An Initial Study and Application of Basic Plant Characteristics That Aid in the Reduction of High Urban Temperatures

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Abstract

Urban heat is an ongoing phenomenon that affects everyone living in urban environments. Unhealthy living conditions have been produced as a result of high temperatures in urbanized areas. There are many studies on this and the ways in which to mitigate these high temperatures. Botanical controls have often been used as mitigation measures, using vegetation as a means to bring down urban heat, however little study has been done on what actually comprise the characteristics of plants that help bring down high temperatures. This study stresses that plants should not just be analyzed at a superficial level but rather, analysis of plants and their capabilities should go much deeper, looking at anatomical/physiological characteristics for their proper application in controlling excessive heat in urban environments.

The objectives of the study is to understand what causes high urban temperatures and the botanical mechanisms that effect reduction in temperatures with prime focus on evapo-transpiration. The study is also an attempt to quantify a highly subjective (qualitative) component of Landscape Architecture of which are planting materials and planting design. These botanical mechanisms are applied in a method that can portray quantifiable reduction in high temperatures given by plants. The method gives an idea and an estimate on the cooling afforded by plants for given heat loads.

To answer these objectives, a method was developed for ascertaining temperature reduction extents of plants by applying existing standard conversion factors for temperature, heat/energy, transpiration, heat load and cooling capacity. The output of this method is an estimate only, largely due to the limitations in data for actual urban environmental conditions and lack of equipment in the measurement of botanical characteristics. From the methodology employed, the study was able to come up with general values that equate cooling given by plants with specific characteristics and that can be used in their proper siting in urban locations. The methodology results in a planting framework that dictates the correct use of plant species with measured cooling potential for the control of high urban temperatures. This would thus be a significant contribution to planting design.

The study impacts several entities as these have an effect on the total cooling potential given by plants and the total cooling of the urban environment. Firstly Landscape Architects and planting design, secondly Architects and the design of structures and thirdly Urban Planning and Design with the locations of buildings and structures. The study will also impact nursery as well as maintenance practices.

Background

Figure 1 Concrete Jungle of Manila. From: www.u2asean.com/.../images/manila_skyline.jpg

Urban heat is a phenomenon common in built up urban centers. Because of the color and material of these environments, temperatures are significantly higher as compared to non-built up areas in the surrounding environs (Fig. 1). The high temperature common in these urban centers make them "heat islands." Concrete as a material releases absorbed heat through long wave radiation well after the sun has set (Fig. 2).

Figure 2: Actual and Infrared image showing high heat absorbing (low albedo) materials versus low heat absorbing (high albedo) materials. Blue colored region at the right is a gravel paved area. From: http://www.invisiblestructures.com/GreenBuilding1/heatisland.htm

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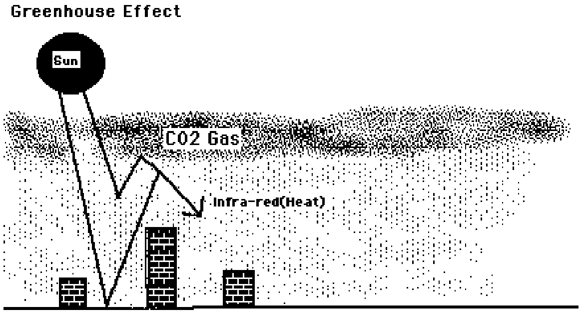

Figure 3 Carbon Dioxide from cities and retention of heat. From: www.gpc.edu/~jaliff/air6.gif

CO_2 is a factor in rising temperatures. "…the urban atmosphere tends to retain heat because of higher carbon dioxide content. On balance then, the urban landscape yields and retains more heat, thereby accounting for the overall heat island effect." (Marsh 1998, 321) (see Fig. 3) Carbon dioxide causes a Greenhouse Effect.

This excess pollution in the atmosphere above urban areas has the effect of <u>hindering the input</u> of heat and yet urban heat is just too excessive that this reduction in the input of solar radiation is hardly felt. 'When compared to rural environments, cities have a higher generation of sensible heat at ground level.' This "increase in sensible heat output coupled with lower rates of heat loss is more than enough to offset the reduced input of solar radiation resulting in somewhat higher temperatures in urban areas throughout most of the year…" (Marsh 1998, 321) (Fig. 4)

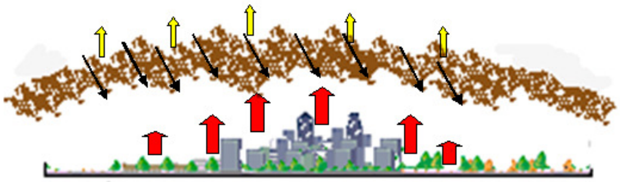

Figure 4: Reduced input of solar radiation (black arrows) and lower rates of heat loss (yellow arrows) as caused by pollution. Red arrows: increased sensible heat.

a. Problem setting

How can plants aid in the reduction of urban heat? What plant characteristics should one look for in the control of high temperatures in urban areas? How can we better apply these plants in urban environments for the control of excessive heat?

Objectives of the paper

- To understand what causes high urban temperatures.
- To understand botanical mechanisms that effect reduction in temperatures.
- To determine temperature reducing characteristics from existing botanical data, and apply this knowledge in a method that can control and reduce high temperatures in the urban environment.
- To determine the cooling potential of plants.
- To determine an application of such plants in the urban environment.

Scope and Limitations

This paper will focus on <u>characteristics</u> to look for in choosing plants for the control of high temperatures in urban environments. The other focus of this paper is to quantify transpiration from leaves for its potential in cooling an environment. Transpiration alone is a process of photosynthesis and is not enough by itself to produce any cooling. Transpired water must evaporate to be able to produce the cooling needed (B. Kehoe[2], personal communication, January 26, 2008).

