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Shade Management Beneath Trees

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One key concern in sustaining top performance in tree and ground covers under shade of overstory trees is the effective management of light energy. Overstory trees paint the site below with highly variable shade patterns. These patterns change over the day and growing season. Figure 1 demonstrates the changing sun position in the sky over growing season days. Mapping shade patterns on the ground surface behind a tree (or other obstacle) is key to understanding shade impacts.

Attempt to draw onto a landscape area a shade field where, as the sun moves during the growing season, shade is projected onto other plants and soil surface. Depending upon whether this shade field is direct shade, diffuse shade, or combined with sunflecks will determine how well other trees and plants will perform. It is important to understand the shading process in order to effectively manage trees on any site. In addition, shade stress can only be appreciated by understanding photosynthesis and the requirement for light in plants.

Tree Life

The basic functions of tree life requires maintenance of a clear and distinct gradient between living tissue and the outside environment. This gradient is maintained by a water supply system (wet inside / dry outside) and an energy concentration system (energy dense inside / energy sparse outside). This wet energy environment inside is sustained by use of carbon – carbon dioxide (C-CO2) interchanges in an oxygenated space powered by light -- photosynthesis.

Photosynthesis means “light construction.” Photosynthesis is a multi-step process where light energy is used to weld carbon dioxide derived carbons together and store protons (H^+). Oxygen is produced as a by-product from processing raw materials CO2 and H2O. The carbon containing materials produced comprise more than 99% of everything visible in a tree. These carbon chains are formed, transported and used within a mineral water bath inside living tree cells. Figure 2.

Most photosynthesis in trees occurs in leaves, primarily in leaf mesophyll cells. Some photosynthesis does occur in leaf petioles, fruits, buds, flowers, twigs, branches, stems, and roots exposed to light. Tissues with green coloration can photosynthesize, but may be limited by carbon dioxide (CO2) availability or by the quality and amount of light present. This non-leaf photosynthesis partially uses CO2 respired (released) inside tree tissues, thus recycling captured carbon.

Light Resources

Sunlight is the ultimate power source in trees. But not all light is usable in trees for sustaining life. Only a narrow band of light energy can be absorbed and converted into chemical energy. Figure 3 shows the spectrum of sunlight we can see and among which are specific energies of light trees can use in photosynthesis. The shorter the wavelengths, the higher the frequency and the more energy light contains which impacts tree tissue. Well beyond biologically useful light energy wavelengths are x-rays of very shortwave radiation, and radio waves of very longwave radiation.

Sunlight (photons) of various energies strike the Earth in a massive river of light. Figure 4 shows the relative amount of sunlight striking the Earth's surface at each wavelength. The only light energy usable by trees for photosynthesis are in the blue and red areas of the visible spectrum. The blue end of visible light (shorter wavelengths) have more than 1.5 times more energy per photon than longer wavelength red visible light photons. Most sunlight striking Earth's surface does not significantly impact tree growth except for changes in temperature (longwave radiation -- sensible heat) and damaging radiation (UV).

Light Chemistry

Photochemical reactions involve a photon of light crashing into an organic material. The energy exchange in these collisions propel electrons into higher energy positions. These electrons fall back to the state they were in before the collision within a nano-second (10^{-9} second). This short amount of time is not sufficient for chemical reactions within a leaf to harvest energy from the collision. The fast return of an energized electron to its previous energy state is accompanied by released energy dissipated as heat and/or generation of a photon of a longer (lower energy) wavelength called florescence.

In photosynthesis, electrons are inserted into a chlorophyll gun which uses sunlight energy to fire an electron into a higher energy state. As soon as an electron is available, it must be used. Once it has been boosted to an elevated energy state, it must be quickly moved away along a series of transport molecules to prevent the boosted electron from falling back to where it was and giving up all its added energy as heat or as a photon (fluorescence).

Photostart

To start electrons moving in photosynthesis, electron ammunition is needed. In an electron barren environment, where can these be found? In photosynthesis, electrons are generated for use by splitting water. Water is split into its component parts including oxygen given off as gas, protons (H+), and electrons. The process of splitting water to begin photosynthesis is one of the most difficult and unique in all life on Earth. Humans can split water into its component gasses with input of great amounts of energy. Trees accomplish this process of water decay, to a much greater extent and at room temperature, using specialized machinery.

Starting Line

To start photosynthesis in a tree, two water molecules (H2O + H2O) are split at the same time. This produces one molecule of oxygen (O2), four protons banked within the chloroplast, and four available electrons. This water splitting site (or oxygen generating site) acts as a bio-capacitor, briefly holding electrons. The four electrons are forwarded one at a time as ammunition into the chlorophyll boost gun. These electrons are now available to be energized by light. One oxygen molecule (O2) is generated once every four times this chlorophyll system fires.

Chlorophyll Magic

Light energy is used to boost the energy level of these electrons using a pigment called chlorophyll. Chlorophyll captures light of two narrow wavelengths and quickly transfers this light energy to electrons and onto surrounding materials. Chlorophyll has a compound ring structure. Chlorophyll is a carbon matrix surrounding a magnesium (Mg) atom in a four nitrogen (N) setting. This chlorophyll "head" has many loosely bound and easily movable electrons. Chlorophylls have a long (21C) tail section which attaches chlorophylls in place onto proteins of a chloroplast. The functional component of a chlorophyll molecule is an energy race track surrounding a magnesium atom. Figure 5.

Reddish Blue / Bluish Red?

Chlorophyll absorbs light energy in narrow wavelength zones. Light with too much energy (violet wavelengths and smaller) break chlorophyll apart. Light with too little energy (far red wavelengths and longer) can not activate chlorophyll and just generates heat in tissues. The wrong light means chlorophyll damage and repair is a continual maintenance task. Chlorophyll is a big, breakable molecule which must be constantly repaired at great expense. As much as 30% of all energy captured by leaves is used to fix broken chlorophyll. Figure 6.

A's & B's

There are two forms of chlorophyll in trees – chlorophyll "a" (Chla) is a full sun pigment and chlorophyll "b" (Chlb) is a shade pigment. Actually, both are usually present in all leaves and the proportion between the two shifts with changing light resources. The two forms of chlorophyll differ only in two hydrogens and one oxygen at one point opposite from the tail across from the pigment's magnesium head. This subtle difference of 3 atoms out of 129 atoms, all in the same configuration, changes the absorption of each chlorophyll slightly.

Chlb is more efficient at processing light which has already passed through other leaves. Chla is more effective capturing (absorbing) direct sunlight. Figure 8. Chla is best at collecting light wavelengths of 410, 430, and 660 nm. If chla filters out all usable light, then what will lower positioned chlorophylls and leaves use? Chla captures only a tiny amount of light energy with much usable energy still remaining.

Chlb is best at collecting light wavelengths of 435, 455, and 640 nm. Chlb absorbs at slightly different wavelength peaks than chla to avoid self shading effects. Chlb absorbs at slightly longer wavelengths in the blue light zone and at slightly shorter wavelengths in the red light zone (i.e. more shaded conditions). Chlb absorbance peaks nestle just inside chla absorbance peaks by about 20nm.

Banging Around

As a photon of appropriate energy (wavelength) slams into a chlorophyll, the chlorophyll shifts its bonds making the area around the magnesium head center similar to an electron raceway or relay, quickly and easily allowing electron energy to transfer to surrounding materials. Energy captured by one chlorophyll is continually passed from one chlorophyll to another until the light energy can be harvested (i.e. an energized electron removed as chemical energy). Most chlorophylls serve as an antenna or photon net. These nets are composed of arrays of 100-250 chlorophylls which relay energy of photon absorption to reaction centers. Each chlorophyll only absorbs a few photons per second.

Only a few chlorophylls are involved with the final electron conversion to chemical energy. Most chlorophylls just move energy from a photon along to photosynthesis reaction centers. In these reaction centers, captured light energy is used to fire electrons into higher energy states, which then can be used by biological machinery.

Within a tree leaf, photosynthesis is not limited by reaction centers firing electrons, but by having enough photon impacts (i.e. enough light) to keep the system energized. Many servant chlorophylls absorbing light are needed to keep a select few reaction center chlorophylls firing electrons for chemical energy capture. It takes roughly 2,500 chlorophyll molecules absorbing 10 usable photons in a tree leaf to generate one oxygen molecule (O2). Figure 8.

Changing Leaves

Leaves develop photosynthetic systems carefully tuned for the light environment in which they grow. In some species, leaf preparation begins in the bud as the light environment is sensed. Shade tolerant trees, and trees which have grown up in shade of other trees, can have photosynthetic machinery slowed or damaged by too much additional light. Trees develop two primary types of leaves, continuously change chlorophylls, and constantly shift light harvesting machinery positions to assure photosynthesis is tuned to current light availability.

