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Air Conditioning and Noise Control Using Vegetation

SYNOPSIS

The constructive uses of vegetation in building engineering services are acoustic quieting, air molecular and particulate filtration, water filtration and chemical polishing, shading from solar gain, cooling and humidification. A water conservation regime should form part of the integrated solution.

1 BACK GROUND

The environment inside buildings is the result of interaction between the outdoor climate, the building fabric, its contents and the air conditioning with its heat sources and sinks. Designing the built environment and air conditioning to work in harmony as environmental modifiers to meet the needs of those accommodated, in an energy efficient manner is important for home and workplace comfort and health. There is an increasing dissatisfaction with present air conditioning solutions, for largely non-specific reasons sometimes labelled sick building syndrome. This dissatisfaction is further compounded by fears regarding the wider environmental impact caused by air conditioning, for example through the release of greenhouse gases or high energy consumption. New approaches to air conditioning are sought as a result.

Plants that were hitherto valued solely for their appearance can play an important role in influencing indoor air temperature, humidity, and quality and acoustics, however the benefit derived from an individual plant is small. Many plants are needed match the performance of mechanical services systems in buildings.

A minimalist strategy where elements of a building perform more than one function lies well with the current commercial themes of cost efficiency, and environmental protection. The integration of air-conditioning using vegetation satisfies these objectives. *Air-conditioning and Noise Control using Vegetation* will make a significant contribution towards the development of building techniques that meet current demands for environmental sustainability.

2 INTRODUCTION

Considerable information is available on what plants can filter out of air and water. Work on air filtration by plants on a molecular level has been done mainly in America.

Water filtration has been covered extensively both in Europe and in America. These systems are generically called constructed wetlands or reed beds. A British guide for the design and installation of reed beds has been published. [Ref. 52]. *The information on air and water filtration by plants has yet to be collated into a manner that could show how vegetation could be used as part of a building services installation. This is one of the aims of the research currently being undertaken by the Author.* To a lesser extent information is available on plant acoustics.

As far back as 1905 Sabine noted that further work was required on the acoustic properties of plants. *An absorption co-efficient for a number of plants commonly used in buildings have been established by the Author.*

Existing data on transpiration and photosynthetic rates of vegetation are being collected by the Author. With these data it should be possible to examine evaporative cooling and humidification by plants. *A mathematical model will be developed by the Author to determine the level to which plants may influence the temperature and relative humidity of the built environment.*

3 ACOUSTICS

Sound passing through a canopy of foliage interacts with both the leaves and branches. Individually a leaf obstructs the transmission of the incident sound wave by responding with mechanical vibrational excitation that follows the sound vibrations especially for frequencies around the natural resonant frequencies of the leaf. The sound wave is thus partially reflected back and partially dissipated as heat. Leaves can also alter the noise waves by interference and diffraction, which are processes that scatter the sound but do not result in any net loss of energy.

Assessments made in America [Ref. 25] indicate that large numbers of people are exposed to excessive highway noise. The cost of planting as a barrier is about 11% of concrete barriers. 3 dB(A) per 30.4m has been given as the sound reduction for a 4.6m tall area of planting. To be effective a barrier should have optical penetration limited to 60 cm. A planting width of 6m should provide a suitable barrier for a typical road noise spectrum. Most work relating to the sound attenuating capability of vegetation suggests that insertion loss is approximately linear for narrow, dense vegetation belts, less than 15m.

Narrow vegetation barriers planted in such a way as to encourage maximum density growth could provide a sound reduction of about 0.3 dB(A) per 0.3m of shrub depth. Wide tree zones have been found to provide less attenuation, insertion losses in the range 0.06 to 0.12 dB(A) per 0.3m of depth. [Ref. 26]

Field experiments [Ref. 27] indicate that a wide tree zone would provide about a 0.04 dB(A) sound reduction per 0.3m. It has also been indicated that vegetation is more effective at blocking the higher frequencies generated by a traffic stream.

The role of tall street trees in Singapore has been investigated [Ref. 28], using a computer model of attenuation by tree foliage. The results show that attenuation occurs at the height of the foliage and in the higher frequency end of the spectrum.

It has been observed [Ref. 29] that trees planted at the top of a barrier may deminish its sound reduction by acoustic scattering.

A detailed report [Ref. 30] suggests that the noise reducing ability of plants is overrated and goes on to detail various plant types and their acoustic properties. The four groups operate best in the range. No details of size or arrangement of the screens were provided with the data. Attenuation offered by plants has been summarised in table 1.

Table 1 Attenuation by Trees & Shrubs. [REF30]

Plant Group 1	Common Name	Notes	Attenuation
Juniperus chinensis *Pfitzeriana* *Lonicera maackii*	juniper shrub	narrow divided leaves	4dB to 6dB
(Betula pendula) Crataegus x prunifolia	birch tree	small leaves, hairy underneath	
Alnus incana, *Lonicera ledebourii*	alder, honey suckle		
Cornus sanguinea, *Acer negundo*	dogwood, sycamore, introduced		
Pterocarya fraxinifolia, *Corylus avellana*	hazel		
Forsythia x intermedia *Tilia cordata*	hybrid lime tree	deciduous	
Sambucus nigra	elder tree		
Plant Group 2			**Attenuation**
Philadelphus pubescens, *Ilex aquifolium*	holly		6dB to 8dB
Carpinus betulus, *Ribes divaricatum*	hornbeam, current bush	wriggly leaves	
Syringa vulgaris, *Quercus robur*	oak		
Fagus sylvatica, *Rhododendron spp*	beech tree, rhodidodies		
Plant Group 3			**Attenuation**
Populus x berolinensis, *Viburnum rhytidophyllum*	hybrid black poplar		8dB to 10dB
Viburnum lantana, *Tilia platyphyllos*	snowberry, broad leafed lime		
Plant Group 4			**Attenuation**
Acer pseudoplatanus	sycamore		10dB to 12dB

In Germany, the development of living noise isolation walls [Ref. 31] has led from pre-cast crib walls with plantings to systems using a concrete or metal central framework, filled with compost and planted.