Botanical data used to ascertain effectiveness of the plant for temperature reduction are limited but which are enumerated in this paper. Volume of tree crowns will need to be computed to yield overall leaf quantity to see the evaporated amount. There will be high variations and no exact value within these computations. Individual rates of growth and variations in growing conditions will vary findings and will only yield very rough estimates. This paper is also based on the assumption that the overall computed leaf population of a tree crown are in a healthy, green, transpiring state.

Transpired amount is dependent on various botanical factors namely, the root-shoot ratio, area and structure of the leaf. Environmental factors influencing transpiration include light, humidity of the air, temperature and wind. (Devlin 1966, 54-58). Lack of both these local botanical as well as environmental data limits the study to rough figures.

There is a lack of local study on how environmental data such as humidity, light and wind affect transpiration specifically. However the study implies a process that would subsequently allow the input of these data once they are ascertained by further studies and lead to better <u>near</u> realistic results.

For the computations, the results used to see cooling are in themselves only estimates however the conversions used are existing standards. In spite of these setbacks it is still possible to see the cooling potential of plants by using average values.

What causes High Urban temperatures?

Urbanization changes surfaces from soft and vegetated to hard and concrete. Indirect heat can come from radiated heat from the sky vault or reflected heat from the surface. Both of these contribute to the so called Urban Heat Island Phenomenon (Fig.5).

Dark surfaces contribute to heat islands due to their low "albedo" or reflectivity (Voogt, 2004). In contrast natural ground and vegetation areas have a high albedo, reflecting sunlight. (Cleare n.d.) It can be contested, that vegetation also has dark surfaces, however when vegetation absorbs

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heat, we can see this energy converted into a means for cooling.

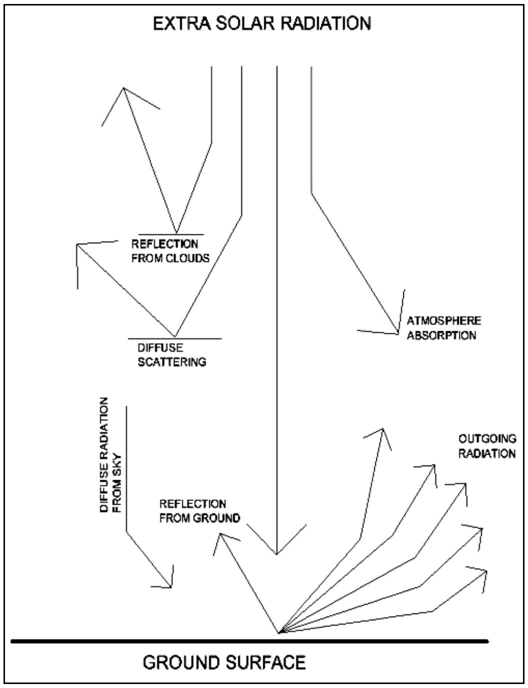


Figure 5: Solar Radiation and Heat exchange on the environment

"Tall buildings within many urban areas provide multiple surfaces for the reflection and absorption of sunlight, increasing the efficiency with which urban areas are heated. This is called the "canyon effect" (Fig. 6).

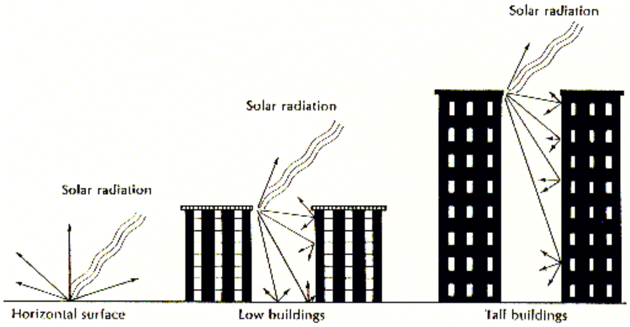


Figure 6: Canyon Effect
from: http://geog.arizona.edu/~comrie/geog430/34urban/urban.htm

Buildings also block wind which inhibits cooling by convection. Waste heat from air conditioning, industry, and other sources also contributes to excessive heat. High levels of pollution increase heat, as many forms of pollution change the radiative properties of the atmosphere (Wikipedia, 2008).

How do plants lower high temperatures

"Of the radiation that strikes a plant, very little will penetrate it, whether the radiation is direct or indirect. There will be reduction in temperature in a given area even if the plants are not high enough to provide shade. Vegetation reduces high temperatures by scattering light and radiation, absorption of solar radiation and by releasing water into the air through evapo-transpiration." (Robinette 1972, 95-96)

"The amount of temperature reduction depends upon the species of trees providing shade"(Robinette 1972, 96). "Due to the absorption and reflection of heat by the canopy, the understory is cooler" (Robinette 1972, 96). This reduction in temperature is not only felt in the shade of the tree but immediately adjacent to it.

"On an individual tree basis, the impact on human comfort of shade is due to blocking solar energy, not to lower air temperatures in the shade. A person feels cooler in the shade even though the air temperature is the same as it is a few feet away in the sun (Robinette, 1972 in Miller, 1988)."

'In the long run, vegetation will act as buffers to temperature fluctuations so common in urban landscapes. During the summer months, day temperatures in forested areas are commonly 10 degrees Fahrenheit cooler than open areas.' (Carpenter et. al. 1990). "Maximum mid-day temperature reductions due to trees range from 0.04° – 2° C per 1% canopy cover increase" (Wikipedia, 2007).

Because of the thermals produced in cities there is a low pressure in these urbanized areas attracting cooler air from rural areas. Because these areas are relatively well vegetated, the winds blowing from rural environments are cooler helping to lower the temperature in cities (Fig. 7). "Forest managers, in fact, have substantiated this through the use of infrared aerial photography, and use this information to discourage encroachment on these forests by urban sprawl." (Miller, 1988. 55).