PAR!

Light resources on a site are critical to powering photosynthesis. In trees, it is the arrangement of light absorbing arrays (leaves) which can prevent other plants from receiving enough light for surviving or thriving on a site. For example, it is estimated 25% of turf acreage in the United States is under shade. The definition of shade used here will be the filtering or blockage of light of physiologically active wavelengths.

Approximately 50% of all incoming solar radiation is in the wavelength range of 400-700 nm (called photosynthetically active radiation (PAR)) with only about 1% used in photosynthesis. All trees use PAR to make food (carbohydrate (CHO)). If photosynthesis rates drop below tissue respiration requirements, trees decline and die. A positive net photosynthesis rate must be maintained or trees will not be able to sustain themselves against other plants and the environment.

Light Thresholds

As PAR strikes and passes through leaves, a minimum level of light is required to activate the photosynthesis machinery. The more PAR, the greater the photosynthetic rate climbs to some maximum rate. PAR above this amount does not provide any more value to a tree. The maximum light which can be utilized depends upon each tree's photosynthetic equipment and its maintenance. Trees reach a photosynthetic optimum around 75^{o}F, and are limited by temperatures >90^{o}F.

Trees can tolerate, survive and thrive at various full sun levels of ligfht. Most trees do well with >90% full light and easily move through their life cycles. From 66% - 90% full sunlight shade tolerant trees can perform well and shade intolerant species can survive. From 33% - 66% full sun only the most shade tolerant trees thrive, while most trees have many stress issues beside dense shade. Below 33% full sunlight all trees have major issues and usually decline and die. At some point, based upon tree / site conditions and genetics, the cost of maintaining positive photosynthesis becomes too great.

Light Power

Light of value to trees can be generally divided into blue range (B = 400-500nm), green inactive range (G = 500-600nm), red range (R= 600-700nm), and far red range (FR = 700-800nm). The blue range is active in powering photosynthesis and is found in direct and diffuse sunlight. The green range is generally not used by plants and is reflected or passed through to our eyes. The red range is also used in powering photosynthesis and is found in direct sun light. The far red range is used to measure light quality by plants, and affects growth control processes when measured by a sensor pigment called phytochrome.

Tree leaves act as selective filters to incoming sunlight. Tree leaves remove portions of the PAR for use in food production. The more leaves filtering the sun, the less energy available for capture below and the deeper the shade. Blue and red wavelengths of light are used (filtered out), leaving remaining green colors to paint shady areas. Most full sun plants require at least six hours of full sun every day even if they spend the rest of a day in shade. Perpetual or constant shade is a low energy, stressful environment. Sunflecks are short duration points of light which deliver full sun for periods of 2-10 minutes. Some plant species depend upon these bursts of full sun to survive and may not be able to survive perpetual shade.

Shade Types

Shade comes in many different forms. Shade varies by duration, timing, density, and source. Light perpetual shade can be more damaging than six hours of heavy shade. Morning shade has been shown to be worse for understory plants than the same duration of shade in the afternoon. A dense shade has much less energy to power any photosynthesis than a light or spotty shade. Sunfleck number, size, and duration variations can mean the difference between decline and thriving.

Buildings and awnings produce a different quality of shade than tree canopies. Building shade tends to be richer in blue (B) and less far red (FR) than tree canopies. Tree shade is enriched in far red (FR) and short of red (R) from leaf filtering. Because far red (FR) initiates tree growth changes, shade quality differences from different shade sources affect plants differently.

The shade behind a leaf has two components, a full shade where no direct light is available and a partial shade where more diffuse and scattered light is available. Based on the diameter of the light emitting disk of the sun in the sky, and its distance from a leaf, a cone of full shade called an umbra exists for a given distance behind the leaf. Figure 9. Proper terms for these shade areas behind or below a leaf are given in Figure 10. This full shade or umbra cone exists for a distance of approximately 60 times the effective leaf diameter (ELD) of a leaf. Each leaf has a different effective leaf diameter.

ELD & DSED

Effective leaf diameter (ELD) is the average of short and long axis length of the largest ellipse which can be scribed within a leaf which does not cross any leaf edge. Figure 11. Here each leaflet will be considered the same as a leaf. Figure 12 provides a definition of effective leaf diameter for various leaf shapes. Effective leaf diameter in inches multiplied by 60 yields the direct or full shade effect distance (umbra length or DSED) behind the leaf in inches. Leaves in bundles (pine needles) should have effective leaf diameters calculated by bundle diameter not by single needle width.

Figure 13 provides a list of tree species and their average effective leaf diameters and direct shade effect distance (DSED) behind or below a leaf. Note that the DSED is not a vertical umbra distance, but an umbra which moves behind a leaf as the sun traces an arc through the sky. This arc will never be vertically above the leaf at any latitude greater than the tropics, but always at some angle less than 90^o to the horizon.

Direct or Indirect?

Figure 14 shows the effect of distance below a leaf upon the quality and quantity of the shade produced. Leaf layers create complex patterns of direct and diffuse shade at any one moment in time. The soil surface beneath a tree will be a mix of direct (full) shade, diffuse (partial) shade, and sunflecks (short duration full sun). Figure 15 shows the direct shade effect distance (DSED) behind or below leaves with various effective leaf diameters. For example, a leaf with a four inch effective leaf diameter (4" ELD) directly influences sunlight below/behind for 20 feet (umbra length or cone of full shade or DSED = 20 feet).

Pruning For Effect

Trees can be effectively managed to increase light passage through crowns by reducing foliage density. Two pruning methods used to reduce shade density are crown raising and crown thinning. Crown raising is properly pruning lower branches. The distance to leave between the first live branch and soil surface can be estimated by calculating average shade effect distances. Raising allows more blue band light to diffuse onto soil and plant surfaces, and more total light passing through and around the crown. Crown thinning is the removal of foliage-bearing branches and twigs within the living tree crown, but not affecting total reach and extent of the crown. Thinning can allow more sunflecks of full sunlight and more total light to reach soil and plant surfaces.

Few plants will perform well in direct full shade. Changing the shade pattern over the day and season by pruning overstory trees can allow more leaves to be successful. Overstory tree pruning using crown raising and crown thinning can help improve light resources below. Note some trees (magnolia and holly as examples) have values within landscapes and growth patterns (low branch skirts) which preclude attempting to increase DSED with crown raising.

Light Competition

A critical form of light competition on trees is the presence of vines and epiphytes. Traditional landscapes with large trees may also use ivy, jasmine, grapes, Virginia creeper, or other woody vining plants at the base of trees. Interference for site resources from these plants as shaded ground covers is not intense. When vines are allowed to climb trees into the sun (or are exposed to full sun), they use more site resources, especially light and water. Vines present both ecological interference and mechanical support problems (in wind and ice storms.) Some epiphytes like Spanish moss do not actively interfere with tree roots and soil resources, but physically block light from tree foliage. Periodic control and removal is needed.

Thin Is In

A major problem in some landscapes is the perception that more trees are better than fewer trees. It is aesthetically better to have a few, great impact, structurally sound, and biologically healthy trees than many stressed, pest ridden, and poor quality stems. Trees grow and occupy more space over time. A group of trees planted for a specific shade impact can grow and over-occupy a site. Thinning trees is a good management tool because it removes the poorest trees, leaves the best trees, and releases new resources. Overcrowding or overstocking leads to premature death, increased pest problems, and less resistance to site stress.

Two means of gauging overstocking of tree stems on a site is using a PAR light meter, or measuring the effective basal area (dbh) in square feet of a site. A PAR meter will demonstrate how much usable light is present (or could be made available) through tree thinning. Basal area measures are an easy means to determine stocking levels and measure thinning impacts. Basal areas between 35 -- 70 square feet per acre (measured with a prism or angle gauge) are appropriate for a tree covered area. Basal areas between 20 -- 40 square feet can be used for open park-like areas.

Conclusion

Shade can be a stressful attribute on a site. Planning for shade patterns and number of leaf arrays over any site can pay tree health and other plant dividends in generating fewer problems and better sustainability. Use shade assessments to better quantify shade impacts.

