Effects of Vegetated and Synthetic (Impervious) Surfaces on the Microclimate of Urban Area

[1]*OBIAKOR, M. O; [2]EZEONYEJIAKU, C.D; [3]MOGBO, T.C

[1]Department of Environmental Management; [2,3]Department of Zoology;
Nnamdi Azikiwe University, P.M.B 5025, Awka, Anambra State, Nigeria

ABSTRACT: The present paper shows the considerable impacts of both vegetated and synthetic surfaces on the microclimate of urban area. Vegetation of a particular place affects the microclimate through reduced solar radiation and lower air temperature due to shading and evapotranspiration. Lower air temperatures are essential both to improve thermal comfort conditions of residents and to limit energy use for cooling. The growth and spread of synthetic (impervious) surfaces within urbanizing areas pose significant threats to the quality of natural and built environments. These threats include increased stormwater runoff, reduced water quality, higher maximum summer temperatures, degraded, and destroyed aquatic and terrestrial habitats, and the diminished aesthetic appeal of streams and landscapes. This paper provides a basic introduction to microclimate, vegetated and impervious surfaces and an overview of the effects of increased imperviousness and vegetation on the microclimate of urban areas. Although urban and suburban growth is inevitable, many of the environmental impacts of impervious surfaces are avoidable or controllable. Working together, local governments and citizens can reduce the amount of land rendered impervious, and can reduce its adverse impacts, promoting a healthier environment through sound landuse planning and improved land management. @JASEM

The existence of microclimates has long been recognized in its practical application in the importance of aspect and contour in determining the climate of local areas. It has been recognized in the difference between sunny and shady slopes in hill country; in the occurrence of cold air drainage and frost in the siting of crops and orchards; in the tolerance of forest trees to shading and its relation to natural regeneration; and even in the choice of position for the different plants in the home garden (Barbara, 1956).

Microclimate has been defined as the climatic environment of a very local area, such as the north- or the south-facing slope of a hill, or an even smaller area. It refers strictly to local combinations of atmospheric factors, which differ from the macroclimate because of uneven topography or differences in plant cover. Within the area of one macroclimate there may exist a whole series of microclimates some of which may differ sufficiently to be of ecological importance. Biologists have frequently pointed out that the climate in which plants and animals actually live is very different from that measured by the meteorologist in a Stephenson screen at 4 ft. 6in. off the ground; but in the past many studies of plant and animal habitats have relied almost entirely on measurements of the physical factors of the environment obtained from the meteorologist.

Apart from the practical applications in forestry and agriculture, research on microclimate has been confined to the habitats of a few plants and animals. The main source of inspiration for studies of microclimate has been the work of the meteorologist R. Geiger (1927, 1942) who showed that the climate near the ground differed from the macroclimate because of the effect of the ground and the presence of a plant cover. Microclimate differs from micrometeorology since it is concerned with the local atmospheric conditions as they affect the living conditions of plants and animals, and not with the mechanics of the weather itself. The factors measured are the same as in ordinary meteorological studies, but the type of ground, the presence of vegetation and the type of plant are important in determining the microclimate. Terry and Evyatar (2001) noted that there are five main differences between the urban climate and that of the natural rural surroundings: the radiation budget, sub-surface (storage) heat flux, advection, anthropogenic heat release, and turbulent heat transfer including the effects of vegetation.

More than half of the world's population now lives in urbanized ecosystems. Continues human population growth over the next several decades will place unprecedented demand on urban water resources, resulting in escalating water quality and supply challenges. Urbanization exerts significant impacts on stream ecosystems including increases magnitude and frequency of peak flows, altered microclimates, and reduced biodiversity. Increased impervious surface area in urban settings reduces or eliminates soil infiltration and increases the amount of storm water runoff delivered to stream channels. Storm water routing networks in urban areas channelize runoff, reducing storm water transit time. Storm water flow serves as an important transport mechanism for nonpoint source pollutants, and

*Corresponding author & e-mail: maxiugobiks@yahoo.com; 08038989932

impervious surfaces serve as conduits to flow, replacing soils and vegetation that would otherwise attenuate runoff and transport of pollutants (Hubbart, 2009). Given these scenarios, urbanization can have drastic impact on the microclimate. The paper tries to portray the effects of vegetated and synthetic (impervious) surfaces on the microclimate of urban area.

Vegetated and Synthetic (Impervious) Surfaces: The partitioning of energy between sensible and latent forms depends on the availability of water. Urban environments may vary from inner-city surroundings consisting almost entirely of masonry, concrete, asphalt, and glass, to suburban developments with dense vegetation and well irrigated lawns. The former may result in a very dry system with very little latent heat, while the latter create more humid microclimates that are dominated by the effects of evapotranspiration.

