Impact of green infrastructures on urban microclimates. A critical review

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ABSTRACT: Temperature is the most relevant factor affecting the urban microclimate. Increased urban density, hard surfaces with inappropriate thermal property and lack of vegetation have resulted in the increase of temperatures in urban areas and high pollution levels. In return, greening is known as the best solution for mitigating high temperatures in urban context, thus has recently become the focus of extensive research. In this paper, a systematic literature review is performed to investigate the effect of vegetation on microclimate in urban context focusing on air temperature, humidity and wind speed. Parks and urban green spaces are the features studied with respect to two different methodologies used for data collection: on-site measurements and numerical calculation or modelling. The aim of this study is to compare results of the two methodological approaches used by researchers in order to investigate their similarities and differences. The comparison shows that both methods can be applied for studies at various scales, from circumscribed areas such as parks and their surroundings (micro scale) to investigation including the whole city (mesoscale). However, due to costs and time constrains, studies using field measurements are mostly limited to one season thus lacking comparative analysis of effects of vegetation over longer periods. Instead, the use of simulations and modelling can help including different temporal scenarios and a variety of parameters in the study, even though in a more simplified form than in real case studies. According to the review while empirical data collection was more popular in the past, simulations and modelling have been used more frequently in recent years due to the advantages mentioned above. It also shows that best results can be achieved integrating the two approaches, where field measurements can either provide realistic data for simulation input or represent a means for validation of modelling outputs.

Conference theme: Urban and Landscape studies
Keywords: Urban microclimate, vegetation, density, empirical field measurements, modelling and simulations.

INTRODUCTION

There is a reciprocal relationship between cities and their climate. Cities affect their own climate, and in turn, the climate influences the usage of urban public open spaces (Kleerekoper, van Esch et al. 2012). Increased urban density, hard surfaces with inappropriate thermal properties and lack of vegetation have resulted in the increase of temperatures in urban areas and high pollution levels (Katayama, Ishii et al. 1993). The 2009 UN-Habitat report investigated different challenges that cities face these days, including the lack of green development ratio to the built environment. Accordingly, a comprehensive set of green policies and strategies (e.g. distributed green infrastructure strategies, renewable energy and carbon-neutral strategies, etc.) has been indicated to be used for filling the gap between urban and green development toward a higher resilience and adaptability to climate change (UN-Habitat 2009).

Many studies have already pointed out problems that medium to high density cities are currently facing due to lack of green areas, such as the urban heat island (UHI) effect, with consequent increasing energy consumption and pollution. As vegetation is an important component in the microclimate of urban areas and plays a key role in mitigating the air temperature, in the last two decades, there has been an increasing interest in investigating different ways vegetation can improve the quality of open spaces, both physically and psychologically.

UHI is the best-known phenomenon referring to temperatures in urban areas, being higher than in the surrounding rural environment. Various studies (Potchter, Cohen et al. 2006; Yu and Hien 2006; Georgi and Dimitriou 2010) have confirmed that the presence of green areas contributes to the mitigation of the UHI by decreasing the air temperature and creating a cooling effect on the surrounding areas (Oliveira, Andrade et al. 2011). Besides the positive effects of vegetation on urban microclimate, advantages of urban greenery with regard to human behaviour and the perception of the urban context, UHI can be summarized in different categories including economic, physiological, perceptual, and symbolic functions as stated by Smardon (1988).

Many important effects of vegetation in the urban context have been verified in relation to different aspects of city life. Pollution and air quality (Steffens, Wang et al. 2012), microclimate and thermal comfort (Dimoudi and Nikolopoulou 2003; Santamouris, Synnefa et al. 2011), and noise levels (Watts, Chinn et al. 1999) are some of the most important
areas where vegetation has a relevant physical impact, while neighbourhood safety (Li 2012) and reduced energy consumption of buildings surrounding green areas (Sailor 1998) are other significant effects to be mentioned.

Evaluation of monitored data and modelling studies with numerical calculations are the two main methodological approaches used for assessing the effects of vegetation in urban areas, at both macro and micro scale (Chow, Pope et al.; Andrade and Vieria 2007; Zoulia, Santamouris et al. 2009; Bowler, Buyung-Ali et al. 2010; Oliveira, Andrade et al. 2011; Chow and Brazel 2012). At a micro scale, either microclimatic conditions of different parts of green areas are compared, or the mean air temperature of a green area is compared to air temperatures of its immediate surroundings (Chang, Li et al. 2007; Zoulia, Santamouris et al. 2009; Georgi and Dimitriou 2010; Oliveira, Andrade et al. 2011). At a macro scale instead, the role of green areas is analysed in relation to complex dynamics of the whole urban context (Katayama, Ishii et al. 1993; Wong and Yu 2005; Yu and Hien 2006).