A number of plants commonly used in indoor planting have been examined to establish an absorption co-efficient for each type of plant by the Author. Two field trials have been done to validate the absorption co-efficients derived from the laboratory experiments. These have shown that care must be taken in application of these values. They may not readily be used for other plants. The absorption co-efficients have been presented in table 2.

Table 2 Absorption Co-efficients for Plants

Item & Notes Hz	125	250	500	1k	2k	4k
Spathyphylum 600 mm	0.01	0.06	0.04	0.03	0.1	0.16
Kentia Palm 1200 mm	-	0.01	-	0.06	0.09	0.19
Dracaena Marginata 1200 mm	-	0.06	-	0.05	0.07	0.19
Dracaena Fragrance 1200 mm (Yucca), (Dracaena Wareneki), (Janet Craig)	-	0.06	0.02	0.08	0.13	0.21
Ficus 1000 mm	0.01	0.1	0.07	0.11	0.13	0.2
One of each of the above	0.05	0.19	0.23	0.35	0.46	0.53
Philadendron 1200 mm	0.1	0.15	0.43	0.42	0.39	0.65
Bark mulch 50 mm thick per m^2	0.01	0.16	0.26	0.46	0.73	0.88
Marion Bluegrass 50 mm high **	0.11	0.26	0.6	0.69	0.92	0.99
Snow freshly fallen 100 mm deep**	0.45	0.75	0.9	0.95	0.95	0.95
Gravel soil, loose,moist 100 mm thick**	0.25	0.6	0.65	0.7	0.75	0.8
Balsam Firs 2.44 m, 1.8 m^2 graded area per tree**	0.03	0.06	0.11	0.17	0.27	0.31

**Published by others, unspecified reference.

Vegetation and acoustics inside buildings is more to do with quieting than with shielding isolation or filtration. No amount of quieting treatment can reduce the level of noise received directly from a source. Full coverage of a wall or ceiling is unlikely to be practicalfor example because leaf orientation may alter with direction of sunlight, so the planting should be arranged as several small patches in preference to concentrated in one location. The same area of material will be more effective when applied to non-opposite walls and ceiling than to than when concentrated on one of these areas, and more effective when located near the edges and corners of a given area than when located in the centre. [Ref. 53]

4 WATER CONSERVATION BY FILTRATION & RECYCLING

Water treatment by planted beds is a well-established technology for sewage treatment and to a lesser extent grey water polishing. The main body of research was done some twenty or more years ago in Germany. [Ref. 50,51] The processes used may be divided broadly into two systems, vertical flow and horizontal flow beds. The principles are much the same as other plant filtering processes where the microbes and bacteria at the plant roots break down the chemicals into nutrients that the plants use for growth. This offers a natural method of water filtration and polishing. One of the main attractions, in addition to the low environmental impact of this type of process is the minimal amount of energy used in achieving the result. Another attraction of water treatment using vegetation is conservation of water, in this case not only by reducing consumption but by filtering through the planted beds for reuse. *This form of water conservation is fundamental to air conditioning using vegetation since sufficient water is required to prevent water stress in the plants.*

The Author has been closely involved with the installation of a number of small scale reed beds. The purposes range from filtration of a lake to remove phosphates and nitrates, minimising algal bloom, to polishing grey water in a domestic environment for reuse in the down water service, reducing the use of mains water and for polishing rain water for use as down water and drinking water.

Effluent quality from tertiary (grey water) treatment reed beds is comparable in terms of BOD (biological oxygen demand), TSS (total suspended solids), COD (chemical oxygen demand) and organic nitrogen with that from the best conventional treatment plants. [Ref. 50, 51] The best levels of tertiary treatment meets the EC directives for bathing water.

The use of reeds for the treatment of sewage was first developed by Seidel and Kickuth some thirty years ago. Since then, more than 500 reed beds have been constructed in Western Europe, more than 100 of which have been installed in the UK. In Europe it is more common to use horizontal flow constructed wetlands for water treatment. In America the use of naturally occurring wetlands is the norm. These types of biological filters are used principally for secondary sewage treatment and grey water polishing. Stripping of noxious chemicals and heavy metals can also be done with constructed wetlands. The plants frequently used are reeds *(Phragmites sp)*, but may include a range wetlands plants.

The principles behind the horizontal flow beds are:

1. Rhizomes (roots network) of the reeds grow vertically and horizontally, opening up the bed to provide a "hydraulic pathway".
2. Within the Rhizosphere (the small area surrounding the rhizomes), large populations of common aerobic and anaerobic bacteria grow, which effect the biological breakdown of the organic components of the grey water.
3. Oxygen is passed to the rhizosphere via the leaves and stems of the reeds through the hollow rhizomes and out through the roots to provide some of the oxygen required by the aerobic bacteria.
4. Suspended solids are aerobically composted in the above ground layer of straw debris formed from dead leaves and stems.
5. Uptake of nutrients, principally nitrogen and phosphorous, to the plant via its rhizomes.

The principle species used is *Phragmites australis* (common reeds), because of the distribution both horizontally and vertically of the plant's rhizosphere. Other wetland species such as *Typaa angustifolia* (narrow leafed reedmace), *Carex sp.* (Sedges) and *Juncus sp.* (rushes)are often included.

A constructed wetlands system should use species in conditions that suit them, according to depth and lighting levels.

A mixed wetland system has the following advantages:

1) Different species remove different substances from the water, as can be seen from table 3:
2) A hardier bed is developed since perturbations will adversely affect one species more than others.
3) Is more aesthetically pleasing
4) There will be some plant cover throughout the growing season.
5) Attracts and provides a habitat for native fauna.
6) Different species have different preferences for light level. water table depth and bed media

Table 3 Water Treatment by Vegetation

Species	Substances removed/added	Preferred habitat
Phragmites australis (Common reed)	SS, BOD, phosphates	emergent plants
Iris pseudacorus (Iris)	Oxidised N, nitrates	emergent plants
Schoenoplectus tabernaemontani (Club rush)	Oxidised N, BOD SS,	emergent plants
Typae augustifolia (Reed-mace)	Ammonia, organo-phosphates, heavy metals	emergent plants
Acorus sp & *Sparganium sp.* (Bur-reed)	Ammonia, organo-phosphates	emergent plants
Carex sp (Sedge)	Nitrates, phosphates, BOD	emergent plants
Juncus sp (Rush)	Nitrates, phosphates, BOD	emergent plants
Nuphar lutea (Common water lily)	heavy metals	floating aquatic
Elodea canadensis (Canadian pondweed)	Adds oxygen	submerged aquatic
Lemna (duckweed)	Adds oxygen	floating aquatic
Eichhornia		

UK designs[Ref. 50,51] are based on 5m^2/pe(population equivalent), although the 1985 Mannersdorf report indicated practical experience had shown that the area may be reduced to 3-4m^2/pe. in particular situations. Depth is normally set at around 0.6m, since beyond this depth roots start to weaken. Most UK beds have been built using gravel. The type of gravel is important, for example silica gravel will remove less phosphates than limestone gravel.

