Constructive Use of Vegetation in Office Buildings

P. Costa C.Eng. and Prof. **R.W. James**
South Bank University, Borough Road, London SE1

Presented at the *Plants for People* Symposium
23 November 1995 at the Hague, Holland

1. Summary

The engineering benefits of plants include acoustics, water polishing, deciduous shading, air scrubbing, humidification and evaporative cooling. Vegetation offers the opportunity to create at low cost a building services installation that makes negligible noxious discharges to its surroundings. Plants have been polishing water, filtering and scrubbing air, humidifying and cooling adiabatically long before engineers started synthesising these processes to deal with the "plague proportions" in which we live, or at least more often most of us work.

2. Introduction

Building Services has become a complex field of engineering. Systems that result from many currently accepted mainstream design approaches can be difficult to maintain effectively resulting in high maintenance and running costs. There is an increasing trend towards simple systems. Amongst the growing number of clients, users, Engineers and Architects who follow this school of thought the highly serviced, air conditioned, sealed building housing a dissatisfied work force is without doubt a thing of the past. There will of course in our modern society always be a need for some parts of some buildings to be highly serviced. The emerging solutions are unlikely at this stage to replace mainstream building engineering services but there will be a shift towards a more balanced approach.

This leads to naturally ventilated buildings with openable windows, effective use of daylight, greatly reduced energy consumption and maintenance costs. In order for these solutions to be effective a dedicated commitment must be made by the client, the entire design team and later the contractor and his sub-contractors. There is currently a broad shift taking place in favour of more natural biologically oriented solutions than chemically oriented highly engineered solutions. This is perhaps a search for a more 'intermediate technology' than the 'high tech' solution. Distributed systems providing processing on site help relieve the burden on an overstreched infrastructure. In this way high quality infrastructure services may be reinstated and sustained into the future in a cost effective manner for the end user.

2.1 The Horniman Museum's CUE & Watford New Hope Trust Day Centre

An example of the visual appeal of a building using some of these principles is the Horniman Museum's Centre for Understanding the Environment (CUE) in Forest Hill, South East London, where the building engineering services and the vegetation on and around the building work in harmony. It will have irrigated turf to minimise solar gain on the low pitched roofs. Deciduous shading will cut summer solar gain to the South facing seminar room and link corridor glazing but admit the useful solar gain in the winter. Reed beds will polish the grey water from the hand basins and keep the pond water clean. The pond holds rainwater and polished grey water for reuse in flushing the toilets, irrigating plants and cooling the auditorium at the height of summer.

A more moderate example would be the Watford New Hope Trust's 'Day Care Centre'. This modest building in a quiet area of North London will also be insulated with recycled newspaper and have passive stack ventilation. The irrigated turf roof will minimise overheating. Deciduous vines will also be used to shade the south facing day room in the summer. The use of irrigated vegetation on buildings can reduce the size of openings required for effective natural ventilation. Some rain water is stored in a planted pond.

3. Water Polishing

Water polishing is an area that has been extensively covered both in Europe and the United States. The pioneering work in constructed wetlands was done in the 1940's in Germany. Since then, many reed beds have been installed world wide. The scale varies from town sites to single dwellings and all in between. The plants, working in a symbiotic relationship with the bacteria in the soil, strip nutrients and chemicals from water passing through the plant beds that would otherwise pollute water courses or be discharged to the sewage system. Although higher process rates may be achieved from biological filters without plants growing in the media, sustainabilty and low maintenance shifts the balance in favour of reed beds (as these systems have come to be known because reeds are the plants most frequently used).

An easily used reference guide that would take the 'mystique' out of structured wetlands (reed beds) is required to enable engineers to select sizes and capacities from tables, simple charts and equations. While a design guide already exists for the construction of reed beds, applying it to the built environment may prove difficult without further development. In discussions with a leading specialist in this field the two points that were felt to restrict the use of this form of water treatment directly in, on or around buildings was the significant space requirement and the risk of a possible build up of slime in cisterns due to the nutrients remaining in the polished water being reused. The space limitation may be readily addressed by using decorative planting to perform this engineering function. Ozone treatment or UV filtration could be used to combat slime growth in recycled water. The research currently being undertaken will pull together the considerable information available on this subject into a definitive guidance volume that may be applied by services engineers in pursuit of the autonomous building.