Many impervious urban surfaces, such as asphalt roads, channel their entire net radiant surplus during the daytime into sensible heat, warming the substrate or the adjacent air. Natural surfaces are rarely impervious, so in the presence of moisture, the surplus radiant energy may be converted to latent heat. On the other hand, in the event of precipitation, the natural surfaces absorb much of the additional water, while impervious urban surfaces remain wet, and considerable moisture may be available for a limited period to be converted into latent heat. In terms of climatic response, there are thus two surface types of great importance, first, impervious surfaces that can cover the full moisture range from 'wet' (after rain) to 'dry' in a very short period, and second, pervious natural surfaces that can cover a similar range, but over more extended periods and with a much slower response (Terry and Evyatar, 2001).
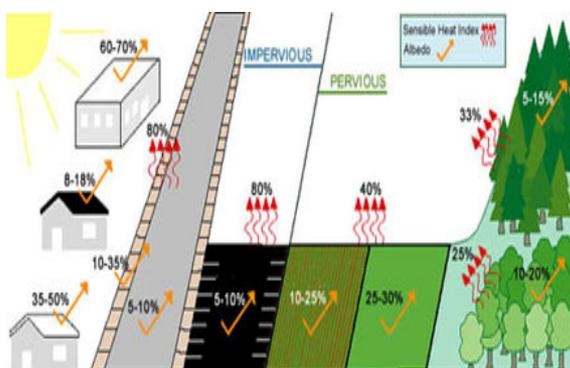
Source: CGIS

The close juxtaposition of surfaces that react so differently to radiant heat flux, such as those found in many urban systems, is also very likely to result in micro-scale advection.

Effects of Vegetated Surfaces on the Microclimate of Urban Area: In the tropics, the outdoor thermal comfort conditions during daytime are often far above acceptable comfort standards due to intense solar radiation and high solar elevations (Ali-Toudert and Mayer, 2007; Johansson, 2006). While the urban heat island is less of a problem in temperate climates, it is unwanted in low and mid latitude cities as it contributes to increase in the cooling load and results in increased energy use (Taha, 1997). Vegetation is an important design element in improving urban microclimate and outdoor thermal comfort in urban spaces in hot climates (Spangenberg, 2004). Due to urbanization, however, vegetation is scarce in many tropical cities. There has often been a tendency to replace natural vegetation and permeable soils with impervious surfaces such as asphalt and concrete, which leads to more sensible than latent heat flux (Emmanuel, 2005). In urban streets, vegetation is often considered a problem for several reasons. For example, trees are costly to maintain, their canopies often interfere with overhead telephone and electric lines and their roots may destroy pavements and underground sewers.

The Use of Vegetation in Hot Climates: The main benefits of vegetation in hot climates are reduced solar radiation and lower air temperature due to shading and evapotranspiration. Lower air temperatures are essential both to improve thermal comfort conditions of pedestrians and to limit energy use for cooling. According to Akbari *et al.* (2001), peak energy demand in the USA rises 2–4% for every 1°C increase in maximum air temperature. Among other factors, the effect of vegetation on the microclimate depends on the size of the vegetated area. While the cooling effect on the air temperature is limited for a single tree or a small group of street trees (Oke, 1989), larger areas such as parks can have a significant cooling effect (Yu and Hien, 2006). The evapotranspiration of vegetated areas is highly dependent on soil humidity; for dry soils, which are common in urban areas due to sealing of the ground, evapotranspiration cooling will be limited (Oke, 1989).

There are also negative effects of vegetation in warm climates. One drawback with trees is that they block the wind; a deciduous tree may reduce wind speeds by 30-40% (Ali- Toudert and Mayer, 2007). Trees

with large canopies will also reduce nocturnal cooling as they block some of the net outgoing long-wave radiation.

Several recent studies have shown that vegetation is beneficial in lowering air temperatures, in providing shade and in improving thermal comfort. Field measurements by Shashua-Bar and Hoffman (2004) showed that some tree-aligned streets and boulevards in the Tel-Aviv area, Israel, had 1–2.5°C lower air temperatures than non-vegetated streets at the hottest part of the day (15:00 h). Applying the simulation software, ENVI-met (Bruse, 2006) to the climate of Thessaloniki, Greece, Chatzidimitriou *et al.* (2005) found small temperature decrease for tree-aligned streets (less than 1°C), but up to 20°C lower surface temperatures and more than 40°C lower mean radiant temperatures. The cooling effect was found to increase with rising number of trees. In the hot dry climate of Ghardaia, Algeria, Ali-Toudert and Mayer (2007) found that shading trees could improve the thermal comfort in streets considerably. In another simulation study of different greening scenarios using ENVImet in Rio de Janeiro, Brazil, Spangenberg (2004) found that an increased amount of urban green (tree cover of 30% of the ground and 100% green roofs) could nearly re-create the comfortable conditions of a natural forest.

