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Drought, Heat & Trees:
-- a learning manual --

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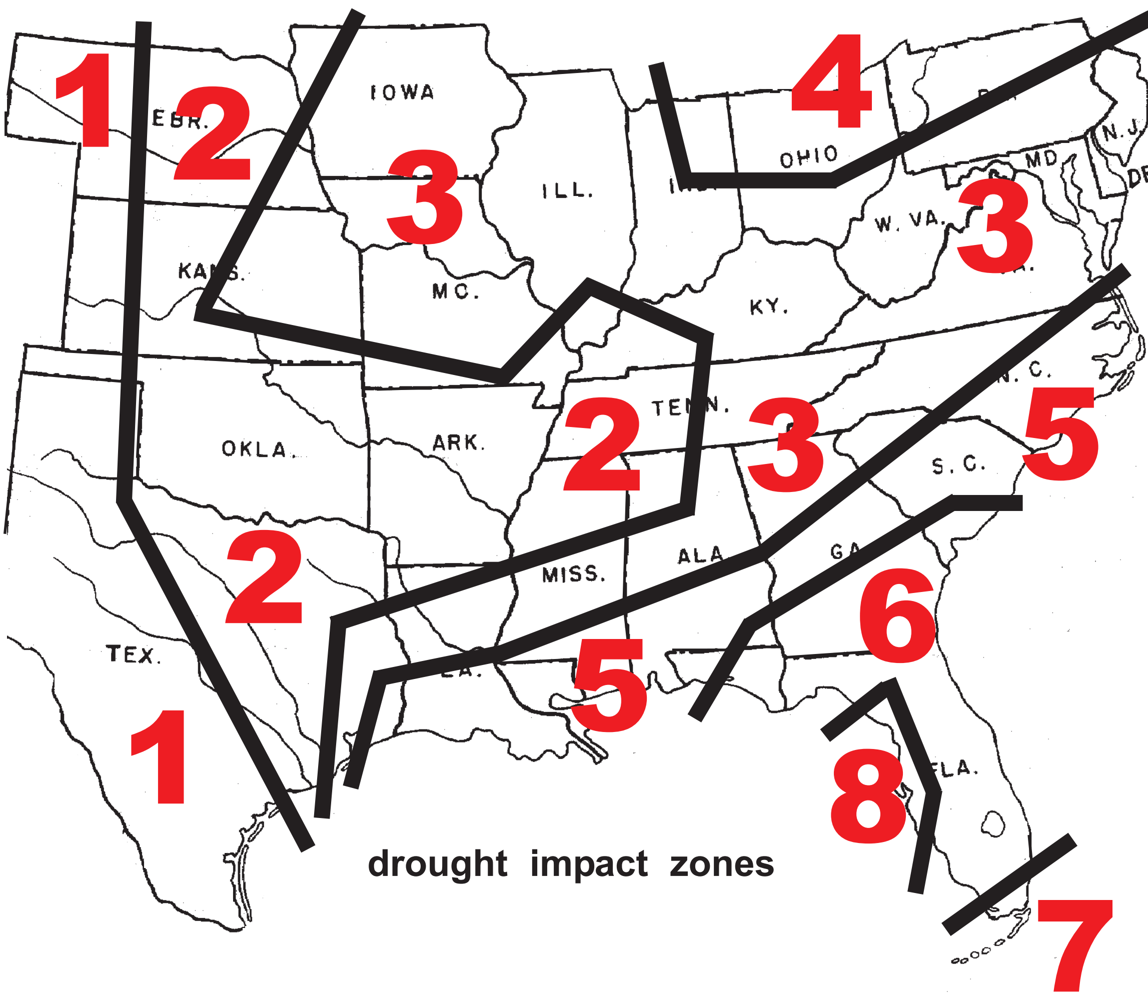

This manual is an educational product designed for helping tree health care professionals appreciate and understand drought and heat interactions with water availability in trees. This product is a synthesis and integration of research and educational concepts regarding drought, heat loading, and trees. This educational product is for awareness building and professional development.

At the time it was finished, this manual contained educational materials and models concerning trees and drought stress thought by the author to provide the best means for considering fundamental tree health care issues associated with water shortages. 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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Drought, Heat & Trees: A Learning Manual

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 only have a limited set of responses to any stressful situation as directed by their genetic material. Trees can only react to water and heat 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 and heat loading can provide for long tree life.

Drought Stress

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, 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 variability.

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 exteremes of water availability, interacting with site constraints like heat loading, which damage trees. Examining climatic patterns can suggest what is normal and what is atypical.

Figure 1 represents land areas in the Southeastern United States which share common climatic patterns during the month of June. Figure 2 represents land areas in the Southeastern United States 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. Climate expectations for tree health change over each month of the growing season. In these figures, the larger number listed, the less water stress expected for tree growth over time under normal conditions.

Drought Potential

Figure 3 shows multi-year composite climatic zones based upon annual average evaporation, precipitation, and temperature in finer detail. As in previous maps, the larger number listed, the less water stress expected for tree growth over time under normal conditions. Prolonged drought conditions will be more devestating the higher the number listed, although risk of drought may be less.

Figure 4 cites a temperature line, an evaporation level, and a precipitation amount forming areas with similar potential for droughts. Hot, moderate precipitation, and strong evaporation means significant risk of tree stress like drought.

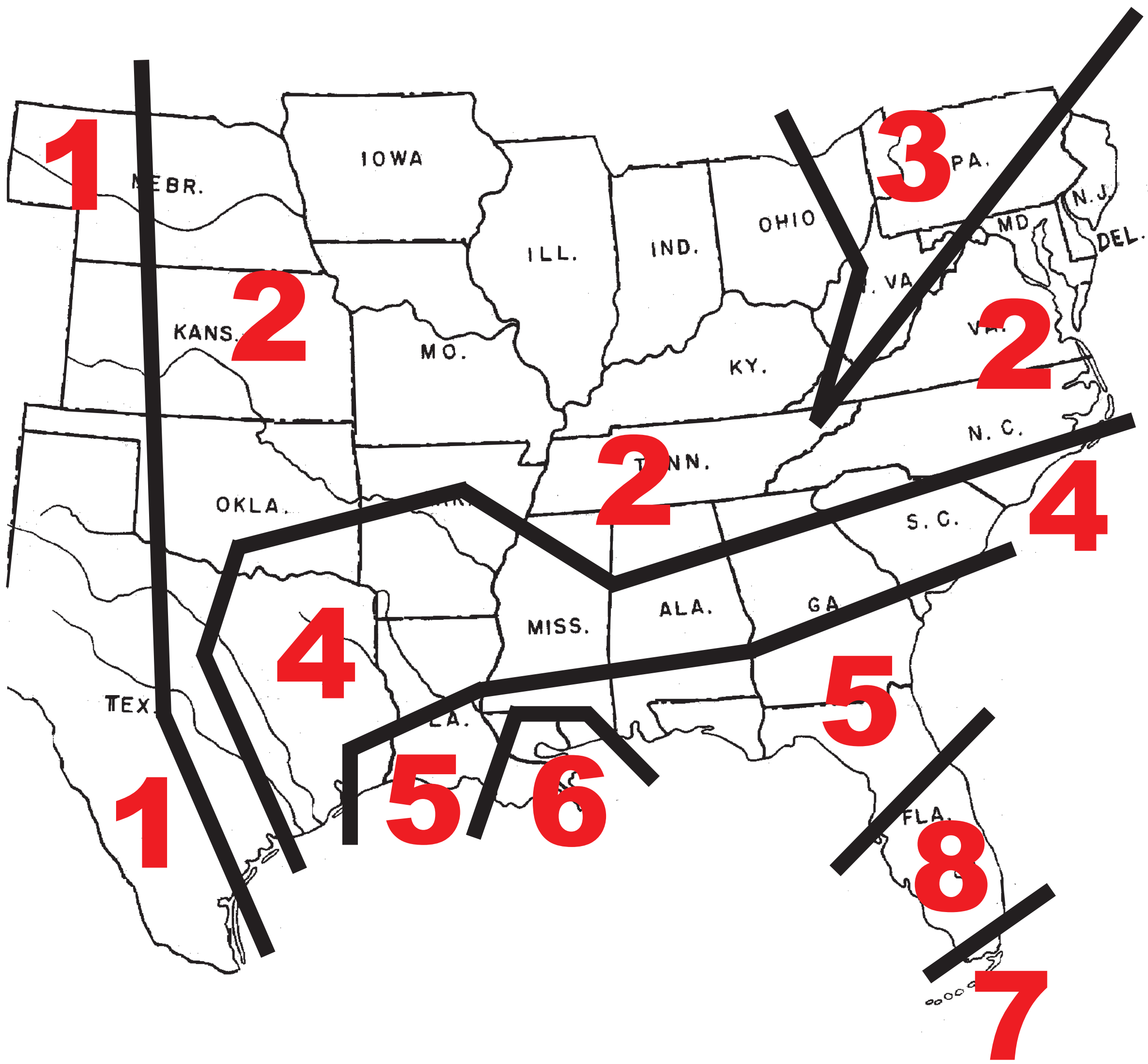


Figure 1: Areas of the Southeastern United States with similar composite multi-year average climatic features for the month of June. Composite data includes evaporation, precipitation, and temperature. Generally, the larger the number, the less water stress expected for tree growth over time under normal conditions.

