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Water & Tree Health Manual

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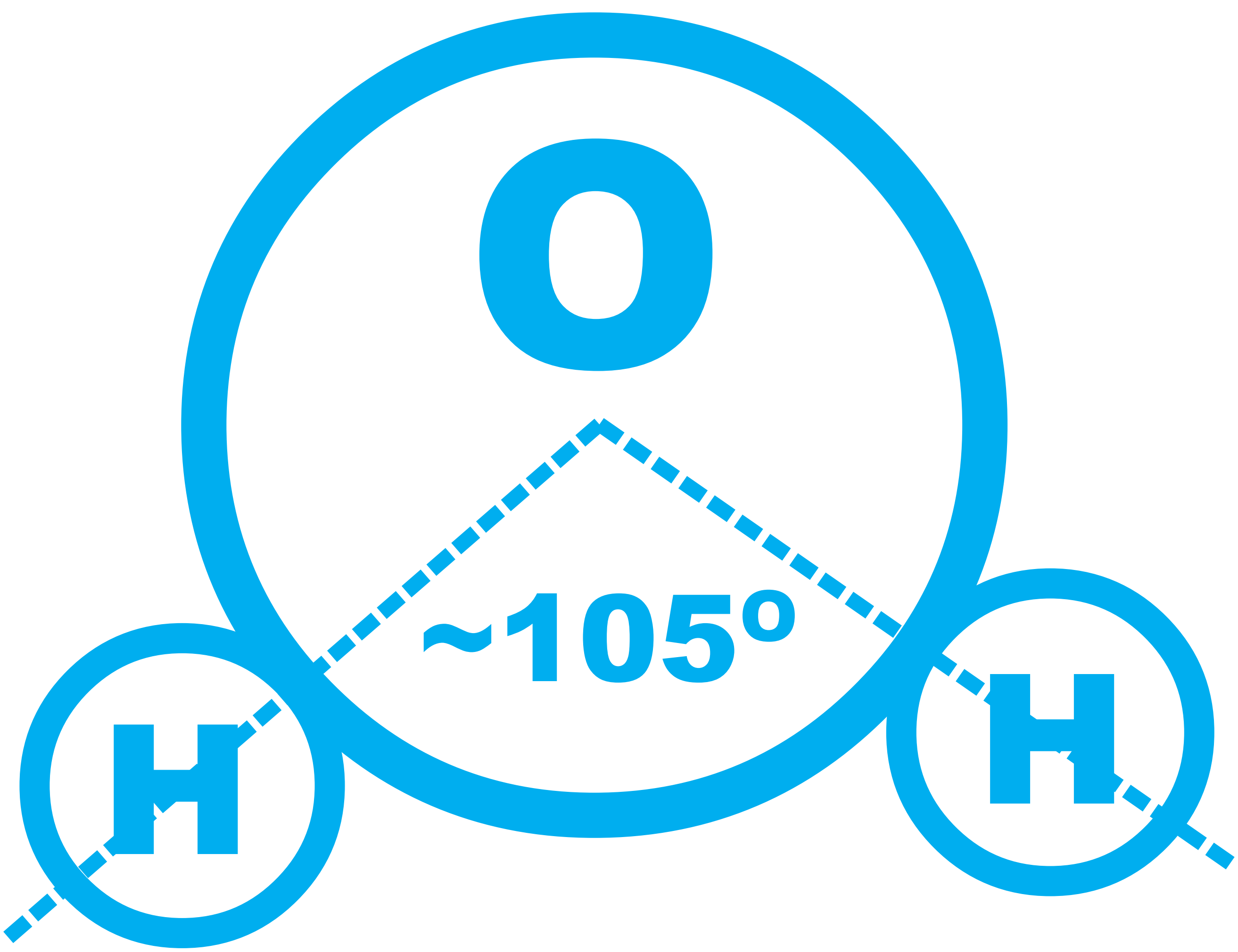

This training manual is an educational product designed for helping tree health care professionals appreciate and understand water attributes and tree water use. This manual is a synthesis and integration of research and educational concepts regarding water, soils and trees. This educational product is for awareness building and professional development.

At the time it was finished, this publication contained educational materials and models concerning trees and water thought by the author to provide the best means for considering fundamental tree health care issues associated with water. The University of Georgia, the Warnell School of Forestry & Natural Resources, and the author are not responsible for any errors, omissions, misinterpretations, or misapplications stemming from this educational product. The author assumed professional users would have some basic tree and soil educational background. This product was not designed, nor is suited, for homeowner use. Always seek the advice and assistance of professional tree health care providers.

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Water & Tree Health Manual

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Trees act as conduits through which water passes. Instead of water evaporating from the soil surface, a tree provides an elevated surface for water evaporation. A tree can be visualized as a water fountain lifting and evaporating water from its leaves. The water interface between tree and atmosphere (i.e. the leaf) is the major biological control point for water movement in a tree, and for water conservation.

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

Most Valuable Resource (MVR)

Water is essential to tree life as well as the most limiting of resources. 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 in the ecological system which sustain trees. Water is a starting point for photosynthesis capturing energy from the sun, a hydraulic fluid, a transport stream, and a solvent. Water comprises 80% of tree mass on average.

Within each living tree cell is a water-based solution which contains, supports and dissolves a variety of materials and molecules responsible for life. This water solution of life is called "cytoplasm" or "cytosol." A 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 a dry environment. Trees are a standing pipe of soil water held against gravity and dryness of the atmosphere.

Water Everywhere?

Approximately 97% of all water on our planet is in oceans. Ocean water contains about 35,000 parts per million (ppm) dissolved materials, comprised of more than 80 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.

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 a heat reservoir, heat exchanger, cooling system, 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. World-wide and continental water cycles generate deserts and rainforests, depending upon ratios of evaporation and precipitation. Attributes of water make it the driving force of small scale and large scale climate.

Life Sustaining Attributes

Water is an unique substance. Pure water in small portions is clear and colorless with no taste or odor. It is easily tainted with all kinds of other materials. 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 State

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 at 32^{o}F (0^{o}C) and boils at 212^{o}F (100^{o}C), under one atmosphere of air pressure. Our temperature scales are set by these properties of water.

Water in a gas phase surrounds us in the atmosphere. The most simple weather descriptions usually include a relative humidity measure. On a large scale, water vapor blankets 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. Growing ice crystals can act like daggers to living cells. Depending upon its molecular energy level and environment, 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 and various numbers of neutrons. The third atom in water is a massive oxygen which has an atomic structure which 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 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 -- H2O 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 light water. Figure 2.

Charge Exposure

In binding with oxygen, hydrogens tend to loose their negative electron charges most of the time. The almost continuous loss of negatively charged electrons from both hydrogens to oxygen 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. 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

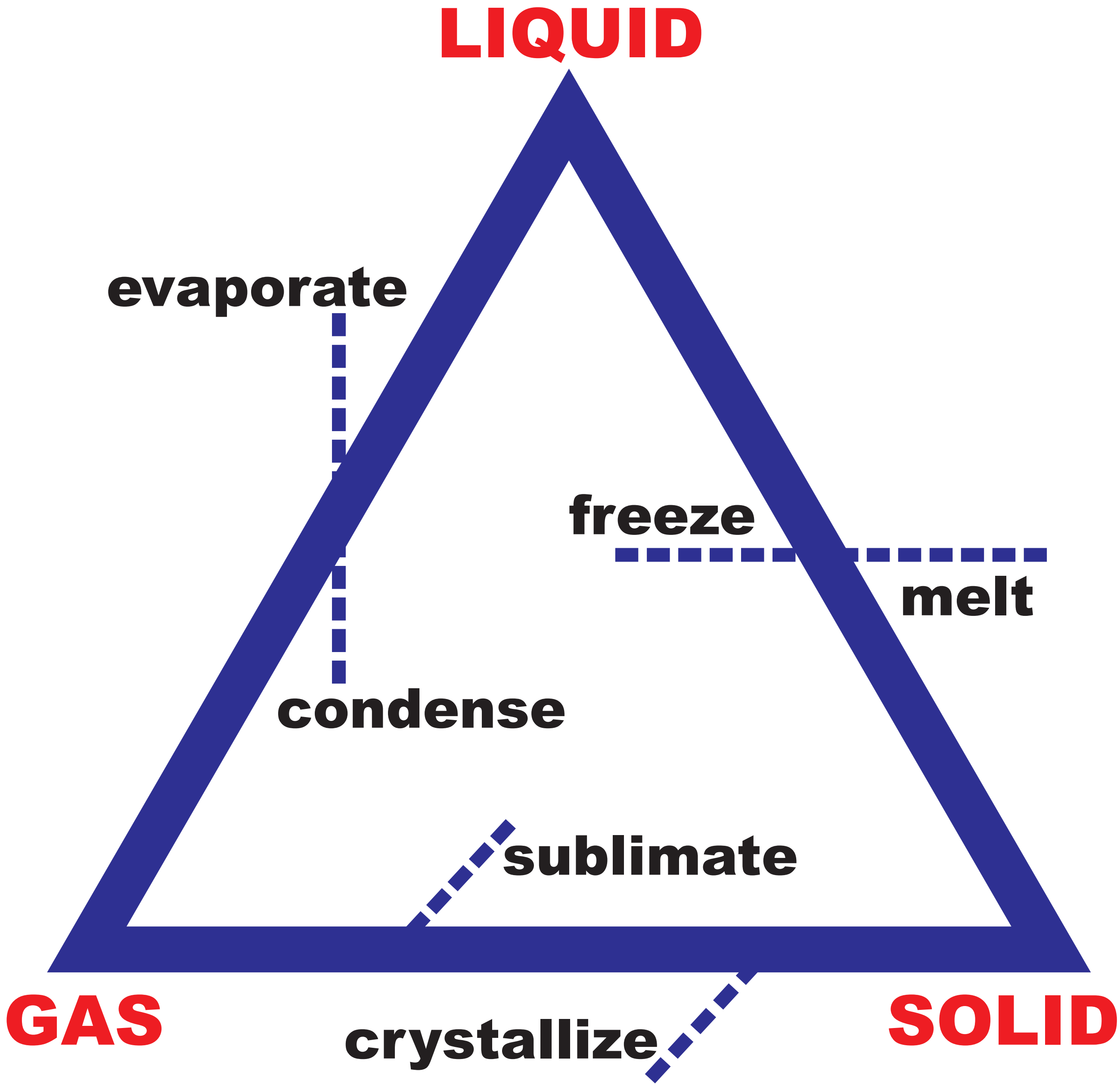

Figure 1: Diagram showing states of water and names of transitions between states.

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.
The rest of synthesized hydrogens & oxygens have short half-lifes (< few seconds).

Figure 2: Percent of nine (9) naturally occurring water molecule forms in the atmosphere.

(Note percents are NOT in decimal form).

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 (pH=7), one in 10 million water molecules are ionized. As pH becomes lower (more acidic), more H+ ions exist. A pH of 4 means the concentration of H+ is one in 10,000. Figure 3. Water molecules generally stay as one molecular unit, unequally sharing hydrogen's electrons.

Sticky Shapes

Part of understanding partial charge attraction is examining the shape of a water molecule. There are many ways to envision three atoms in water attaching to each other. Atoms in water molecules are not straight or in 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. Figure 4. The two hydrogens can only be attached to a single oxygen in one way. Hydrogens are always at a ~105^o angle from each other over the surface of a much larger and massive oxygen atom. At this angle, each hydrogen presents a partial positive charge to other water molecules and materials. Oxygen presents a variable partial negative charge to other molecules. Figure 5.

The interactions between water molecules involve partial negative charges attracting partial positive charges among all other near bye 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 can also occur over longer distances (1.8X longer) than 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. Figure 6. The mutual attraction between water molecules is called "cohesion." Even though one hydrogen bond continuely 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, and at the liquid water surface, more molecules escape from liquid into a gas form.

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 not simply 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-like areas develop and line-up with each other, water can be described as having a semicrystalline form in a liquid state. This semi-structure confers stability which makes water unique. Water is dominated by this stable semicrystalline structure up to about 105^oF (40.5^oC). At this temperature, 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

pH	ionized water proportion
2	1: 100
3	1: 1,000
4	1: 10,000
5	1: 100,000
6	1: 1 million
7	1: 10 million
8	1: 100 million
9	1: 1 billion

Figure 3: Ionic proportions of water at various pH levels.

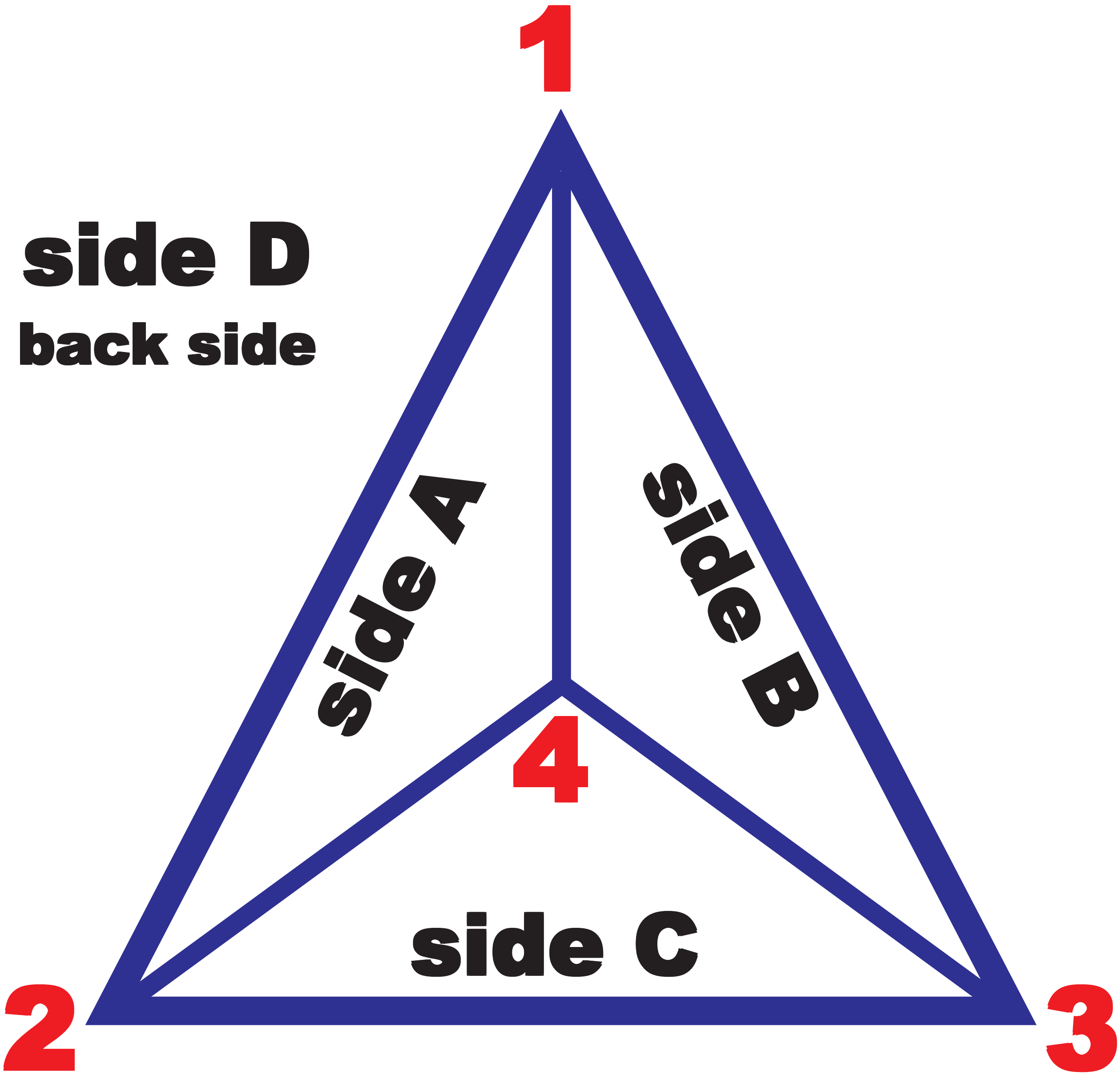

Figure 4: Oxygen bond attachment geometry is in the form of a tetrahedron with four corners (1-4) and four sides (A-D), only two of four corner positions can be filled with hydrogens.

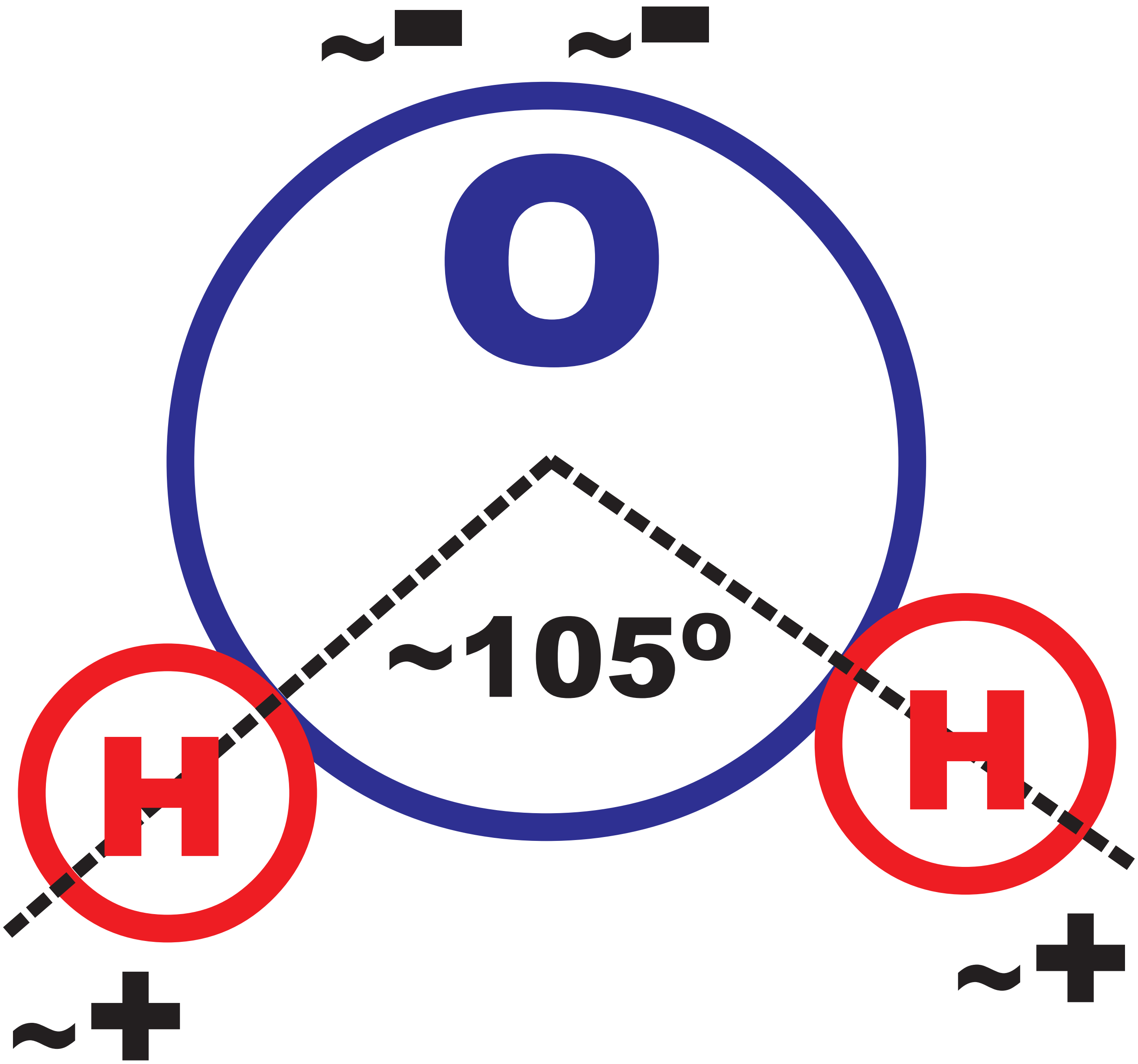

Figure 5: Diagram of water molecule with oxygen (O) and two hydrogen (H) atoms. Hydrogen atoms are always separated by ~105º as they glide over the oxygen perimeter, never on opposite sides. Oxygen draws electrons away from hydrogens generating a polar molecule with partial negative charges (~**-**) on the oxygen side and partial positive charges (~**+**) on the hydrogen side.