Role of Evapotranspiration on the Microclimate:
Less attention has been paid to the role of urban evapotranspiration (ET) by urban hydrologists, even though this it is often the biggest output in the water balance. Evapotranspiration is the process that links the movement of water through a landscape with the local climate, with the process using energy that would otherwise contribute to elevated air temperatures. This passive control of the local climate via urban vegetation and ET has a direct influence on quantities of energy used in space heating and cooling through the role of urban ET and because trees provide shade and shelter (Cleugh *et al.*, 2007).
.
This link between the urban water and energy balances, and microclimate, is demonstrated by considering the following simplified expressions for i) the urban water balance:

$$P + I = ET + D + \Delta S .... (1)$$

where the inputs are: P = precipitation; I = piped water supply (for external and internal uses); and the outputs are: ET = urban evapotranspiration; D = stormwater and wastewater; ΔS = change in stored

water on and within the surface materials; and ii) the urban energy balance:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S .... (2)$$

where the energy inputs and outputs are; Q^* = net all-wave radiation; Q_F = anthropogenic energy sources (space heating, cooling etc.); Q_E = energy used to evaporate the water flux E; Q_H and ΔQ_S = energy used to heat the air, soil and built surfaces.

Urban ET also contributes to reducing net greenhouse gas emissions, directly because water loss via transpiration is the consequence of the uptake of CO_2 during photosynthesis, and indirectly because reduced energy consumption reduces greenhouse gases consumed in burning fossil fuels to generate electricity. Maintaining urban green space *via* vegetation is therefore a quantifiable benefit in terms of reduced energy consumption and net greenhouse gas emissions (Cleugh *et al.*, 2007).

Effects of Synthetic (Impervious) Surfaces on the Microclimate of Urban Area: The growth and spread of synthetic, impervious surfaces within urban areas pose significant threats to the quality of natural and built environments. These threats include increased stormwater runoff, reduced water quality, higher maximum summer temperatures, degraded, and destroyed aquatic and terrestrial habitats, and the diminished aesthetic appeal of streams and landscapes (Kent *et al.* 2008).

Impervious surfaces are mainly constructed surfaces - rooftops, sidewalks, roads, and parking lots--covered by impenetrable materials such as asphalt, concrete, and stone. These materials effectively seal surfaces, repel water, and prevent precipitation and meltwater from infiltrating soils. Surfaces covered by such materials are hydrologically active, meaning they generate surface runoff. According to Novotny and Chesters (1981), impervious surfaces are nearly 100 percent hydrologically active, and high percentages of such surfaces occur within urbanized areas containing commercial, industrial, transportation, and medium to high-density residential land uses. Other impervious, hydrologically active surfaces include compacted soils, high clay content soils, frozen soils, saturated soils, and soils with high groundwater tables (Novotny and Chesters, 1981). With the last three, imperviousness and hydrological activity is usually seasonal or temporary, in marked contrast to urbanized areas, which are permanently impervious and hydrologically active.

Paving watershed areas with asphalt and concrete makes these surfaces "desert-like" in terms of hydrology and climate. Storm water washes over paved, sparsely vegetated urban surfaces in much the same manner as it does over a desert landscape. Intense storms over urban and desert areas can quickly generate large volumes of runoff, even flash floods, followed by relatively dry conditions a short time later (Christopherson, 2001). Rapid runoff and the paucity of vegetation over these surfaces also reduce the amount of water available for evapotranspiration. Therefore, much of the incoming solar energy that could have been utilized to evaporate water is instead transformed into sensible heat. This effectively raises the temperatures of these surfaces and of the overlying atmosphere. Moreover, impervious urban surfaces behave like rocky desert surfaces in that they tend to have high thermal conductivities and heat storage capacities in comparison to vegetated, pervious surfaces (Douglas, 1983; Christopherson, 2001). The differences in the thermal characteristics of surface materials that overlie urban areas versus those that overlie natural pervious areas have profound implications not only for microclimates, but also for stream and watershed health.

Many types of pollutants, originating from a variety of sources, accumulate over impervious urban surfaces. These pollutants are subsequently washed into water bodies during, and immediately following, storm events, severely degrading water quality and harming aquatic life. Furthermore, the temperatures of stormwater runoff during summer months can be dramatically increased via heat conduction from impervious surfaces. These forms of water pollution, which arise over broad land areas, are known as nonpoint or diffused source pollution, with pollutants being conveyed to water bodies via overland flow rather than by pipes, ditches, or conduits issuing from factories or sewage treatment plants. This type of pollution is linked to land-use activities, and its severity is a function of land-use type and intensity, including the amounts of impervious surface and the frequency and magnitude of storm events.