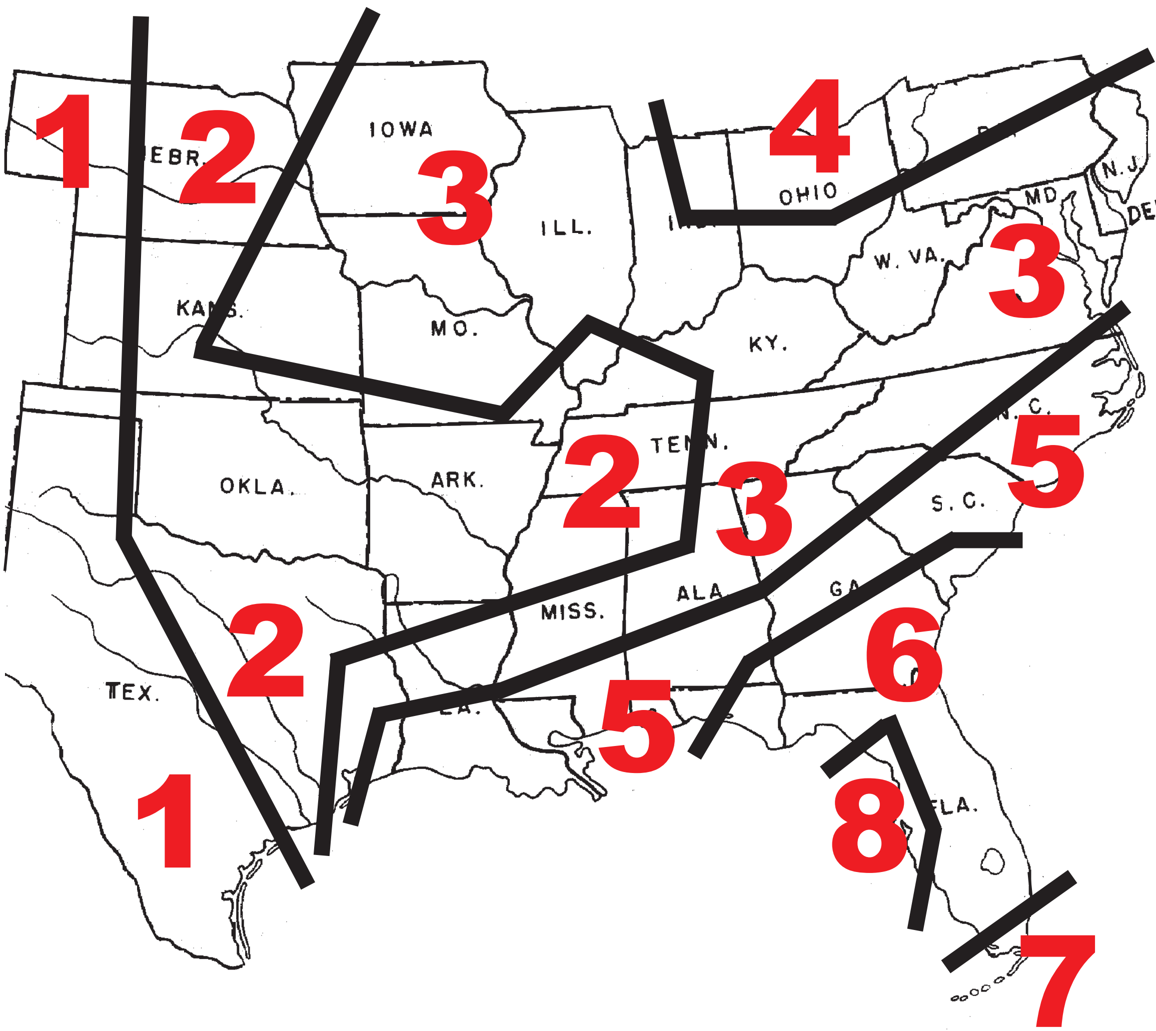


Figure 2: Areas of the Southeastern United States with similar composite multi-year average climatic features for the month of August. Composite data includes evaporation, precipitation, and temperature. Generally, the larger the number, the less water stress expected for tree growth over time under normal conditions.

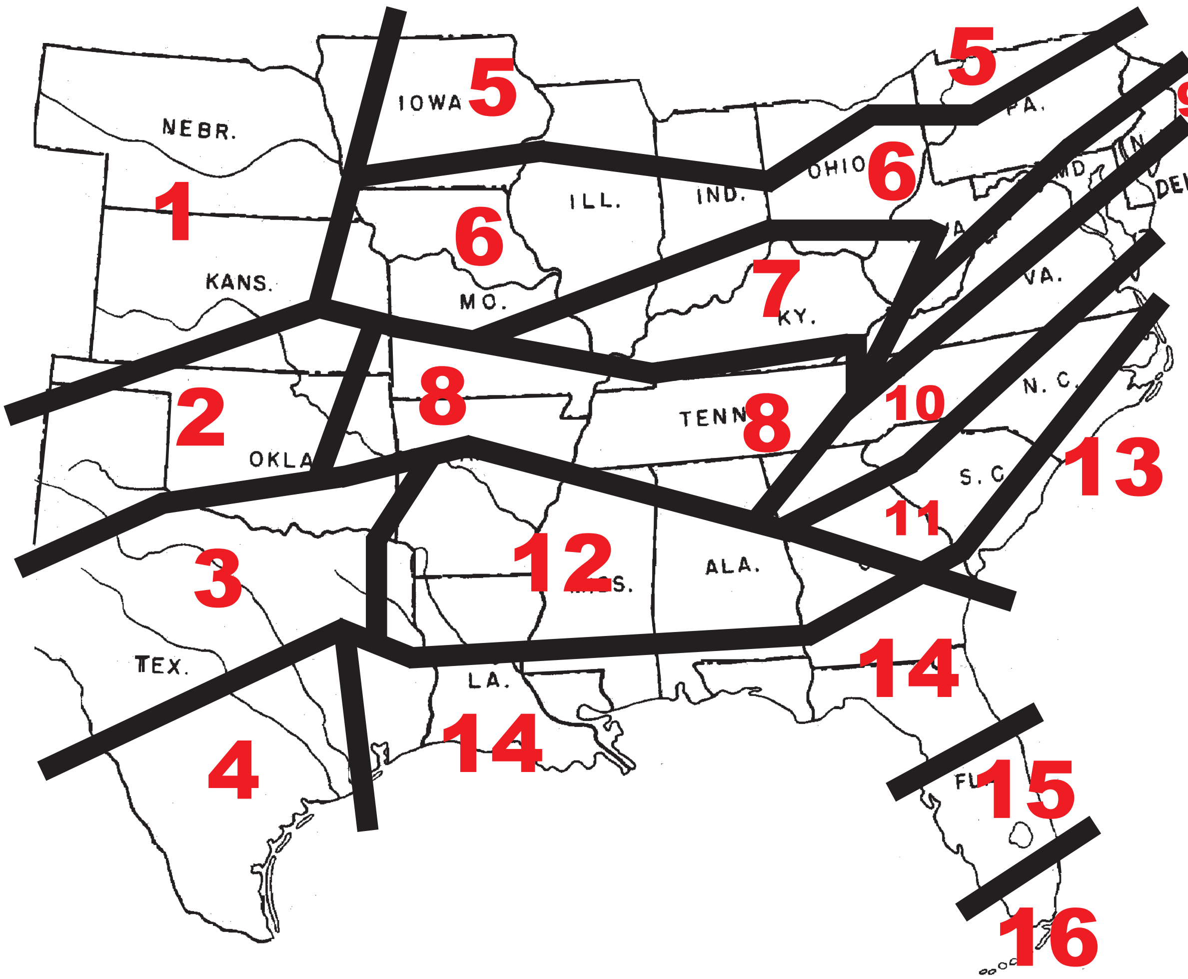


Figure 3: Areas of the Southeatern United States sharing similar composite climatic zones based upon annual average evaporation, temperature, and precipitation. Generally, the larger the number, the less water stress expected for tree growth over time under normal conditions. Prolonged drought conditions will have a more devastating impact on areas with larger numbers listed, although the overall risk of severe drought is less.

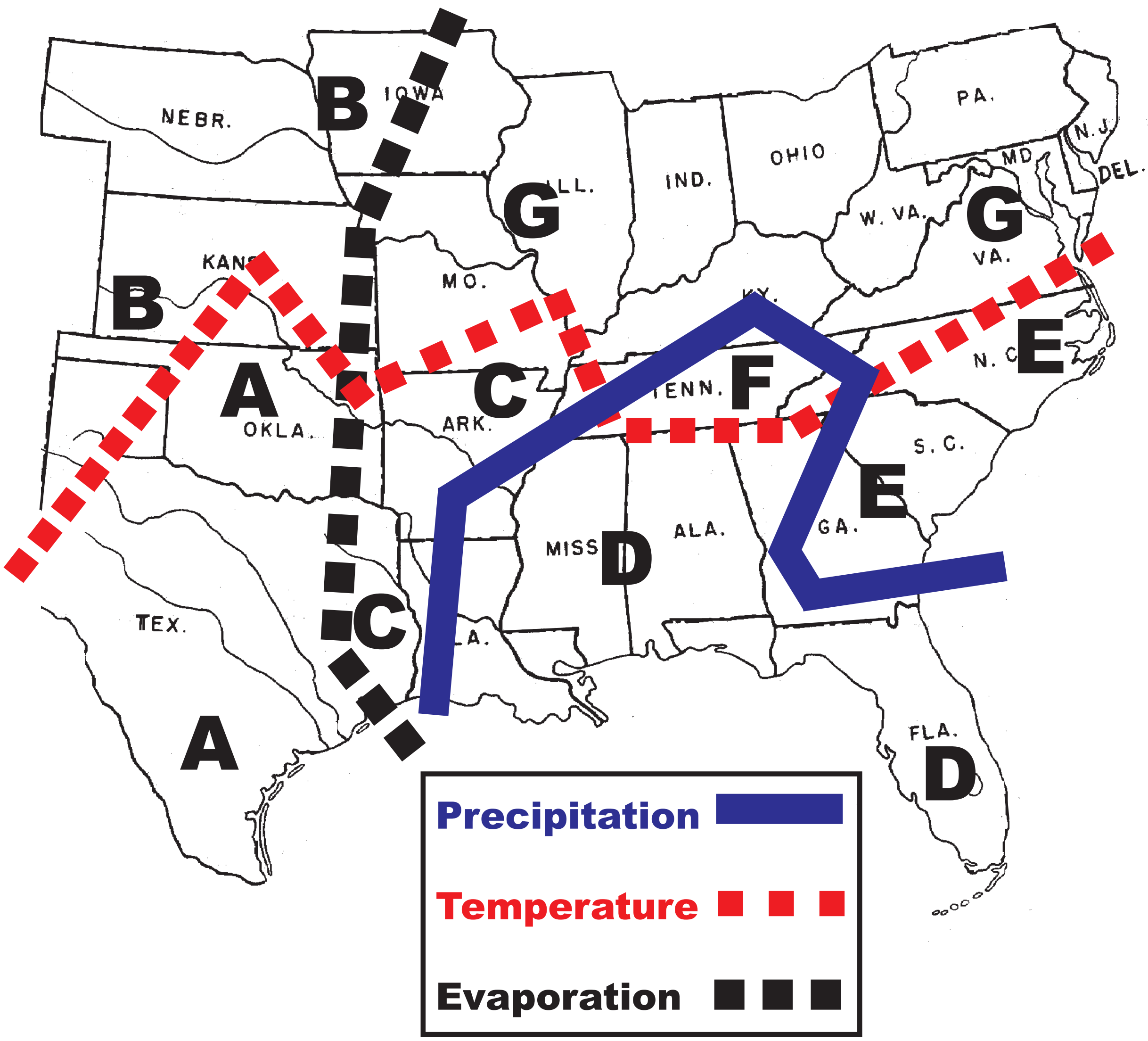


Figure 4: Tree Drought Potential Areas in Southeastern US.

A is greatest potential risk & G is least potential 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).

Drought

The term "drought" denotes a period without precipitation, during which 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 (suberize 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.

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 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 which curl, then yellow and turn brown. By comparison, 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 small valve-like openings on undersides 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, a tree can not make food and must depend upon stored food being mobilized and transported, if any is available. Drought causes 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 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 which slows or prevents stomatal opening when a 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 levels, may not occur for a long period after rehydration.

Stomatal closure will not prevent water loss. Trees lose significant amounts of water directly through leaf surfaces after 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. 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. 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 a 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 impact is 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 were injured by drought, even after water had been restored.