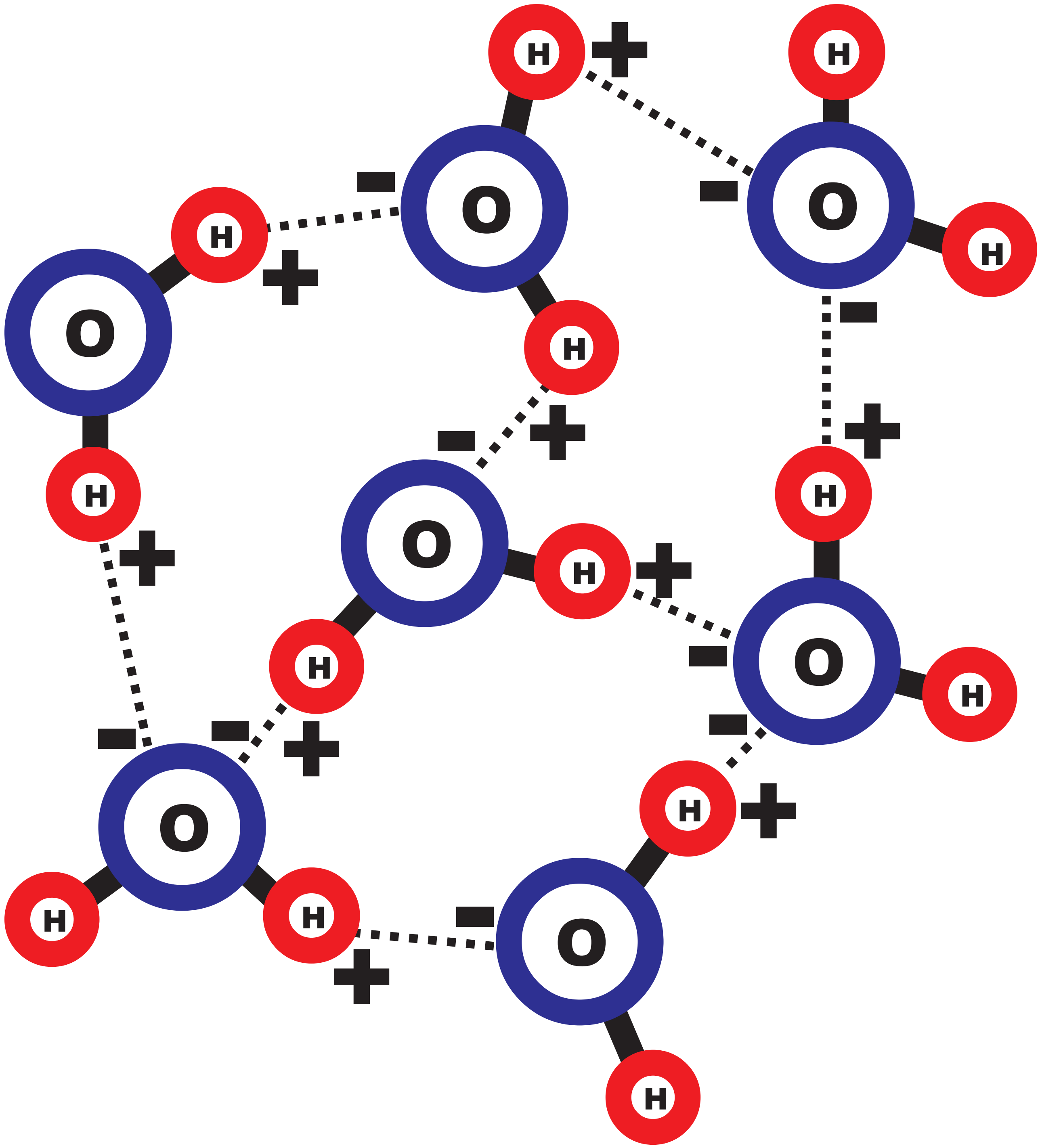

Figure 6: Diagram of seven water molecules interacting with each other due to partial electrostatic charges associated with 0 to 4 hydrogen bonds. Dotted lines represent hydrogen bonds. Remember, this is a simple two dimensional diagram, while actual water molecules are in a four dimensional framework of constantly shifting hydrogen bonds.

surrounds, supports, and interfaces with many tree enzymes and molecular conformations begin to subtly change properties above this temperature.

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, hydrogen bonding of cold water begins to reorganize into large areas of more crystalline-like structures. As energy content in liquid water declines to 32°F (0°C), hydrogen bonds setup a liquid crystal structure made of tetrahedron shapes packed together.

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 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 in liquid water, 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 because 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 interconnections shift and slide 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 lower energy semicrystalline patchworks 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 associated 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 material having at least small irregularities in their electronic composition. Water will adhere to many surfaces which have partial charges and ionic terminals.

Water forms a thin film around most soil and biological materials. For example, a landscape soil under increasing drought conditions contain 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^{o}F (100^{o}C), most of this 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 surface films of water to enlarge, filling ever larger soil pores. Any added water becomes part of a water matrix already in soil which sticks together, and a portion of which can be dragged into a tree.

Electric Shells

Many tree essential elements dissolve readily in water and form ions, either positively charged "cations" or negatively charged "anions." Figure 7. Ions come from disassociation or separation of neutral molecular components. Table salt easily ionizes into positive cation sodium (Na^+) and negative anion chlorine (Cl^-) when stirred into water. The full charges on ions cause partially charged water molecules to line-up and surround each ion in a hydration sphere or layer. Ions with hydration spheres tend to behave as much 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 various charges on soil particles. 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 other molecules which helps break loose or 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.

Wet Sphere

Materials which are ionic or polar can be pulled into water and surrounded by a shell of many water molecules hiding or covering (neutralizing) 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 and modify their physical properties. Figure 8.

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.

element name	element symbol	most common form(s) available for tree
carbon*	C	HCO_3^- CO_2
oxygen*	O	O_2 H_2O
hydrogen*	H	H_2O
nitrogen*	N	NO_3^- NH_4^+ $CO(NH_2)_2$
potassium	K	K^+
calcium	Ca	Ca^{+2}
magnesium	Mg	Mg^{+2}
phosphorus	P	$H_2PO_4^-$ HPO_4^{-2}
sulfur*	S	SO_4^{-2} SO_2
chlorine*	Cl	Cl^- Cl_2 ClO_3^-
iron	Fe	Fe^{+2} Fe^{+3}
manganese	Mn	Mn^{+2} Mn^{+4}
zinc	Zn	Zn^{+2}
boron*	B	H_3BO_3
copper	Cu	Cu^+ Cu^{+2}
silicon*	Si	H_4SiO_4
molybdenum	Mo	MoO_4^{-2}
nickel	Ni	Ni^{+2} Ni^{+3}
cobalt	Co	Co^{+2} Co^{+3}

* = trees can take up element as neutral molecule

Figure 7: Tree essential element ionic uptake forms.

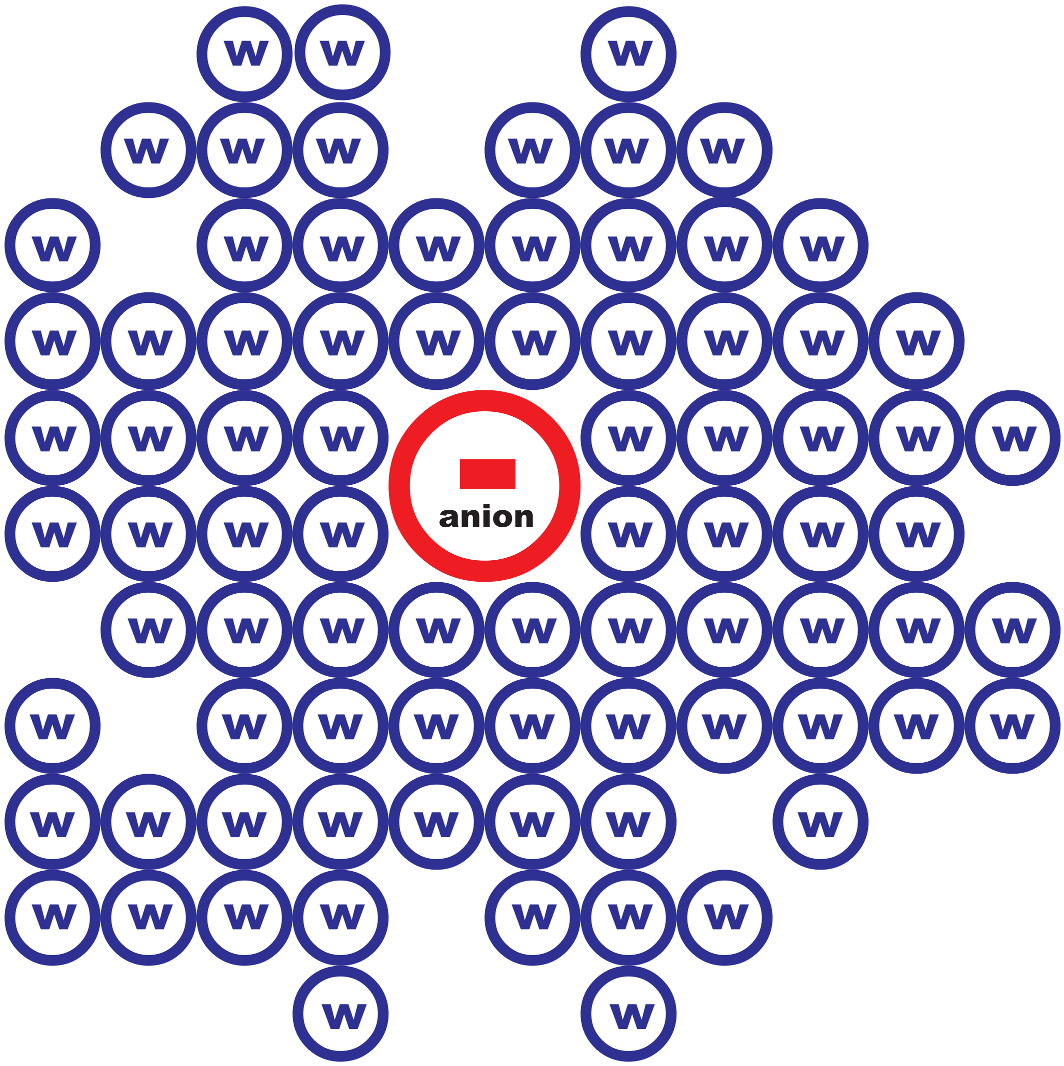

Figure 8: Two-dimensional diagram of water molecules surrounding an ion with a negative charge, generating a hydration sphere and effectively increasing ionic size. The partial positive charges on water molecules line up facing toward the negative ion, in this case.

Surface Tension

Water molecules in a liquid state are pulled equally (on average) from all sides by hydrogen bonding. Water molecules at the liquid 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 water. "Water strider" insects use water surface tension as a means of transportation. Water has a strong surface tension force, like tension in 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 are 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 (like 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 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 from the water mass 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 attraction of water for a wettable surface. Cohesion is 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 cohesive forces of 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 tube walls allow cohesion forces among the rest of the water molecules to be pulled up and supported like spanning cables between bridge uprights carrying weight. Cohesive forces keep all the water molecules together, reaching a minimum surface area for the diameter of the tube (distance between bridge uprights). The smaller the diameter of tube, the greater the adhesive / cohesive forces pulling-up on the water column for the same mass suspended beneath. Extremely small diameter tubes, soil pores, or intercellular spaces can attract water, allowing it to move a relatively long way (many inches).

Capillary movement components can be seen where liquid water touches the side of a glass. The water surface is not flat or evenly suspended, but is drawn slightly up the sides of a glass. This raised rim is called a "meniscus." A meniscus is the visible sign of adhesive forces between the glass and water.

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 (interfibril voids) 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 break. 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.

This 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 mineral soil materials present, in order to record 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. Surface water molecules with higher than average energy levels can overcome 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 accelerates.

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 a leaf, a large amount of heat is needed and a large amount of evaporative cooling takes place. Alternatively, 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). For example, water molecules under saturated conditions comprise a maximum of less than 1% in air at 40^{o}F and up to 9% at 112^{o}F of the air. The maximum amount of water vapor which could be in air is called the "saturated vapor pressure." Rarely is 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 a liquid surface would be evaporating faster than being captured. The lower the relative humidity (farther from saturation vapor pressure), the faster evaporation from a water surface. This can be thought of as a vapor pressure deficit or "dryness" of the atmosphere.

For example from Figure 9, 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 air of -142 bars and -482 bars of water potential tension, respectfully.

Drying Force

The rate water molecules evaporate 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 212^{o}F (100^{o}C) at one atmosphere of pressure (or ~1 bar or ~1,000 millibars). Changing air pressure will change the boiling temperature (equilibrium between vapor pressure and air pressure). Temperature and air pressure are key components governing water 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 moist inner leaf surfaces, and escapes from stomates and tree surfaces into 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 internal leaf surfaces. Except under fog conditions (100% relative humidity), trees are always losing water to a dry atmosphere. Figure 10. As temperatures increase during the day, relative humidity plummets making the drying force of the atmosphere much greater. Figure 11.

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, diameter of xylem water columns, amount and types of dissolved materials present, and discontinuities in the semicrystalline structure of water around H+ and OH- groups will all lower tensile strength in a water column. Water from 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 in a water column.

Tiny Bubbles

Gas bubble formation in tree xylem water columns is called cavitation. As temperatures rise and tension in a water column increases, more gases will fall out of solution and form small bubbles. These tiny bubbles may gather and coalesce, "snapping" a 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 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 tem-

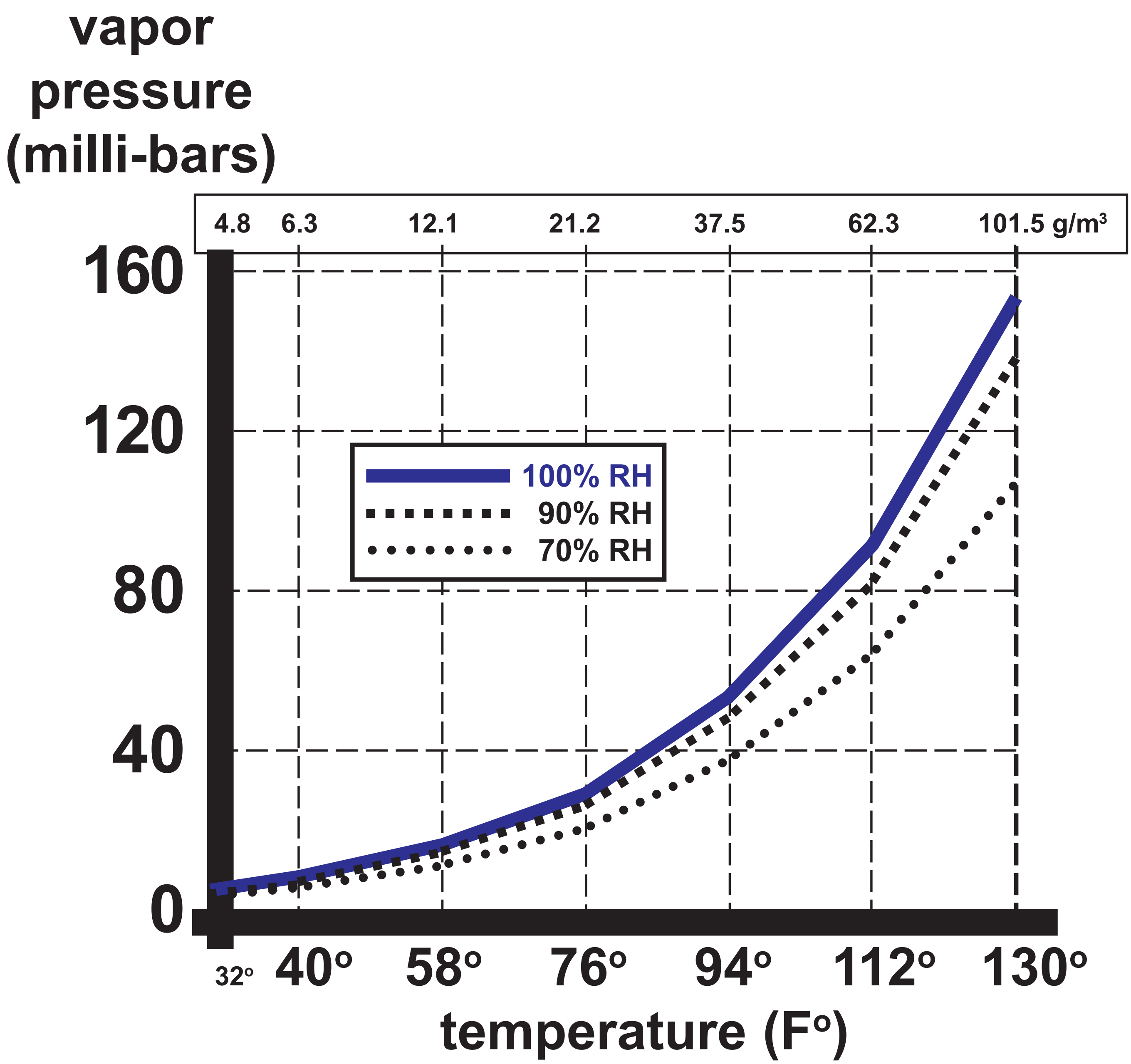

Figure 9: Saturated vapor pressure of water in atmosphere (100% relative humidity), the most water vapor normally found in air above liquid water. Also shown are 90% and 70% relative humidity (RH%). The box over the graph contains the actual amount of water (vapor density in grams per cubic meter) in air for each temperature.
(value approximations derived from Tabata, 1973)

relative humidity (%)	air temperature (F°)				
	50°	60°	70°	80°	90°
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 10: Estimated water potential (bars) of air for various relative humidity values (percent) and temperatures (F°).