Table 1. Urban Nonpoint Pollutants: Categories, Parameters, and Sources

Category	Parameters	Potential Sources
Bacteria	Total and fecal coliforms, fecal streptococci, other pathogens	Animals, birds, soil bacteria, humans
Nutrients	Nitrogen and phosphorus	Pets, birds and animals; lawn; fertilizers; decomposing organic matter (leaves and grass clippings); urban street refuse; atmospheric depositions.
Biodegradable chemicals	Biological oxygen demanding wastes, chemical oxygen demanding wastes, total organic carbon	Leaves, grass clippings, animals, street litter, oil and grease
Organic chemicals	Pesticides, PCBs	Pest and weed control, packaging, leaking transformer, hydraulic and lubricating fluid
Inorganic chemicals	Suspended solids, dissolved solids, toxic metals, chloride	Erosion (lawns, stream banks and channels, construction sites), dust and dirt on streets, atmospheric deposition, industrial pollution, illegal dumping during storms, traffic, deicing salt
Physical and aesthetics	Thermal, discoloration, odours	Heated streets, parking lots, sidewalks, and rooftops (summer only); runoff from industrial sites; animal wastes and organic matter, hydrocarbons

Source: Novotny and Chesters (1981); Hansen *et al*. (1988); Whipple (1977).

From a hydrological perspective, the impervious areas of a watershed can be differentiated between total impervious area (TIA) and effective impervious area (EIA). The former refers to all areas within a watershed that are "covered by constructed, non-infiltrating surfaces (Booth and Jackson, 1997). Impervious areas, which drain onto pervious surfaces such as lawns, gardens, and grassy fields, would be included in calculations of TIA, but excluded from EIA calculations; if, however, those areas contribute runoff directly into streams and other surface water bodies, they would be included in calculations of EIA. It must also be noted that most impervious surfaces are not 100 percent impervious, even in effective impervious areas, since cracks and gaps in concrete and other surface materials allows some water to infiltrate underlying soils.

Most of the impervious surfaces within the watersheds and coastal bays are the result of urbanization. The majority of these surfaces are associated with transportation, specifically roads and

Effects of Vegetated and Synthetic (Impervious) Surfaces…..

parking areas. Transportation land-uses account for between 63 percent and 70 percent of the impervious covers measured for urban sites in Olympia, Washington (Schueler, 1994). As residents, businesses, and industries relocate to suburban and rural locations within the urban areas, the amount of land covered by roads, parking lots, driveways, sidewalks, and structures will also increase. Impervious surfaces are diffusing from the urban centers into surrounding areas, subsequently altering the land's physical characteristics and functions.

Why Consider Impervious Surfaces in Land Use Decisions?: The increasing imperviousness of the urban landscapes has five broad, interrelated impacts: 1) alteration of local and regional hydrological cycles (changes in water quantity); 2) changes in water quality; 3) changes to local energy balances and microclimates; 4) habitat degradation, loss, and fragmentation; and 5) changes to stream and landscape aesthetics. Imperviousness directly affects stormwater runoff and water quality. Moreover, the temperature response and reflective properties of impervious surfaces are linked to the "urban heat island" effect, which affects human comfort and health because of changes in sensible heat fluxes and the concentration of atmospheric pollutants (Kent *et al.* 2008).

Table 2: Factors Strongly Affecting Urban Nonpoint Source Pollution

Factors which are closely correlated with urban landuse and landcover	Factors which are poorly correlated with urban landuse and landcover	Factors unrelated to urban landuse and landcover
Amount of impervious area (usually correlated with population density)	Street surface conditions	Meteorological and climatic factors
Curb length density and height	Amount of impervious area hydraulically connected to stream channels	Soil texture, structure, and composition
Vegetation cover and pervious surfaces	Net amount of nonpoint pollutants delivered to streams compared to gross amounts of pollutants available (Delivery Ratio)	Permeability
Traffic density	Surface storage	Soil cation exchange capacity
Atmospheric fallout	Organic content of soils	slope
Street litter accumulation rates	Nutrient content of soils	
Street clearing practices		
Pollutant conveyance systems (storm sewers, combined sewers, unsewered)		

Source: Novotny and Chesters (1981) as cited in Kent *et al.* (2008).

The measurement of imperviousness provides a succinct, straightforward indicator of stream degradation and terrestrial habitat loss and degradation (Arnold and Gibbons, 1996; Schueler, 1994). Increasing imperviousness can also result in dramatic changes to the aesthetic character of streams and landscapes within the bay's watershed, indicating a shift from forested and rural landscapes to more suburban and urban settings, and is a measure of both directed and undirected (sprawl) urban development. These changes profoundly affect the quality of life for millions of residents within the urban areas.

A recent report on climate change issued by the Mid-Atlantic Regional Assessment Team, MARA (2000), predicts continued population growth in the Mid-Atlantic region, especially in coastal areas and the Piedmont. This will lead to more land conversion and development, with increases in impervious surfaces throughout many of the urban areas, particularly those within or adjacent to metropolitan areas. Unless actions to control development are undertaken now, the environmental impacts of imperviousness will increase along with population growth (Kent *et al.* 2008).