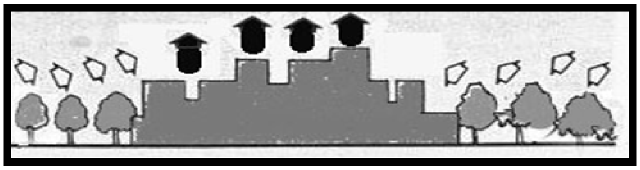


Figure 7: Rising thermals (black arrows) pull in cooler air (white arrows) from surrounding rural areas

The next mechanism to influence reduction is evapo-transpiration. Evapo-transpiration is a mechanism that is well understood but is not well applied. Transpiration as a natural process of vegetation essentially comprise the focus of the study.

"Transpiration can dissipate up to one quarter of the heat absorbed by plant leaves (Rashcke 1960, Lange and Lange 1963, Gates 1965, Thofelt 1975, Gates 1980, Levitt 1980, Kappen 1981, Larcher 1983 in Kolb and Robberecht 1996). "Because evaporating molecules absorb heat from the surroundings, evaporation functions as a cooling process"(Chesick, 1982. 327). Kramer and Kozlowski, 1960 (in Treelink 1996-2006) stated that 'On hot summer days, a tree can act as a natural "evaporative cooler" using up to 100 gallons of water a day lowering the ambient temperature.'

It is estimated that "on a single day in summer, an acre of turf will lose about 2,400 gallons of water to transpiration and evaporation" (Robinette, 1972. 89). Even a single mature tree with a crown diameter of 30ft. can evaporate up to 40 gallons of water in a day, which is comparable to taking away the heat produced by an electric heater. Consequently, within the time it takes a tree to grow to a significant size, strategically placed trees can reduce cooling costs…by an average of 10-20% (Estes et. al. 1999). It is suggested that roof environments be fitted with rooftop storage of stormwater. "Upon evaporation, large quantities of sensible heat are taken up and released with the water vapor, thereby cooling the roof surface and the air over it"(Marsh, 1998. 333).

Plant Characteristics that can aid reduction of high temperatures

Leaf size. "Generally, the larger the plant leaf surface area, the higher the transpiration rate" (Wolverton Environmental Services, 2006). This means that transpiration is directly proportional to leaf area (Floyd, 2001).

High Stomata Density. The next factor to look for is density of stomata for "the major anatomical features that affect water loss are the density of stomata on the leaf, as well as how wide the stomata are opened"(Transpiration Main n.d.). If there are more stomata on the leaf and given the right conditions, there is more water being transpired and this possibly translates into a higher cooling effect. It must be noted that the number and density of stoma on a leaf surface varies. This variation is a response to conditional changes of the environment namely due to carbon dioxide and light levels. CO_2 and light influence the number and opening sizes of stomata. More light and large gradients of carbon dioxide means more and wider stomata openings (Lake et. al. 2001). However, Hewitson (2007) tells us that the minimum light levels required for opening stomata in most plants is only about 1/1000 to 1/30 of full sunlight. 'Transpiration is the evaporation of water from plants. It occurs chiefly at the leaves while their stomata are open for carbon dioxide and oxygen during photosynthesis.' (Transpiration, 2001). We can infer that as long as stomata are open they will transpire and as explained by Hewitson (2007) it takes only a minimum level of light to open stomata. In addition, Devlin (1966) explains that 'the stomates of a plant exposed to light are opened, allowing transpiration to proceed.' Clearly, leaves inside the crown receiving minimal light are also transpiring water.

In urban environments there are high levels of carbon dioxide. For plant species to be used as temperature controls, the presence of high levels of carbon dioxide translates into a possible beneficial symbiosis. Another example of a beneficial symbiosis is the relationship between temperature and transpiration, for "transpiration rates go up as temperatures go up" (Perlman, 2007).

Humidity. Having more stomata doesn't always mean higher transpiration rates. HIGH HUMIDITY=LOW TRANSPIRATION; LOW HUMIDITY=HIGH TRANSPIRATION. Essentially there "has to be a strong difference in vapor pressure in the leaf and the surrounding air"(Transpiration Main, n.d.). Moving air carries away humidity. Favorable wind velocities can be used to continually flush away the envelope of heated, humid surface air. Wind essentially transfers water vapor from plants to the dry atmosphere. "Because of the aerodynamic roughness added by tall buildings, cities tend to have much lower wind speeds at the ground level, therefore heated air tends to be retained as opposed in rural landscapes (Marsh, 1998. 321). Wind might well be the second most important factor in determining evapo-transpiration rates. The wind…transports heat that builds up on adjacent surfaces such as…asphalt to vegetation which accelerates evaporation (Brown, n.d.).

Deep Roots. Trees with deep roots encourage high transpiration rates (Floyd, 2001). "The depth roots penetrate into a soil depends on the availability of water. If no water is in the subsoil, plants develop a shallow root system"(Floyd, 2001). We can speed up root penetration if we manipulate the growing medium (soil) making it softer and conducive for root growth.

In this light, a given practice can be used to create deeper root systems for chosen plant species: "frequent light watering encourages shallow roots while less frequent heavy watering ensures water penetrates deep into the subsoil and encourages growth of deep roots."(Floyd, 2001)

Rate of Growth. Water lost through evapo-transpiration is a function of the rate of plant growth. Transpiration is very low during the dormant season of the individual species. This means that plants to be established must possibly not undergo dormancy in a time when their temperature reduction qualities are needed. Transpiration is highest during the summer months when soil moisture, solar radiation, temperature and wind speeds are high. These parameters in turn become beneficial when coupled with the right plant species in terms of lowering high urban temperatures as explained in the previous paragraphs.

Evidence show that "transpiration rates are higher in arid climates…because of the greater water vapor deficit between the leaf and the dry air." (Duble, n.d.). In the tropics, wind is needed to carry away the excess moisture.

Temperature, Pollution and Plants

To note, plants control air-borne particles through their leaves, branches and stems as well as pubescence on the leaves. These elements of a plant can trap particles and hold them to be washed to the ground by rain. There are also specialized plants that can assimilate gaseous pollution removing it from the surrounding atmosphere, greatly aiding in the reduction of high urban temperatures.