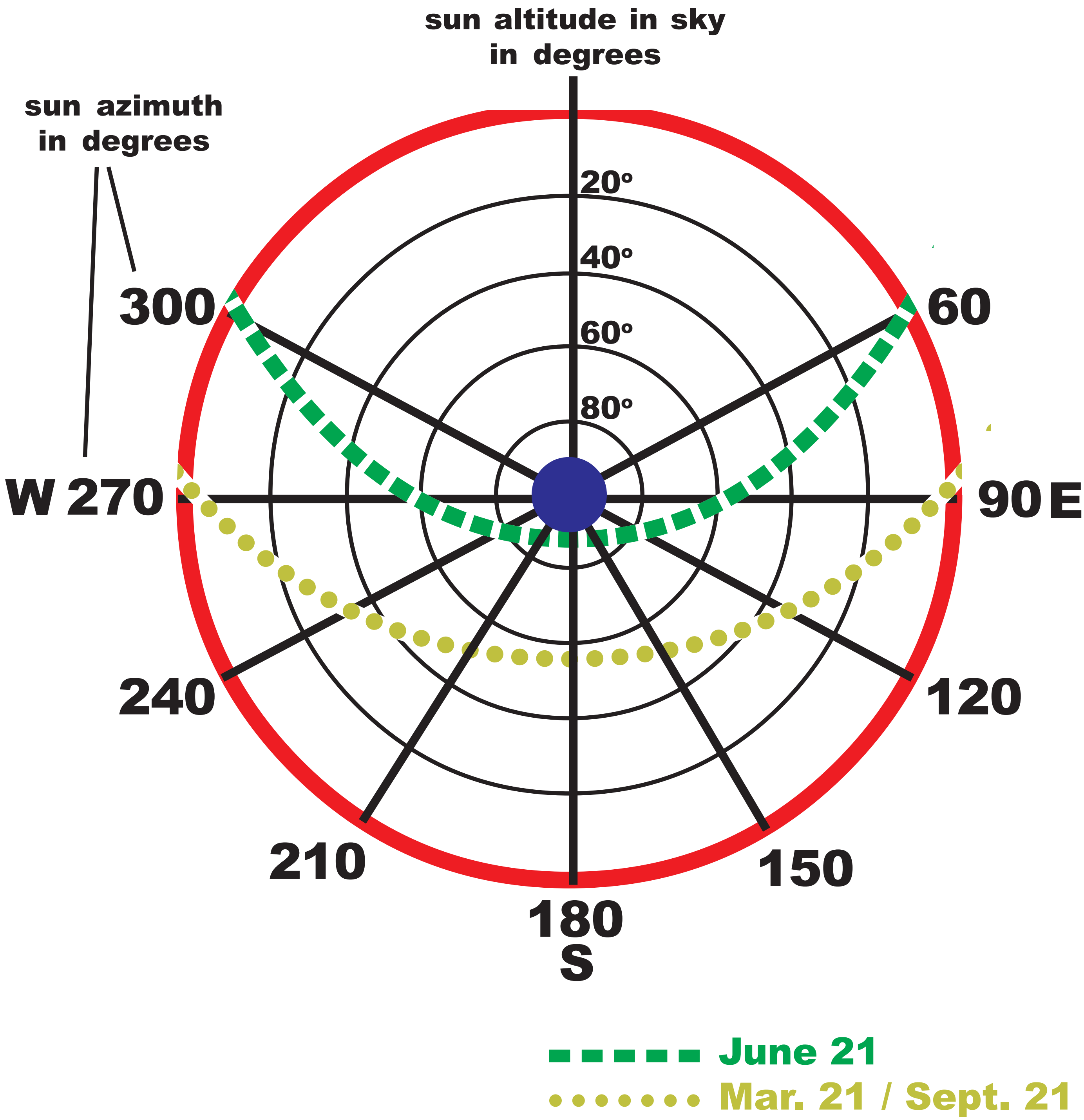


Figure 1: Generalized pathway of the sun during growing season (between the two dotted lines). The shade field is the opposite side of tree / building from sun.
(this example for Atlanta, GA)

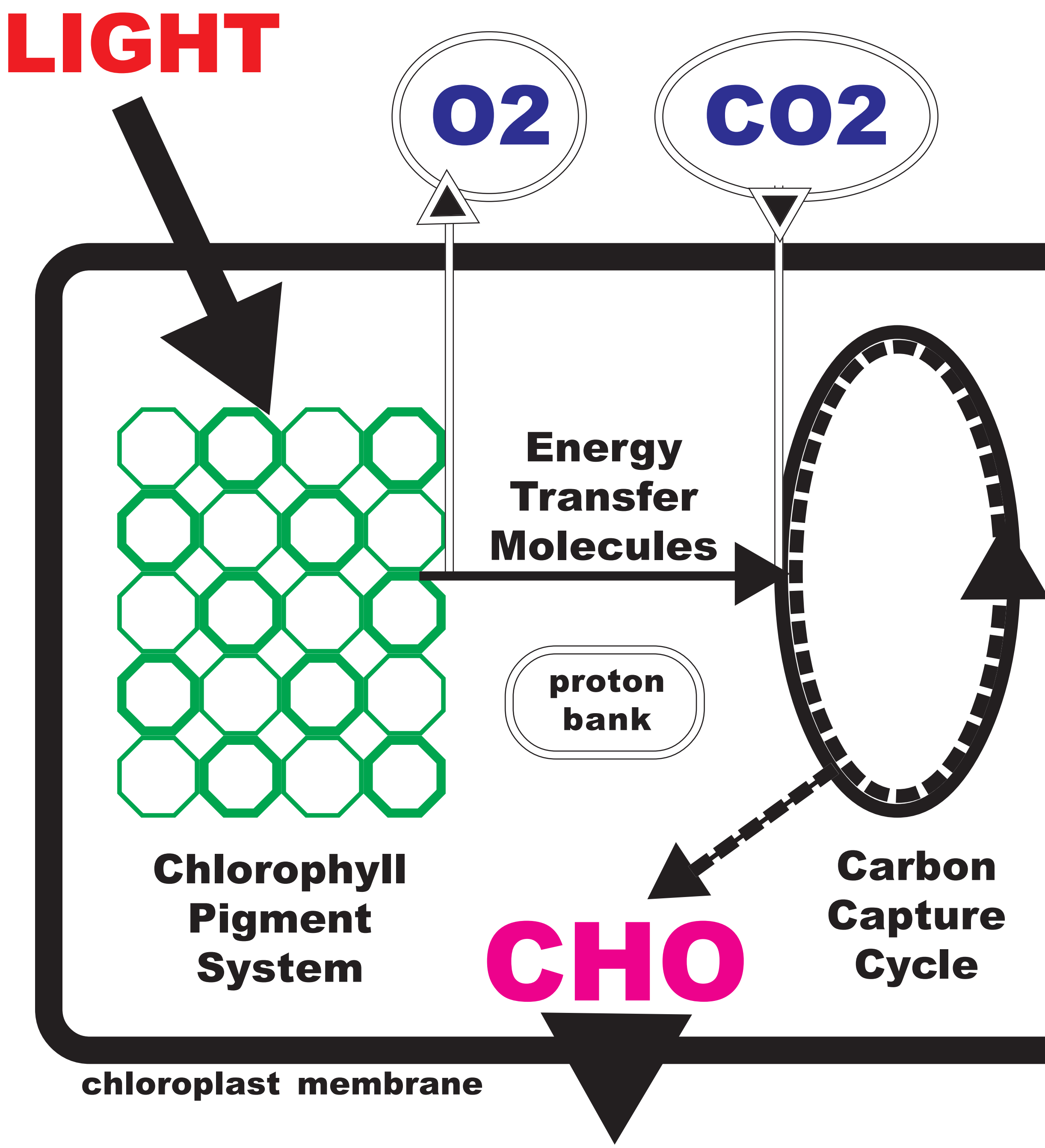


Figure 2: Light energy capture and carbon fixation process (photosynthesis) inside a tree chlorplast. (after Taiz & Zeiger 2006)