To stimulate discussion on water conservation, a strategy for an office block is proposed. It would considerably reduce mains water consumption, possibly to as little as drinking water only, by using vegetation. After dealing with all the obvious points such as spray taps, low volume cisterns, urinal flush controls, and management aspects such as tariffs and maintenance aspects such as leakage loss control, the strategy would extend to rain water collection and waste water recycling and could even extend to recycling foul water. To minimise plantroom space, the various stages of water treatment would be on display, in atriums, on roofs, down the walls and around the building. It would include water features and planting on several levels. In this strategy the vegetation would reduce the revenue expenditure of the building by cutting the mains water consumption which currently costs on average £1.50 per 1000 litres (cubic metre). In this way the psychological, aesthetic and engineering benefits of plants may be exploited.

3.1 Tooting Bec Pond Water Polishing

A working example of a reed bed with which the Author has been closely involved is installed at Tooting Bec Common, 15 minutes walk from Tooting Bec Underground Station in South East London. The pond in the centre of this park, east of the tennis courts acts as a reservoir for the land drains. The park is regularly fertilised and appears to have been heavily contaminated with oil and diesel many years ago. The public also add considerable quantities of stale bread to the pond for the ducks, most of which sinks to the bottom to rot acting as nutrition for the algae and weed. The three stage reed bed installed about two years ago draws water from the pond passing it into the reed beds which strip the phosphates and nitrates (nutrients) from the water. This reduces the available nutrition in the pond itself minimising algal bloom. The effectiveness of this reed bed installation is somewhat reduced by the absence of an appropriate corporate commitment to its success by the local authority. The reeds grow well despite the polluted water. There are minimal odours from the installation and these could be easily controlled, if it is required in a confined environment.

3.2 Water Conservation By Filtration & Recycling

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 as they transpire.*

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. 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 fifty 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 and vertical 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 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. In addition the roots provide a substrate for the microbiota, and a gaseous exchange region where because of the hollow stems and roots, oxygen can be brought down and nitrogen, methane and hydrogen sulphide removed by diffusion The plants frequently used are reeds *(Phragmites sp)*, but may include a range of 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 biologically 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 *Typha augustifolia* (narrow leafed reedmace), *Carex sp*. (Sedges) and *Juncus sp*. (rushes) are often included.

A constructed wetlands system should use a mixture of 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 1 below
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 3.2.1 Water Treatment by Vegetation

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

Table 3.2.1 above shows the plants most commonly used for water polishing. UK designs 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. The vertical stages can be $1m^2$/pe. This means that for an office block housing 100 people at a normal design density of 9.3 m^2 (100 ft^2) per person giving a floor area of 930 m^2, planting in the range $30m^2$ to $50m^2$ would be required. 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 establishment 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.

Other key points important to the success of reed beds are aeration, flow rate, retention time and having several stages. It would be normal to use three or more stages and that the stages would be a mixture of vertical beds followed by horizontal beds. It would also be normal to provide enough beds to permit rotation for resting and aeration. This might require 2 to 5 stages of vertical and horizontal beds in parallel and in series. Settlement tanks or ponds would also be required. Care must be taken to prevent stagnation in the settlement ponds.

Dr Wolverton who at one time worked for NASA 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.

4. Air Scrubbing

Vegetation can filter chemicals from air and from water. Chemical scrubbing and dust filtration are two areas to be covered in detail in later work that will collate research already undertaken by others. Most of which has been done by NASA and Dr. Bill Wolverton in the United States who have examined the ability of plants to chemically scrub air. It will pull together the information available into a guidance volume that may be considered by services engineers in pursuit of the autonomous building.

There is a symbiosis between the plants and the microbiota (bacteria, algae and micro-organisms) in the sediment The chemicals removed and the rate of removal varies between plant types. 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. There is far less research data available on air scrubbing and filtration compared to that for water polishing.

4.1 Air Molecular Filtration

A report by A. Muldoon 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 although research by Wilson & Hedge is vague about sick building syndrome symptoms. They consider it could be from tiredness.

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, he suggests a mixture to deal with different chemicals. 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. He observes that "If man is to move into closed environments ...or in space, he must take along natures life-support system."

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 in office environments 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 $9.3m^2$ (100 square feet) was not obvious and is felt to be lower than may be needed in practice.

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.

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.

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 normally be accepted in a conventional office environment but this does not mean that planting for this purpose should be discounted without further consideration in an open minded way.