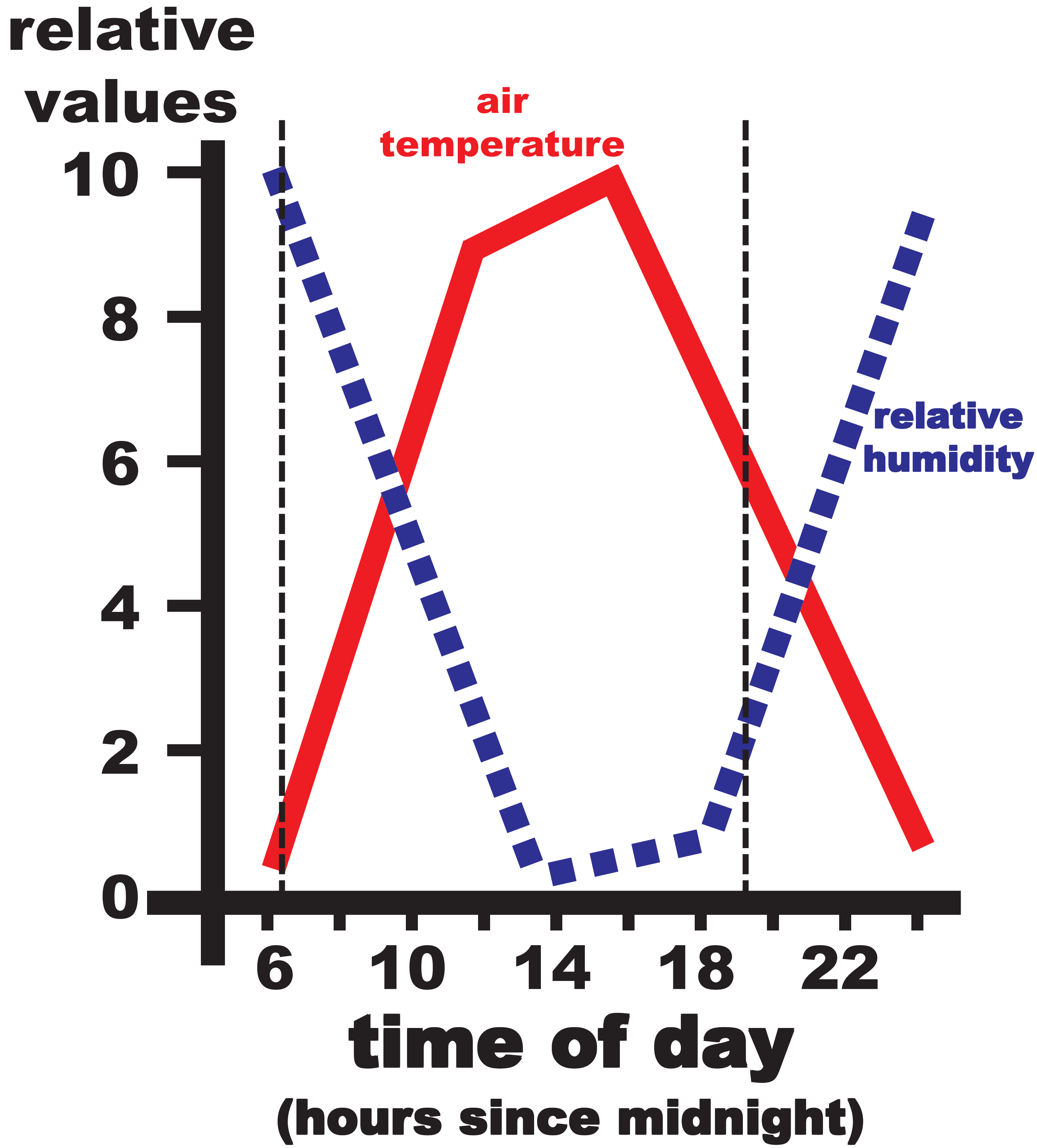

Figure 11: Relative value or measurement throughout a day for relative humidity and air temperature. Note the inverse relationship between temperature and relative humidity.

perature of 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°F (0°C) to liquid at 32°F (0°C) 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°F to 212°F (0°C to 100°C)). 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°F (100°C), 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. Bonds between atoms in pure water can remain intact beyond 3,630°F (2,000°C). Water can be decomposed into its component 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. It is impurities and ionization which allow water to be conductive.

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 by diffusion alone 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), 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 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 O2 gas released in photosynthesis are derived from water. The hydrogens (protons) concentrated from water are used as an energy source to capture carbon dioxide used in manufacturing carbohydrates. 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 a cell at its new dimensions until cell wall fibers and lignification constrain expansion. Visible wilting and petiole drooping in trees during drought periods are derived from loss of cellular pressure because of water loss.

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 refill with water during the night. Trees obtain almost all of their water from soil. Under some conditions other sources of atmospheric moisture in the form of dew or fog may prevent or postpone dehydration in tree crowns.

The rate of absorption of water by roots can be 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 soil solution (salts); and, G) combinations and/or interactions of A-F above.

Soil Waters

Water in soil consists of: (Figure 12)

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 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, soil is traditionally considered to be at "field capacity." At field capacity, which is considered an 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 a soil water content below which trees cannot extract enough water for

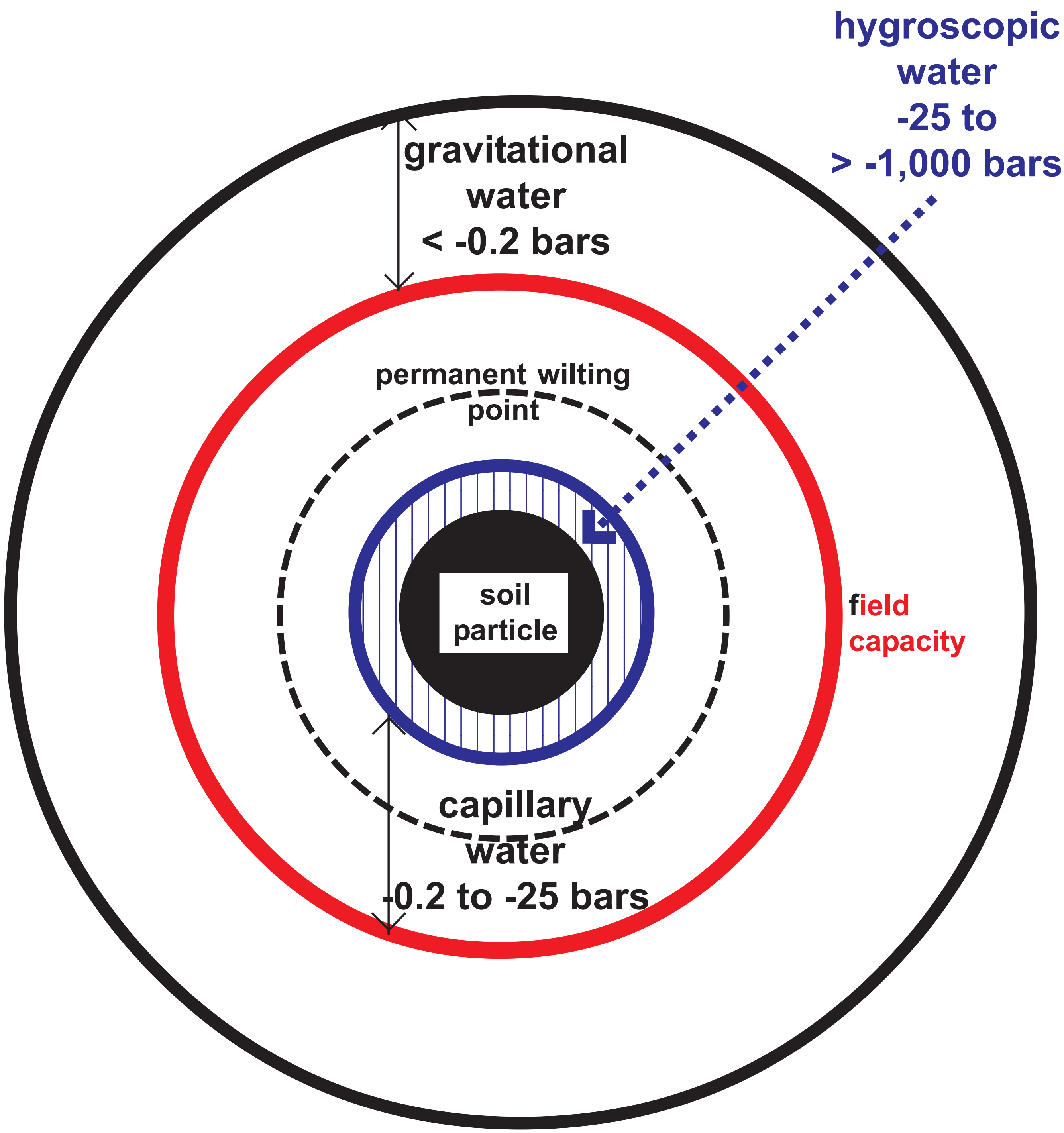

Figure 12: Idealized view of water layers surrounding a single soil particle. Tree available water is held loosely in the outer (low energy) areas as far inward as the permanent wilting point level (dotted circle). Water closer than the permanent wilting point to the soil particle can not be extracted by a tree. (after Brady, 1974)

survival. Note tree foliage can wilt for a number of internal and external reasons before 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 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 sized particles present.

Figure 13 provides a description of soil textures by general name. Note only clay and sand are shown here, because silt would be the remainder. Figure 14 provides specific soil texture names and compositions by showing how each particle size classification dominates soil water relations. Note clay contents greatly impact soil water-holding pore space.

In each soil, texture helps determine how many water holding pores (micro-pores) are present. Figure 15 provides the percent of water holding pores at field capacity in uncompacted soils, compared with total soil pore space. Some soil pore spaces hold water more tightly than trees can exert force to remove water. Figure 16 shows the amount of unavailable water held by soils with various textures. This water can not be pulled from soil and into a tree through transpiration.

Figure 17 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 18 shows the total amount of tree-available water present in soils of various textures. Subtracting Figure 16 from Figure 17 produces Figure 18. In Figure 18, 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 soil.

Drops To Drink

For example, a tree's roots occupy an area of loam soil three feet deep. Use Figure 16 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 17 to determine the total amount of water per foot held in a loam soil which is 3.1 inches of water, or 9.3 inches of total water in a loam soil three feet deep. The shaded area of Figure 18 shows the inches of water available for tree use per foot of soil.

In this example, Figure 18 = Figure 17 minus Figure 16, 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 water X 3 feet soil depth). If evapotranspiration loss 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 at field capacity three feet deep.

Movement

When a soil is wet, the rate of water movement and absorption by tree roots can be great, if 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, resistance to water movement increases in soil and in a 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 soil become thin and convoluted, with many water connections

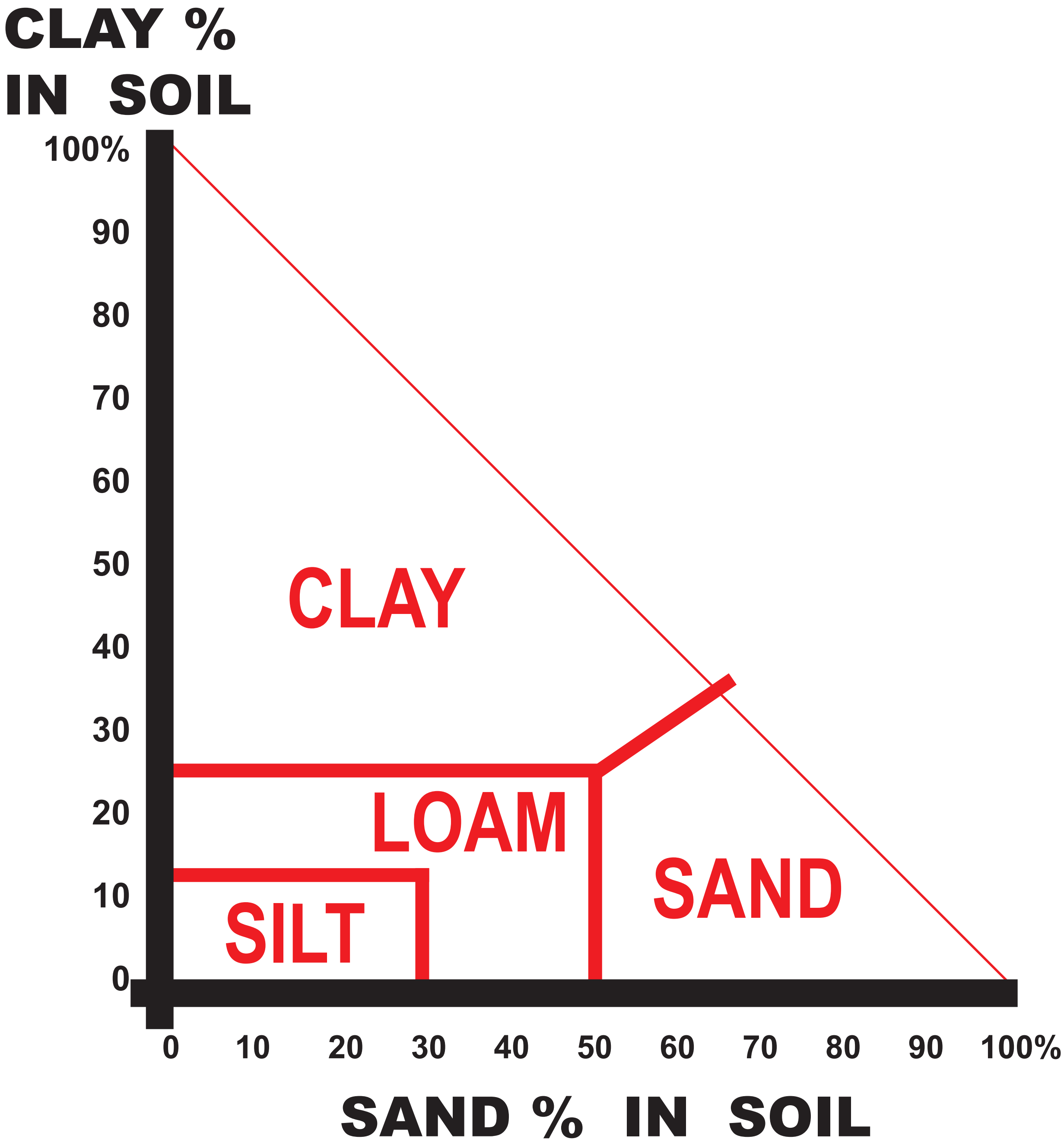

Figure 13: Dominance of physical water related attributes for soils with different particle sizes (textures).

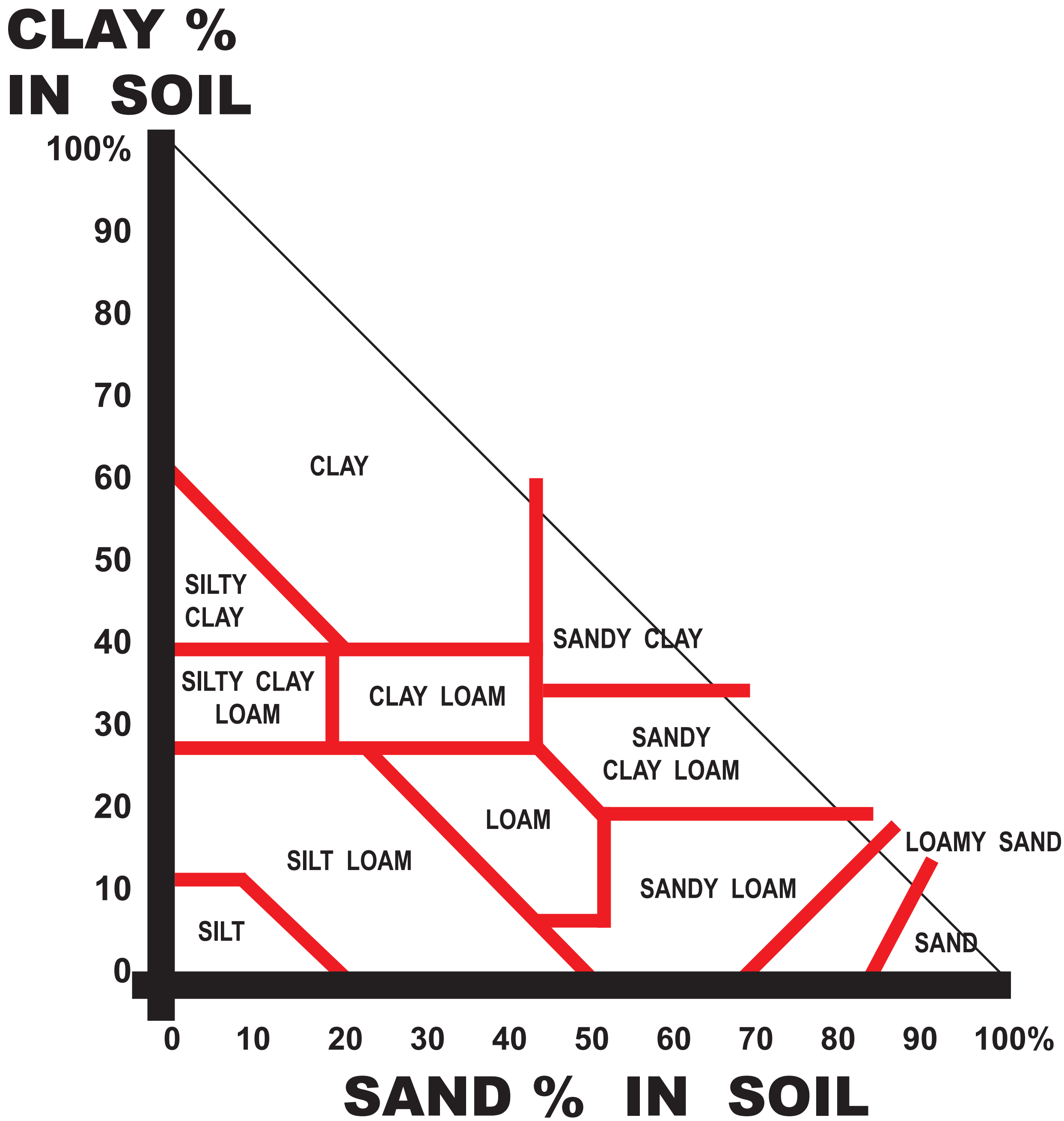

Figure 14: Soil texture types and associated particle size percentages of sand (large / coarse) and clay (small / fine). Silt is a mid-sized particle.

