Outreach
Warnell School of Forestry & Natural Resources
UNIVERSITY OF GEORGIA

Drought, Heat Stress & Trees

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

Heat Increases

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°F, beginning at 40°F where water is densest, continuing through 58°F, 76°F, 94°F, 112°F, and 130°F, each allow a physical doubling of respiration and water loss. Figure 1 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.

Loaded

Heat loading comes primarily from reflected energy from surfaces, radiated energy from local materials, and energy moved onto the site in the form of heated air (advection). 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 2. 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 in dissipating heat, not necessarily in 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 3 is a diagram showing how heat loading can be estimated on a site using the Coder Heat Load View-factor with ten equal (36°) 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 & 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% (all 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 4 and provide a multiplier for site and tree water use.

For example, if a young tree in a parking lot has a estimated heat load multiplier of 1.9 (view factor 60%), then this tree will require nearly two times (2X) the water of a tree in a nearby park with a heat load multiplier of 1.0 (view factor 0%). It is critical to also provide soil drainage to handle two times the water volume.

Temperatures

Most temperate zone trees reach optimum growing conditions across a range of temperatures from 70°F to 85°F. Figure 5. 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 duration of hot temperatures, absolute highest temperature reached, tissue age, thermal mass, water content of tissue, and ability of a tree to make adjustments as temperatures change.

Tree temperature usually runs run around air temperature (+ or - 4^{o}F). Trees dissipate heat (long-wave radiation) through convection into the air, and transpiration (water loss from leaves). Moist soil around trees also dissipates heat through convection and evaporation.

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

Cooking

Figure 6 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 its 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 shades (blocks sunlight from) the soil surface which eliminates 400 incoming heat energy units. Everyone understands it is cooler in the shade of a building, awning, or umbrella than in full sun. Without water available for a tree to transpire and soil to evaporate, a tree simply acts as an umbrella. If trees can not dissipate tissue heat through transpiration, tissue temperatures will 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 one-fifth of the heat energy away from a site. Trees under these dry conditions can not survive for long.

3) A tree in moist soil -- representing active shade, where energy is blocked from soil surfaces and heat is dissipated through tree and site evapotranspiration. A tree in moist

> soil with plenty of water available for transpiration physically blocks 400 heat units through a tree generating shade. In addition, 350 heat units are transferred away from tree through transpiration of water from leaves.
>
> This transpirational heat dissipation in a landscape is called "active shading" because a biologically controlled process is helping to dissipate heat. Heat energy units passing through a 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.

Trees can dissipate huge 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 leads 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 7. 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 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 hot, dry air is pushed by wind over surrounding landscapes which heat and dries tree tissues as it passes. Advected heat propels 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 tree dehydration. Structures and topographic features can modify or block advected heat flows across a site.

Double Trouble

Daytime temperatures obviously provide the greatest heat load, but night temperatures are also critical for many tree growth mechanisms, especially new leaves and reproductive structures. Night temperatures are critical for controlling respiration rates in the whole tree and soil environment. The warmer the temperature, the geometrically faster respiration precedes and water is lost.

Other processes are also impacted by heat. For example, gross photosynthesis rates generally double with every 18^{o}F (10^{o}C) until 94°F and then rapidly fall-off. Figure 8. The duration of hot temperatures for trees must not exceed a tree's ability to adjust, avoid, or repair problems. Less absolute amounts of sensible heat are needed to damage trees as the duration of any high temperature extreme lengthens.

Heat Damage

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

Nitrogen Enrichment

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 in soil can damage trees under large heat loads. The internal processing of nitrogen fertilizer inputs require stored food (CHO) be used.

Excessive heat loads and supplemental nitrogen lead to excessive root food use. When no food is being produced in a 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 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. Excessive heat loading causes large amounts of water to be transpired, initiates major metabolic problems, and can generate heat lesions on stems just above the ground / tree contact juncture (root collar / stem base area). Heat lesions are usually first seen on the South / Southwest side of stems months after the damaging event.

Trees growing within above-ground containers in full sunlight can be under large heat loads which quickly injure roots and shoots. Depending upon color, exposure, and composition, planting containers can quickly absorb heat. For example, black plastic containers can absorb energy at +9°F per hour until they reach 125°F or more. The damage sequence 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 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 which 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 the general sequence shown in Figure 9. As machinery within a tree slow due to heat loads, and respiration related mechanisms accelerate, more resource availability and processing paths become constrained and damaged. Cells finally reach the end of their coping mechanisms and lose membrane integrity and energy control.