In modern air-conditioned buildings at maximum heating and cooling load periods more air is recycled within the building than exchanged with outside, a factor that may give rise to sick building syndrome. Plants 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. At a press conference in the summer of 1995 Rentokil’s Dr. Stiles was able to show statistically that a psychological benefit is derived by people from indoor planting. Research has been done on Azaleas, Scindapsis & Dieffenbachia that absorb gases given off in office environments 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.

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.

Rhapis palms and Marantas that need regular misting or plants with high moisture content could benefit offices with low humidity. Tests carried out by Rentokil also supported the findings in America that plants can increase the relative humidity of an un air-conditioned environment by about 5% although the planting density to achieve this was higher than would normally be provided for a commercial office environment.

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.

In October of 1995 it was reported on Tomorrow’s World that NASA have successfully completed the first of a series of experiments with plants for people. In the first experiment they used 30 000 wheat plants grown in a space nominally 3m x 4.25m in a sealed container housing a person for 15 days. The plants produced oxygen for the astronaut while he produced carbon dioxide for the for plants. The astronaut had to exercise to produce enough carbon dioxide for the wheat plants. Their next experiment will be to house four people in a sealed container for 90 days, recycling air and water. The third experiment will run for 12 months when air, water, food and waste will be recycled. The plants don't produce any thing that the people don't like and the people don't produce anything the plant's don't like. Wheat was chosen because of it's higher than usual oxygen production. This research into regenerative systems is being carried out for use on space trips to Mars. The astronaut described a feeling of freshness when he entered the room containing the plants. The point was also made that the processes were related to photosynthesis. By comparison, Biosphere housed 8 people in a 12 000m^2 sealed and air conditioned space. Care is required in plant selection because some plants do produce noxious substances.

4.2 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. 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 30cm may capture 1500mg over a single season. This figure is only indicative 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. Sampling of vegetation for trace heavy metals has revealed a direct correlation between the roughness of tree bark and the amount of deposit.

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.

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. 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 70cm^2 collected the maximum amount of dust (8.81mg/cm^2), on the other hand *Acacia melanoxylon* collected only 0.53mg/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.

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.

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.

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.

5. Deciduous Shading and Evaporative Cooling by Vegetation

Deciduous shading is an obvious application that should be used much more than it is at present. It may be applied to clear or opaque elements of the fabric. Water to permit evapo-transpiration must be readily available for the vegetation to perform effectively in this role. It minimises solar gain by reducing albedo (solar absorptance), shading and evaporative cooling in the summer, reducing air conditioning sensible loads by reducing transmission of heat into the building, while admitting useful solar gain in the winter, permitting reduced heating loads. A model that expresses the cooling benefits of deciduous vegetation and long grass as found in meadows in terms of sol-air is currently being developed. Although grass planted in 100 mm of soil may appear to be a large load to be considered by the structural engineer it is only a little heavier than the concrete slabs and pebbles often used on flat roofs. It would be about four times the weight of clay roof tiles.

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 reduce heat island effects and can be used to good effect in and around buildings. This can be attributed to a lower albedo (solar absorptance) than most man made surfaces and evaporative cooling that results as plants transpire. Evaporative cooling occurs during evapo-transpiration as water and nutrition is drawn from the soil for growth and to keep the plants cool in sunlight. The process is directly related to sunlight which stimulates photosynthesis. A significant increase in urban trees can produce an oasis effect. For example a beech tree with a 14m crown can offer 680 watts of evaporative cooling and a 200 mm high stand of grass can cut solar gain by a factor of 6. In order that plants may provide evaporative cooling they require a readily available source of water. In the event of insufficient water, the plants respond by reducing the amount of water transpired to prevent their dehydration. Under those conditions they offer less cooling.

Trees affect energy use in buildings by:

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 that reduce cooling or heating demand depending on outdoor conditions.
4. reducing the infiltration rate by lowering micro climate wind speeds.
5. reducing transmittance heat gains by lowering summer micro climate ambient temperatures through evapo-transpiration and shading.
6. possibly increasing latent air conditioning loads by adding moisture to the outside air micro climate by evapo-transpiration

A free standing 100 year old beech tree *Fagus sylvatica* of dimensions:
1. Height 25m
2. Crown diameter 14m
3. Volume of crown $2700m^3$
4. Ground area $160m^2$
5. Leaf area $1600m^2$

performs the following services:
1. Water consumption 0.960 kg/hour
2. Carbon dioxide consumption 2.352kg/hour
3. Oxygen production 1.712kg/hour
4. Sugar production 1.600kg/hour
5. Total water transpired $10.0m^3$ /year
6. Energy consumption 6 000 000kcal/year
7. The tree produces enough oxygen for 10 people/year.

