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The climatic dependencies of urban ecosystem services from green roofs: Threshold effects and non-linearity

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ABSTRACT

This paper proposes a methodology for quantifying benefits and costs of extensive green roofs as an urban strategy for adaptation to climate change. It seeks to highlight the consequences of threshold effects in the delivery of the benefits and non-linearity with respect to green roof coverage. The analysis focuses on energy savings for cooling, carbon footprint reduction, avoided water treatment and reduction of heat-stress related mortality. Applying the methodology to the case study of the city of Madrid (Spain) reveals that for climate scenarios where observed temperatures are closer to thresholds, misspecification of the services is more likely to bias the decision of using green roofs as an urban strategy to mitigate the effects of climate change.

1. Introduction

Urban intensification is a driver of global environmental change and a primary source of greenhouse gas emissions (Grimm et al., 2008). Also, urbanization itself significantly impacts the local and regional climate (Kalnay and Cai, 2003; Zhou et al., 2004). Locally, the urban heat island effect reflects how anthropogenic activities modify the climate: the temperature in cities tends to be higher than in the surrounding rural areas, an effect that is especially pronounced at night-time. Urban areas are largely covered by impervious built surfaces, which store incoming solar radiation during the daytime. The lack of soil moisture to dissipate heat, therefore contributes to local temperature increase locally. In a city like Madrid (Spain), the urban heat island effect can reach 5–6 °C (Fabrizi et al., 2011; Yagüe and Zurita, 1991). This urban warming increases the demand of energy for cooling (Hirano and Fujita, 2012; Izquierdo et al., 2011; Kolokotroni et al., 2012; Wong et al., 2003). In turn, the cooling of indoor spaces generates outdoor heat that further contributes to the urban heat island effect (Boehme et al., 2015; Salamanca et al., 2012; Tremeac et al., 2012).

Another environmental consequence of the imperviousness of urban areas is related to water management. Water from rainfall is rapidly drained through storm water and wastewater infrastructure systems. Point-source pollution accumulates in these systems through overflows to rivers and natural environments, whilst wastewater treatment plant efficiency is reduced due to the dilution of wastewater (Frazer, 2005).

One way to mitigate these environmental changes at the local scale is to increase urban vegetation cover, albedo and perviousness. Green infrastructures provide valuable services that can enhance the resilience and quality of life in cities (Bolund and Hunhammar, 1999; Elmqvist et al., 2015; Gómez-Baggethun and Barton, 2013; Wang et al., 2014). The effectiveness of green infrastructures (planting of trees in pedestrian areas, green roofs, green walls, etc.) has been experimentally studied at the micro scale (Alexandri and Jones, 2008, 2007; Kumar and Kaushik, 2005) and simulated at the meso scale (Bass et al., 2002; Georgescu et al., 2014; Rosenzweig et al., 2006; Salamanca et al., 2012; Susca et al., 2011; Taha, 1999). In a climate change context, Georgescu et al. (2014) simulated the outdoor temperature reduction for six US states, and found temperature reductions between 0.2 °C and 1.2 °C from implementation of green roofs.

Among green infrastructures, green roofs present a high potential to provide multiple urban ecosystem services (Berardi et al., 2014; Oberndorfer et al., 2007), including regulation of urban peak temperatures (Li et al., 2014; Santamouris, 2014; Sharma et al., 2016). However, the social profitability of these infrastructures remains unclear from the current empirical evidence found in the literature (Bianchini and Hewage, 2012; Carter and Keeler, 2008; Claus and

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Rousseau, 2012; Peng and Jim, 2015). Furthermore, the urban climate regulation capacity of green roofs is largely dependent upon local conditions (Li et al., 2014) and future climate.

Services provided by green roofs include: urban temperature regulation, carbon sequestration, water runoff regulation, provision of habitat and biodiversity, air purification, sonic and aesthetic services (Berardi et al., 2014; Gómez-Baggethun and Barton, 2013; Oberndorfer et al., 2007; Wang et al., 2014). Based on Fisher and Turner (2008) and Fisher et al. (2009), we consider urban ecosystem services as "the aspects of ecosystems utilized to produce human well-being"[1]. In green roof ecosystems, ecological processes are numerous and provide final services that have multiple benefits to humans. Evapotranspiration provides a service of urban temperature regulation with benefits related to heat-stress reduction for the population and reduced cooling demand for buildings. Photosynthesis and soil formation provides carbon sequestration services that directly affect climate regulation. These processes also provide services of insulation and energy absorption that in turn reduce energy consumption. Percolation together with soil formation impact water runoff management from roofs with benefits of sewage overflow reduction.