Conclusions

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

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

Figure 1: 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 a tree and site double due to physical impacts of heat.

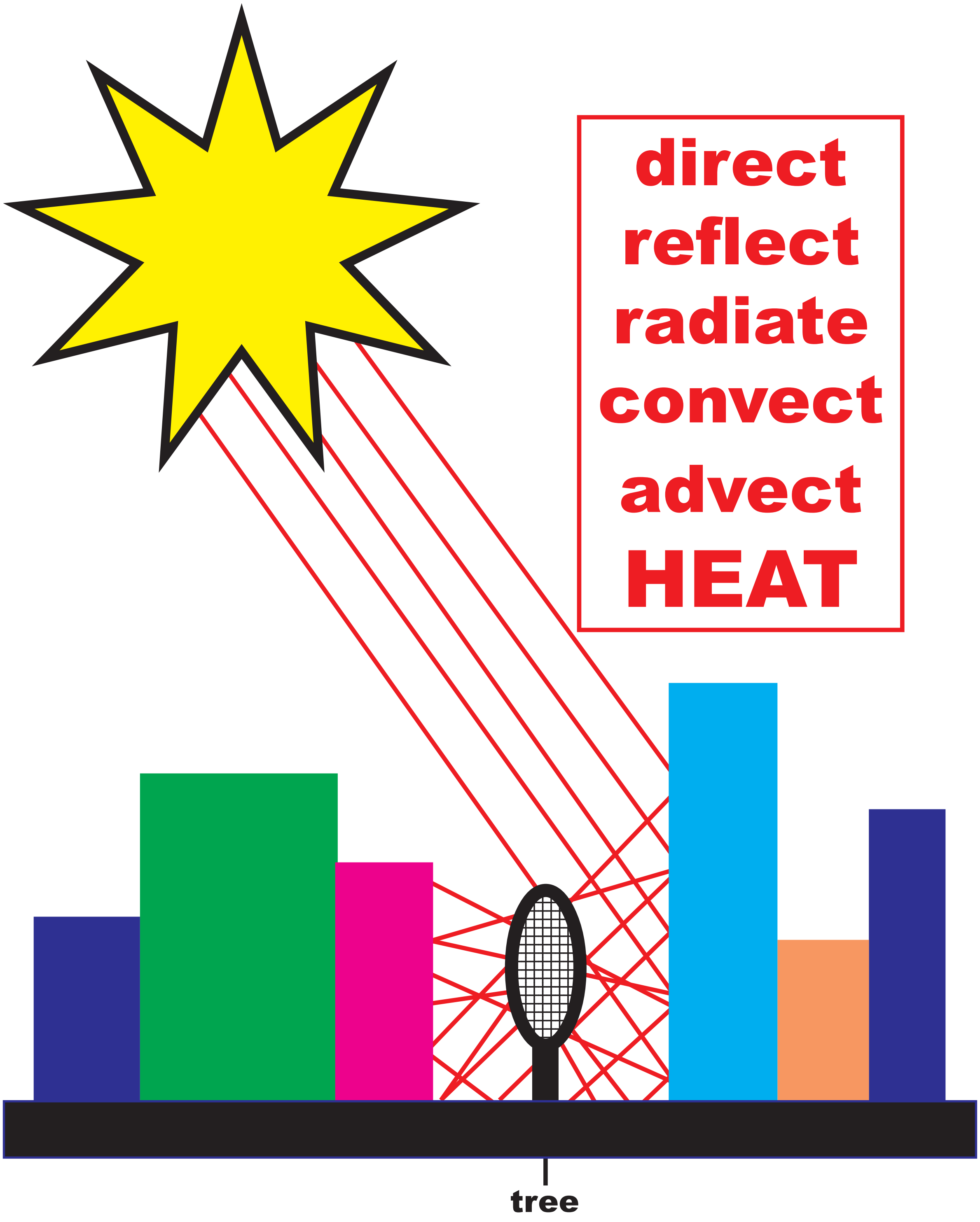

Figure 2: Diagrammatic view of a tree growth area impacted by heat loading from surrounding hard, dense, non-evaporative surfaces in an urban canyon.
(heat load view factor in two dimensions = 70%)