Following sections in this paper provide an overview of the microclimate impact listed above. It is important to consider this impact in light of projected population growth and recent efforts to control sprawl development such as Smart Growth, rural land preservation, and similar initiatives. Dealing with the problems of imperviousness should be an integral part of land use planning and land management activities within the urban areas.

Energy Balances and Microclimatic Impacts of Synthetic (Impervious) Surfaces: As development changes land from pervious forests, grasslands, and croplands to impervious surfaces, balances between solar energy intercepted at the surface (insolation) and outgoing terrestrial energy are also changed. Solar radiation that reaches the Earth's surface is reflected, absorbed and transformed into sensible heat, or utilized in evapotranspiration. In addition, a very small percentage of solar radiation is used in photosynthesis. It is important to note that the

atmosphere is heated mainly by energy radiating off the earth's surface and not by direct solar heating. Surface materials therefore affect the amount of solar radiation which is either reflected or absorbed, and also affects the flow of heat from the surface to the atmosphere. This, in turn, influences the temperature and humidity of the overlying air. The conversion of pervious surfaces to impervious surfaces alters local energy balances through changes in:
- the albedos of surfaces;
- the specific heat capacities and thermal conductivities of surfaces; and
- the ratio of sensible heat to latent heat flowing from the surface into the atmosphere
(Oliver, 1973).

According to Strahler: "The thermal effect is that of converting the city into a hot desert. The summer temperature cycle close to the pavement of a city may be almost as extreme as that of a desert floor" (Strahler, 1975). These changes, coupled with a handful of other factors, contribute to a phenomenon known as the "urban heat island," which affects human health and comfort and increases energy demands for cooling.

Albedo: Albedo is the percent of incoming solar radiation reflected by a surface. It determines relative rates of surface heating and evaporation since radiant energy rejected by surfaces returns to space and is not transformed into either sensible heat or latent heat. Less energy reflected by surfaces means that more energy is absorbed and transformed into heat energy. The various types of surfaces commonly found within watersheds have different reflective properties, and a high degree of impervious surfaces profoundly alters the proportions of incoming solar energy reflected or absorbed (Kent *et al.* 2008). The albedos of surfaces typically found within the urban areas are presented in Table 3.

Table 3. Albedos of Various Urban Surface Covers

Surface Cover	Albedo (%)
Brick and Stone	20-40
Blacktop surfaces (asphalt)	5-10
Dry concrete	17-20
Dark roof	8-18
Light roof	35-50
Crops	15-25
Deciduous forest	10-20
Coniferous forest	5-15
Grass	25-30

Source: Conway (1997); Christopherson (2001); Kent *et al.* (2008).

The overall albedo of impervious urban surfaces is about 10 percent lower than that for rural surfaces (Oliver, 1973), leading to higher percentages of absorbed radiation. The lower albedo for urban areas is likely due to the prevalence of impervious surfaces associated with transportation.

Specific Heat Capacity and Thermal Conductivity: Surface materials differ as to: 1) the amount of heat energy they can store; 2) their ability to conduct heat; and 3) their changes in sensible temperature when exposed to solar radiation. Some substances, such as water, can absorb and store a considerable amount of energy before increasing in temperature; likewise these substances can lose a good deal of energy before declining in temperature. On the other hand, some substances experience a rapid rise or decline in temperatures with the gain or loss of a relatively small amount of energy. This relationship between heat energy and temperature is referred to as a substance's specific heat capacity, which is the ratio of the gain or loss of energy to a corresponding rise or fall in temperature. This is also expressed as: the change in heat / the change in temperature (Kent *et al.* 2008).

The specific heat of some representative substances, in calories/gram/^{0}C, is presented in Table 4. By comparing the specific heat of water (1) with that of concrete (0.2), it can be seen that five times more energy is needed to raise the temperature of water 1^0 C than that which is required to raise the temperature of a corresponding mass of concrete (Danielson, *et al.*, 1998).

Table 4. Specific Heat of Some Common Substances

Substance	Specific Heat (calories per gram per ^{o}C)
Water	1.0
Wet mud	0.6
Wood	0.420
Brick	0.214
Concrete	0.2
Dry sand	0.19
Asphalt	0.1785*

Source: Danielson, *et al.* (1998); Forsythe (1959); Moran and Morgan (1986); Marsh (1998).

Conduction, which is the flow of energy from molecule to molecule, is an important heat transfer process at the earth's surface. Once radiant energy is absorbed and transformed into sensible heat, it is transferred by conduction towards areas of lower temperatures in the surrounding air and soil. The thermal conductivity of a substance is "the amount of heat transmitted per unit time per unit perpendicular area per unit temperature gradient" (Bueche, 1979). This can be expressed as:

W/mK

Effects of Vegetated and Synthetic (Impervious) Surfaces…..

for the heat flux through a column 1 m^2, where W is watts, m is meter, and K is a temperature gradient of 1 Kelvin per meter (Marsh, 1998).

