Positive effects of vegetation: Urban heat island and green roofs

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ABSTRACT

This paper attempts to evaluate the positive effects of vegetation with a multi-scale approach: an urban and a building scale.

Monitoring the urban heat island in four areas of New York City, we have found an average of 2°C difference of temperatures between the most and the least vegetated areas, ascribable to the substitution of vegetation with man-made building materials.

At micro-scale, we have assessed the effect of surface albedo on climate through the use of a climatological model. Then, using the CO2 equivalents as indicators of the impact on climate, we have compared the surface albedo, and the construction, replacement and use phase of a black, a white and a green roof. By our analyses, we found that both the white and the green roofs are less impactive than the black one; with the thermal resistance, the biological activity of plants and the surface albedo playing a crucial role.

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1. Introduction

At the beginning of the twentieth century, 15% of the world population lived in cities. Currently, about 50% of the world population lives in urban areas, which is approximately 2.8% of the total land of our planet (Millennium Ecosystem Assessment, 2005). The increase in urban inhabitants has led to urban sprawl, especially in developing countries (United Nations, 2004). It is often associated with the rise in urban temperatures (Bacci and Maugeri, 1992), the so-called urban heat island (UHI) effect.

The UHI mainly depends on the modification of energy balance in urban areas which is due to several factors: urban canyons (Landsberg, 1981), thermal properties of the building materials (Montavez et al., 2000), substitution of green areas with impervious surfaces that limit evapo–transpiration (Takebayashi and Moriyama, 2007; Imhoff et al., 2010), and decrease in urban albedo (Akbari and Konopacki, 2005).

Many studies established the correlation between an increase in green areas and a reduction in local temperature (e.g., Takebayashi and Moriyama, 2007), suggesting the augmentation of urban vegetation as a possible mitigation strategy for the UHI. Since in densely urbanized areas there are few residual spaces that can be converted into green areas, one solution could be to turn traditional black flat roofs into green ones.

Roofs constitute about 20–25% of the urban surface (Akbari et al., 2003). Their urban-wide conversion into green roofs can give rise to many benefits both on urban scale – effects on UHI, air quality, storm-water management, biodiversity and urban amenities (Oberndorfer et al., 2007); and on building scale – increase in life span of the building materials underneath the soil, reduction of noise, decrease in building energy use especially during summer (Saiz et al., 2006). In particular, several existing traditional black flat roofs could be converted into extensive green roofs – characterized by being relatively lightweight – without their structural support will be improved (Castleton et al., 2010; Johnston and Newton, 1996). In fact, extensive green roofs are constituted by shallower growing media (5–12 cm) than intensive green roofs (>12 cm) (Carter and Keeler, 2008) and, as a consequence, they constitute lower dead and live loads for the structure underneath than intensive green roofs.

Although both vegetation and green roofs have been explored in previous literature, the aim of this paper is twofold. First, we want to show the positive effect of vegetation through a multi-scale approach monitoring both the air temperature in New York City and the surface temperature of three roofing systems, since previous research mainly focus on just one of these two aspects. Second, in order to provide information about environmentally preferable choices, we have compared three types of roofs: a black, a high-reflective and an extensive green roof. Since much of the research on
roofs' building materials.

2. Methodology

The research has been developed in five stages:

- analysis of the field data recorded in different areas in New York City;
- comparison of the temperatures recorded in the core of the city (Columbia University) and in a widely forested area (Fieldston in the Bronx);
- evaluation of the difference of heat fluxes through the three roofing systems;
- application of a climatological model capable of translating the increase in surface albedo into avoided kilograms of equivalents of CO₂ (CO₂eq) emitted;
- evaluation of the building materials’ life span.

2.1. The urban scale

The UHI in New York City is characterized by an annual average difference of temperatures between urban and rural sites of about 2.5 °C (Gaffin et al., 2009). The UHI is the cause of about 1/3 of the total warming the city is experiencing since the beginning of the twentieth century (Gaffin et al., 2008).

