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The role of green roofs in climate change mitigation. A case study in Seville (Spain)

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A B S T R A C T

The intense anthropogenic urban activity generates a phenomenon known as heat island, which is related with high temperatures in cities, as compared against adjacent suburban and rural areas. Due to this effect, the comfort conditions of the citizens deteriorate. In the case of the city of Seville (Spain), several models of climate change forecast increases in the maximum temperatures ranging from 1.5 to 6 °C in summer. This article explores the role of green roofs as a supplement to the green spaces of the city, in order to buffer the negative effects of the increase of the maximum temperatures due to climate change. Images from the Landsat 7 ETM+ and Sentinel-2 satellites have been used in order to verify the inverse relationship between land surface temperature and the abundance of vegetation, expressed by the normalized difference vegetation index. For Seville, a green roof surface of 740 ha should be implemented, in the most adverse scenario, which means covering 40.6% of the existing buildings. In the most optimistic scenario, the forecasted green roof surface required is 207 ha (11.3% of the roofs).
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1. Introduction

Numerous studies on climate change predict a global rise in temperatures. The consequences of this increase will be more troublesome in urban areas, where the temperatures are already higher than in surrounding rural areas. This heating phenomenon is mostly due to anthropogenic development in the urban area [1] and the increase of building covered areas [2]. The construction materials commonly used absorb most of the radiation and release it as heat. This generates the urban heat island phenomenon, which has direct and indirect impacts on the health and life quality of the citizens [3]. Urban heat islands vary in magnitude and structure according to two main groups of factors: climatological factors (such as climatic region, season, time of day, synoptic conditions and wind regime) and those related to the physical and human nature of the built environment, such as geographic location, topography, urban landscape geometry, type of building materials and intensity of human activities [4]. In fact, a study aiming to identity heat islands at different height levels conducted in Tel-Aviv (Israel) showed that parks and open areas were the coldest elements within the city during day and night [5]. There is a clear correlation between plant cover and land surface temperature [6,7], and consequently, an urban increase in green areas would contribute to mitigate the Heat Island [8]. Nevertheless, in many modern cities, there is a high density of building covered areas which does not allow raising the number of green areas. Thus, in order to increase the presence of urban vegetation, it is necessary to draw on systems implemented on existing buildings. Currently, the sum of all the building roofs represents a high percentage of exposition in urban areas. Estimations for dense cities prove that the fraction of roof area varies between 20 and 25% of the total area [9]. Because of this, the use of these surfaces to increase urban vegetation is an interesting option.

Green roofs are urban greening systems that precisely allow installing plant life in the roofs of buildings through more or less complex elements. They can be extensive, lighter, and with less substrate when establishing smaller species, or more intensive and heavier with greater amount of substrate where small trees and shrubs can be included [2]. Green roofs have existed for more than a thousand years, although their use has become more relevant in modern times and new technical solutions that favor their implementation have appeared. This development has come about since

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not only do they provide a nice relaxing space or scenery, but also ecosystems services such as microclimate regulation, rainwater management, improved building insulation (with an influence on inner temperature), noise absorption, decrease of air pollution, and biodiversity enhancing [3,10]. Moreover, they contribute to increasing the albedo of urban areas [11].

Many studies on green roofs are oriented to their capability to regulate temperature. However, depending on the climate and the type of green roof (different plant material, substrate, and construction features), their efficiency can vary [12]. The thermal efficacy of a green roof is closely related with the climate, and it becomes more significant when the environmental temperature rises [3]. This efficacy is measured from the point of view of energy savings in warm areas for their capacity to lower temperatures [2] of both the roof surface and the air above it [13]. For example, an analysis of the surface temperature before and after the placement of a green roof in Singapore showed a significant decrease once the green roof was installed, especially for high plant cover, making the maximum temperature difference approximately 18 °C [14]. Another study in Hong Kong proved that the heat stored in a bare roof was 75% higher than that of a green roof [15]. In the city of Chicago, the temperatures in summer of the surface of a green roof and a neighboring building were compared. The temperature of the green roof varied from 33 to 48 °C, while in the conventional dark roof of the adjacent building the temperature was 76 °C. The air temperature near the surface of the green roof was 4 °C lower than near the conventional roof [16]. This decrease in temperature happens because, in a green roof, the flux of sensible heat is low due to the high latent heat flux from evaporation, even if the net radiation is high. This works to lower the temperature in a specific area [17]. Also, some simulation studies indicate that green roofs can decrease the mean environmental temperature from 0.3 to 3 °C at a city scale, and drastically decrease the heat island effect [2].