Growth Inhibition

Growth of vegetative and reproductive tissues are constrained by supply of growth materials, effective 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 bud expansion 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 which are in full sun. These leaves show drought associated signs of leaf rolling, folding, curling, and shedding.

Vascular Cambial Growth – Drought will effect the width of annual growth increments, distribution of annual increments 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 and associated water availability.

Cambial growth is constrained by water supply for 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), allows trees a better chance to survive drought conditions.

When first exposed to drought, allocation of food to root growth may increase. This provides more root absorptive area per unit area of foliage, and increases volume of soil colonized. Extended drought leads to roots being suberized to prevent water loss back to 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 determanant 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 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 which exhibit continuous growth or multiple flushing. Drought may not inhibit the first growth flush, but may decrease number of stem units formed in a new bud which 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 within 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 resourced, unstressed pre-conditioning 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 within 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 which 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 plant called 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.

Wet & Wetter

Supplemental watering of trees can be timed to help 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 (dew) will not change pest/host dynamics. Watering which 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 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 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 soil surface; and, effective suberization and compartmentalization of root areas.

Heat Load 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 alleaviate 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 avialable 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, and continuing through 58°F, 76°F, 94°F, 112°F, and 130°F, each step allows a physical doubling of respiration and water loss. Figure 5 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, must be estimated accurately.

Heat loading comes primarily from reflected energy from surfaces, radiated energy from local materials, and energy moved onto a site in the form of heated air (advection). 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 6. This additional heat load forces a tree, through physical processes of water loss, to lose more water whether stomates are open or closed. A tree is forced to lose water 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 7 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 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).

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 Figure 8 and provide a multiplier for site and tree water use. For example, if a young tree in a

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

Figure 5: 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 physical impacts of heat.

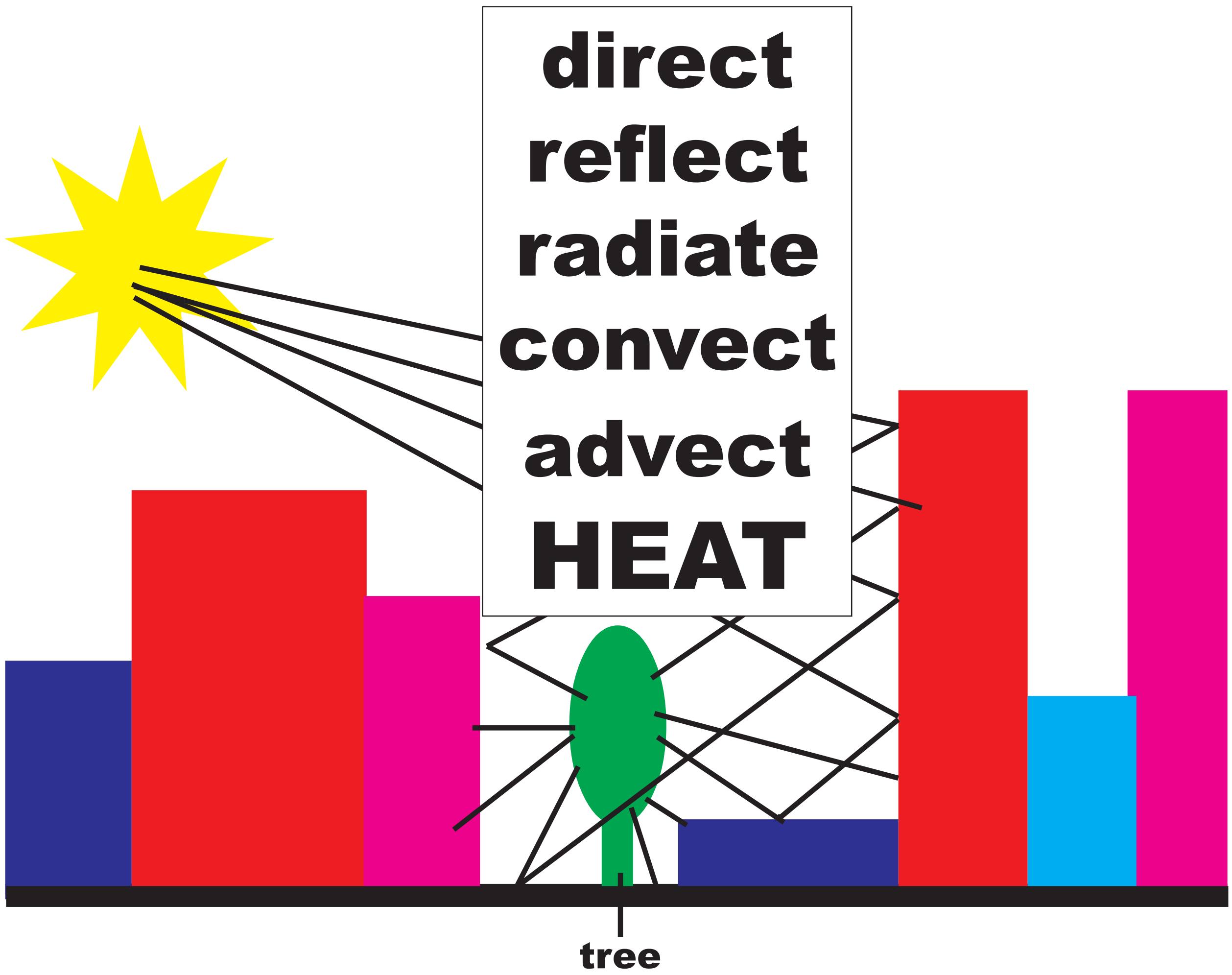


Figure 6: Diagrammatic view of a tree growth area impacted by heat loading from surrounding hard, dense, non-evaporative surfaces in an urban canyon.
(heat load view factor in two dimensions = 70%)

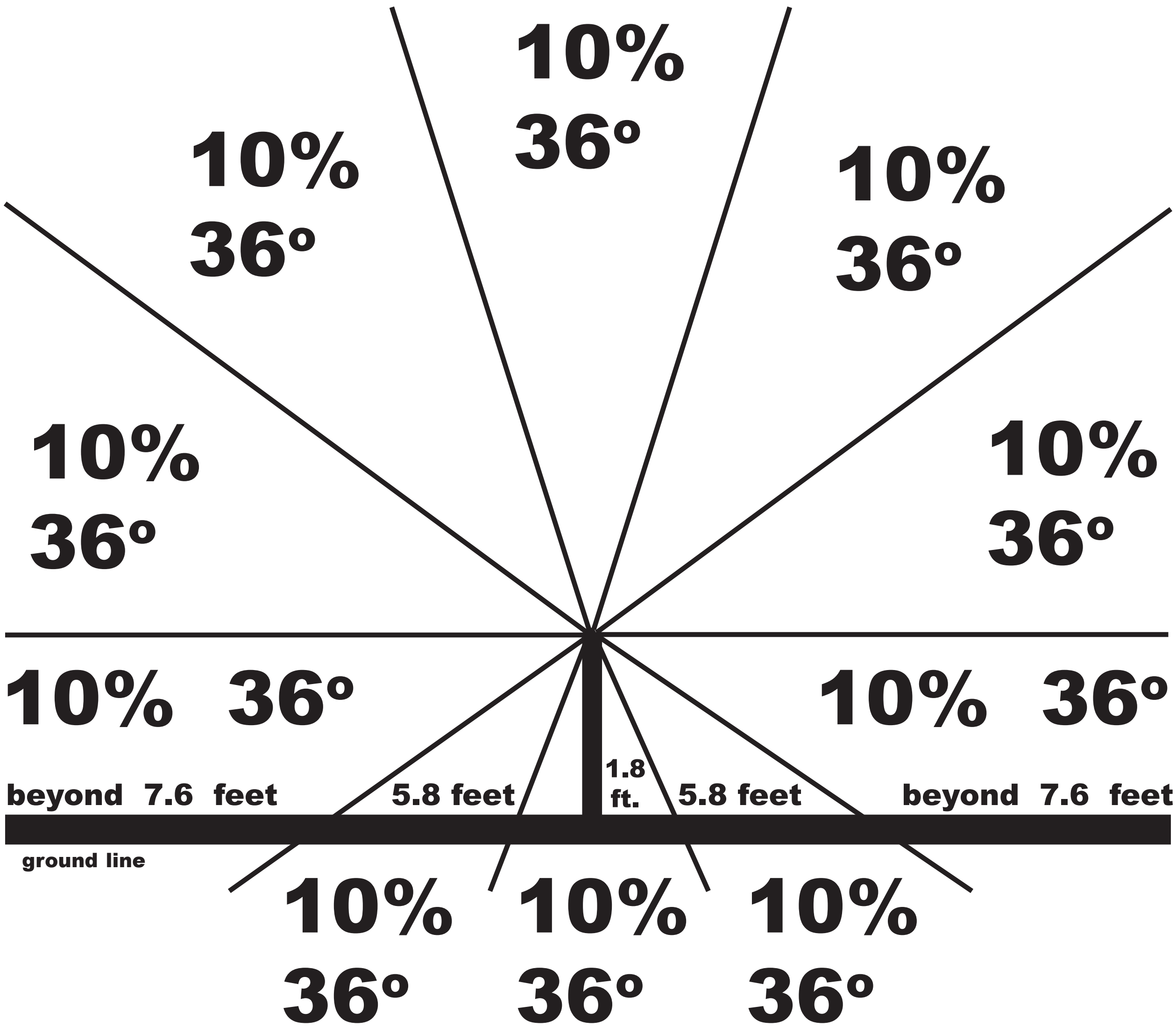


Figure 7: Diagram showing how heat loading can be estimated on a site using the Coder Heat Load Viewfactor containing ten equal (36°) observation angles.

In each of ten angle segments, the dominant surface facing a 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.

viewfactor percent non-evaporative, dense surfaces facing the site	heat load multiplier
100%	3.0
90%	2.7
80%	2.4
70%	2.1
60%	1.9
50%	1.7
40%	1.5
30%	1.3
20%	1.2
10%	1.1
0%	1.0

Figure 8: Coder Heat Load Viewfactor multiplier values for various non-evaporative, dense surface viewfactors (nearest 10% class) for a site or tree. Use heat load multiplier to increase water use values for trees.

Every 10% / 36^{o} 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.

parking lot has a estimated heat load multiplier of 1.9 (view factor 60% hardscape), then this tree will require nearly two times (2X) the amount of water of a tree in a nearby park with a heat load multiplier of 1.0 (view factor 0% hardscape).

Temperatures

Most temperate zone trees reach optimum growing conditions across a range of temperatures from 70°F to 85°F. Figure 9. 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 around air temperature (+ or - 4°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 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 10 shows idealized energy distribution senarios on three sites:

1) A hard, dense-surfaced parking lot -- 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 which is then blown across a neighboring landscape which raises heat loading and associated water loss.

2) A tree (or could be an awning) standing over dry soil -- which demonstrates passive shade blocking of energy from the soil surface -- 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 to the soil. 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 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 40% of the heat energy on a site. Trees under these conditions can not survive for long.