In the first step of our research we have monitored some weather parameters such as solar radiation, wind-speed, relative humidity, precipitation, wind direction and air temperature in four areas of New York City distinguished by different urban structures. The temperatures have been recorded by four full weather stations installed in: Columbia University; Con Edison building in Long Island City; Fieldston in the Bronx; and Queens Botanical Garden (Fig. 1).

The surveys – started at different times in the different areas of the city – have been considered in the overlapping period: from October 6th, 2008 throughout May 31st, 2009. For the cited time-frame, we have constructed the mean hourly trend of the air temperatures recorded in the four areas and we have compared it with a vegetation map. By this comparison, we found what we expected: to the most densely urbanized area corresponds the highest temperatures, and to the most vegetated area the lowest ones. Then, we have collated the urban temperatures carried out in Columbia University area – the most urbanized area – and in Fieldston – the most vegetated area among the four – for a period longer than that of the previous analysis: from March 2008 throughout February 2009. We have analyzed both diurnal/nocturnal and seasonal behavior of the differences of temperatures in order to detect the positive effects of vegetation on the UHI in New York City.

2.2. The micro-scale

The purpose of the second part of our study is to assess the effects of vegetation on micro-scale and, in detail, to compare an extensive green roof and a high-reflective white roof with a traditional black one. Although previous studies evaluated the benefits of white and green roofs (e.g., Saiz et al., 2006; Kosareo and Ries, 2007), and the potentiality of green roofs in decreasing air temperature and energy use for cooling during summer (e.g., Alexandri and Jones, 2008; Wong et al., 2003; Akbari et al., 1992), in none of them was the effect of surface albedo on RF evaluated. Just one research study has been conducted which took into account the global warming potential associated with pavement albedo (Santero and Horvath, 2009). Furthermore, no studies can be found in literature about the influence of surface albedo on both energy fluxes and RF responsible for climate change.

In our research, we provide information about environmentally preferable choices among the three roofing systems evaluated in a time-frame of 50 years. In this perspective, we have assessed — through the use of a climatological model – the effect of the surface albedo on climate change in terms of kilograms of CO₂eq. Furthermore, we have investigated the difference of heat fluxes through the three roofs using field data and the enhancement of the life span of green roof building materials using data from the literature. Finally, we have used the CO₂eq as environmental descriptor in order to compare the effects of the construction, replacement and use phase on climate change with those of the surface albedo.

The outcomes of the vegetation on the building scale have been investigated through the monitoring carried out from October 2008 through September 2009 on the three roofing systems installed on the three-storey Con Edison ‘Learning Center’ office building in Long Island City, Queens, New York. On the office building, a small part of the black Ethylene–Propylene Diene Monomer (EPDM) membrane has been substituted with a high-reflective membrane. In addition, about 1000 m² of the same black roof have been converted into an extensive green roof. The three roofing systems feature the same structural support (Figs. 2 and 3). The white and the black roof differ only in the surface albedo (Fig. 2, Table 3). The green roof is constituted by a 10 cm deep growing medium layer, that increases the thermal resistance and the latent thermal capacity of the roof (Eumorfopoulou and Aravantinos, 1998), covered with more than 21,000 plants of sedum. Beneath the soil there is a filter membrane, a drainage layer and a waterproof roof repellent layer (Fig. 3).

The three roofs are constantly monitored. A system of probes is settled at different depths in the green roof in order to record the temperatures on the soil.

Fig. 1. Vegetation map by Small (2006) with the indication of the localization of the weather stations.
surface, at 5 cm depth, at 10 cm depth, and above and below the insulation board. The recorded temperatures at 10 cm depth have been used to calculate the differences of heat fluxes between the green and the conventional black roof.