Nowadays, in many cities of several countries, such as Germany, the U.S.A., Denmark, and Canada, their governments have developed a variety of norms, incentives, and technical services to promote the naturalizing of roofs [18]. These measures will foster the increase of the area covered by green roofs, which will have favorable consequences on the specific climatic conditions in the urban areas where they are installed. In fact, the mass installment of green roofs might work as a mechanism to decrease the Heat Island effect and counteract the temperature increase due to climate change. In order to do so, the remaining question would be how much surface would be needed to mitigate the effect of climate change. This is, precisely, the main objective of this study. This is why the effect on the temperature when increasing the vegetation areas by means of green roofs in the city of Seville (Spain) is assessed.

2. Methods

2.1. Regionalized scenarios of climate change for Spain

The National Plan of Adaptation to Climate Change (Plan Nacional de Adaptación al Cambio Climatico – PNACC) in Spain has a priority work line for developing regionalized climate change scenarios, which consists of generating and making publicly available a collection of scenarios that projects how climate change will be manifested throughout the 21st century in Spain [19]. For this study case, the average evolution of the mean annual and monthly maximum temperatures in the Andalusia region is used. These are calculated for the three 30-year periods comprised between 2001 and 2100. Herein are included comparisons with the different global models used, with different methods of regionalization, and according to the SRES-IPCC emission scenarios [19].

The emission scenarios are useful in the analysis of climate change, particularly to create climate models, to evaluate impact, and for initiatives on adaptation or mitigation [20]. The A2 family of evolutionary lines and scenarios used in the present study describes a very heterogeneous world. Its most distinctive features are self-sufficiency and preservation of local identities. The fertility patterns in the group of regions converge very slowly, thus obtaining an ever growing world population. Economic development is basically oriented toward regions, while per capita economic growth and technological changes are more fragmented and slower than other evolutionary lines [20].

2.2. Relationship between land surface temperature and the normalized difference vegetation index (NDVI)

The NDVI is a numerical index used in remote sensing analysis to evaluate if a determined objective contains live vegetation. Healthy plant life absorbs visible light (0.4–0.7 μm) and reflects near infrared light (0.7–1.1 μm). Scarce or unhealthy vegetation generally reflects more visible light and less near infrared [21]. Therefore, more near infrared radiation reflected than visible light wavelengths generally indicates the presence of green vegetation, whereas a small difference in the intensity between these two wavelengths is generally an indicator of scarce vegetation or surfaces devoid of plant life [22]. Since the near infrared and red bands of satellites are the most sensitive to information from vegetation, these bands can be used to quantify the growth density of a plant in a given pixel [22]. This index has been used in some works to determine the abundance of plant life in a determined area [23]. The NDVI values vary from 0.0 to 1.0, depending on the degree of plant cover and the physiological state o health of the plants. An NDVI over 0.2 indicates the presence of vegetation, depending on the amount and health state of the plant cover [24,25].

According to [26] and [27], areas with high NDVI values can lower land surface temperature (T_s). This correlation is due to the influence of the humidity in the ground and evapotranspiration of plants on the surface. The values of both variables can be fitted to a linear model which describes an inverse dependence between T_s and the NDVI [23], so the temperature is defined by the following general expression:

$$T_s = -x * (NDVI) + y \quad (1)$$

Therefore, the increase in temperature due to climate change (ΔT_{max}) could be mitigated by a substantial increase in the mean value of the NDVI ($NDVI_{mean}$); that is to say, increasing the current plant cover ($NDVI^{CC}$) (Fig. 1).

Therefore, $NDVI^{CC}$ is obtained as follows:

$$NDVI^{CC} = NDVImean + [\Delta Tmax^* (NDVImax- NDVImin)/(Tmax - Tmin)] \quad (2)$$

where $NDVI_{mean}$ is the mean of the NDVI values obtained from the satellite image for the whole study area. ΔT_{max} are the degrees that the maximum temperature increases due to climate change; these values are provided by the [19], and are shown in Table 2. $NDVI_{max}$ and $NDVI_{min}$, are the maximum and minimum NDVI values obtained from processing the satellite image of the whole study area. T_{max} and T_{min}, are the maximum and minimum temperature values obtained from processing the satellite image of the whole study area.

An image from the United States Geological Survey (USGS) taken by the Sentinel-2 satellite on August 31st, 2016 was used to calculate the T_s and NDVI in the study area. It was acquired at around 14:00 local time with atmospheric conditions of 0% cloud

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