Once temperatures are lowered, air quality is improved "because the emission of many pollutants and/or ozone-forming chemicals are temperature dependent."(Nowak, n.d.). There is a need to lower temperature with the aid of pollution controlling plants and once there is a reduction in temperature this provides an environment that will hinder the further production of more pollutants. This principle can be applied in parking areas where it is studied that high temperatures causes volatile chemicals to diffuse or leak so to speak from gas tanks and from other leaks, spills etc.; these volatile chemicals in turn become air-borne pollution that induces high temperatures.

The cooling potential of plants

As water evaporates it carries away heat. This cooling is achieved not just by transpiration of water from leaves but also evaporation from the soil. This simple principle has been used by ancient Egyptians to cool their residences. The idea was further refined in succeeding designs: by mechanical fans to provide air movement, cooling towers and swamp coolers in the 20th Century (The Basics of Evaporative Cooling , 2007).

One way to see cooling given by evaporating water is to use a psychrometric chart (Fig. 8) which shows graphically the relationship between air temperature and moisture content. What the chart shows is that as moisture is added, cooling results.

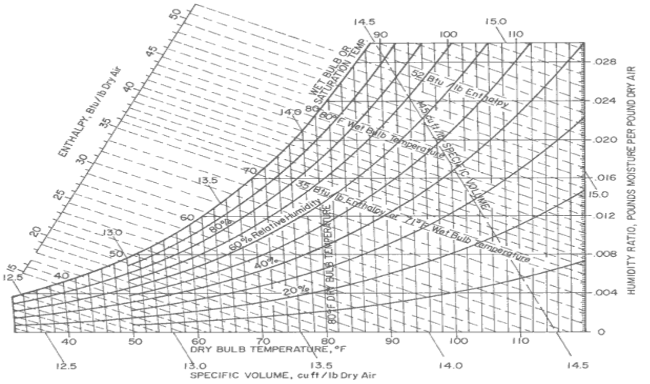


Figure 8 A Psychrometric Chart.
From: www.sp.uconn.edu/~mdarre/NE-127/NewFiles/psychrometric_inset.html

It has been discussed that each species transpires at different rates. It is possible to compute the amount that plants transpire to the air; once the amount is known, it is possible to see reduction in temperature. The procedure discussed in this paper is an attempt to answer the following questions:

- How much water does a tree leaf transpire?
- How much does this transpired amount from the leaf, help in reducing temperatures?
- How many leaves in a tree?
- How much does the evaporated amount from the leaf population of the tree reduce temperature?

The output of this procedure is a theoretical and rough estimate quantity of evaporated or vaporized water from transpiration and its cooling potential. At this point it must be pointed out that there is an existing procedure/formula to estimate evapo-transpiration. The work of Saxena (n.d.) portrayed a method of estimating evapotranspiration utilizing values such as net radiation, soil heat flux, vapor pressure, heat flux of air, surface resistance, aerodynamic resistance, latent heat and others. This method by Saxena (n.d.) looks at transpired amount from trees and relates this to a psychrometric chart to quantify the cooling or reduction in dry bulb temperature as provided by trees. The method is comprehensive by integrating factors that affect evapotranspiration that cause cooling.

Saxena (n.d.) utilized data difficult to achieve for this paper. Computing these values is a limitation primarily because of the lack of equipment that are needed to find the said values. The method of Saxena (n.d.) relates cooling to reduction of dry bulb temperature as seen in a psychrometric chart while the method as explained in this paper relates cooling to "tons of cooling"; a unit of cooling measurement used for air-conditioners.

To answer the question how much water a leaf transpires, it is possible to acquire an estimate possibly across all plant species. "The usual rates, under conditions favorable for stomatal transpiration, fall within a range of 0.5 to 2.5gms per dm² of leaf surface per hour"(Meyer, 1973. 81). Assuming the lowest value of:

$$\frac{0.5gms}{dm^2}\ \textit{of transpired water per hour on a single leaf}$$

Secondly, a simple way of finding the quantity of leaves in a given tree would be to first compute the volume of 1 leaf then equate this to a number of leaves (x) in a cubic meter (m^3).

To find the quantity of leaves in a cubic meter an equality of ratios can be used (Hartley, 1982) of the form:

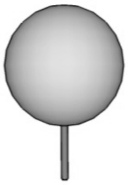
$$\frac{a}{b}=\frac{c}{d}$$

Where a = volume of one leaf of a species, b = 1leaf, c = volume ($1m^3$), d = target quantity of leaves inside $1m^3$:

$$\frac{volume\ of\ 1\ leaf\ in\ m^3}{1leaf}=\frac{1m^3}{d}$$

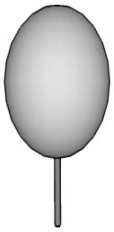
Because there is already an estimate quantity of leaves in a cubic meter all that is needed is to find the total volume of the tree crown to find the total estimate quantity of leaves. To facilitate this condense tree crowns into their basic geometric forms. "Form refers to the shape and structure of a plant or plant mass. It is used to indicate two-dimensional shapes as well as three dimensional shapes. General plant forms are rounded or globular, oval, conical or pyramidal, upright, weeping or drooping, spreading or horizontal and irregular" (Austin, 2002).

These plant forms can also be used to describe tree crowns. Each of these geometric solid forms has corresponding volume formulas. If in the case that there is a tree form that doesn't fit a geometric solid with a known formula for volume, the tree form can be split further into standard geometric solids thereby facilitating computation of its volume. This activity can yield a value that is still workable. The following are some examples of plant forms with corresponding volume formulae:

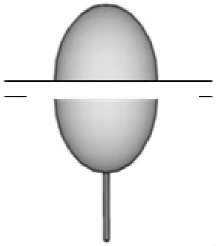


Rounded or Globular, Spherical: Volume of Sphere $V_{sphere} = 4/3\pi r^3$

Conical or Pyramidal: $V_{cone} = \frac{\pi d^2 h}{12}$ Where *d* is the base of the cone, h is the height (Benson, 2006)



Oval,



A combination of 2 Elliptical Cones: $V_{2\,elliptical\,cones} = \frac{\pi d^2 h}{6} + \frac{\pi d^2 h}{6}$

Where *d* is the diameter of the bases of the elliptical cone, h is the height (Benson, 2006)

Upright, Geometric solid= Frustum: $V_{frustum} = \frac{\pi h}{12}(d^2 + db + b^2)$

Where *d* is the diameter of the smaller circle and *b* is the diameter of the bigger circle, h is the height (Benson, 2006).