2.2.1. Energy fluxes

The differences of heat fluxes between the flat traditional black roof — considered as reference — and the white and the green roof have been calculated using the following one-dimensional equation calculated in a steady-state:

\[ \Delta Q = \frac{\Delta T}{R} \quad [\text{W m}^{-2}] \]

\( \Delta Q \) is the difference of heat fluxes between the black roof and one of the two other roofs (white or green). \( \Delta T \) is the hourly difference of the surface temperatures between the black membrane and the white one. On the green roof the hourly temperature recorded on the soil bottom has also been considered. Indeed, in reducing the uncertainties due to the oscillation of the thermal resistance of the soil, which depends on its dampness, we have calculated the heat fluxes through the green roof using the temperatures recorded under the soil layer at a depth of 10 cm. At this depth, the thermal resistance of the building materials underneath (Table 2) is approximately the same as that of the white and the black roofs (Table 1). \( R \) is the thermal resistance of the black and white roof that is approximately equal to the thermal resistance of the structure underneath the soil in the green roof.

The difference between the fluxes through the black and the white roofs, and between those through the black and the green roofs has been calculated both in winter (December 2008—February 2009) and in summer (June—August 2009) (Table 3). The differences of heat fluxes have been used for calculating the use of energy in the offices considering two scenarios: electric power for cooling and heating.
2.2.2. Albedo

In the evaluation of the three roofing systems, we have assessed the effects of a key characteristic of the surface materials: the surface albedo. Surface albedo influences absorption and reflection of the solar radiation. This affects energy use, especially during the warm season, local air quality, and greenhouse gas concentration (Taha, 2008). The albedos of the three roofs have been evaluated by applying a climatological model capable of converting variation in surface albedo into variation in RF, and then into CO2eq. By the climatological analysis, an increase of 0.01 in the surface albedo corresponds to an amount of biomass such as fungi or algae (Levinson et al., 2005). Since at the time of application on the roof surface to 0.6 for the deposition of dust and soot or for the consideration the typical albedo of 0.05 for the black roof (Table 3) as reference. The in order to evaluate the effects on the climate change, we have translated the

<table>
<thead>
<tr>
<th>Layer of the building elements</th>
<th>Thickness [mm]</th>
<th>R [m² K/W]</th>
<th>Life span [years]</th>
<th>Service life mass [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPDM membrane</td>
<td>6</td>
<td>0.03²</td>
<td>20</td>
<td>3.6</td>
</tr>
<tr>
<td>Dense deck</td>
<td>16</td>
<td>0.12²</td>
<td>20</td>
<td>1.13</td>
</tr>
<tr>
<td>Polystyrene board</td>
<td>110</td>
<td>3.35⁴</td>
<td>40</td>
<td>5.5</td>
</tr>
<tr>
<td>Gypsum board</td>
<td>16</td>
<td>0.02²</td>
<td>50</td>
<td>0.33</td>
</tr>
<tr>
<td>Dense deck</td>
<td>16</td>
<td>0.12²</td>
<td>50</td>
<td>1.13</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>3.64</td>
<td></td>
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<tr>
<td>U (Transmittance)</td>
<td>0.27 [W/m² K]</td>
<td></td>
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</tbody>
</table>

² The thermal resistances have been taken by manufactures data considering all the brands and products really used in the project.
⁴ The amount of kilograms of CO2eq has been assessed through the use of the software SimaPro 7.1, method Impact 2002+.

2.2.3. Replacement phase: life span of the roofs’ building materials

In the replacement phase, the substitution of the materials due to the aging has been considered. Since the time horizon we have considered is 50 years, through the use of data from literature and manufacturers we have established the amount of building materials necessary in order to guarantee the efficiency of the three roofing systems.