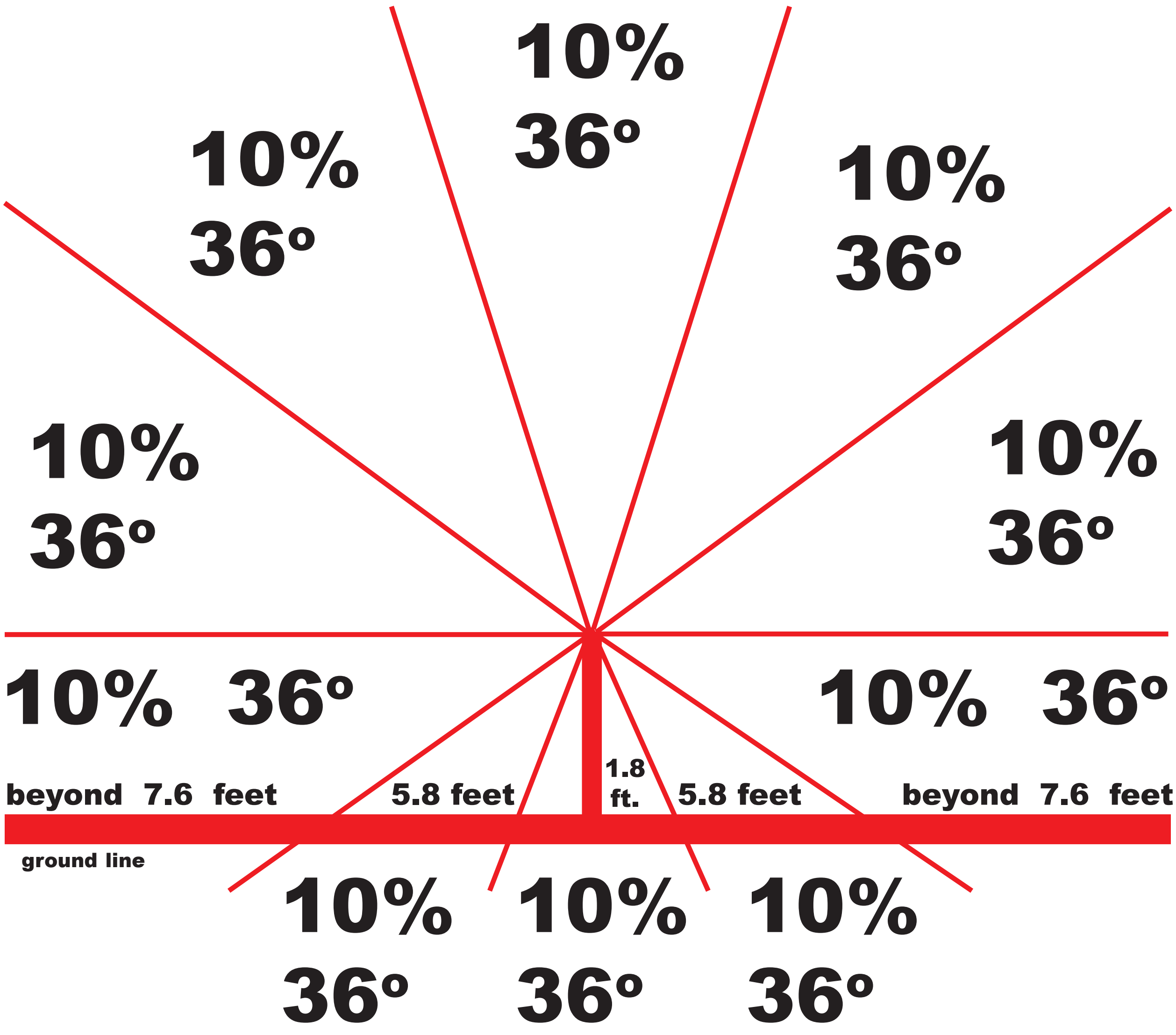

Figure 3: Diagram showing how heat loading can be estimated on a site using the Coder Heat Load Viewfactor containing ten equal (36°) observation angles.

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 4: Coder Heat Load Viewfactor multiplier values for various non-evaporative, dense surface viewfactors (nearest 10% class) measured on a site. Use heat load multipliers 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 surface types.