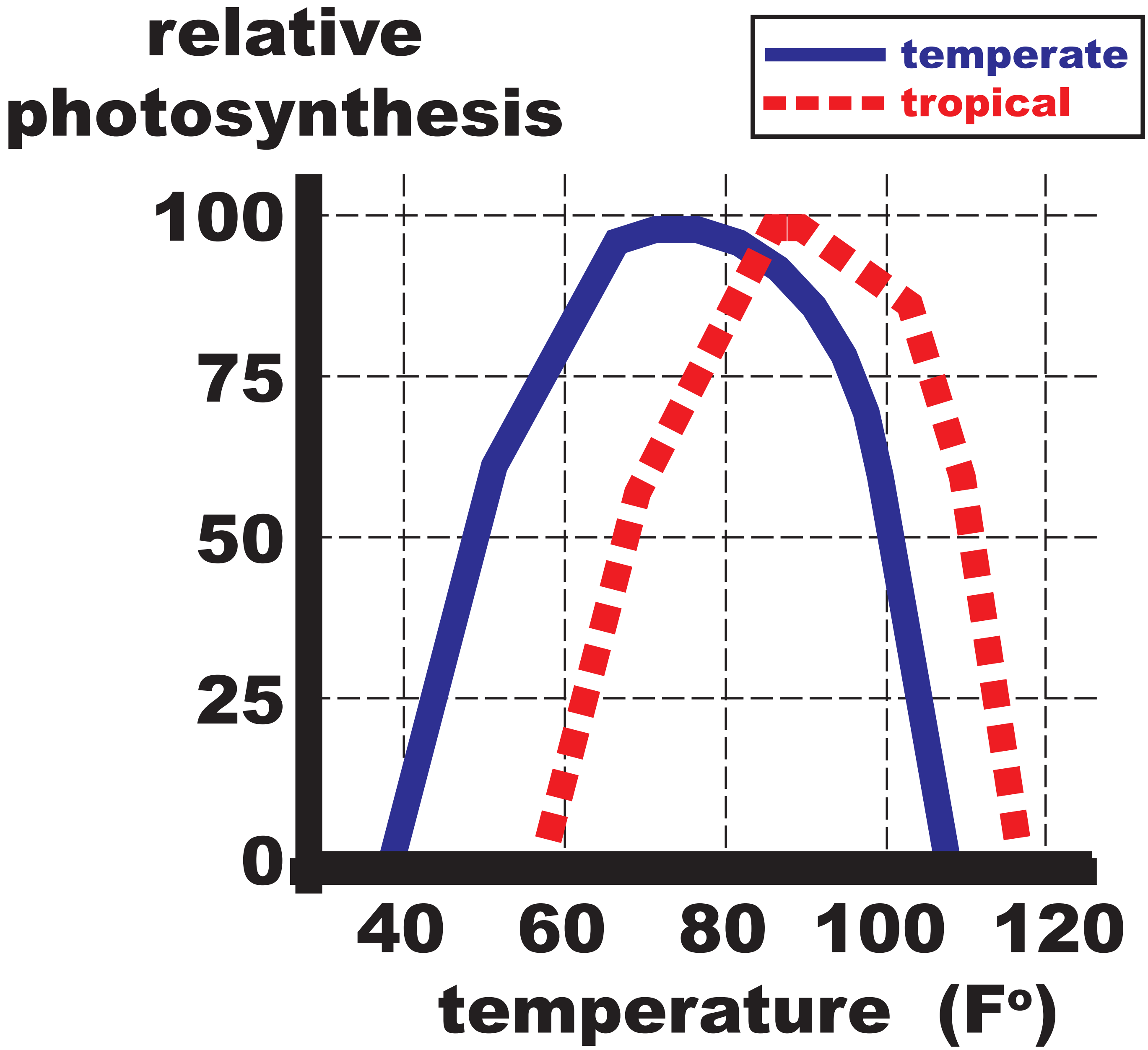


Figure 9: Impact on photosynthesis of temperature for temperate and tropical tree species.
(modified from Larcher 1969)

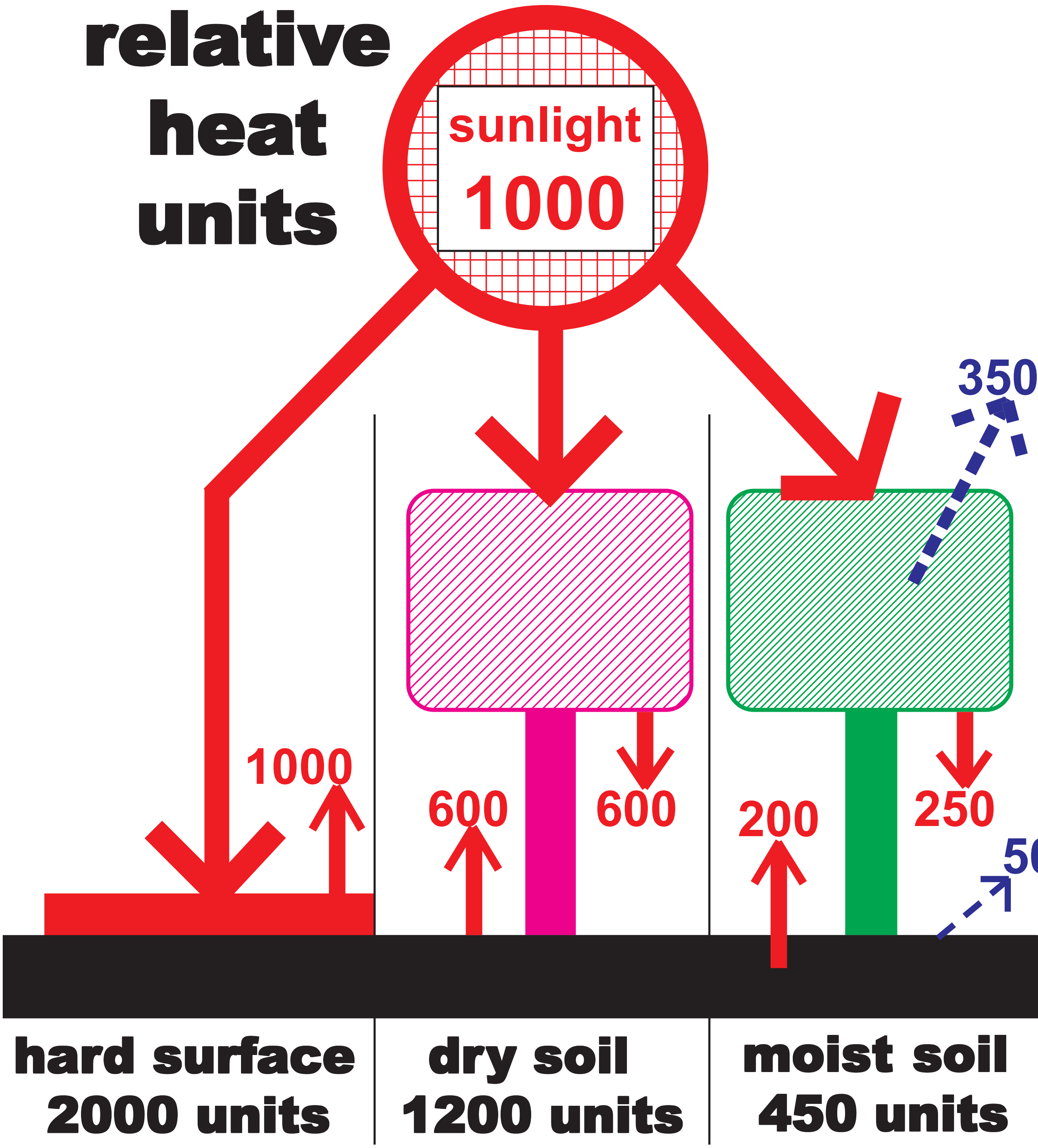


Figure 10: Three types of sites and heat loads -- hard dense surface of a parking lot; passive shade of a tree in dry soil (equivalent to an awning); and, active shade of a healthy tree in moist soil.

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 -- A tree in moist soil with plenty of water available for transpiration. As before, 400 heat units are physically blocked by tree generating shade. In addition, 350 heat units are transferred away from the tree through transpiration of water from leaves. This transpirational heat dissipation effect in a landscape is called "active shading" because a biologically controlled process is helping to dissipate heat. 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 soil). Total heat energy units in the landscape from this example is 450, roughly 38% of the heat load in senario two and 23% of the heat load in senario one above.

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 (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 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 11. When transpiration is limited by hot temperatures, and a tree is surrounded by non-evaporative surfaces (hard surfaces), leaf temperatures may approach 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 vapor pressure deficits between leaves and atmosphere, as well as increasing the rate of water loss from other tree surfaces.

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 humidy. 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 proceeds and water is lost.

Other processes are also impacted by heat. For example, gross photosynthesis rates generally double with every 18°F (10°C) until 94°F and then rapidly falls-off. Figure 12. The duration of hot temperatures for trees must not exceed a tree's ability to adjust, avoid, or repair problems. Less absolute amounts of heat are needed to damage trees as the duration of any high temperature extreme lengthens.