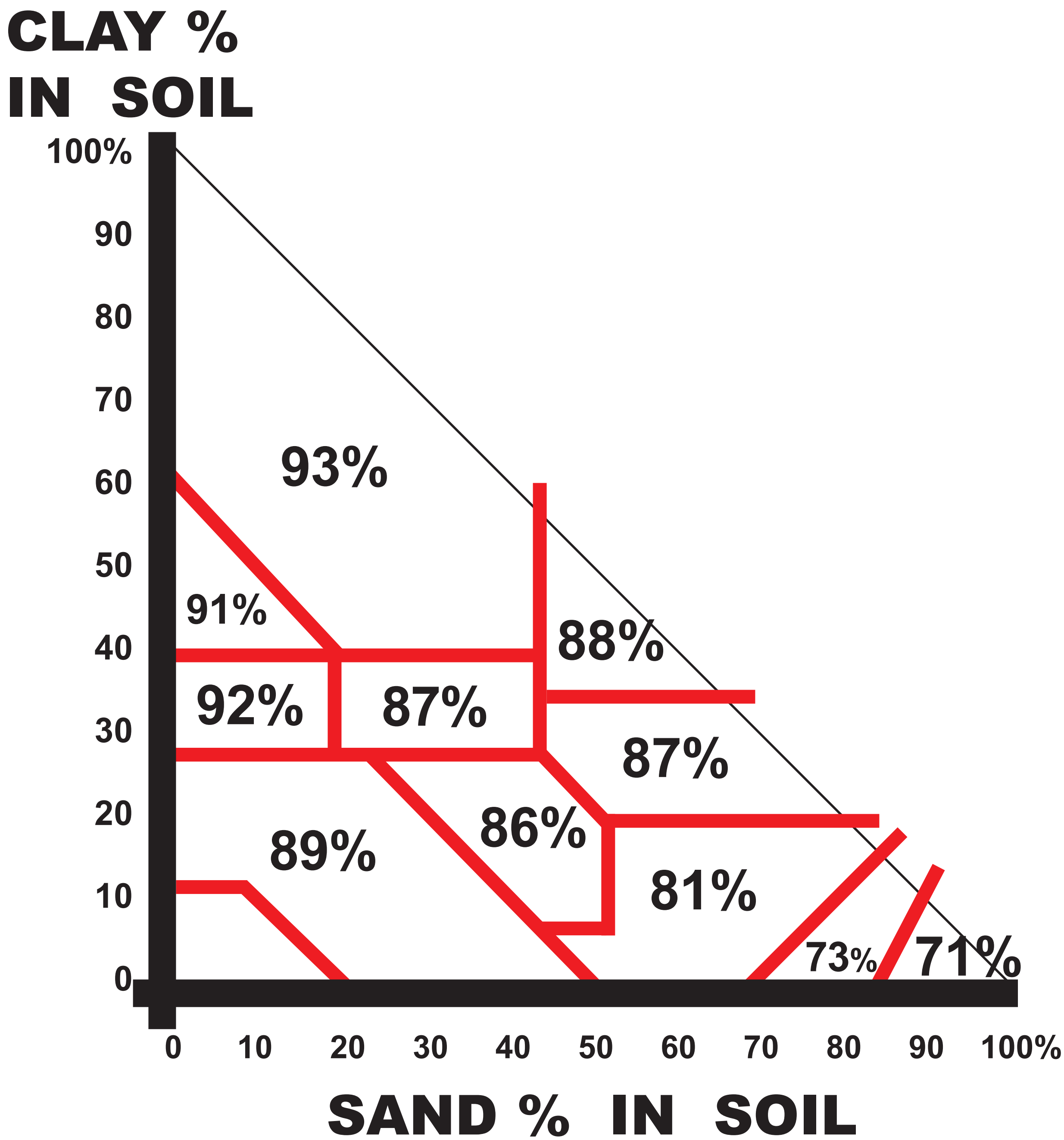

Figure 15: Approximate percent of water containing pore space (micropore) compared to all pore space in uncompacted soils of various textures at field capacity.

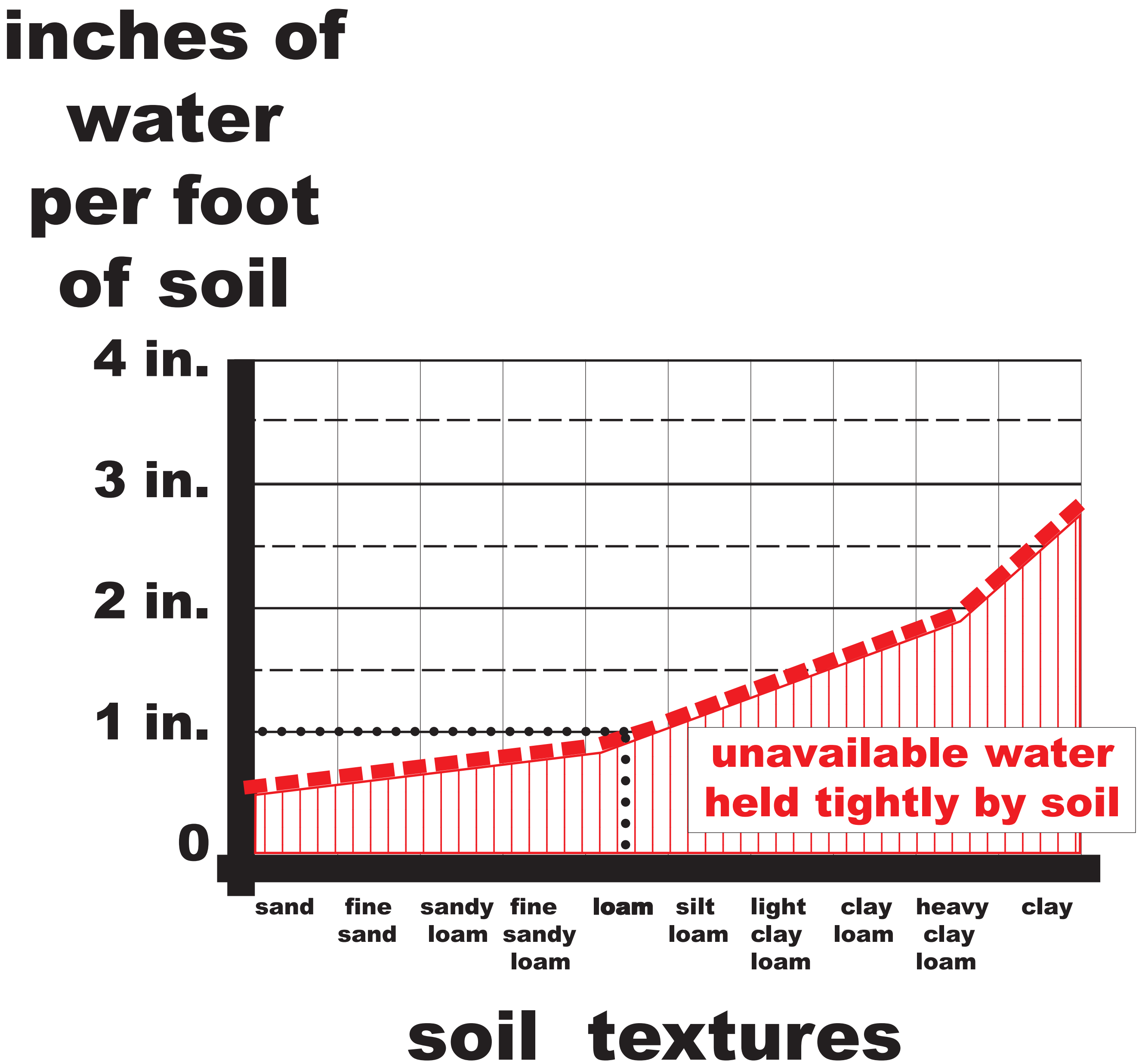

Figure 16. Unavailable water per foot in soils of various textures. The large dotted line represents permanent wilting point. (Small dotted lines are for an example in text.)

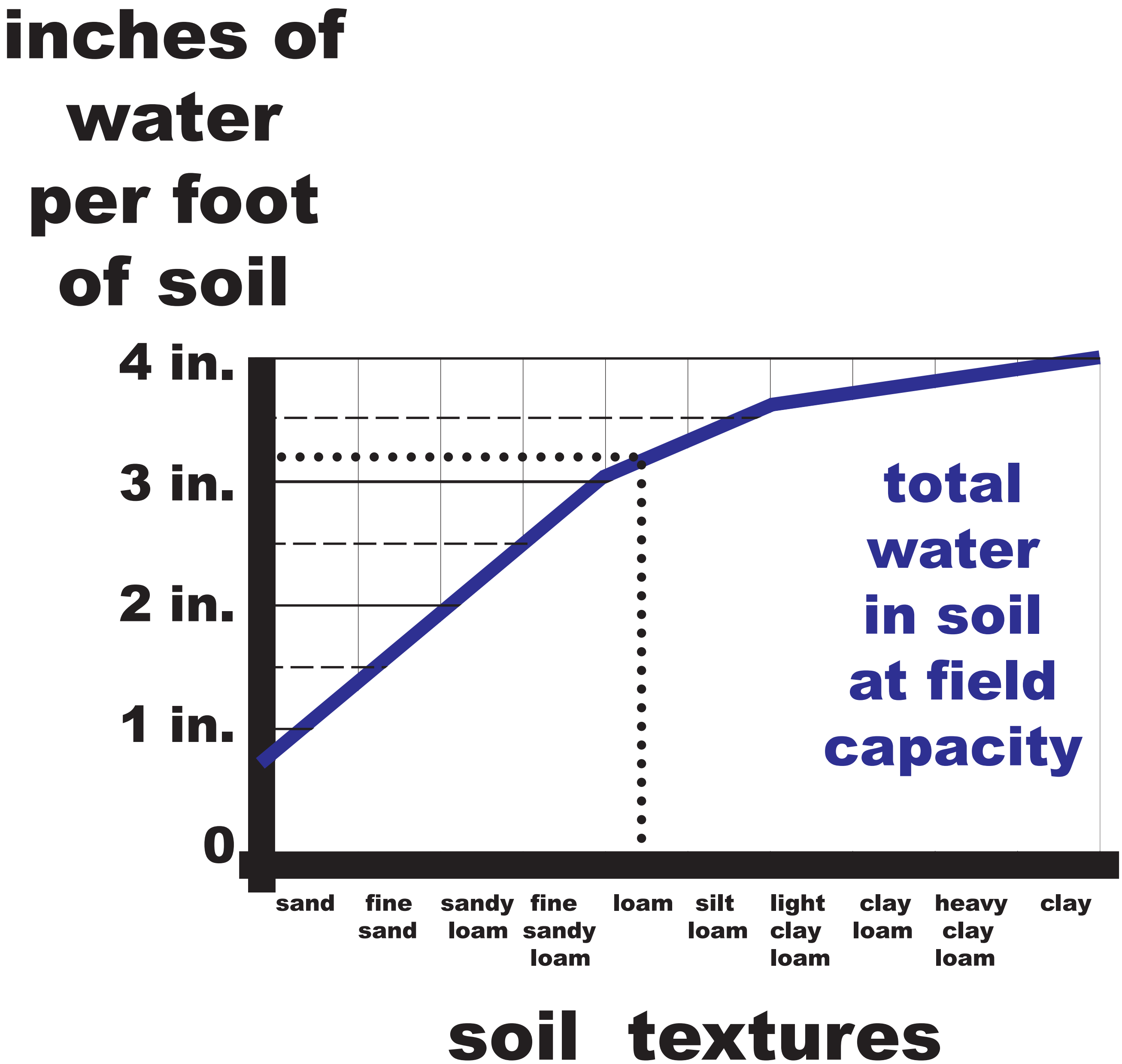

Figure 17. Total water held in soil against the pull of gravity (field capacity) for various soil textures.
(Small dotted lines are for an example in text.)

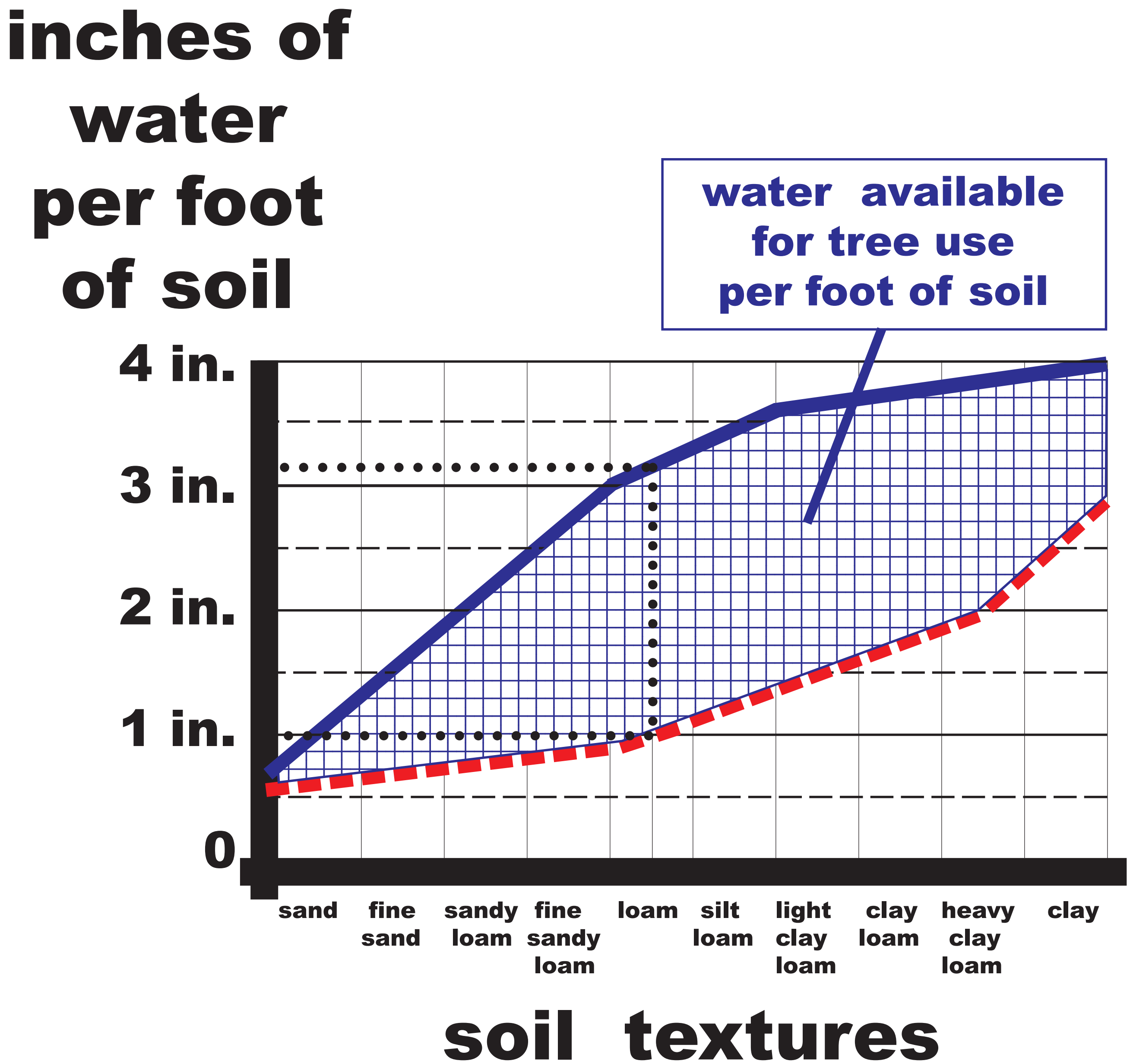

Figure 18. Difference between total water at field capacity and unavailable water held by soil. (Figure 16 subtracted from Figure 17). (Small dotted lines are for an example in text.)

narrow and broken. Soil hydraulic conductivity (inverse of resistance) falls as the amount of fine texture particles in soil increase. Figure 19.

Water in the portion of soil which 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 tree-available essential elements are present as ions dissolved in the soil water solution. Most 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, and so, tree roots must continue to "mine" soil.

Tree 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 tree stress.

Spell "Essentiality"

All tree life processes 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 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 covering a surface. In this case, water would rather stick to other water molecules than to a waxed surface. Using your finger, you can "pull" water droplets over a waxy surface and consolidate them into larger drops.

Trees utilize water's special chemical features in many ways, most noticeably in transporting materials from soil, into roots, and then on to leaves. Water in a tree is pulled through thousands of long columns or tubes, located around the outside of a tree stem within the last few annual increments. These long columns of water (within dead xylem cells) are functionally continuous between the source of water (soil) and leaves.

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

Figure 19: 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.