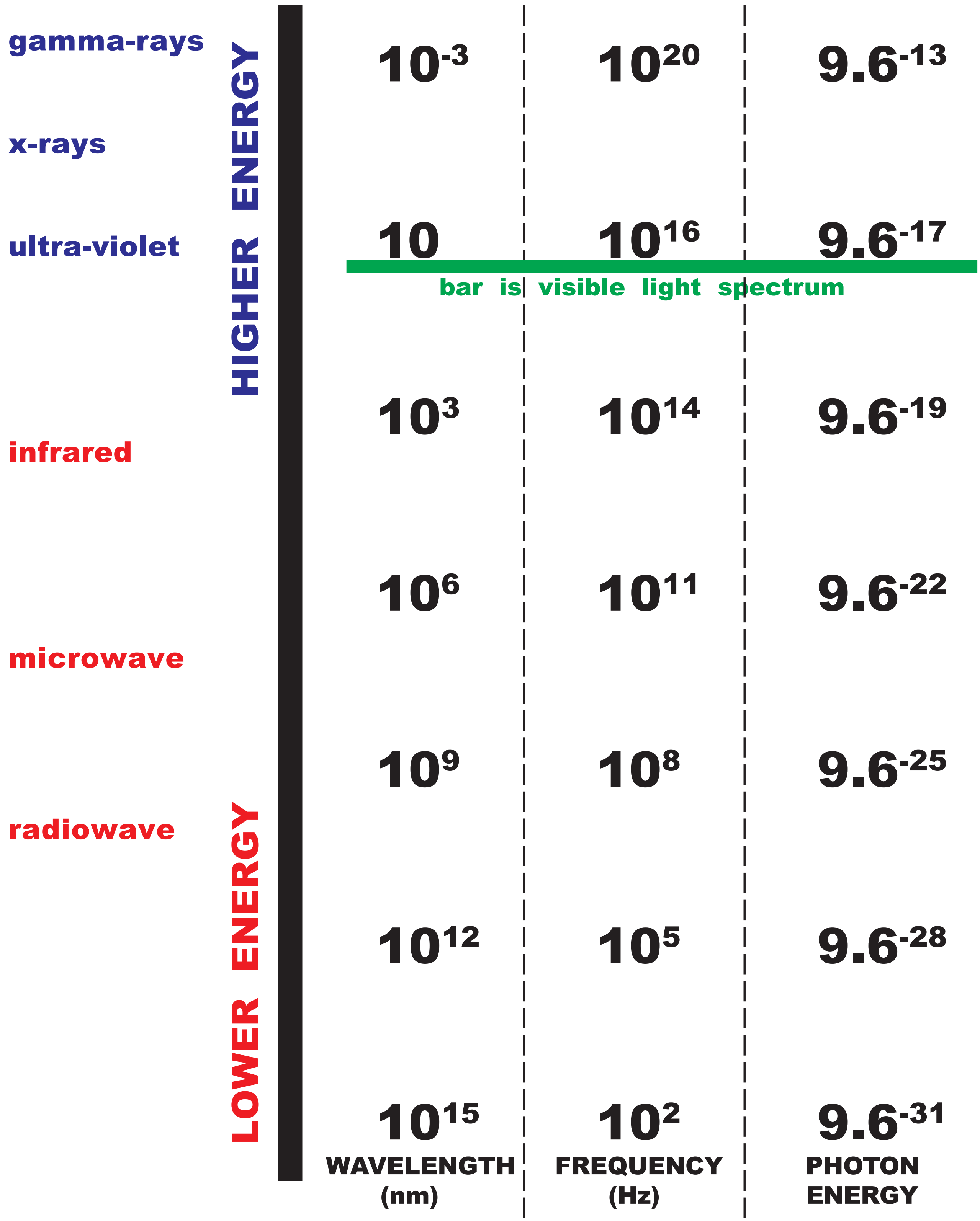


Figure 3: Light radiation wavelengths, frequencies, common names, and energy of one photon.
(modified from Taiz & Zeiger 2006)

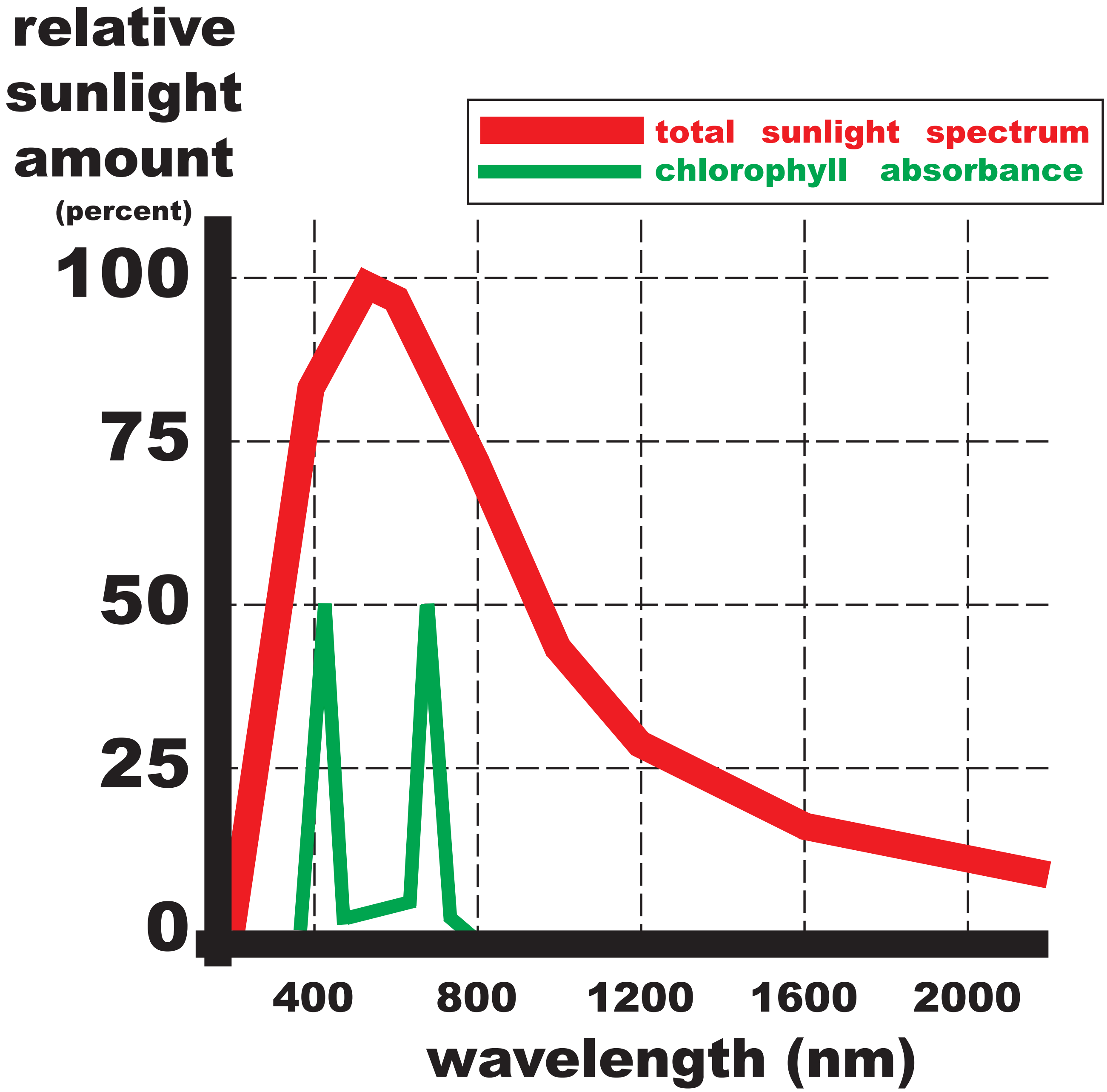


Figure 4: Relative amount of sunlight striking the soil surface by wavelength, and the absorbance of chlorophyll. A general curve with no atmospheric absorbance is shown. (from Taiz & Zeiger 2006)