A life expectancy of 20 years has been considered for the dense deck and the rubber membrane — as suggested by most of the manufacturers — and 40 years for the polystyrene board. Since in the U.S.A. the installation of green roofs has started more recently than in Europe, no specific data are available about the life span of the green roof’s building materials. Thus, data deriving from literature regarding green roofs in other countries, and in particular in central Europe, have been used (e.g., Saiz et al., 2006). A previous research study reports that the life span of green roofs and of all their materials is at least three times longer than that of traditional roofs (Porsche and Köhler, 2003). In detail, many manufacturers ensure an increase in the life span of the waterproofing membrane over 200% compared to the usual life expectancy (Carter and Keeler, 2008). The extensions of the life expectancy of the building materials underneath the soil is due to the reduction of the thermal oscillations on the soil bottom compared to those on the white and on the black membranes (e.g., Figs. 4 and 5). The enhancement of the life span of green roofs’ building materials ensures that in a 50 years evaluation, green roofs do not need any replacement (Wong et al., 2003; Carter and Keeler, 2008; Berghage et al., 2007).

3. Results

The four stations, settled in different areas of New York City, show an average difference of temperatures — evaluated in the period from October 2008 through May 2009 — between the warmest area (Columbia University) and the coldest one (Fieldston) amongst the four, of about 2 °C (Fig. 6). The Columbia University station is installed in the city core characterized by a high rate of impervious surfaces (Lynn et al., 2009). While the Fieldston station — as the vegetation maps reveal (Small, 2001, 2006; Simmon, 2005) — has been mounted in a densely vegetated area. Since the reduction of the latent heat fluxes due to the replacement of the vegetated areas with impervious ones gives rise to the increase in the sensible heat, the amplitude of the UHI can be expressed as a difference of urban surface temperatures (Imhoff et al., 2010) as well as a difference of air temperatures. By the comparison between the surface temperatures and the vegetation abundance map (Small, 2006) with the surveyed air temperatures, we have found a correspondence between the vegetation abundance and the air temperature, as also confirmed by previous studies (e.g., Gaffin et al., 2008; Petrali et al., 2006). Furthermore, the air temperature in Con Edison is likely influenced by its closeness to the river which mitigates the extremes in temperature.

The two stations with the highest and lowest temperatures located in Columbia University area and in Fieldston have been monitored from March 1st, 2008 through February 28th, 2009 in order to investigate the seasonal behavior of the UHI in New York City. By our monitoring, we have found that during spring and summer, the amplitude of the UHI is highly correlated to the solar
radiation reaching the soil. The temperature in Columbia area is primarily influenced by the tall buildings and narrow streets which trap the solar radiations. In Fieldston, the air temperature is influenced by the abundance of vegetation – in particular, the evapo-transpiration and the shading of vegetation – that keeps the temperature lower than in Columbia. The difference of temperatures between the two investigated areas is higher in summer – both during day and night – than in winter (Fig. 7). During fall and winter, when the solar radiation is modest, the UHI principally depends on the wind-speed (Giridharan and Kolokotroni, 2009). In our analyses, we have found that the wind-speed in Columbia area is on average about 26% lower than in Fieldston. The multi-storey buildings and the narrowness of streets in the Columbia area consistently reduce the permeability to the wind, not allowing the heat to disperse. During winter in Fieldston, the air temperatures are just slightly affected by the biological activity of trees that in this season is heavily reduced. As a consequence, the temperature in Columbia is higher than in Fieldston. Furthermore, we found by our monitoring that during winter, the differences of temperatures between Columbia and Fieldston are almost constant. The differences of temperatures increase during spring and summer – due to the influence of evapo-transpiration – and decrease during fall.