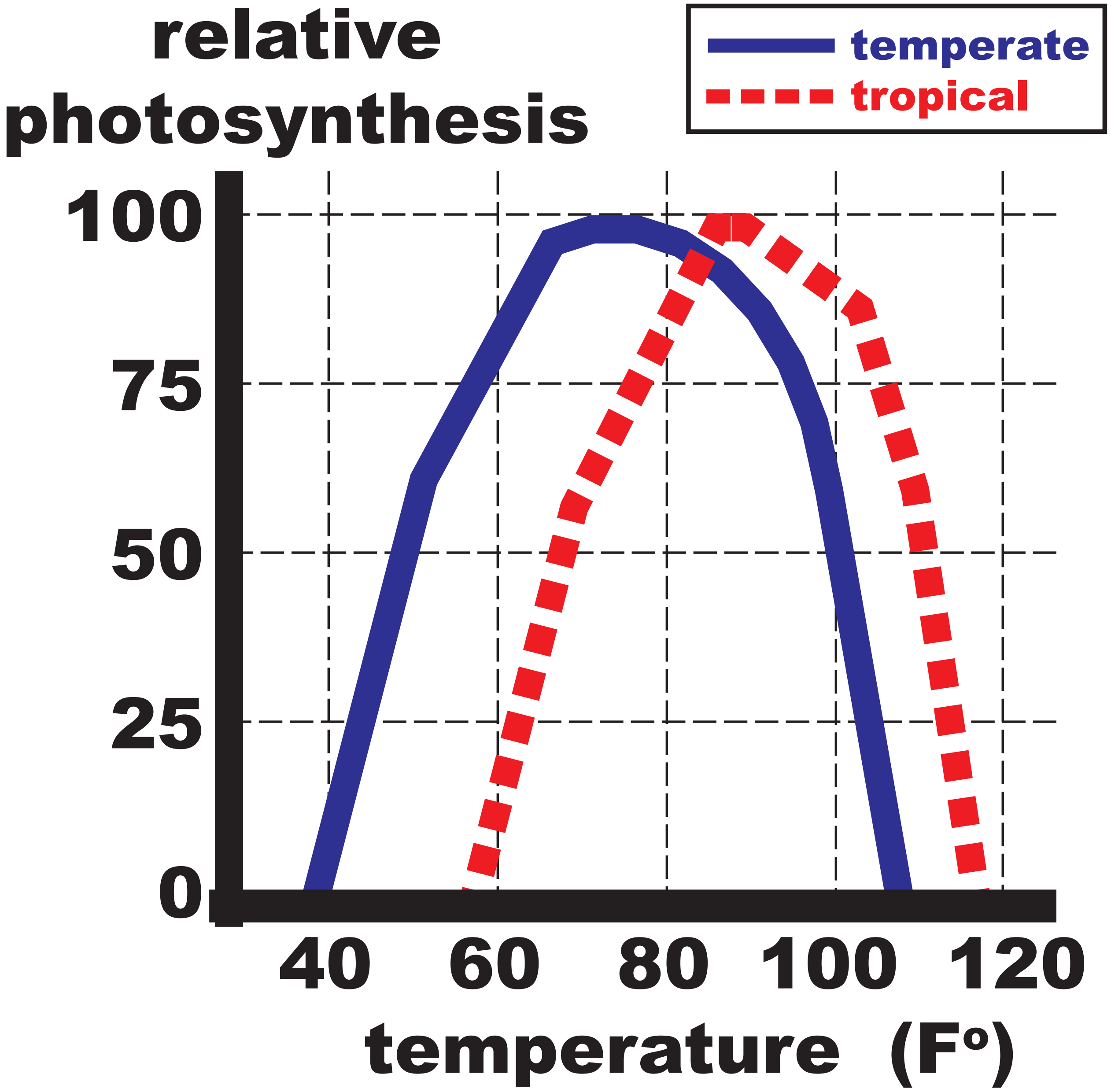

Figure 5: Impact on photosynthesis of temperature for temperate and tropical tree species.
(modified from Larcher 1969)