Recommended planting density is 2-4 plants/m^2. For *Phragmites sp.*, clumps from existing reed beds are preferred although planting from seed is possible as is elstablishment from seedlings.

Weed control is normally only a problem during the first growing season, but weeds can normally be pulled out by hand, when a gravel medium is used.

5 AIR FILTRATION

Plants have been filtering air and water as part of a sustainable environment long before man began to affect the environment. Vegetation can filter chemicals from air and from water. The chemicals removed and the rate of removal varies from between plant types. The bacteria that live around the plant roots assist in breaking the chemicals down into those elements that the plants can use as nutrients to create plant material. There is an interrelationship between the plants and the bacteria they need. Neither can survive without the other.

NASA and Dr. Bill Wolverton have done considerable research into the ability of plants to chemically scrub the air. While plants may be able to achieve results in laboratory trials, difficulties have been experienced when field trials have been carried out. Rentokil have validated the laboratory trials but have not succeeded in validating field trials. Dr Wolverton is now involved in the use of vegetation to reprocess animal waste into vegetable matter through its metabolic pathways. For example the collection of chicken excrement that can be diluted and used as fertiliser to grow duckweed *(Lemna sp)* that may then be harvested and fed back to the chickens. At a conference held by the indoor planting industry where Dr Wolverton was the keynote speaker the Author had the opportunity to discuss with him some of his work, including a college building in Germany where grey water is recycled for use in toilet cisterns. It was Dr. Wolverton's opinion that the future in the integration of building services and vegetation in the UK would revolve around indoor planting. The Author concurs with this view. A wealth of information on what plants can filter out of the air and some information on acoustics exists. [Ref. 4, 5]

Schemes have been developed that use plants bedded in activated carbon to purify air. The carbon removes toxins from the air and the plant removes the toxins from the activated carbon. The plant absorbs the toxins and converts them to vegetable matter using its chemical processes. [Ref. 2]

5.1 Air Molecular Filtration

A report [Ref. 18] by Anthony Muldoon of Enterprise Plants ties in research by Dr. Wolverton done at NASA with sick building syndrome. It seeks to show that plants make at least an apparent if not an actual contribution to mitigating the effects of sick building syndrome. Mention is made of the possible cooling effect of plants, together with other aspects like filtration at a molecular level and acoustic properties. This article is of particular interest because it brings together the horticultural and building services industries.

With the assistance of Mr. Muldoon, contact has been made with Rentokil who have carried out research based on the Wolverton studies, with the BRE. While Mr Michael Lothian of Rentokil was unable to disclose the details of their research for commercial reasons, he was able to confirm that the work they had done on replicating Wolverton's test rigs did support his findings. However when full scale tests were carried out the results were found to be inconclusive when the control was evaluated. Difficulties were reported in monitoring the low levels of contaminants reported to reduce air quality. The relationship between experimental results and recommendations of one plant every 100 square feet was not obvious. [Ref. 19]

The tests carried out by Wolverton were over short periods of one day or so. The concentrations of chemicals used were considerably higher than would normally be encountered in an office environment. In addition the planting density used in the test chambers considerably exceeded the density of planting normally used in an office environment. In photographs of the test rigs, the plant matter occupies most of the test chamber volume. Planting to this level would not be accepted in a conventional office environment.

Tests carried out by Rentokil also supported findings in America that plants can increase relative humidity of an un air-conditioned environment by 5% although the planting density to achieve this was higher than would normally be provided for a commercial office environment. At present they are also examining the psychological effects of office plants. [Ref. 19]

Essence of yucca is reported to be able to largely eliminate the smell of urine from piggeries and battery hen houses despite the differing chemical composition of urines. Yucca binds ammonia in such a way as to make the naturally volatile and toxic chemicals non-volatile and non-toxic. The plants then exploit the nitrogen in ammonia to manufacture the proteins for rapid growth. It is reported that at present the identity of the ammonia binding molecules remain mysterious. The reason behind the ammonia affinity of the yucca is that in it's normal environment in the south-western deserts of America where both nitrogen and water are in short supply, use is made of waste products of animals. Denis Headon at the National University of Ireland, Galway, who has researched the yucca is now studying the Quillaia plant that dominates the Chilean deserts. It too binds ammonia. [Ref. 20]

In modern air-conditioned buildings more air is recycled within the building than exchanged with outside, a factor that may give rise to sick building syndrome. Plants may have additional effects to removing chemicals from the air. Transpiring water increases humidity & hence decreases static. Photosynthesis decreases carbon dioxide and increases oxygen levels. Plant screens dull office noise. Stress may be reduced through viewing natural scenes. Plants absorb gases given off in office environments these including:

1) **Formaldehyde**-from insulation materials, ceiling tiles, particle board, carpet glue, cigarette smoke.
2) **Benzene**-a carcinogen found in cleaning solutions & tobacco smoke.
3) **Trichloroethylene**-found in spray adhesives and thought to cause liver cancer.

Research has been done on Azaleas, Scindapsis & Dieffenbachia.

Rhapsis palms, Marantas that need regular misting or plants with high moisture content could benefit offices with low humidity.

Research cited (Wilson & Hedge) is vague about sick building syndrome symptoms. It could be from tiredness. [Ref. 21]

After almost twenty years of tests, NASA revealed that house plants could combat indoor air pollution. NASA's interest in this area stemmed from a search to deal with indoor air pollution of sealed environments like space capsules. According to Wolverton plants absorb the chemicals through pores on the underside of the leaves. Bacteria associated with the roots help break down contaminants, which are then taken up by the roots as nutrients.