Water is pulled in long chains into a root, up through narrow xylem columns or channels, and to leaf surfaces where it evaporates into perpetually dry air. Water evaporates as bonds between molecules are broken at the liquid water / air interface in a 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 temperature (sensible heat or energy) and humidity in the atmosphere, water molecules are pulled away from wet leaf cell wall surfaces. This is called evaporation.

The pull (water demand or deficit) of 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 air generating an evaporative "pull" at the wet leaf surface measurable down through water columns to roots and into soil.

Water in a tree is a tightly connected stream moving from soil pores and surfaces, into the root, up the stem, out to leaf surfaces and into the atmosphere. 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 (tension) system assist with monitoring the transpiration stream.

Holiday Traditions

The faster evaporation from leaf surfaces, the more energy exerted to pull water to a 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 soil or too rapid (high energy) evaporation at a 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 indoors, causing a cut tree or foliage to dry rapidly. Usually, after many well-meaning rehydration treatments (waterings), people give-up and finally discard these once living tissues. While a tree is in a 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 a tree, but by water columns snapping inside the stem and branches due to severe dryness. Some tree drought indices quantify severity using microphones to count snapping water columns.

Communicating Stress

As water moves from soil through roots and into 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 roots and by neighboring cells along 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 cell pathways to the farthest root tips.

Organic growth materials are also added by roots to the transpiration stream. Any nitrogen captured by tree roots is processed into amino acids within roots using carbon captured by leaves. These amino acids are transported in the water stream to 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.

CO_2 vs. H_2O

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 evaporative loads on water columns throughout a tree. Leaves can close or open leaf valves (stomates) used for taking in carbon-dioxide gas required by photosynthesis to make food. A diagram of stomates on undersides of a broad leaf is shown in Figure 20.

Note the epidermis cells (leaf surface cells) are covered with a waxy cuticle to minimize water loss. When stomates are closed, the cuticle and stomates have roughly the same resistance to water loss, assuring neither stomate guard cell areas or cuticle is over-engineered. When 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 a leaf, but water rapidly evaporates and escapes. Theoretically, for conditions in a yard tree, 5-10 water molecules evaporate from a leaf for every one (1) carbon-dioxide captured. In reality, more than 250 water molecules are lost per carbon gain. In other words, a lot of water is transpired for small gains capturing food making carbon atoms.

The more food made for the least water used is calculated as "water use efficiency" (WUE) and is used to compare water demand by different trees. 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. Figure 21 provides a number of different water potential (pressure) measurement units found across the scientific literature. Here the use of an old measure called "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 in growth.

A simplified way of understanding water potential is illustrated in Figure 22. This figure shows a gradient of energies from water inside to water surrounding a cell. Water brought into a cell causes it to either swell like a balloon and change volume, or as in tree cells with a solid cell wall, pressure inside a cell increases. Increasing pressure means increasing energy to do work (positive water potential or pressure).

As water is removed from a cell, cell membranes can either collapse away from the wall changing volume (deflating), or a 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 (negative pressure) is caused by water being attracted to and held around small compounds within cells. A clump of starch in a cell is large and has a relative small hydration sphere or coating layer of water. If individual components of starch are broken apart (sugars), the amount of water needed to form hydration spheres around each sugar is increased geometrically and can be immense, demanding much more water. This process pulls water into a cell.

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

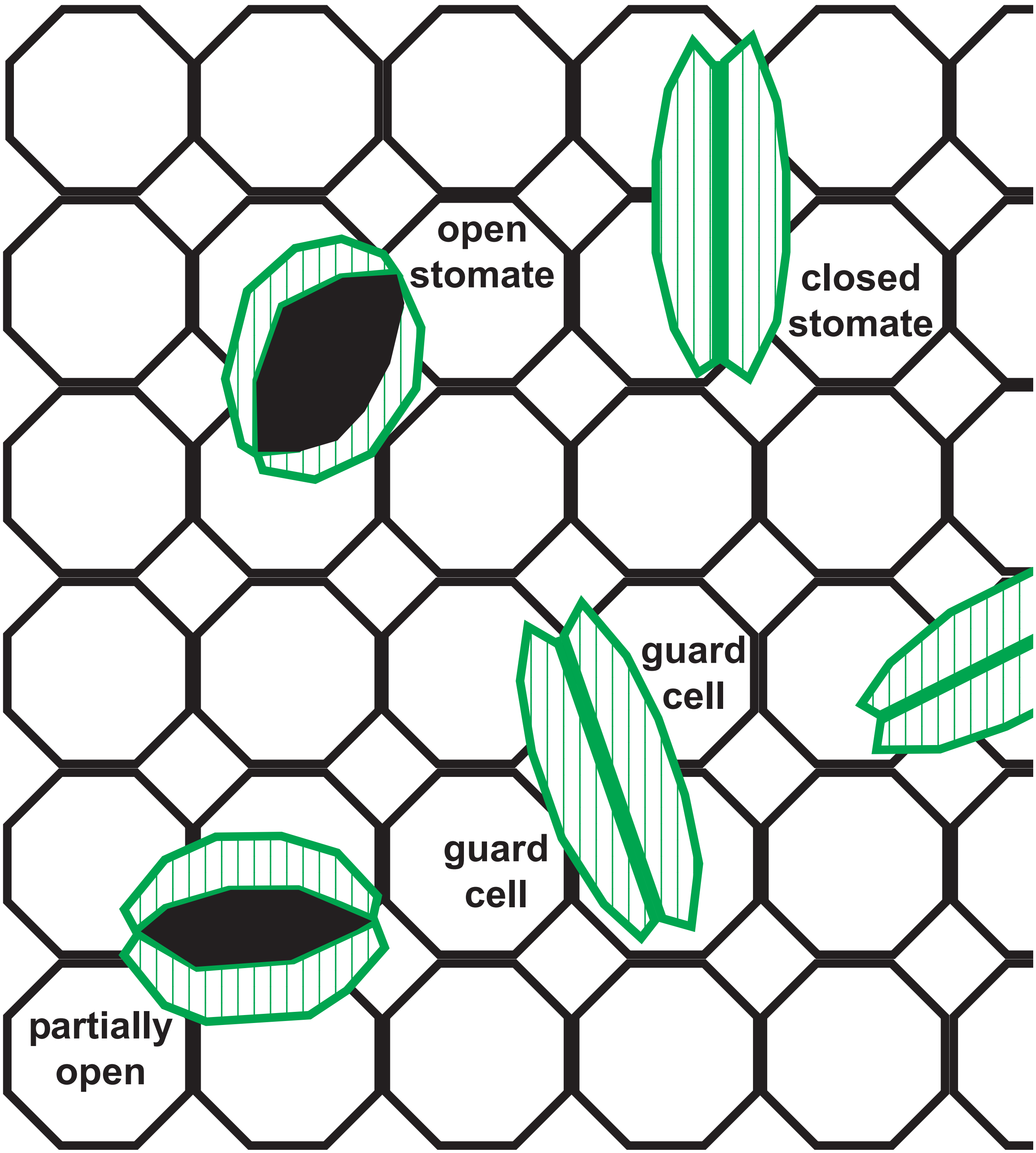

Figure 20: Idealized diagram showing open and closed stomates on underside of a tree leaf blade. The geometric pattern background represents leaf epidermis cells covered by a waxy cuticle.

units of measure	bar	atmosphere	pds-force/in²	mega-pascal
1 bar	1	0.99	14.5	0.1
1 atmosphere	1.01	1	14.7	0.1
1 pds-force/in²	0.07	0.07	1	0.007
1 megapascal	10	9.9	145.0	1

Figure 21: Different units for measuring water potential in trees from the scientific literature, both old and new. Here the older pressure unit measure called "bars" will be used. Read across a single line not down a column. (values have been rounded to fit figure)

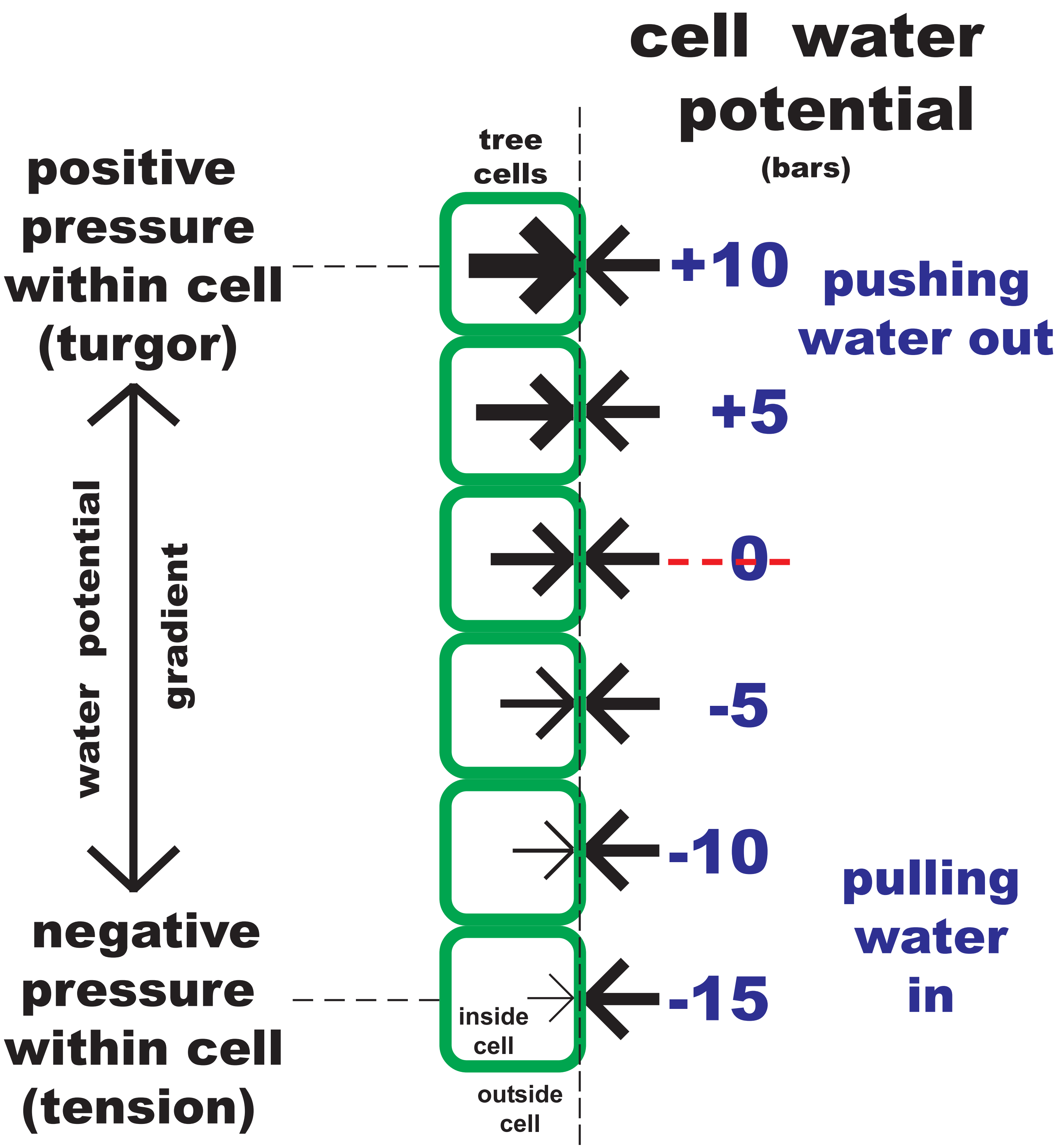

Figure 22: Simplified view of water potential gradient from pressure (positive water potential) to tension (negative water potential) within tree cells.

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 a leaf initiates a gradient of water potentials from the air surrounding a leaf through the tree to 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 23.

Increasing Tension

As water potential concepts demonstrate, when water is pulled up to tree tops and/or resistance to soil-water movement increases (uptake slows), a tension or negative pressure develops in water columns. Water continues to move from relatively low tension areas (like soil at field capacity), to 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 surrounding soil. As leaf water loss continues to exceed root water uptake, greater tension develops in water columns, and a water deficit begins to build.

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 a leaf and a tree cannot make food to feed itself. As water in 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 24.

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, energy in the band will snap it back. If you hold both end of the band and pull too hard, the band will break.

Transfer of the rubber band model to water movement in a tree is easy. As stomates lose water, water columns are pulled tighter and tighter down the tree and out into roots. If stomates close and stop adding more tension to the water column, roots will continue taking in water pulled by tension remaining in the water column. If soil is dry and transpirational pull too great, 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 stomates (and prevent any other surface evaporation), or to apply water to soil.

What A Drag

Water movement and evaporation is a function of temperature (energy) in the environment. Evaporative pull from leaf surfaces moves water from around soil particles and into roots. Water is not moved in a tree by "pumping," "suction," or "capillary action." Water in trees moves by sticking together and being dragged up/out to leaf surfaces where evaporation through stomates (transpiration) generates a "pulling" force on water columns. Water also evaporates from all other tree surfaces – buds, periderm, 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. Water will be pulled into the sponge and into air by evaporation across a large surface area. Evaporative force to move water through a tree is generated by the dryness of the air.

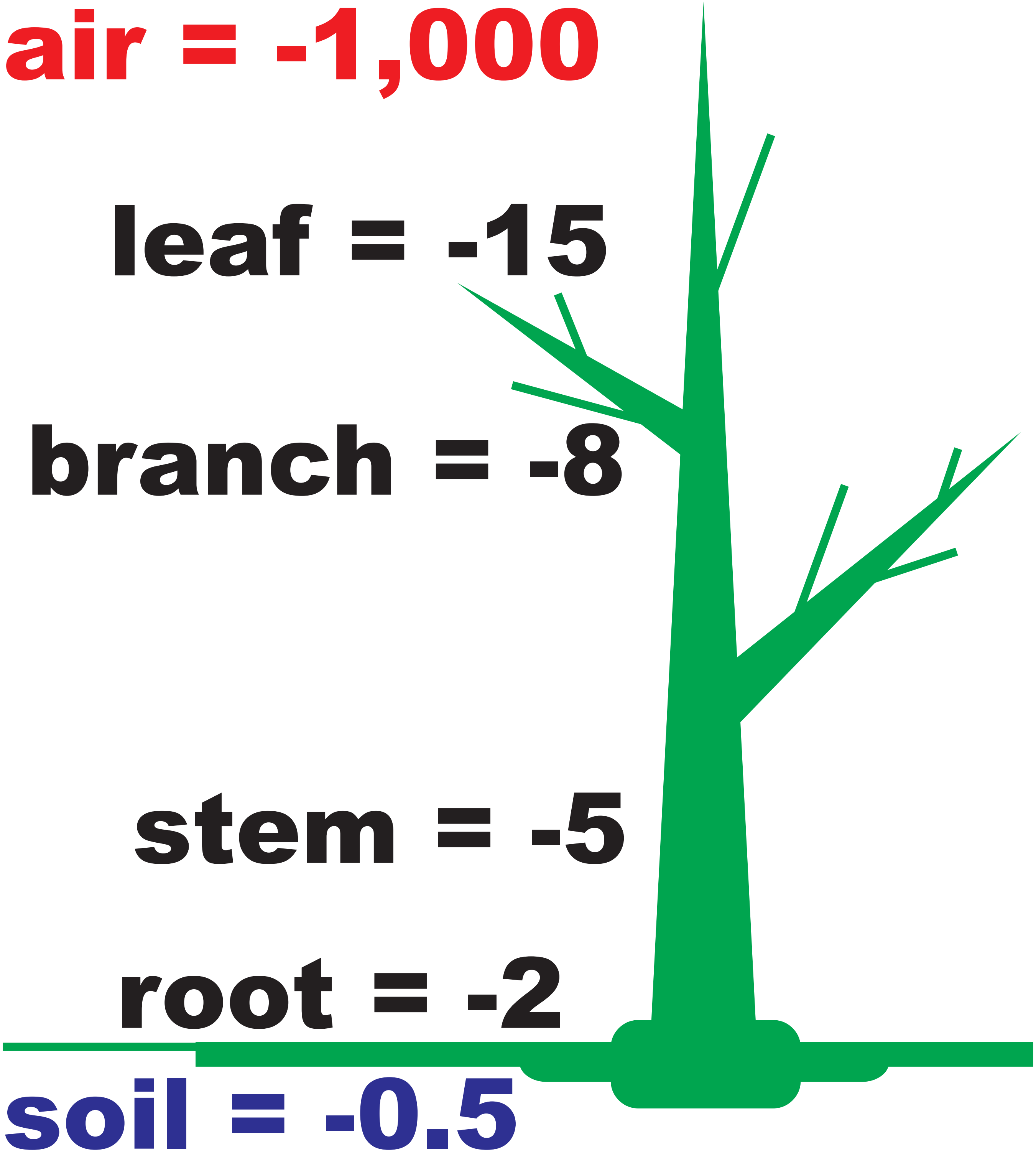

Figure 23: Example water potentials in bars from atmosphere to soil through a tree. Water moves (is pulled by tension) from more positive water potential regions (soil) to more negative water potential regions (leaf).