In order to detect the nocturnal/diurnal behavior of the UHI in New York City, we have compared the nighttime (1am) and daytime (1pm) differences of temperatures recorded in the Columbia and Fieldston areas (Fig. 7). According to the typical behavior of the UHI, the difference of temperatures between the two areas is greater during the night than during the day, because the canyon effect does not permit the heat accumulated during the day by the urban building materials to be easily dissipated during the nighttime. We have also compared the nighttime and daytime differences of temperatures between the two sites during days of low wind-speed ($<2.5 \text{ m s}^{-1}$), when the wind velocity does not affect the UHI amplitude. We have found that during winter, the difference of approximately 1.5 °C is likely due to the substitution of vegetation with building materials (i.e., decrease in albedo, canyon effect, decrease in evapo-transpiration). Moreover, during nighttime, the differences of temperatures between Columbia and Fieldston recorded during summer and during winter are almost the same. While during daytime, the differences of temperatures between Columbia and Fieldston recorded in summer are about 1 °C higher than in winter. Thus, the variation between the winter and the summer differences of temperatures is likely due to the diurnal process of evapo-transpiration.
In the second part of our study, we have compared the differences of heat fluxes through the black roof and the white and green ones in winter and summer. By our surveys, we have found that from December 2008 through February 2009, the white roof has heat penalties during the warmest hours of the day, when its surface temperatures are lower than those on the black membrane. During the night, the white roof — because of its emissivity — slowly releases the storage heat, keeping the surface temperature higher than the black membrane. Considering both the diurnal and nocturnal fluxes of heat through the roofs, we have found that on average, during winter, the white roof does not have any penalty, because the heat fluxes from indoors to outdoors are less than those through the black roof. During summer, the high reflectivity of the white membrane permits the surface to reflect back a large amount of energy and to reach lower temperatures than the black roof.

We also monitored the green roof and we have found that both in winter and in summer, its thermal resistance and evapo-transpiration reduce the heat fluxes through the roof. During winter — because of the additional thermal resistance provided by the soil and by the biomass of plants — the temperatures recorded on the soil bottom are almost constant with peak of oscillation of approximately 10 °C. While the thermal oscillations on the black membrane are approximately 30 °C with peaks of more than 40 °C; and on the white roof, they are approximately 10–20 °C with peaks of 30 °C (e.g., Fig. 4). Furthermore, on the soil bottom, the below zero temperatures are reached approximately 50% less frequently than on the black roof (e.g., Fig. 4). During summer, on the green roof, the evapo-transpiration dissipates heat and guarantees low temperatures with thermal oscillation on the soil bottom of less than 20 °C (e.g., Fig. 5). While the summer daily thermal oscillation on the black surface is approximately 60 °C and on the white roof, as well as on the green roof is approximately 30 °C.

The surface albedos of the white and green roofs influence the surface temperatures, and as a consequence, the energy use for heating and cooling the offices. As shown in Fig. 8, the substitution of the black roof with the white and green roof results in a reduction in energy use and, in detail, the installation of a green roof instead of a white one results in an energy saving of approximately 40–110%.

In the time period of 50 years, we have also evaluated the surface albedo using the results of a climatological model (Akbari et al., 2009). Considering the surface albedo of the black roof as a reference, the substitution of the black membrane with a high-reflective one or with a green roof, positively affects the atmospheric chemistry in decreasing RF. Substituting one square meter of black roof with a white one, the high albedo of the white roof reduces the impact on climate change by approximately 140 kg of CO₂eq (Fig. 9). The increase in surface albedo due to the substitution of one square meter of black roof with one square meter of green one would be responsible for approximately 38 kg of avoided CO₂eq (Fig. 9).

In the evaluation of the replacement phase, no differences have been highlighted about the life span of the building materials on the white and the black roof. Indeed, even though the maximum surface temperatures recorded on the white roof are lower than those recorded on the black roof, many manufacturers report the same life span for both the white and the black EPDM rubber membrane (Table 1). In 50 years, the enhancement of the life span of the green roof’s building materials (Table 2) in comparison to the black or white roof, causes an avoided substitution of 7.2 kg of EPDM, 2.26 kg of dense deck and 5.5 kg of polystyrene board for each square meter of roof. We have assessed the avoided emission of CO₂eq per each kilogram of building material through the use of the life cycle assessment methodology, both in the construction and in the replacement phase, in order to make the effects of the life span of the building materials comparable with those deriving by the evaluation of the surface albedo. In detail, we have used the software SimaPro 7.1 and the method Impact 2002+.
By our analyses of the energy saving, construction, replacement phase and surface albedo, both white and green roof result in less impact than the black roof (Figs. 8 and 9). Indeed, the installation of both white and green roof guarantees a decrease in energy use for the offices underneath compared to black roofs (Fig. 8). The construction phase and the replacement phase for the white and the black roofs do not present any difference. The construction phase of the green roof produces less kilograms of CO₂eq than the black roof (Fig. 9). Moreover, the green roof needs less replacement of building materials during time and as a consequence, the green roof is less impactful on climate change than both the white and the black roof (Fig. 9). The total amount of the avoided environmental loads from the substitution of the black roof with the white one is due to the surface albedo. For the green roof, avoided environmental loads are due to the surface albedo, the thermal resistance of the soil and the biomass. In particular, considering scenario I, the green roof is less impactful on climate than the white one. Indeed, in the U.S., electric power is mainly produced by coal (U.S. Department of Energy, 2010) and has a greater impact on climate change than natural gas. In this case, the thermal resistance provides the greatest contribution in decreasing the environmental impact on climate. Considering scenario II, since natural gas is less impactful on climate than electric power, the surface albedo significantly contributes making the white roof the most environmentally preferable choice. In a typical life cycle assessment in which the effect of the surface albedo is not considered, green roof would be considered the most preferable choice when considering scenario II.