Since no one plant can tackle all pollutants, a mixture to deal with different chemicals is suggested. [Ref. 22] One or two plants every 9.3 m^2 (100 ft^2) is recommended. A need to ventilate areas with severe problems is recognised. Use of a planter that includes a charcoal bed with air drawn through it to improve filtration and its possible use to trap radioactivity from Radon gas in the plant roots instead of peoples' lungs is mentioned. 24 l/s (50 cfm) is drawn through the filter medium. The article observes "If man is to move into closed environments ... or in space, he must take along natures life-support system." [Ref. 22]

Wolverton's earlier work has been extended to include the ability of orchids and bromeliads to reduce concentrations of chemicals in the air. Although plant root micro organisms are the major pathway for removing volatile organic chemicals, leaves are also involved in the process of cleaning the air.

Plants such as succulents that are native to hot, dry climates, orchids and bromeliads that are native to hot, humid conditions behave opposite to most plants during the day-night cycle. This allows these plants to conserve water while collecting carbon dioxide. These plants were reported to successfully remove bioeffluents from a sealed environment. By combining these and conventional plants, carbon dioxide and oxygen levels could be more closely controlled in tightly sealed buildings while enhancing air pollution removal rates. [Ref. 23]

Removal of Formaldehyde from sealed experimental chambers by Azalea, Poinsettia and Dieffenbachia has been examined over periods of up to 24 hours. Comparisons against control chambers indicated that the levels of formaldehyde had been reduced over that time. Trials carried out in darkened chambers showed a 30% drop in the rate at which formaldehyde was removed from the test chambers. The reduced rate was attributed to the reduced photosynthetic process and the continued scrubbing action of bacteria laden soil in the plant pot. The bacteria associated with healthy plants was isolated as contributing to formaldehyde removal by comparison with unplanted soil laden pots. It was concluded that plant leaves, roots, soil and micro-organisms working together in a symbiotic manner create a complex ecosystem that can function in high or low light and dark conditions inside buildings, the major requirement for lighting being to maintain healthy plants. [Ref. 46]

A conclusion has been drawn between the off gassing of modern office and household materials and sick building syndrome. The NASA lead research concludes that the potted plant ecosystem removes smoke, volatile organic chemicals, pathogenic micro-organisms and possibly radon from the air in a tightly sealed chamber. By drawing air across the planted filter bed the contaminants are trapped in the plant bed matrix. The roots and their associated micro-organisms then destroy the pathogenic viruses, bacteria and organic chemicals and eventually convert these pollutants to new plant tissue. The trials indicated that the concentration of contaminants was reduced considerably to levels difficult to measure after two hours. [Ref. 47]

5.2 Gross filtration of Air

The use of trees as a means of filtering airborne industrial contaminants has been studied on a town size scale in India. [Ref. 12] It was concluded that leaf shape and surface area have a bearing the filtration effectiveness of trees. Their survival in hostile environments was also assessed.

Trees will function as either short or long term sinks for pollutants. Temporary retention can occur on the leaves, the particulate pollutant being retained as either a surface coating or become impacted on the leaf surface. The residence time of particles on the leaf will be governed by the leaf morphology and local meteorological conditions. Leaves with hairy surfaces will be more efficient in retaining atmospheric heavy metals. The leaf and stem surfaces of trees function as temporary sinks for pollutants; for instance deciduous trees will drop leaves in the autumn so enriching the soil area with pollutant. The foliage of a young Norway Maple (Acer platanoides) with a crown diameter of 30 cm may capture 1500 mg over a single season. This figure is indicative only because lead capture will be a function of local pollutant levels and leaf morphology. Trees can also act as long term sinks for pollutants, heavy metals can be retained in the longer lived tissues of the tree, in particular the wood and bark. [Ref. 32] Sampling of vegetation for trace heavy metals has revealed a direct correlation between the roughness of tree bark and the amount of deposit. [Ref. 39]

The planting of 17,000 chlorine resistant trees and shrubs around the Kwangchow Chemical works in South China has resulted in a detectable reduction in airborne chloric dust. The Kwangtung Provincial Botanical Research Institute has screened plants for their effectiveness in collecting or absorbing pollutants. [Ref. 33]

The ability of trees to reduce the overland movement of particulate pollutants in rural and urban locations has been examined over a five month period. Overall dust fall reduction by deciduous trees was of the order of 30%, by conifers of the order of 40%. Interception of total suspended particles was generally about 12% for both rural and urban sites. [Ref. 36] An examination of the relationship between leaf morphology and dust capture indicates a correlation between leaf size and dust captured. Calotropis procera with leaves of average 70 cm^2 collected the maximum amount of dust (8.81 mg/cm^2), on the other hand Acacia melanoxylon collected only 0.53 mg/cm^2. A variety of morphological features, alone or in combination, influence the capture of dust particles: orientation of the leaf on the main axis, leaf size and shape, the presence or absence of trichomes and epi-cuticular wax. [Ref. 37]

Trees have been shown to reduce the transport capacity of the air so that particulate matter is deposited. In parks 85% of particles can be filtered out, and up to 70% by trees in avenues at optimal arrangement. When leafless, trees can retain 60% of their efficiency. [Ref. 40]

Hawthorn, with a rounded scrub canopy, has a smaller vertical resistance to penetration than a tree such as poplar or lime, more particles penetrate vertically down through the canopy. Accumulation of particulates increases with leaf age and surface area, and the central areas of a tree's canopy tend to accumulate the higher concentrations of pollutants. Outer leaves are subjected to a high particulate exposure as they offer the first resistance to the prevailing wind, however the amount intercepted is limited due to factors such as wind disturbance. A tree has increased vertical resistance to particulate penetration, thus a peak with respect to particulate accumulation is produced. Evidence suggests that there is a compromise between age and surface area, and particulate penetration. [Ref. 41]

Leaf characteristics play an important role in particulate accumulation. *Ranunculus repens* (buttercup) which has relatively large leaf surface areas with horizontal presentation and a rough hairy cuticle accumulates more particulates than *Trifolium sp*. with a smaller area and smoother surface. Both plants carry more particulates than the grass which although having a rough cuticle has a vertical presentation. This suggests that herbaceous vegetation makes a more effective filter than grass.