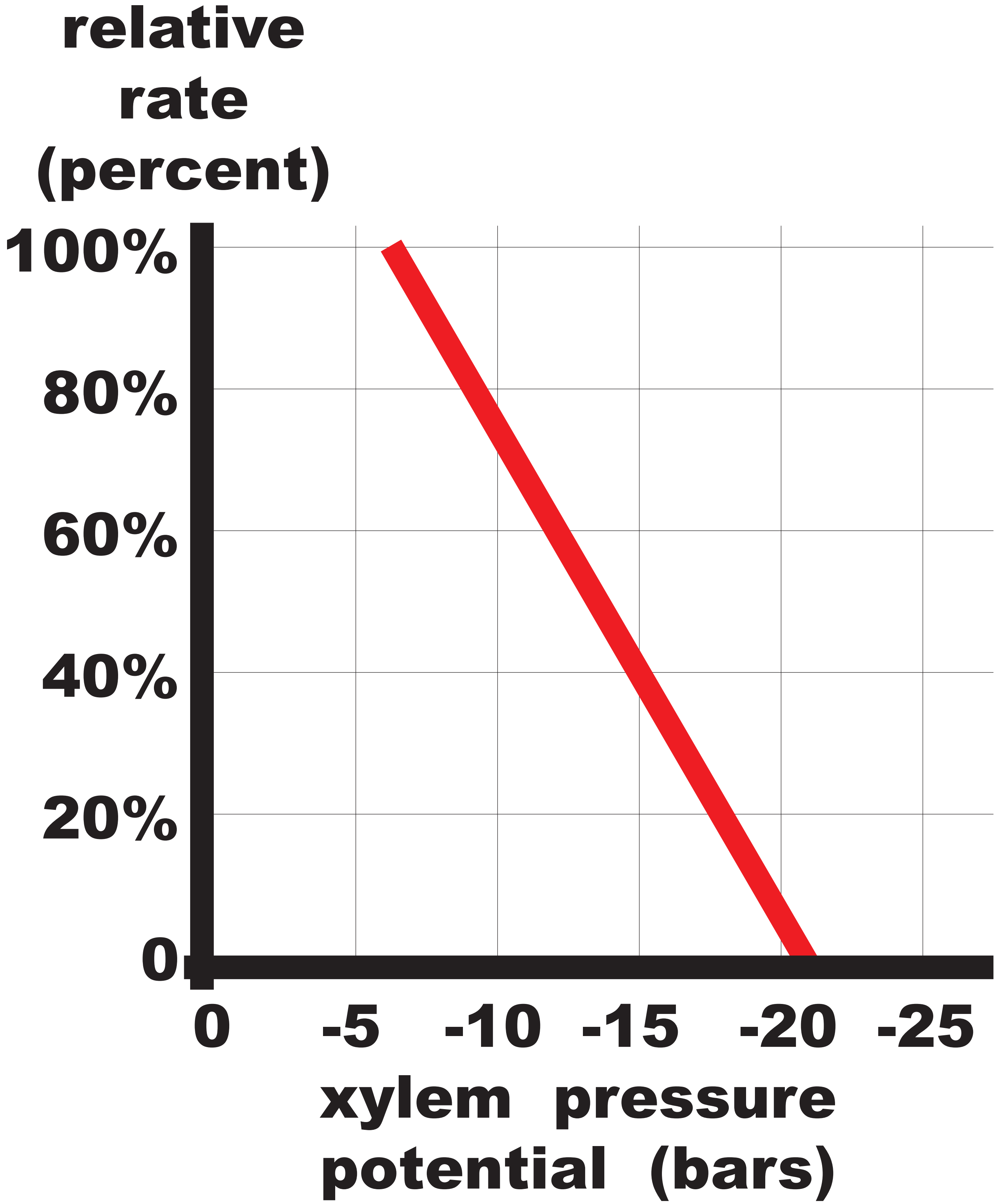

Figure 24: Relative rates of transpiration, net photosynthesis, & stomatal conductance compared with xylem pressure potential. (from Teskey, et. al. 1986)

The ability of air to evaporate water depends upon the water content gradient between air and leaf surfaces. A normal range of water content gradient over which tree growth occurs is -0.1 to -15 bars. Drought conditions and damage occurs in a leaf as it approaches -15 to -20 bars.

Sultry

The gradient between internal leaf atmosphere at 100% relative humidity (0 bars) and the external 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 98% relative humidity, the air is 100 times drier than the inside of a leaf. Trees are always losing water. See previous Figure 10.

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 surfaces and structures which water must move through. The engine that powers water movement in trees is the dryness of the atmosphere and associated rate of evaporation through stomates. Anything which effects atmospheric demand for water, and stomate control of water loss rates, would affect water movement in a tree.

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 a tree closes many stomates on many leaves for several hours. Water column tension continues to pull in water from soil, and as tension values decline (i.e. 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 25. 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 watered 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 a 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 during the day, even after 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 26.

Even though there is little evaporation at night because stomates are closed and the relative humidity is high, water is still moving from 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 roots from soil, and all other plants in the area are pulling water from soil, tensiometers in soil can measure a 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

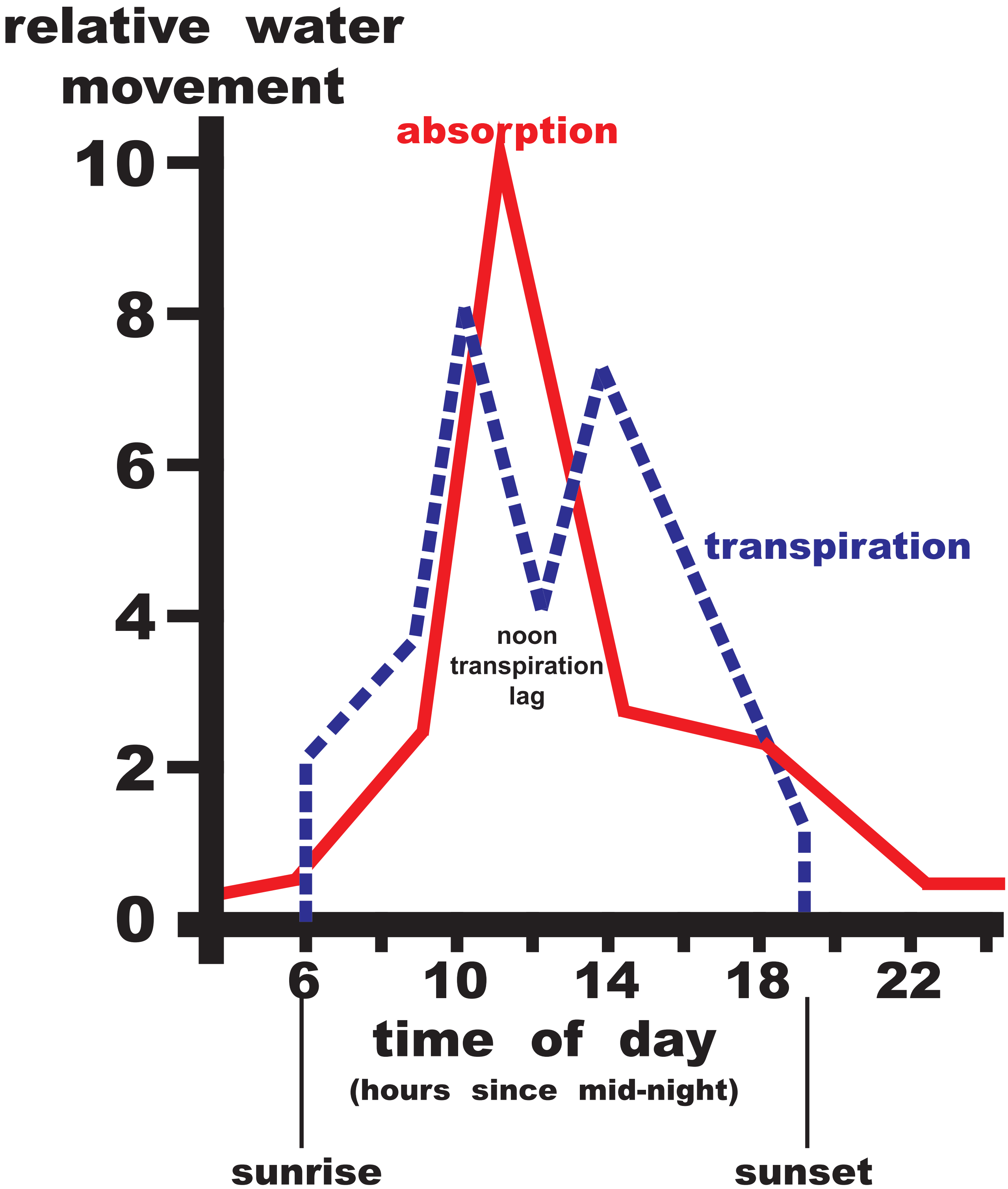

Figure 25: Root absorption and leaf transpiration within a tree and relative amount of water being moved by each process. Note transpiration in leaves begins just after sunrise, is slowed at mid-day, and stops just before sunset. Root absorption continues through the night.

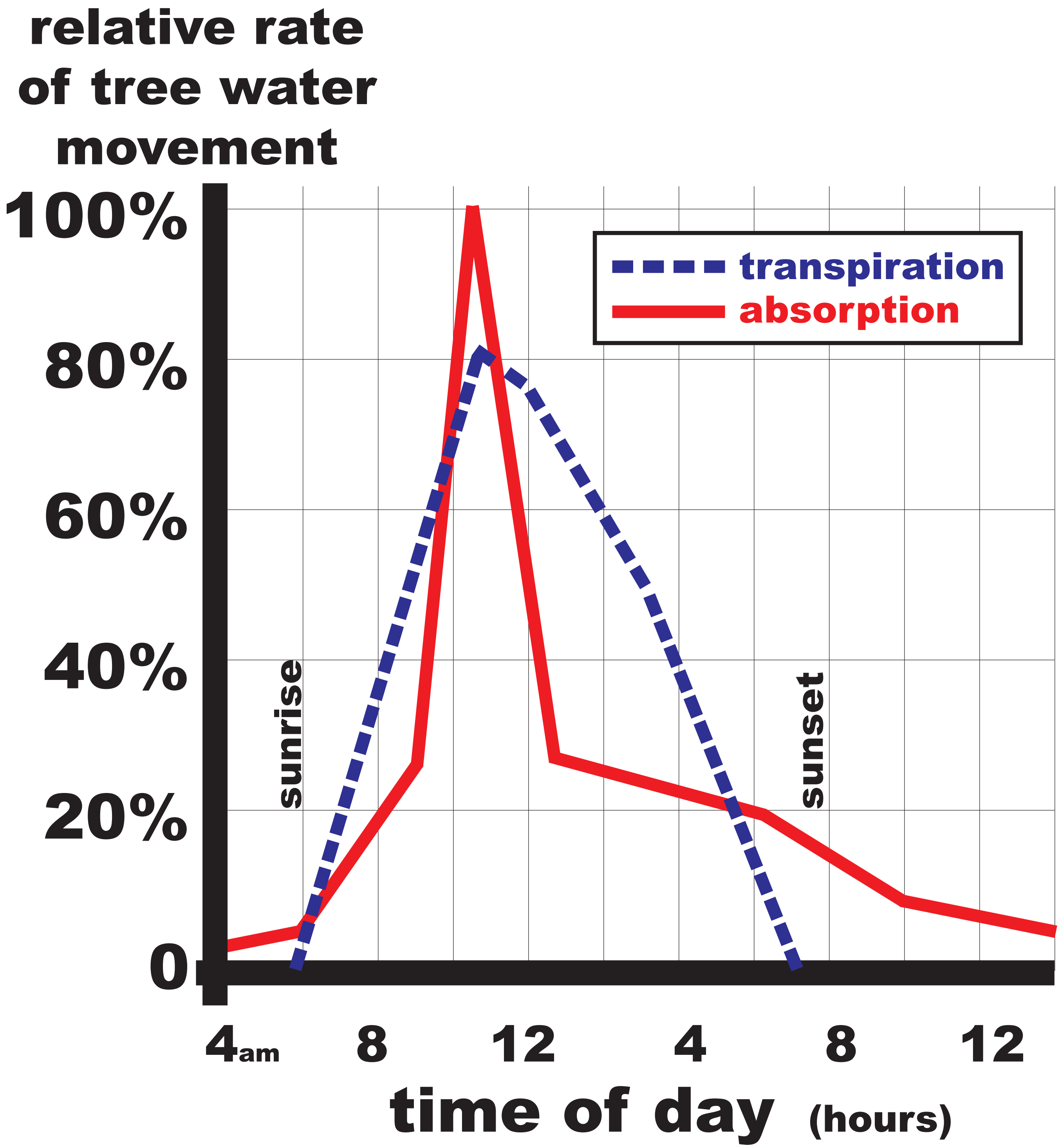

Figure 26: Example of relative rate of water movement from transpiration and root absorption within a tree over a growing season day under field capacity soil water conditions with no noon transpiration lag.
(derived from Waring & Schlesinger, 1985)

evaporation and energy impact. All 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. As discussed earlier, stomates are tiny valve-like openings spread across the underside of leaf surfaces.

A dissecting microscope is needed to see most stomates. In temperate trees (C3 Ps), 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 usually residual and do not function. Figure 27 is an idealized cross-sectional diagram of a broadleaf stomate.

By definition, a stomate is an opening in a leaf's epidermis which is 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 a leaf surface.

These stomatal leaf openings are required in order for a tree to capture carbon-dioxide from 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 which allows water to be pulled through a tree.

Water Guards

Two flaccid guard cells lay side-by-side covering the opening to an interior of a leaf. When these guard cells sense sunlight with their photosynthetic units, they begin to be pumped-up with water. Guard cells and surrounding cells convert stored starch and other large materials into sugars and many smaller sized materials. Guard cells release potassium ions which attract large water shells. Because guard cells are tethered to each other only at the ends, they absorb water and lengthen creating a gap between, unveiling an unprotected entrance to inside a leaf.

Carbon-dioxide moves into leaves through stomates and dissolves onto water-saturated cell walls for use in food making. Water from saturated leaf cell walls evaporate quickly and escape through stomates. The only place in a tree with control of water loss, food resource gathering, and the tree's transpiration stream is at 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 and closing of stomates.

Spreading Out Evaporation

Little can be done to greatly 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 28 demonstrates how transpirational loss of water from soil increases with climbing temperatures.

The efficiency of water use can be improved by increasing the vertical and horizontal distribution and extent of shade (tree crowns) on a 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 to generate the most food produced per unit of water evaporated.

Figure 29 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 reach a similar water use efficiency.

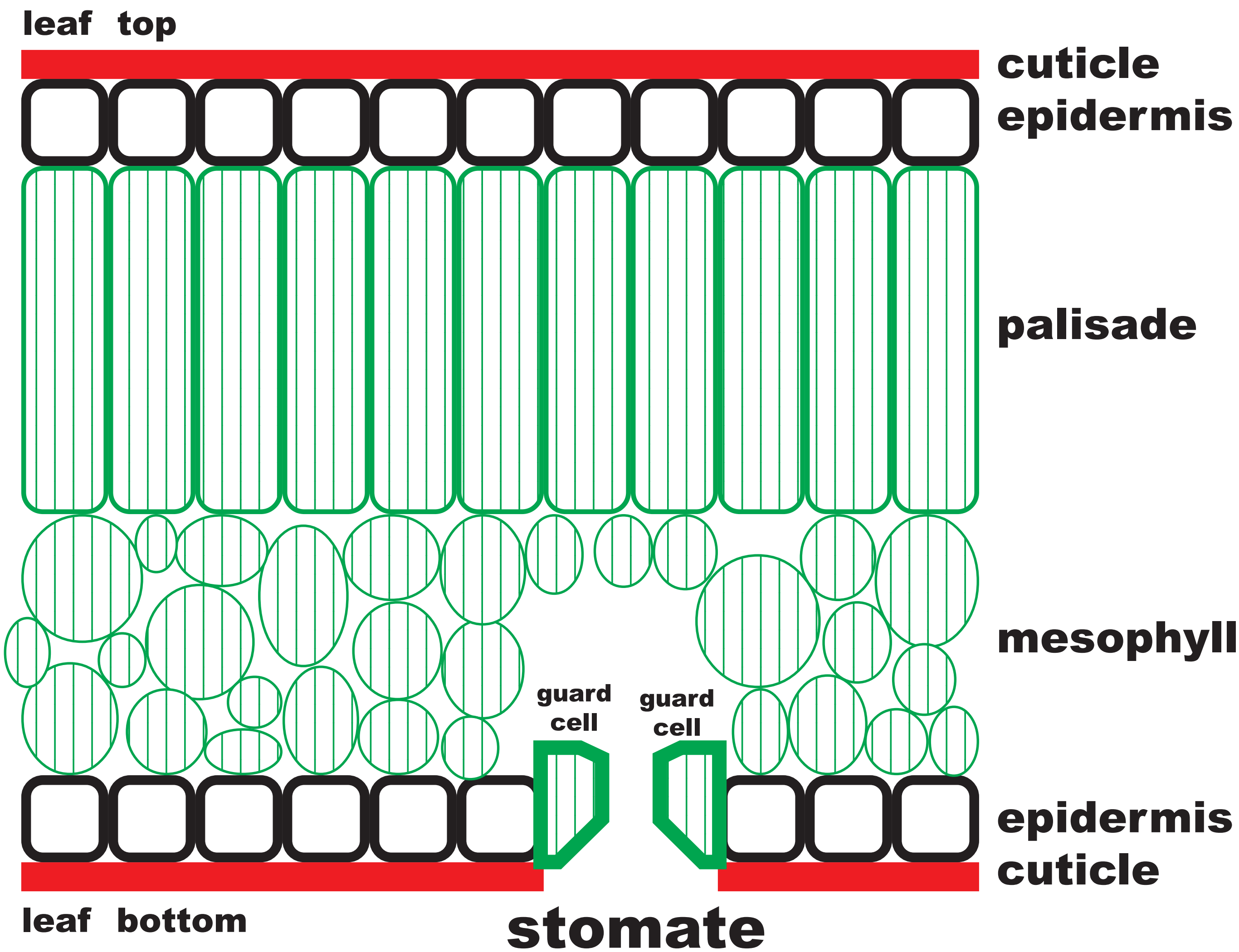

Figure 27: An idealized cross-sectional diagram of a tree leaf blade showing different non-vascular cell layers and a stomate. Cells with shading have chlorophyll. The top and bottom leaf surface is covered with a wax cuticle.