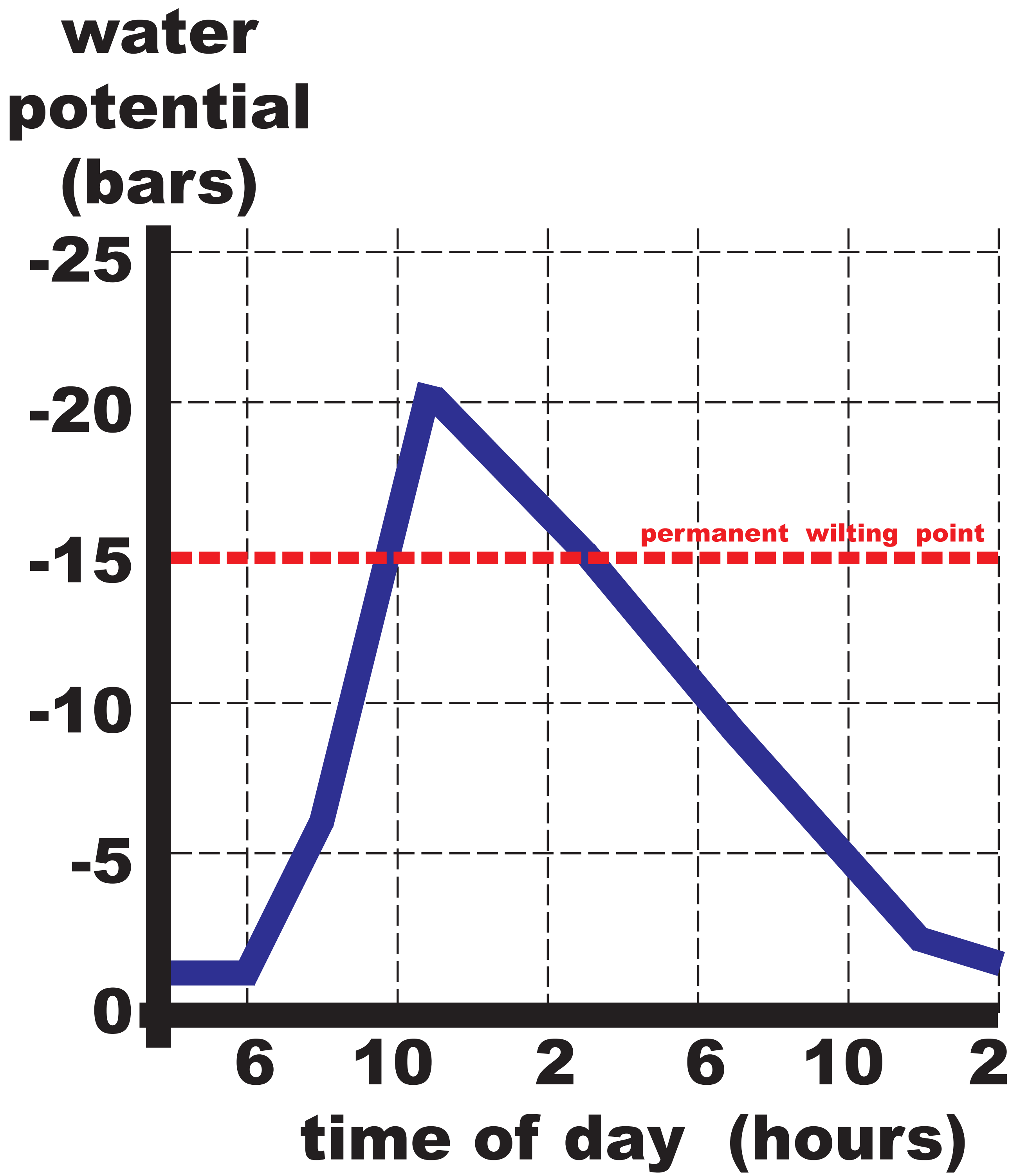


Figure 11: Generalized open-grown single tree water potential in bars over a mid-growing season day.
(derived from Bacone et. al., 1976)

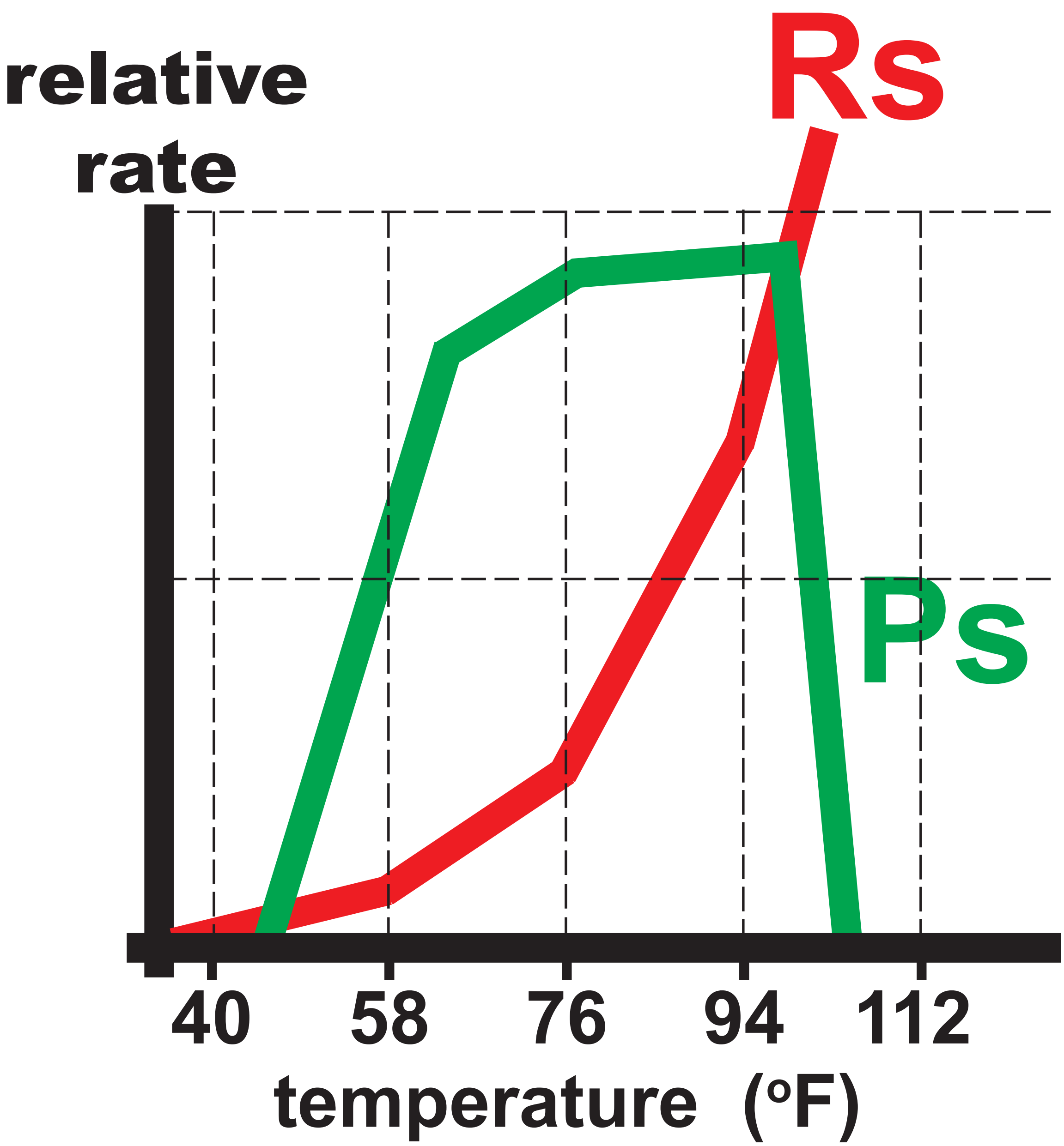


Figure 12: The relative rates of photosynthesis (Ps) and respiration (Rs) in a tree. Note respiration continues to climb exponetially with increasing temperatures and the photosynthesis process quickly falls apart as 105°F is passed.

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 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 which 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 transported or 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 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 140°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°F per hour until they reach 125°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 a 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 & increase respiration;
2) close down photosynthesis (turn-over point for photosynthesis and respiration around ~95°F) by closing stomates, stoping CO_2 capture, and increasing photo-respiration;
3) major slow-down in transpiration which prevents heat dissipation and causes internal temperature increases;
4) cell membrane leakage signal changes in protein synthesis;
5) continued physical water loss from all tree surfaces;
6) growth inhibition;
7) tree starvation through rapid use of food reserves, inefficient food use, and an inability to call on reserves when and where needed;
8) toxins generated through cell membrane releases and respiration problems;
9) membrane integrity loss and proteins breakdown.

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 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 (use 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 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 correct proportions to perform best. Water, and soil volumes which hold 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 (TSWR) assessment, and the Coder Days Until Dry (DUD) 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!

TSWR ASSESSMENT

The Coder Tree Soil Water Resources (TSWR) 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 13.

Step #1 is used to estimate crown volume of a tree. The larger tree crown volume, the greater number of leaves, buds, and twigs, and the greater potential for water loss. 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 14. The shape factor multiplied by crown volume provides actual crown volume of a tree in cubic feet. Figure 15.

> Crown Shape Factor – To accurately determine tree crown volumes, 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. Calculation of tree crown volume consolidates variations within tree crowns by using calculations for solid geometric objects, helping simplify calculations.
>
> Note within 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.

Step #2 is used to determine the effective crown surface area of a tree. 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 effective crown surface area of a tree in square feet.

Step #1: Determine crown volume.

$$\left[\text{crown diameter (ft)}\right]^2 \times \text{crown height (ft)} \times \text{shape factor (value) [FIGURE 14]} = \text{crown volume (ft}^3\text{)}$$

Step #2: Determine effective crown surface area.

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

Step #3: Determine daily tree water use.

$$\text{effective crown surface area (ft}^2\text{)} \times \text{daily water evaporation (ft / day) [FIGURE 16]} \times \text{pan factor (value) [FIGURE 17]} \times \text{heat load (multiplier) [FIGURE 18 \& 19]} = \text{daily tree water use (ft}^3\text{ / day)}$$

NOTE: 1 ft³ water = ~7.5 gallons

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

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

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

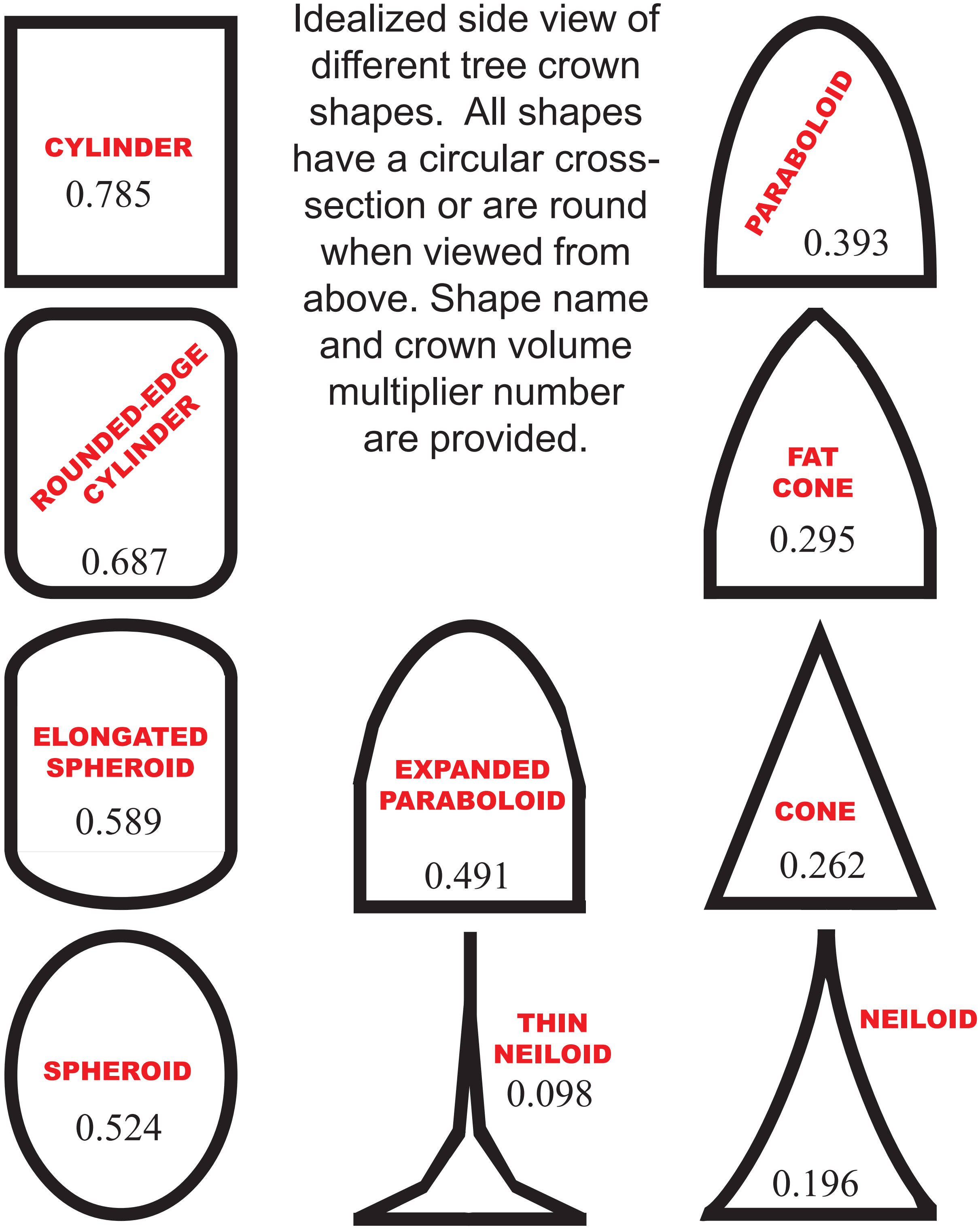
$$\text{two week tree water needs (ft}^3\text{ of water for 14 days)} \,/\, \text{tree available water in soil (in decimal percent) [FIGURE 20]} = \text{total soil volume needed (ft}^3\text{)}$$