As an example, assuming a roughly globular form for a tree having a radius of *r*=2m, the rough volume of the tree crown therefore is:

$$V_{tree} = \frac{4}{3}\pi r^3$$

$= 4(3.1416)(8m^3)/3$

$= 100.5/3$

$= 33.5m^3$ rough volume of the tree crown

The total quantity of leaves in the total volume of the example is thus given by:

$$\frac{d}{m^3}(33.5m^3) = x \text{ Leaves}$$

Where *d* is the quantity of leaves per cu. meter or *d/m*^{3}

$33.5m^3$ rough volume of the tree crown given an assumed radius of 2mtrs.

x is the quantity of leaves in tree crown

The quantity of leaves derived from the volume of the tree crown is incorrect because this means that the entire computed volume is made up entirely of leaves. Of course tree forms are not just leaves, other elements need consideration; air spaces in between, branches and stems etc. The volume of all other elements within the tree crown except for the leaves should be subtracted from the volume of the total that would be computed as given by the procedure above. In as much that each species have distinct characteristics of form, habit of growth etc., it might be possible that the subtracted volume of elements other than leaves be termed as a constant value for a species. This method however yields only a rough estimate of the number of leaves. Once a value is attained, the overall transpired then evaporated amount of the tree crown from leaves can be estimated and this estimate value used to ascertain the cooling potential of the plant.

The expression to compute the estimate quantity of leaves in a tree crown may thus take the form:

$$Q_{et} = \{(Q_l)(V_{tc})\} - C_{os}$$

Where - Q_{et} is the estimate total quantity of leaves in a given tree sample

- Q_l is the quantity of leaves in a cubic meter (*d*)
- V_{tc} is the volume of the tree crown ($33.5m^3$)
- C_{os} is the constant value, (volume) of open space and other elements to subtract from $(Q_l)(V_{tc})$.

Given the apparent difficulty of computing leaf quantity at this point in time, this study will use existing known data. "A mature tree has an average 200,000 leaves" (Wisconsin's County Forests Unique to the Nation, 1999-2006).

As established, one leaf may transpire $\frac{0.5gms}{dm^2}$ of leaf area.

Taking an example leaf area (from a known species) of $0.38dm^2$ and with an assumed total of 200,000 leaves in the whole tree crown this translates into a leaf area of:

$(200{,}000 leaves)(0.38dm^2) = 76{,}000dm^2$

With this much leaf area, the whole tree crown will roughly transpire:

$$(76{,}000dm^2)\left(\frac{0.5gms}{dm^2}\right) = 38{,}000 gms\ of\ water\ per\ hour$$

What is the cooling potential of this amount (38,000gms) of transpired water? Rather, what is the cooling potential of this amount of evaporated water. Since there is an existing relationship between energy and cooling, we have a means to convert this evaporated amount to cooling potential by converting it into a unit of energy (Btu)

1 ton of cooling = 12,000Btu (Merritt and Ricketts, 2001: 13.16)
Where 1Btu (British Thermal unit) is equivalent to raising the temp. of a pound of water 1° F (Weast, 1976. F-95). Btu can be expressed as energy required to heat or can be expressed as the energy or heat extracted to create cooling (since cold temperatures is a result of the absence of heat).

1 ton of cooling is the amount of cooling provided by melting 1 ton of ice over a 24 hour period. Air conditioning systems are also measured in tons of cooling. A term to designate the cooling rate of air-conditioning equipment; also indicates the ability of an evaporator to remove 12,000Btu per hour (Merritt and Ricketts, 2002. 13.16).

Essentially, we are looking for the amount of energy/heat (or Latent heat of vaporization, L_v (DeMuth, 2007) that evaporates water from leaves. Approximately, this value is at:

$\frac{600 calories}{gm} = \lambda = approximate\ energy\ required\ to\ transpire\ water\ from\ leaves$ (Ritter, 2007)

The conversion factor to convert from calories to Btu is:

$252\ calories = 1\ Btu$ (Renner, 1982; Weast, 1976: F-306)

Thus conversion from evaporated water to energy units can be expressed as such:

$38{,}000 gms \left(\frac{600cal}{gm}\right) = 22{,}800{,}000$ calories

Since 252 calories = 1 Btu then:

$$22{,}800{,}000\ calories \left(\frac{1Btu}{252cal}\right) = 90{,}400\ Btu,$$

the amount of heat/energy extracted from the area thereby cooling it proportionately.

Since 1 ton of cooling = 12,000Btu then:

$$90{,}400 Btu \left(\frac{1 ton}{12{,}000 Btu}\right) = 7.5 tons\ of\ cooling$$

A tree species transpiring and subsequently evaporating 38,000gms of water would thus "pull in" or extract 90,400Btu of heat. In tons of cooling as a unit, that tree would have produced the equivalent of 7.5 tons of cooling.

Since typical room air conditioners produce a range of 1 to 5 tons of cooling (Barovic et.al., 2002) and supposing a mean of 2.5 tons, our example tree evaporating 38,000gms. for just 1 hour will have produced the energy of approx. 3 air-conditioners working to remove heat:

$7.5 tons\ of\ cooling \left(\frac{1 room AC}{2.5 tons}\right)$ = approx. 3 room ACs

As studied, 'One mature tree can provide the equivalent of five 10,000 BTU air conditioners running 20 hours a day'(Leo, 2006).