Trees create a cool microclimate under their canopy, which may be sensed subjectively as a lower air temperature under trees on a sunny day. The 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 in such a situation is due mainly to a reduction in radiation received. This interception varies with both species and variety of tree. In a forest the cooling effect may readily be experienced. Additionally, trees draw water from a ground source where because of the depth from which is drawn, it is likely to be at a lower temperature than the air, (typically at about 10^oC) there is the opportunity for the lower parts of the canopy to be nearer the temperature of the ground water. At the top of the canopy, however, temperatures may be above ambient as the tree stores solar energy by raising the temperature of the vegetation itself and of water being transpired.

Considerable data are available on the transpiration rates of vegetation, mostly crops. 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. In general plants use evapo-transpiration as a means of transferring nutrients from the soil and to minimise thermal stress. More specifically deciduous plants and grasses appear to perform in a way that could be of interest in minimising solar gains.

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 microclimate air movement. Evapo-transpiration uses solar radiation as the energy source so 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 (biological valves in the leaves) 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.

At present plants grown around or on a building are considered to offer shading of direct solar gain thereby altering the albedo of the micro climate. However, the plants have an altogether superior albedo to offer which by and large is not considered. The evaporative cooling power is likewise not considered.

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. Applying 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.

Ventilation would remain an important part of this type of solution because it is the main method of heat dispersal. 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. The albedo also varies with leaf density. Cooling achieved is approximately equal to, or greater than solar gain, all year round, providing sufficient water is available for evaporation. Air-conditioning using vegetation will be effective in all warm climates except humid tropics such as Singapore or Hong Kong.

Ways in which vegetation could make a useful engineering contribution to building services are shown in table 5.1 below.

Table 5.1 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 the weight penalty of turf
Irrigated internal planting	raise humidity and 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, cut solar gain
Structured or natural wetlands/marsh	water filtration/polishing, cut solar gain, reduce surface temperature in summer, exploiting wet bulb depression

To stimulate discussion, a scenario is proposed where a modern metal clad, reasonably well insulated industrial building is to be used as a retail outlet, where the summer time temperature is to be limited to say 24^{o}C. Perhaps the building is to be a hypermarket. Under normal circumstances since natural ventilation might limit the temperature to two or three degrees above ambient, considerable mechanical air conditioning could be required to maintain our target temperature. However, a hypermarket generates sizeable volumes of waste water that could be polished then used to irrigate vines growing over trellises on the building there by eliminating solar gain from the cooling load. Indirect evaporative cooling could then be used to offset occupancy and ventilation loads.

5.1 Suggested Sol-Air Temperature of Vegetated Surfaces

Sol-Air temperature is an engineering term for the theoretical temperature that may be used in heating and cooling calculations to represent solar gain, usually through an opaque fabric.
There are three differences between the equation for the sol-air temperature of a man made surface and a vegetated surface. The albedo (solar absorptance) differs and varies, the total solar irradiance is reduced to 14% for meadows and to 20% for deciduous vegetation, the surface resistance is lower because of the dynamic conditions created by the vegetation. It is important that the vegetation has available to it sufficient water to prevent water stress during evapo-transpiration. This information is derived from meteorological texts and will need validation by field trials.

Table 5.1.1 below of albedo for vegetation over the year shows how it varies with the solar altitude and in the case of deciduous vegetation also with the state of foliage. This contrasts with man made surfaces where a light surface is assigned the value 0.5, for a dark surface the value 0.9 is assigned. These values are used in the equations given in the CIBSE (Chartered Institution of Building Services Engineers) Guides as modified below to reflect the evaporative cooling effect of vegetation. In the first instance only horizontal surfaces will be considered. The equations may be readily modified for vertical surfaces and the wall-solar azimuth.