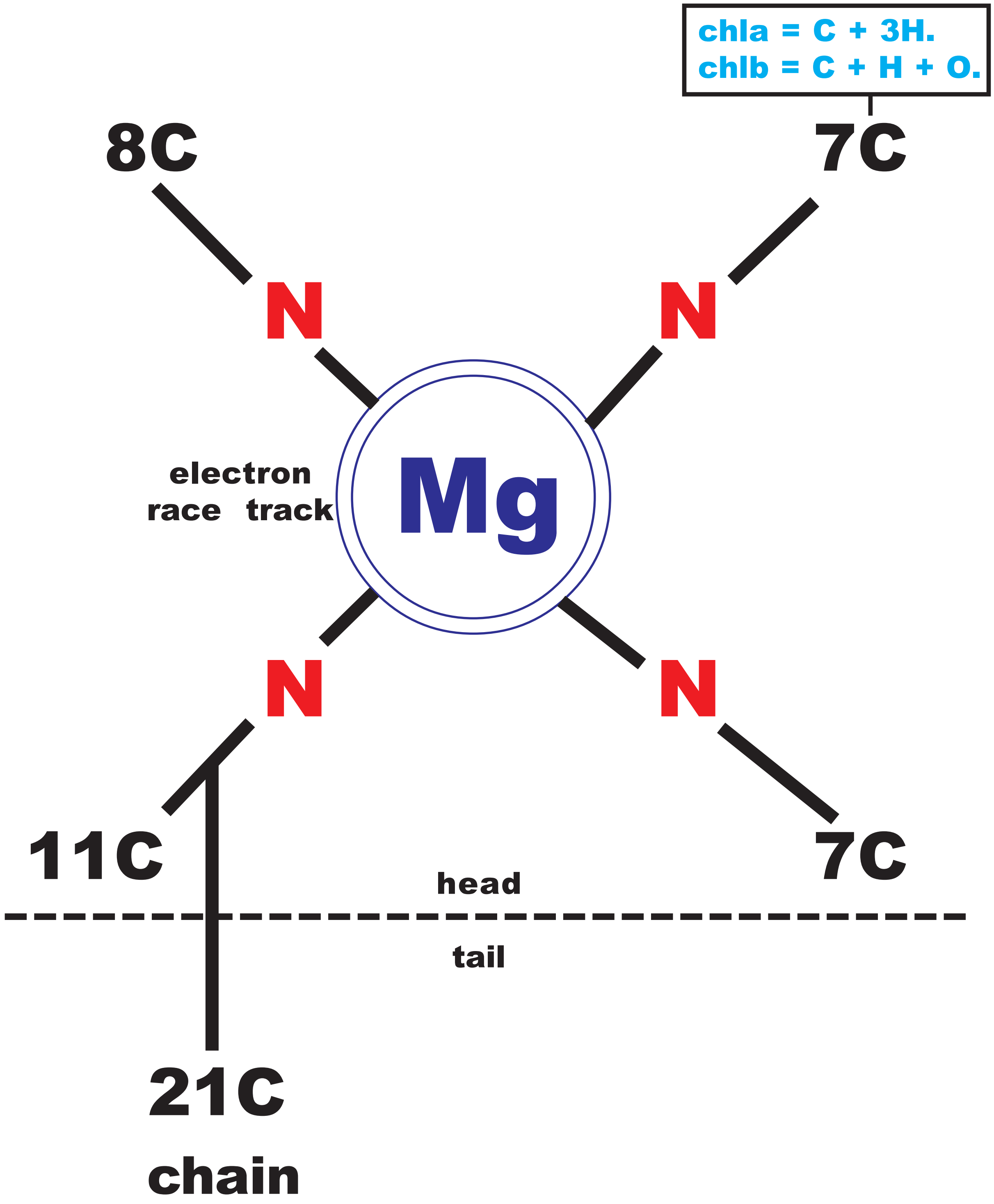


Figure 5: General structure for chlorophyll. There are 33 carbons in the chlorophyll head and 21 carbons in the tail. Four nitrogens (N) and one magnesium (Mg) are enclosed within the chlorophyll head.

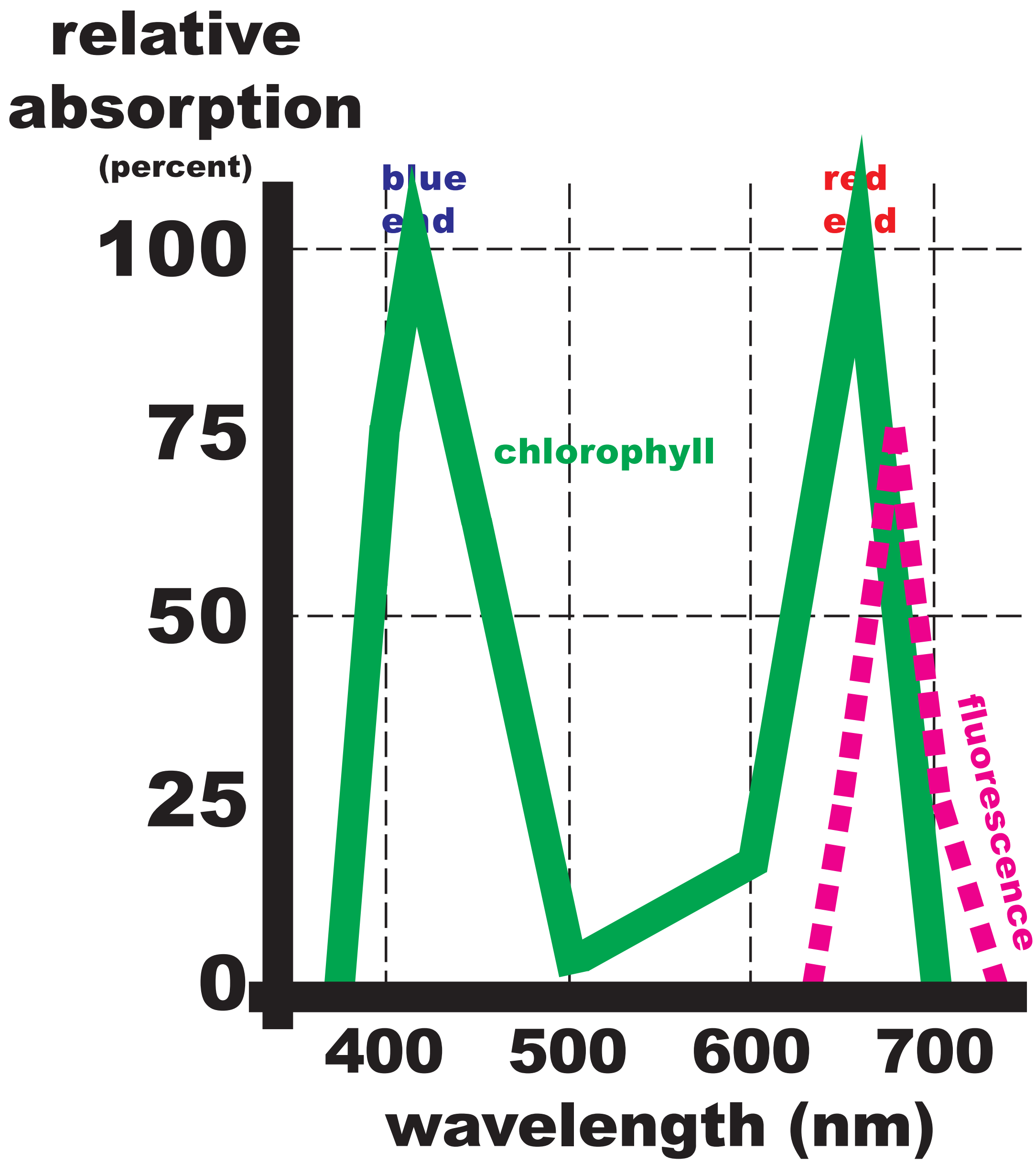


Figure 6: Simplified view of light wavelength absorbance by chlorophyll and its fluorescence.
(from Taiz & Zeiger 2006)