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

$$\sqrt{\left[\text{total soil volume needed (ft}^3\text{)} \,/\, \text{effective soil depth (ft) [FIGURE 22]}\right] / 0.785} = \text{diameter of resource area (ft)}$$

Figure 13: Coder Tree Soil Water Resources assessment method (TSWR) in six steps.

Figure 14:
Idealized side view of different tree crown shapes. All shapes have a circular cross-section or are round when viewed from above. Shape name and crown volume multiplier number are provided.



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

Figure 15: 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. Idealized crown shape names are visualized based upon solid geometric figures.

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.

Step #3 is used to determine the daily water use of a tree. 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 16); an evaporative pan factor (Figure 17); and, a heat load multiplier (Figures 18 & 19). The result of this calculation is a daily water use for 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. Daily water use of a tree is multiplied by a value representing average number of days in the growing season between normal rain events (which can be daily rain in some places with a 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 holding and supplying two weeks of tree water needs taken 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, run through, and not be tree-usable. The two weeks tree water needs amount in cubic feet from Step #4 is divided by tree available water in soil as a decimal percent (Figure 20 as modified by Figure 21). The result is 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. 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-useable water. Figure 22. 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 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 23 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.

DUD ASSESSMENT

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" (DUD) containerized soil water assessment is targetted 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 which can not be accounted for within this simple calculation.

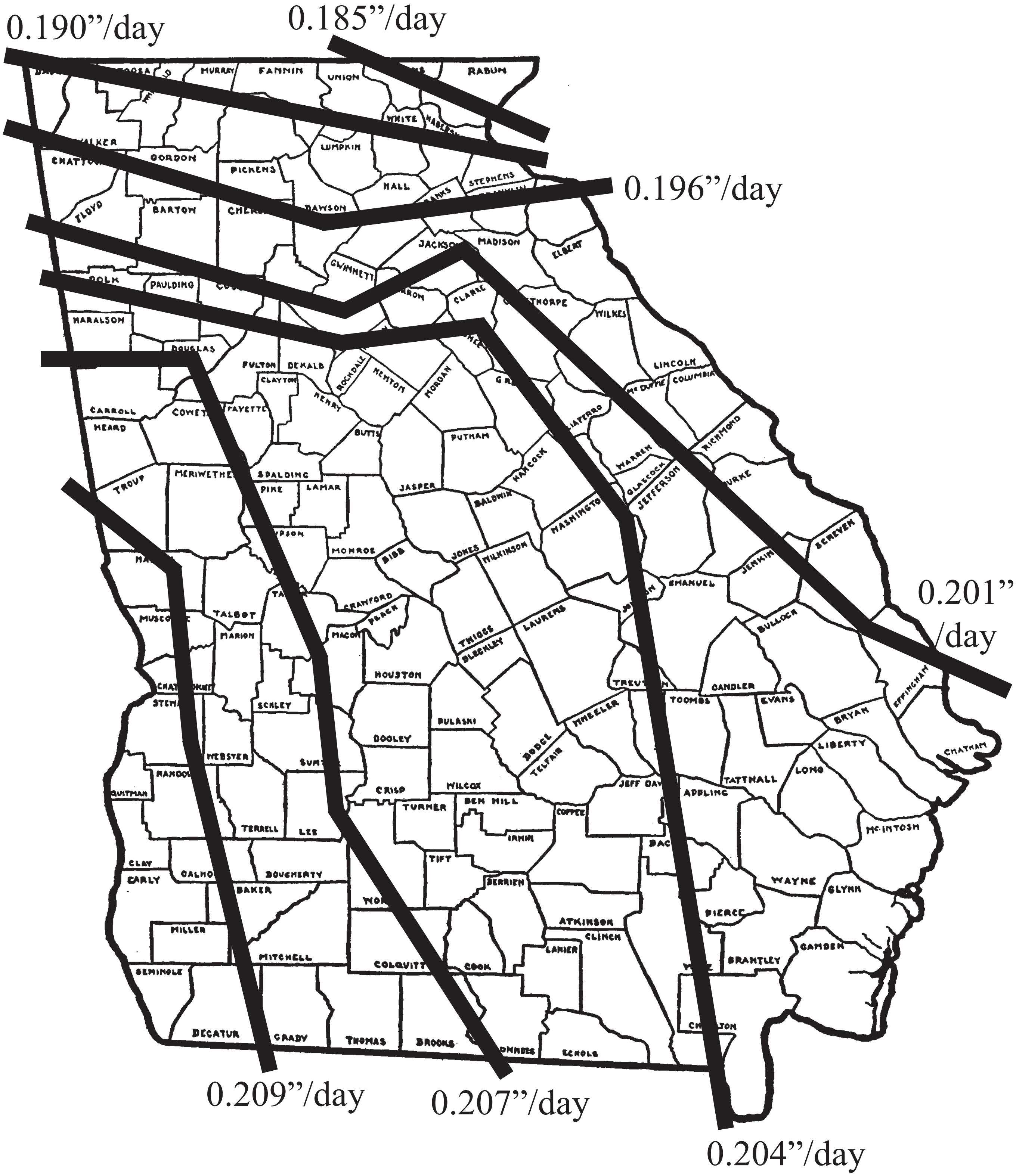


Figure 16: An example pan evaporation map from Georgia.

This map shows historic average daily pan evaporation during the growing season (May through October) in inches per day.

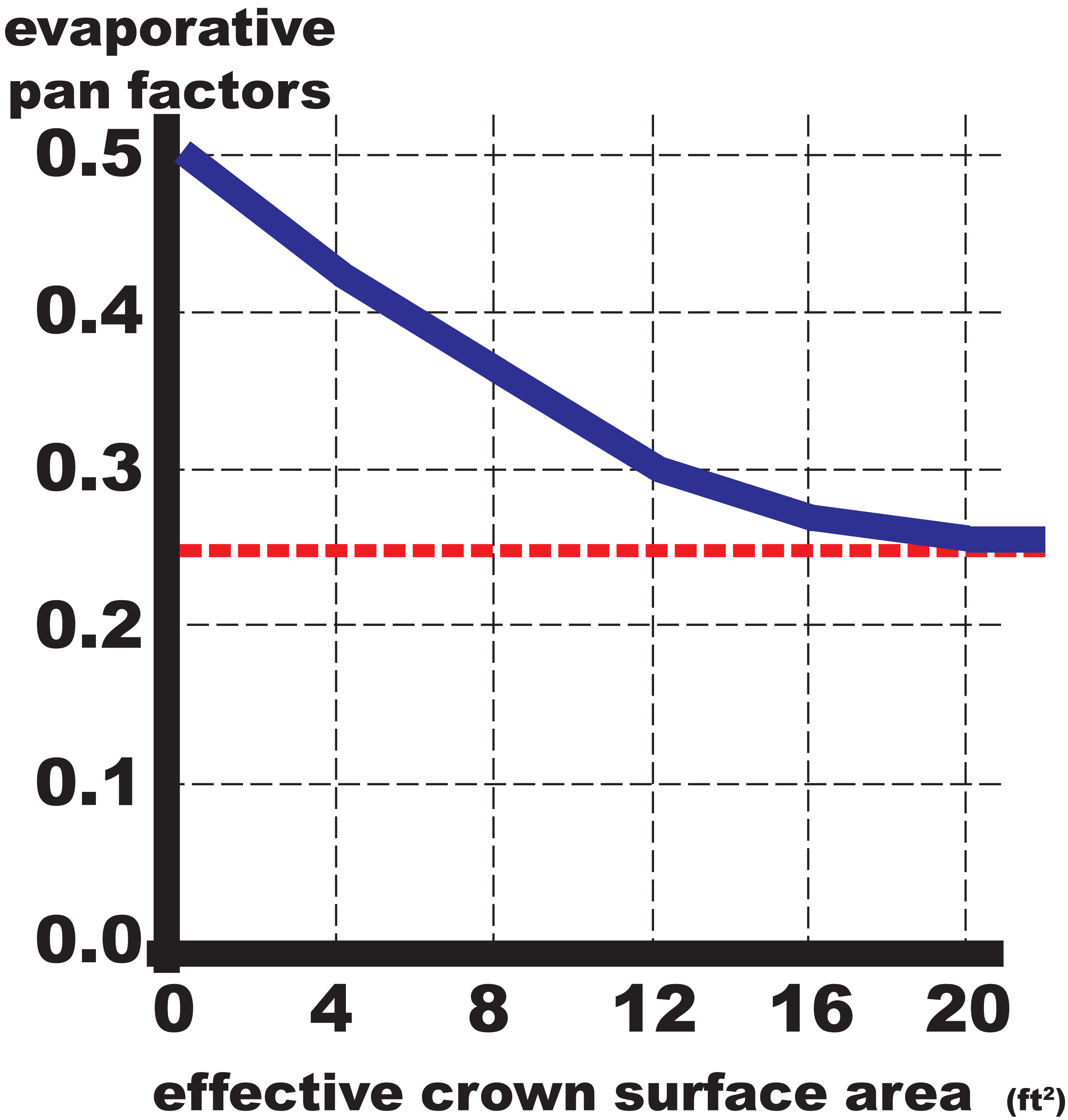


Figure 17: Ratio of tree transpiration to pan evaporation (pan factor or pan coefficient). Pan factors are not less than 0.25 for trees with larger than 20 ft^2 of effective crown surface area. (after Lindsey & Bassuk, 1992)