Table 5.1.1 Albedo (Solar Absorptance) & Long Wave Loss for Vegetation Through the Year

Albedo	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Altitude ^{o}	20	20	40	40	40	60	60	60	40	40	40	20
Meadow (Kale)	0.25	0.25	0.2	0.2	0.2	0.18	0.18	0.18	0.2	0.2	0.2	0.25
Deciduous	0.18	0.18	0.13	0.13	0.15	0.15	0.15	0.15	0.15	0.13	0.13	0.18
Leaves status	none	none	part	part	full	full	full	full	full	part	part	none
I_L : W/m^2 **	53.5	53.5	73	74	78	80	79	76	73	74	53.5	53.5

** Value given in CIBSE Guide Tables A2.33 (a) to (h) for March to October, for November to February given by $I_L = 93 - 79 \times C$, (eq'n A2.24) where cloudiness 'C' is taken as 0.5

For the purposes of this model the surface resistance $R_{so} = 0.02\text{m}^2$ K/W, the value given in CIBSE table A3.6, high emissivity roof in a severe location has been taken for vegetation For man made surfaces the value 0.07m^2 K/W has been used as given by CIBSE. The CIBSE Guides gives an equation A5.110, for the calculation of sol-air temperatures of horizontal surfaces.

$$t_{eo} = (\alpha .\ I_{THd} - \in .\ I_L)\ R_{so} + t_{ao}\ ; \quad (A5.110)$$

where:

t_{eo} = Sol-air temperature ^{o}C
α = Albedo (solar absorptance), the ratio of irradiance absorbed to reflected
I_{THd} = Total Horizontal. Design Solar Irradiance, W/m^2
$\in$ = 0.9 near black body radiator (applies to most objects)
I_L = Long wave loss, W/m^2
R_{so} = 0.07 surface resistance of man made surfaces, m^2 K/W
t_{ao} = outside air temperature

For meadow covered horizontal surfaces, where the grass is at least 200mm long the above equation is modified as shown below. The factor 0.14 is derived from the reduction of solar gain by this vegetated surface and shown in graphs by T.R.Oke. The surface resistance is taken as 0.02 W/m^2.

$$t_{eo} = ((\alpha .\ I_{THd} .\ 0.14) - \in .\ I_L)\ R_{so} + t_{ao}\ ; \quad \text{(eq'n for meadow covered surface)}$$

For surfaces covered with deciduous vegetation the CIBSE equation above is modified as shown below. The factor 0.2 is derived from the reduction of solar gain by this vegetated surface and shown diagrams by T.R.Oke. The surface resistance is taken as 0.02 W/m^2.

$$t_{eo} = ((\alpha.\ I_{THd}\ .\ 0.2) - \in.\ I_L)\ R_{so} + t_{ao}\ ; \quad \text{(eq'n for deciduous vegetation)}$$

For comparison a sample calculation of four situations are presented using the following common data, I_{THd} = 850W/m^2 , t_{ao} = 19 C, (21June @ 12:00), I_L = 80W/m^2, $\in$ = 0.9.

Table 5.1.2 Sample Calculation Results Comparing Man Made & Vegetated Roofs

Surface	α albedo	R_{so} surface resistance	t_{eo} sol-air temperature C
Dark man made	0.9	0.07	67
Light man made	0.5	0.07	44
Meadow covered	0.18	0.02	18
Deciduous covering	0.15	0.02	18

From this table it can be seen that transmittance through the fabric would no longer contribute to summer time overheating on vegetated surfaces. This would contribute to naturally ventilated buildings by reducing the size of passive stack ventilation paths. In the case of air conditioned buildings, fabric gains could be ignored on the top floor of a building.

The vegetation needs sufficient water available to it to prevent water stress during evapo-transpiration. Without that water the evaporative cooling will not be available, the vegetation may become water stressed, overheat in the sun light and die.

6. Humidification

Humidification by transpiration by plants would be of most benefit indoors in the winter when the relative humidity may occasionally drop below that normally accepted as comfortable in an office and the air conditioning may be required to add moisture to the air to reduce the build up of static, usually by steam humidification, an expensive and energy intensive process. Plants could raise humidity without an energy penalty, but would need daylight or artificial lighting that permits photosynthesis. It should be borne in mind that even clear glass reduces the transmission of light and this should be considered in examining the humidifying potential of vegetation. For humidifying in winter evergreen plants are required.

6.1 A Suggested Model for the Humidifying Power of Vegetation

It is intended to develop a mathematical model to relate transpiration by vegetation into humidification rates. In the first instance the equations below is offered for a horizontal surface. This model requires validation by experimentation.