6 COOLING. DECIDUOUS SHADING AND HUMIDIFICATION

Photolysis is the process by which plants absorb light energy. Electrons are moved through molecules, leaving positive holes that are subsequently filled by other electrons. [Ref. 4] A thermoelectric device (PN junction) operates in a similar manner. [Ref. 9] The photolysis process of energy conversion and storage revolves around the splitting of water molecules to separate the hydrogen and the oxygen, the aim being to store the hydrogen fuel for use later. [Ref. 15,16] The movement of electrons, in an appropriate combination of materials may result in a heat pumping effect.

Concentrations of people and their associated environs cause a heat island effect that raises the temperature of a built up area. Vegetation has been shown to mitigate heat island effects to some extent. The cooling effect of vegetation on individual facilities has also been examined in some detail. [Ref. 10,11,13]

Trees affect energy use in buildings through direct processes such as:

1.reducing solar heat gain through windows, walls and roofs through shading

2.reducing the radiant heat gain from surroundings by shading.

3.acting as windbreaks, which may reduce building cooling or heating demand depending on outdoor conditions.

The indirect effects of trees:

1.reducing the outside air infiltration rate by increasing the surface roughness and lowering ambient wind speeds.

2.reducing the heat gain into buildings by lowering summer ambient temperatures through evapo-transpiration and shading provision.

3.increasing latent air conditioning load by adding moisture to the air by evapo-transpiration; a significant increase in urban trees can produce an oasis effect.

A free standing 100 year old beech tree *Fagus sylvatica* of dimensions:

Height 25 m
Crown diameter 14 m
Volume of crown 2700 m^3
Ground area 160 m^2
Leaf area 1600 m^2

according to Bernatzky performs the following services:

Water consumption 0.960 kg/hour
Carbon dioxide consumption 2.352 kg/hour
Oxygen production 1.712 kg/hour
Sugar production 1.600 kg/hour
Total water transpired 10.0 m^3 /year
Energy consumption 6 000 000 kcal/year
The tree produces enough oxygen for 10 people/year.
[Ref. 40,42,44,45]

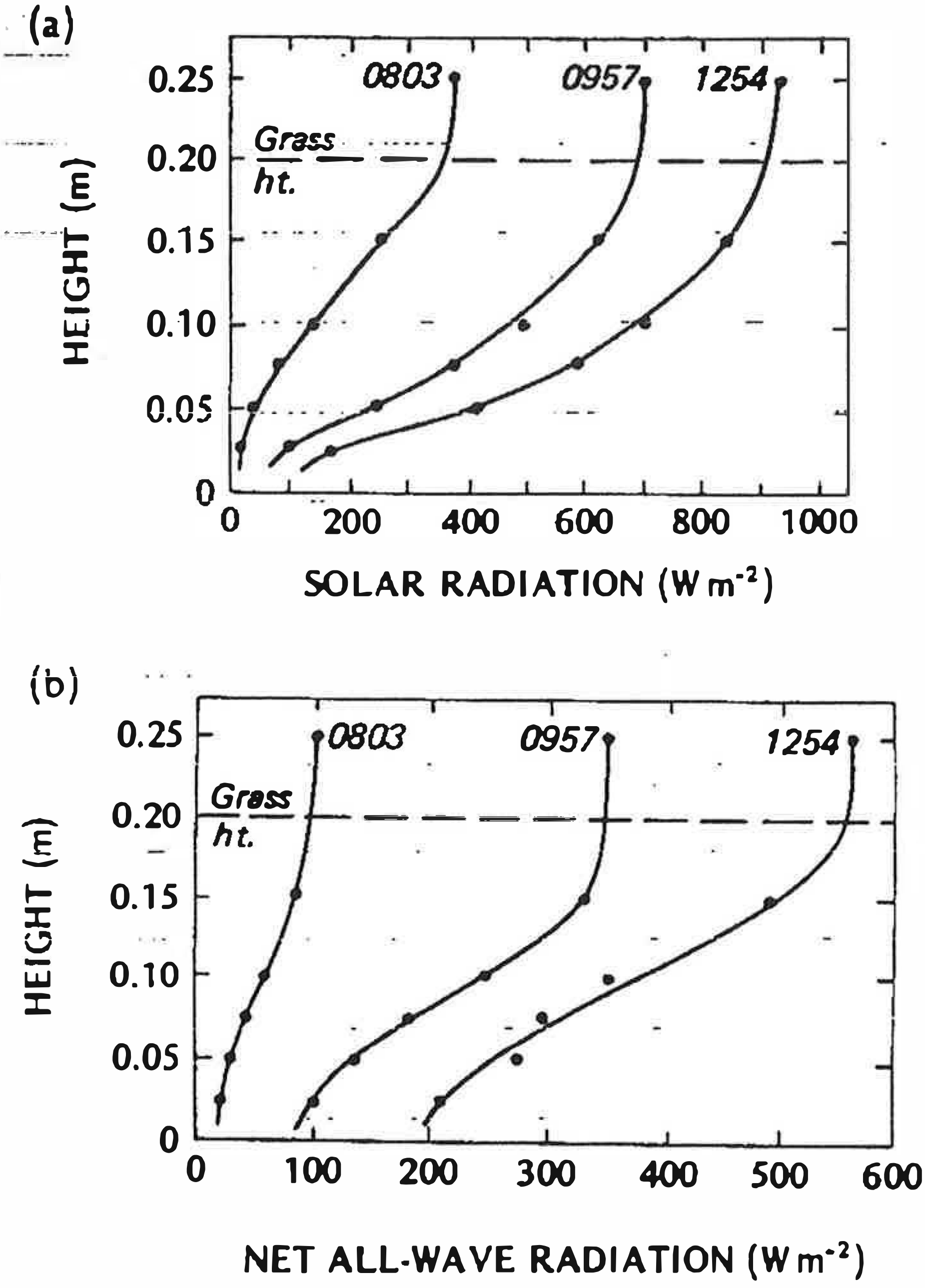
Trees create a cool microclimate under their canopy, it being sensed subjectively that air temperature is lower under trees on a sunny day, in fact temperature under a single tree is almost the same as in the open. Although there is considerable cooling power from evapo-transpiration from the canopy this is largely nullified in single or widely scattered trees by air movement and mixing. The perceived reduction in temperature is due to a reduction in radiation received. This interception varies with both species and variety of tree. [Ref. 43] In a forest the cooling effect may readily be experienced.

