directed by their genetic material. Trees can only react to water problems in genetically pre-set ways. The eventual result of site limitations and stress like drought, will be death. Effective management, damage control, and minimizing drought stress can provide for long tree life.

Spell "Essentiality"

All life processes of a tree take place in water – food making, food transport, food storage, food use, and defense. Water is a reagent in chemical reactions, a chemical bath for other reactions, a transporter, a hydraulic pressure liquid, a coating, buffer, and binder. Water is a universal liquid workbench, chemical scaffold, and biological facilitator. Water comprises 80% of living tree materials. As such, water is aggressively gathered, carefully guarded, and allowed to slowly escape in exchange for work energy within a tree. Of all the resource components of stress impacting tree survival and growth, water stress is the most prevalent. The largest single use of water in a tree is for transport of essential materials from roots to leaves.

Pulling Bonds

Water has an affinity for sticking closely to other water molecules. Because of electrostatic forces among the oxygen and hydrogen atoms in water, one side of the water molecule carries a partial positive charge (the hydrogen side) and one side carries a partial negative charge (the oxygen side). These polar charges cause water to stick together unlike other molecules of similar size. This property allows drops of water placed on a wax (hydrophobic) surface to bead-up rather than flattening out and cover the surface. In this case, water would rather stick to other water molecules than to the waxed surface. Using your finger, you can "pull" water droplets over the waxy surface and consolidate them into larger drops.

Trees utilize water's special chemical features in many ways, most noticeably in transporting materials from the soil, into the roots, and then on to the leaves. Water in a tree is pulled through thousands of long columns or tubes, located around the outside of the tree stem in the last few annual increments. These long columns of water (inside dead xylem cells) are functionally continuous between the source of the water (the soil) and the leaves. Water is pulled in long chains into the root, up through narrow xylem columns or channels, and to the leaf surface where it evaporates into the perpetually dry air. Water evaporates as bonds between molecules are broken at the liquid water / air interface in the leaf.

Sticky Evaporation

As one water molecule is exposed at the wet internal surface of a leaf, it is still bound to surrounding water molecules. Because of the temperature (sensible heat or energy) and humidity in the atmosphere, water molecules are pulled away from the wet leaf cell wall surfaces. This is called evaporation. The pull (water demand or deficit) of the air has enough energy to break water connections between water molecules, and at the same time pull neighboring water molecules onto the surface. These water molecules, in turn, evaporate into the air generating an evaporative "pull" at the wet leaf surface measurable down through the water columns to the roots and into the soil.

Water in a tree is a tightly connected stream moving from the soil pores and surfaces, into the root, up the stem, out to the leaf surface and into the air. The water molecules in a continuous line are held together by water's affinity for sticking to other water molecules. This "stickiness" allows water to be pulled to the top of the tallest of trees against gravity, conduit resistance, and pathway complexity. This transport pathway and process is called the "transpiration stream." Living cells surrounding this xylem pull system assist with monitoring the transpiration stream.

Holiday Traditions

The faster evaporation from leaf surfaces, the more energy exerted to pull water to the leaf. Too much exertion, and the continuous line of water molecules with billions of interconnections, break and are pulled apart. Water column breakage (cavitation) can be catastrophic for a tree because once broken, transport stops. Too much resistance in the soil or too rapid (high energy) evaporation at the leaf, can quickly snap ascending water columns.

For example, many people bring cut trees and evergreen foliage into their house during Winter holiday observances. Most houses have relatively low humidity and the interior cut tree or foliage dries rapidly. Usually, after many well-meaning rehydration treatments (waterings), people give-up and finally discard the once living tissues. While a tree is in the house, faint clicks or pops can be heard on quiet nights coming from inside the tree crown. These noises are not caused by vermin brought in with the tree, but by water columns snapping inside the stem due to severe dryness. Some tree drought indices quantify severity using microphones to count snapping water columns.

Communicating Stress

As water moves from the soil through the roots and into the leaves, it carries with it essential elements, nutrients, and chemical messages. As water and elements move from root to shoot, growth regulators (cytokinins) are added by the roots and by neighboring cells along the water columns. Through this chemical communication link, shoots of a tree can react to the status of roots. Shoots can then produce their own growth regulator (auxin) and ship it along living cells to the farthest root tips. Organic growth materials are also added by the roots to the transpiration stream. Any nitrogen captured by the roots is processed into amino acids within the roots using carbon captured by the leaves. These amino acids are transported in the water stream to the leaves. Shoots of a tree continually update growth processes in response to root functions, and roots continually modify life processes in response to shoot functions.

CO2 vs. H2O

In addition to growth regulation signals providing environmental supply and demand information in a tree, leaves have an additional environmental sensor. Leaves are the focus of the evaporative load on water columns throughout the tree. Leaves can close or open leaf valves (stomates) used for taking in carbon-dioxide gas required in photosynthesis to make food. A diagram of stomates on the underside of a broad leaf is shown in Figure 13.

Note the epidermis cells (leaf surface cells) are covered with a waxy cuticle to minimize water loss. When the stomates are closed, the cuticle and the stomates have roughly the same resistance to water loss, assuring that neither the stomate guard cell area or the cuticle is over-engineered. When the stomates are open, resistance of the cuticle to water movement averages more than 25 times greater than the stomate.

When stomates are open, carbon-dioxide can move into the leaf, but water rapidly evaporates and escapes the leaf. For average conditions in a yard tree, 5-10 water molecules evaporate from the leaf for every one (1) carbon-dioxide captured. In other words, a lot of water is transpired for small

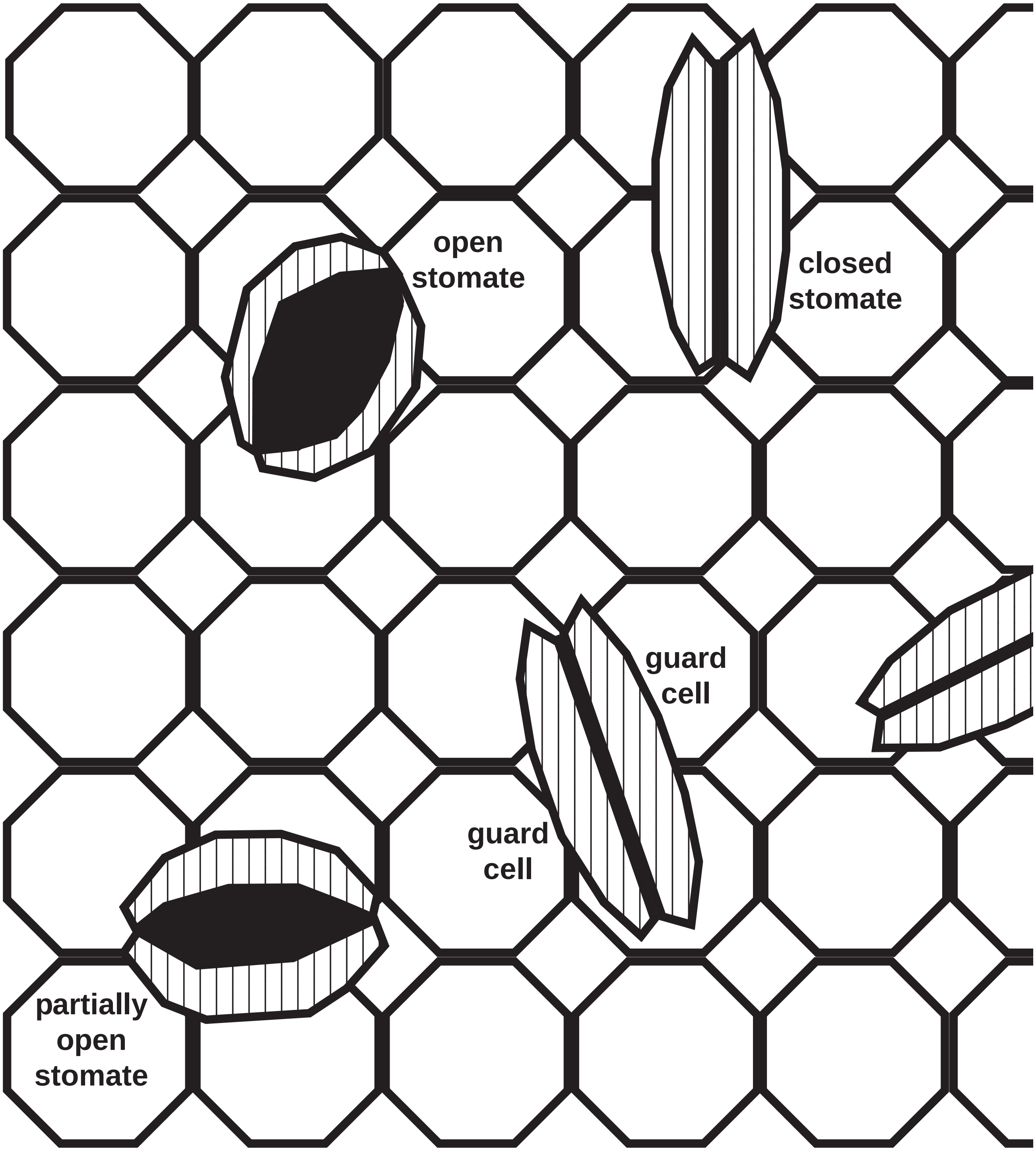


Figure 13: Idealized diagram showing open and closed stomates on underside of a tree leaf blade. The geometric pattern background represents leaf epidermis cells covered by a waxy cuticle.

gains in food making carbon atoms. The more food made for the least water used is called "water use efficiency" (WUE) and is used to compare water demand by different plants. As water availability declines, leaves sense and respond by closing down stomates and photosynthetic processes.

Measuring Potential

Water is measured inside tree cells using a construct called "water potential." Water potential is measured in many ways and using many different units of measure. Table 4 provides a number of different water potential (pressure) measurement units found across the scientific literature. Here the use of bars of pressure will be used. Water potential is an estimate of the energy in water to accomplish work, like moving materials or inflating cells for growth.

A simplified way of understanding water potential is illustrated in Figure 14. Figure 14 shows a gradient of energies from water in and around a cell. Water brought into a cell causes it to either swell like a balloon and changes volume, or as in tree cells with a solid cell wall, pressure inside the cell increases. Increasing pressure means increasing energy to do work (positive water potential or pressure). As water is removed from a cell, the cell membrane can either collapse away from the wall changing volume (deflating), or the cell can exert a pull on water in the area to move it into the cell. Increasing pull on water inside a cell generates a negative water potential or tension.

Swelling Or Drying

Water potential in trees has two primary components, an osmotic tension and a turgor pressure. The osmotic tension is usually negative and is caused by water being attracted to and held around small compounds within the cells. A clump of starch in a cell is large and has a relative small hydration sphere or coating layer of water. If the individual component of the starch is broken apart (i.e. sugars), the amount of water needed to form hydration spheres around each sugar is increased geometrically and is immense, demanding much more water. This process pulls water into the cell.

The turgor pressure in a tree cell is usually positive caused by outward pressure from within the cell. Cells use energy to bring in more water and hold it in order to generate internal pressure for cell growth or to keep the cell fully expanded. Turgor pressure in a fully turgid cell is equal to the osmotic tension in the cell. When turgor pressure is no longer positive, the cell no longer fully occupies its cell wall space and is flaccid.

Example Potential

For example, in the morning of a bright sunny day during the growing season, water loss through transpiration begins. This causes a drop (becoming more negative) in leaf cell water potential. Turgor pressure drops causing total water potential to drop. This tension from lower water potential generated by transpiration in the leaf initiates a gradient of water potentials from the air surrounding the leaf through the tree to the soil. Water will continue to move from higher pressure zones (more positive water potentials) toward lower pressure zones (more negative water potentials) by tension pulling water along. Figure 15.

Increasing Tension

As water potential concepts demonstrate, water is pulled up to the tree tops and the resistance to soil-water movement increases (uptake slows), a tension or negative pressure develops in the water columns. Water continues to move from relatively low tension areas (like soil at field capacity), to the high tension areas of rapidly evaporating leaf water. Because of the effectiveness of stomates in evaporating water, leaves can loose water faster than roots can pull water in from the soil. As leaf water loss continues to exceed root water uptake, greater tension develops in water columns, and a water deficit begins to build.

Table 4: Different units for measuring water potential in trees from the scientific literature, both old and new. This publication will use the older pressure unit measure called "bars."

units of measure		bar	atmosphere	pds-force/in^2	pascal	megapascal
1 bar	=	1	0.9869	14.504	100,000	0.1
1 atmosphere	=	1.0133	1	14.696	101,325	0.10133
1 pounds-force/in^2	=	0.069	0.0681	1	6,894.8	0.0069
1 pascal	=	0.00001	0.00001	0.00015	1	0.000001
1 megapascal	=	10	9.869	145.04	1,000,000	1

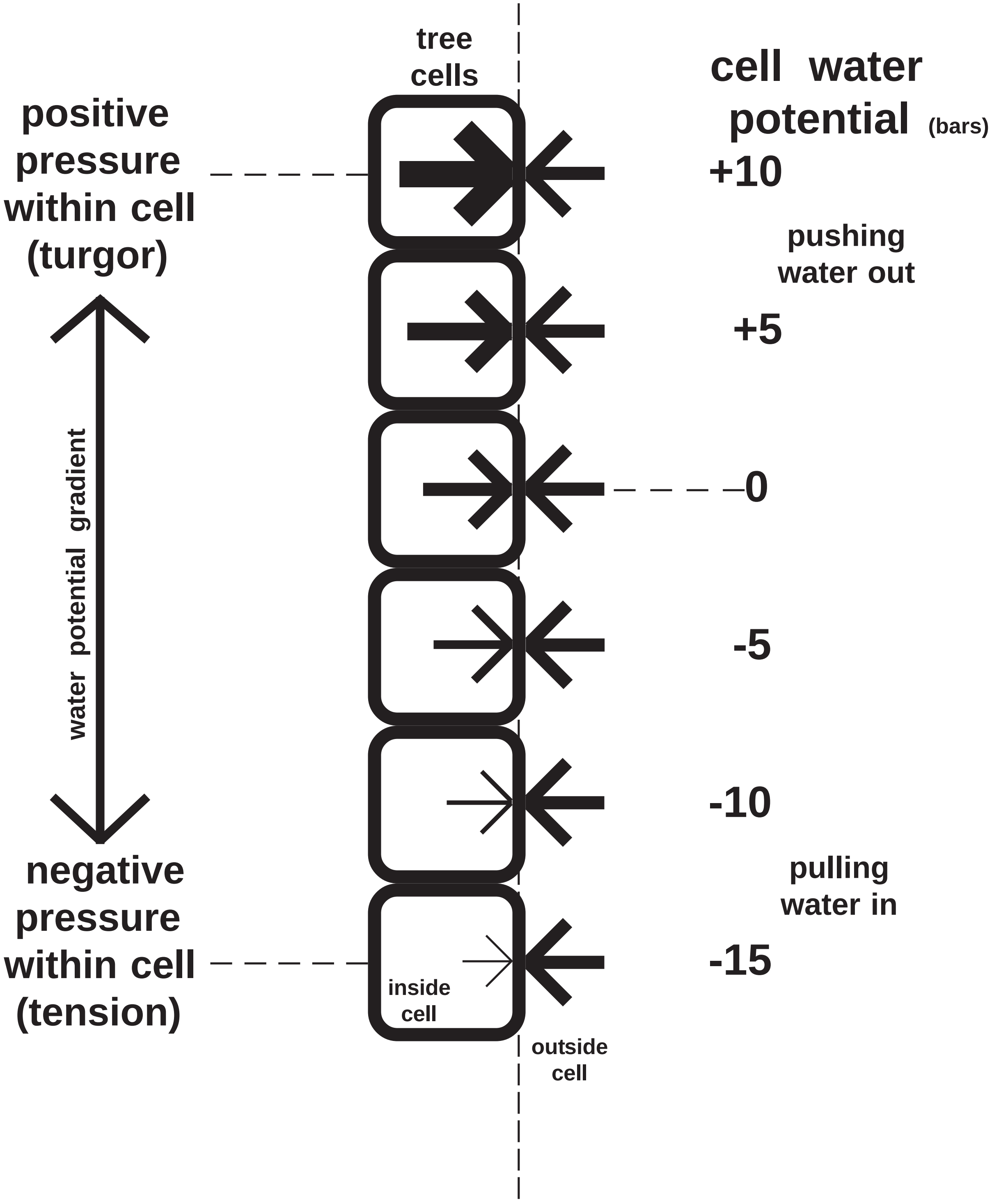


Figure 14: Simplified view of water potential gradient from pressure (positive water potential) to tension (negative water potential) within tree cells.

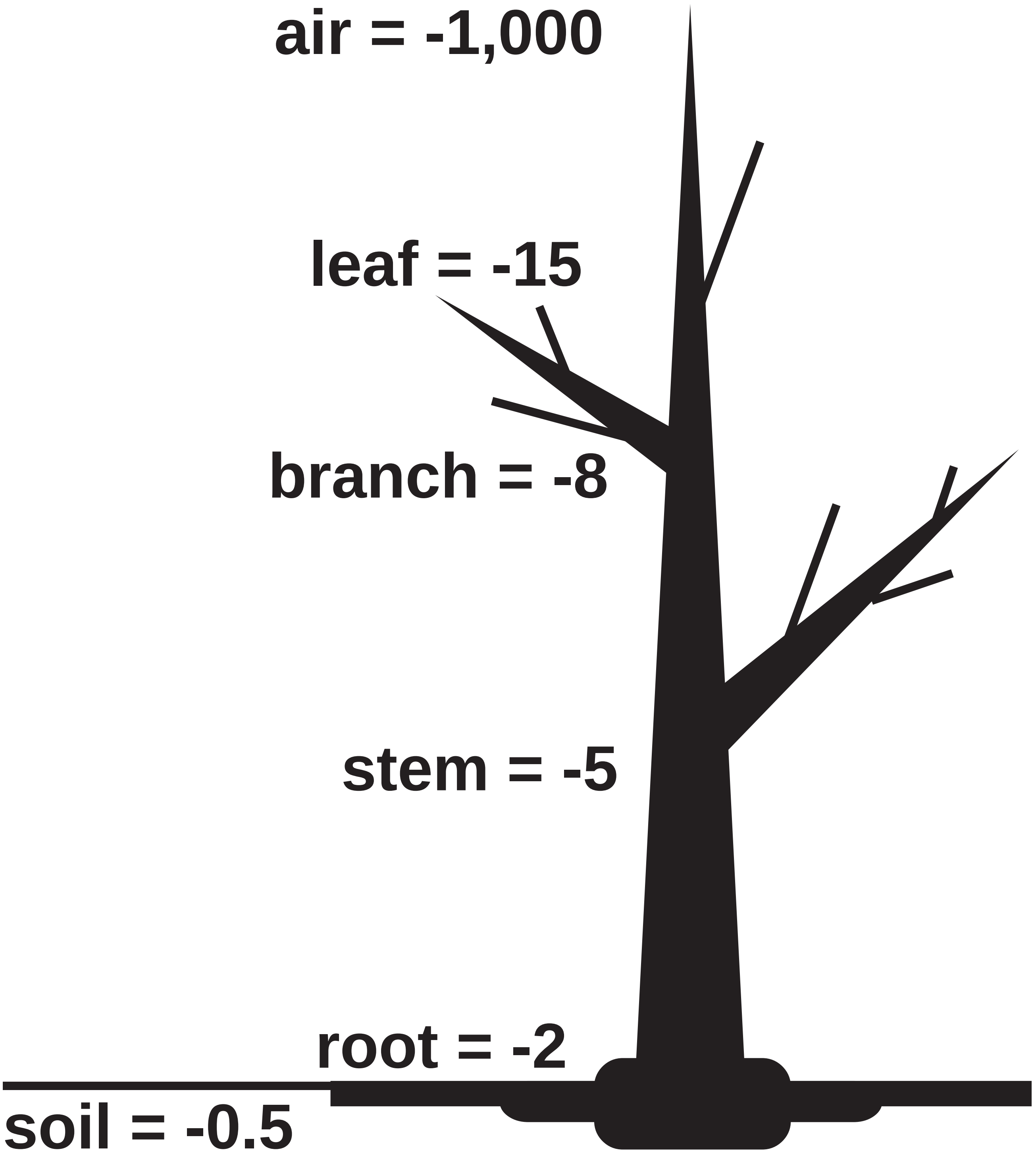


Figure 15: Example water potentials in bars from the atmosphere to the soil through a tree. Water moves (is pulled by tension) from more positive water potential regions (the soil) to more negative water potential regions (the leaf).

When the water deficit becomes too great, stomates are closed until water uptake in roots catch-up. When stomates are closed, no carbon dioxide can get into the leaf and the tree cannot make food to feed itself. As water in the soil becomes increasing scarce, the transpirational pull energy in a tree becomes greater. The whole tree dries as water is pulled away from various tissues. Cellular machinery is shut-down and damaged, as water loss becomes progressively greater. As soil dries, the tree water conduction system is under tremendous tension. Figure 16.

Rubber Bands

To visualize water movement and water column tension in a tree, think of a rubber band. The more you stretch one end of a rubber band, the tighter the band becomes, similar to water columns under transpirational pull. If you stop pulling on one end of the band and release the other end, the energy in the band will snap it back. If you hold both end of the band and pull too hard, the band will break.

The transfer of the rubber band model to water movement in a tree is easy. As the stomates lose water, the water columns are pulled tighter and tighter down the tree and out into the roots. If the stomates close and stop adding more tension on the water column, the roots can continue taking in water pulled by the tension remaining in the water column. If the soil is dry and the transpirational pull too great, the water columns snap or cavitate, preventing any more water movement in the cavitated water column. The only way to reduce water column tension in a tree is to close all the stomates (and prevent any other surface evaporation), or to apply water to the soil.

Water Is A Drag

Water movement and evaporation is a function of temperature and energy in the environment. The evaporative pull from leaf surfaces move water from around soil particles and into the root. Water is not moved in a tree by “pumping,” “suction,” or “capillary action.” Water in trees moves by sticking together and being dragged to the leaf surface where evaporation through the stomate (transpiration) generates a “pulling” force on the water columns. Water also evaporates from all tree surfaces – buds, bark, lenticels, fruit, etc. – but leaves have the only significant tree-controlled system for modifying water loss.

One way of thinking about water movement through evaporation is to visualize a tall glass of water with a wick or sponge. The water will be pulled into the sponge and into the air by evaporation across a large surface area. The evaporative force to move water through a tree is generated by the dryness of the air. The ability of the air to evaporate water depends upon the water content gradient between the air and leaf surface. Normal range of the water content gradient over which tree growth occurs is -0.1 to -15 bars. Drought conditions and damage occurs in the leaf as it approaches -15 to -20 bars.

Sultry

The gradient between the internal leaf atmosphere at 100% relative humidity (0 bars) and the atmosphere can be great. For example, fog is a condensate occurring around 100% relative humidity, while summer rain downpours range from 90% to 98% relative humidity. Trees can lose water even during rain storms because at 99% relative humidity, the air is 100 times drier than the inside of a leaf. Trees are always losing water. See previous Table 2.

The soil, soil/root interactions, vascular system, and leaf all provide resistance to water movement. Increased resistance to water movement makes water less available at the leaf. Water movement resistance is based upon the surfaces and structures which water must move through. The engine that powers water movement in trees is the dryness of the air and the associated rate of evaporation through the stomates. Anything that effects atmospheric demand for water, and stomate control of water loss rates, would affect water movement in a tree.

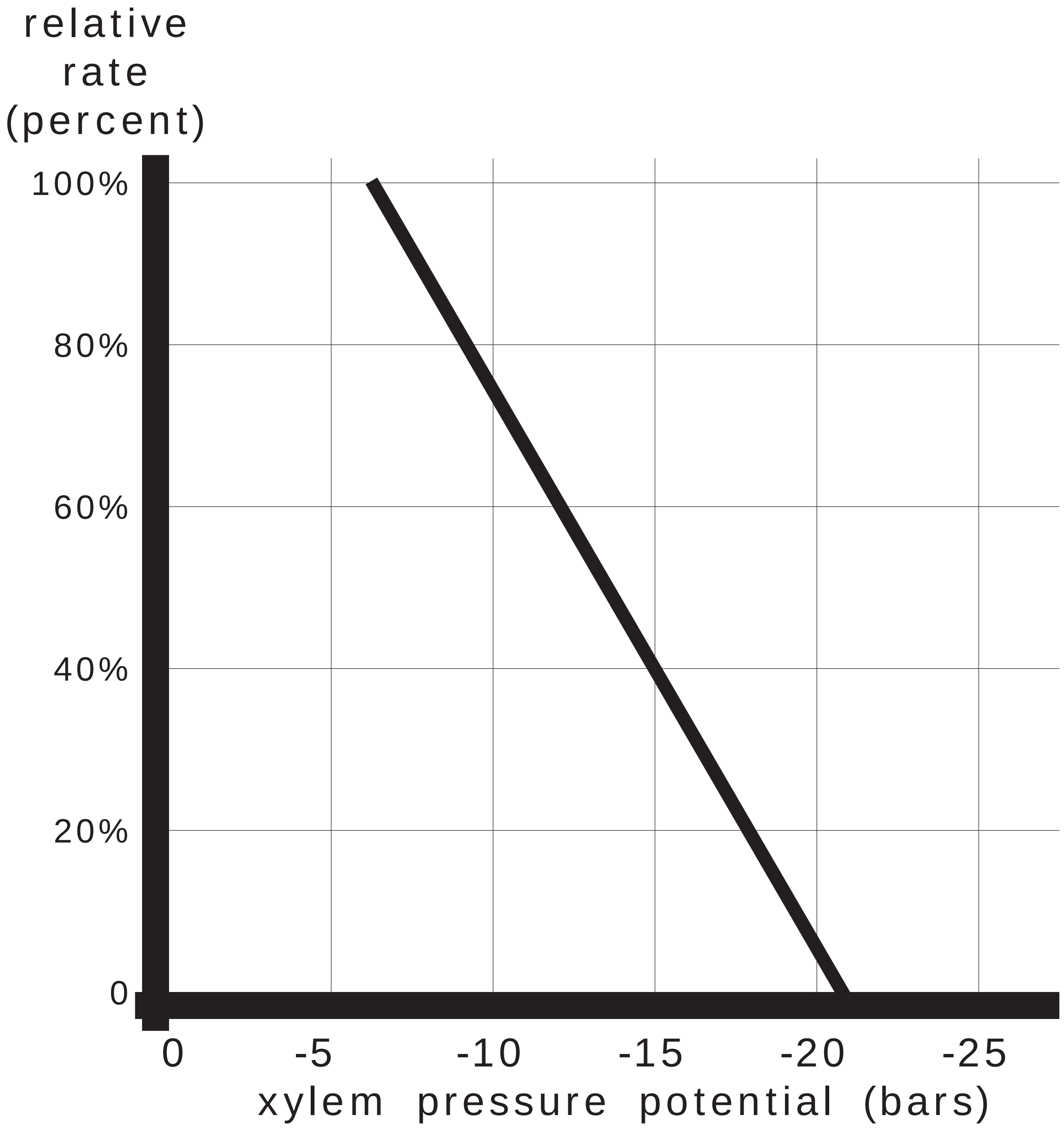


Figure 16: The relative rates of transpiration, net photosynthesis, and stomatal conductance all compared with xylem pressure potential in bars.
(from Teskey et. al. 1986)

Taking A Break

The consequences of water movement in trees produce two interesting results: siestas and night refilling. During bright, sunny, hot days when the sun is high enough from the horizon to cause stomates to open, transpiration increases until it out-runs the root's ability to keep-up. As water column tensions increase, a point is reached near mid-day when the tree closes many stomates on many leaves for several hours. The water column tension continues to pull in water from the soil and as tension values decline (water availability increases), stomates begin to reopen.

