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Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review

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ABSTRACT

The influence of urban green infrastructure on the indoor environment and the effects on human comfort and economic consequences are still unclear. This paper gives a systematic overview of the relationship, in terms of so-called 'ecosystem services', between urban green infrastructure and the indoor environment through a literature review in different disciplines. Urban green infrastructure (mainly trees, green walls and roofs) was found to contribute, both positively and negatively, to the indoor environment via the influence on the climate, energy use, air quality, sonic environment and aesthetic quality. Four main factors that influence these effects were identified, being vegetation characteristics, building characteristics (including layout and geometry), and geographical conditions. Although the reviewed papers have investigated the different ecosystem services on a wide range of space and time scales, the performance of urban green on the meso- and macro climate has received less attention than on the micro scale. Also direct effects of urban green infrastructure on indoor air quality and sonic environment were rarely studied. Another finding is that, whereas the modelling approach on climate regulation has been widely adopted by researchers throughout the world, empirical studies have mainly been performed in the USA. We also analysed the data found on economic implications. The economic effects of adjoining vegetation and green roofs on climate regulation provided energy savings of up to almost \$250/tree/year, while the air quality regulation was valued between \$0.12 and \$0.6/m^2 tree cover/year. Maximum monetary values attributed to noise regulation and aesthetic appreciation of urban green were \$20 – \$25/person/year, respectively. Of course these values are extremely time- and context-dependent but do give an indication of the potential economic effects of investing in urban green infrastructure. Based on this review, we conclude that new methods, measurement instruments and field experiments are needed to improve empirically supported correlations and develop concrete recommendations for urban planning and design.

1. Introduction

People living in urban areas depend on natural ecosystems not only beyond the city limits, but also within the urban area [1]. Natural elements in urban areas have many proven benefits to human society, including material and spiritual aspects [2–4] which are positively related to human well-being and comfort, especially human physical and mental health, as demonstrated by numerous epidemiological studies [5–7]. All the benefits that people derive, directly or indirectly from ecosystems are known as ecosystem services [8]. Due to the different types of ecosystems (e.g. grasslands, forests, wetlands), the types of ecosystem services are different as well. A recent study by Gómez-Baggethun et al. identified 13 important ecosystem services in urban areas (e.g. urban temperature regulation, air purification, waste treatment) [3]. Within the urban system, indoor areas take up a large amount of space and people spend most of their time indoors. Low quality indoor environments can therefore pose serious risks to human health [9].

This paper focuses on the urban ecosystem services and disservices relevant for the indoor area. Many studies have discussed the contribution and effects of urban green infrastructure, especially urban forests, to the indoor environment through both direct and indirect processes. The indoor environment is generally affected by urban green infrastructure (e.g. urban trees, green walls

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and roofs) via four main mechanisms. First of all, the climate is regulated through buffering of solar radiation, lowering of wind speeds, and evapotranspiration processes [5,10–13]. Secondly, urban greenery affects the air quality through removing air pollutants by dry deposition and by influencing the smog (O_3) formation process [1,5,14–17]. The third mechanism relates the urban green infrastructure to noise abatement [18–20], as well as noise masking by generating pleasant sounds in the canopy [21–23]. Finally, views from windows provide both amenities and dis-amenities to residents [24–26].

In this paper, we reviewed literature from different disciplines to synthesize the current knowledge on the effects (both positive and negative) of natural elements on the indoor environment and human comfort in urban areas. The aim of this study was to (1) provide a systematic overview of state-of-the-art research in the field of urban ecosystem services and indoor human comfort; (2) logically classify the reviewed studies and information into four main categories of ecosystem services; (3) identify the strengths and weaknesses in the existing literature and (4) provide suggestions for future studies to improve the knowledge base in this important research area.

2. Methods

The methods used for this review are described in three sub sections: 1) search strategy; 2) establishing the relation between the functions of urban greenery, ecosystem services and the effects on the indoor environment; and 3) typology of the benefits and economic analysis.