Considerable data are available on the transpiration rates of vegetation. Plants move water from the ground into the air. A small amount of the water is used chemically but the bulk of it is transpired. Plants use evapo-transpiration as a means of transferring nutrients from the soil and to minimise thermal stress.

An evaporation rate of 1 mm per hour per m^2 (one litre per hour) yields 680 W/m^2 of cooling. A loss of water to the air depletes the energy store of the soil and air as a result of taking up latent heat. This manifests itself as a reduction in soil and air temperature. Evaporation depends upon water, the energy to enable the change of state, a vapour pressure gradient and a turbulent microclimate. [Ref. 49] Evapotranspiration uses solar radiation as the energy source. The process is directly related to solar gain. This yields a self regulating cooling system that exploits the wet bulb temperature depression resulting from evaporation.

Water loss by transpiration is a means of nutrient movement and the uptake of latent heat is a major means of dissipating the energy load on leaves and roots. The stomata control transpiration. The degree of opening of the stomata is determined by factors including light intensity, ambient temperature, humidity and carbon dioxide concentration. Stomatal closure is linked to insufficient light and/or loss of water content by the guard cells

Plants can act as a thermal sink absorbing short wave radiation by evaporating water. Graphs a & b [Ref. 49] show how solar radiation and net all-wave radiation are reduced by a 200 mm stand of grass. The solar radiation is reduced by a factor of 6 and net all-wave radiation by 2.75.



Graphs (a) incomming solar radiation and (b), net all wave radiation, in a 0.2 m stand of native grass at Matador, Sack., on 28 June 1972 (after Ripley & Redmann,1976) [Ref. 49]

At present plants grown around or on a building are considered to offer shading of direct solar gain and altering the albedo of the micro climate.

If the temperature of the water flowing through a planted bed was reduced by a few degrees by the plants then there is the opportunity to perform cooling. Using engineering solutions that use a relatively high water flow temperature (secondary chilled water) and a small temperature difference it should be possible to regulate comfort conditions. This type of solution would fit in with the current trend towards the use of chilled ceilings and radiant panels.

While ventilation may also be required because advection is the main method of heat dispersal, [Ref. 49] deciduous vines offer shade and evaporative cooling in the summer when relief from solar radiation is most needed. In the spring and the autumn when solar gain is less of a problem. deciduous vines have fewer leaves, resulting in less shading and cooling. In the winter when solar gain is a bonus the deciduous vines are dormant, minimising their influence. Buildings with large glazed areas may benefit most from the use of deciduous shading.

The climates in which air-conditioning using vegetation is most likely to succeed are temperate, cool temperate, arid, semi-arid, sub tropical and dry tropical. This approach is unlikely to be effective in humid tropical climates, eg.Singapore or Hong Kong.

Ways in which vegetation could make a useful engineering contribution to building services have been shown in table 4.

Table 4 The Constructive Uses of Vegetation in Building Services

Description of Vegetation	Engineering Benefit
Irrigated 200 mm high turf meadow roof or sloping wall embankment	cut solar gain by a factor of 6, cut net all-wave radiation by a factor of 2.75 reduce roof surface temperature exploiting wet bulb depression, polish water, acoustic quieting
Irrigated deciduous vines over glazing, walls or roof	cut solar gain in summer, admit solar gain in winter, reduce surface temperature exploiting wet bulb depression, polish water, all without weight penalty
Irrigated internal planting	raise humidity, reduce internal temperature, exploiting wet bulb depression, polish water, air gross & molecular filtration, acoustic quieting
Copse, Woodlands	reduce water temperature, air gross filtration, water filtration
Structured or natural wetlands/marsh	water filtration/polishing

The method by which plants deal with solar gain is transpiration and evaporation both beneath the canopy and from the canopy water store. [Ref. 49] Cooling achieved is approximately equal to solar gain, providing sufficient water is available for evaporation.

Initially a model based largely on one used in meteorology is proposed. [Ref. 49] The sum of the elements that form the energy cascade equal the incident solar gain

$$Q^* = Q_H + Q_E + dQ_S + dQ_P + dQ_A \qquad (1)$$

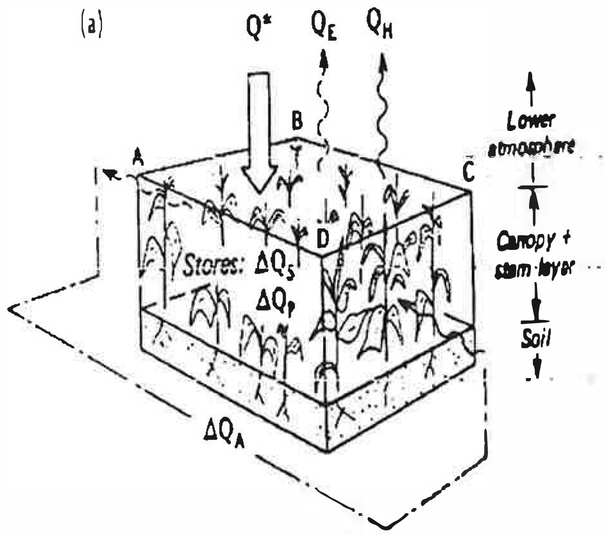
where:
Q^* net all wave radiation flux density W/m²
Q_H turbulent sensible heat flux density W/m²
Q_E turbulent latent heat flux density W/m²
dQ_S net in rate of energy storage W/m²
dQ_P net rate of storage in photosynthesis W/m²
dQ_A net rate of energy change by advection W/m²