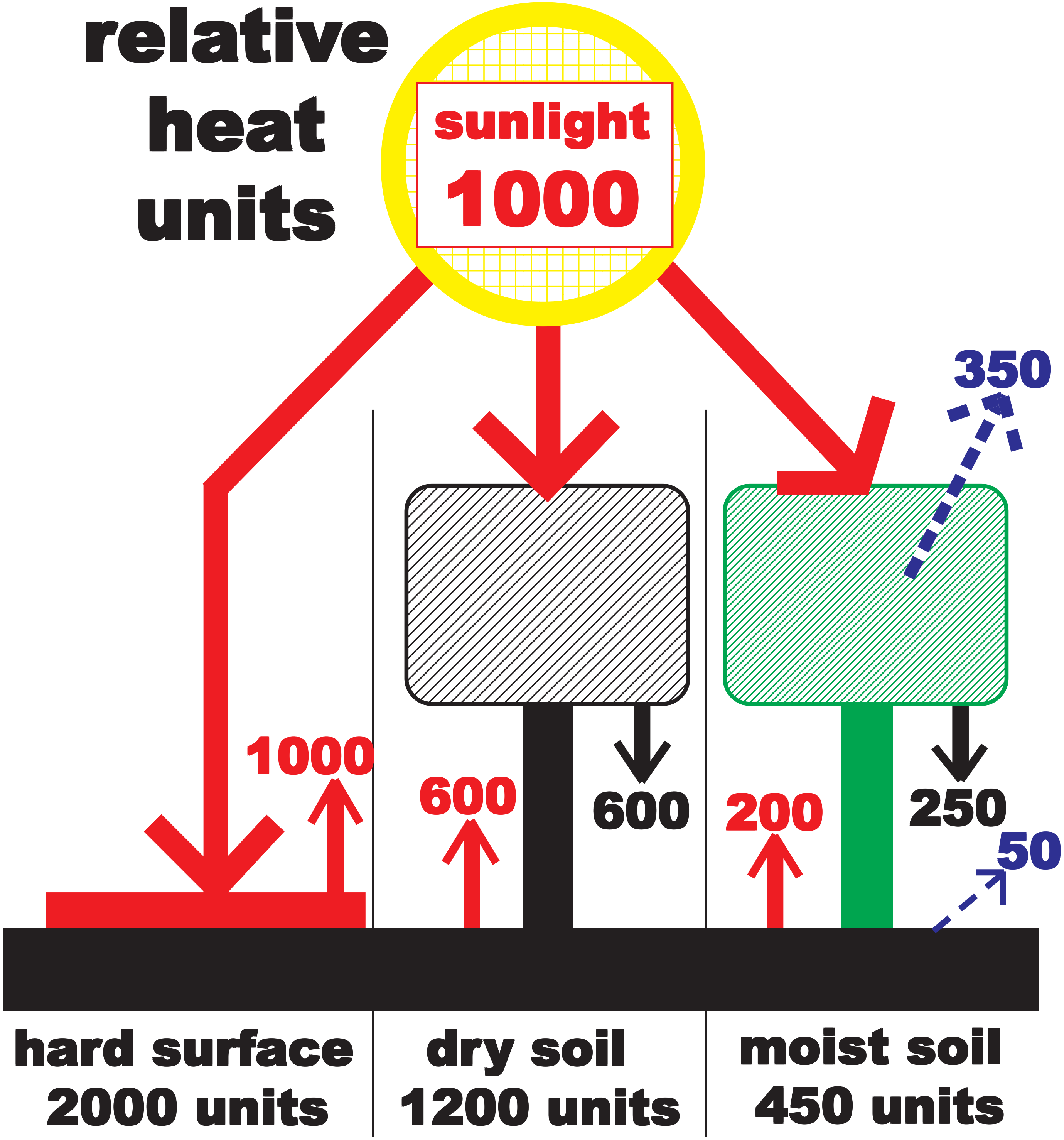

Figure 6: Three types of sites and heat loads -- hard dense surface of a parking lot; passive shade of a tree in dry soil (equivalent to an awning); and, active shade of a healthy tree in moist soil.