Surface heat is conducted into the ground where it is stored and later released. Rapid conduction enables heat to penetrate to greater depths. This allows more heat to be absorbed and delays its introduction to the atmosphere through conduction and convection. Solids are generally better conductors of heat than liquids, and liquids more so than gases; hence dense impervious urban surfaces of concrete, stone, and asphalt conduct heat more efficiently and absorb more heat than do the pervious surfaces they replaced (Strahler, 1975; Douglas, 1983). In fact, the thermal effects of impervious urban surfaces are "more intense than … a sandy desert floor" (Strahler, 1975). Loose, dry soils are comparatively poor thermal conductors because of the air contained in porous spaces within the soil. The thermal conductivity of soils increases, however, with the addition of water (Ellis and Mellor, 1995).

As noted, the materials that typically comprise impervious surfaces are thermally conductive. In addition, these materials have low specific heat capacities and thus heat rapidly when exposed to solar radiation. This is demonstrated by comparing a dry asphalt parking lot with an adjacent lawn. The parking lot has a low albedo; the lawn has a higher albedo. Radiant energy is transformed into sensible heat over the parking lot, whereas the lawn utilizes a significant amount of radiant energy in evapotranspiration. Also, the water contained in the grass and soil has a high specific heat capacity compared to asphalt, and hence the lawn's temperature does not increase as rapidly as that of the parking lot.

Lastly, the parking lot is more thermally conductive than the lawn; thus these two surfaces experience a striking difference in daytime surface temperatures. The daytime temperatures of impervious urban surfaces during the summer can be very hot, with temperatures at the surfaces of parking lots often exceeding 60^0 C (140^{0}F). Fortunately, air is a poor thermal conductor, since otherwise air temperatures over these surfaces would be even more uncomfortable and dangerous to human health (Kent *et al.* 2008).

Ratios of Sensible Heat to Latent Heat: Terrestrial heat energy enters the atmosphere as either sensible heat or as latent heat. Sensible heat is infrared energy that can be sensed and measured with a thermometer, and the other is energy that is used to evaporate

water. Latent heat cannot be felt, for it is essentially "locked-up" or stored in water vapor, keeping the molecules in a gas state. Evaporation of moisture serves to lower surface temperatures since the energy used in evaporation is not available for sensible heating. Therefore, evaporation is a cooling process. Only after water vapor condenses is this energy felt. This is because condensation releases latent heat to the atmosphere as sensible heat. Since impervious surfaces retain little rainfall and are drier than vegetated surfaces, most of the solar radiation reaching the surface is transformed into sensible heat rather than used in evapotranspiration (Douglas, 1983; Christopherson, 2001). Evapotranspiration is limited to lawns, patches of bare soil, and street trees (Strahler and Strahler, 1999). The results are higher daytime temperatures and lower relative humidity levels over urban areas.

Unfortunately, heat indices, which reflect felt temperatures based on the human body's reactions to temperature and humidity, remain higher for cities than for surrounding suburbs and rural areas. Any reductions in humidity over urban areas, providing hope for increased comfort, are essentially negated by temperature increases. This, coupled with restricted street level air circulation due to buildings, effectively raises summer heat indices and human discomfort levels in urban areas, especially during heat waves. This does not bode well for cities within the urban areas given projected increases in the frequency of summer heat waves due to global warming (EPA, 2000; MARA, 2000). However, the adverse impacts of heat waves and urban island effects in general can be partially offset by revegetating urban areas and by curtailing, or even reversing, the conversion of pervious surfaces to asphalt and concrete within and around cities.

The ratio of energy available for sensible heating (SH) to energy available for latent heating (LH) is known as the Bowen Ratio (Moran and Morgan, 1986) and is expressed conceptually as:

$$B = SH/LH$$

The Bowen Ratio, in turn, is used to calculate the Sensible Heating Index (SHI), which is the ratio of sensible heating to total heating (sensible + latent). It represents the proportion of total heat energy used to raise the temperature of air and is formulated as:

$$SHI = B/ (B+1)$$

Multiplying the index by 100 converts the value to a percentage. The higher the index value, the greater the percentage of available energy that is used for

sensible heating. Conversely, lower index values indicate higher latent heat fluxes to the atmosphere, which means greater evaporative cooling at the surface over the summer months. A comparison of Bowen Ratios and Sensible Heat Indices for different surfaces is presented in Table 5. Comparing warm season values for both measures reveals interesting similarities between deserts and urban areas, and striking contrasts between these two surfaces and more pervious surfaces. Although the Bowen Ratio for desert is much higher than that for urban, the magnitude of difference between the two values is less than that between the values for urban and grasslands. Moreover, the sensible heat indices for desert and urban surfaces are much closer in value to each another than is the sensible heat index for urban surfaces and those for grasslands and forests. It is not surprising that temperatures in urbanized areas are thus higher than in adjacent rural areas.