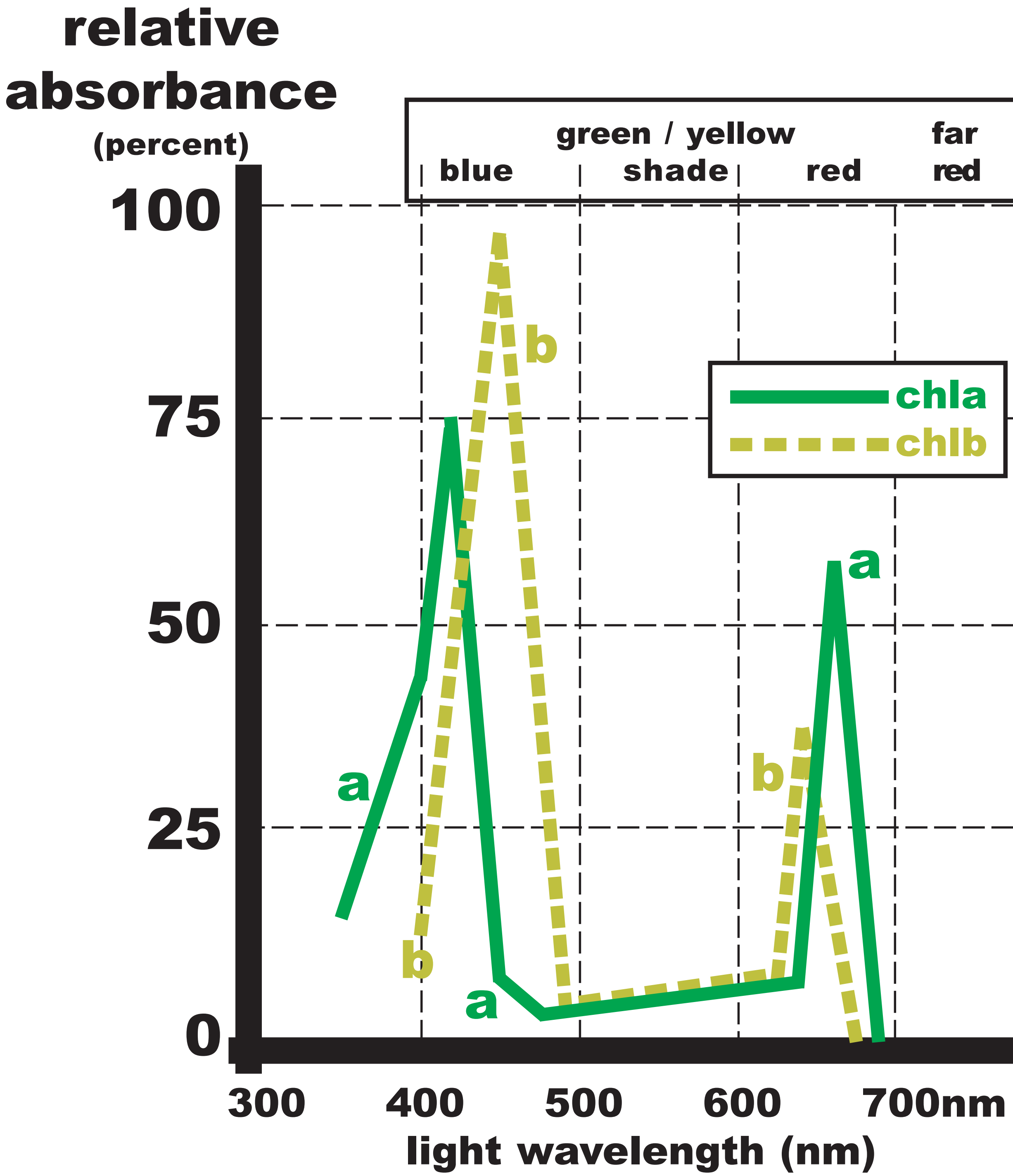


Figure 7: Relative absorbance values for chlorophyll a (chla = full sun pigment), and for chlorophyll b (chlb = shade pigment). General light color descriptors for wavelengths are given.

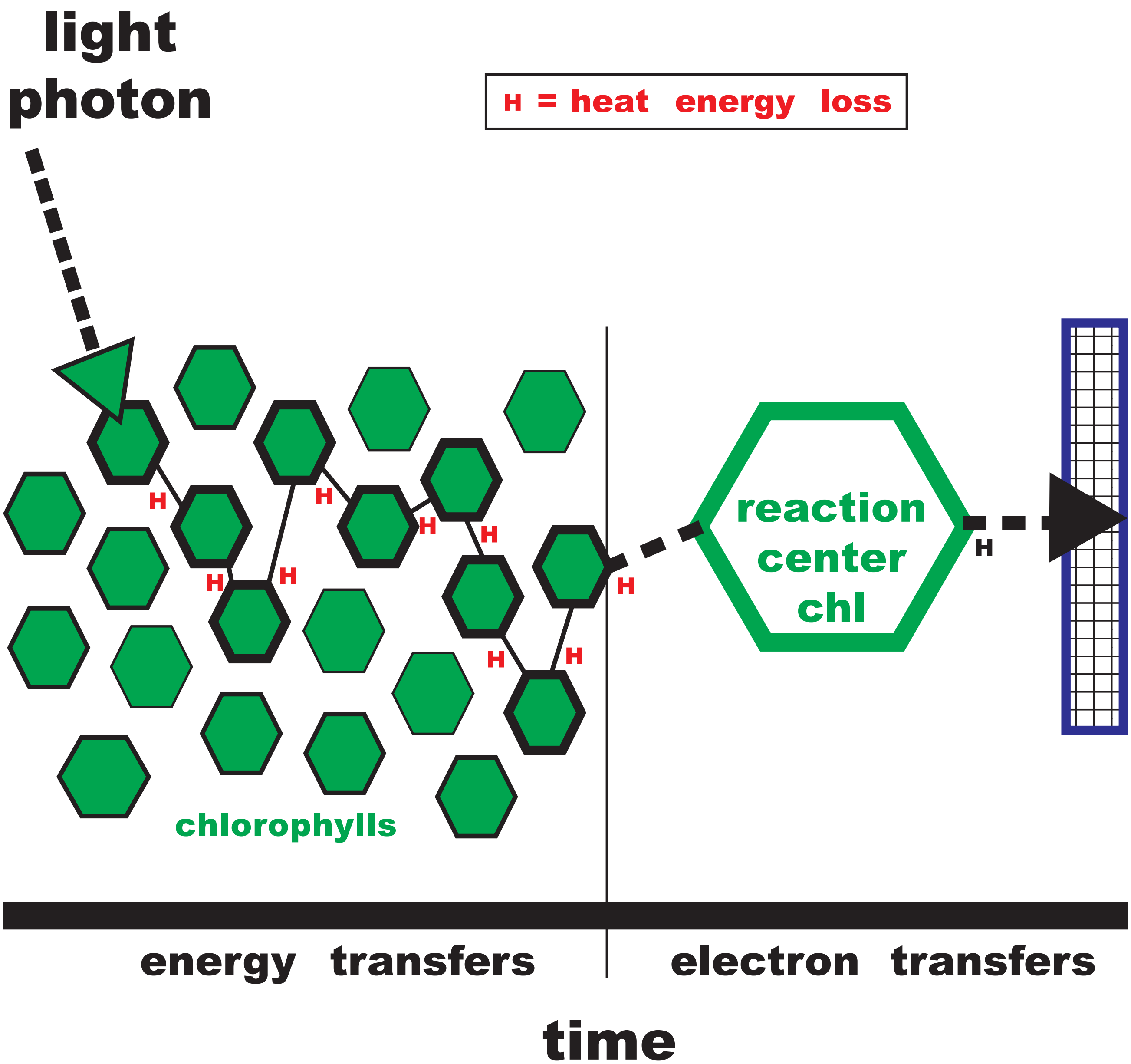


Figure 8: Light energy capture and energy transfer by resonance in chlorophyll antenna, and then electron transfer. (from Taiz & Zeiger 2006)

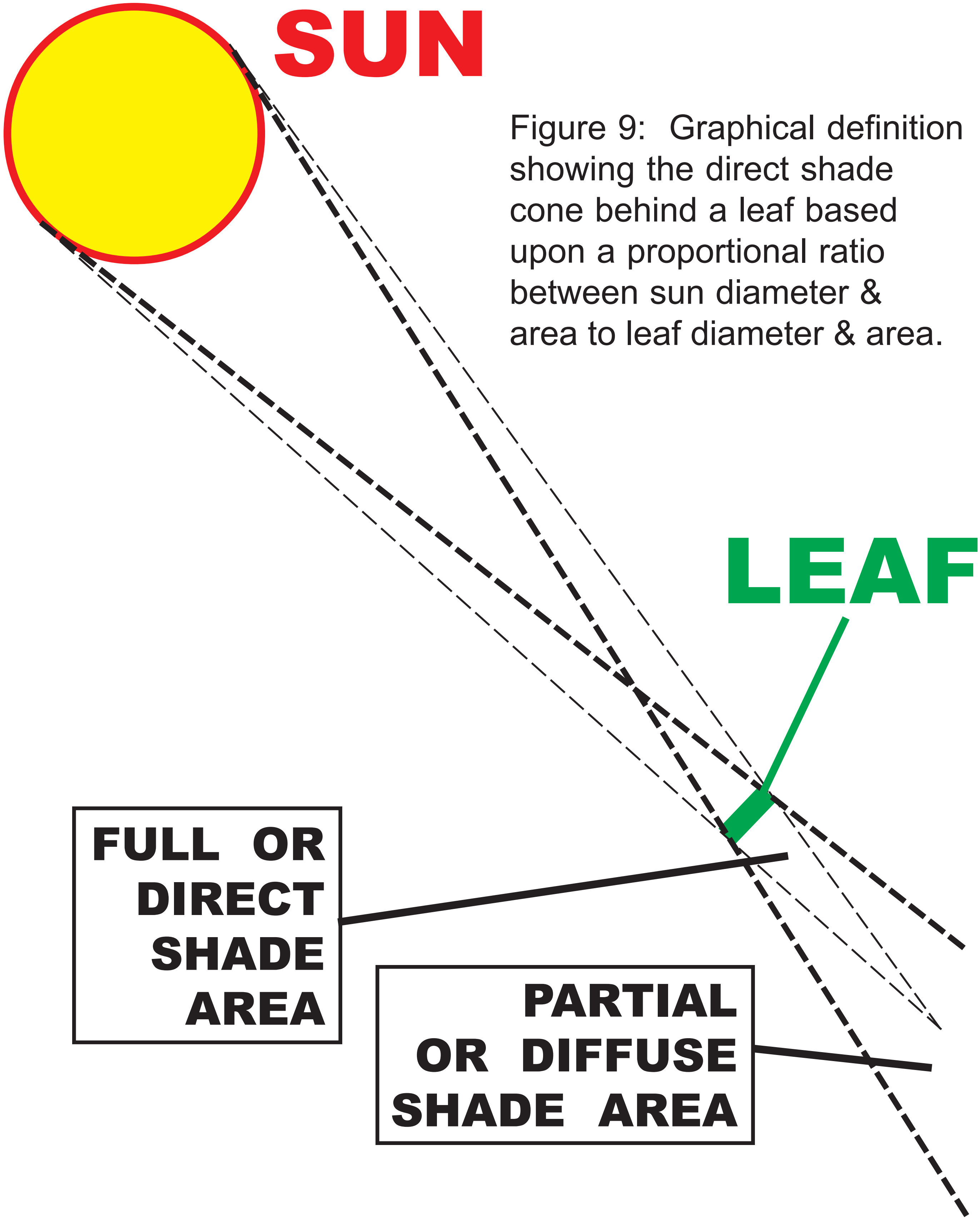


Figure 9: Graphical definition showing the direct shade cone behind a leaf based upon a proportional ratio between sun diameter & area to leaf diameter & area.