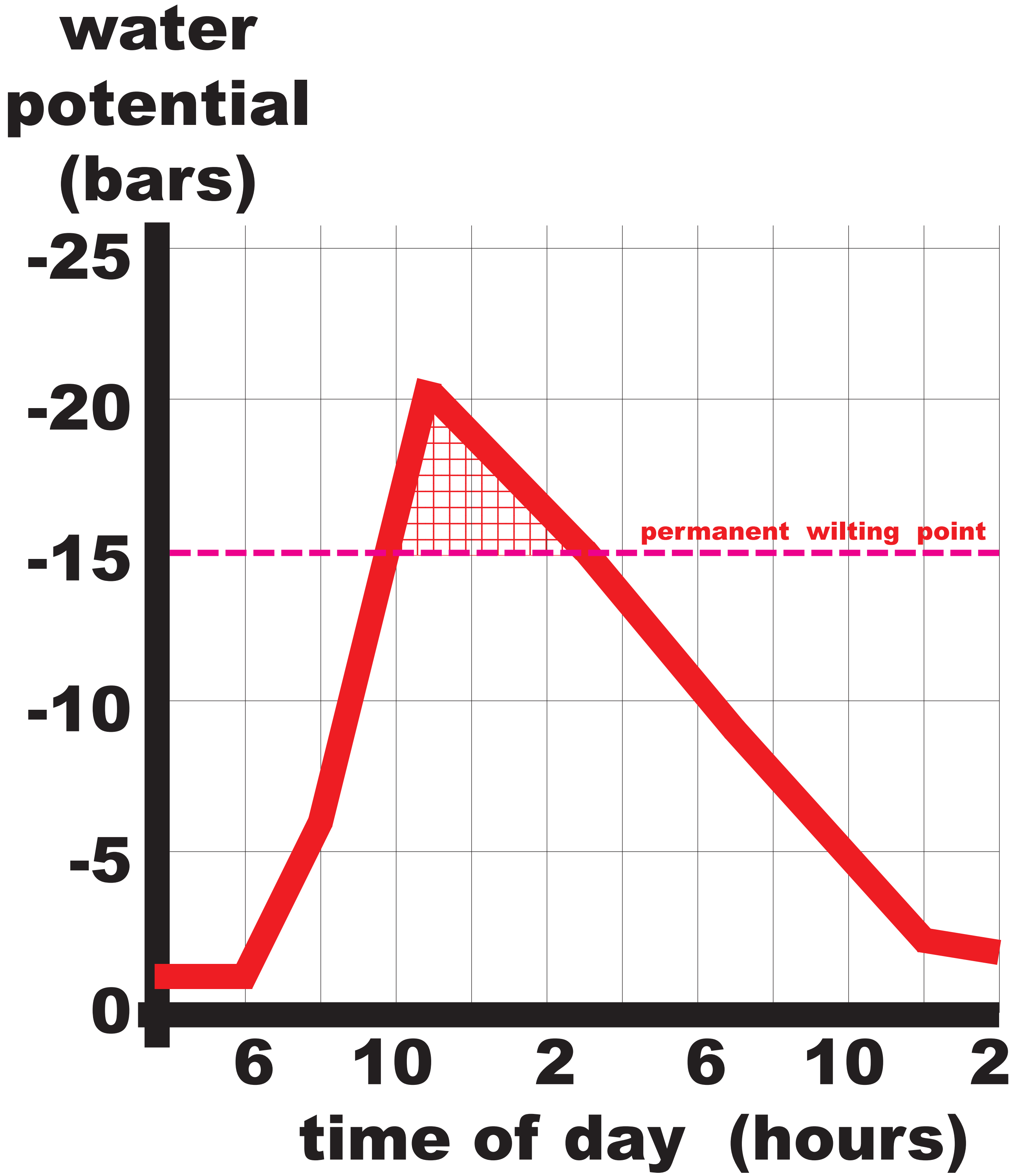

Figure 7: Generalized open-grown, single tree water potential in bars over a mid-growing season day.
(derived from Bacone et. al., 1976)