Essentially what is happening is the extraction of heat/energy from the surrounding area. In this case for each gram of water to be evaporated from leaves, approximately 600 calories (Ritter, 2007) are needed and this energy is pulled from the surrounding air. Once that much heat/energy (600 cal. or approx. 2Btu) is removed from the surroundings , proportional cooling results. In other words, seeing proportional cooling in "tons of cooling" given by each gram of vaporized water would be .00016 tons of cooling. Dooling (1998) explains that 'the energy required to evaporate water is taken from the air and from the sunlight intercepted by the leaves, thus cooling the air.' If 12,000 Btu of energy is extracted from the environment then following the definition, that translates to 1 ton of cooling. Given the amount of water transpired by the example tree above with the corresponding energy required to evaporate it, the result was 7.5 tons of cooling.

At this point, it must be as well explained that existing Ambient Temperature of the transpired water plays a part in the amount of energy that is required to evaporate or vaporize it from leaves, and not just 600cal/gm. It cannot be discounted that the water on the surface of leaves have a pre-existing temperature reading. Thus from existing ambient temperatures, different levels of energy will be required (DeMuth, 2007). Thus temperature regimes in the urban heat island profile will have distinct heat/energy requirements to evaporate water from leaves on plants within that temperature regime. According to DeMuth (2007) and Kehoe (personal communication, Jan 27, 2008), before transpired water can evaporate or change state from liquid to vapor, its temperature must be raised to 100°C first, then additional energy must be applied to change the state from liquid to vapor. The amount of energy needed to raise the temperature to 100°C is given by the following relationship (DeMuth, 2007):

$Q = mc\Delta T$ (DeMuth, 2007)

Where Q is the amount of energy or heat entering an object (in this case being absorbed by water) and depends on the following: mass of the object m, capacity of the object to hold heat (or its specific heat) c, and the temperature change ΔT. Mass m of the object is in grams, specific heat for water c is at $\frac{1\ cal}{g°C}$, the temperature change, ΔT is given by T_2-T_1 where T_2 is the final temperature intended (in this case 100°C) and T_1 is the existing ambient temperature to begin with (DeMuth, 2007).

As an example, if we analyze the relationship at the level of 1 gm of water being raised from ambient temperature of 30°C to 100°C, the amount of energy Q needed is:

$Q = mc\Delta T$

Where: m = 1gm.
$c = \frac{1\ cal}{g°C}$
$\Delta T = T_2 - T_1 = 100°C - 30°C = 70°C$

$$Q = (1gm)\left(\frac{1\ cal}{g°C}\right)(70°C)$$

Q = 70 cal. amount of heat/energy needed to raise temperature of 1gm of water from 30°C to 100°C

From 100°C, the amount of energy now required to evaporate or vaporize 1 gm of water is given by the following equation (DeMuth 2007):

$$Q = mL_v$$

Where: m = mass of 1gm.

L_v = Latent heat of vaporization of water = 539 cal/gm.

$$Q = (1gm)\left(\frac{539cal}{gm}\right)$$

Q = 539 cal. amount of energy needed to vaporize 1gm of water

In effect, the total energy required to <u>evaporate</u> water from leaves is: 70 cal./gm + 539 cal./gm. = **609 cal./gm.** This total amount is the requirement for an ambient temperature of 30°C. A sample temperature range for an urban heat island is roughly 30°C to 33°C (Pon, 2000). The required energy to evaporate 1gm of water at these ambient temperatures are:

30°C = 609 cal/gm.
31°C = 608 cal/gm.
32°C = 607 cal/gm.
33°C = 606 cal/gm.

Within this temperature range of an urban heat island, the <u>average</u> total energy needed to vaporize water and produce cooling is very close to 600cal per gram (average of the four is 607.5 cal./gm). Ritter's (2007) value as shown is thus an acceptable approximation <u>within this given temperature range for an urban heat island</u>. However, because urban temperatures may spike to higher readings it is important to refrain from using this average but instead compute for the proper energy requirement. Further,it can be seen that as ambient temperatures increase lesser energy is required and vice versa.

If a tree transpires 38,000gms for evaporation at 600 cal/gm, the energy needed or extracted from the environment is 22,800,000cal. This same relationship can be used to find the amount of water needed to be evaporated to control a given amount of heat:

$$x\left(\frac{600cal}{gm}\right) = \text{an existing heat or energy amount in an area for example.}$$

Given an example heat level in an area of 30,000,000cal. The amount of water needed to be evaporated *x*, is:

$$x\left(\frac{600\,cal}{gm}\right) = 30{,}000{,}000\,cal$$

$$x = \frac{30{,}000{,}000cal}{\frac{600cal}{gm}}$$

x = 50,000gms of water needed and evaporated to extract 30,000,000 cal of heat from the environment.

This can be another way to see how much vegetation we need to place in an area to control a given heat load. If we know how much a species transpires and subsequently evaporates, estimating how many vegetation species needed for a given heat level would be relatively straightforward.

Another possible way to arrive at a number of species needed for a given heat load is to use the following procedure: Since computing required cooling is possible, what can be employed here is a process where-in given heat loads are matched with required "tons of cooling". In cold storage facilities (enclosed environment), large volumes of heat are pumped to an outside environment.

A formula for calculating cooling required for given heat loads used in cold storage facilities is given in the following expression (Boyette et.al. 2002):

$$RC = \frac{\text{heat load to be removed in } \frac{Btu}{hr}\,(1 \text{ ton of cooling})}{12{,}000\frac{Btu}{hr}}$$

Where *RC* (refrigeration capacity) is the cooling required for given heat loads in *tons of cooling*

The total heat in the area to be cooled is termed as the *Heat Load.* It is further defined as the "The total amount of heat that the [vegetation] must remove from the [area]" (Design of Room Cooling Facilities: Structural & Energy Requirements, 2002). Heat generated in urban areas are caused by several factors of which their contribution to the total heat load can be computed in Btu. The method can tell us <u>how many plants needed</u> for a given area for the sole purpose of controlling excessive temperatures.