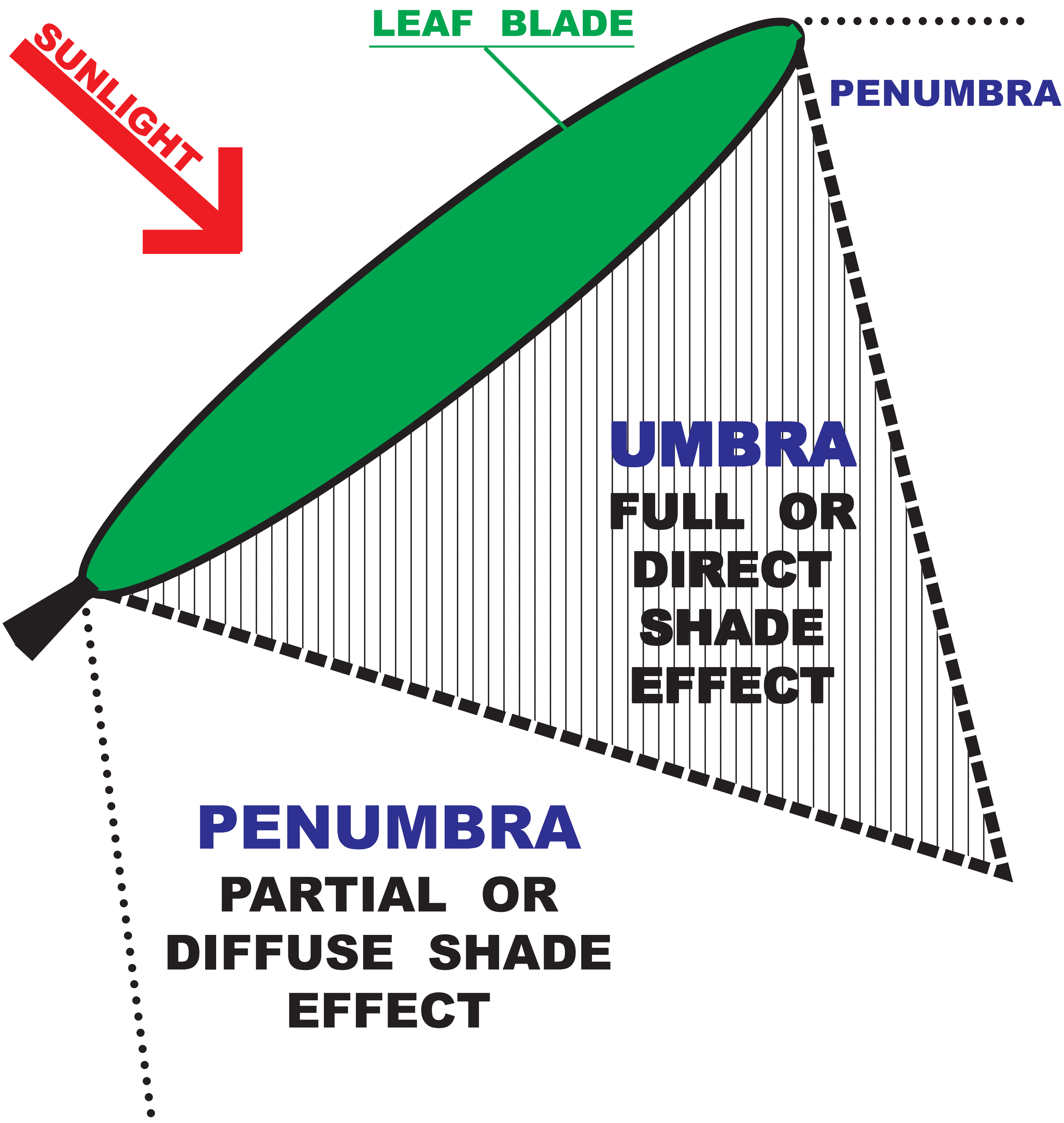
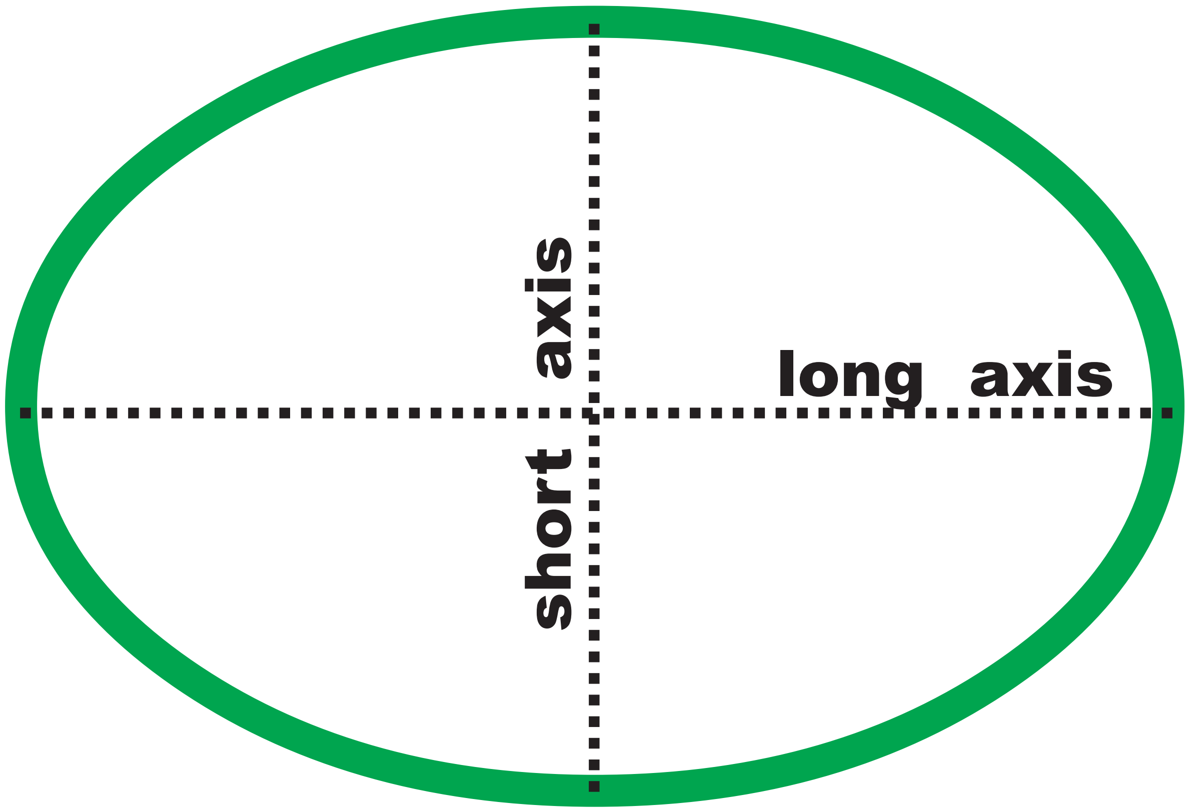


Figure 10: Shade terms of the two volumes behind or below a leaf, opposite incoming sunlight.

ellipse to be scribed completely inside leaf



(long axis distance in inches + short axis distance in inches) / 2 =

effective leaf diameter or ELD

Figure 11: Graphical representation of how effective leaf diameter is determined. ELD is an average length of the long and short axis for the largest ellipse scribed inside a leaf outline without crossing a leaf edge.