Table 5. Warm Season Bowen Ratios and Heat Indices for Selected Surfaces

Surface Type or Cover	Bowen Ratio	Sensible Heat Index (%)
Desert surface	20.0	95
Impervious urban surface	2.0	80
Grassland cropland	0.67	40
Coniferous forest	0.50	33
Deciduous forest	0.33	25

Source: Oliver (1973) as cited in Kent *et al.* (2008).

Conclusion: In general, trees provide, under their canopies (locally restricted), significant improvements on thermal comfort, principally during midday and in the early afternoon as they provide overhead shading by attenuating the solar radiation. The crucial benefit of shade, resulting in considerably lower mean radiant temperatures, has more influence on the thermal comfort expressed in PET than the decrease of the wind speed. Moreover, trees increase the quality of the public space, also due to other benefits, not included in this study yet, like absorption of rainwater and CO_2 and other air pollutants uptake.

Isolated trees and even rows of trees have a rather small impact on the decrease of air temperatures, and thus, apparently a limited potential for mitigating air temperatures of the urban heat island. Consequently, the possibility to improve energy efficiency of buildings by decreasing heat loads is limited. However, the lower surface temperatures of roofs and façades caused by the vegetation will contribute to lower cooling loads (Akbari *et al.*, 2001).

The uncontrolled conversion of land covers from permeable to impervious is a serious threat to the integrity of both natural and built environments within the urban areas, and to the comfort and overall quality of life for its residents. The increase in surface imperviousness and the outward diffusion of impervious surfaces from established urban and suburban core areas into rural lands are dramatically increasing the volumes of stormwater with which communities must contend. This increased runoff creates flood hazards and contaminates surface water with pollutants that accumulate on the streets, highways, parking lots, and even the lawns of urbanized areas, all the while degrading the physical quality of streams and environment. Due to the contributions of impervious surfaces to the urban heat island effect, human comfort is reduced during the summer. Aquatic and terrestrial habitats are degraded or lost as commercial, industrial, and residential land uses consume more and more space. Finally, the destruction and alteration of stream channels and the transformation of forests and croplands to residential subdivisions, malls, and parking lots are degrading the aesthetic quality of many of the urban areas and landscapes and invariably, its microclimate

Although urban and suburban growth is inevitable, many of the environmental impacts of impervious surfaces are avoidable or controllable. Working together, local governments and citizens can reduce the amount of land rendered impervious, and can reduce its adverse impacts, promoting a healthier environment through sound land use planning and improved land management. If there is a will to save the urban areas, there are ways to do it. Only the implementation of city-wide changes (from groups of trees to large-scale green space interventions), encouraged by modified building codes and citizens' initiatives, could promote a greener (well distributed vegetation in) urban areas and mitigation of the urban heat island. For this purpose, even in the 21st century, vegetation remains an irreplaceable urban element.

REFERENCES

Akbari, h., Pomerantz, M., Taha, H (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy Tampa*, 70(3), p. 295-310.

Ali-Toudert, F., Mayer, H. (2005). Thermal comfort in urban streets with trees under hot summer conditions. In: *PLEA 2005 – Passive and Low Energy Architecture*, 2005, Beirut International, p. 699-704.

Ali-Toudert, F., Mayer, H (2008). Effects of asymmetry, galleries, overhanging façades and

Effects of Vegetated and Synthetic (Impervious) Surfaces…..

vegetation on thermal comfort in urban street canyons. *Solar Energy Tampa*, 81, p. 742-754.

Arnold, C. L., Jr., and Gibbons, C.J (1996). Impervious surface coverage: the emergence of a key environmental indicator. *Journal of the American Planning Association* 62 (2): 243-258.

Barbara, C (1956). Microclimate. *Tuatara* 6 (2). 52-56

Booth, D. B., and Jackson, C.R (1997). Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association* 33(5): 1077-1090.

Bruse, M. ENVI-met v. 3.0. Available at: <http://www.envi-met.com>. Accessed 1 July 2009.

Bueche, F. J. (1979). College Physics. 7th ed. New York: Schaum's Outline Series, McGraw-Hill Book Company.

Chatzidimitriou, A., Chrissomallidou, N., Vannas, S (2005). Microclimate modifications of an urban street in northern Greece. In: PLEA 2005 – Passive and Low Energy Architecture, 2005, Beirut. *Proceedings PLEA 2005 – Passive and Low Energy Architecture*, Beirut: PLEA International, p. 689-694.

Christopherson, R. W. (2001). Elemental Geosystems. 3rd ed. Upper Saddle River, NJ: Prentice-Hall.

Cleugh, H. A., E. Bui, D. Simon, J. Xu and V.G. Mitchell (2007). *The impact of suburban design on water use and microclimate.* CSIRO Marine and Atmospheric Research, CSIRO Land and Water Institute for Sustainable Water Resources, Department of Civil Engineering, Monash University: Pp. 2019-2025.