Humidifying Power of Vegetation — Moisture Added to Air by Vegetation

$$Q_L = (I_{THd} - 16) \times 0.49 \times S \qquad \Delta g = (Q_L / h_{fg}) \times 3600$$

where:

Q_L = Latent Heat, W/m^2

I_{THd} = Total Horizontal. Design Solar Irradiance, W/m^2

h_{fg} = Latent Heat of Vaporisation ~ 2.45MJ/kg

Δg = Moisture transpired to air per hour, $kg/m^2 .h$

S = Transmission Loss Factor for Glazing

The value of 16 W/m^2 subtracted from I_{THd} allows for energy used in photosynthesis by vegetation.

The factor of 0.49 is given by T.R.Oke as the proportion of Solar Irradiance absorbed by vegetation.

7. Plants and Room Acoustics

Vegetation offers a truly green solution to engineering challenges through lowest embodied energy, running and maintenance costs. In addition they can look good and be on display where they may offer further benefits like acoustic quieting.

7.1 Sabine offered 0.11 m per m^3 absorption for house plants in 1906

Considerable work has been done in terms of plants and road noise but very little in terms of room acoustics. In 1906 Sabine, one of the founders of modern acoustic theory, found the absorption of house plants hard to express, but arrived at 0.11 m per m^3 . He felt it would be of great value to determine the absorbing power of plants because of their extensive use in decorating on festival occasions. Until now, no further work has been done on plants and room acoustics. A few mechanisms associated with the study of sound need to be put into context to appreciate the contribution by plants to room acoustics.

.

The average sound insulation by a brick wall weighing 450 kg/m^2 is 48 dB. A plaster board wall offers 22 dB weighing in at 7.5 kg/m^2. The relationship is:

$$R_{AV} = 10 + 14.5 \log_{10} m, \qquad \text{where } m = \text{mass/unit area in kg/m}^2$$

It can be seen that plants with a mass of grams per square metre could not begin compare with these materials and so cannot offer very much in terms of sound insulation. Plants are more likely to offer acoustic quieting by absorption i.e. providing resilient surfaces and modifying reverberation times, than to offer acoustic insulation.

7.1.1 Absorption determined from Reverberation Time

Apparent insulation by absorbents is achieved where the sound level in a room may be reduced by reducing the reflections by sound waves that ricochet around the room. Reverberation time is an indication of how a room may perform acoustically. A live room is characterised by hard surfaces, a tinny sound, echoes and a long reverberation time. The longer the echo, the longer the reverberation time . An acoustically dead or quiet room has soft surfaces, a low sound, no echoes and a short reverberation time. The sound absorbed by an element may be determined by the reduction in reverberation time it causes. Reference values established in a reverberation test chamber may be used in the study of room acoustics for practical applications in buildings.

Four validation trials were undertaken to examine the use of plants in room acoustics. These show that, particularly at higher frequencies, plants reduce the reverberation time and, hence, make the room quieter. To achieve a useful difference at low frequencies increased planting densities are required. These trials also confirmed that better performance was achieved in live rooms than in quiet rooms.

7.2 How do Plants Work Acoustically?

Plants offer absorption, diffraction and reflection of sound. The balance between these mechanisms may vary with the frequency at which the sound is generated and the nature of the room itself. The species, specimen size, pot size, moisture content of the potting medium and the type of mulch all have an effect on the absorption offered by a plant. Care should be used in consideration of the contribution made by plants in the study of room acoustics. A key point in plants and acoustics is that the plants should be big, healthy and full bodied. To work at their best they should be happy plants that look good.

7.2.1 Absorption

Plants alter room acoustics by reducing the reverberation time which is usually considered a benefit. The acoustic performance of plants is best in an acoustically live room that has hard surfaces such as marble walls, exposed concrete and stone floors. The effect of plants is unlikely to be noticeable in an acoustically quiet room, characterised by soft furnishings such as carpets, mineral fibre tiles and heavy pleated curtains. This is because the absorption of the soft furnishings is greater, and, therefore, masks the absorption by the plants. An increasing awareness of the environment is leading designers to wider use of durable, hard finishes with lower embodied energy, which on the whole, result in an acoustically live room where plants could have more to offer. In general, to make a noticeable difference higher densities of indoor planting than currently used would be required.