This paper presents a review of studies evaluating the effects of the vegetation on urban microclimates, at both macro and micro scale. However, among all the possible green infrastructures - including street planted trees, parks, gardens, green roofs and green walls – it focuses on parks and gardens. In particular, it considers studies that measure air temperature within green areas and compared them to the air temperature of either their immediate surroundings or other parts of the city.

The parameters that are investigated in this paper include the different types of methodologies used for assessing the effect of vegetation on urban microclimates, questions and objectives of the studies in relation to their methodology, and advantages and disadvantages of the applied methods.

1. URBAN HEAT ISLAND

Temperature is the most affecting feature of the urban microclimate and the one most characterizing city’s climate (Gomez, Gaja et al. 1998). After the Industrial Revolution, cities and urban spaces started to grow rapidly. Usage of hard materials and the general lack of vegetation had a direct effect on the microclimate of urban spaces especially in city centres, causing an increase in ambient air temperatures, named as “Urban Heat Island” (UHI) (Alexandri and Jones 2008). This term was first mentioned by meteorologists (Howard 1833) and finally coined by Marley in 1958 (Manley 1958). Since then it has been widely used, especially in recent years and was recognized by Landsberg (1981) as the most obvious climatic manifestation of urbanization, which can be observed in every town and city.

The primary cause of the UHI effect is the solar radiation absorbed by mass building structures, hard surfaces and roads during the day, and being re-radiated at night to the environment (Wong and Yu 2005). The intensity of this phenomenon depends on the heat sources’ intensity and may vary from 1 to 10 degrees Celsius of air temperature increase, with huge environmental impacts (Zoulia, Santamouris et al. 2009). However, high temperatures are not the only recognized negative effect of UHI. There are more consequences that can be observed such as heat strokes affecting humans’ well-being, the dust dome worsening the air pollution and, as an indirect effect, a higher demand of electricity for building air-conditioning (Chang, Li et al. 2007).

Furthermore, the problem of UHI is not just limited to cities and urban areas, but has become a serious problem globally, as a steady increase of temperatures within and around urban areas has been detected worldwide (Chang, Li et al. 2007). For example, according to McPherson (1994), the temperature of the downtowns in US cities has been increasing by 0.1-1.1°C per decade for the last 50 years. In addition, rapid urbanization and cities’ development have caused an increase in greenhouse gases’ emissions leading to a further increase of global temperature. Given the global impact of this phenomenon, mitigation strategies for decreasing the negative effects of UHI are imperative and require urgent actions (Chang, Li et al. 2007).

Based on literature on the subject and according to Chang Li et al. (2007), there are six main strategies for mitigating the UHI effect; modification of urban geometry, use of light-coloured surfaces, policies and measures to increase energy efficiency, management of traffic and better transportation system design, use of permeable surfaces, and use of vegetated surfaces.

Research done in recent years clearly proves the direct correlation between UHI and the decrease of greenery in the urban context (Wong and Yu 2005). It also suggests that temperatures in urban areas (both air and surface temperature) can be decreased to various extent by greening urban surfaces, depending on the climate of the place, the amount and type of vegetation and the urban geometry (Alexandri and Jones 2008). Indeed, a study by Rowntree et al. (1982) in Dayton, Ohio analysing urban parks, shows that approximately 25-50% of UHI temperature increase can be avoided through usage of vegetation.

2. VEGETATION AND MICROCLIMATE

The microclimate of a specific site is influenced by many different factors that can be summarized in four main categories; (1) Urban Heat Island, caused by buildings, traffic, surfaces absorbing solar radiation, lack of vegetation and high urban density. (2) Topography and geometry of urban gorges, including their altitude, slope, orientation, nearby hills and valleys. (3) Terrain surface and heat sources, including the type of surface (natural / man-made), and its characteristics (water / soil / colour). (4) Vegetation and obstructions, such as hedges, trees, walls and buildings (Giannas 2001; Hocine and Bougadah 2010).
The high rate of solar radiation absorption of greenery and its low heat capacity and thermal conductivity, have made green spaces the most effective solution in mitigating high air temperatures. The two main ways for trees to mitigate high temperatures and reduce summer peaks in urban areas are through shading and via evaporation (Georgi and Dimitriou 2010). Therefore, various vegetative areas affect the urban microclimate differently, depending on the characteristics of the existing plants, such as their evaporation rate. Indeed, a specific area of beech wood has 83.8% of evaporation which would be reduced to 64.8% for the same area of pine forest.