4. Discussion

The increase in temperature in the New York City core compared to the air temperature in Fieldston is ascribable to the local morphology of the Columbia area. The analysis of the data carried out during the daytime and under slow wind conditions, shows that the differences of temperatures are consistently higher during summer than during winter, when the biological activity of vegetation is reduced. Since the solar radiation reaching the soil in the two sites is the same, and the low wind velocity is not capable of influencing the local temperatures, the differences are likely due to the evapo-transpiration of the vegetation in Fieldston. This finding stresses the correlation between local temperatures and the vegetation abundance.

In the evaluation of the effects of green roofs on the building scale, the incidence of the albedo on energy use and on climate change, mostly depends on the assumptions of this research. Any modification on the building materials’ life span considered in this research and on the thermal resistance of the roofs could consistently alter the final results of the evaluation. Thus, the values provided in this research refer just to the above-mentioned case study.

Some uncertainties about the assessment of the effect of the surface albedo on climate change are intrinsic to the climatological model (Akbari et al., 2009). Indeed, it provides mean values that supply a valid measure that can be applied in every urban context. A more detailed analysis can be carried on, taking into account the specific conditions of the context such as geographical coordinates (Oleson et al., 2010) and meteorological conditions.

Moreover, because of the lack of data, some approximations have been introduced in this study. It has been hypothesized that over 50 years, the thermal resistance of the roofs and the efficiency of the cooling and heating system remain constant. Furthermore, it has been supposed that the fluxes through the roofs do not vary consistently among the values we have found for the detected period (December 2008—February 2009, June 2009—August 2009).

The main findings show the surface albedo positively influences the environmental assessment of the white roof. The high surface albedo reduces both the energy use and the impact on climate change. The surface albedo also consistently influences the environmental burden relating to the green roof, even though most of the avoided impacts are due to the decrease in energy use. In this case, not only is the surface albedo important, evapo-transpiration and the increase in the thermal resistance of the roof also play crucial roles.

5. Conclusions

This study provides useful information for decision-makers and policy-makers about environmentally preferable choices in urban planning, mitigation strategies and for building energy demand. In addition, this research highlights the positive effects that vegetation has on the UHI mitigation, and at building scale. Indeed, green roofs are capable of decreasing the use of energy for cooling and heating and as a consequence, the peaks of energy use. Moreover, the evaluation of the effect of the surface albedo on RF is not only a broadening and an enhancement for the environmental evaluation tools, but it provides useful environmental information.
Indeed, as shown in this research, the variation in surface albedo strongly influences the impact of the roofing systems. The urban-wide conversion of the black roofs into white or green roofs can have positive effects not only on micro-scale, but also on urban scale. Indeed, the reduction of the energy use for cooling lessens the probability of summer blackouts. The urban-wide conversion of black roofs into green roofs can provide better storm–water management, improvement of air quality and increase in urban biodiversity.

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