2.1. Search strategy

In the first selection stage, the keywords “urban ecosystem services”, “urban green infrastructure”, “indoor environment” and “human comfort” were used and only peer reviewed scientific papers were selected. Since the comprehensive relationship between urban green infrastructure and indoor human comfort is difficult to establish, this study reviews literature that focussed on the quantification of four major ecosystem services (i.e. climate regulation, air quality regulation, sonic environment regulation and aesthetic information services). For the air quality regulation service, direct effects of the urban green infrastructure on the indoor air quality were rarely studied. To gain more insight into these effects, specific literature on indoor pollutants from outdoor sources and the impact of green infrastructure on these pollutants were reviewed. In addition, articles studying the relationship between urban green infrastructure and indoor sonic environment have not be found, since most studies have only explored the effect of urban green infrastructure on the outdoor sonic environment. In the second selection stage, socio-economic aspects were obtained by adding additional keywords: “socio-economic valuation” and “costs and benefits”. After screening, in total 148 papers were selected, of which, 86 investigated the quantification of urban green effects, and 24 explored the costs and benefits of urban green. The remaining papers were analysed for gaining general knowledge on urban ecosystem services, and their contributions to the indoor environment.

2.2. Establishing the relation between the functions of urban greenery, the related ecosystem services and the effects on the indoor environment

The 86 articles that focused on the quantification of urban green effects (see Section 2.1) were reviewed by analysing the study design and their interpretations and findings. Fig. 1 shows the established relations between the main ecosystem services provided by the urban green infrastructure and the indoor environment. The main functions associated with each service provided by green infrastructure were used to classify the selected papers.

The literature that described the effects of urban green infrastructure on the indoor climate and energy use mainly focused on two major categories of urban green infrastructure, i.e. adjoining vegetation [11,27–42], and roof and wall greenery [43–65]. For both categories we analysed three main biophysical effects, being shading, evapotranspiration and shelter (Table S1).

Due to the complex biophysical processes involved in the air quality regulation service, the effect of urban green infrastructure was grouped into direct and indirect effects. Direct effects are comprised of removing air pollution via dry deposition processes [66–73], storing and sequestering carbon [68,72,74–80], and releasing pollen and spores of fungi [81–85]. In addition, vegetation indirectly affects the air quality through biogenic volatile organic compound (BVOC) emissions and by regulating the climate, thereby reducing the potential air pollution as a result of energy saving [86–93]. A potential indirect effect of vegetation on air pollution concentration through regulating temperature and air flow has been investigated recently [94,95]. Finally, reduced energy consumption due to the contribution of green infrastructure can also reduce the CO_2 emission [5,96,97] (Table S2).

Urban green infrastructure not only acts as an acoustic screen between noise-sources and receivers [18,20,22,98–101], but also masks noise by generating pleasant sounds [21]. This literature study reviews both perspectives.

Finally, we summarize and integrate the results of studies that investigated the aesthetic information service of urban green infrastructure seen from the point of people’s mental and physical health [102–105], and based on the effect of views on outdoor green and effect of green spaces on children’s educational results [106,107].

2.3. Typology of benefits and economic analysis

The urban green infrastructure affects the indoor environment directly through climate, air quality, sonic and aesthetic aspects. However, greenery also has many secondary effects on human well-being and the economy.

Reduced energy costs resulting from indoor temperature modification provided by urban green infrastructure is often used to value the benefits of the climate regulation service. The reviewed articles focused on the direct contribution of urban green on the indoor energy saving (for cooling and heating) via altering the indoor thermal environment [14,30,36,37,108–110], and the indirect contribution through changing the wind speed [37].

The potential value of the air quality regulation service, associated with both air pollutant removal [67–70,108] and carbon storage and sequestration [77], was mostly calculated by measuring the effects on health care and replacement costs of artificial treatment systems.

To value the benefits of sonic environment regulation (noise abatement) mainly survey-based valuation studies were used, such as assessing the citizens’ willingness to pay (WTP) for quiet acoustic environments and small group discussions and consensus building [19,20,98,111].

In terms of aesthetics information services, the difference in price of building units in relation to the surrounding vegetation situation and density (so-called “hedonic pricing”) was often used to calculate its monetary value [26,112–116]. In addition, people’s WTP was another method to estimate the value of this service [117,118].