In addition to the type of vegetation, the value of park-induced coolness, i.e. the park cool island (PCI) effect, differs depending on the time of the day. A research conducted by Spronken-Smith in Vancouver in 1996, revealed that in a garden park with a mixture of grass, trees and shrubs, the largest cooling effect occurs soon after sunset, while a park with open grass surface will have the largest PCI shortly before sunrise. As a matter of fact, parks with huge tree coverage have a warmer surface temperature than open grassed parks after sunset, which is caused by the higher heat transfer due to less horizontal obstructions in the open grassed parks. It means that the PCI of a park occurs differently depending on its vegetation type. Indeed, according to Bernatzky (1982) during the day time, the cooling effect of trees is greater than lawns due to evaporation while, at night, cooler air can be found in areas covered with lawns and meadows.

Besides the effectiveness of the type and amount of vegetation used in open spaces for reducing air temperatures, when planning mitigation strategies there are other factors to be considered, which could potentially have an even higher impact. The meteorological conditions at the time of the field measurement and the usage of different data collection methods could indeed lead to significantly different results of otherwise identical studies.

As a consequence, if the effect of vegetation on urban microclimates differs due to specific climatic conditions, it can be concluded that detailed studies are required for each city, focusing on the interaction of vegetation with local climates and the specific urban development (Ng, Chen et al. 2012). As a general rule though, as mentioned by Alexandri and Jones (2008), the hotter and drier a climate is, the more the presence of vegetation is beneficial for the mitigation of the UHI effect.

Once the need for conducting research in each city has been established, the scale of the area under observation becomes of primary importance. There are two scales at which the effects of vegetation can be investigated; the micro scale, when the research focus is on single green areas, and the macro scale, which considers the interaction between green areas and the wider urban context.

The micro scale approach usually includes two different types of investigation. The first type compares different parts within the same green area (Chang, Li et al. 2007; Zouila, Santamouris et al. 2009) to verify how various characteristics of the greenery can differently affect the air temperature. In the other type of investigation, the mean air temperature of a target green area is compared to the air temperature of its immediate surroundings in order to investigate the PCI effect (Alcoforado 1996; Spronken-Smith and Oke 1998; Shashua-Bar and Hoffman 2002; Andrade and Vieria 2007; Zouila, Santamouris et al. 2009; Oliveira, Andrade et al. 2011).

In the macro scale approach instead, the air temperature inside the green area is compared to that of other parts of the city, especially the city centre, which is expected to have the highest temperature due to its high density with high rise commercial zones (Wong and Yu 2005).

Studies conducted so far at both scales show that factors influencing the extent of green areas’ effects on the urban climate are almost the same regardless of the research scale (micro or macro scale). The most influencing factors include the characteristics of the green area (i.e. its size, type and the amount of existing vegetation in the green space), the characteristics of the urban area where the green infrastructure is located (i.e. topography, UHI and city density), the meteorological conditions of the location, and season and time of the day. However, some of the mentioned factors do not apply at the micro scale, such as UHI and the urban density, which are not relevant when considering variations within the same green area. At this scale though, several studies have proved that amongst the characteristics of the urban area, topography is the most important parameter affecting the PCI intensity.

For example, a recent study done in Lisbon, a city characterized by a subtropical-Mediterranean climate (Köppen climate classification: CsA) revealed that the value of PCI effect can reach the maximum of 6.9 °C, (Oliveira, Andrade et al. 2011). This result was similar to those of previous studies carried out in the same city in 1996 and 2007, during late spring and in summer by Alcoforado (1996), and Andrade (2007), which found the value of the PCI to be respectively between 3.9 and 5.7°C, and 4.1°C. In these studies temperature differences were ascribed to the topographic features of the green areas’ surroundings and the subsequent different solar exposure.

3. LOCAL COOL ISLAND OR LOCAL HEAT ISLAND

So far the cooling effect of vegetation has been investigated in many studies at different scales and in various cities, confirming the benefits of green areas in different climates, generally characterised by hot, either dry or humid summers. For example, Berkeley and Sacramento have both Mediterranean climates, according to the Köppen climate classification. However, the summer in Berkeley, is cooler than a typical Mediterranean climate, while in Sacramento summer days are hot and dry. Despite this difference, the cooling effect of green area has been observed in both cities. Parker (1989) reported a medium reduction of 3.6 °C in air temperature during the summer in Berkeley. These findings were confirmed by results of the research done in Sacramento by Spronken-Smith and Oke (1998), which found a value of 1.2-2.4 °C for an average daytime PCI that could reach 6.5 °C "under more ideal
conditions”, for example the usage of appropriate type of vegetation with high rate of evaporation, or the parks’ moisture condition, depending on irrigation, and a more suitable park design.