Many trees take siestas in the middle of the day to minimize water loss and improve resource efficiency. From about 12 noon til 2 pm stomates may be closed and no food produced. Figure 17. As root water uptake catches up with leaf losses, stomates open up in the afternoon and remain open until the sun is about five degree above the horizon before setting. In a well water and drained soil, stomates may not close at all. In a flooded soil, or soil with little water, stomates may remain closed for a greater part of the day. Under severe water stress, stomates may not open at all for days. In this case, trees must depend upon stored food for survival.

Night Moves

As the sun nears the horizon and night approaches, stomates close in trees. Because of the tension (stored energy) in the water column generated in the day, even after the stomates close and the sun sets, water continues to be pulled into a tree, reducing the water deficit (column tension). Water uptake continues through the night. Figure 18. Even though there is little evaporation at night because stomates are closed and the relative humidity is high, water is still moving from the soil and up into a tree. Night uptake by roots can amount to 20-40% of tree water needs if water is available. Just before sunrise a tree has pulled in the most water it can and is the most hydrated it will be all day. Because water is being pulled into the roots from the soil, and all the other plants in the area also are pulling water from the soil, tensiometers in the soil can measure the site's transpirational pull.

Stomates

Trees act as conduits through which soil water passes into the atmosphere. Instead of water evaporating at the soil surface powered by sunlight energy, a tree provides elevated surfaces for water evaporation and energy impact. All the movement of water in a tree is governed by evaporation from tree surfaces. A tree maintains one point of biological control of water movement called stomates. Stomates are tiny valve-like openings dotting the underside of leaf surfaces. A dissecting microscope is needed to see most stomates. In temperate trees (C3 Ps), the working stomates are on the leaf blade underside or running along the bottom of indentations on needles. Some tree leaves may have stomates on the upper side of the blade, but these are residual and do not function. Figure 19 is an idealized cross-sectional diagram of a broadleaf stomate.

By definition, a stomate is an opening in the leaf epidermis opened and closed by pressure differences in surrounding guard cells. Generically, stomates include the opening and the valve system components taken all together. Some stomates are protected with clumps of trichomes (tree hairs), some are surrounded with deposits of wax, and some are imbedded in pits or fissures deep into the leaf surface. These leaf openings are required in order for the tree to capture carbon-dioxide from the air to make food, but unfortunately, an open stomate which allows carbon-dioxide to enter also allows water to escape. Each tree has millions of stomates, which when open, are continually evaporating water and pulling water through the tree.

Water Guards

Two flaccid guard cells lay side-by-side covering the opening to the inside of a leaf. When these guard cells sense sunlight with their photosynthetic units, they begin to be pumped-up with

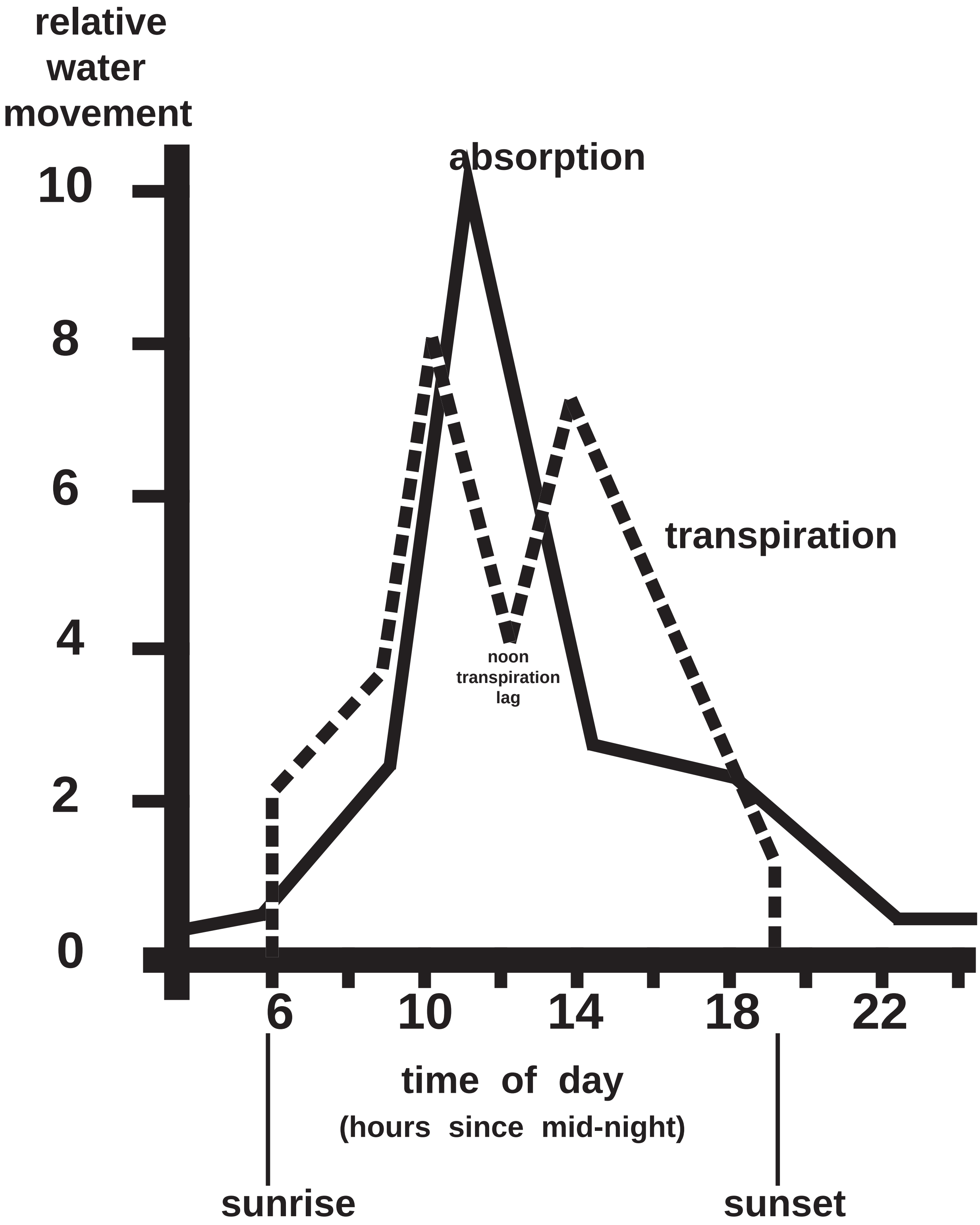


Figure 17: Root absorption and leaf transpiration within a tree and the relative amount of water being moved by each process. Note transpiration in leaves begins just before sunrise, is slowed at mid-day, and stops just before sunset. Root absorption continues through the night.

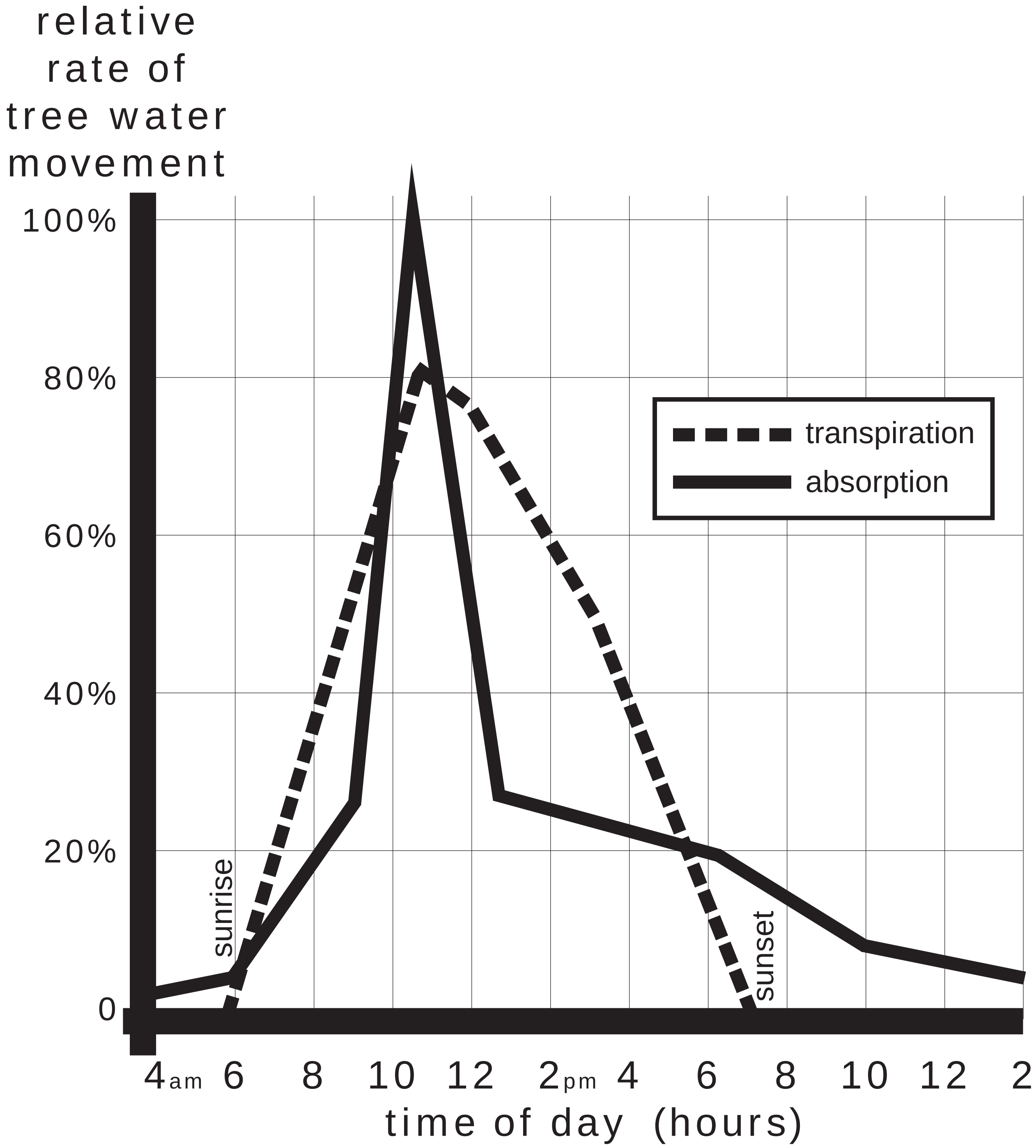


Figure 18: Another example of the relative rate of water movement from transpiration and root absorption within a tree over a growing season day under field capcity soil water conditions with no noon transpiration lag. (derived from Waring & Schlesinger, 1985)

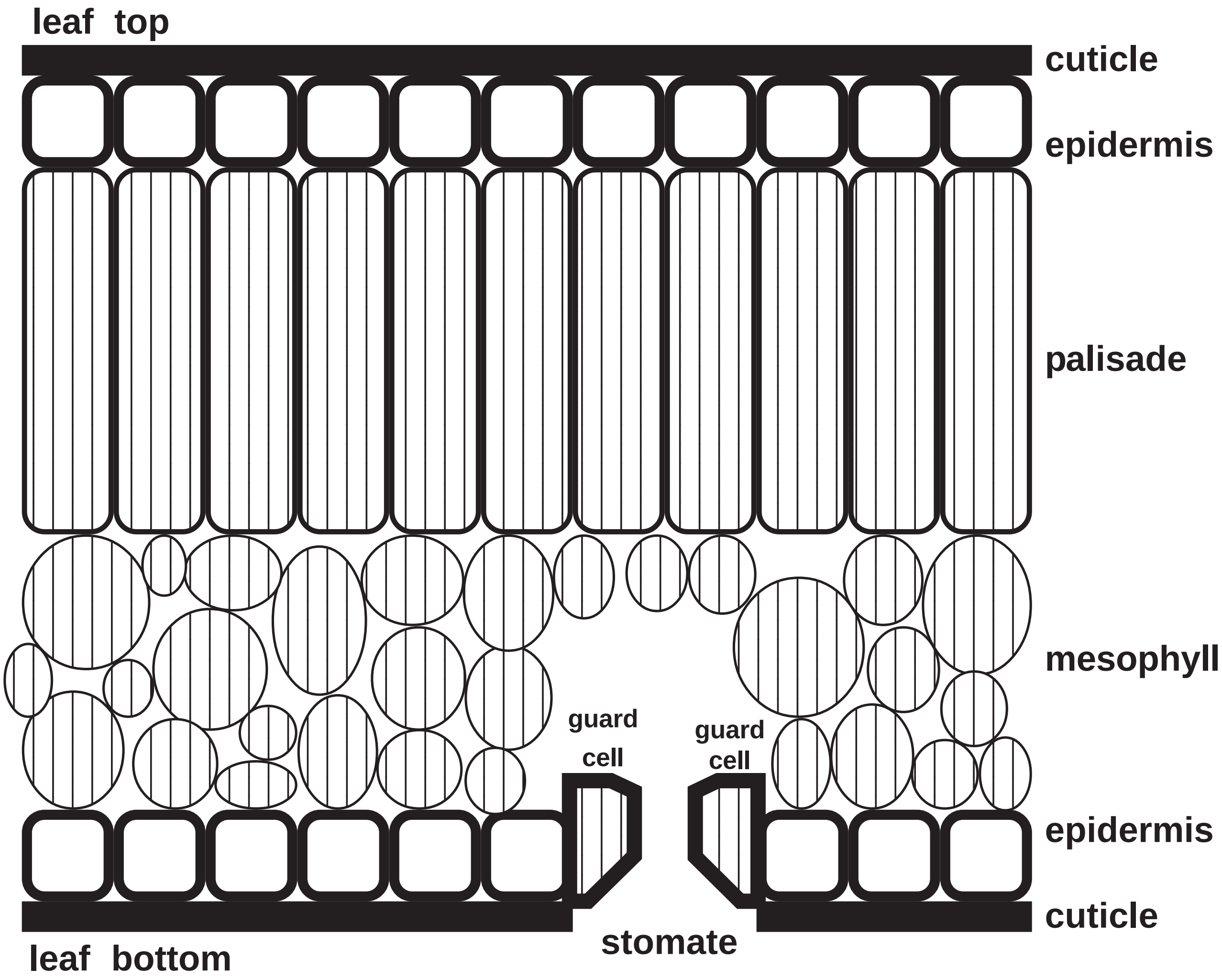


Figure 19: An idealized cross-sectional diagram of a tree leaf blade showing different non-vascular cell layers and a stomate. Cells with shading have chlorophyll. The top and bottom leaf surface is covered with a wax cuticle.

water. Guard cells and surrounding cells convert stored starch and other large materials into sugars and many smaller sized materials. Guard cells free potassium ions which attract large water shells. Because they are tethered to each other only at the ends, they absorb water and lengthen creating a gap between, unveiling an unprotected entrance to the inside of the leaf.

Carbon-dioxide moves into leaves through stomates and dissolves into the water-saturated cell walls for use in food making. Water from the saturated leaf cell walls evaporates quickly and escapes through the stomate. The only place in a tree with control of water loss, food resource gathering, and the tree's transpiration stream is the guard cells and the leaf entrance they cover. Over-all water loss is passively dependent upon, but strongly tied to, temperature and associated vapor pressure deficits. The physiological health of guard cells, including supplies of sugars, starch, potassium, and water, all influence opening of the stomate.

Water Movement

Little can be done to reduce the rate of evapotranspiration from a tree and the surrounding site. Water loss is controlled primarily by the amount of energy present to evaporate water and by soil water availability. Figure 20 demonstrates how transpirational loss of water from the soil increases with climbing temperatures.

Spreading Out Evaporation

The efficiency of water use can be improved by increasing the vertical and horizontal extent of shade (tree crowns) on the site and by use of low density and organic mulches. Shade and mulch assure little direct sunlight reaches the soil surface and evapotranspiration is kept to a minimum. Under these conditions, the largest possible fraction of energy can be used in photosynthesis and the most food produced per unit of water evaporated.

Figure 21 is a diagram of a tree with a multi-layered crown surrounded with an organic mulch bed. This tree form is efficient at conserving site water because sunlight energy is spread over a vertically spread, relative large but widely distributed crown surface area which has some self-shading. The low density organic mulch assures little energy directly impacts the soil surface. A multi-height, multi-tree planting configuration could accomplish the same water use efficiency.

Tree Vascular System

Trees have a vascular system with great water transport capacity. The transport system can deliver water rapidly and preferentially to those parts of the canopy which are most actively transpiring. The transport system is also resistant to environmental stress, especially temperature extremes and pest attack. Vertical water movement is restricted to the outermost one or two annual increments (rings) in ring-porous trees like oaks. The pattern of water movement is more complex in conifers and diffuse-porous trees since a larger number of annual increments are usually involved (3-15 annual increments). Horizontal water movement, or storage, occurs throughout the sapwood increments.

Morning Trees

Water is “stored” in the stem. The water content of heartwood is usually much lower than sapwood. The heavier the wood, the less water present in the stem, per unit volume. Although considerable water is passively stored in tree trunks, the volume is small in comparison to seasonal loss by transpiration. (Figure 22) As transpiration increases in the mornings, root absorption initiated by the current day’s water loss does not begin to increase until later due to stem water. Leaf water lose must produce sufficient tension in xylem water columns to overcome the resistance to water flow through the xylem and from the soil into the root. As water is lost to evapotranspiration from leaf cells, a water deficit can be developed severe enough to cause wilting of leaves.

Night Trees

The lag period between leaves transpiring water and strong root absorption of water shows there are significant resistances to water movement in soil, roots, stems, branches and leaves. In the evening, as temperatures decrease and stomates close, transpiration is rapidly reduced. Water absorption by roots continues until the water potential in the tree comes into near equilibrium with the soil. This absorption process may require all night. As soil dries, there is less water recovery on succeeding nights until permanent wilting occurs. Figure 23. A prolonged, severe water deficit will cause tree death.

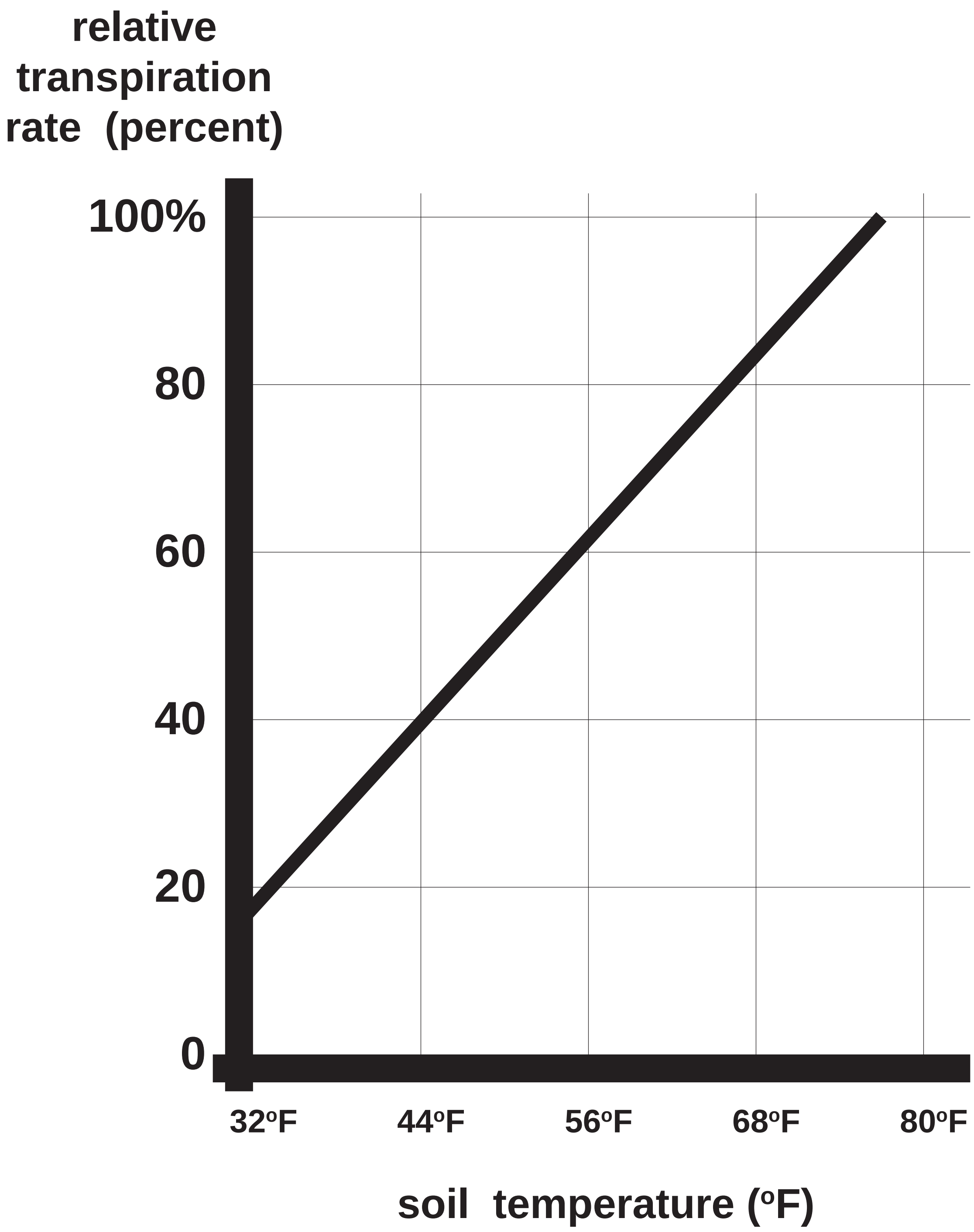


Figure 20: Example impact of soil temperature on the transpiration of pines. (derived from Kramer, 1942)

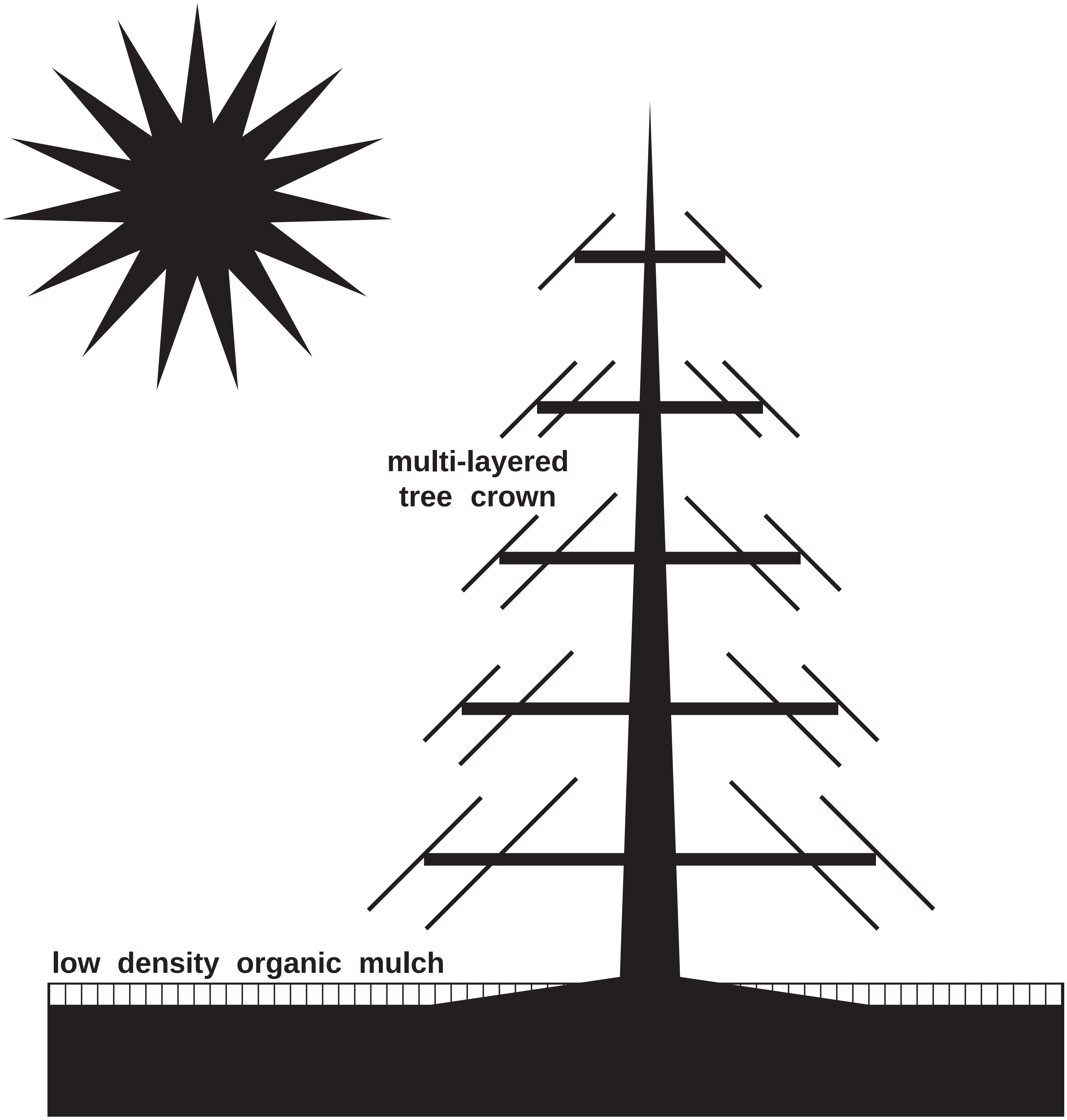


Figure 21: Diagram of a tree with a multi-layered crown surrounded with an organic mulch bed. This tree form is efficient at conserving water because sunlight energy is spread over a vertically spread, relatively large, widely distributed crown surface area. Low density organic mulch assures little energy directly impacts the soil surface.