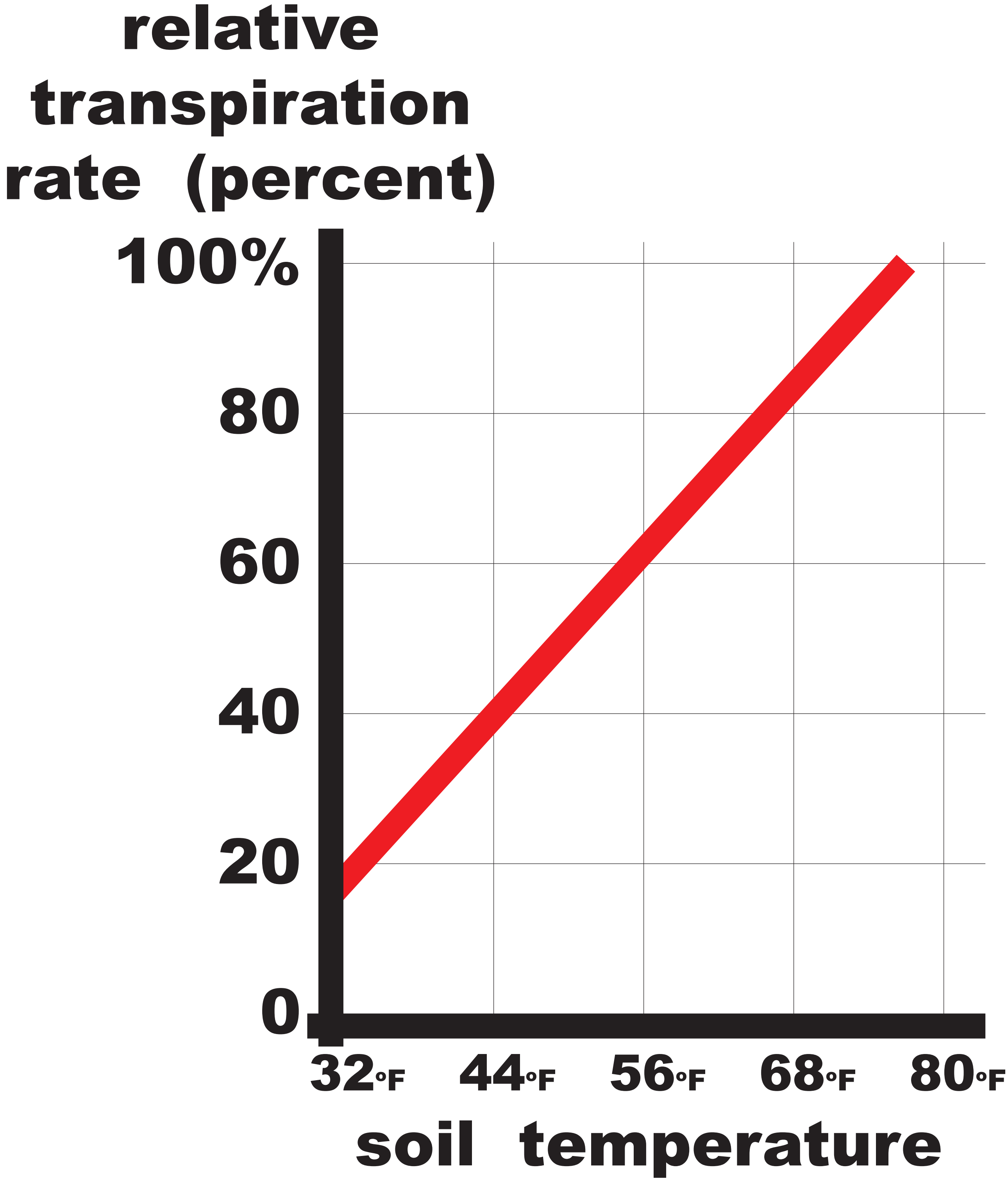

Figure 28: Example impact of soil temperature on transpiration in pines. (derived from Kramer, 1942)

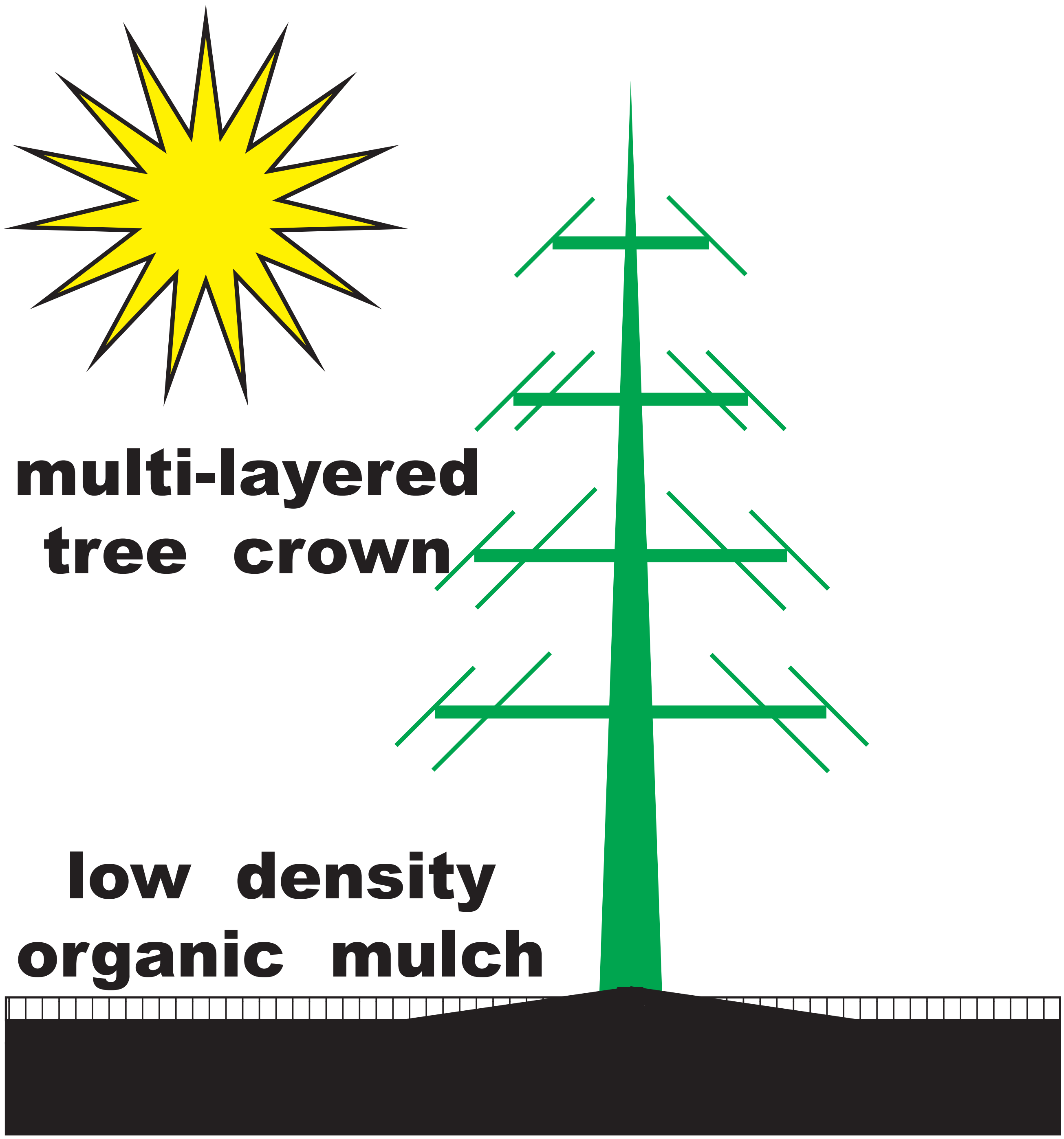

Figure 29: Diagram of tree with a multi-layered crown and organic mulch bed. This tree form is efficient at conserving water because sunlight energy is spread over a vertically spread, relatively large, widely distributed crown surface area. Low density organic mulch assures little energy directly impacts soil surfaces.

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 a canopy which are most actively transpiring. The water 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 sapwood and limited heartwood increments.

Morning Trees

Water is "stored" in the stem. 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 30.

As transpiration increases in the morning, root absorption initiated by the current day's water loss does not begin to increase until later due to stem water availability. Leaf water loss must produce sufficient tension in xylem water columns to overcome the resistance to water flow through xylem and from soil into roots. 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 evening, as temperatures decrease and stomates close, transpiration is rapidly reduced. Water absorption by roots continue until water potential in a tree comes into near equilibrium with soil. This absorption process may require all night. As soil dries, there is less water recovery on succeeding nights until permanent wilting occurs. Figure 31. A prolonged, severe water deficit will cause tree death.

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 32 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 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 soil and subject to a greater impact by gravity pulling down on the water columns. An early drought priority which favors the most productive leaves, shifts to favoring the most survivable leaves as drought conditions worsen.

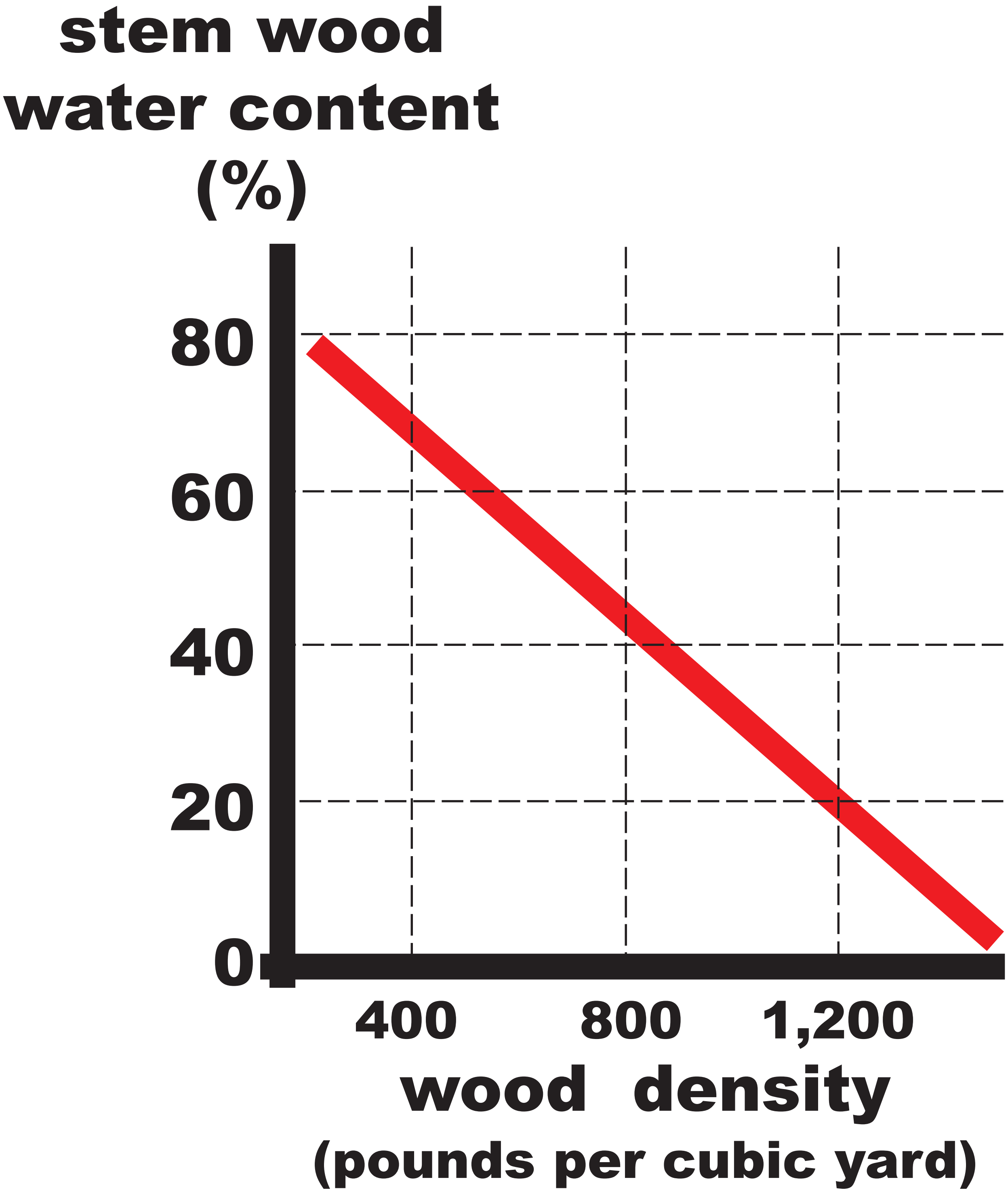

Figure 30: Water available in tree stems with various densities of wood. (after Borchert, 1994)

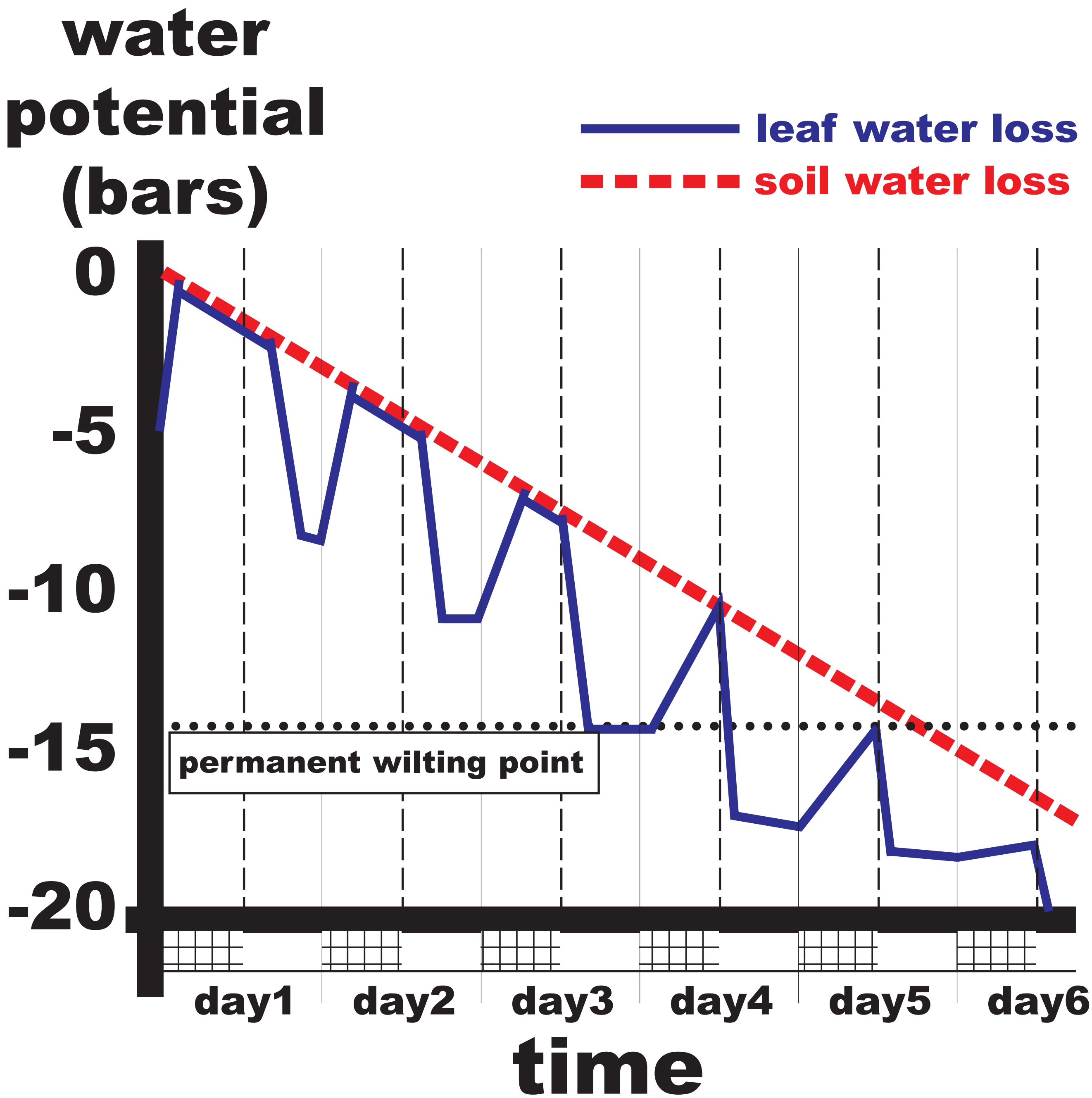

Figure 31: Diagram of daily water potential changes (with no addition of water) as tree leaves and soil dry.
(derived from Slatyer, 1967)

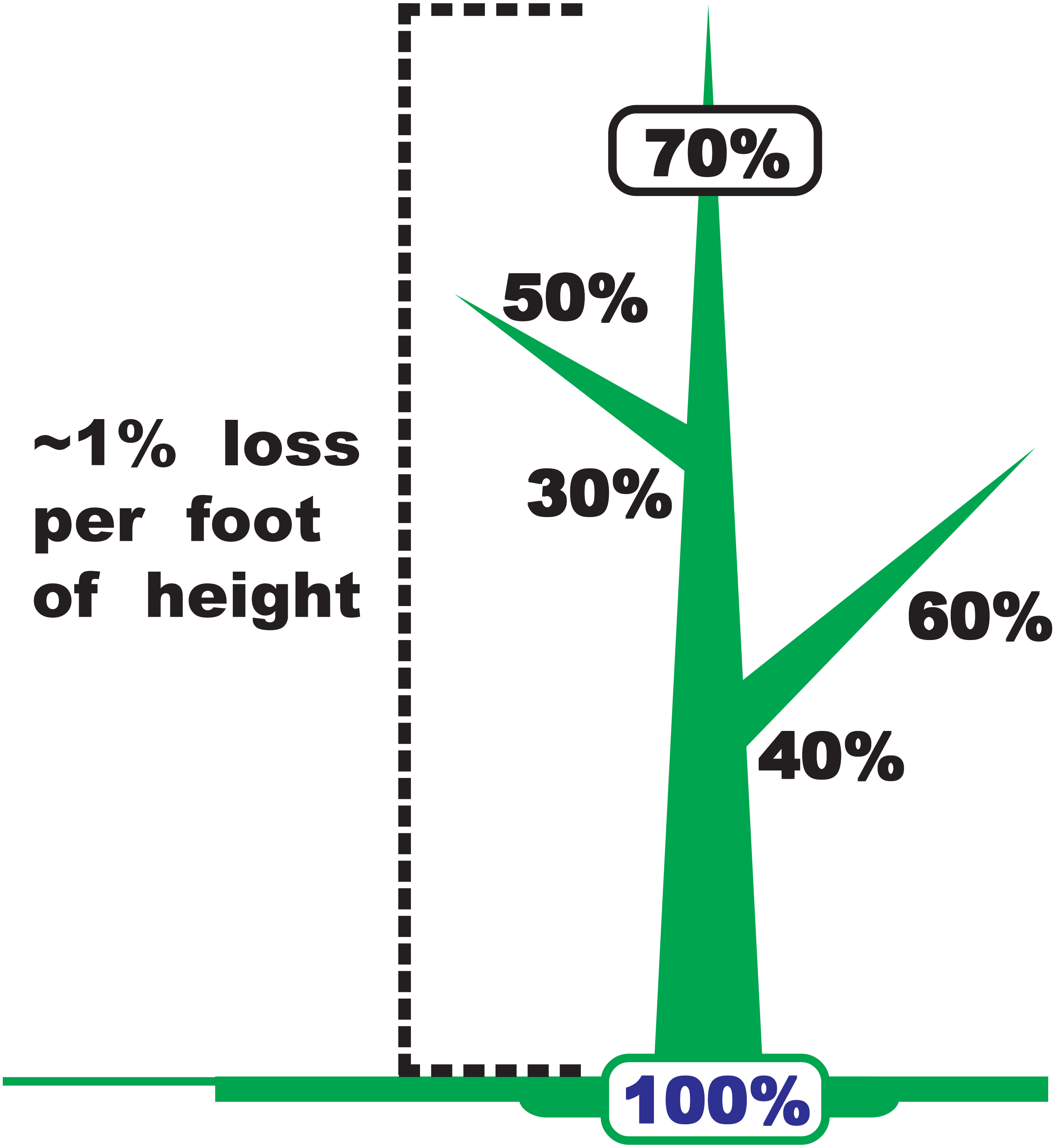

Figure 32: An idealized diagram of relative values for water conduction (inverse of resistance) within a tree. Branch & twig connections (nodes) greatly limit water movement. (derived from Zimmermann, 1978)

Blown Away

Another drying force acting on a tree is wind. Wind blowing past a tree crown can desiccate a 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 warm air coming from over a hot parking lot to a site, greatly increasing transpiration. Figure 33 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 34 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 (more negative) than a lower point. Sun and wind generate larger water deficits within trees.