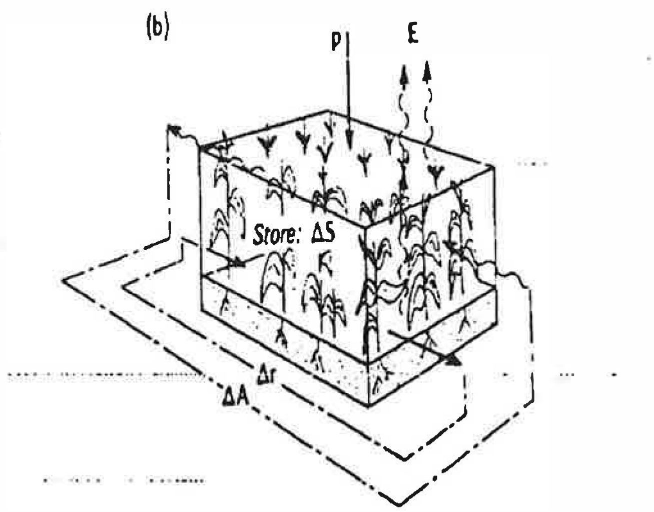
A water balance may be written as:

$$p = E + dr + dS + dA \qquad (2)$$

where:
p precipitation mm
E evapotranspiration mm.kg/m²s
dr resistance to flow s/m
dS net water storage m³
dA net horizontal moisture change m³

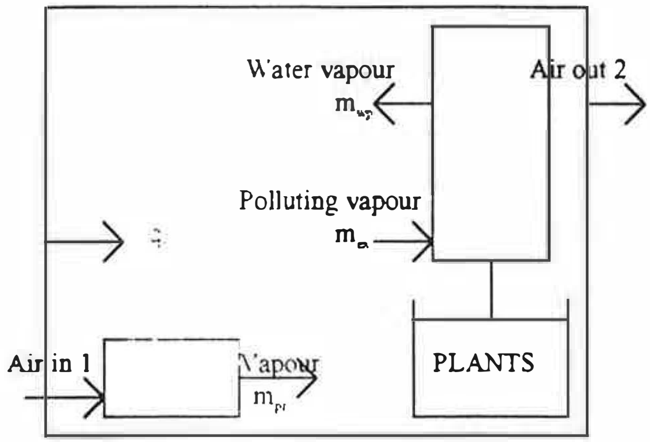
Schematic depiction of the fluxes involved, Diags. (a) the energy &. (b) the water balances of a soil-plant-air volume.





Considerable data have been collected from existing sources, in terms of the volume of water transpired by plants and the level to which the various plants may alter relative humidity of the built environment. Some desert plants draw moisture from the air. There is a chance that these plants may dehumidify the air. This might become a particularly novel way of dehumidifying the air in a building

Initially this second model considers water vapour as a contaminant. A room containing a polluting source and plants that cool and humidify the air is shown in diagram C.



Diag.C Assumed zoning of room with plant and polluting source.

It has been assumed that the air inside the zone is not stratified with respect to temperature, water vapour pressure or pollutants. This implies that combined mixing and vapour diffusion rates have sufficient influence to justify this simplification. It is also assumed that the water vapour and pollutants added to the air do not significantly change the mass flow rate. i.e., $m_1 = m_2$.

Energy, water vapour content and pollutant balances on the room gives:

$$m_1 h_1 + q_s - q_r + h_{fg} m_{wp}/1000 - m_1 h_2 = VD\ dh_2/dt \qquad (3)$$

$$m_1 g_1 + m_{wp}/1000 - m_1 g_2 = VD\ dg_2/dt \qquad (4)$$

$$m_1 p_1 + (m_{pf} - m_{pa})/1000 - m_1 g_2 = VD\ dp_2/dt \qquad (5)$$

where:

D	mean density of mixture	kg/m^3
g	specific humidity	kg/kg
h	specific enthalpy	kJ/kg
m	mixture mass flow rate	kg
m_{wp}	water vapour added by plants	g/s
m_{pa}	polluting vapour absorption rate	g/s
m_{pf}	polluting vapour formation rate	g/s
p	pollution concentration	ppm
q_r	heat transfer rate	kW
t	time	s
V	room volume	m^3
T	temperature	C

The cooling rate on the plant which results from the evaporation process, assuming for practical purposes a mean value for h_{fg} of 2450 kJ/kg:

$$q_r = m_{wp} * h_{fg}/1000 \qquad (6)$$

Neglecting any time delay between the plant's combined cooling and humidifying process the overall influence on the room is:

$$m_1 h_1 + q_r - m_1 h_2 = VD\ dh_2/dt \qquad (7)$$

It can be seen that with these assumptions the plants will reduce the room temperature and will increase room humidity, but they will not influence the enthalpy of the mixture.

The mass flow rate and enthalpy of the entering air were calculated from:

$$m_1 = D\ Q_1 \qquad (8)$$

and

$$h_1 = T_1 + g_1(2500 - 0.9\ T_1) \qquad (9)$$

The temperature of the mixture at exit was calculated by transposing an equation similar to equation (9).

From inputs of:
Room volume and mean mixture density;
Temperature, volume flow rate, specific humidity and pollution concentration of the air entering;
Room heat gain and pollutants added and extracted.

The response of the equations representing the room can be studied.

References

[1]R.Manly, J.Holmes. Minerals with a Natural Advantage. New Scientist 25MAR89, p39-43.

[2]Alison Alford. Plants With a Mission. Horticulture Week 02FEB90, p31.

[3]Heavy metal tolerant grasses by Bradshaw eltal, various

[4]Nature's Approach to Splitting Water, New Scientist 15JAN87, p35.

[5]The Soft Sell of Plants that Clean the Air, Horticulture Week 26JUL91, p22.

[6]K.Matsuki, Y.Saito. Dessicant Cooling R&D in Japan. ASHRAE Trans. 1988, Vol. 94, part 1, p537-551.

[7]Indoor Plants Get Credit, Horticulture Week 04OCT91, p4.

[8]Water-Splitting: The search for Oxygen. New Scientist 21FEB85, p18.

[9]P.Costa. Thermoelectric Device as a Heat Pump, Southbank Polytechnic 1991.

[10]A.H.Rosenfeld, H.Taha.Summer Heat Islands, Urban Trees, and White Surfaces, ASHRAE Trans

[11]I.Saito, O.Ishibara, T.Katayama. Study of the Effect of Green Areas on the Thermal Environment in an Urban Area, Energy and Buildings 15-16(1990/91)p493-498.