Once these factors that contribute to the total heat are added we attain a Heat Load (in Btu) for the said area. <u>Assuming</u> an area in a city producing a Heat Load of 150,000Btu, what is the required tons of cooling to handle this much heat/energy (150,000Btu). Since 1 ton of cooling is equal to 12,000Btu per hour, the cooling capacity that would handle the given heat load is given by this expression <u>adapted</u> from the existing formula for computing cooling required for cold storage (Boyette et.al, 2002).

$$C_{cap} = \frac{\left(\text{Measured Heat Load of Urban Area in} \frac{Btu}{hr}\right)(1 \text{ ton of cooling})}{\frac{12{,}000Btu}{hr}}$$

Where C_{cap} is the cooling capacity needed for a given heat load

$$C_{cap} = \frac{\left(150{,}000\frac{Btu}{hour}\right)(1 \text{ ton of cooling})}{\frac{12{,}000Btu}{hr}}$$

$$C_{cap} = 12.5 \text{ tons of cooling}$$

Thus 12.5 tons of cooling is the required amount per hour to handle the existing heat load of the said area. By this procedure, 12.5 tons of cooling can be given by roughly 2 tree species of given dimensions(as explained previously) or a number of shrubs or groundcovers with the same transpiration output to control heat.

Heat loads in cities will be much higher than what is portrayed in the example, once measured on site it may reach up to a higher range due to the high heat gain of materials and the sheer size of the area whose temperature must be lowered. What this suggests is a need for large planted areas to set temperatures at comfortable levels.

Combination planting and their total tons of cooling will be required to attain the needed cooling capacity. As well, with combination plantings of large quantities of high transpiring vegetation, it might be possible within right conditions, to increase transpired amount to further compensate for those factors that would otherwise hinder appreciable cooling.

At best, what can be achieved here with the application of the formula by Boyette et.al.(2002) is to try and maintain temperature at a given range. Vegetation can only minimize rising temperatures from pre-existing temperature conditions, however if vegetation is already present to begin with, pre-existing temperature conditions should be much lower.

In its simple principle, a heat gain of 30,000 Btu would need the same amount extracted to maintain a given temperature (Sleeth, n.d.). The equation of Boyette et. al.(2002) reinforces this idea because 12.5 tons of cooling as computed is equivalent to 150,000Btu being extracted; it shows that existing heat levels need the same amount extracted to produce cooling, but this is in an enclosed environment i.e. cold storage facilities where heat is isolated on the outside. Theoretically this should be possible but because the urban environment is not enclosed, whatever heat that was extracted would quickly be replaced. At this point the best possible solution is to increase the quantity of vegetation applied.

Application

Once the cooling potentials of given species are measured, this can be used to ascertain the siting of plants. Figure 9 shows a generic heat island temperature profile common in many cities and urban centers. Within the profile we can ascertain regimes of similar temperature readings.

From this point an infrared image plan of the area or city allows seeing areas of similar temperature. Each temperature regime should, in effect, have a distinct computed heat load (Fig. 10):

This image shows areas of distinct temperature readings with supposedly distinct heat loads. Darker areas are the higher temperatures, while succeedingly lower temperatures are denoted by lighter colors. From these images , it is possible to demarcate the areas that require a distinct cooling capacity (Fig. 11) and thus apply a grouping or combination of vegetation species with known cooling potentials.

Areas of similar color will have a distinct heat load value requiring a specific cooling capacity.

In effect, what is being established here is a sort of planting framework that dictates the placement of plant species in proper settings. Combinations of plantings with their total tons of cooling will be properly located in areas with measured heat loads. This framework will serve as a guide or 'zoning plan' for Landscape Architects in terms of plant materials.

There is also the possibility that plant species with their known cooling potential or tons of cooling are applicable throughout the urban heat profile. Another way to create tons of cooling for higher heat loads is to simply introduce more plants. In other words, higher heat loads means more cooling capacity required thus more vegetation to be applied, while lower heat loads means less cooling capacity and less vegetation. This can be portrayed in the urban profile where the built up areas (hotter areas) will have more vegetation as compared to other areas where there are only a few structures (Fig. 12).

Within the urban core itself there will still be variations in temperature as can be seen in various satellite infrared images of cities and these will thus have corresponding densities of vegetation.

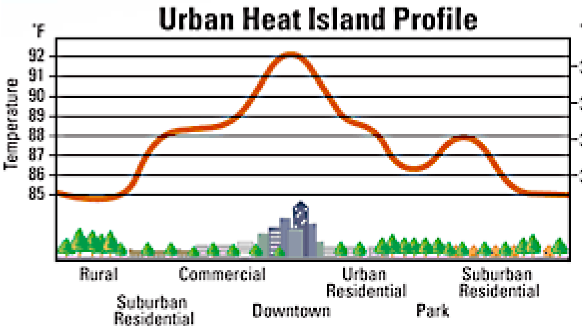


Figure 9: Urban Heat Island Profile.
From: http://www.epa.gov/heatisland/about/index.html

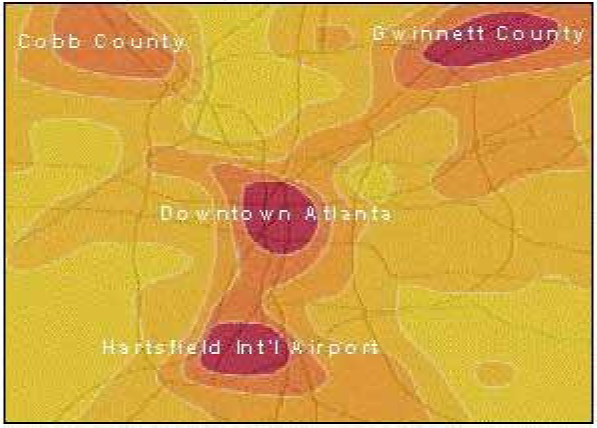


Figure 10: Satellite (Lands at TM) image of multi-nodal heat island in Atlanta, GA. Darker tones denote higher temperatures.
From: http://www.epa.gov/heatisland/about/measurement.html