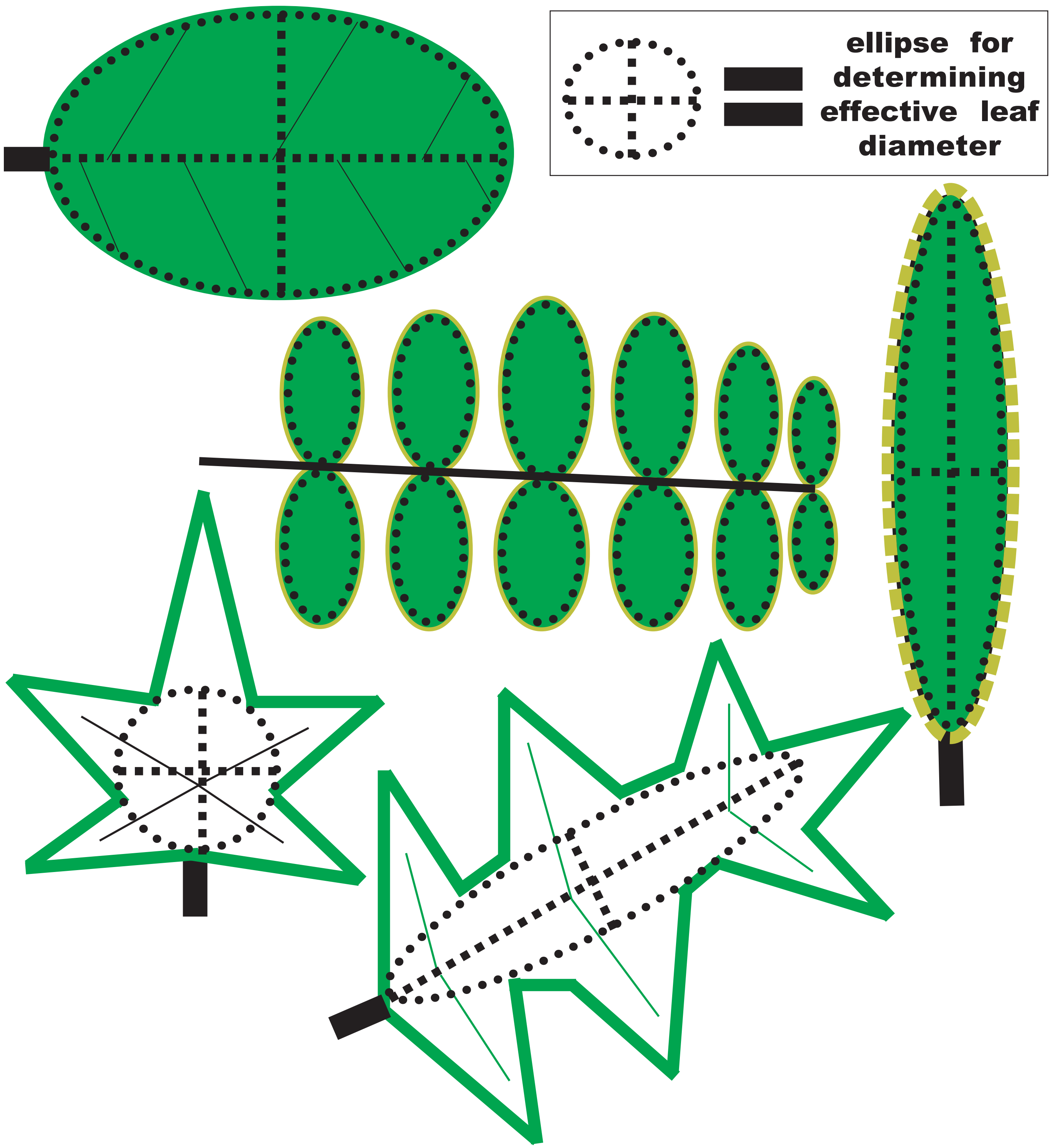


Figure 12: Graphical definition of effective leaf diameters (ELD)

species	effective leaf diameter (inches)	direct shade effect distance (feet)
black gum	3.5	17.5
black locust	.75	4.0
catalpa	6.0	30.0
cherries	2.0	10.0
holly	1.5	7.5
honeylocust	.5	2.5
large-leaf elms	3.5	17.5
lobed oaks	1.5	7.5
magnolia	5.0	25.0
pines	.25	1.5
red maple	2.5	12.5
river birch	2.5	12.5
sugar maple	3.0	15.0
sweetgum	2.0	10.0
unlobed oaks	3.0	15.0
willows	1.5	7.5
yellow poplar	3.5	17.5

direct shade effect distance in feet =
((effective leaf diameter in inches) X 60) / 12

Figure 13: Example shade effect components (ELD & DSED) for selected tree species.

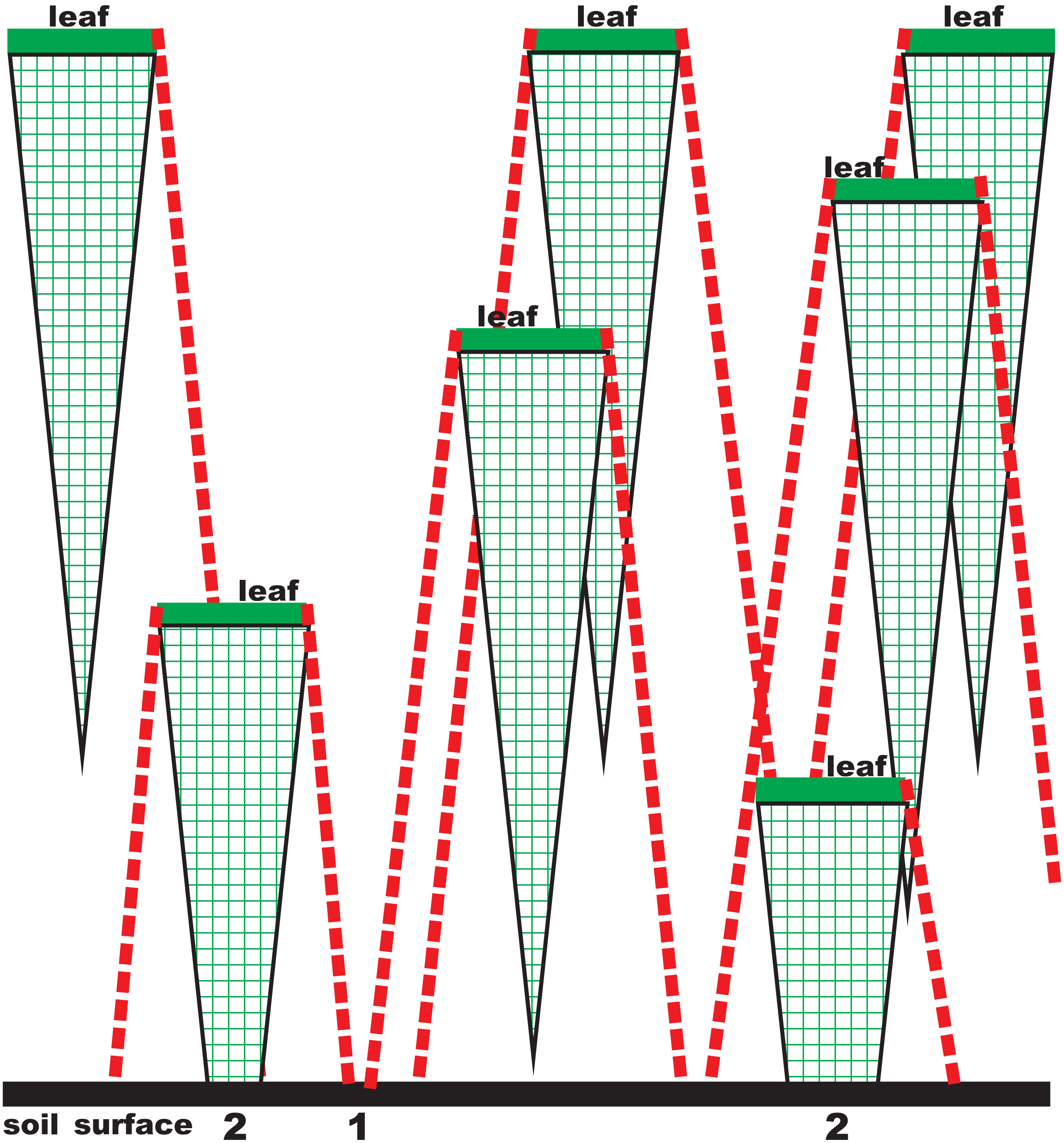


Figure 14: Diagram of additive effects of several leaf layers upon direct and diffuse shade. In only one spot (#1) does full sunlight strike the soil surface. In two places (#2) a direct shade effect is present at ground level. The rest of the soil surface is covered with diffuse shade.

ELD in.	DSED ft.	ELD in.	DSED ft.
0.25	1.3	5.5	27.5
0.5	2.5	6.0	30
0.75	3.8	6.5	32.5
1.0	5	7.0	35
1.5	7.5	7.5	37.5
2.0	10	8.0	40
2.5	12.5	8.5	42.5
3.0	15	9.0	45
3.5	17.5	9.5	47.5
4.0	20	10.0	50
4.5	22.5	10.5	52.5
5.0	25	11.0	55

Figure 15: Calculated value of direct shade effect distance (DSED) in feet for a number of effective leaf diameters (ELD) measured in inches.
DSED ft.= ((ELD in.) X 60) /12.

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