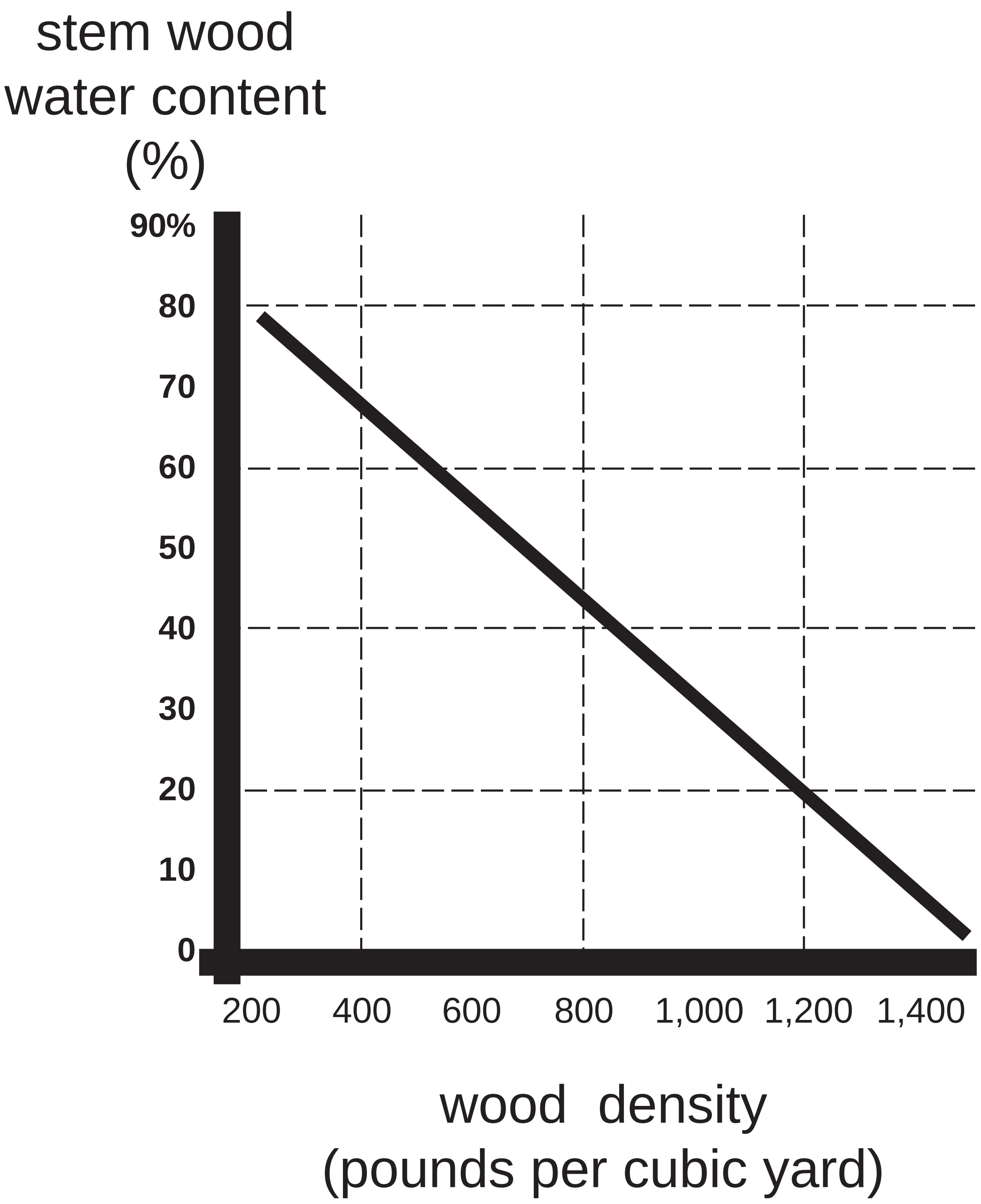


Figure 22: Water available in tree stems with various densities of wood. (after Borchert, 1994)

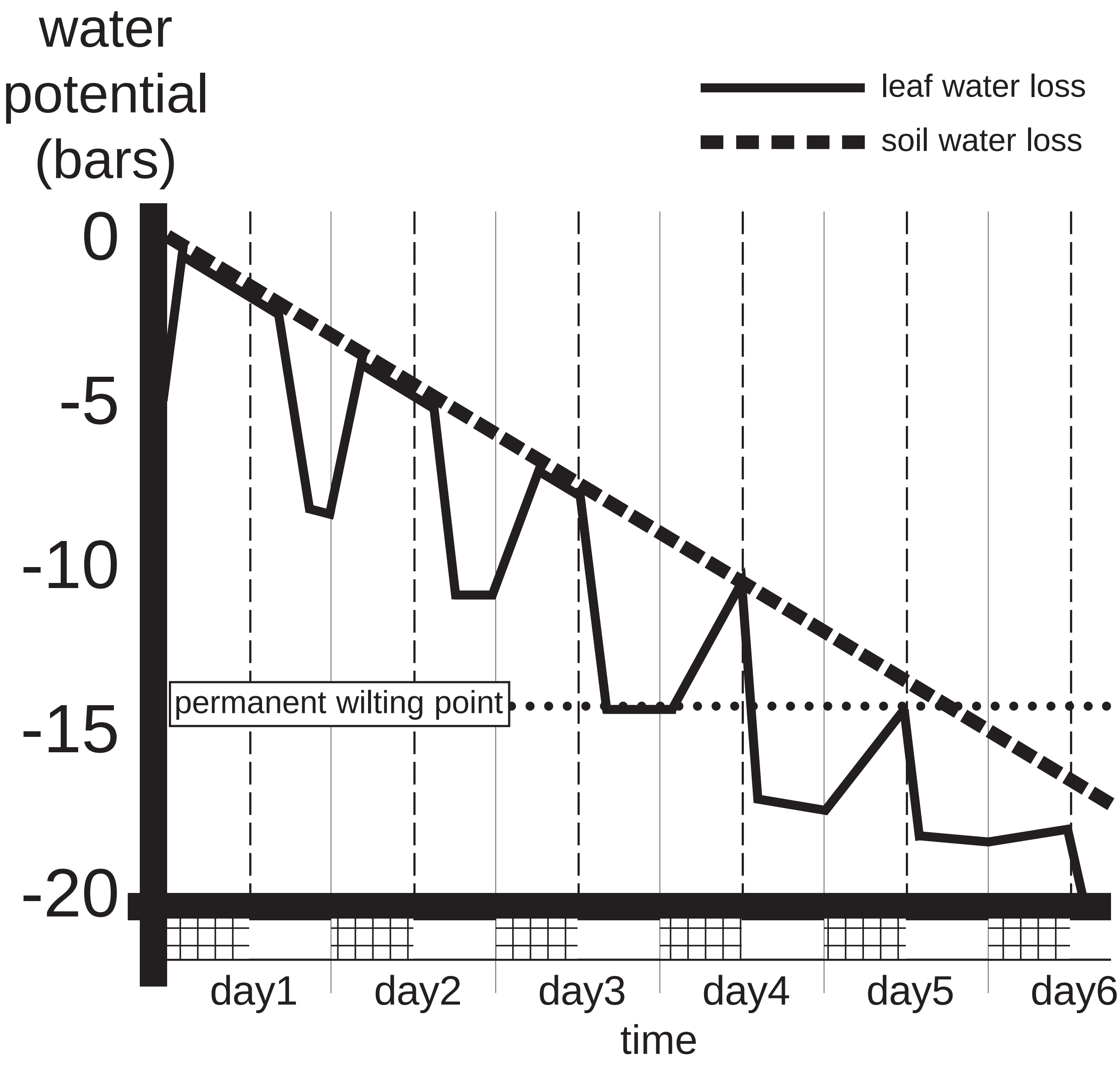


Figure 23: Diagram of daily water potential changes (with no addition of water) as tree leaves and soil dry. (derived from Slatyer, 1967)

Complex Roadmap

The water supply pathway of a tree is a complex series of resistances to water movement, including a stored water component. The path of water flow between roots and foliage is not a simple single path. At each junction (i.e., branch to stem, branch to branch, or leaf to branch) there is a reduction in water conduction (increased resistance). Because of this greater resistance to water flow associated with tree part junctions, a priority system for water and associated essential element distribution is established by growth regulator interactions between shoot and root. Figure 24 shows an idealized diagram of relative values for water conduction (inverse of resistance) within a tree.

The "sun" leaves at the top of a tree canopy are exposed to greater water and thermal stress than leaves lower down, or shaded within the canopy. Because of constrictions in xylem of multiple order lateral branches and twigs, pathway resistance for supplying water to "sun" leaves at the top of the canopy is less than that supplying lower and more shaded leaves on many side twigs. With increasing water stress, sun leaves which require the most water, are furthest from the point of supply in the soil and subject to a greater impact by gravity pulling down on the water columns. An early drought priority favoring the most productive leaves shifts to favoring the most survivable leaves as drought conditions worsen.

Blown Away

Another drying force acting on a tree is wind. Wind blowing past a tree crown can desiccate the tree, evaporating water from lenticels, buds, fruits, and leaves. Wind decreases the protective blanket of still air around a leaf (boundary layer). With less boundary layer, the drying effect of air on a leaf is greater. Wind movement of leaves stimulates stomate closure, reducing transpiration and food production. Wind can have a cooling effect on leaves lessening transpiration. Unfortunately, wind can also be a source for advected heat, like air coming from over a hot parking lot to the site, greatly increasing transpiration. Figure 25 shows how a small wind velocity increase can quickly increase transpiration.

The site upon which a tree thrives can conspire to constrain water use in many ways. Figure 26 provides general estimates of water potential differences for three site conditions with increasing height in trees. The conditions examined were all in the middle of the growing season and included a calm cloudy day, a calm sunny day, and a windy sunny day. Remember in order for water to move up a tree, water potential at a higher point in the tree must be less. Figure 26 shows sun and wind generating larger water deficits (the slope becomes less steep).

Water Content Differences

Because of differences in shading and concentration of cell solutions, various locations of a tree crown lose water at different rates. At any one time, different parts of the tree will have different water tensions (deficits). Since water moves from highest concentration (lowest tension) to lowest concentration (greatest tension), tree parts that develop the lowest water concentrations and greatest tensions, like top-most terminal young shoots, obtain water at the expense of older tissue. This type of water stress hastens leaf senescence.

Trees are composed of about 1% soil derived essential elements, 19% materials derived from carbon-dioxide (CO_2) in the atmosphere, and 80% water from the soil. Water concentrations vary widely in different parts of a tree. Under increasing water stress, the upper, more exposed parts of tree crowns are subjected to greater water stress than lower crown parts. Twig and branch death around the outside of a tree crown is a common result of water stress. On the other hand, lower, shaded branches are stressed because they can not compete to pull enough water. These shaded branches produce less food and growth regulators than upper, better exposed leaves.

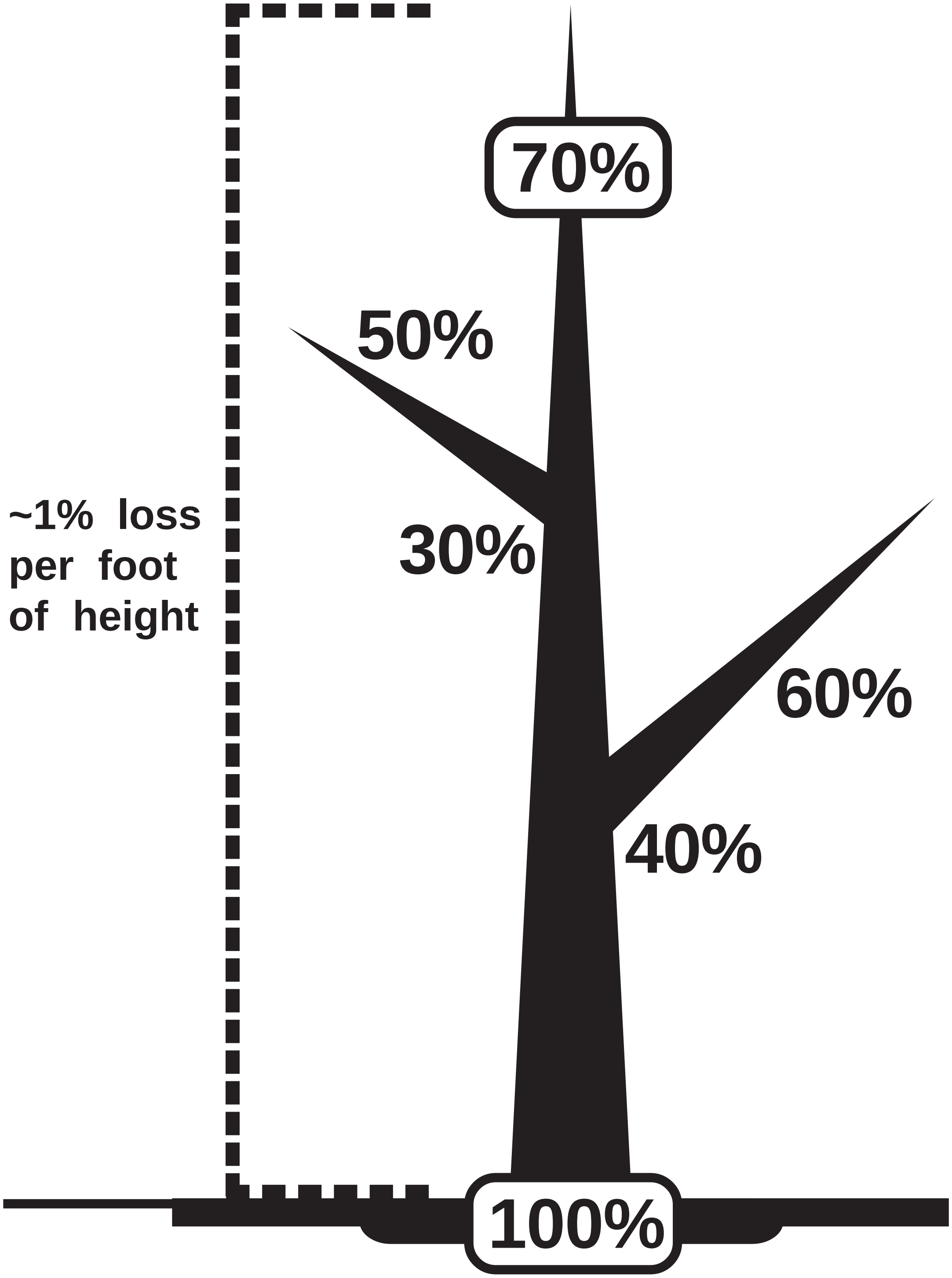


Figure 24: An idealized diagram of relative values for water conduction (inverse of resistance) within a tree. The branch and twig connections (nodes) greatly limit water movement.
(derived from Zimmermann, 1978)

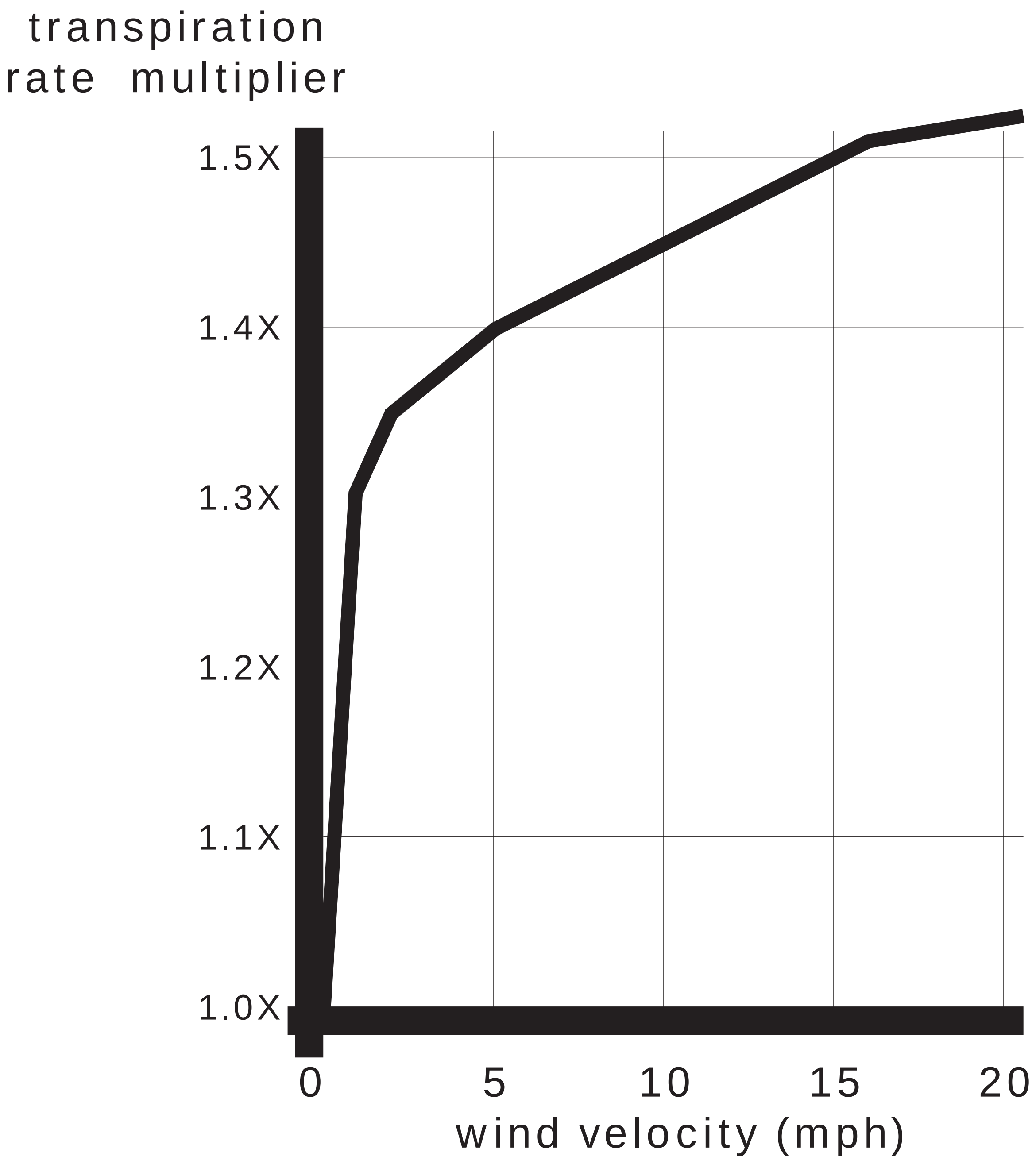


Figure 25: The additional transpiration rate of a tree under various wind speeds in miles per hour compared with transpiration rates under calm conditions.

(derived from Kramer & Kozlowski, 1979)

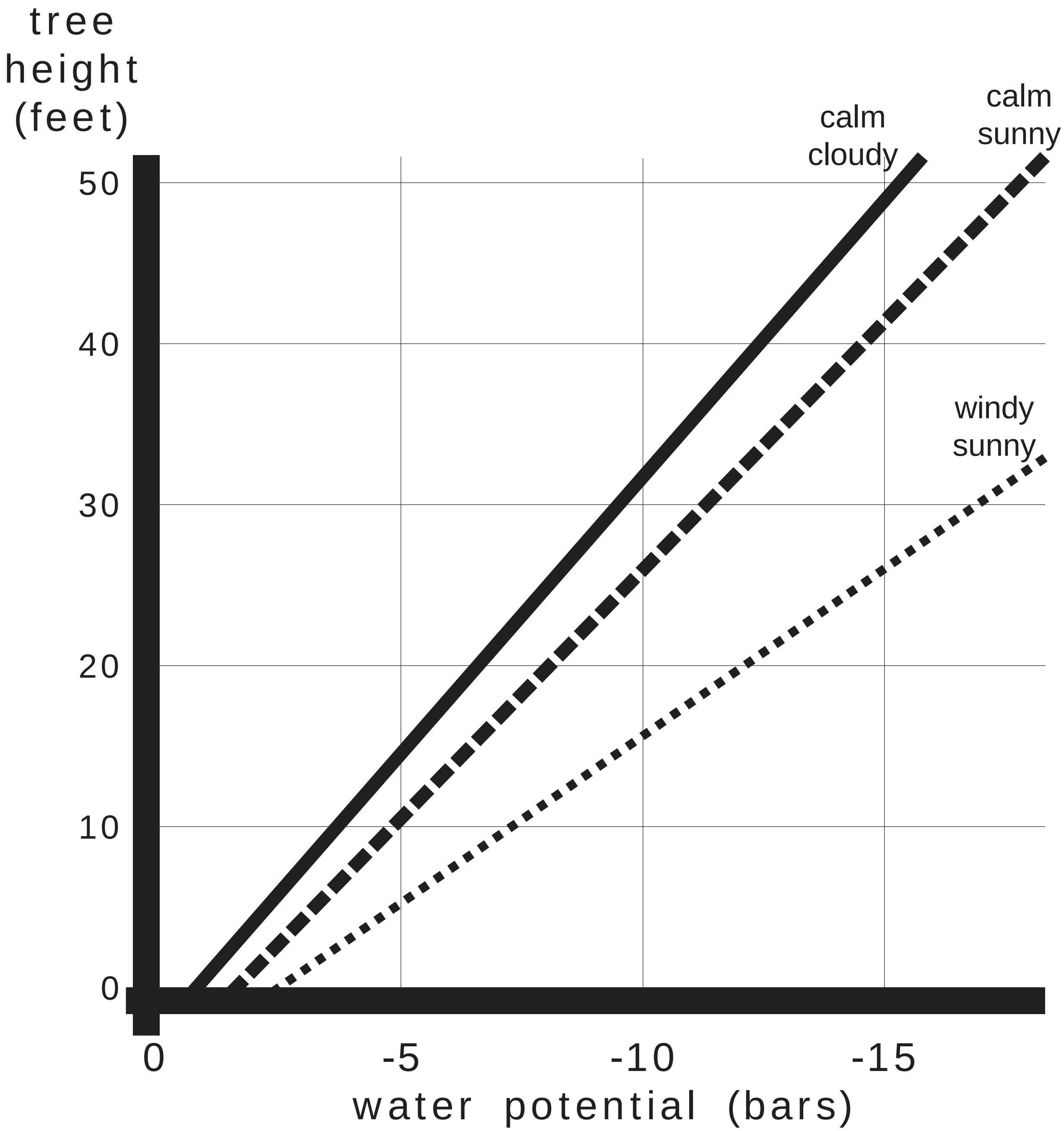


Figure 26: Mid-season water potential values at various tree heights under three site conditions: calm wind and cloudy; calm wind and sunny; and, windy and sunny.
(derived from Hellkvist et. al. 1974)

Speed

Water movement through a tree is controlled by the tug-of-war between water availability and water movement in soil versus water loss from leaves. The average seasonal rate of water movement in selected trees is given in Table 5. For example from Table 5, water movement in feet per hour in a ring porous tree like a red oak is 92 ft/hr, in a diffuse porous tree like a basswood is 11 ft/hr, and for a conifer like pine is 6 ft/hr. Note there are some trees which can not rehydrate over a short summer night due to internal resistances to water movement.

Soils

As soils dry, there is less and less water sticking to the surfaces of the soil particles and left in pore spaces between particles. Sandy soils dry rapidly because the spaces between the particles are large. Little water sticks to the surface of sand particles. In clay soils, water is held tightly on and between clay surfaces, with some water held so tightly, it is difficult for a tree to exert enough pull (tension) to capture this water from the soil.

As soil water contents decline, tree leaves must develop large water tensions in order to pull up the last bits of water from soil. Some point occurs when water tension in the leaf is so great, tissue is damaged while water loss continues. Even tree death does not stop water movement. Standing dead trees continue to be a pathway of water loss from soil.

Roots

A major portion of the active tree root system is concentrated in the top few moist inches of soil, just below areas rich in organic matter and associated with microorganisms. These roots must absorb water. This ephemeral root system (absorbing roots) take up a majority of water in a tree. Annual roots are not the woody roots seen when a tree is dug. Large woody roots have bark and any bark crack or damage is quickly sealed-off so little water flows through these roots.

It is young roots, roots easily damaged by drought, that are major absorbers of water and essential elements in a tree. These roots are generated, serve, and then are sealed off between 5 and 25 times during the year, depending upon species. A tree may have a single set of leaves per year, but many sets of absorbing roots. Figure 27 demonstrates how critical absorbing roots are for overall tree health. The more roots a tree has to absorb water, the more transpiration will occur and the more food can be made. More food means more growth and more roots.

Soil Water

As soil dries the availability of water begins to be limited by decreasing water potentials and hydraulic conductivity. Figure 28. Dimensional shrinkage of both the soil and roots occur as soils dry. Soil aeration, soil temperature, and the concentration and composition of the soil solution also limit absorption of water by trees. As soils dry, resistance to water flow through soil increases rapidly. The loss of water cross-sectional area through a soil plummets as films of soil water decrease in thickness and discontinuities develop around soil particles. The presence of mycorrhizae (fungal modified tree roots) can act to moderate early drought stress in trees.

Conclusions

Water is the most critical of the site resources trees must gather and control. Water movement and control in trees can be summarized as a physical process of evaporation – controlled by temperature and humidity – being utilized to move essential materials from root to shoot. This process is partially biologically controlled by opening and closing leaf valves called stomates. Stomates help convert atmospheric evaporative pull into the power for a supply highway in a tree. Water shortages can prevent tree food production and damage tree life processes.

Table 5: Rough estimate of water velocity through tree stem vascular tissue for various genus and species of trees in feet per hour, categorized by xylem porosity.

tree species	water velocity (feet/hour)
Ring-porous trees	
European red oak	144
black locust	95
red oak	92
ash	85
chestnut	79
tree-of-heaven	72
hickory	62
sumac	53
elm	20
Diffuse porous trees	
balsam poplar	21
black walnut	14
butternut	13
basswood	11
willow	10
yellow poplar	9
maple	8
magnolia	7
alder	7
birch	5
hornbeam	4
beech	4
buckeye	3
Conifers	
larch	7
pine	6
spruce	4
hemlock	3

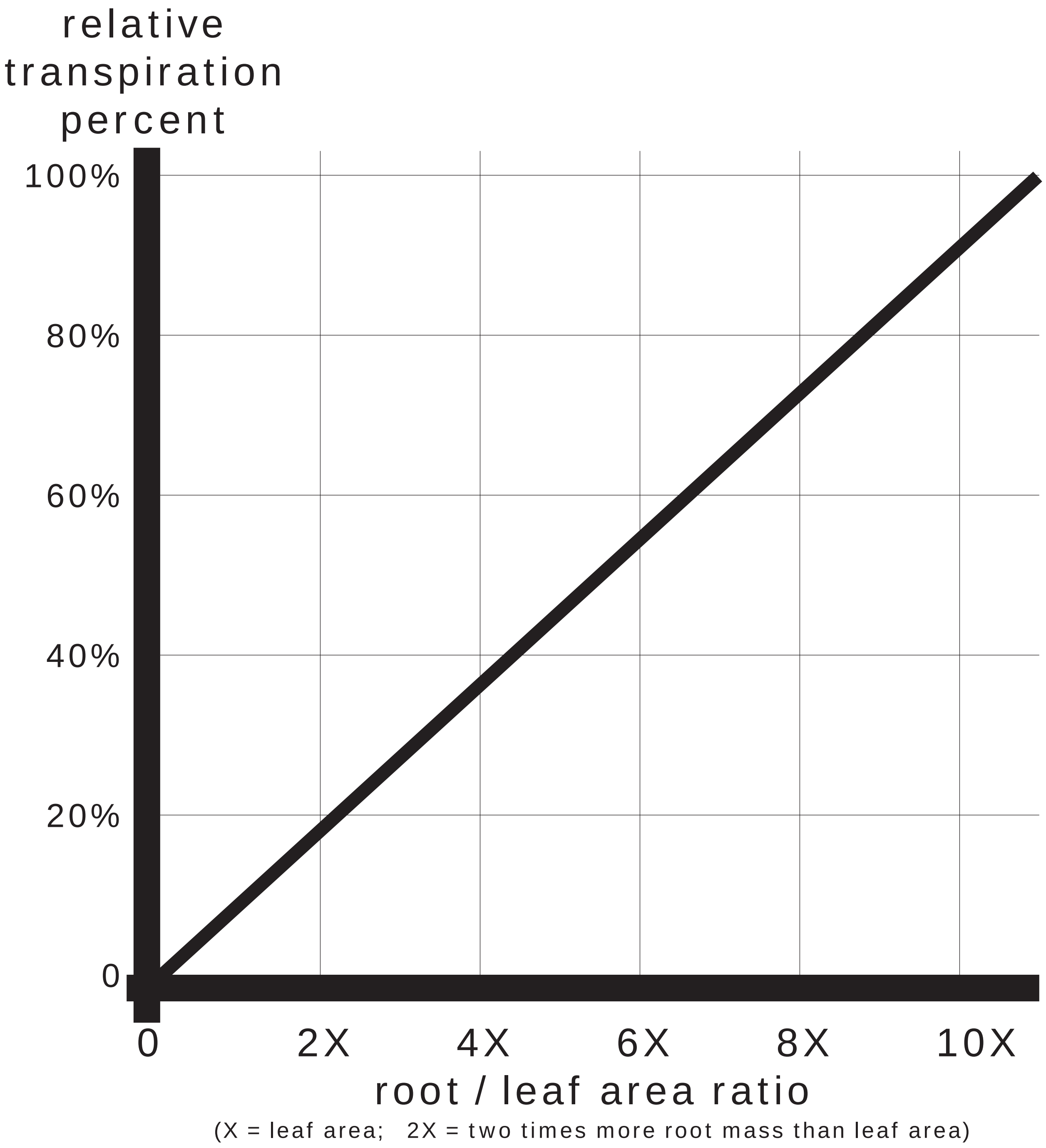


Figure 27: The relative amount of tree transpiration in percent compared with the root / leaf area ratio of the tree. Root values were on a dry weight basis and leaf values were on a square foot basis. (derived from Parker, 1949)

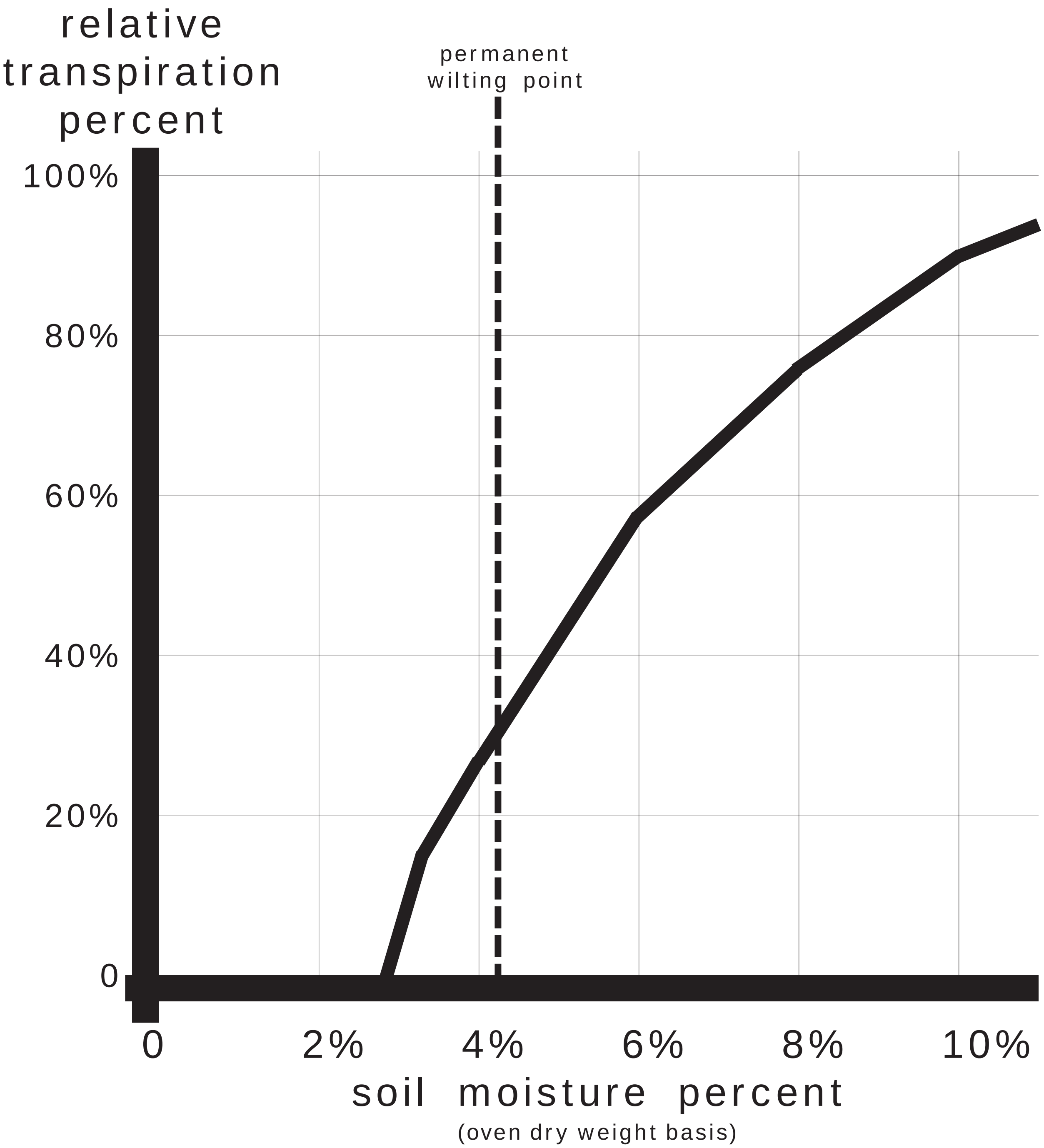


Figure 28: The relative amount of tree transpiration in percent compared with various soil moisture percents based upon an oven dry weight basis.
(derived from Bourdeau, 1954)

Heat Stress

Because water loss in trees is primarily a physical process controlled by temperature, heat loading on trees must be quantified and appreciated. Trees, hot temperatures, and water deficits are intimately bound together in a stress syndrome. Any discussion of water in trees must deal with site heat loads to fully understand tree water stress and provide adequate water resources to alleviate stress.