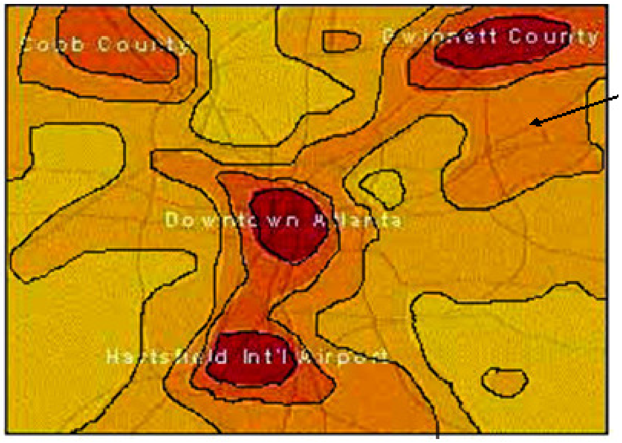


Figure 11: Demarcated areas of similar temperature readings. From: http://www.epa.gov/heatisland/about/measurement.html

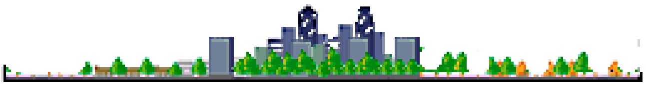


Figure 12 Urban profile with massing of vegetation at higher heat loads. Illustration adapted from From: http://www.epa.gov/heatisland/about/index.html

Conclusion

Simple analysis of vegetation show that they possess qualities that can be quantified and aid in the reduction of high temperatures. These qualities can be set as criteria that can be followed when choosing plant species. The characteristics presented in this paper are limited to a handful, and when enough botanical data are gathered, the selection criteria can be increased narrowing down the selection for plant species that are more equipped to handle excessive heat loads. As far as this paper is concerned what has been looked at in terms of transpiration are:

1. **Leaf sizes**
2. **Stomatal density**
3. **Amount of moisture transpired**
4. **Deep root systems**

Within the study it is possible to determine cooling potential or the extent of temperature reduction of a measured species. Although there is no concrete temperature reading it is assured that the measured tons of cooling given by plants will create some sort of appreciable cooling. Fathy (1986) explains that 2 tons of cooling is a requirement for human comfort. Though this value is a microclimate condition needed in indoor conditions, the principle allows it to be used as a benchmark. Because it is possible to acquire data on heat levels in urban areas, computed cooling potentials of plants can be related. This process opens up two possibilities that (1) certain species of plants will now be required in certain areas while (2) on the other hand these species that we have chosen can <u>also</u> be applicable throughout the urban profile.

For water to be evaporated or vaporized from leaves, a certain amount of energy/heat is needed. Once this amount is extracted from the surrounding environment, theoretically there is proportional "cooling". This shows that transpiring vegetation maintains temperature. With more vegetation and more shading plant species, heat will be hindered from building up in urban environments. This shows that for cooling to function during the hottest times of the day, vegetation will need to be continuously transpiring.

The next step in a study like this would be to ascertain those species that exhibit characteristics or qualities worthy of usage in temperature reduction. The presented figures or values in this paper are based on estimates and hypothetical dimensions. A recommendation therefore is for botanists and horticulturists to undertake studies to ascertain botanical characteristics and values. Others include undertaking further studies of physical data on urban temperatures and conditions in cities such as used by Saxena (n.d.). The values attained from these studies would fill in the gaps in equations creating a much closer representation of cooling potential.

Further recommendations include developing computer models of botanical species (at the very least of tree forms) and transpiration rates. These programs would greatly aid studies such as the one being put forth by this paper. Simulations can be conducted; these computer models can be easily subjected to a lot more factors and environmental conditions than what would be possible in real-life measurements and tests.

The study impacts how Landscape Architects will choose plant materials for implementation in urban areas. This in time creates a Planting Design Framework that dictates the choice of vegetation within specific urban environments.

Primarily at this point our concern with urban planning is the way structures are located. Structures, buildings and the like should be located with certain restrictions to allow maximum ventilation of prevailing winds to carry away heat and transpired moisture as well as to avoid the canyon effect. Wind tunnel tests would show what models are appropriate for maximum ventilation in between buildings. "There is a heightened awareness that scientific knowledge of the urban heat island must be more effectively communicated to architects, engineers, and planners and translated into intelligent urban design" (Yow 2007).

In terms of overall planning, studies like these may integrate with existing planning frameworks and zoning ordinances requiring the strict implementation of specific plant types and shading such as in parking lots and heavy vehicular emission areas.

Landscape Contractors will end up growing specialized plant species in their nurseries. Nursery equipment and techniques may have to be developed to maintain plants for urban heat reduction. Further studies in soil types should be conducted to test for its effectiveness in allowing soil water to be quickly absorbed by the plant to be transpired.

One point of consideration for computing leaf quantity in tree crowns is the fact that plants also go through seasons of wilting the entire foliage at one time or wilting continuously, individual leaves. Therefore the entire foliage as counted from a measured tree crown will have at any given time fewer "functioning" leaves. This means that realistic measurements of transpired amounts from measured tree crowns will be as well far fewer than values as computed in this paper.

What this implies at the very least is that individual plants within a species will have to be individually measured for their transpiration. However, once a significant number of plants within a species have been measured, statistical analyses will allow us a safe but significant value representative of the species. Further, we can see that aside from increasing planting quantities to compensate for additional heat inputs, plant quantities also have to be increased to compensate for wilting, abscission, dead and / or dying leaves. Plants would thus need specialized care to ensure an optimum number of healthy/transpiring leaves.

As well these plants will provide no heat control whatsoever because of the horticultural practice of trimming/pruning leaves from vegetation upon installation at the site. Depending on the species, there will be a significant length of time before foliage density is reestablished.

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