Conway, E. D. and The Maryland Space Grant Consortium (1997). An Introduction to Satellite Image Interpretation. Baltimore, MD: The Johns Hopkins University Press.

Danielson, E. W., J. Levin, and E. Abrams. (1998). Meteorology. New York: WCB/McGraw-Hill.

Douglas, I. (1983). The Urban Environment. Baltimore: Edward Arnold.

Ellis, S. and A. Mellor. (1995). Soils and Environment. New York: Routledge.

Emmanuel, M. R (2005). An Urban Approach to Climate-Sensitive Design – Strategies for the Tropics. New York, Spon Press, 2005.

Forsythe, W. E. (1959). Smithsonian Physical Tables. Washington, D.C.: The Smithsonian Institution.
Geiger. R. (1927) — 'Das Klima der Nodennaben Luftschicht.' (Revised 1942.) '*The Climate near the Ground*', an English translation by M. N. Stewart and others, 1950.
Hansen, N. R., Babcock, H.M., and E. H. Clark II. (1988). Controlling Nonpoint-Source Water Pollution: A Citizen's Handbook. Washington, D.C.: The Conservation Foundation and The National Audubon Society.

Hubbart, J.A (2009). *Urban ecosystems: alterations to peakflow, microclimate, and the natural environment.* University of Missouri, PS 74-184

Johansson, E (2006). *Urban design and outdoor thermal comfort in warm climates – studies in Fez and Colombo.* Thesis (PhD in architecture), Housing Development & Management, Lund University, Lund, Sweden.

Kent B. B., Morgan III, J.M., and Martin C. R (2008). *Impervious surfaces and the quality of natural and built environments.* Department of Geography and Environmental Planning, Towson University Baltimore, Maryland 21252: Pp. 1-28.

Mid-Atlantic Regional Assessment Team - MARA. (2000). *Preparing for a changing climate: the potential consequences of climate variability and change.* Available from http://www.essc.psu.edu/mara.

Marsh, W. M (1998). Landscape Planning: Environmental Applications. 3rd ed. New York: John Wiley & Sons, Inc.

Moran, J. M. and Morgan, M.D (1986). Meteorology: The Atmosphere and the Science of Weather. Edina, MN: Burgess Publishing.

Novotny, V. and G. Chesters. (1981). Handbook of Urban Nonpoint Pollution: Sources and Management. New York: Van Nostrand Reinhold Company.

Oliver, J. E. (1973). Climate and Man's Environment: An Introduction to Applied Climatology. New York: John Wiley & Sons, Inc.

OBIAKOR, M. O; EZEONYEJIAKU, C.D; MOGBO, T.C

Effects of Vegetated and Synthetic (Impervious) Surfaces…..

Oke, T. R (1989). The Micrometeorology of the Urban Forest. Phil. Trans. Royal Society London, London, B324, p. 335-349.

Schueler, T. R. (1994). The Importance of Imperviousness. *Watershed Protection Techniques* 1(3): 100-111.

Shashua-Bar, l., Hoffman, M. E (2004). Quantitative evaluation of passive cooling of the UCL microclimate in hot regions in summer, case study: urban streets and courtyards with trees. *Building and Environment*, Oxford, 39, p. 1087-1099.

Spangenberg, J (2004). *Improvement of Urban Climate in Tropical Metropolis – A case study in Maracanã/ Rio de Janeiro*. Thesis (Master in architecture), University of Applied Sciences, Cologne, Germany, 2004. Available at: < http://www.basis-id.de/science >.Acessed 3 March 2008.

Spangenberg, J., Shinzato, P., Johansson, E., Duarte, D. (2007). The impact of urban vegetation on microclimate in hot humid São Paulo, In: PLEA 2007 – Passive and Low Energy Architecture, 2007, Singapure. *Proceedings PLEA 2007 – Passive and Low Energy Architecture*, Singapure: PLEA International.

Strahler, A. N. (1975). Physical Geography. 4th ed. New York: John Wiley & Sons, Inc.

Strahler, A. and Strahler, A.N (2000). Introducing Physical Geography. 2nd ed. New York: John Wiley & Sons, Inc.

Taha, H (1997). Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings*, Oxford, 25, p. 99-103.

Terry J. W., and Evyatar, E. (2001). Thermal performance simulation and the urban microclimate: measurements and prediction; *Seventh International IBPSA Conference* Rio de Janeiro, Brazil,August 13-15, 2001: 159-164

U. S. Environmental Protection Agency (2000). *EPA Global Warming State Impacts*. Available from http://www.epa.gov/globalwarming/impacts/stateimp.

UWYO. Soundings (2007). Available at: <http://weather.uwyo.edu/upperair/sounding.html>. Accessed 1 July 2007.

Whipple, W. Jr. (1977). Planning of Water Quality Systems. Lexington, MA: Lexington Books.

Yu, C., and Hien, W. N (2006). Thermal benefits of city parks. *Energy and Buildings*, Oxford, 38, p. 105-120.