Plants could be used to eliminate flutter echoes that may be particularly noticeable in small rooms with parallel walls and ceilings and floors. Flutter echoes could otherwise be avoided by building the wall and ceiling a few millimetres out of parallel.

The plants work more consistently at higher frequencies which is where many annoying high pitch noises may be encountered. At lower frequencies the performance of the plants has been found to be variable and there are other materials that function far better than plants at these frequencies.

7.2.2 Diffraction and Reflection

At lower frequencies where the wave lengths of sound may be about a metre or more, plants may offer diffraction because the leaf size is small by comparison to the wave length. At higher frequencies the leaf sizes may reflect the sound onto other surfaces that may then absorb the sound. Larger leaf sizes would offer increased reflection at lower frequencies.

7.3 Where Plants Work Best Acoustically

The principles that apply to many acoustic absorbents may be applied to determine where to locate plants to maximise their contribution.

7.3.1 Better at higher frequencies

The use of plants to “fine tune” room performance at higher frequencies should yield useful results. At lower frequencies other readily available materials are likely to provide more noticeable benefits.

7.3.2 Big plant pots offer more than small ones

Bigger planters contain more mulch and support larger plants. It follows from this that they make a larger impact on the room acoustics. Arrangements comprising different plants in groups of three or five appear to work better than individual plants. Additionally, planters offer the opportunity to introduce Helmholtz resonators (resonance cavities that deal with noise at specific frequencies) discretely into the room. The South Bank University Acoustics Department of the School of Engineering Systems and Design is exploring this opportunity.

7.3.3 Several arrangements work better than a concentrated location

Positioning several plant arrangements around a room would be more effective than concentrating the planting in one location. The motivation for this is to maximise the surface area of the plants exposed to noise, increasing the opportunity for reflections onto other surfaces.

7.3.4 Near edges and corners are better locations than in the centre

Near the room wall surfaces and corners would be more effective than in the centre of the space. In these positions sound reflected from walls may be more effectively intercepted by the plants.

7.4 Further Acoustic Work

Since great care should be taken in the application of plants acoustically, a wider variety of plants and planter configurations should be tested. Soil moisture content alters the absorption. The type of top cover over the growing media also makes a difference. Plants are variable in nature even amongst the same species. This appears particularly evident in acoustic performance. To ensure a good reliability in predicting the contribution made by plants a wider study should be done to cover more of the plants used by the indoor planting industry. More plant types and sizes should be examined to determine their absorption. The contribution by the planter (i.e. the pot and its compost) to absorption is sufficiently significant to warrant a detailed study of the performance of the differing planter sizes and shapes used in indoor planting. The contribution by bark mulch to absorption is also sufficiently significant to warrant a detailed study of the performance of the differing mulches used in indoor planting such as mosses and pebbles. Finally, the general well being of the plant is imperative for rational acoustic performance.

7.5 Experimentally Derived Absorptions

The absorption by the plant combinations tested have been scheduled in table 7.5 below. Three separate tests were carried out in the reverberation chamber at the South Bank University. Four validation trials were undertaken at Rentokil Tropical Plant's headquarters in East Grinstead, where it could be shown that adding the vegetation did reduce the reverberation time of the rooms with hard surfaces.

Table 7.5 Absorptions by Vegetation 125 to 4k Hz

	Hz	125	250	500	1k	2k	4k
Plant	*m^3						
Ficus Benjamina, test 1	0.149	0.04	0.19	0.24	0.23	0.24	0.15
Group@3 test 1	0.428	0.42	0.28	0.21	0.42	0.49	0.48
Howea Forsteriana (Kentia) test 1	0.154	0.21	0.11	0.09	0.22	0.11	0.08
Dracaena Fragrans test 1	0.125	0.13	0.14	0.12	0.12	0.16	0.11
350 dia tubs test 2	0.034	****	0.14	0.14	0.04	0.13	0.44
Spathiphyllum test 2	0.013	0.09	0.07	0.08	0.13	0.22	0.44
Howea Forsteriana (Kentia) test 2	0.149	****	0.13	0.03	0.12	0.19	0.52
Shcefflera Arboricola test 2	0.139	****	0.13	0.06	0.22	0.23	0.47
Dracaena Marginata test 2	0.149	0.13	0.03	0.16	0.08	0.14	0.47
Philodendron test 2	0.149	****	0.23	0.22	0.29	0.34	0.72
Ficus Benjamina test 2	0.149	0.06	0.06	0.1	0.19	0.22	0.57
Spathiphyllum test 3	0.101	0.08	0.07	0.05	0.06	0.1	0.17
Howea Forsteriana (Kentia) test 3	0.129	0.03	0.04	0.03	0.06	0.09	0.19
Dracaena Marginata test 3	0.129	0.08	0.06	0.02	0.05	0.08	0.14
Dracaena Fragrans test 3	0.129	0.07	0.06	0.06	0.09	0.13	0.22
Ficus Benjamina test 3	0.129	0.11	0.11	0.08	0.11	0.13	0.21
Group@5 test 3	0.617	0.17	0.2	0.23	0.35	0.46	0.53
Bark mulch test 3	1 m^2	0.05	0.16	0.26	0.46	0.73	0.88