Many old, young, and soil-limited trees are damaged by hot temperatures. The combination of drought, heat, and harsh site conditions provided by parking lots, along streets, on open squares, and from surrounding pavements lead to a number of tree symptoms. The old human term "heat stroke" fits trees where heat loads have become extreme and no tree available water is present.

Heat Loading

The evaporative force on a tree is greatly impacted by heat loading. Increasing site temperatures provide energy for evaporation. As a general rule, each temperature increase of 18^{o}F, beginning at 40°F where water is densest, continuing through 58°F, 76°F, 94°F, 112°F, and 130°F each allow a physical doubling of respiration and water loss. Table 6 presents a doubling sequence for tree water use. It is clear small increases in site temperature can greatly increase site water demands. As a greater share of water on a site is physically used to dissipate heat, less is available for tree life functions. Trees under heat loads need extra water. Heat loads, and associated additional water demands, should be estimated.

Heat loading comes primarily from reflected energy from surfaces, radiated energy from local materials, and energy moved onto the site in the form of heated air (advection). The different sources of energy combine to impact a tree causing tissue temperatures to increase, relative humidity to fall, and air and surfaces temperatures surrounding a tree to increase. Figure 29. This additional heat load forces the tree, through physical processes of water loss, to lose more water whether stomates are open or closed. A tree is forced to lose water in dissipating heat, not making food.

Baked

Estimating tree heat load allows for correcting water loss values on sites with elevated temperatures. Non-evaporative, dense surfaces absorb energy, quickly increase in temperature, radiate heat, and heat surrounding air. Heat load estimates quantify the amount of non-evaporative, dense surfaces in view of, or surrounding, a tree or planting site.

Figure 30 is a diagram showing how heat loading can be estimated on a site using the Coder Heat Load View-factor with ten equal (36^o) observation angles. In each of the ten angle segments, the dominant surface facing a tree or planting site is recorded. Surface components include either: A) sky and vegetation; or, B) non-evaporative, dense surfaces (hardscape). The horizontal distances given in Figure 30 are based upon an observation height of 5.5 feet.

More Water!

The view-factor percentage determined is an average of one complete circle observed in a North / South direction and a second complete circle observed in an East / West direction. The possible ranges of view-factors facing the site are 0% (100% sky and vegetation) to 100% (100% non-evaporative / dense hardscape surfaces). Heat load multiplier values for various view factors (nearest 10% class) are given in Table 7 and provide a multiplier for site and tree water use. For example from Table 7, if a young tree in a parking lot has a estimated heat load multiplier of 1.9 (view factor 60%), then this tree will require nearly two times (2X) the water of a tree in a nearby park with a heat load multiplier of 1.0 (view factor 0%).

Table 6: A water use doubling sequence for trees exposed to increasing heat loads. For each 18°F (10°C) site temperature increase above 40°F, water use by the tree and site double from the physical impacts of heat.

temperature	multiplier effect
40°F	1X
58°F	2X
76°F	4X
94°F	8X
112°F	16X
130°F	32X

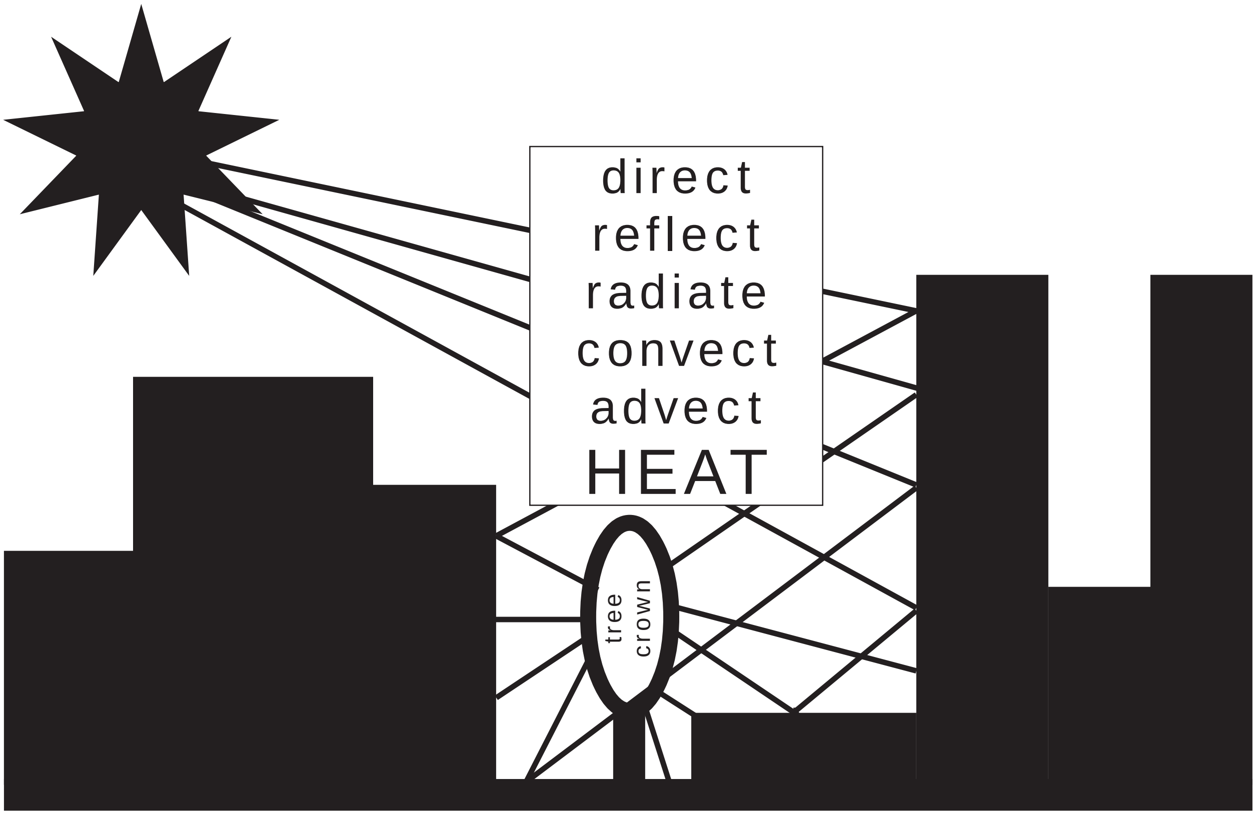


Figure 29: Diagrammatic view of a tree growth area impacted by heat loading from surrounding hard, dense, non-evaporative surfaces, in an urban canyon.

(heat load view factor in two dimensions = 70%)

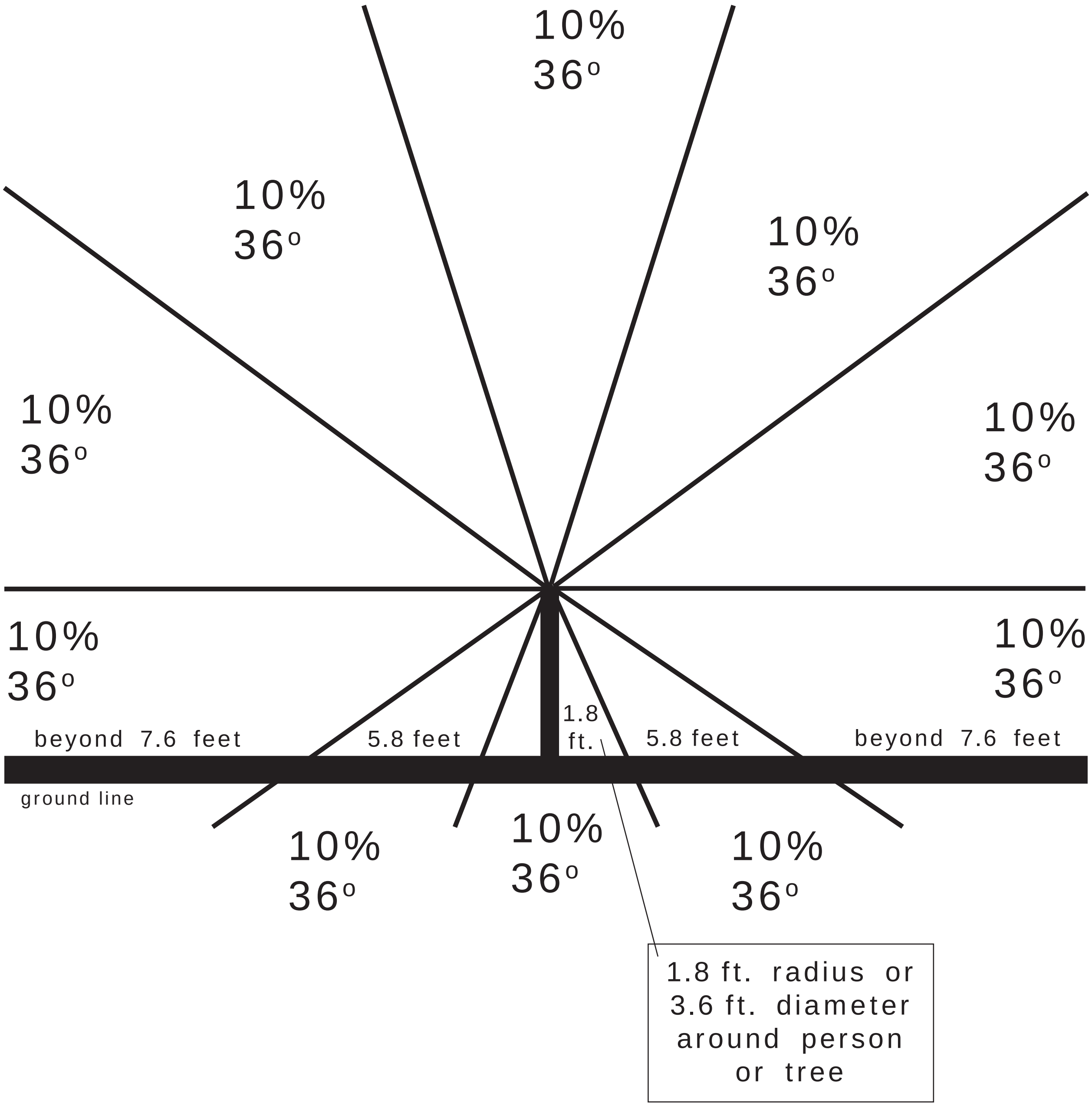


Figure 30: Diagram showing how heat loading can be estimated on a site using the Coder Heat Load View-factor containing ten equal (36°) observation angles.

In each of ten angle segments, the dominant surface facing the tree or planting site is recorded. Surface types include sky & vegetation, or non-evaporative, dense surfaces (hardscape). The first estimate is made North/South and a second estimate is made East/West, with the two estimates averaged together to provide a single view-factor value (in 10% classes) which can then be used for determining a site heat load multiplier. Distances given above are based upon an observation height of 5.5 feet.

Table 7: Coder Heat Load View-factor multiplier values for various non-evaporative, dense surface view-factors (nearest 10% class) for a site or tree.

Every 10% / 36° of angle around a point, starting at the ground directly below and observing along a circular arc which passes through zenith, is determined to have either open sky / vegetation or non-evaporative, dense surfaces facing the measurement point. Each 10% angle segment is considered to be dominated by one or the other of these surfaces.

view-factor percent of non-evaporative, dense surfaces facing the site	heat load multiplier**
100%	2.9
90%	2.6
80%	2.3
70%	2.1
60%	1.9
50%	1.7
40%	1.5
30%	1.3
20%	1.2
10%	1.1
0%	1.0

**Use heat load multiplier to increase water use values on trees under various heat loads.

Temperatures

Most temperate zone trees reach optimum growing conditions across a range of temperatures from 70°F to 85°F. Hot temperatures can injure and kill living tree systems. A thermal death threshold in trees is reached at approximately 115°F. The thermal death threshold varies depending upon the duration of hot temperatures, the absolute highest temperature reached, tissue age, thermal mass, water content of tissue, and ability of a tree to make adjustments as temperatures change. Tree temperature usually runs run around air temperature (+ or - 3^{o}F). Trees dissipate heat (long-wave radiation) through convection into the air, and transpiration (water loss from leaves). Moist soil around trees also dissipates heat through convection and evaporation.

Transpiration is a major mechanism of tree heat dissipation. Without water used for transpirational heat dissipation or "cooling," heat radiated to tree surroundings and wind cooling are the only means of keeping tree temperatures near air temperatures. Sometimes radiated heat from immediate surroundings and hot breezes (advection) prevent tree heat dissipation, add to a tree's heat load, and increase associated water demand.

Cooking

Figure 31 shows idealized energy distribution on three sites: 1) a hard, dense-surfaced parking lot; 2) a tree (or could be an awning) standing over dry soil -- which demonstrates passive shade blocking of energy from the soil surface; and, 3) a tree in moist soil -- representing active shade where energy is blocked from the soil surface and heat is dissipated through tree and site evapotranspiration.

The first example shows sensible heat generated in a parking lot with a hard, non-evaporative, paved surface. Sunlight beats down on the parking lot with 1,000 heat units of energy. The hard surface absorbs and then reradiates heat into its surroundings for a total of 2,000 heat units on-site. This heat load can either be reflected onto trees, or used to heat air that is then blown across a neighboring landscape which raises heat loading and associated water loss.

The second landscape example in Figure 31 shows a tree standing in dry soil. A tree under these conditions shades (blocks sunlight from) the soil surface which eliminates 400 incoming heat energy units. Everyone understands it is cooler in the shade of a building, awning, or umbrella than in full sun. Without water available for a tree to transpire and soil to evaporate, a tree simply acts as an umbrella. If trees can not dissipate tissue heat through transpiration, tissue temperatures climb. In this example, a total of 600 heat units pass through to the site and 600 heat units are absorbed and reradiated back from the soil, for a total of 1200 heat energy units on-site. This process of physically blocking sunlight for shade is called "passive shading" and can reflect and radiate roughly one-fifth of the heat energy away from a site. Trees under these conditions can not survive for long.

Dissipation

The third example in Figure 31 shows a tree in moist soil with plenty of water available for transpiration. As in the passive shade example above, 400 heat units are physically blocked by the tree generating shade. In addition, 350 heat units are transferred away from the tree through transpiration of water from the leaves. This transpirational heat dissipation effect in a landscape is called "active shading" because a biologically controlled process is helping to dissipate heat. The heat energy units passing through the tree, and radiating from the tree crown, amount to 250 heat units. The soil below is radiating 200 heat units (50 heat units are dissipated by water evaporation from the soil). The total heat energy units in the landscape from the third example is 450, roughly 38% of the heat load in example two and 23% of the heat load in example one.

Trees can dissipate tremendous heat loads if allowed to function normally and with adequate soil moisture. Unfortunately, hot temperatures greatly increase the water vapor pressure deficient

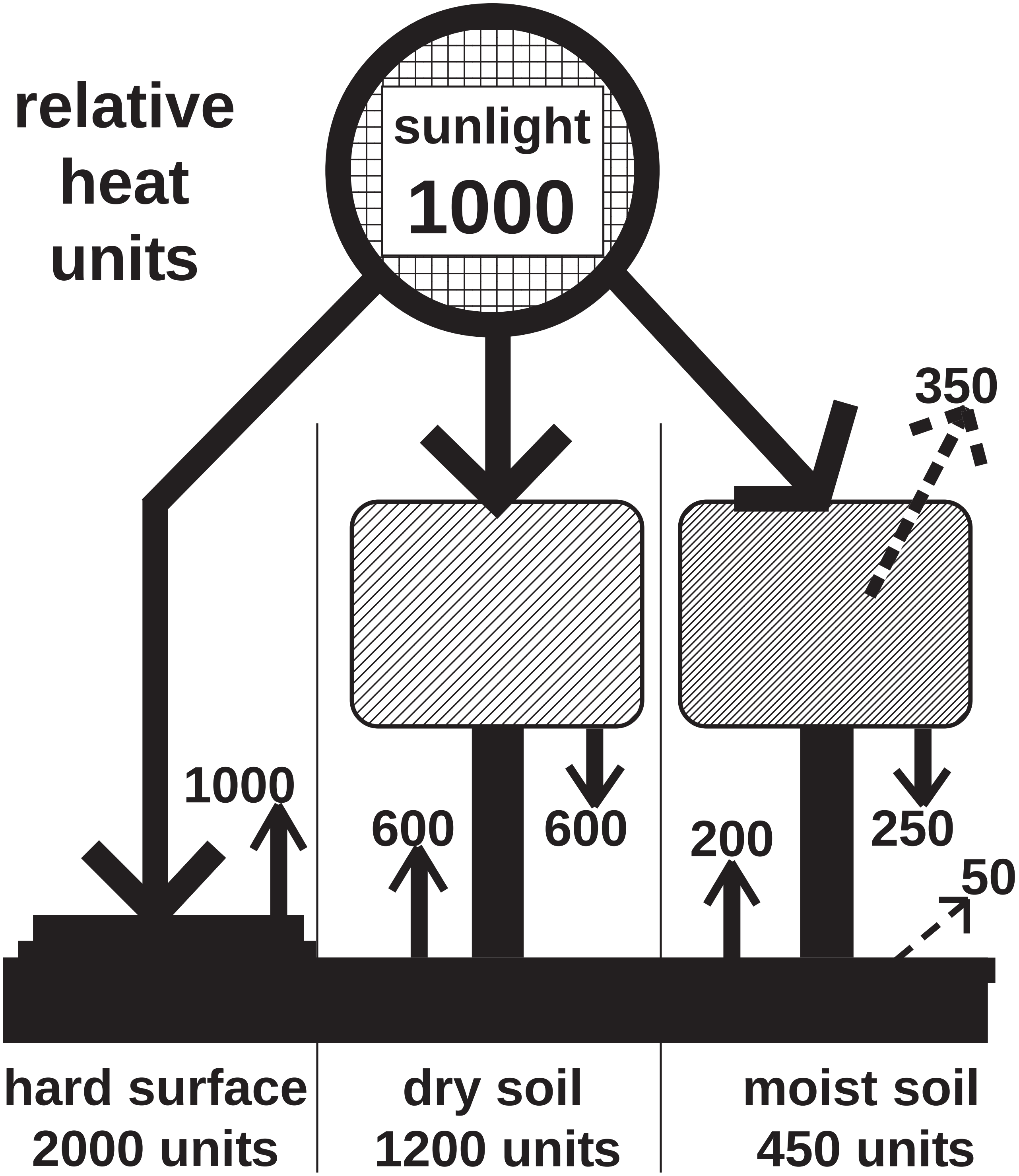


Figure 31: Three types of sites and heat loads -- hard dense surface of a parking lot; passive shade of a tree in dry soil (equivalent to an awning); and, active shade of a healthy tree in moist soil.

(dryness of the air) which lead to leaf stomates closing due to rapid water loss and, in turn, limits transpirational heat dissipation or cooling of the leaves. Heat injury from tissue temperature increases can be prevalent during sunny mid-days and afternoons when air temperatures are high and transpirational heat dissipation is limited. Figure 32. When transpiration is limited by hot temperatures, and a tree is surrounded by non-evaporative surfaces (hard surfaces), leaf temperatures may rise to near the thermal death threshold.

Hot Water

Heat injury is difficult to separate from water problems, because water and temperature in trees are so closely bound together in biological and physical processes. Water shortages and heat buildup are especially critical in leaves, and secondarily, in the cambial and phloem area of twigs and branches. Increased temperatures increase the vapor pressure deficit between leaves and atmosphere, as well as increasing the rate of water loss from other tree layers.

One of the most dangerous forms of heat transfer for trees and landscapes is advected heat. For example, large paved areas heat air above them and drive down relative humidity. This air is pushed by wind over surrounding landscapes which heats and dries tree tissues as it passes. Advected heat powers excessive water evaporation in a tree just to dissipate heat generated somewhere else. Wind also decreases the protective boundary layer resistance to water movement and can lead to quick dehydration. Structures and topographic features can modify or block advected heat flows across a site.

Double Trouble

Daytime temperatures obviously provide the greatest heat load, but night temperatures are also critical for many tree growth mechanisms, especially new leaves and reproductive structures. Night temperatures are critical for controlling respiration rates in the whole tree and soil environment. The warmer the temperature, the geometrically faster respiration precedes and water is lost. Other processes are also impacted by heat. For example, gross photosynthesis rates generally double with every 18^{o}F (10^{o}C) until 94°F and then rapidly falls-off. Figure 33. The duration of hot temperatures for trees must not exceed the tree’s ability to adjust, avoid, or repair problems. Less absolute amounts of sensible heat are needed to damage trees as the duration of any high temperature extreme lengthens.

Heat Damage

Heat injury in trees include scorching of leaves and twigs, sunburn on branches and stems, leaf senescence and abscission, acute leaf death, and shoot and root growth inhibition. In tree leaves, wilting is the first major symptom of water loss excesses and heat loading. Leaves under heavy heat loads may progress through senescence (if time is available), brown-out and finally abscise. Leaves quickly killed by heat are usually held on a tree by tough xylem tissues and the lack of an effective abscission zone. Rewatering after heat damage and drought may initiate quick leaf abscission.

Heat stroke is a series of metabolic dysfunctions and physical constraints that pile-up inside trees and become impossible to adjust, avoid or correct. In other words, the more dysfunctional and disrupted growth functions become due to heat loading, the easier it is to develop further stress problems. For example, nitrogen is an essential element which has serious interactions with heat loading in trees. Because nitrogen processing is physiologically demanding, the presence of moderate concentrations of available nitrogen can damage trees under large heat loads.