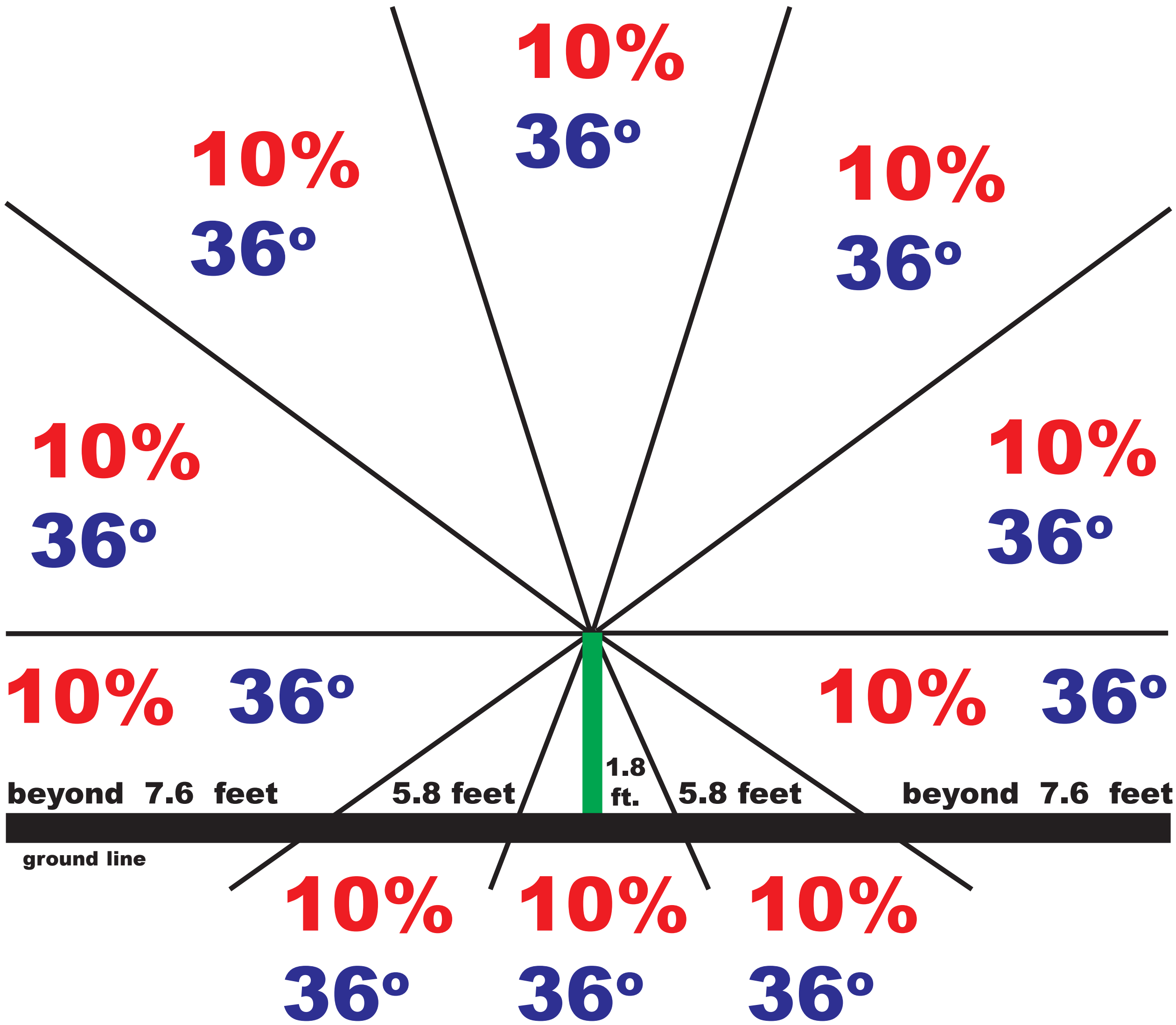


Figure 18: Diagram showing how heat loading can be estimated on a site using the Coder Heat Load Viewfactor containing ten equal (36°) observation angles.

viewfactor percent of non-evaporative, dense surfaces facing the site	heat load multiplier
100%	3.0
90%	2.7
80%	2.4
70%	2.1
60%	1.9
50%	1.7
40%	1.5
30%	1.3
20%	1.2
10%	1.1
0%	1.0

Figure 19: Coder Heat Load Viewfactor multiplier values for various non-evaporative, dense surface viewfactors (nearest 10% class) for a site or tree. Use heat load multiplier to increase water use values for trees.

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 20: 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.
(after Cassel, 1983; Kays & Patterson, 1992; Craul, 1992 & 1999)

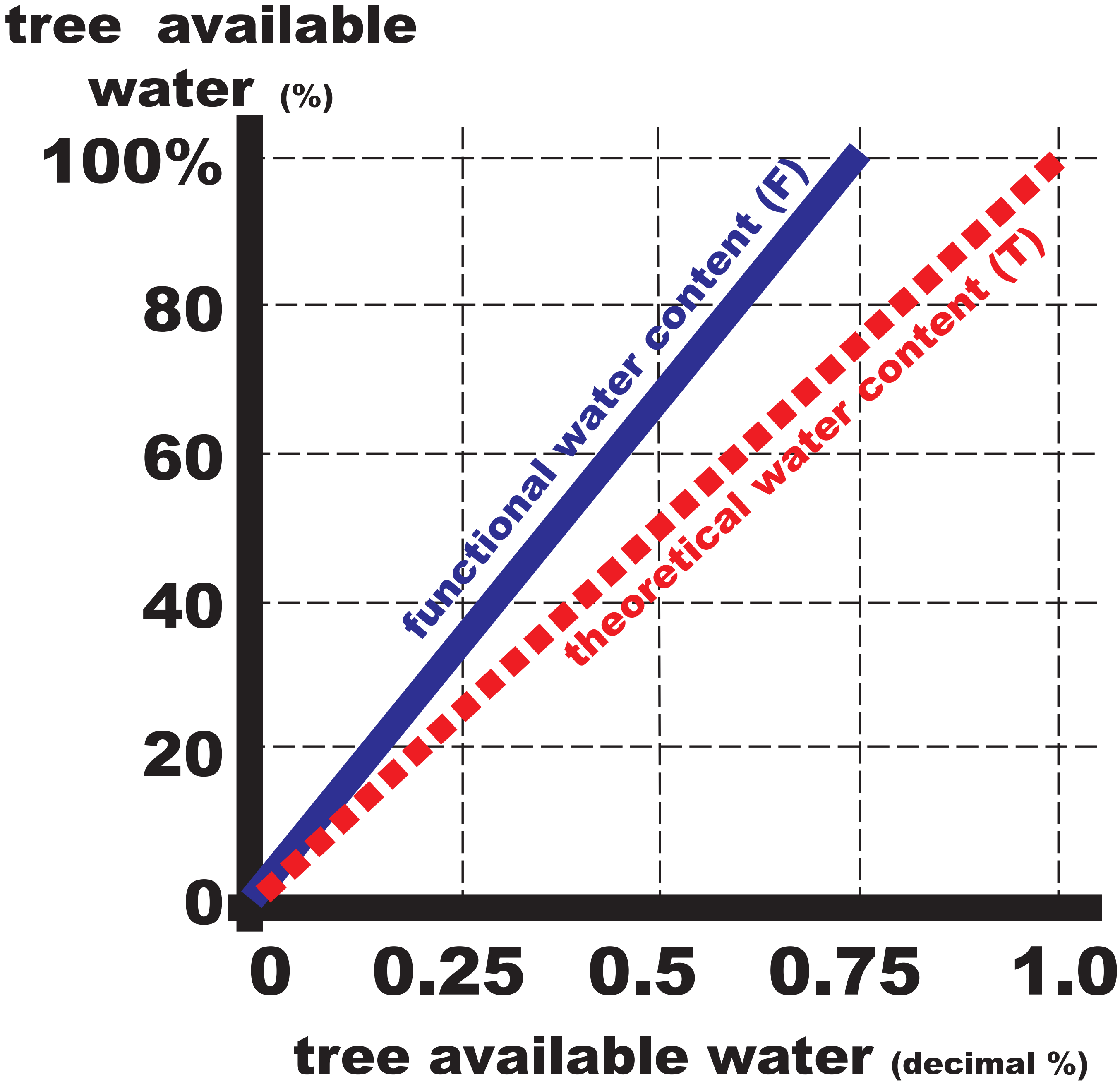


Figure 21: Estimate of functional tree available water in a soil compared with theoretical water availability. Functional water availability to a tree is less than the actual calculated amount of water in a soil. As soil dries, water is held progressively more tightly, and soil / root interface behaves as if there is less water in soil. (after DeGaetano, 2000)