* includes pot, nominally 350 dia, 350 high

8. About the Author

Peter Costa completed an honours degree in environmental engineering, studying part time at the South Bank University in 1991. In 1992 he chose to pursue post graduate research on a part time basis, at the South Bank University, in his chosen specialisation 'Air conditioning and Noise Control Using Vegetation'. In 1993 he co-founded the consultancy '*Brotchie, Costa* *and Grant ltd, Ecologists and Engineers'* to offer environmental solutions to clients who genuinely wish to respect the environment. In 1994 he achieved the H&V News Building Services Engineer of the Year for his 'highly original and environmentally worthwhile work'. In 1995 he was runner up for the same award, when the judges again highly commended his company's 'significant contribution to the development and use of environmentally-appropriate HVAC technologies and designs'. In 1995 he was accepted as a 'Corporate member' of the Institute of Energy and a 'Graduate member' of the CIBSE. He has worked in building services for fifteen years in contracting and design, in office based positions and on site. He has worked on small projects ranging from a few thousand pounds to multimillion pound projects in the United Kingdom and abroad.

9. References

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

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

Heavy metal tolerant grasses by Bradshaw eltal, various

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

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

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

Indoor Plants Get Credit, Horticulture Week 04OCT91, p4.

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

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

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

I.Saito, O.Ishihara, 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.

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.

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

P.O.Fanger. Designing for Good Air Quality in Air-Conditioned Buildings, Institute of Refrigeration Paper 17JAN91.

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

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

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

A.Muldoon, Prepublication Report: How Plants Help Neutralise Symptoms Associated with Sick Building Syndrome. 070192.

M.Lothian, Rentokil Tropical Plants. 270492 oral references and various subsequent papers.

G.Vines. How Yuccas Neutralise Nasty Niffs, New Scientist. pp12, 310891

A.Muldoon, Plant Aid for Sick Buildings, ILG/BALI paper.

K.McAuliffe, Air,Earth and Water, Longevity pp24, 1190

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

The Stanhope Guide to Healthier Buildings, pp20,

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

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

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.

S.H.Tang & P.P.Ong, A Monte Carlo Technique to Determine the Effectiveness of roadside Trees for Containing Traffic Noise. Applied Acoustics 23: 263- 271. 1988

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

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

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

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

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

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.

M.Madders (1981) Traffic Pollution and Roadside Plants. Landscape Research 5(2):18-19.

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

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.

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

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

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

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.

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

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

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

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

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

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

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

Sewage Treatment by Reed Bed Systems P.F.Cooper and Hobson, IWEM Feb 1989

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

The Design of Reed Bed Treatment Systems, Cooper et al

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

The Environmental Benefits of Vegetation at aGlobal, Local and Personal Level: A Review of the Literature, undertaken for the Horticultural Trades Association by the Gardens Development Unit, Royal Botanic Gardens, Kew

Building Green, A guide to using plants on roofs, walls and pavements, Jacklyn Johnston and John Newton, London Ecology Unit.

10. Acknowledgements

Prof. R. W. James South Bank University

Dr. B. Sheilds South Bank University

Ms. J. Williamson, Electric Air Building Engineering Services

Mr. R. J. Oughton

Mr. G.Grant, Ecoschemes, Creative Ecologists.

Mr. A.Muldoon, Enterprise Plants.

Mr P. Cooper, IAWQ

Mr. M.Lothian, Rentokil.

Mr. M. Maunder, Kew Gardens

prcprcphdhagg1.doc121195petersphd3