The internal processing of nitrogen fertilizer inputs require stored food (CHO) be used. Excessive heat loads and supplemental nitrogen lead to excessive root food use. When no food is being produced in the tree due to heat loading and drought, transport systems are only marginally

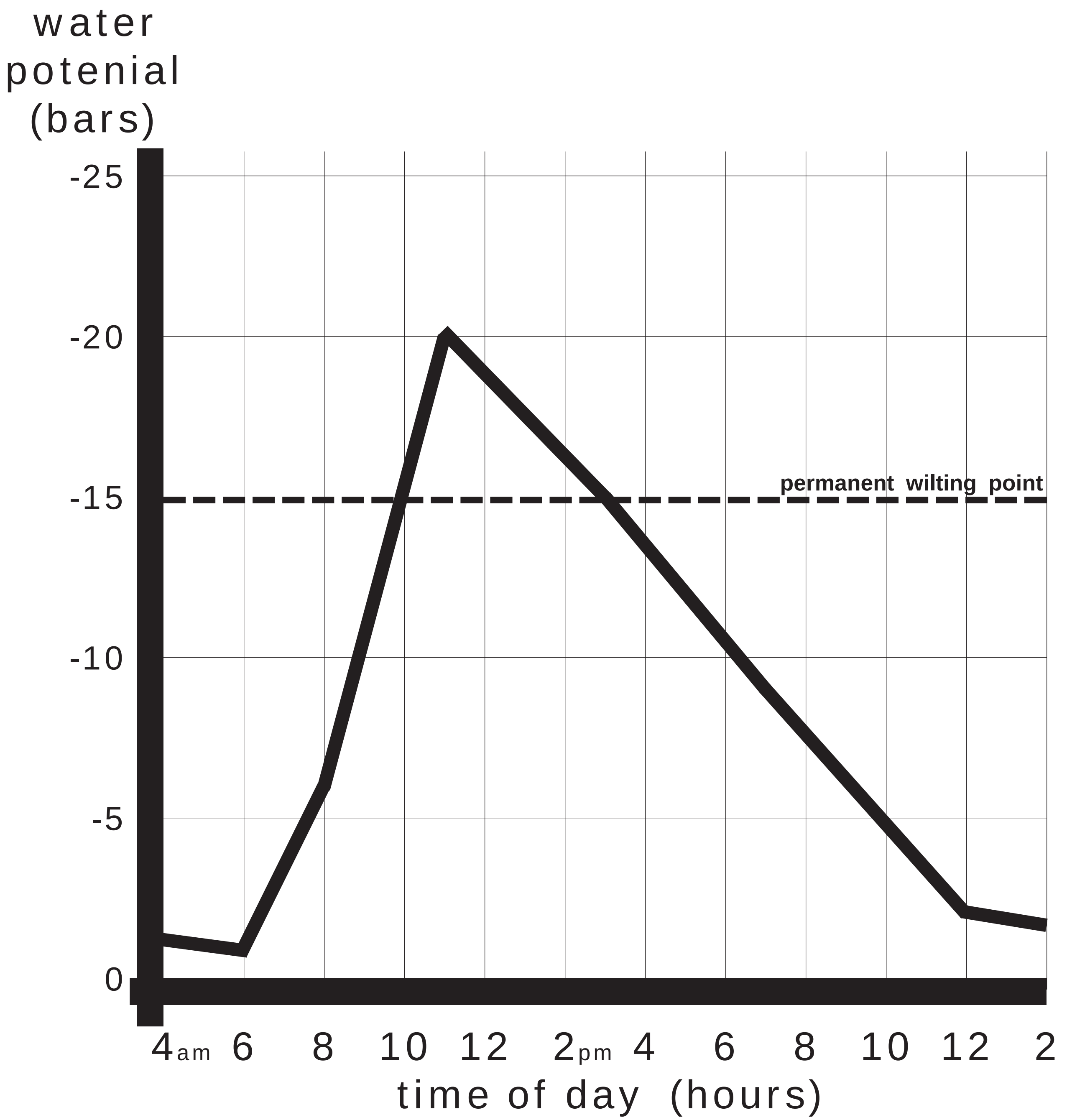


Figure 32: Generalized open-grown single tree water potential in bars over a mid-growing season day. (derived from Bacone et. al., 1976)

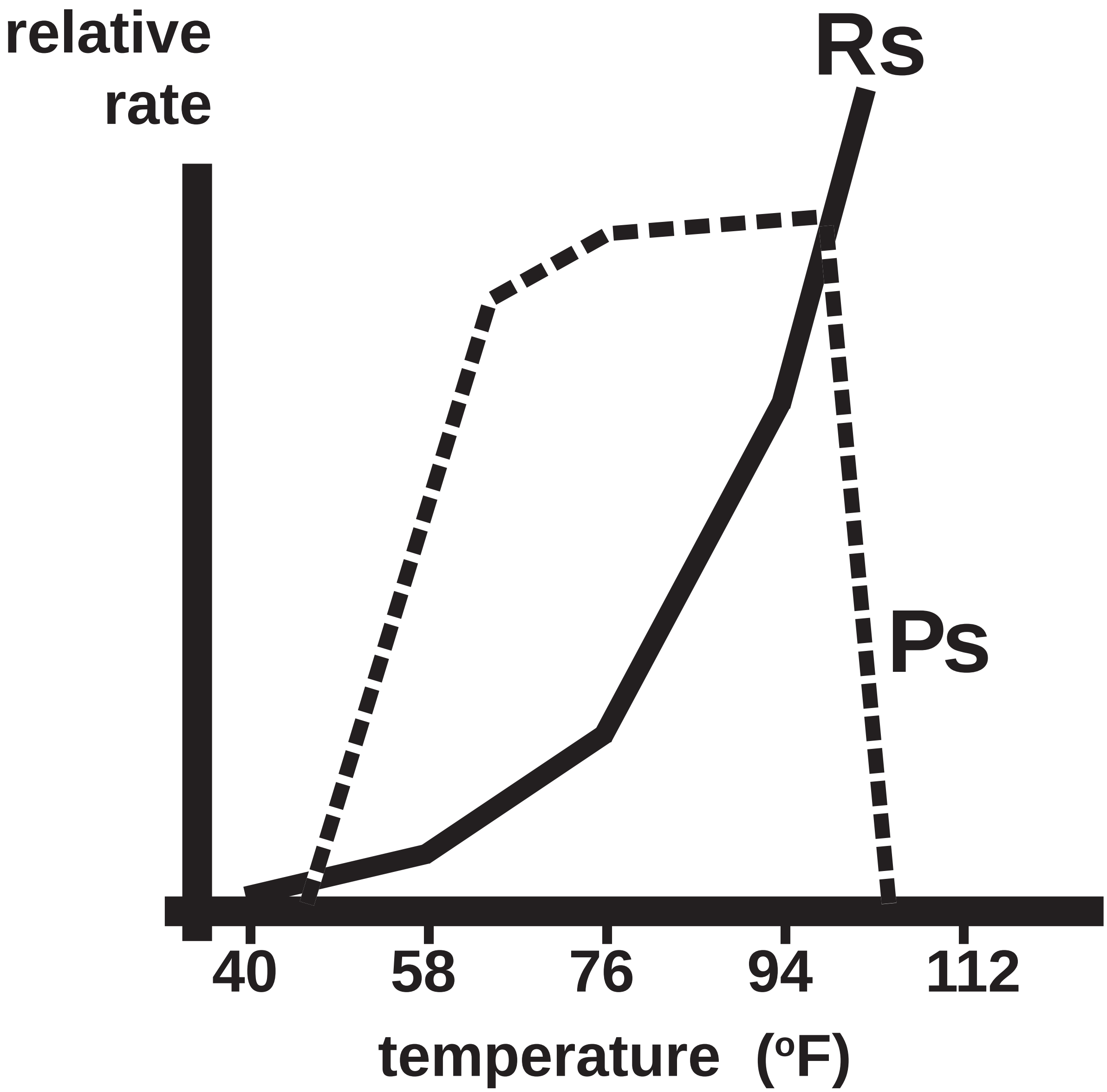


Figure 33: The relative rates of photosynthesis (Ps) and respiration (Rs) in a tree. Note respiration continues to climb exponetially with increasing temperatures and the photosynthesis process quickly falls apart as 105°F is passed.

functional, and respiration is accelerating, nitrogen applications should be withheld. Fertilizer salt contents or activity in the soil can also be damaging when soil moisture is limiting.

Hot Soil

The soil surface can be both a heat reflecting and absorbing layer. In full sunlight, soils can reach 150°F. This heat can be radiated and reflected into a landscape and onto trees causing tremendous heat loading. As discussed before, excessive heat loading causes large amounts of water to be transpired, initiates major metabolic problems, and can generate heat lesions just above the ground / tree contact juncture (root collar / stem base area). Heat lesions are usually first seen on the south / south-west side of stems months after the damaging event.

Trees growing within above ground containers in full sunlight can be under large heat loads that quickly injure roots and shoots. Depending upon color, exposure, and composition, planting containers can quickly absorb heat. For example, black plastic containers can absorb radiation at 9^{o}F per hour until they reach 125^{o}F or more. The sequence in damage within a container begins with the inhibition of root growth followed by water uptake decline, heavy wilting, physical root damage and death, and finally leaf and shoot death.

Melting Membranes

Living tree cell membranes are made of a double layer of lipids (fats/oils) within which is contained living portions of the cell. As temperature increases, membranes become more liquid which is similar to heating butter and watching it melt. With rising temperatures, cells use two strategies to maintain life: A) increase the saturated fat proportion in membranes; and, B) increase structural proteins holding membranes together. As temperatures continue to climb, enzymes and structural proteins are inactivated or denatured. Respirational by-products produce toxic materials that are difficult to transport away, destroy, compartmentalize, or excrete. Tree cell death is the result.

Death Sequence

Trees (C3 photosynthesis plants) develop heat stress syndrome (heat stroke) following this general sequence: 1) decrease photosynthesis; 2) increase respiration; 3) close down photosynthesis (turn-over point for photosynthesis and respiration around ~95^{o}F) by closing stomates, stopping CO_2 capture, and increasing photorespiration; 4) major slow-down in transpiration which prevents heat dissipation and causes internal temperature increases; 5) cell membrane leakage signal changes in protein synthesis; 6) continued physical water loss from tree surfaces; 7) growth inhibition; 8) tree starvation through rapid use of food reserves, inefficient food use, and an inability to call on reserves when and where needed; 9) toxins are generated through cell membrane releases and respiration problems; and, 10) membrane integrity loss and proteins breakdown.

Drought Damage

Water is the most limiting ecological resource for most tree and forest sites. As soil-water content declines, trees become more stressed and begin to react to resource availability changes. A point is reached when water is so inadequately available that tree tissues and processes are damaged. Lack of water eventually leads to catastrophic biological failures and death. Growing periods with little water can lead to decreased rates of diameter and height growth, poor resistance to other stress, disruption of food production and distribution, and changes to the timing and rate of physiological processes like fruit production and dormancy. More than eighty percent (80%) of the variation in tree growth is because of water supply.

Climate Vulgarities

Climatic variation will always provide times of both water surplus and deficits, with the average being the most cited growing season value. It is non-average growing seasons and periods with the extremes of water availability, interacting with site constraints, which damage trees. Examining climatic patterns can suggest what is normal and what is atypical, like drought. Figure 34 and Figure 35 are maps of the Southeastern area of the United States. Figure 34 represents land areas which share common climatic patterns during the month of June. Figure 35 represents land areas which share common climatic patterns during the month of August. These two maps represent a composite multi-year average for three climatic attributes impacting trees -- evaporation, precipitation, and temperature. Generally the larger the number listed, the less water stress expected for tree growth over time under normal conditions.

Figure 36 shows multi-year composite climatic zones based upon annual average evaporation, precipitation, and temperature. As in the previous maps, the larger the number listed, the less water stress expected for tree growth over time under normal conditions. Prolonged drought conditions will be more devastating the higher the number listed although the risk of drought is less. Figure 37 cites a temperature line, an evaporation level, and a precipitation amount for forming areas with similar potential for droughts. Hot, moderate precipitation, and strong evaporation means significant risk of tree stress like drought.

Drought

The term “drought” denotes a period without precipitation, during which the water content of soil is reduced to such an extent trees can no longer extract sufficient water for normal life processes. Droughts can occur during any season of the year. Water contents in a tree under drought conditions disrupt life processes.

Trees have developed a series of prioritized strategies for coping with drought conditions listed here in order of tree reactions:

1) recognizing (“sensing”) soil / root water availability problems.
2) chemically altering (osmotic) cell contents.
3) closing stomates for longer periods.
4) increasing absorbing root production.
5) using food storage reserves.
6) close-off or close-down root activities (suberized roots).
7) initiate foliage, branch and/or root senescence.
8) set-up abscission and compartment lines.
9) seal-off (allow to die) and shed tissues / organs unable to maintain health.

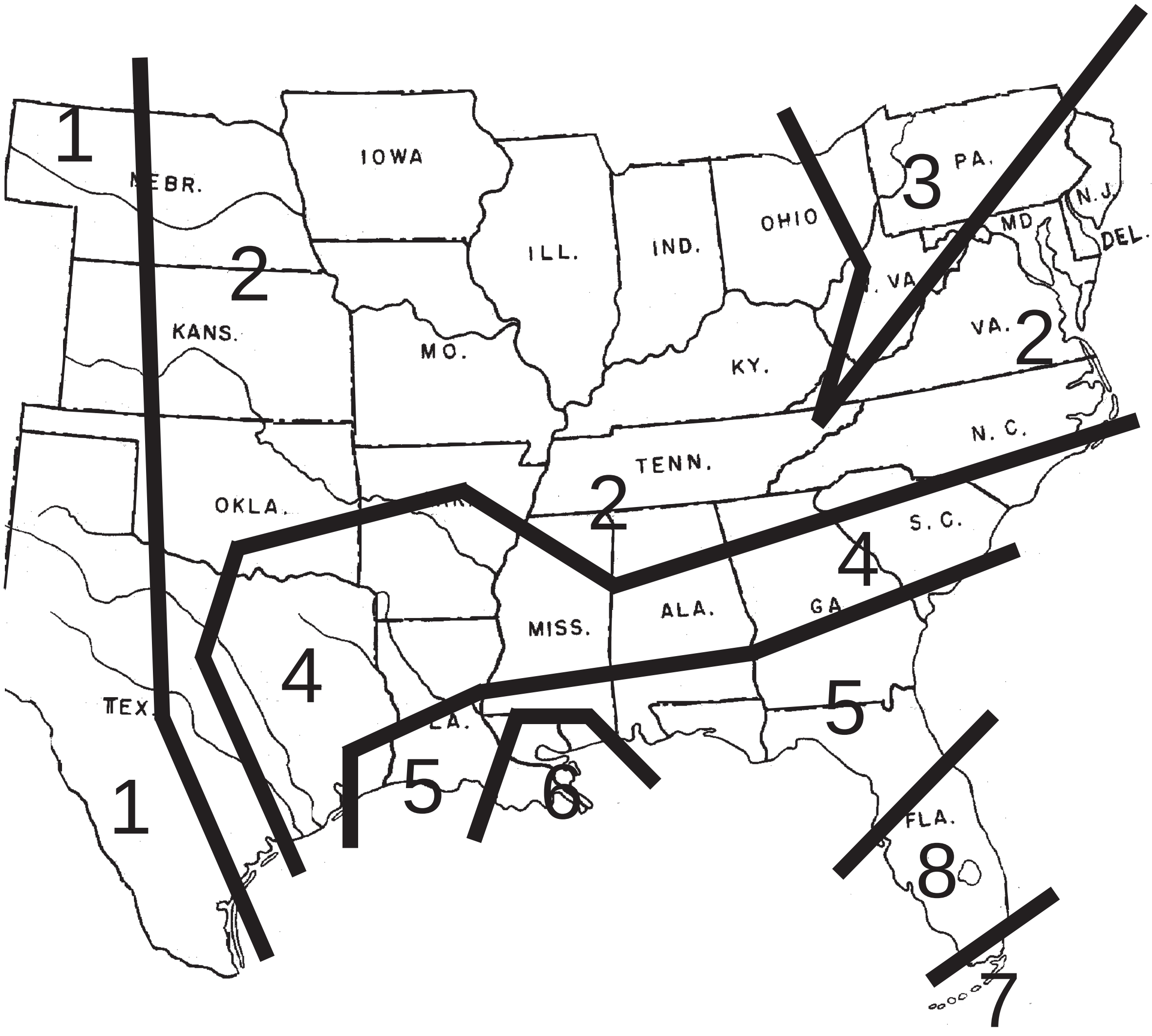


Figure 34: Areas of the Southeastern United States with similar composite multi-year average climatic features for the month of June. Composite data includes evaporation, precipitation, and temperature. Generally, the larger the number, the less water stress expected for tree growth over time under normal conditions.

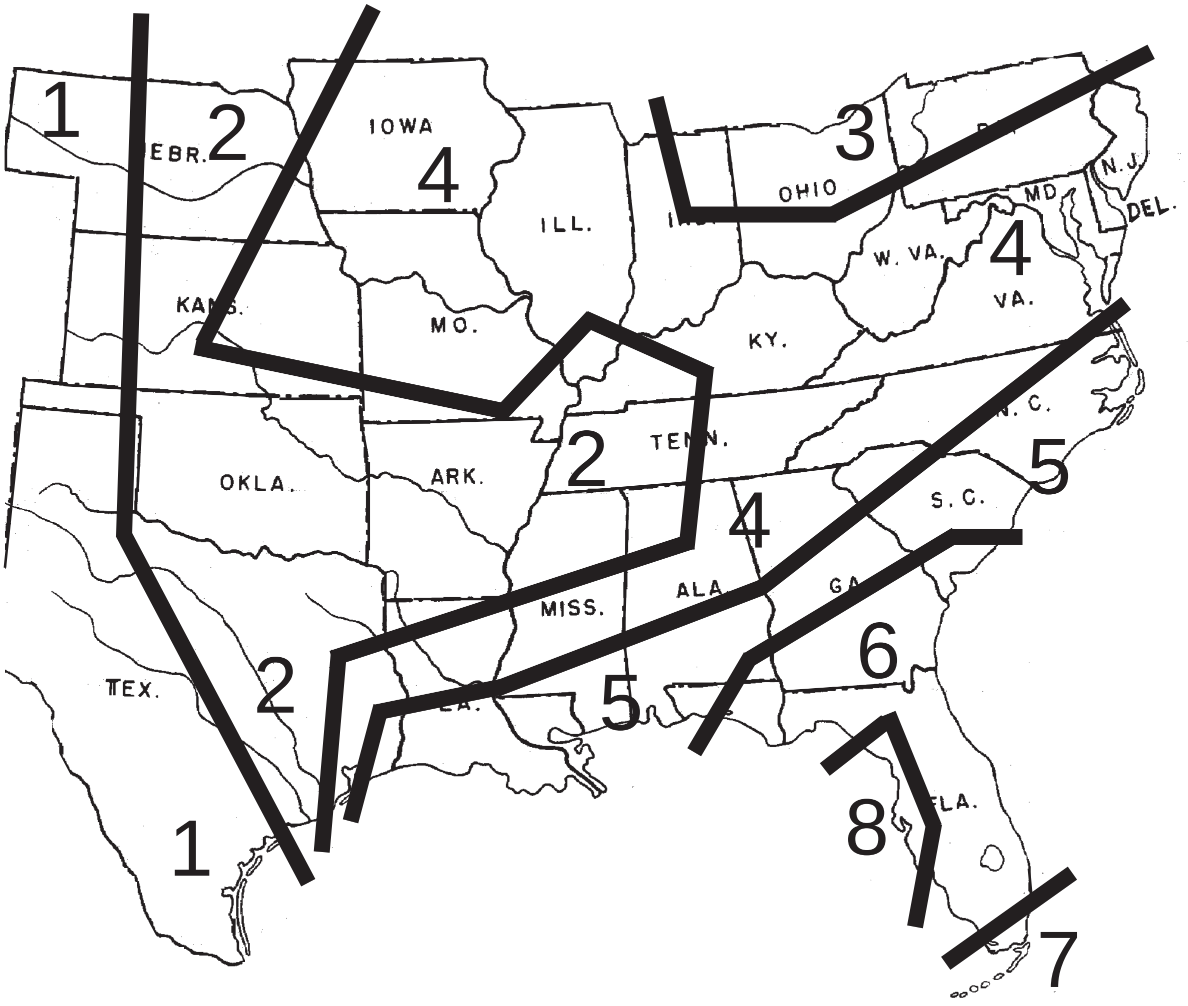


Figure 35: Areas of the Southeastern United States with similar composite multi-year average climatic features for the month of August. Composite data includes evaporation, precipitation, and temperature. Generally, the larger the number, the less water stress expected for tree growth over time under normal conditions.

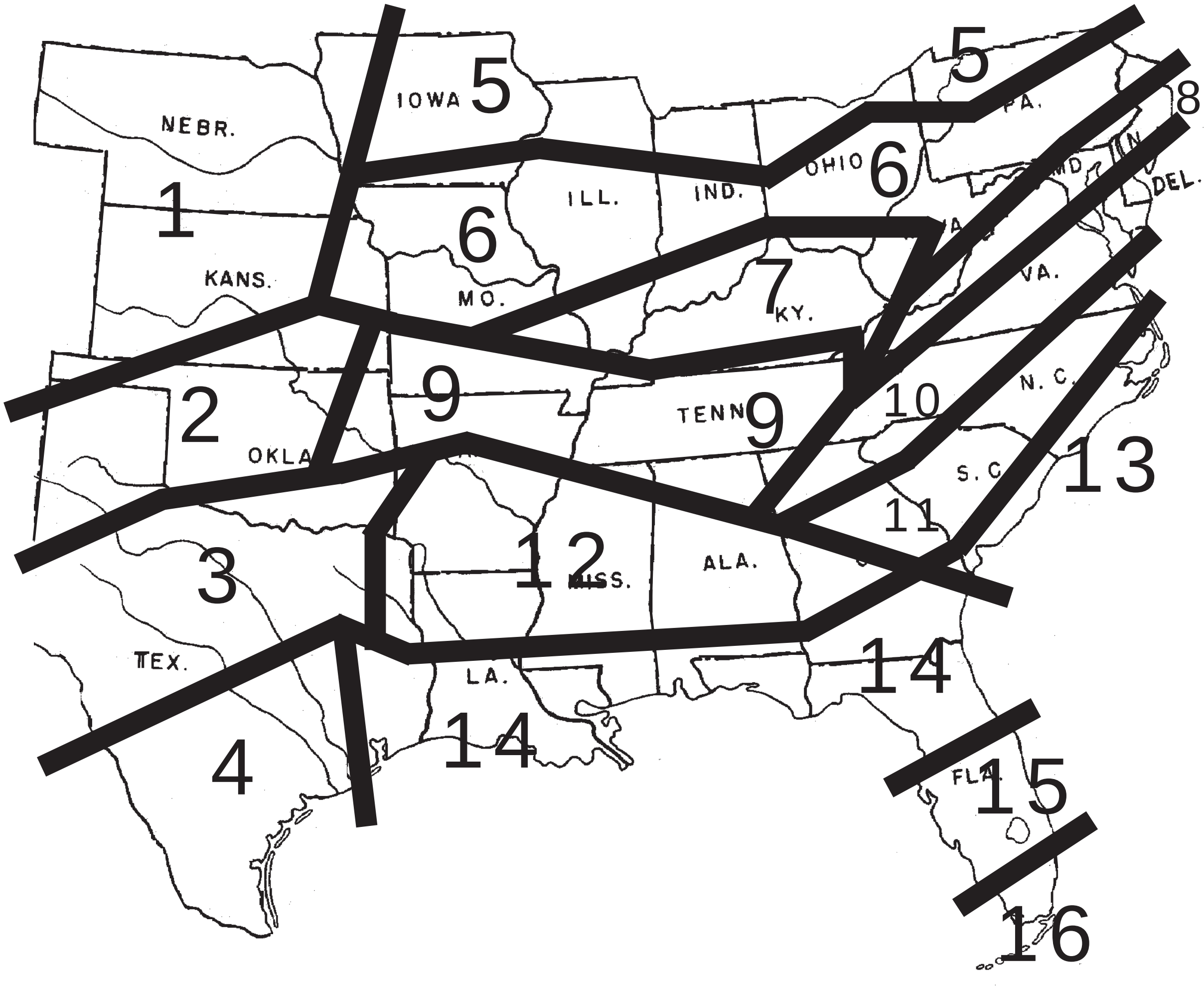


Figure 36: Areas of the Southeatern United States sharing similar composite climatic zones based upon annual average evaporation, temperature, and precipitation. Generally, the larger the number, the less water stress expected for tree growth over time under normal conditions. Prolonged drought conditions will have a more devastating impact the larger the number listed, although the risk of drought is less.

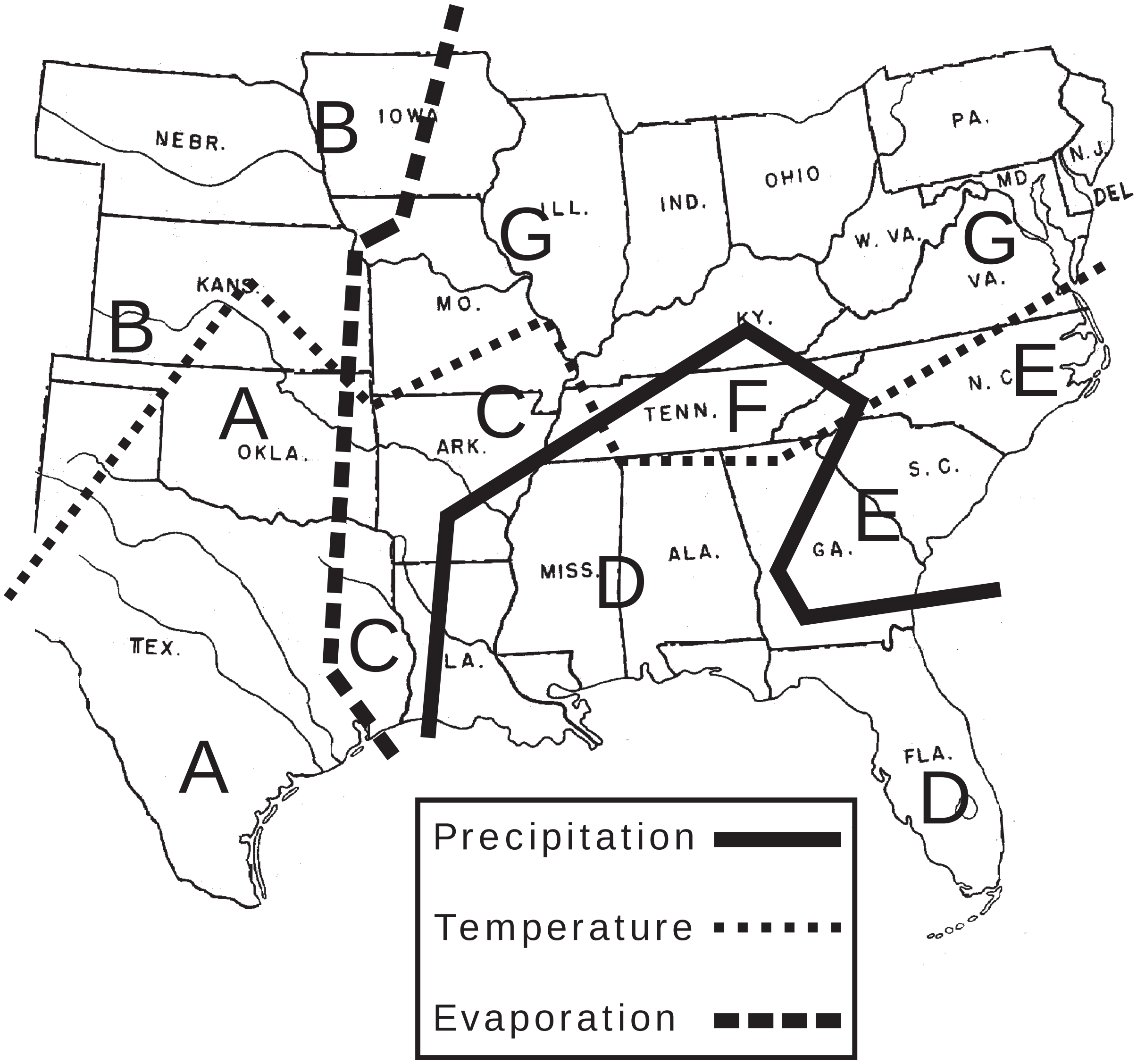


Figure 37: Tree Drought Potential Areas (A is greatest potential risk & G has the least risk):

A & B = marginal for trees with great drought potential;
C & E = hot zone, moderate precipitation & strong evaporation;
D = hot zone, good precipitation & strong evaporation;
F = somewhat cooler, good precipitation & moderate evaporation;
G = cooler on average, less precipitation & moderate evaporation.

Priority order for average climatic values setting up drought impacts: 1) south of heat line (77°F); 2) east of evaporation line (16 inches per month); and, 3) south of precipitation line (60 inches per year).

As drought continues and trees respond to decreasing water availability, various symptoms and damage occurs. Tree decline and death is the terminal result of drought.

Wilting

Wilting is a visible effect of drought. As leaves dry, turgor pressure (hydraulic pressure) pushing outward from within leaf cells decreases causing leaf petiole drooping and leaf blade wilting. The amount of water lost before visible leaf wilting varies by species.   Temporary wilting is the visible drooping of leaves during the day followed by rehydration and recovery during the night. Internal water deficits are reduced by morning in time for an additional water deficit to be induced the following day. During long periods of dry soil, temporary wilting grades into permanent wilting. Permanently wilted trees do not recover at night. Permanently wilted trees recover only when additional water is added to the soil. Prolonged permanent wilting kills trees.

The relation between water loss from leaves and visible wilting is complicated by large differences among species in the amount of supporting tissues leaves contain. Leaves of black cherry (*Prunus*), dogwood (*Cornus*), birch (*Betula*), and basswood (*Tilia*) wilt readily. Leaf thickness and size alone do not prevent wilting as rhododendrons are extremely sensitive to drought with leaves that curl, then yellow and turn brown. By comparison, the leaves of holly (Ilex) and pine (*Pinus*) are supported with abundant sclerenchyma tissue (i.e. tough, strong tissue) and do not droop readily even after they lose considerable water.

Closing-Up

One of the earliest responses in leaves to mild water stress is stomate closure. Stomates are the small valve-like openings on the underside of leaves which allow for gas exchange and water loss. Stomates often close during early stages of drought, long before leaves permanently wilt. Different species vary greatly in their stomate closing response. Gymnosperms usually undergo more leaf dehydration than angiosperms before they close stomates.