Water Content

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 a tree will have different water tensions (deficits). Since water moves from highest concentration (lowest tension) to lowest concentration (greatest tension), tree parts which 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.

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.

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 Figure 35. For example, 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 surfaces of soil particles and left in pore spaces between particles. Sandy soils dry rapidly because spaces between 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 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 a 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.

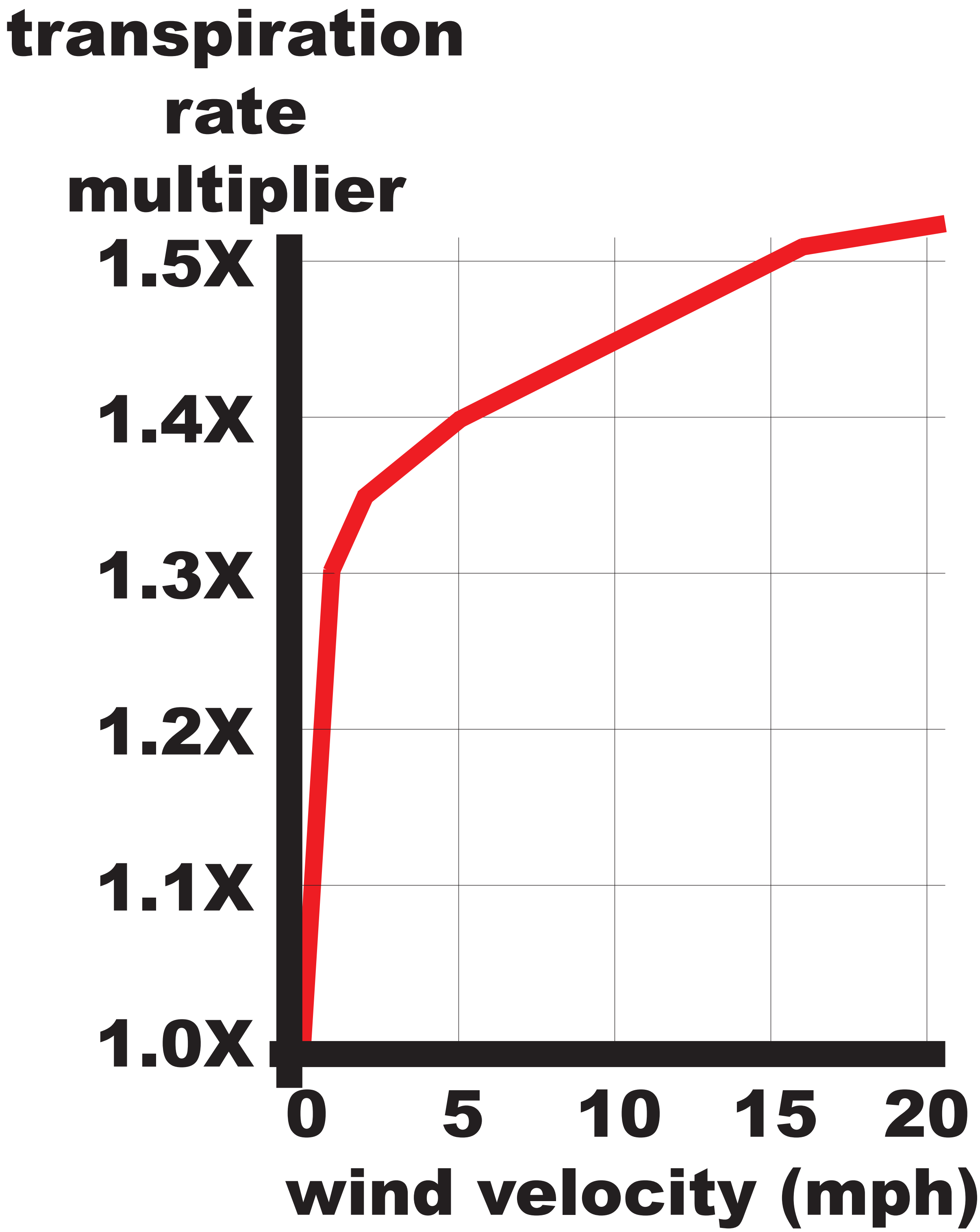

Figure 33: Additional transpiration rate of a tree under various wind speeds in miles per hour compared with transpiration rates under calm conditions. (derived from Kramer & Kozlowski, 1979)

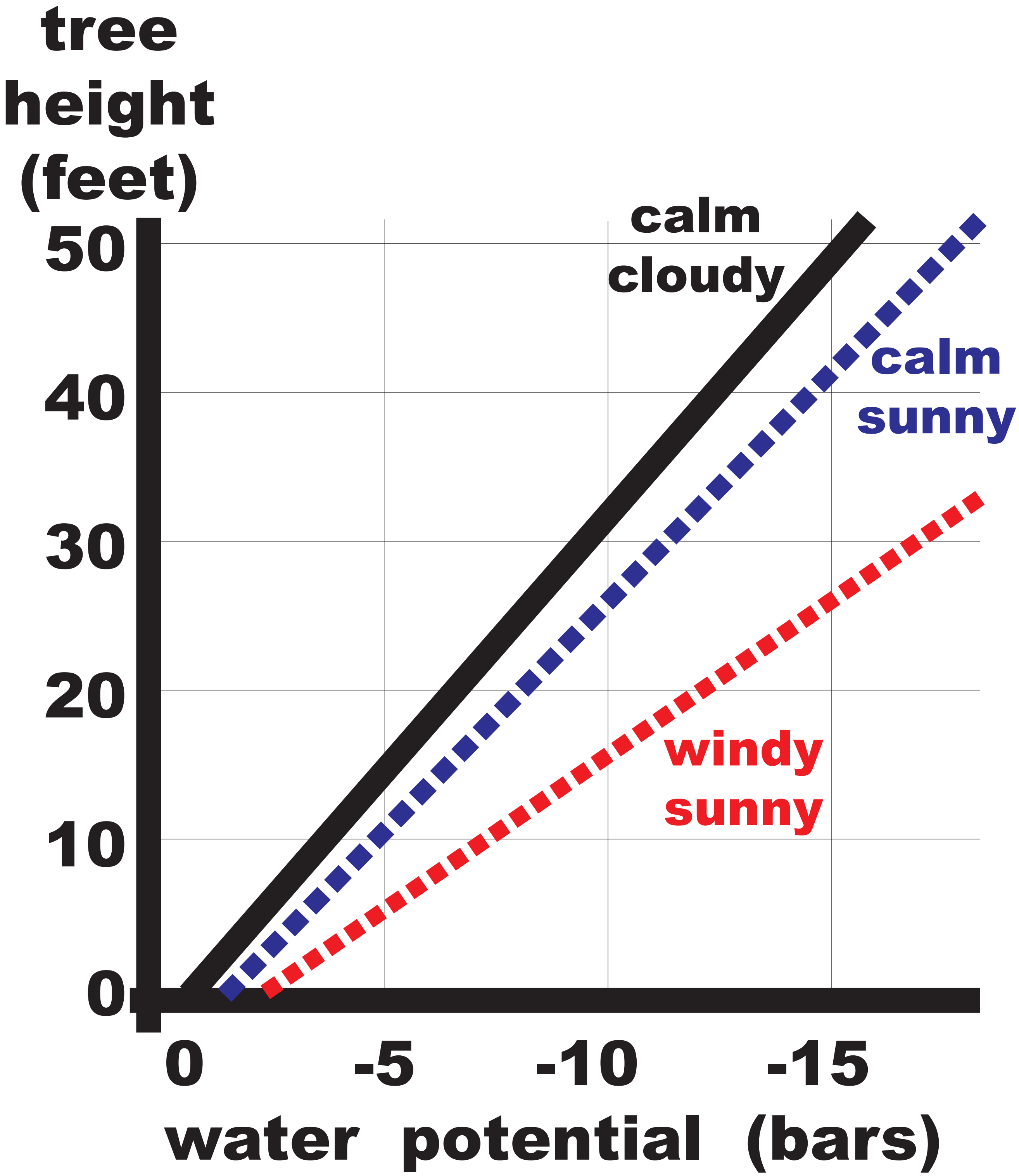

Figure 34: Mid-season water potential values at various tree heights under three site conditions: calm wind and cloudy; calm wind and sunny; and, windy and sunny. (derived from Hellkvist et. al. 1974)

tree species	water velocity (ft/hr)
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
Gymnosperms (non-porous) trees	
larch	7
pine	6
spruce	4
hemlock	3

Figure 35: Rough estimate of water velocity through stem vascular tissue for various genus and species of trees in feet per hour, categorized by xylem porosity.

Roots

A major portion of 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 periderm and any crack or damage is quickly sealed-off, so little water flows into these roots.

It is young roots, easily damaged by drought, which 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 a growing season, depending upon species. A tree may have a single set of leaves per year, but many sets of absorbing roots. Figure 36 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, availability of water begins to be limited by decreasing water potentials and hydraulic conductivity. Figure 37. Dimensional shrinkage of both soil and roots occur as soils dry. Soil aeration, soil temperature, and 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 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 (i.e. water loss) into the power for a supply highway within a tree. Water shortages can prevent tree food production and damage tree life processes.

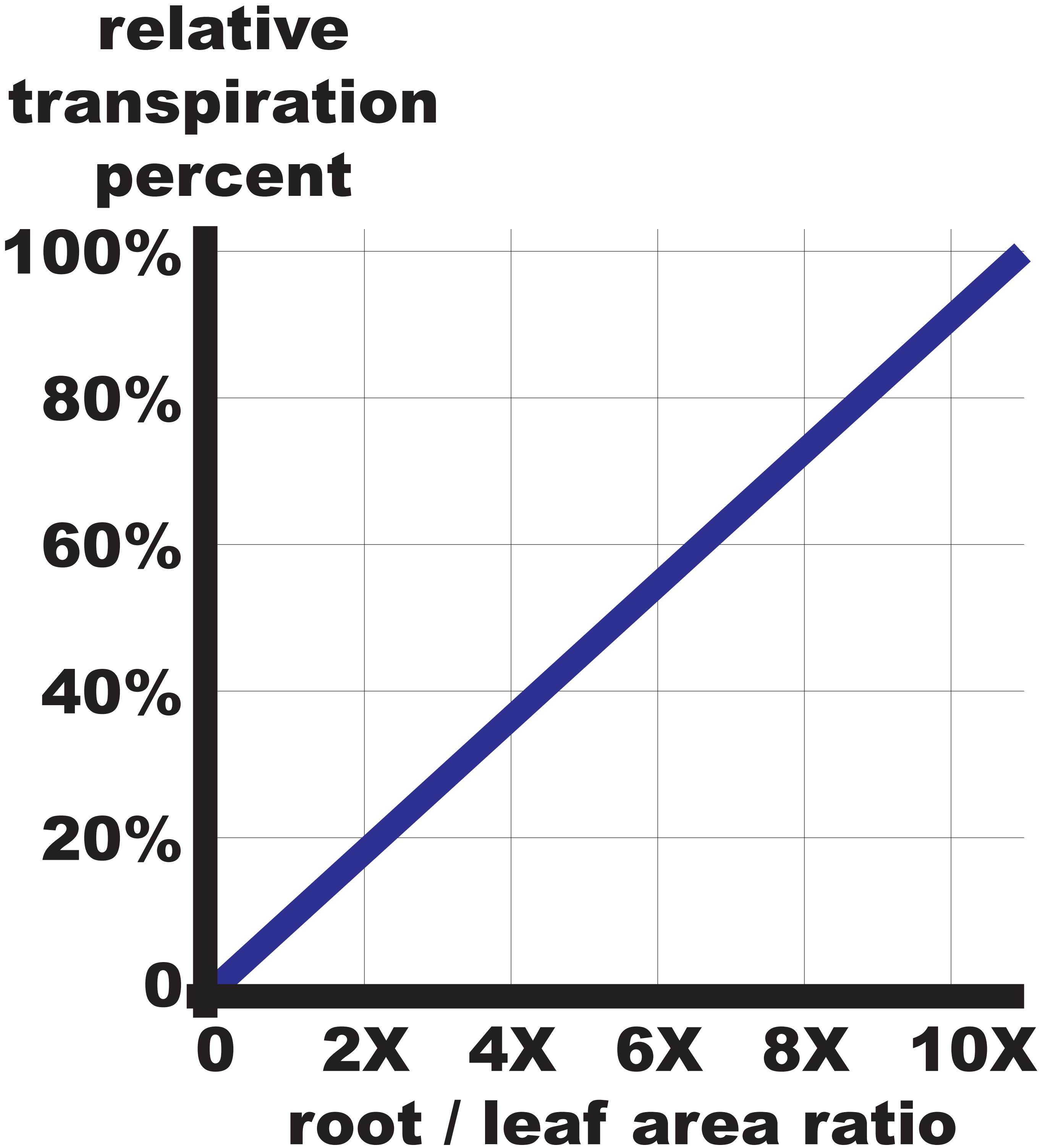

Figure 36: Relative amount of tree transpiration in percent compared with root / leaf area ratio of a tree. Root values were on a dry weight basis and leaf values were on a square foot basis. X = leaf area; 2X = two times more root mass than leaf area. (derived from Parker, 1949)

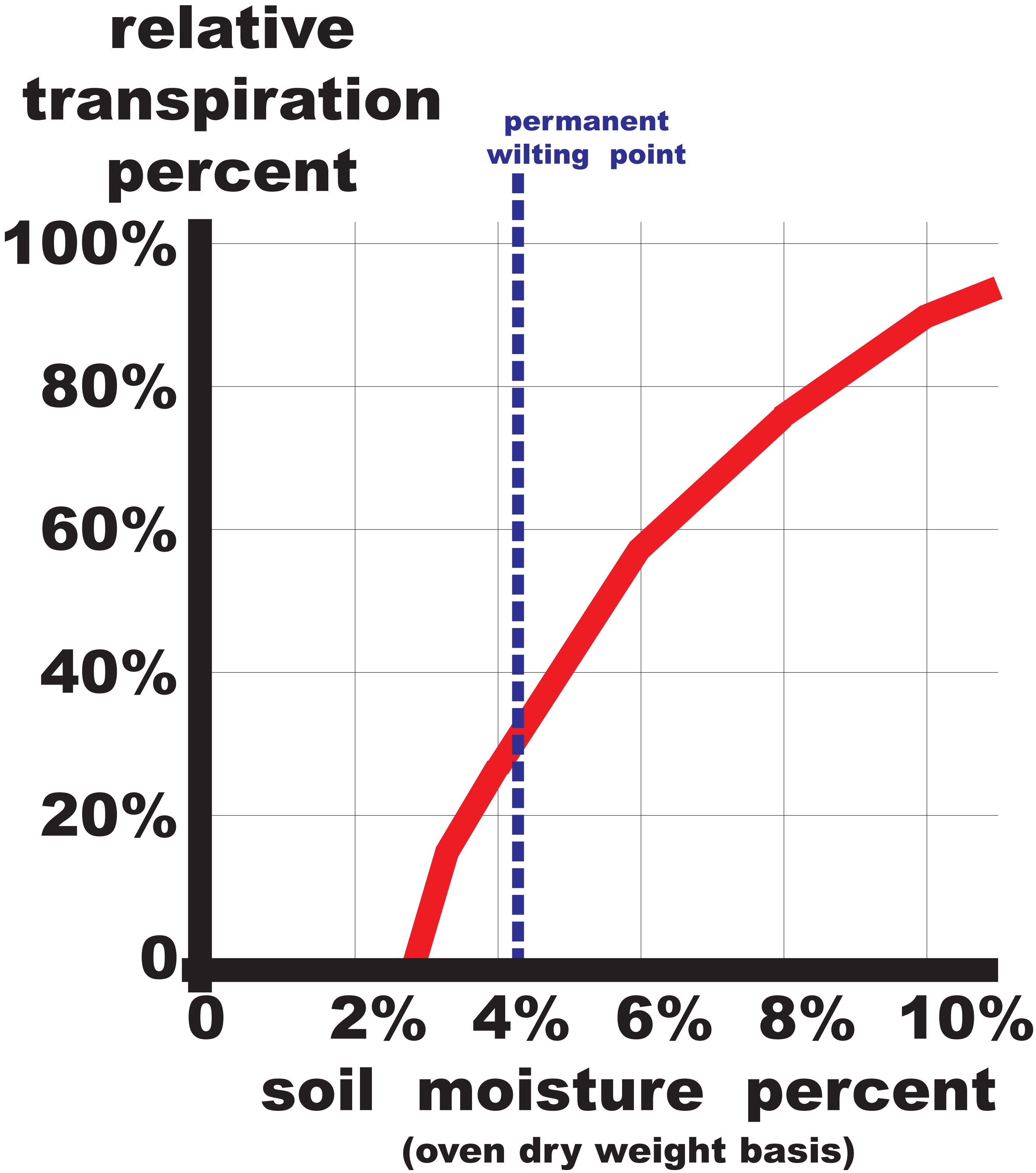

Figure 37: Relative amount of tree transpiration in percent compared with various soil moisture percents based upon an oven dry weight basis. (derived from Bourdeau, 1954)

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