Effects of vegetation were also tested in the more extreme climatic condition of an arid region of southern Israel, with hot dry summers and cool winters. Here Shashua-Bar et al. (2009) compared the temperature of two courtyards, one with bare pavement and mesh and the other with grass and trees, both oriented along the North-South axis and with the same height to width ratio. Results revealed that the most effective situation in terms of cooling was the combination of trees over grass, which allowed achieving up to 2 °C air temperature reduction.

In the different context of Mexico City, with tropical highland climate, the influence of a park of 500 hectares on its surrounding build-up area was investigated by Jauregui (1990). The study verified that the air temperature in the park was 2-3°C cooler and the influence of vegetation affected a neighbouring area with the same size as the park’s width.

The cooling effect of green areas at macro level was also proved by two surveys conducted by Wong and Yu in 2002, mapping out the Singapore island temperature distribution. In Singapore, which has a tropical climate with hot and humid summer, a maximum difference of 4.1°C between well planted areas and the CBD – with the highest temperature - was observed.

This seems to confirm that city centres can benefit the most from the presence of vegetation. However they are not the only ones. For example, through measurements conducted in Valencia, Spain – a city characterized by subtropical climate with long, warm to hot summers, Gomez et al. (Gomez, Gaja et al. 1998) emphasized the importance of green zones for tempering the temperature even in situations that were not favourable to the formation of heat islands.

Although all the mentioned studies agree with the fact that different climates can benefit from the cooling effect of green areas, some research found parks can sometime work as local heat islands instead. An example is the study conducted by Chang et al. in 2006 and 2007, comparing air temperatures in 61 different urban parks in Taipei to those of their surroundings. Data was collected in summer and winter at noon and during the night. Results confirmed that on average parks were cooler than their surroundings, with the greatest difference being at noon in summer - when parks were 0.81 K cooler on average - while the least difference was 0.16 K during winter nights. However, results also revealed that almost one fifth of the parks with more than 50% of paved surface and little greenery coverage, had higher air temperatures in comparison to their surroundings and had a function of ‘local heat islands’ instead of being ‘local cool islands’ (Chang, Li et al. 2007). These results are similar to those in research conducted by Zoulia et al. (2009) in the National Garden of Athens, where 5 different routes inside the garden were compared to its immediate surroundings in terms of air temperature. The garden was found not to be cooler or hotter than its immediate surroundings. However, it was found to be cooler than other areas in the city centre (Zoulia, Santamouris et al. 2009).

4. ALTERNATIVE METHODOLOGICAL APPROACHES

According to the objectives of each specific research, different methodologies can be applied for assessing the effect of vegetation on the urban climate. From the reviewed studies (Zoulia, Santamouris et al. 2009; Bowler, Buyung-Ali et al. 2010; Oliveira, Andrade et al. 2011) results show that there are two main methodological approaches commonly used; evaluation of monitored data and modelling studies with numerical calculations, both applicable at macro and micro scale, as shown in the graph 1 below.

Graph1: methodological approaches used for assessing the effect of vegetation in urban areas

In research done using either of the two methodologies at the macro scale, the area under investigation would be extended to the whole city. The green area at this scale is mostly compared with other parts of the city, especially the city centre, and it is emphasized on the necessity of having green areas as the city’s ‘breathing’ places. At the micro scale instead, both methodologies would investigate only a limited portion of the city, which can be up to the size of an urban block. Different parts of a single green site are compared in order to establish possible relationships between variables, such as air temperature reduction and the ratio of hard surfaces materials used in green areas. At the same scale, another possible approach is the comparison of parameters measured inside the green area and in its immediate surroundings, in order to investigate how effective a green area can be or to verify the extent of the PCI.
Field measurements are done at the micro scale either by using fixed sensors placed on site in representative locations and regularly measuring variables of interest, or recording data by conducting mobile surveys across the green area and their immediate surroundings. At the macro scale instead, data is collected by either employing meteorological data from stations around the city, remote sensing data (Cheng, Su et al. 2008), mobile measurements by crossing parts of the city, or a combination of the above (Zoulia, Santamouris et al. 2009). For mobile surveys, depending on the scale and size of the case study, walking, bicycle or cars equipped with measurement devices can be utilized.

The other methodological approach, modelling studies, at both scales, uses models to investigate basic patterns of vegetation’s urban effects, e.g. air temperature rise and humidity decrease. In order to obtain a better understanding of theoretical issues, numerical modelling can be strengthened through input of data from on-site measurements (Ng, Chen et al. 2012).