Many trees normally close stomates temporarily in the middle of the day in response to rapid water loss. Midday stomatal closure is generally followed by reopening and increased transpiration in late afternoon. Final daily closure occurs as light intensity decreases just before sundown.   The extent of midday stomatal closure depends upon air humidity and soil moisture availability. As soil dries, the daily duration of stomatal opening is reduced. When soil is very dry, stomates may not open at all. Under these dry conditions the tree can not make food and must depend upon stored food being mobilized and transported, if any is available. Drought cause a tree to run on batteries!

Stomatal Control

Trees resist excessive rates of water loss through stomatal regulation. Stomates can be controlled by growth regulators transported from the roots during droughts. Drought effects on roots, stomates and other leaf cells can limit photosynthesis by decreasing carbon-dioxide uptake, increasing food use for maintenance, and by damaging enzyme systems.

One effect of severe drought is permanent damage that slows or prevents stomatal opening when the tree is rewatered. Additional water supplies after a severe drought period will allow leaves to recover from wilting, but stomate opening (necessary for food production) to pre-drought conditions, may not occur for a long period after rehydration.

Stomatal closure will not prevent water loss. Trees lose significant amounts of water directly through the leaf surface after the stomates close. Trees also lose water through lenticels on twigs, branches, roots, and stems. Trees in a dormant condition without leaves also lose water.   Water loss from tree surfaces depend upon tissue temperature – the higher the temperature, the more water loss.

Leaf Shedding

Premature senescence and shedding of leaves can be induced by drought. The loss of leaves during drought can involve either true abscission, or leaves may wither and die. In normal abscission, an organized leaf senescence process including loss of chlorophyll, precedes leaf shedding. With severe drought, leaves may be shed while still full of valuable materials. Sometimes drought-caused leaf shedding may not occur until after rehydration. Abscission can be initiated by water stress but cannot be completed without adequate water to shear-off connections between cell walls. The oldest leaves are usually shed first. The actual physical process of knocking-off leaves is associated with animals, wind, or rain.

For example, yellow poplar (*Liriodendron*) is notorious for shedding many leaves during summer droughts, sycamore (*Platanus*) sheds some leaves, and buckeye (*Aesculus*) may shed all of its leaves as drought continues. On the other hand, leaves of dogwood (*Cornus*) usually wilt and die rather than abscise. If water becomes available later in the growing season, some trees defoliated by drought may produce a second crop of leaves from previously dormant buds. Many times these leaves are stunted.

Photosynthesis

A major drought effect is the reduction of whole-tree photosynthesis. This is caused by a decline in leaf expansion, changing leaf shapes, reduction of photosynthetic machinery, premature leaf senescence, and associated reduction in food production. When trees under drought are watered, photosynthesis may or may not return to normal. Recovery will depend upon species, relative humidity, drought severity and duration. It takes more time to recover photosynthetic rates after watering than for recovery of transpiration (food demand lag). Considerable time is required for leaf cells to rebuild full photosynthetic machinery.

Failure of water-stressed trees to recover photosynthetic capacity after rewatering may indicate permanent damage, including injury to chloroplasts, damage to stomates, and death of root tips. Often drought can damage stomates and inhibit their capacity to open despite recovery of leaf turgor. When stomatal and non-stomatal limitations to photosynthesis caused by drought are compared, the stomatal limitations can be quite small. This means other processes besides carbon-dioxide uptake through open stomates are being damaged by drought. Drought root damage has a direct impact on photosynthesis. For example, photosynthesis of loblolly pine seedlings were reduced for a period of several weeks when root tips are injured by drought, even after water has been restored.

Growth Inhibition

Growth of vegetative and reproductive tissues are constrained by supply of growth materials, transport, and cell expansion problems. Cell enlargement depends upon hydraulic pressure for expansion and is especially sensitive to water stress. Cell division generating new cells is also decreased by drought.

> **Shoot Growth** – Internal water deficits in trees constrain growth of shoots by influencing development of new shoot units (nodes and internodes). A period of drought has a multi-year effect in many species from the year of bud formation to the year of expansion of that bud into a shoot. Drought also has a seasonal effect of inhibiting expansion of shoots within any one year. The timing of leaf expansion is obviously later than shoot expansion. If shoot expansion is finished early, a summer drought may affect leaf expansion but not shoot expansion. In many trees, injury to foliage and defoliation are most apparent in portions of the crown that are in full sun. These leaves show drought associated signs of leaf rolling, folding, curling, and shedding.

Cambial Growth – Drought will effect the width of annual growth increments, distribution of annual increment along trunk and branches, duration of cambial growth, proportion of xylem to phloem, and timing and duration of latewood production. Cambial growth slows or accelerates with rainfall amounts.

Cambial growth is constrained by water supply of both the current and previous year. Last year's annual increment sets growth material supply limits on this year's growth. This year's drought will effect next year's cambial growth. Such a delayed effect is the result of drought impacts upon crown development, food production, and tree health. Drought will produce both rapid and delayed responses along the cambium.

Root Growth – Water in soil not penetrated by tree roots is largely unavailable. Trees with widely penetrating and branching root systems absorb water effectively, acting to prevent or postpone drought injury. A large root / shoot ratio reflects high water-absorbing capacity. Good water absorbing ability coupled with a low transpiration rate for the amount of food produced (high water-use efficiency), allow trees a better chance to survive drought conditions.

When first exposed to drought, the allocation of food to root growth may increase. This provides more root absorptive area per unit area of foliage and increase the volume of soil colonized. Extended drought leads to roots being suberized to prevent water loss back to the soil, and slows water uptake.

Biological Lag Effects

In determinant shoot growth species, environmental conditions during the year of bud formation can control next year's shoot lengths to a greater degree than environmental conditions during the year of shoot expansion. Shoot formation in determinate growth species is a two-year process involving bud development in Summer of the first year and extension of parts within the bud during the Spring of the second year. Drought during the year of bud formation in determinant growth trees decreases the number of new leaves formed in buds and new stem segments (internodes) present. Drought then influences the number of leaves, leaf surface area, and twig extension the following year when those buds expand.

Summer droughts can greatly reduce shoot elongation in species that exhibit continuous growth or multiple flushing. Drought may not inhibit the first growth flush, but may decrease the number of stem units formed in the new bud that will expand during the second (or third, etc.) flush of growth. If drought continues, all growth flushes will be effected.

For example in southern yellow pines (*Pinus*), late summer droughts will influence expansion of shoots in the upper crown to a greater extent than those in the lower crown. This is because the number of seasonal growth flushes varies with shoot location in the crown. Shoots in the upper crown normally exhibit more seasonal growth flushes than those in the lower crown. Buds of some lower branches may not open at all in droughts.

Drought Hardening

Trees previously water stressed show less injury from drought than trees not previously stressed. Trees watered daily have higher rates of stomatal and other tree surface water losses than trees watered less frequently. Optimum resource, unstressed preconditioning can lead to more severe damage from drought conditions. Trees challenged by drought conditions in this growing season tend to react more effectively to another drought period in the same growing season.

Advantage Pests

Drought predisposes trees to pests because of lower food reserves, poorer response to pest attack, and poorer adjustment after pest damage. Unhealthy trees are more prone to pest problems, and drought creates unhealthy trees. Attacks on trees by boring insects that live in the inner bark and outer wood can be more severe in dry years than in years when little water stress develops. But, little water and elevated temperatures can also damage pest populations.

Heat and water deficit stress problems make trees more susceptible to pests and other environmental problems. A number of pathogenic fungi are more effective in attacking trees when trees are under severe water deficit or heat stress. Heat loving bark borers and twig damaging beetle populations can swell under heavy tree heat loads and water deficits. Loss of defensive capabilities and food supplies allow some normally minor pests to effectively attack trees.

Water Tick

A classic pest which thrives under drought conditions at the expense of trees is the parasitic flowing plants leafy mistletoes (*Phoradendron* spp.). Trees under chronic water stress are especially damaged by mistletoe infections. Mistletoe must use tree gathered water, and generates much lower water potentials than tree leaves in order to pull in a greater proportion of tree water on a per leaf basis. Mistletoe has extremely poor water use efficiency and acts as a "water tick" on tree branches, leading to branch decline and death.

Supplemental watering of trees can be timed to help trees recover water and minimize pest problems on surrounding plants. Watering from dusk to dawn does not increase the normal wet period on tree surfaces since dew usually forms around dusk. Watering during the normal wet condensate period will not change pest/host dynamics. Watering that extends the wet period into mornings or begins wet periods earlier in the evening can initiate many pest problems, especially fungal foliage diseases.

Visible Symptoms

In deciduous trees, curling, bending, rolling, mottling, marginal browning (scorching,) chlorosis, shedding, and early autumn coloration of leaves are well-known responses to drought. In conifers, drought may cause yellowing and browning of needle tips. As drought intensifies, its harmful effects may be expressed as dieback of twigs and branches in tree crowns. Leaves at the top-most branch ends generate the lowest water potentials, and decline and die. Drought effects on roots cause inhibition of elongation, branching, and cambial growth. Drought affects root / soil contact (roots dry and shrink) and mechanically changes tree wind-firmness. Drought also minimizes stem growth.

Among the important adaptations for minimizing drought damage in tree crowns are: shedding of leaves; production of small or fewer leaves; rapid closure of stomates; thick leaf waxes; effective compartmentalization (sealing-off) of twigs and branches; and, greater development of food producing leaf cells. The most important drought-minimizing adaptations of tree roots are: production of an extensive root system (high root / shoot ratio); great root regeneration potential; production of adventitious roots near the soil surface; and, effective suberization and compartmentalization of root areas.

Therapeutics

Treatments for heat loading and water deficits (drought) conditions in trees include:

A. Watering, sprinkling, and misting for improved water supply, reduction of tissue temperature, and lessening of the water vapor pressure deficit;

B. Partial shading to reduce total incoming radiation but not filter photosynthetically active radiation;

C. Reflection and dissipation of radiative heat using colorants and surface treatments around landscapes and on trees;

D. Block or channel advected heat away from trees and soils (like berms and wooden walls);

E. Use of low-density, organic, surface covers, mulches or composted materials which minimize water loss, do not add to heat loading on-site, and do not prevent oxygen movement to roots;

F. Cessation of any nitrogen fertilizer applications in or around trees, and resumption only after full leaf expansion in the following growing season;

G. Prevent or minimize any soil active / osmotically active soil additions which increase salt index or utilize soil water for dilution or activation;

H. Be cautious of pesticide applications (active ingredients, carriers, wetting agents, and surface adherence) and performance under hot temperatures, low water availability, and with damaged trees;

I. Minimize green-wood pruning due to the trade-offs between wounding responses, transpiration loads, and food storage reserve availability;

J. Utilization of well-designed and constructed active shade structures in the landscape like arbors and trellises; and

K. Establish better tree-literate design and maintenance practices which deal with heat / water problems while monitoring other stresses (treat causes not symptoms!).

Assessing Soil Water Resource Space

Trees require high quality resources in the correct proportion to perform best. Water, and the soil volume which holds water, are critical to great tree growth. In trees, 80% of growth variability is due to water availability differences, and 85% of tree demand for water is related to the tree's evaporative environment and crown volume. To better assess soil water resource space needed for trees, a set of calculations can be completed. Two of these calculation methods will be used here -- the Coder Tree Soil Water Resources Assessment and the Coder Days Until Dry Containerized Soil Water Assessment. Specific calculations use measurable values to determine soil volumes required, which are based primarily upon water availability and tree needs. Do not guess at tree water needs – calculate!

The Coder Tree Soil Water Resources Assessment method used here can be completed in six (6) steps. Each step builds on previous steps to assure a reasonable amount of space and water can be provided for a tree. Figure 38.

Step #1 is used to determine crown volume of a tree. The larger the crown volume, the greater number of leaves, buds, and twigs, and the greater potential for water loss. The average crown diameter in feet squared is multiplied by crown height in feet. This value gives the volume of a square cross-section shaped crown. Trees are not ideally square shaped, so a reduction in the volume is made by picking a shape factor for a tree crown from Figure 39. The shape factor multiplied by crown volume provides the actual crown volume of a tree in cubic feet. Table 8.

> Crown Shape Factor – To accurately determine tree crown volumes, the size and shape of the living crown must be measured. Tree crown volumes are used to calculate daily water use. Standard linear dimensions of tree crowns, like height and diameter, are easily determined. Tree crown shape is another easily estimated value which can assist in more accurately calculating tree crown volumes. Calculations of tree crown volumes here consolidate variations within tree crowns by using calculations for solid geometric objects, helping simplify calculations.
>
> Table 8 provides names and formulae for a variety of different idealized crown shapes. Note that within the various formulae for crown shape, the only portion which changes is a single decimal multiplier value, referred to as a "tree crown shape factor" or a "shape factor multiplier." These formulae represent a calculated volume for an idealized round cross-sectional shape. All shapes are found along a calculation gradient from a multiplier of 0.785, to a multiplier of 0.098. Figure 39 helps graphically define idealized tree crown shapes which have the same diameter and height.

Step #2 is used to determine the effective crown surface area of the tree. The crown volume in cubic feet determined in Step #1 is divided by crown height in feet. The result is multiplied by an average leaf area index, here with a value of four (4). A leaf area index is an approximation ratio of how many square feet of leaves are above each square foot of soil below. This value depends upon tree age, species, and stress levels. Here a value of four for an average community tree is used. The result of the Step #2 calculation is the effective crown surface area of a tree in square feet.

Step #3 is used to determine the daily water use of a tree. The effective crown surface area in square feet is multiplied by three atmospheric factors which impact tree water use: daily evaporation

Figure 38: The Coder Tree Soil Water Resources Assessment method in six steps.

Step #1: Determine crown volume.

$$\left[\begin{array}{c}\text{crown}\\ \text{diameter}\\ \text{(ft)}\end{array}\right]^2 \times \begin{array}{c}\text{crown}\\ \text{height}\\ \text{(ft)}\end{array} \times \begin{array}{c}\text{shape}\\ \text{factor}\\ \text{(value)}\\ \text{[FIGURE 39]}\end{array} = \begin{array}{c}\text{crown}\\ \text{volume}\\ (\text{ft}^3)\end{array}$$

Step #2: Determine effective crown surface area.

$$\left[\begin{array}{c}\text{crown}\\ \text{volume}\\ (\text{ft}^3)\end{array} \Big/ \begin{array}{c}\text{crown}\\ \text{height}\\ \text{(ft)}\end{array}\right] \times \begin{array}{c}4\\ \text{(LAI)}\\ \text{leaf area index}\end{array} = \begin{array}{c}\text{effective crown}\\ \text{surface area } (\text{ft}^2)\end{array}$$

Step #3: Determine daily tree water use.

$$\begin{array}{c}\text{effective crown}\\ \text{surface area } (\text{ft}^2)\end{array} \times \begin{array}{c}\text{daily water}\\ \text{evaporation}\\ \text{(ft / day)}\\ \text{[FIGURE 40]}\end{array} \times \begin{array}{c}\text{pan}\\ \text{factor}\\ \text{(value)}\\ \text{[FIGURE 41]}\end{array} \times \begin{array}{c}\text{heat}\\ \text{load}\\ \text{(multiplier)}\\ \text{[FIGURE 30 \&}\\ \text{TABLE 7]}\end{array} =$$

$$\text{daily tree water use } (\text{ft}^3\text{ / day})$$

NOTE: 1 ft^3 water = ~7.5 gallons

Step #4: Determine tree water needs over a period of time.

$$\begin{array}{c}\text{daily tree}\\ \text{water use}\\ (\text{ft}^3\text{ / day})\end{array} \times \begin{array}{c}14\\ \text{(days)}\end{array} = \begin{array}{c}\text{two week}\\ \text{tree water needs}\\ (\text{ft}^3\text{ of water for 14 days})\end{array}$$

Step #5: Determine total soil volume needed for water storage.

$$\begin{array}{c}\text{two week}\\ \text{tree water needs}\\ (\text{ft}^3\text{ of water for 14 days})\end{array} \Big/ \begin{array}{c}\text{tree available}\\ \text{water in soil}\\ \text{(in decimal percent)}\\ \text{[TABLE 9]}\end{array} = \begin{array}{c}\text{total soil}\\ \text{volume needed}\\ (\text{ft}^3)\end{array}$$

Step #6: Determine ground surface diameter of the tree resource area.

$$\sqrt{\left[\begin{array}{c}\text{total soil}\\ \text{volume needed}\\ (\text{ft}^3)\end{array} \Big/ \begin{array}{c}\text{effective}\\ \text{soil depth}\\ \text{(ft)}\\ \text{[FIGURE 43]}\end{array}\right] \Big/ 0.785} = \begin{array}{c}\text{diameter of}\\ \text{resource area}\\ \text{(ft)}\end{array}$$

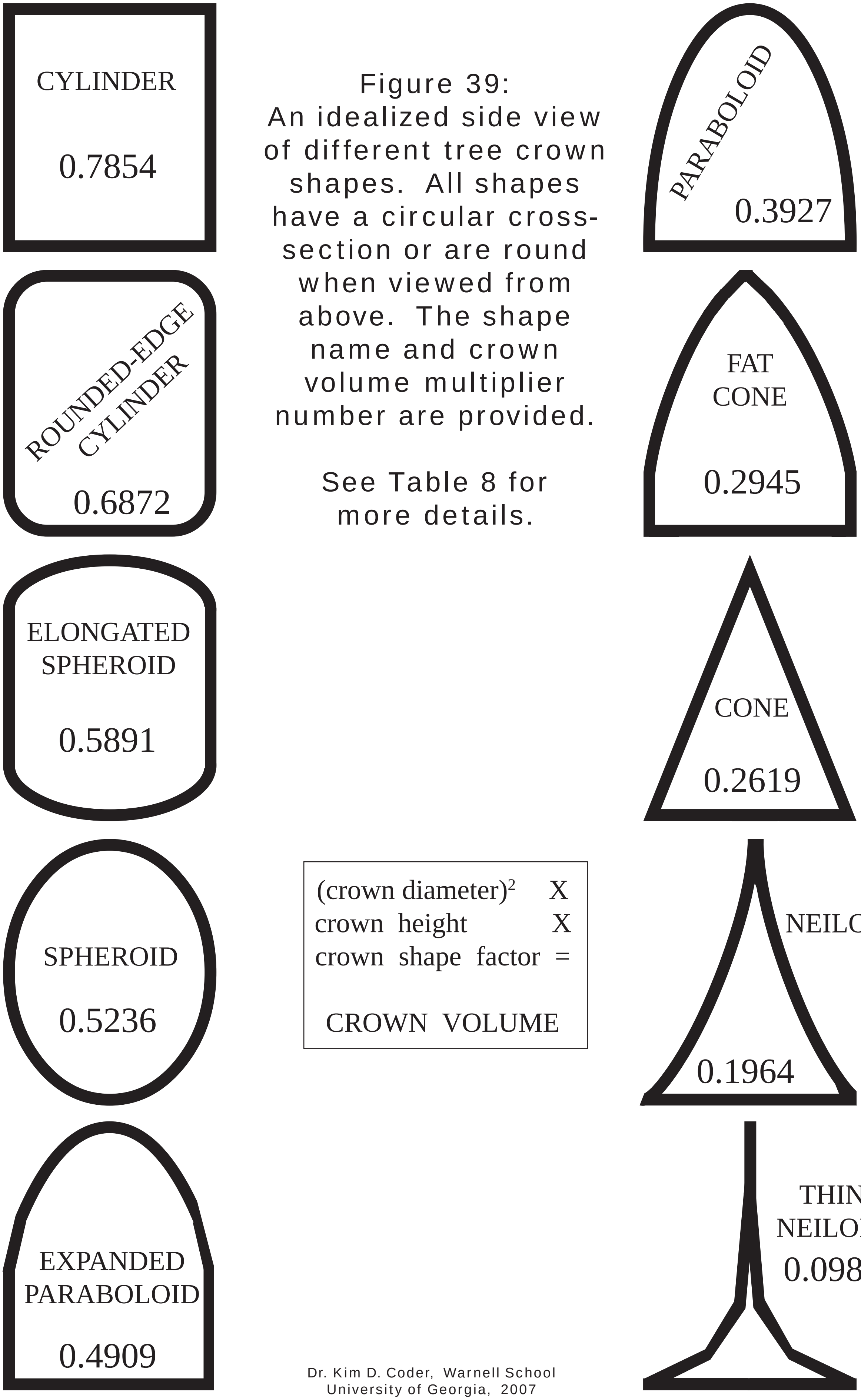


Figure 39:
An idealized side view of different tree crown shapes. All shapes have a circular cross-section or are round when viewed from above. The shape name and crown volume multiplier number are provided.

See Table 8 for more details.

(crown diameter)^2 X
crown height X
crown shape factor =

CROWN VOLUME

Table 8: Tree crown volume estimates for different crown shapes. Shape formula for these cylindrically based crown shape models range from a multiplier of 0.7854 for an ideal cylinder, to 0.0982 for a thin neiloid crown shape. Crown shape formula use crown diameter and crown height measures in feet to calculate crown volumes in cubic feet. The crown shape name is a descriptive approximation for visualizing idealized crown shapes based upon solid geometric figures. Figure 39 describes the shapes involved.

shape value	shape formula	shape name
8/8 (1.0)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.7854)	CYLINDER
7/8 (0.875)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.6872)	ROUNDED-EDGE CYLINDER
3/4 (0.75)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.5891)	ELONGATED SPHEROID
2/3 (0.667)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.5236)	SPHEROID
5/8 (0.625)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.4909)	EXPANDED PARABOLOID
1/2 (0.5)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.3927)	PARABOLOID
3/8 (0.375)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.2945)	FAT CONE
1/3 (0.333)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.2619)	CONE
1/4 (0.25)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.1964)	NEILOID
1/8 (0.125)	$(\text{Crown Diameter})^2$ x (Crown Height) x (0.0982)	THIN NEILOID

Note: Tree crown shape factors with multiplier values between 0.999 and 0.786 have a cylindrical appearing side view but would not have a circular cross-section. A multiplier value of 1.00 would be square in cross-section. Tree crown shape factors or multipliers greater than 0.785 are not shown here.

in feet per day (Figure 40); an evaporative pan factor (Figure 41); and, a heat load multiplier (earlier Figure 30 & Table 7). The result of this calculation is the daily water use of a tree in cubic feet (ft^3/day). For comparisons, one cubic foot of water is approximately 7.5 gallons ($1ft^3$ = ~7.5 gallons).

Step #4 is used to determine how much water a tree needs over time. The daily water use of a tree is multiplied by a value representing the average number of days in the growing season between normal rain events which can be daily rain in some places (multiplier = 1) up to once every 21 days (multiplier = 21). Here, for community trees on average sites, the multiplier value of 14 will be used (14 days between significant growing season rain events). This calculation generates a two week tree water needs amount in cubic feet of water.

Step #5 is used to determine total soil volume needed for supplying two weeks tree water needs amount over 14 days, from Step #4. Having plenty of water and no where to store it wastes water and trees. With no soil volume for storage, any water added will run-off and not be tree-usable. The two weeks tree water needs amount in cubic feet from Step #4 is divided by the tree available water in the soil as a decimal percent (Table 9 as modified by Figure 42). The result is the total soil volume needed for a tree in cubic feet over a 14 day water supply period.

Step #6 is used to determine diameter in feet of the required tree resource area on the ground surface centered upon a tree. The total soil volume needed for a tree in cubic feet value from Step #5 is divided by the effective soil depth in feet for storing tree-usable water. Figure 43. For most community trees the “compacted” values should be used. The result is multiplied by 0.785, with the answer taken to the 0.5th power (square root). The final number is the diameter of a resource area in feet which will supply a tree with water for 14 days.

One concern tied to the calculations above is with the use of percentages for soil water values. Actual inches of water per foot of soil represents real volumes while percentages are used in calculations. Figure 44 helps convert percent soil water into inches of water per foot of soil for use in irrigation and for measuring precipitation impacts on a site.

Contained Trees

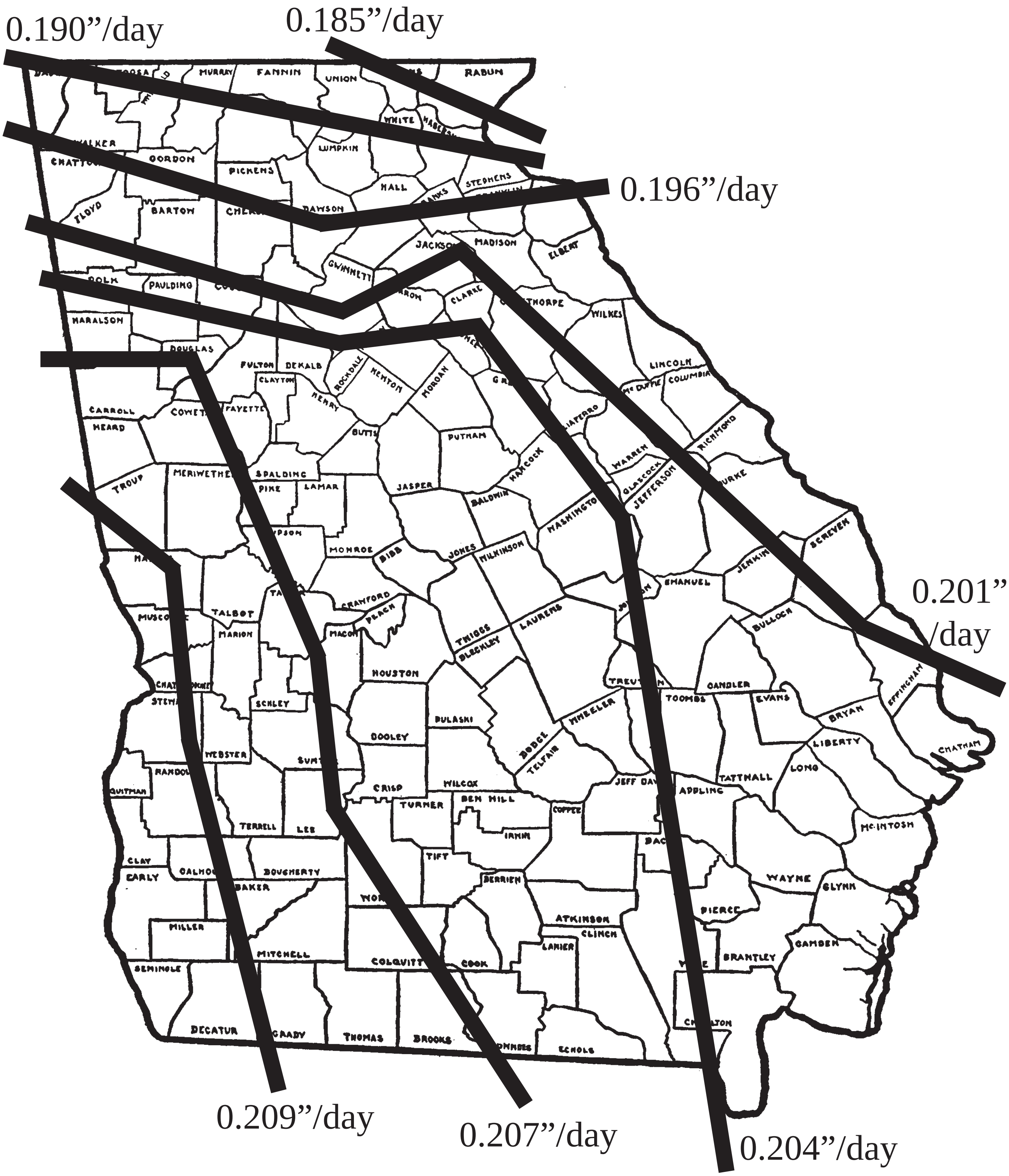
Another soil water assessment helps determine how many days without precipitation or irrigation under current site conditions can pass before a tree with a limited soil area can no longer extract water. The time period before a soil has no tree-usable water remaining is critical in preventing major tree damage. The Coder “Days Until Dry” Containerized Soil Water Assessment is targeted at in-ground and above ground containers, and sites where tree rooting space and soil resources are physically limited. This is only a basic estimate because each container or site will have unique attributes impacting water availability, and can not be accounted for within this simple calculation.