[12]S.Raza, M.Murthy, O.Bhagya Lakshmi, G.Shylaja. Effect of Vegetation on Urban Climate and Healthy Urban Colonies. Energy and Buildings 15-16(1990/91)p487-491.

[13]A.Meyer. Strategic Landscaping and Airconditioning savings: A Literature Review. Energy and Buildings 15-16(1990/91)p479-486.

[14]P.O.Farger Designing for Good Air Quality in Air-Conditioned Buildings Institute of Refrigeration Paper 17JAN91.

[15]I.Willner I.Steinberger-Willner. Solar Hydrogen Production Through Photobiological. Photochemical and Photoelectrochemical Assemblies. Int.J.Hydrogen Energy Vol.13 No10 pp593-604, 1988.

[16]N.Getoff. Photoelectrochemical and Photocatalytic Methods of Hydrogen Production: A short Review. Int.J.Hydrogen Energy Vol.15 No6 pp407-417. 1990.

[17]A.Guyot. Climatic Control in Architecturual Design Using Vegetation. Clima 2000 World Congress on Heating Ventilating and Air Conditioning. Copenhagen.1985

[18]A.Muldoon Prepublication Report: How Plants Help Neutralise Symptoms associated with Sick Building Syndrome. 070192.

[19]M.Lothian. Rentokil Tropical Plants. 270492 oral references and various stated papers.

[20]G.Vines How Yuccas Neutralise Nasty Niffs. New Scientist. pp12. 310891

[21]A.Muldoon. Plant Aid for Sick Buildings, ILG'BALI paper.

[22]K.McAuliffe. Air.Earth and Water. Longevity pp24. 1190

[23]J.Wolverton & B.C Wolverton. Interiorscape pp6, 01/0292

[24]The Sh hop. Guide to Healthier Buildings. pp20.

[25]R.A.Harris Vegetative barriers: an alternative highway noise abatement measure. Noise Control Engineering Journal 27 (1):4-8. 1986

[26]B.K.Huang. An Ecological Systems Approach to Community Noise Abatement-Phase 1. US DOT. Report Number DOT-05-30102. 1974

[27]J.Borthwick H.Halverson. G.M.Heisler, O.H.McDaniel & G.Reethof Attenuation of Highway Noise by Narrow Forest Belts. Federal Highway Administration. Report No FHWA-RD-77-140, March, 1978.

[28]S.H.Tang & P.P.Ong. A Monte Carlo Technique to Determine the Effectiveness of roaside Trees forContaining Traffic Noise. Applied Acoustics 23 263-271 1988

[29]G.C.Tocci & W.H.Pickett. Practical Applications of Outdoor Noise Control Barriers Sound & Vibration. 10-16: June 1979

[30]A.Bernatzky. The Contribution of Trees and Green Spaces to a Town Climate. Energy and Buildings. 5(1):1-10.

[31]H.G.Schiecht. Acoustic Screen Walls, Garten und Landschaft, May, 1989:51-54.

[32]N.W.Lepp. Some Relationships Between Trees and Heavy Metal Pollution. Arboricultural Journal 3(1):16- 22, 1977

[33]L.Wei. Trees that Help to Reduce Pollution, Clean Air 9(1):6-7, 1978

[34]G.H.Heichel & L.Hankin (1976). Roadside Coniferous Windbreaks as Sinks for Vehicular Lead Emissions. J. of the air Pollution Control Association 26(8):767-770.

[35]M.Masters (1981) Traffic Pollution and Roadside Plants. Landscape Research 5(2):18-19.

[36]L.S.Dochinger (1980). Interception of Airborne Particles by Tree Planting. J.Environ.Qual. 9(2):265-268.

[37]M.Yunnus, A.K.Dwivedi. K.Kulshreshta & K.J.Ahmad (1985). Dust Loadings on Some Common Plants Nears Lucknow City. Environmental Pollution 9:71-80.

[38]K.Okana & T.Machida (1989). Differences in ability of Nitrous Oxide Absorption in Various Broad Leaved Tree Species. Environmental Pollution 58:1-17.

[39]C.M.A.Ademoroti (1986) Levels of Heavy Metals on Bark and Fruit of Trees in Benin City, Nigeria. Environmental Pollution 11:241-253.

[40]A.Bernatzky (1982) The Contribution of Trees and Green Spaces to a Town Climate. Energy in Buildings 5(1):1-10.

[41]F.B.Pyatt & W.J.Haywood (1989). Air Borne Particulate Distributions and Their Accumulation in Tree Canopies. Nottingham. UK The Environmentalist 9(4):291-298.

[42]S.Amir & A.Misgav (1990). A Framework for Street Tree Planning in Urban Areas in Israel. Landscape and Urban Planning. 19:203-212.

[43]R.D.Brown & Gillespie (1990). Estimating Radiation Receveived by a Person Under Different Species of Shade Trees J.Arb. 16(6):158-161.

[44]K.G.Kim (1986). Design for Energy Conserving Cities: a New Town Example. Nature and Resources, XXII(3):20-27.

[45]A.Whyte (1985) Ecological Approaches to Urban Systems: Retrospect and Prospect. Nature and Resources. XXI (1):13-19.

[46]B.C.Wolverton (1991) Removal of Formaldehyde From Sealed Experimental Chambers by Azalea, Poinsettia and Dieffenbachia

[47]B.C.Wolverton. A.Johnson & K.Bounds (1989). Interior Landscape Plants for Indoor Air Pollution Abatement. Interiorscape 11/12 1989:37-63.

[48]W.F.Stoecker,J.W.Jones(1988) Refrigeration & Air-conditioning McGraw Hill Singapore. 2nd Ed ISBN 0-07-Y66591-5

[49]T.R.Oke(1979) Boundary Layer Climates J.Wiley & Sons New York ISBN 0 416 705308

[50]Sewage Treatment by Reed Bed Systems P.F.Cooper and Hobson. IWEM Feb 1989

[51]Growing Confidence in the Use of Constructed Reedbeds for Polishing Wastewater effluents-M.B.Green 1993

[52] The Design of Reed Bed Treatment Systems. Cooper etal

[53] Mark's Standard Handbook for Mechanical Engineers 9th ed. McGraw-Hill pp12-135..12-140

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