With this paper, we mainly intend to contribute to the understanding of temperature-related ecosystem services delivery by green roof infrastructures in urban areas. The originality and aim of the study lies in the design of a methodology that accounts for the threshold effects in the provision of benefits. To this end, the analysis focuses on climate and threshold dependent services. Thresholds interrupt the flow of services and benefits and affect temperature-related exposure-response relationships. Indeed, the benefits related to energy savings, as well as those associated with heat-stress, are determined by the exceedance of temperature thresholds. Air conditioning in buildings depends on temperature set-points related to thermal comfort. Heat-related mortality rises rapidly above a baseline mortality rate from natural causes when a threshold temperature is exceeded. (Davis et al., 2003; Díaz et al., 2006, 2002; Gasparrini et al., 2015). To illustrate these threshold effects, we focus on the assessment of climate-related socio-economic benefits obtained from extensive green roofs. We estimate, based on the avoided costs method, multiple direct and indirect benefits derived from urban temperature regulation services, carbon sequestration and water runoff regulation services. These benefits include energy savings achieved through mitigation of the urban temperature and energy absorption (insulation); avoided CO_2 emissions due to lower energy demand for cooling; carbon sequestration; reduced heat-related mortality through urban temperature reduction; and avoided water treatment expenditures.

We apply our methodology to the city of Madrid (Spain). We believe this to be a relevant location as it is expected that the Mediterranean region will experience intense summer warming during the 21st century, with a high level of confidence that the duration, frequency and intensity of heat waves in this region will increase (Christensen et al., 2013).

We propose a method for both the estimation of the benefits and the costs (Section 2). The results are presented in Section 3. Section 4 discusses the results and tests the main assumptions of the model. Section 5 concludes.

2. Materials and methods

2.1. Green roof deployment scenarios

We present hereby our methodological framework to conduct an economic analysis of the potential contribution of green roofs to regulate urban environment in the long term at city scale. To this extent, we (i) define the implementation scenario of the adaptation measure and associated costs, (ii) identify and select the related ecosystem services and the associated benefits and (iii) define the socio-climatic scenarios.

Implementation scenario and costs. We focus on extensive green roofs and consider 4 levels of deployment of 5%, 20%, 50% and 100% coverage of the residential and commercial roof areas of the city. Green roofs are usually categorized into two categories: extensive or intensive. Extensive green roofs have a depth of less than 200 mm, are typically not intended to be accessed, have low maintenance requirements, do not require irrigation, and present a low diversity of plants. In contrast, intensive green roofs are accessible roof gardens with a deeper substrate layer and deliver greater services (e.g. more cooling through evaporation), but at higher costs (Berardi et al., 2014). For the evaluation of the costs we used data collected from national engineering institutes and a manufacturer of building products.

Ecosystem services and benefits. With the objective of illustrating the impact of thresholds in the provision of services and benefits we restrict the analysis to climate-dependent services. The estimation of the benefits follows a prior understanding of the provision of these services. We review the performance of extensive green roofs in providing urban temperature regulation. Based on a literature review of studies conducted in similar climates (Supporting material 2), we have modelled the thermal performance of green roofs in Madrid using plausible estimates of maximum temperature reductions as a function of green roof coverage[2] (Table 1). Although the relationship between green roofs coverage and (peak) outdoor air temperature reduction does not scale perfectly linearly, the relation is according to literature "*not too far from linear scaling*" (Li et al., 2014; page 9) or "*nearly linear*" (Sharma et al., 2016, page 7). Assuming a linear relationship and instantaneous green roof coverage, we assume for the city of Madrid temperature reduction scenarios for different fractions of green roofs coverage α (Table 1). Below 20% coverage, we assume the maximum reduction of temperature to be negligible (less than 0.1 °C).

Socio-climatic scenarios. The flow of future benefits is then determined by future socio-climatic conditions. We consider two socio-climatic scenarios for the period 2020–2099[3]: (1) a conventional high development scenario with a low mitigation of greenhouse gas emissions (the representative concentration pathway RCP 8.5 with the shared socioeconomic pathway SSP 5), and (2) a world more concerned with environmental problems in which greenhouse gas emissions have been stabilized (RCP 4.5 combined with SSP2) (van Vuuren et al., 2014). These two scenarios provide a range for the assessment of the profitability of extensive green roofs allowing us to address the uncertainty relative to climatic- and socio-economic pathways. Both costs and benefits are compared to a baseline scenario of traditional roofs. Future benefits and costs are estimated and then discounted using three different rates: 1%, 3% and 5%.

2.2. Socio-economic evaluation of the benefits derived from ecosystem services provided by extensive green roofs

2.2.1. Energy consumption reduction

The expected reduction of energy consumption delivered by green roofs originates from two sources: reduction of outdoor temperature and improved building insulation. The reduction of out-

[1] This definition classifies phenomena into services not necessarily based on their direct consumption by humans. See Boyd and Banzhaf (2007) for a definition based on direct consumption.

[2] Calibrating an urban climate model for the city of Madrid would improve the estimation of the thermal performance of green roofs. Estimating such a model is outside the scope of this analysis. Our scenarios cover a range from close to 0 °C to a maximum of 0.5 °C in temperature reduction.

[3] See Supporting Material 1 for historical and projected climatic statistics for Madrid.