The Coder Days Until Dry Containerized Soil Water Assessment method is shown in Figure 45. This assessment can be completed in five (5) steps, the first three steps from the previous Coder Tree Soil Water Resources Assessment (Figure 38). Please see the previous text regarding this assessment and figures and tables needed for determining daily tree water use. The fourth and fifth step are unique to this assessment and are used to determine soil water volume available to the tree and how many days will pass before the soil is dry. Figure 45.

Five Step Assessment

Step #1 is used to determine the crown volume of a tree. The larger the crown volume, the greater number of leaves, buds, and twigs, and the greater potential for water loss. The average

Figure 40: An example from the State of Georgia. These evaporation data are available for most places. This map shows historic average daily pan evaporation during the growing season (May through October) in inches per day based upon average annual pan evaporation. Divide by 12 to calculate feet per day.



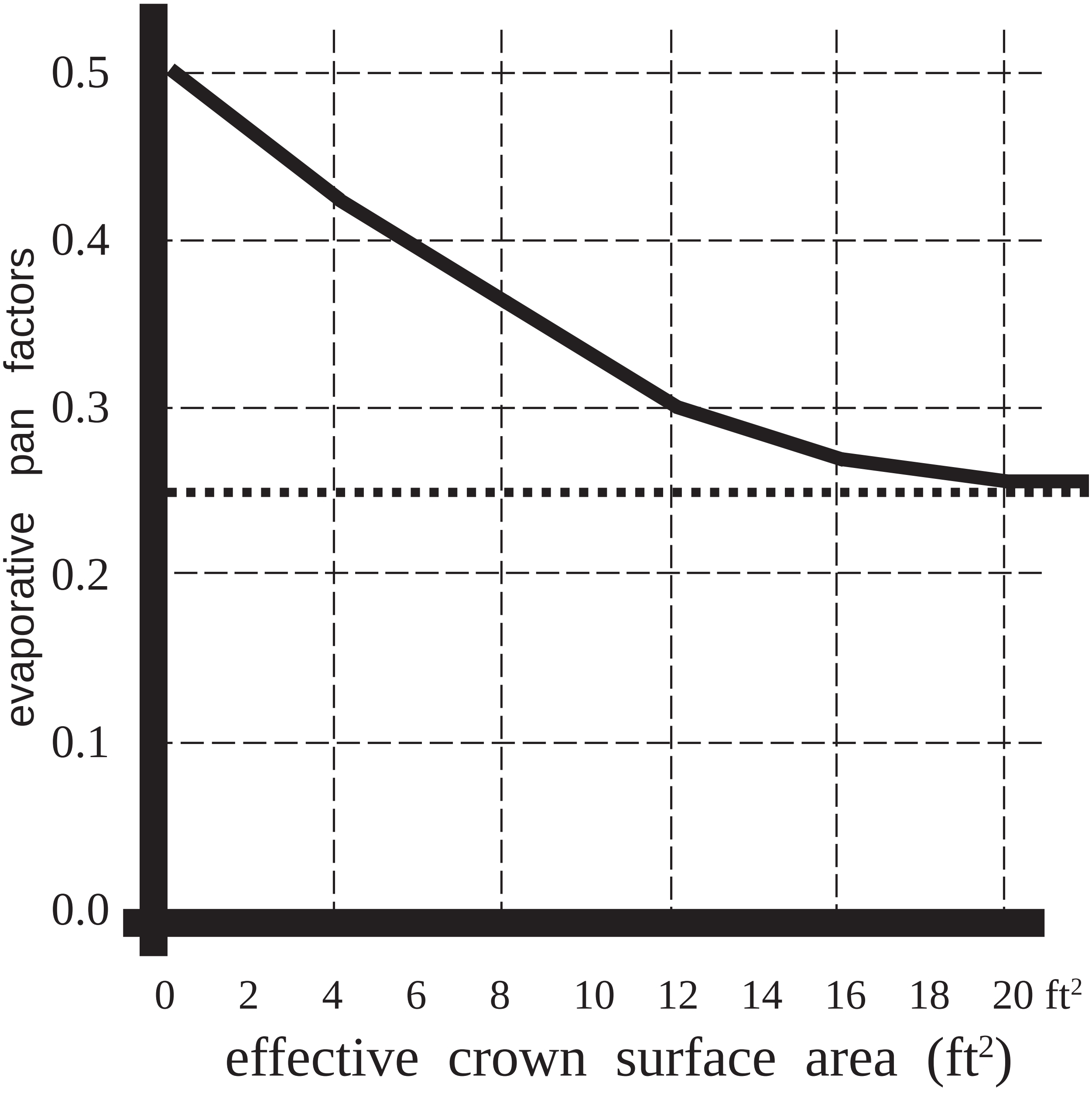


Figure 41: Ratio of tree transpiration to pan evaporation (pan factor or pan coefficient). Pan factors are not less than 0.25 for trees with larger than 20 ft^2 of effective crown surface area. (after Lindsey & Bassuk, 1992)

Table 9: Theoretical (T) and functional (F) tree available water values (in decimal percent) within soils of various textures under normal conditions and under compaction. Functional values should be used in assessments and were determined from Figure 42.

(after Cassel, 1983; Kays & Patterson, 1992; Craul, 1992 & 1999)

soil texture	tree available water (normal)		tree available water (compacted)	
	T	(F)	T	(F)
clay	.13	(.10)	.07	(.05)
clay loam	.17	(.13)	.08	(.06)
silt loam	.19	(.14)	.09	(.07)
loam	.18	(.14)	.09	(.07)
sandy loam	.11	(.08)	.06	(.05)
sand	.05	(.04)	.03	(.02)

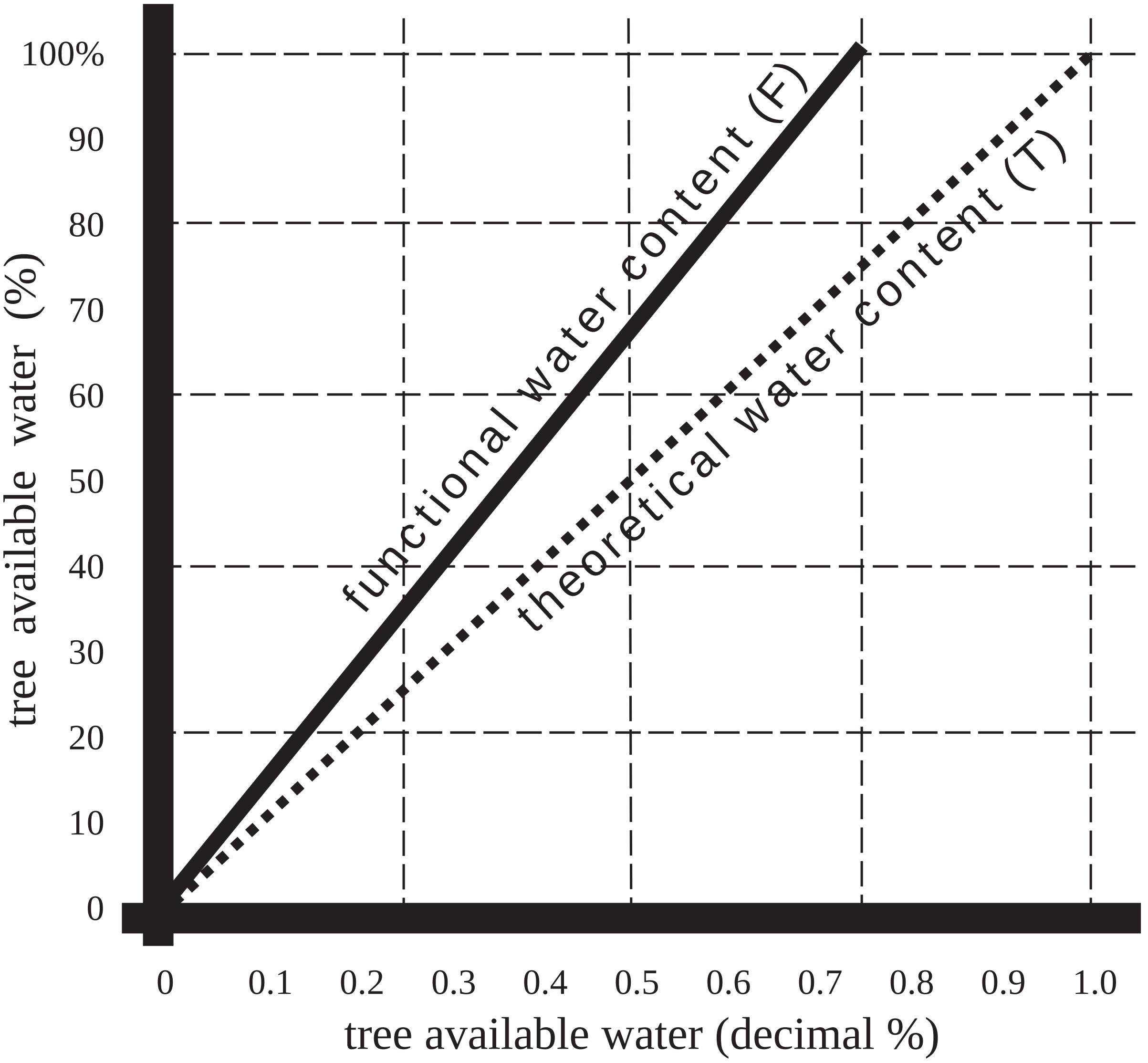


Figure 42: Estimate of functional tree available water in a soil compared with theoretical water availability. The functional water availability to a tree is less than the actual calculated amount of water in a soil. As soil dries, water is held progressively more tightly and the soil / root interface behaves as if there is less water in the soil. See Table 9. (after DeGaetano, 2000)

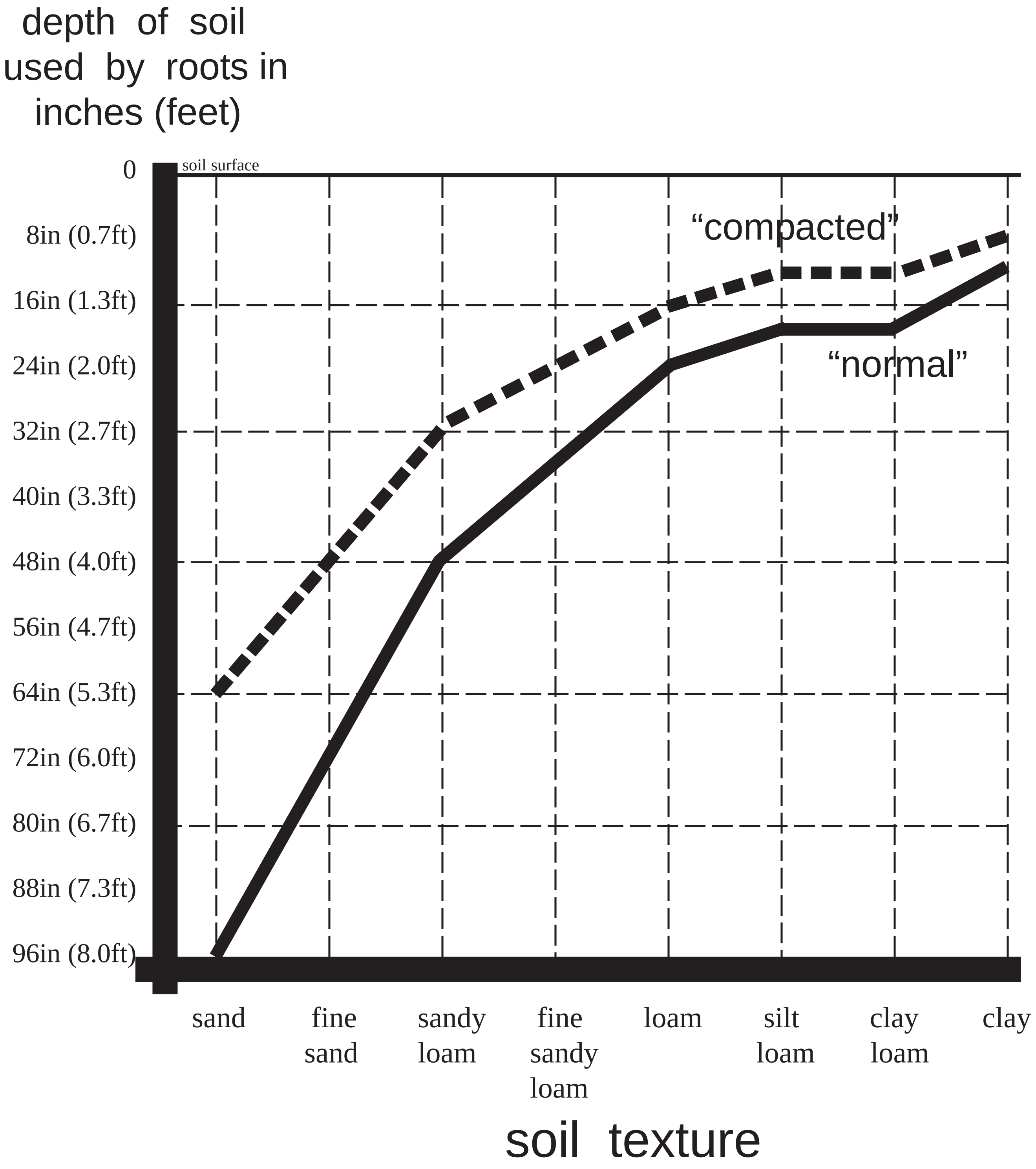


Figure 43: Effective soil depth used for defining biologically available resource depth in soils of various textures.

(solid line = normal; dotted line = moderate compaction)

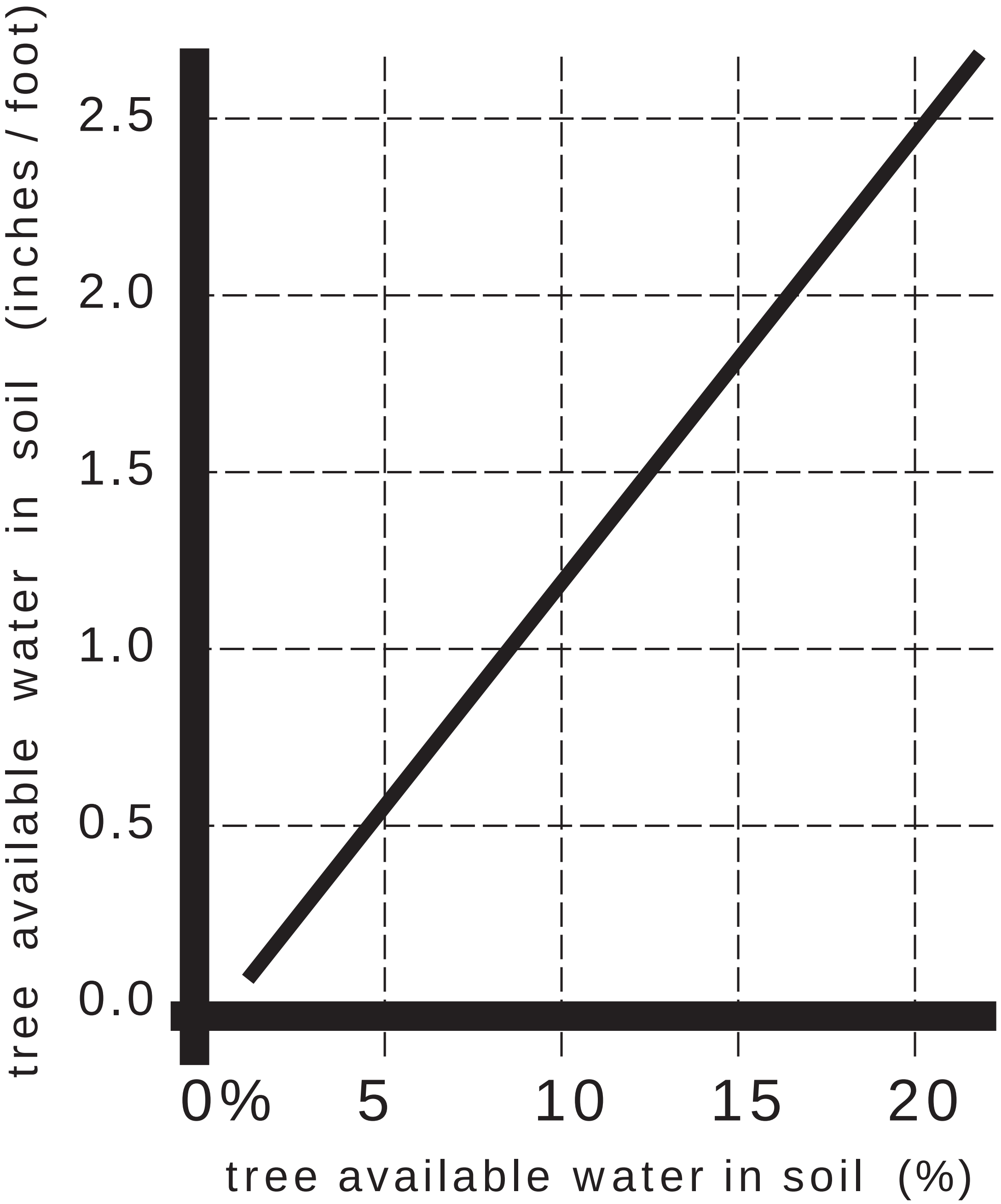


Figure 44: Estimated relationship between the percentage of tree available water in a soil and the number of inches of tree-available water per foot of soil.

Figure 45: The Coder “Days Until Dry” Containerized Soil Water Assessment method.

Step #1: Determine crown volume.

$$\left[\begin{array}{c}\text{crown}\\ \text{diameter}\\ \text{(ft)}\end{array}\right]^2 \times \begin{array}{c}\text{crown}\\ \text{height}\\ \text{(ft)}\end{array} \times \begin{array}{c}\text{shape}\\ \text{factor}\\ \text{(value)}\\ \text{[FIGURE 39]}\end{array} = \begin{array}{c}\text{crown}\\ \text{volume}\\ (\text{ft}^3)\end{array}$$

Step #2: Determine effective crown surface area.

$$\left[\begin{array}{c}\text{crown}\\ \text{volume}\\ (\text{ft}^3)\end{array} \Big/ \begin{array}{c}\text{crown}\\ \text{height}\\ \text{(ft)}\end{array}\right] \times \begin{array}{c}4\\ \text{(LAI)}\\ \text{leaf area index}\end{array} = \begin{array}{c}\text{effective crown}\\ \text{surface area } (\text{ft}^2)\end{array}$$

Step #3: Determine daily tree water use.

$$\begin{array}{c}\text{effective crown}\\ \text{surface area } (\text{ft}^2)\end{array} \times \begin{array}{c}\text{daily water}\\ \text{evaporation}\\ \text{(ft / day)}\\ \text{[FIGURE 40]}\end{array} \times \begin{array}{c}\text{pan}\\ \text{factor}\\ \text{(value)}\\ \text{[FIGURE 41]}\end{array} \times \begin{array}{c}\text{heat}\\ \text{load}\\ \text{(multiplier)}\\ \text{[FIGURE 30 \&}\\ \text{TABLE 7]}\end{array} =$$

$$\text{daily tree water use } (\text{ft}^3\text{ / day})$$

NOTE: 1 ft³ water = ~7.5 gallons

Step #4: Determine soil water volume.

$$\left[\begin{array}{c}\text{container}\\ \text{soil}\\ \text{volume}\\ (\text{ft}^3)\end{array} \Big/ \begin{array}{c}\text{total}\\ \text{soil}\\ \text{water}\\ \text{(d\%)}\\ \text{[Table 10]}\end{array}\right] \times \left[1 - \begin{array}{c}\text{soil}\\ \text{water}\\ \text{limit}\\ \text{(d\%)}\\ \text{[Table 10]}\end{array}\right] = \begin{array}{c}\text{soil}\\ \text{water}\\ \text{volume}\\ (\text{ft}^3)\end{array}$$

Step #5: Determine days until the soil resource area is dry.

$$\begin{array}{c}\text{soil}\\ \text{water}\\ \text{volume}\\ (\text{ft}^3)\end{array} \Big/ \begin{array}{c}\text{daily tree}\\ \text{water use}\\ \text{from Step 3}\\ (\text{ft}^3\text{ / day})\end{array} = \begin{array}{c}\text{days}\\ \text{until}\\ \text{dry}\end{array}$$

crown diameter in feet squared is multiplied by crown height in feet. This value gives the volume of a square cross-sectional shaped crown. Trees are not ideally square shaped, so a reduction in the volume is made by picking a shape factor for a tree crown from Figure 39. The shape factor multiplied by crown volume provides the actual crown volume of a tree in cubic feet. Table 8.

Step #2 is used to determine the effective crown surface area of a tree. The crown volume in cubic feet determined in Step #1 is divided by crown height in feet. The result is multiplied by an average leaf area index, here with an example value of four (4). A leaf area index is an approximation ratio of how many square feet of leaves are above each square foot of soil below and depends upon tree age, species, and stress levels. Here a value of four for an average community tree is used. The result of the Step #2 calculation is the effective crown surface area of a tree in square feet.

Step #3 is used to determine daily water use of a tree. The effective crown surface area in square feet is multiplied by three atmospheric factors which impact tree water use: daily evaporation in feet per day (Figure 40); an evaporative pan factor (Figure 41); and, a heat load multiplier (earlier Figure 30 & Table 7). The result of this calculation is the daily water use of a tree in cubic feet (ft^3/day). For comparisons, one cubic foot of water is approximately 7.5 gallons ($1ft^3$ = ~7.5 gallons). The daily water use of a tree determined here will be used in Step #5.

Step #4 determines the soil water volume present in cubic feet using values from Table 10. Because this assessment is designed for general container estimates, it is critical an accurate value for container soil volume be used. Container soil volume in cubic feet is divided by total soil water as a decimal percent (d%) for the soil texture used, as given in Table 10. This value is then multiplied by one minus the soil water limit (in soil with the same texture) as a decimal percent (d%), also given in Table 10. This limit is an approximation of the permanent wilting point for a soil.

Step #5 determines the number of days, under similar tree and site conditions, a soil volume can sustain water needs of a tree. Note there is no “grace” period of time included. If no irrigation or precipitation are added to soil water resources, a tree will be damaged or killed due to lack of water. Irrigation can be timed to always be applied before a soil is dry.

It is important tree health professionals better quantify soil volumes and surface areas when planning and installing hardscape surfaces and structures for a landscape which will contain trees. Trees must have adequate soil space and water for good performance.

Table 10: Total soil water and soil water limit (~ permanent wilting point) for various soil textures. Values given in decimal percents (d%).

soil texture	total soil water (d%)	soil water limit (d%)
clay	.39	.23
clay loam	.40	.20
silt loam	.39	.17
loam	.34	.14
sandy loam	.22	.09
sand	.10	.04

Supplemental Watering

Trees constantly lose water to the atmosphere. Water is the single most limiting essential resource for tree survival and growth. Water shortages severely damage young and old trees alike, and set-up healthy trees for other problems. Drought conditions can lead to tree decline, pest problems, and non-recoverable damage. Supplemental watering can greatly assist in maintaining tree health during droughts – both during the growing season or during the dormant season.

Save Assets

Trees can be old and valuable, and are usually considered non-replaceable beyond 10 inches in diameter. Many associated landscape plants are low cost and easily replaceable. If these plants are damaged or lost to drought, the landscape can be corrected quickly and relatively cheaply. Large, drought-killed trees can not be replaced in a time period spanning multiple human generations. Please emphasize watering trees during droughts.

BMPs

The best way to water a tree is by providing a burst of soil water followed by a drainage period. In fine soils like clay, the drainage period can be difficult to judge. In sandy soils with good drainage, a constant water supply could be used if no accumulation around the roots occur. Trees can be watered by irrigation which is applied when soil moisture reaches a certain level. Ideally, irrigation should automatically begin when soil moisture reaches some critical measure determined by a moisture probe or soil tensiometers. Careful tuning of irrigation systems are needed to prevent over-watering trees.

Manually, the best ways to water trees are by soaker hose or trickle (drip) irrigation which are turned on and off, as needed. Sprinklers are less efficient for applying water to trees than soaker hoses or drip irrigation, but are easy to use. Use a light organic mulch over the soil under a tree to conserve moisture and then apply water just under or over the top of the mulch.

Do not water at the base of the trunk as this can lead to pest problems. Always keep water application devices and saturation areas at least four feet (4 ft) away from the stem base. Always emphasize areas of soil away from foundations and hardscapes for water applications. Ideally strive to reach at least one-half (½) the tree rooting area under the tree crown for watering.

Sprinkles

Sprinkler systems use on hot days can waste a lot of applied water in evaporation. Water applied in the daytime does cools the soil and hardscapes through evaporation. If excess heat loading is a problem, sprinkling is the best way to dissipate heat around trees. Nighttime sprinkling is best for effective water use by the tree.

Set sprinklers near the outside edge of the tree crown beneath the foliage, assuring the sprinkler area is shaded if used in the daytime. Water should be applied to soak in well, not puddle or run-off the surface, and then drain from the soil. Trees will take up a good share of water even if surrounded by grass. Isolating / zoning trees in special tree watering areas apart from other plants, especially those in full sun, would be ideal.

Trickle irrigation is another excellent method of providing trees an adequate supply of water. Multiple emitters are needed scattered around the tree rooting area. Trickle irrigation maintains easily accessible water near tree roots. Soaker hoses, or even a garden hose moved often, can provide a good soaking. Do not allow water to be wasted by surface runoff or ponding on the soil for lengthy times.

Don’t Go Deep!

Deep watering a tree with a pipe or wand stuck down into the soil 12-24 inches is not as good for trees as surface applications, especially in finer textured soils. Most of the tree’s absorbing roots are in the top foot of soil. Applying water deeper than this level misses the active roots and allows water to drain away from the roots, wasting efforts and water. The net water movement in most soils is downward. Soil hydraulic conductivity and gravity allow little horizontal movement of water unless water is concentrated over a restrictive layer. Apply water across the soil surface and let it soak into the soil. Surface or near surface soaking allows tree roots more chances to absorb any water, maintains soil health, and helps maintain essential element cycling in soil.

Be Neat

Do not spray foliage, new shoots, and wounds of trees when watering at any time. The wetting action of water can initiate and sustain a number of pest problems. The only time you should spray tree foliage or wounds is when cleaning tree surfaces, such as trees in dusty environments. Cleaning sprays should be ideally completed when dew is already on tree tissues, or in daylight when there is sufficient time for tissues to dry before nightfall. Do not continually wet the trunk.

Place water hoses or applicators out to the tree crown edge (drip-line). Try to water the soil areas directly beneath foliage and shaded by the tree. Do not water beyond the drip-line and do not water closer than four feet from the trunk base on established trees. Be sure supplemental water soaks in well. Use mulch and slow application rates on slopes, fine soils (clays), and compacted soils to assure water is soaking-in and not running-off.

Placing Water

If a tree is surrounded with other landscape plants, or by turf, deep soaking water applications will benefit all. Young, newly planted trees need additional watering care. Water does not move sideways in a soil. Water must be applied directly over tree roots. For new trees, concentrate water over the root ball and into the planting area, to assure survival. Old, large trees can be extensively watered over the entire area under their foliage. Another method in watering large trees is to select roughly 1/3 the area within the drip-line for concentrated water applications often, while the whole area below the foliage can be watered occasionally.

Timing

The best time to water trees is at night from 10pm to 6am. Trees relieve water deficits (refill) over the night time hours. Watering at night allows effective use of applied water and less evaporative loss, assuring more water moves into the soil and tree. Night time application hours, when dew is already present, does not expand foliage wetting period for understory plants. This watering timing cycle minimizes pest problems.

The next best time to water is when foliage is dry and evaporation potential is not at its mid-day peak. This watering period is either in late morning as daytime temperatures have not reached their peak, or in late afternoon or early evening. Be sure to allow any dew to dry off foliage surfaces before applying, or assure a “dry gap” between atmospheric condensation and watering to help minimize pests which require longer wetting periods. This is especially critical where turf surrounds a tree.