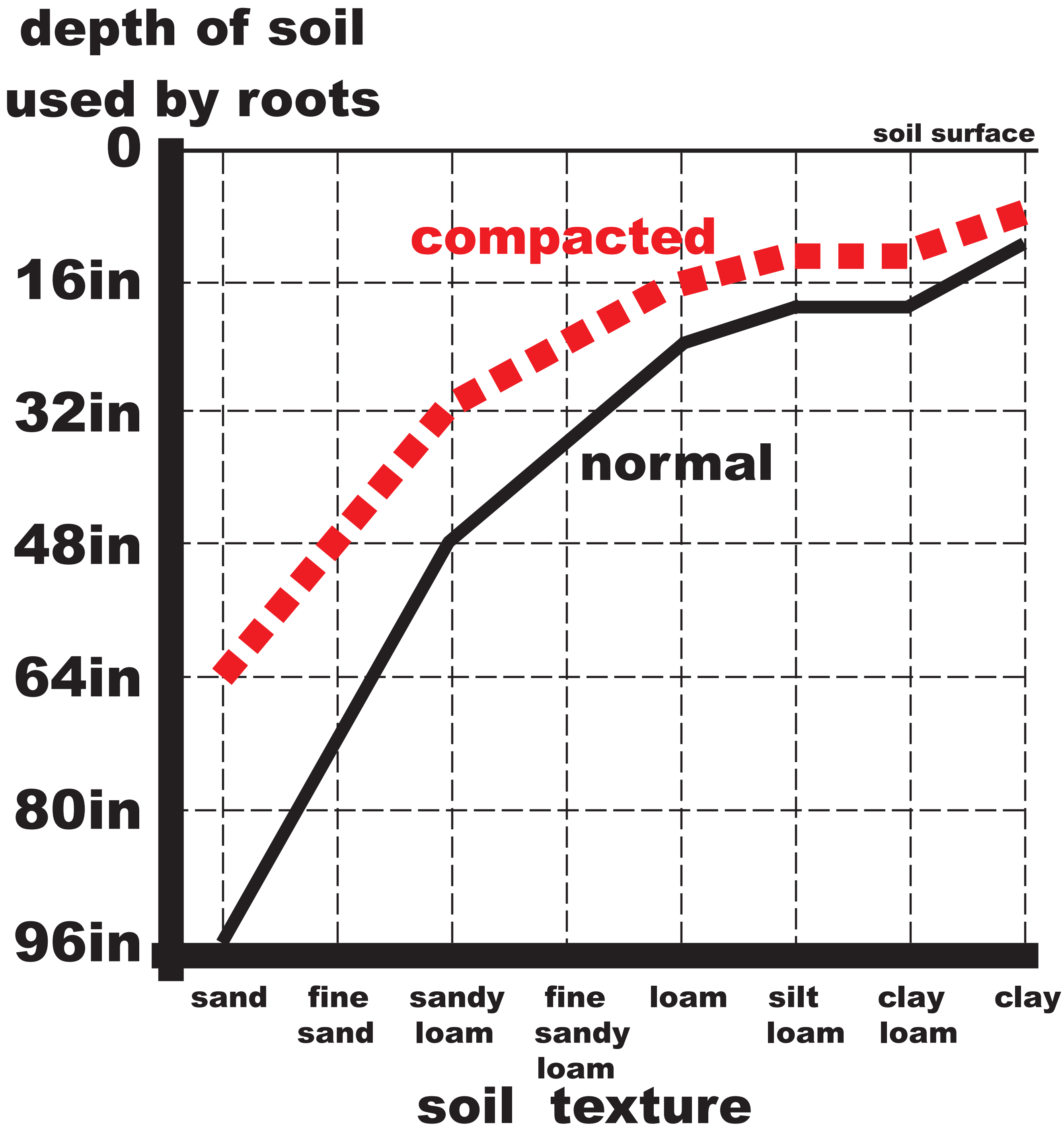


Figure 22: Effective soil depth used for defining biologically available resource depth in soils of various textures.
(solid line = normal; dotted line = moderate compaction)

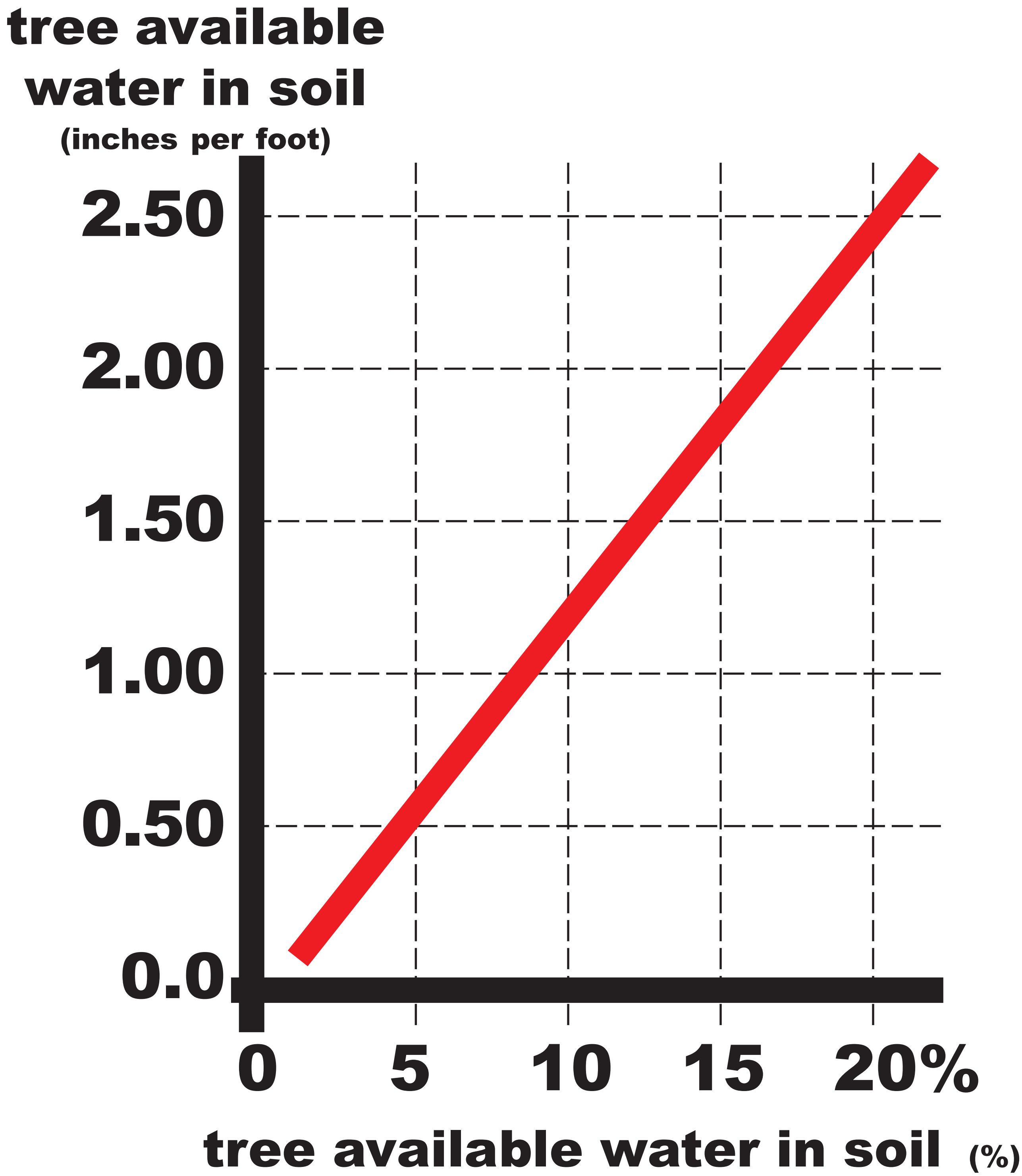


Figure 23: Estimated relationship between percentage of tree available water in soil and number of inches of tree-available water per foot of soil.

The Coder Days Until Dry containerized soil water assessment method is shown in Figure 24. This assessment can be completed in five (5) steps, the first three steps are from the previous Coder Tree Soil Water Resources assessment. Please see previous text regarding this assessment, as well as figures needed for determining daily tree water use. The fourth and fifth step are unique to this DUD assessment and are used to determine soil water volume available to a tree and how many days will pass before soil is dry.

Five Step Assessment

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. Average 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 volume is made by picking a shape factor for a tree crown from Figure 14. The shape factor multiplied by crown volume provides actual crown volume of a tree in cubic feet. Figure 15.

Step #2 is used to determine effective crown surface area of a tree. 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 Step #2 calculation is effective crown surface area of a tree in square feet.

Step #3 is used to determine daily water use of a tree. 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 16); an evaporative pan factor (Figure 17); and, a heat load multiplier (Figures 18 & 19). 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 ($1ft^3 = \sim 7.5$ gallons). Daily water use of a tree determined here will be used in Step #5.

Step #4 determines soil water volume present in cubic feet. 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 Figure 25. 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 Figure 25. 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.

Step #1: Determine crown volume.

[crown diameter (ft)]^2 X crown height (ft) X shape factor (value) [FIGURE 14] = crown volume (ft^3)

Step #2: Determine effective crown surface area.

[crown volume (ft^3) / crown height (ft)] X 4 (LAI) leaf area index = effective crown surface area (ft^2)

Step #3: Determine daily tree water use.

effective crown surface area (ft^2) X daily water evaporation (ft / day) [FIGURE 16] X pan factor (value) [FIGURE 17] X heat load (multiplier) [FIGURE 18 & 19] =

daily tree water use (ft^3 / day) *NOTE: 1 ft^3 water = ~7.5 gallons*

Step #4: Determine soil water volume.

[container soil volume (ft^3) / total soil water (d%) [FIGURE 25]] X [1 - soil water limit (d%) [FIGURE 25]] = soil water volume (ft^3)

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

soil water volume (ft^3) / daily tree water use from Step 3 (ft^3 / day) = days until dry

Figure 24: The Coder "Days Until Dry" containerized soil water assessment method (DUD).

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

Figure 25: Total soil water and soil water limit (~ permanent wilting point) for various soil textures. Values given in decimal percents (d%).

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 otherwise healthy trees for other problems. Drought conditions and heat loading 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 Assests

Trees can be old and valuable, and are usually considered non-replaceable beyond 10 inches in stem diameter. Many associated landscape plants are low cost and easily replaceable. If low cost 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.

BWPs

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 water accumulation around 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 tensiometer. 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 soil under a tree to conserve moisture and then apply water just under or over the top of this mulch.

Do not water at the base of the tree 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 building foundations and hardscapes for water applications. Ideally strive to reach at least one-half (½) the tree rooting area under a 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 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 a tree.

Set sprinklers near the outside edge of the tree crown beneath 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 water must drain from 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 for 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 surface for extended time periods.

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 active roots and allows water to drain away from roots, wasting efforts and water.

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 soil. Surface or near surface soaking allows tree roots more chances to absorb any water, cultivates 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 a tree. Do not water much 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 night time hours. Watering at night allows effective use of applied water and less evaporative loss, assuring more water moves into soil and tree. Night time application hours, when dew is already present, does not expand foliage wetting period for understory plants. This water 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. 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 which 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 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 if soil drainage can be assured.

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 rooting zones quickly. There are some commercial water holding compounds for keeping water near roots. In addition, composted organic material additions and organic mulch covers over soil surfaces can hold and prevent rapid loss of applied water. In all cases, a 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 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 negative 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 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 under high mineral concentrations at high soil pH's.

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 sustainable 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 upon 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 then 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 upon water source, plumbing system, living habits and personal hygiene of users. Attributes of gray-water are impacted by cleaning products used, dishwashing patterns, laundery 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.

Figure 26 provides an average home gray-water generation pattern. Figure 27 provides 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 periodic, well-managed gray-water applications.

Gray-water does have several unique characteristics of note -- grease, heat, and particles. Greywater ususally 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 tremedous 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 dermatitus 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** -- Simply collect 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.

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

Figure 26: Potable water use of an average household during a growing season. Note 57% of non-waste containing water (gray-water) could potentially be reused for tree irrigation & outdoor watering use.

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)

Figure 27: Average characteristics of household gray-water compared with total waste water stream.

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 aboveground, 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 generated.

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 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 seperate in-ground septic tank or vault. A gray-water septic tank can be designed to use seepage lines which are dug into 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 occuring 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 severly 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 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 values.
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 any sprinkler heads which can blow gray-water aerosols downwind.

J) Be careful of applications which apply gray-water directly to leaf surfaces of ground covers and turf 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 periderm, 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 a 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 under drought and heat loaded conditions 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. Basic characteristics of trees which 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 positions.

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 which 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, round 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 can be described: 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. Figure 28.

Obviously you will never find an ideal drought resistant tree. Many trees do come close and have many fine features for a good landscape. 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 a tree to your site and local climate to have a water efficient landscape.

CONCLUSIONS

Trees are part of a water covered and water 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 myrid of secondary and tertiary damaging events. Water is a keystone stress in tree health care.

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

Figure 28: A selected list of drought resistant tree species for the Southeatern United States. (once established in a landscape)

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