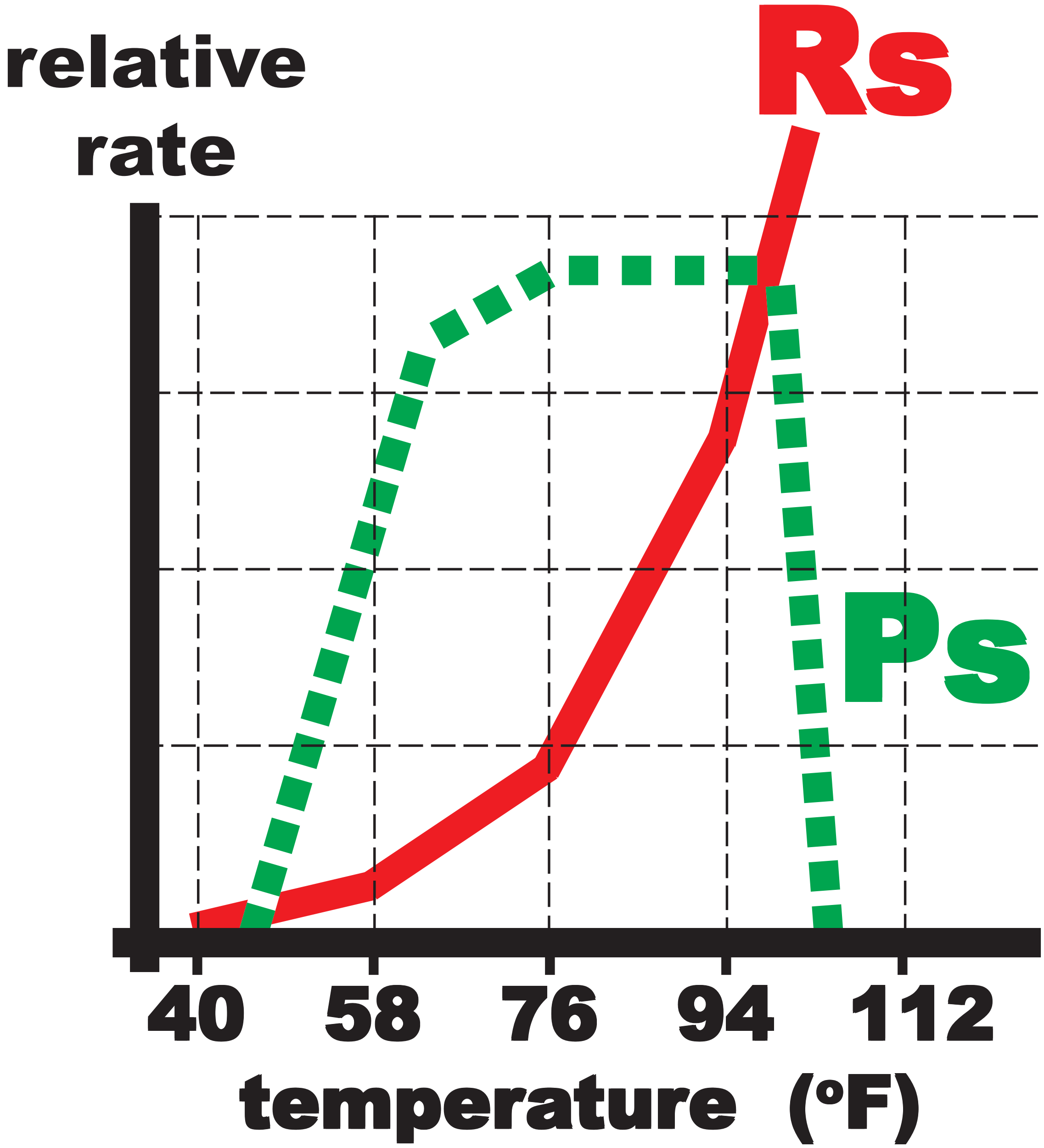

Figure 8: Relative rates of photosynthesis (Ps) and respiration (Rs) in a tree. Note respiration continues to climb exponentially with increasing temperatures and photosynthesis quickly falls apart as 105°F is passed.

1) **decrease photosynthesis & increase respiration**

2) **close down photosynthesis (turn-over point of photosynthesis & respiration around ~95°F) by closing stomates, stopping CO_2 capture, & increasing photorespiration**

3) **major slow-down in transpiration preventing heat dissipation & causing internal temperature increases**

4) **increased cell membrane leakage signals changes in protein synthesis**

5) **continued physical water loss from all tree surfaces**

6) **growth inhibition (elongation & generation)**

7) **tree starvation through rapid use of food reserves, inefficient food use, & inability to call on reserves when & where needed**

8) **toxins generated through cell membrane releases & respiration problems**

9) **membrane integrity loss & protein breakdown**

Figure 9: Sequence followed in tree heat stress syndrome.

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