Watering Seasons

Because trees lose water day to day, month to month, and season to season – dormant season watering during winter drought is important, especially for evergreen trees and juvenile hardwood trees that have not lost their leaves. Because of temperature and relative humidity interactions, much less water is required in the dormant season, but water is still needed. Do not water in the dormant season when the air temperature is less than 55°F.

Heat Interactions

For every 18°F increase in temperature above 40°F, the amount of water lost by a tree and site almost doubles. This feature of water loss must be factored into applying supplemental water to a tree. Trees surrounded by pavement and other hot, hard surfaces can be 20-30°F warmer than a tree in a protected, landscaped backyard. Water use rapidly climbs with increasing temperatures, and so should water application volumes.

A tree can use a large amount of water on a summer's day if water is available in the soil. Twenty to eighty gallons of water being pulled through a tree is common. A large maple in moist soil was once logged using 500 gallons on one hot, sunny day. These amounts of water were under ideal water availability conditions. The drier the soil, the less water is available and the less water used.

How Much?

Depending upon soil texture, daily temperatures, and rainfall amounts, 1 to 2 inch-equivalents of water per week should keep a tree alive. Five gallons per square yard is about 1 inch of water. Trees in limited rooting areas, in containers or pots, or on major slopes, need additional care to assure water is reaching the root system in adequate amounts and not suffocating roots from lack of drainage. Fine soils require careful attention to prevent over-watering, anaerobic conditions, and root death.

Sandy soils can be severely droughty because water runs out of the rooting zone quickly. There are some water holding compounds that are commercially available for keeping water near roots. In addition, composted organic material additions and organic mulch covers on the soil surface can help hold and prevent rapid loss of applied water. In all cases water use formula should be used to determine tree water requirements!

How Often?

In the growing season, trees should be watered once or twice a week if there has been no rainfall. A few heavy (high volume) waterings are much better than many light, shallow waterings. A greater proportion of the applied water is utilized by a tree with heavy watering. Once watering begins you should continue to water until rains come. Tree root systems will survive close to the soil surface to utilize supplemental water. If supplement watering is suddenly withdrawn, large sections of root system may be damaged. Trees use water all year round. Dormant season watering during winter droughts can help trees. In the winter or dormant season, trees should be watered once every two weeks it does not rain and the air temperature is above 55°F.

Competition

Many plants in a small area will all be competing within soil to pull out enough water for themselves. This water competition can be severe, especially for plants in full sun. Water competition will inhibit or slow tree growth. Remove excess plant competition from around any tree to decrease water stress. Use mulch to conserve water and prevent weed competition. Careful applications of herbicides can also reduce weed competition for water, but severe drought conditions can lead to unexpected results. Plants under trees which are not in full sun for any part of the day are not as competitive for water as vines and grass which receive partial full sun.

Hard Water

The water we take from nature can be loaded with dissolved materials, many essential to trees. When water is modified for human consumption, changes can occur which could lead to long-term tree problems. For example, one traditional nemesis of natural water use by humans has been dissolved calcium and magnesium salts, called “hard water.” Soaps react with calcium and magnesium, generating an insoluble film while detergents do not. Trees are not bothered by calcium and magnesium in water except at high mineral concentrations at high pH. Calcium and magnesium can be removed from household water (“softening water”) by adding lime and sodium carbonate producing two insoluble products which can then be filtered. Ion-exchange systems soften water by trading sodium or hydrogen ions for calcium and magnesium. Sodium build-up in soils and acidification of irrigation water can cause tree problems. In addition, grey water use and chlorination systems produce unique problems for water use by trees.

Conservation Ideas

Xeriscaping, developing water-efficient landscapes, water harvesting, cistern use, gray-water use or drought proofing concepts are becoming more important. There are a number of ideas involved in developing a water-efficient landscape, when integrated wisely, can help conserve water while providing a functional and aesthetically pleasing tree-filled landscape. Trees remain a critical part of any water-efficient landscape.

Gray-Water Use

Drinkable water becomes more valuable every year. Some communities restrict water use periodically, curtailing outdoor watering when shortages occur. Water restrictions can be disastrous for young, old, and valuable trees which depend on irrigation to become established or survive.
In times of water shortage, slightly used potable water can provide an alternative tree irrigation water source. Separating slightly used water (gray-water) from sewage (black-water) makes good conservation sense.

Gray-water is a water conserving alternative which merits a close look for tree use in times of drought, or for general tree irrigation. Homeowners and small service businesses tend to waste an average of 1/3 of drinking quality water delivered from wells or public water authorities. A major amount of this water is used for diluting toilet, sink and laundry wastes, and for rinsing hands, bodies, and clothes in sinks, showers and laundries. Every day many gallons of drinkable water are used for tree irrigation, which could employ gray-water.

Restricted!

It is important to note storing and surface applications of gray-water are against health codes in many counties and municipalities. Check with your local health department and/or state environmental water quality regulators for additional information about using gray-water for trees at your address. Also, note this information is for educational use, and does not constitute a gray-water system design or installation standard.

Water By Another Name

Gray-water is potable water which has already been used once, and which can be captured and reused. Gray-water includes: discharge from kitchen sinks and dishwashers (NOT garbage disposals); bathtubs, showers and lavatories (NOT toilets); and, household laundry (NOT diaper water). Using gray-water can greatly increase home water-use efficiency (+20% to +33%) and provide a water source for tree irrigation.

Unfortunately, many health regulations consider any non-drinkable water as black-water or sewage. Many plumbing and health codes do not accept gray-water for reuse because of health risks. For the legal status of gray water in your community, county and state, consult your local building codes, health officials, sanitation engineers and pollution control officials. Many levels of government are now examining if and when gray-water could be used for water conservation.

Would It Make A Difference?

Gray-water separation and use could conserve 20 to 33 percent of drinkable water for re-consumption. Community-wide gray-water use could allow a reduction in the size of water-purification and sewage-treatment facilities. Across the nation, toilet flushing and general landscape irrigation are major home uses for drinkable water. The most effective use of gray-water is for flushing toilets and watering landscapes. Imagine the water conservation benefits from using gray-water for just these two purposes!

What's In It?

Gray-water composition depends on the water source, plumbing system, living habits and personal hygiene of the users. Attributes of gray-water are impacted by cleaning products used, dishwashing patterns, laundry practices, bathing habits, and disposal of household chemicals. The physical, chemical and biological characteristics of gray-water, and when it could be used, varies greatly among families and service businesses.

Table11 provides an average home gray-water generation pattern. Table 12 provides the average characteristics of gray water compared with total (combined) wastewater coming from a home. Notice at normal use concentrations, few materials in gray-water will damage trees if they are applied to a healthy soil. Also, few detrimental soil changes will occur from continuous, well managed gray-water applications.

Gray-water does have several unique characteristics of note -- grease, heat, and particles. Gray-water usually contains large concentrations of oils and grease. Use of a grease trap, and remembering not to pour grease, oils or fats down the drain, minimizes these components. Gray-water is significantly warmer than normal wastewater streams by as much as 15^{o}F. Gray-water also contains a large amount of fibers and particles. Filters must be used to remove these materials before gray-water enters soil or an irrigation system.

Avoiding Trouble

Some materials and water inputs should not be allowed to enter a gray-water collection system for use with trees. Items to avoid include: cleaners, thinners, solvents and drain openers; cleaning and laundry materials containing boron; artificially softened water (softening water replaces calcium and magnesium ions with sodium ions which can initiate severe soil and tree problems); and, drainage water from swimming pools and hot tubs (contains high salt concentrations, and a variety of chlorine and/or bromine compounds.)

Human Health Concerns

Properly treated and continuously monitored gray-water can be a valuable and safe resource for tree irrigation in landscapes. However, ignoring problems and not checking the system periodically can lead to human health and maintenance difficulties. Gray-water held for any length of time can build-up tremendous bacteria loads. Misused gray-water can spread typhoid fever, dysentery, hepatitis and other bacterial and viral problems. Disinfection is critical for gray-water held more than two (2) hours. Health hazards, especially eye contact and dermatitis problems arise from dissolved and suspended organic materials and detergents. To make it easy to identify and to prevent usage mistakes, a vegetable dye can be added to gray-water. In new installation or in a plumbing retrofit, the use of colored pipes to identify lines carrying gray-water is useful.

Collect & Hold

There are three principal ways of collecting and holding gray-water in a household setting:

1) **Pot & Carry** -- This simply collecting water from laundry rinses, sinks and baths by hand. This way of collecting, carrying, and applying gray-water has been used since ancient times. When water had to be drawn by bucket, many uses were made for each gallon.

2) **Plumbed Holding Tank** -- Gray-water can be piped (either in new construction or as a retrofit) from selected household drains to a holding tank. Gray-water from the shower, bathroom sink, or kitchen sink without a garbage disposal, can be carried in drain pipes into an above-ground, usually inside the house, holding tank.

This system uses gravity to move gray-water into the tank and a pump to remove it. The gray-water tank should be durable and non-corrodible. (Never reuse containers for holding tanks that once held corrosive chemicals, wood preservatives, organic solvents or pesticides. Even minute traces of these chemicals might kill trees). Holding tanks will require an attached disinfection unit. Tank size depends upon available space and the amount of gray water produced.

Table 11: Potable water use of an average household during the growing season. Note 57% of non-waste containing water (gray-water) could potentially be reused for tree irrigation and the outdoor watering use of potable water saved.

source	percent of water use	
toilet		**31%**
kitchen	**10%**	**57%**
lavatory	**22%**	
laundry	**20%**	
miscellanous	**5%**	
outdoor watering		**12%**
	total =	**100%**

Table 12: Average characteristics of household gray-water compared with the total waste water stream from a household.

gray-water component	gray-water average (ppm)	gray-water as a percent of total waste water
total solids	530	46%
suspended solids	160	68%
biochemical oxygen demand	200	62%
chemical oxygen demand	365	59%
ammonia (NH_4)	2	1%
total nitrogen	10	7%
detergents	20	--
total phosporus (P)	1.5	7%
potassium (K)	10	18%
calcium (Ca)	1	1%
magnesium (Mg)	3	50%
iron (Fe)	15	94%
chlorides (Cl)	45	32%
sodium (Na)	75	43%
grease	100	98%
temperature	122°F	100°F

total coliform bacteria = 7.1 million per ounce (96X black-water)
fecal coliform bacteria = 0.4 million per ounce (35X black-water)

If gray-water supplies are inadequate for irrigation needs, potable water may be required to supplement the system to keep it full. Be sure to install one-way valves to prevent contaminating drinkable water systems with gray-water due to backflow or siphoning problems. Install an overflow line with a one-way valve to allow excess gray-water to flow into the sewer or black-water septic system.

Tank placement is important for gravity feed, maintenance and aesthetic reasons. Because of warm water temperatures and high humidity levels around the tank, a sealable cover and good air circulation are critical. Elevated humidities in a wood-frame house, for example, can lead to many structural and aesthetic problems. Also, consider personal safety issues to prevent child and pet injury and/or entrapment.

3) **Second Septic System** -- Install a gray-water "septic" tank below ground for collection and holding gray-water. Whether you are hooked into a city sewer system or a private leach field for black-water, gray-water can be held in a separate in-ground septic tank or vault. A gray-water septic tank can be designed to use seepage lines that are dug into the root areas of valuable trees. No disinfection is required, only a coarse filter and grease trap. This type of system is designed for below soil surface distribution only.

In-ground septic tanks can provide a low-maintenance means of using gray-water for landscape trees. Like a black-water septic tank and drain field, a gray-water septic tank and seepage lines must meet all local and state health codes. Seek installation advice from sanitation engineers. Gray-water from this gray-water septic tank should never be pumped without disinfection onto the landscape.

Filter & Disinfect

If gray-water is not to be held and is used immediately upon generation, several concerns should be understood. Disinfecting and filtering gray-water removes solids, prevents odors, controls turbidity, minimizes foaming, and eliminates most health hazards. Before you can use gray water on the landscape, it must be filtered to remove particulate, fiber and floating materials. A grease trap is critical to prevent filter plugging and clogging emitters or soaker hoses.

Gray water held more than two (2) hours must be disinfected because it contains more harmful bacteria than black-water (sewage). Tablet or liquid solutions of chlorine, ultraviolet light or heat can disinfect gray water. Chlorine is most commonly used. A chlorine concentration of 0.5 ppm will disinfect gray-water. As gray-water is held overnight or longer, the chlorine slowly moves out of solution. Any chlorine remaining from laundry wastewater is too dilute to disinfect a gray-water holding tank. To ensure proper disinfection, use a dosing pump to measure chlorine input for every unit of water volume.

Spreading The Wealth

Correctly filtered and disinfected gray-water can be applied through normal irrigation systems. To meet most sanitation regulations, gray-water must be applied somewhere below the soil surface. Avoid sprinkling or forcing gray-water into an aerosol. In some areas, surface applications by soaker hose is acceptable, providing standing puddles and runoff do not occur. Gray-water surface runoff can cause serious erosion and disruption of stream and lake chemistry. Avoid concentrated watering near wells and significant groundwater recharge areas due to potential groundwater pollution. It is important to carefully monitor application and infiltration rates.

Soil Impacts

Gray-water has few long-term effects on soil. Gray-water slightly modifies soil-organism populations and usually initiates no additional pest problems. Changes occurring are usually due to additional water present and lack of adequate drainage. Over-watering and extended periods of soil saturation with gray-water (or regular irrigation water) can cause severe root problems for trees.

Normal residual detergents and soaps are diluted enough for quick degradation in healthy soils. Chlorine bleaching materials, due to their volatility and the warmth of the water, are quickly dissipated or tied-up in soil, especially when applied to medium and fine-textured native soils. However, when applied to coarse sandy soils with little organic matter, tree absorbing-root damage can occur. Organic matter and soil-texture adjustments are critical in raised beds with gray-water irrigation. Do not use gray-water on trees with severely limited root areas or for hydroponics.

Tree Care

Gray-water has few detrimental effects on trees growing in native soils. Acid-loving plants, however, can have problems because detergents make water more alkaline and pH modifications may be occasionally required. Some of the gray-water and tree health issues to understand and manage include:

A) Be sure trees are high-priority watering items under drought and water restrictions because of their individual cultural and biological value.
B) Use gray-water when natural precipitation is not available.
C) Apply gray-water to soil surface or below, never spraying on foliage, twigs or stems. Apply over or under mulch, if present.
D) Never soak bark or root-collar area.
E) Do not spray edible tree parts, or on soils where water splash can move gray water onto edible tree parts.
F) Do not use on or near root or leaf crops consumed by people or domestic livestock.
G) Do not use on new transplants until absorbing root growth has successfully grown into native soil.
H) Do not use on indoor trees with limited rooting space, trees in small containers, or trees normally under saturated conditions (wetlands).
I) Avoid using micro or regular sprinkler heads that can blow gray-water aerosols downwind.
J) Be careful of applications that apply gray-water directly to the leaf surfaces of ground covers and turfgrasses below and around trees.
K) Control gray-water application and infiltration to prevent standing puddles and surface runoff.
L) Test soil periodically to reveal salt, pH, and boron toxicity problems.

Conserving Water -- Under some water restrictions and drought conditions, saving gray-water for tree irrigation is good for trees and landscapes. Using gray-water conserves one of our most precious resources. If managed properly, gray-water creates few detriments and many benefits.

Drought Resistant Trees

One long-term approach to dealing with tree heat and drought problems in a landscape is to plant drought resistant trees. Drought resistance requires tree leaves use water efficiently and continue to grow and make food at relatively low water potentials. Drought resistance involves characteristics like extensive root systems, thick leaf waxes and bark, good stomatal control, and the capacity for leaf cells to function at low water contents.

Resistance

The differences among trees to tolerating heat loads and water deficits revolve around enzyme effectiveness and membrane health. The better enzymes and membranes can be protected from heat effects, the more effective the tree will be in dealing with large heat loads and associated water deficits. Protection or deactivation of enzyme systems in trees due to heat and water deficits are influenced by pH, solute levels in cells, protein concentrations, and protection mechanisms. The ability of a tree to continue functioning demonstrates resistance mechanisms which are primarily genetically controlled. Each individual usually has a wide range of plastic responses to heat and water stress, some of which involve physical and ecological attributes.

No tree-filled landscape can be made completely free of drought problems even under intensive irrigation. With more water shortages and drought periods ahead, planting trees which are drought resistant can be beneficial. Once a drought resistant tree is established it can survive drought periods for short periods during the growing season. There are many lists of drought resistant trees available. The basic characteristics of trees that use water efficiency and are somewhat drought resistant are given below. Note this list is for tree attributes which tend to confer some measure of heat and drought resistance:

1) **Use natives** - Native trees adapted to local soils, moisture availability, climate and pests usually perform better over the long run than exotic plantings.

2) **Use early to mid-successional species** - Trees which colonize old fields, new soil areas, and disturbed sites use available resources, like water, much more effectively than late successional species (climax species). Late successional species can be effectively used in partially shaded understories.

3) **Select proper canopy type** - Select trees for planting in full sun which will develop leaves and branches spread throughout a deep crown. These multilayered trees have many living branches with many leaf layers. Multilayered canopy trees are more water efficient in areas with greater than 60% full sun. The other type of leaf canopy concentrates leaves in a single layer along the outside of the canopy area. These single-layer trees are good in partial shade but are not water efficient in full sun. Examples of multilayered overstory trees include: oaks, pines, soft maples, ash, hickory, gums, walnut, poplars, and birches. Mono-layered understory trees include: beech, sugar maple, hemlock, magnolia, sassafras, sourwood, and redbud.

4) **Select proper crown shape** - Crown shape has a great effect on heat dissipation and water use. Ideal trees would be tall with cone or cylinder shaped crowns. Do not use flat, widely spreading species in full sun. A drought resistant tree should maintain a tall, rather than a wide appearance. Many trees that are wide-spreading when mature have narrow, upright crowns when young.

5) **Select proper leaf size and shape** - Select small leaved or small, deeply lobed leaved trees. These leaves are more easily cooled and have better water use efficiency than larger, rounded leaves.

6) **Select proper foliage reflection** - Hardwood (broad-leaved) trees reflect 25% more light than conifer trees on average. This translates into better water use efficiencies with broad-leaved trees.

7) **Select upland versus bottomland species** - Upland species are usually more drought resistant than bottomland species. Unfortunately, upland species can be much slower growing and do not react well to site changes and soil compaction. Tree selection must be carefully made based upon disturbance, stress, and site use expectations.

From these tree characteristics, an ideal tree for a drought-resistant landscape is a native, early to mid-successional, upland hardwood species with a multi-layered canopy, small and/or deeply lobed leaves, and a conical to cylindrical crown shape. Table 13. Obviously you will never find an ideal drought resistant tree. Many trees do come close and have many fine features for a good landscape. A list of these species can be found in the following table. Remember young trees of any species must be allowed time to become fully established in a landscape before drought resistant features will be evident. Properly fit the tree to your site and local climate, and you will have a water efficient landscape.

Summarizing Water & Trees

Trees are part of a water covered and controlled planet. Trees are surrounded inside and out with water. Water is an essential defining substance for tree life. The properties of water provide the framework, parts, and method for allowing interaction among living cells, and between living processes. Water is both a "problem" and a "solution" when working with trees. Drought is the most damaging of all resource availability problems, leading to a myriad of secondary and tertiary damaging events. To more effectively manage trees and their water resources, a clear understanding of water as chemical, bath, and transport is critical. Water is a keystone stress in tree health care.

Table 13: A selected list of drought resistant tree species for the Southeatern United States. (once established in a landscape)

scientific name	common genus name
Acer buergeranum	maple
Acer negundo	
Acer platanoides	
Acer rubrum	
Acer saccharinum	
Ailanthus altissima	tree-of-heaven
Betula maximowicziana	birch
Betula nigra	
Carya glabra	hickory
Carya ovata	
Carya tomentosa	
Catalpa bignonioides	catalpa
Celtis occidentalis	hackberry
Cercis canadensis	redbud
Crataegus spp.	hawthorn
Cupressocyparis leylandi	
Cupressus spp.	cypress
Diospyros virginiana	persimmon
Elaeagnus spp.	olive
Fraxinus pennsylvanica	ash
Ginkgo biloba	ginkgo
Gleditsia triacanthos	honeylocust
Gymnocladus dioicus	coffee tree
Ilex decidua	holly
Ilex vomitoria	
Juglans nigra	black walnut
Juniperus spp.	juniper
Maclura pomifera	Osage-orange
Morus spp.	mulberry
Nyssa spp.	tupelo
Ostrya virginiana	ironwood
Pinus echinata	pine
Pinus elliotti	
Pinus glabra	
Pinus palustris	
Pinus sylvestris	
Pinus taeda	
Pinus virginiana	
Platanus spp.	sycamore
Populus alba	white poplar
Populus deltoides	cottonwood
Quercus acutissima	oak
Quercus coccinea	
Quercus durandii	
Quercus falcata	
Quercus georgiana	
Quercus imbricaria	
Quercus laevis	
Quercus laurifolia	
Quercus lyrata	
Quercus macrocarpa	
Quercus marilandica	
Quercus muehlenbergi	
Quercus oglethorpensis	
Quercus phellos	
Quercus prinus	
Quercus shumardii	
Quercus stellata	
Quercus virginiana	
Quercus velutina	
Robinia pseudoacacia	black locust
Salix nigra	willow
Sassafras albidum	sassafras
Ulmus americana	elm
Ulmus parvifolia	
Ulmus pumila	
Zelkova serrata	

Selected Literature

Research shows that almost 80% of the growth variability in trees and forests is associated with water availability. Drought remains one of the most biologically damaging and ecologically limiting of all environmental constraints on tree growth and survival. To better understand drought effects on trees, publications dealing with specific aspects of drought were identified and listed. In addition, classic reference works and older key references are cited.

Abrams, M.D. 1988. Sources of variation in osmotic potentials with special reference to North American tree species. Forest Science. 34 (4):1030 1046.

Bourdeau, P.F. 1954. Oak seedling ecology determining segregation of species in Piedmont oak-hickory forests. Ecological Monographs 24:297-320.

Boyer, J.S. 1985. Water transport. Annual Review of Plant Physiology 36:473-516.

Boyer, J.S. 1995. Biochemical and biophysical aspects of water deficits and the predisposition to disease. Annual Review of Phytopathology 33:251-274.

Breda, N., R. Huc, A. Granier, & E. Dreyer. 2006. Temperate forest trees and stands under severe drought: A review of ecophysiological responses, adaptation processes and long-term consequences. Annals of Forest Science 63(6):625-644.

Chang, M. 2003. **Forest Hydrology: An Introduction to Water & Forests**. CRC Press, Boca Raton, FL. Pp.373.

Coder, K.D. 2001. Heat load estimates on trees. University of Georgia Warnell School of Forestry & Natural Resources outreach publication FOR01-28. Pp.4.

Coder, K.D. 1999. Heat stroke in trees. University of Georgia Warnell School of Forestry & Natural Resources outreach publication FOR99-24. Pp.9.

Coder, K.D. 1999. Drought damage to trees. University of Georgia Warnell School of Forestry & Natural Resources outreach publication FOR99-8. Pp.5.

Cregg, B.M. 2004. Improving drought tolerance of trees: Theoretical and practical considerations. Acta Horticulturae 630:147-158.

Dawson, T.E. 1996. Determining water use by trees and forests from isotopic, energy balance and transpiration analysis: The roles of tree size and hydraulic lift. Tree Physiology. 16(1/2):263 272.

Desprez-Loustau, M.L., B. Marcais, L.M. Nageleisen, D. Piou, & A. Vannini. 2006. Interactive effects of drought and pathogens in forest trees. Annals of Forest Science 63(6):597-612.

Dreyer, E. Photosynthesis and drought in forest trees. 1997. Trees: Contributions to Modern Tree Physiology. Backhuys Publishers, Netherlands. Pp.215 238.

Epron, D. & E. Dreyer. 1993. Long term effects of drought on photosynthesis of adult oak trees (*Quercus petraea*) and *Quercus robur*) in a natural stand. The New Phytologist. 125(2):381 389.

Ewers, B.E., D.S. Mackay, & S.Samanta. 2007. Interannual consistency in canopy stomatal conductance control of leaf water potential across seven tree species. Tree Physiology 27(1)11-24.

Fruh, T. 1997. Simulation of water flow in the branched tree architecture. Special issue on Functional-Structural Tree Models. Helsinki workshop on Functional Structural Tree Models, Sept. 12-13, 1996, Helsinki, Finland). Silva Fennica. 31:275-284.

Hellkvist, J., G.P. Richards, P.G. Jarvis. 1974. Vertical gradients of water potential and tissue water relations in Sitka spruce trees measured with the pressure chamber. Journal of Applied Ecology 11:637-667.

Houston, D.R. 1985. Dieback and declines of urban trees. Journal of Arboriculture. 11(3):65 72.

Kozlowski, T.T., P.J. Kramer, & S.G. Pallardy. 1991. **The Physiological Ecology of Woody Plants.** Academic Press, San Diego, CA. Pp.657.

Kozlowski, T.T. & S.G. Pallardy. 1997. **Growth Control in Woody Plants**. Academic Press, San Diego, CA. Pp.641.

Kramer, P.J. 1942. Species differences with respect to water absorption at low soil temperature. American Journal of Botany 29:828-832.

Kramer, P.J. & J.S. Boyer. 1995. **Water Relations of Plants and Soils.** Academic Press, New York, NY. Pp.495.

Kramer, P.J. & T.T. Kozlowski. 1979. **Physiology of Woody Plants**. Academic Press, New York, NY. Pp.811.

Larcher, W. 1980. **Physiological Plant Ecology**. Springer-Verlag, Berlin.

Lohani, V.K. & G.V. Loganathan, GV. 1997. An early warning system for drought management using the Palmer drought index. Journal of the American Water Resources Association. 33:1375-1386.

Orwig, D.A. & M.D. Abrams. 1997. Variation in radial growth responses to drought among species, site, and canopy strata. Trees: Structure and Function. 11:474-484.

Parker, J. 1949. Effects of variations in root-leaf ratio on transpiration rate. Plant Physiology 24:739-743.

Pelah, D., A. Altman, & O. Shoseyov. 1997. Drought tolerance: A molecular perspective. Acta Horticulturae. #447:439-445.

Rathenberger, R. 1988. Reduce drought after-effects. Journal of Arboriculture. 14(10):260.

Rennenberg, H., F. Loreto, A. Polle, F. Brilli, S. Fares, R.S. Beniwal, & A. Gessler. 2006. Physiological responses for forest trees to heat and drought. Plant Biology 8(5):556-571.

Slatyer, R.O. 1967. **Plant-Water Relationships**. Academic Press, London.

Teskey, R.O., J.A. Fites, L.J. Samuelson, & B.C. Bongarten. 1986. Stomatal and non-stomatal limitations to net photosynthesis in *Pinus taeda* under different environmental conditions. Tree Physiology 2:131-142.

Tinus, R.W. 1996. Root growth potential as an indicator of drought stress history. Tree Physiology. 16(9):795 799.

Tsuda, M. & M.T. Tyree. 1997. Whole plant hydraulic resistance and vulnerability segmentation in *Acer saccharinum*. Tree Physiology. 17:351-357.

Waring, R.H., D. Whitehead, & P.G. Jarvis. 1980. Comparison of an isotope method and the Penman-Monteith equation for estimating transpiartion from Scots pine. Canadian Journal of Forest Research 10:555-558.

Waring, R.H. & W.H. Schlesinger. 1985. **Forest Ecosystems: Concepts & Management**. Academic Press, Orlando, FL.

Wiersum, L.K. & K. Harmanny. 1983. Changes in the water permeability of roots of some trees during drought stress and recovery, as related to problems of growth in urban environment. Plant and Soil. 75(3):443 448.

Zimmermann, M.H. 1978. Hydraulic architecture of some diffuse porous trees. Canadian Journal of Botany 56:2286-2295.