At the micro scale, this methodology has been successfully applied either to verify effects of virtual changes of some parameters (e.g. increasing the existing amount of greenery) within an existing green area, or to assess the impact of green areas virtually added to urban blocks that are actually lacking vegetation. While at the macro scale, the existing situation of the whole city can be tested against possible variations and the presence of green areas can be investigated in relation to multiple complex parameters.

Two methods are used for modelling purposes at the micro scale; empirical models based on the statistical analysis of monitoring data, such as ENVI-met – a three dimensional numerical model used for studying the surface-plant-air interactions in the urban environment at the microclimate scale (Ali-Toudert and Mayer 2007) - and simple models describing the basic physiology of plants or Computational Fluid Dynamic (CFD) (Dimoudi and Nikolopoulou 2003). Simple models can be developed and programmed by the researchers for special purposes of the research. For instance, a two dimensional, prognostic micro-scale model was programed in C++ by Alexandri an Jones (2008) in order to investigate how the UHI effect can be decreased in different climates by covering the surface of buildings with vegetation. CFD instead, is a three dimensional modelling tools that can be applied to determine local effects of building and vegetation on the urban environment at the micro scale. Spatial distributions of flow, temperatures and scalar fields can be predicted in detail by using CFD models inside complex urban areas (Lun, Mochida et al. 2009). Both types of investigation though require appropriate information about the physiology of different vegetation types (e.g. their evaporation rate), and their effectiveness, which can be obtained from onsite measurements. Thus they ultimately rely on information obtained through empirical data collection.

At the macro scale instead, meso-scale atmospheric models are utilized (Pielke Sr. 2002), which can provide an overview of the whole city from different points of view, showing different features such as, radiation, heat exchange, soil or vegetation.

5. CONCLUSION AND FURTHER RESEARCH

The methodology chosen for assessing the effect of vegetation on the urban environment ultimately depends on the context, the research question and facts under examination. However there are two main methodologies usually applied, namely the evaluation of monitored data and modelling studies.

Results of the reviewed studies based on both methodological approaches, agree on the beneficial effect of vegetation on urban microclimate. However, similarities and differences between the two research streams – and their related advantages - should be considered when choosing the methodology to apply in specific contexts.

Both methodologies can be used for research at micro and macro scale. However, using modelling and simulation allows researchers to apply specific ‘changes’ – by modifying selected parameters - at the micro scale and then observe and measure their effects at macro level. This results in a greater flexibility of the research set up.

Research based on data gathered through empirical field measurements is certainly more specific, although is limited in time and space. On the other hand, numerical modelling using input of data from on-site observation may provide a more comprehensive and reliable understanding of the investigated phenomena. Otherwise, research based on modelling is mostly simplified and focused on one or two factors only at the time. For instance, a study on the effect of increased size of the vegetated area on air temperature reduction would not be able to consider the vegetation type and the effect it has on other microclimatic parameters such as wind speed or relative humidity. In other words, the parameters’ interaction could not be investigated.

On the other hand, the influence of some factors, such as the green area size, on mitigating air temperature in the same context can only be investigated by modelling. Indeed, field measurements and comparison of different green areas would not be a suitable approach in this case, as it would be unlikely to find two green areas with exactly the same characteristics and just differing in terms of size.

For achieving some practical design guidelines and observing the interaction between parameters, numerical modelling and simulations represent an easier approach, which is also much faster and less expensive than field measurements (Ali-Toudert and Mayer 2007).
All the studies using modelling methods that were considered in the literature review, found the green areas acting as cool islands, even when field measurements were done prior to the simulation phase to provide reliable data input. More recently though, literature dealing with empirical field measurements has emerged that offers contradictory findings about the cooling effect of vegetation, showing that green areas can act as heat islands, and various air temperatures might be experienced in different parts of a green area due to its different characteristics. The answer to such doubts requires further research to examine the cooling effect of green areas and relate their coolness to their specific characteristics.

The reviewed studies have always used an inside-out approach, investigating the cooling effect of green areas on their surroundings. However, the way surroundings may affect the mean air temperature inside green areas has not been investigated so far. The different impact of a same green area, when located in contexts that differ e.g. in terms of density and UHI can be the scope for future research.

Whilst researchers have agreed on the importance of vegetation for cities, few studies have focused on design guidelines to determine the amount, type and distribution of greenery that would be needed to achieve more suitable urban climatic conditions. On the other hand, 'global' principles and rules would not help as specific research and additional measurements are required for each city, due to the characteristics of different urban areas the green spaces used.

REFERENCES


