



Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure



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ABSTRACT

In order to develop climate resilient urban areas and reduce emissions, several opportunities exist starting from conscious planning and design of green (and blue) spaces in these landscapes. Green urban infrastructure has been regarded as beneficial, e.g. by balancing water flows, providing thermal comfort. This article explores the existing evidence on the contribution of green spaces to climate change mitigation and adaptation services. We suggest a framework of ecosystem services for systematizing the evidence on the provision of bio-physical benefits (e.g. CO₂ sequestration) as well as social and psychological benefits (e.g. improved health) that enable coping with (adaptation) or reducing the adverse effects (mitigation) of climate change. The multi-functional and multi-scale nature of green urban infrastructure complicates the categorization of services and benefits, since in reality the interactions between various benefits are manifold and appear on different scales. We will show the relevance of the benefits from green urban infrastructures on three spatial scales (i.e. city, neighborhood and site specific scales). We will further report on co-benefits and trade-offs between the various services indicating that a benefit could in turn be detrimental in relation to other functions. The manuscript identifies avenues for further research on the role of green urban infrastructure, in different types of cities, climates and social contexts. Our systematic understanding of the bio-physical and social processes defining various services allows targeting stressors that may hamper the provision of green urban infrastructure services in individual behavior as well as in wider planning and environmental management in urban areas.

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1. Introduction

Urban areas are facing increasing challenges from climate change, for example, floods, droughts, heat waves and other threats to human comfort and environmental justice. In addressing ways to deal with these challenges, growing attention has been paid to the potential role of green and blue spaces, often approached with the

concept of green (and blue) infrastructure (GUI). Green urban infrastructure can be interpreted as a hybrid infrastructure of green spaces and built systems, e.g. forests, wetlands, parks, green roofs and walls that together can contribute to ecosystem resilience and human benefits through ecosystem services (Naumann et al., 2010; Pauleit et al., 2011; European Environment Agency, 2012). Although GUI cannot fully replace natural areas, it is regarded as beneficial, e.g. as it can provide habitats for diverse biota and thereby help protect terrestrial and aquatic ecosystems (Ignatieva et al., 2011). However, a more integrated approach highlights the need for a holistic view of functions from nature conservation to social benefits, including

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benefits for coping with climate change, for citizens from regional to city (neighborhood) and site specific scales (Naumann et al., 2010; Niemelä et al., 2010; Pauleit et al., 2011).

Green urban infrastructure has been indicated as promising for reducing the adverse effects of climate change in urban areas, for example, by balancing water flows to alleviate flooding, providing thermal comfort by shading vegetation, and supporting coping capacities by providing people with opportunities to grow food for themselves (e.g. Krasny and Tidball, 2009; Cameron et al., 2012; Farrugia et al., 2013). Green urban infrastructure has also gained attention as a resource for mitigating climate change, e.g. its biomass can function as carbon storage (e.g. Davies et al., 2011). In scientific debates on climate change mitigation and adaptation, green urban infrastructure has often been described in terms of policy and governance (Naumann et al., 2010), but less holistically based on empirical evidence of benefits and trade-offs. The services and benefits of green urban infrastructure to climate change mitigation and adaptation have been studied (Gill et al., 2007; Laforteza et al., 2009), and conceptual frameworks have been developed for addressing services and benefits in multi-scalar contexts (Faehnle et al., 2014; Scholes et al., 2013). Improved knowledge on the scales at which these services function and the benefits are delivered can link these processes to the appropriate level of decision-making, municipal or state authorities or individual level (Sternlieb et al., 2013; Wyborn and Pixler, 2013).

This review synthesizes empirical evidence on the contribution of green urban infrastructure to climate change mitigation and adaptation services and benefits. For this purpose, we propose a framework of ecosystem services and identify a set of green urban infrastructure services and benefits reported in the literature. We will address the production of the services, benefits, and potential co-benefits as well as elaborate on trade-offs at various spatial scales. The article concludes with identifying knowledge gaps worth exploring in future research.

2. Evidence on services and benefits provided by GUI

In order to draw together the empirical evidence on the contribution of green urban infrastructure from a climate change

mitigation and adaptation perspective, we have developed a framework for the analysis of the benefits (Fig. 1). Ecosystem services can be defined as the contribution of ecosystems to human well-being, based on ecological phenomena (Fisher et al., 2009). Services are the production of benefits that are of value to the people (Chan et al., 2012). For example, carbon storage and sequestration (service) contributes to decreased CO₂ emissions (benefit), and regulation of climate (service) contributes to human thermal comfort, which can be a benefit (Fig. 1).

Several authors (James et al., 2009; Heidrich et al., 2013; Villarreal Walker et al., 2014) have highlighted the need for more integrated approaches to analyze the physical and social benefits of urban ecosystems and climate change mitigation and adaptation. Addressing this call, the empirical evidence on the role of green urban infrastructure in such a context is described (Fig. 1). Categorization of services and benefits is challenging because of the multi-scalar and multi-functional nature of green urban infrastructure and the multiplicity of interactions between the various phenomena. For example, thermal comfort and improved air quality (physical benefits) contribute to human health and quality of life (health and restorative benefits), but the latter also depend on many other issues. An aesthetically pleasant floodplain provides flood protection by regulating water flows (service), enables recreation (health and restorative benefit), but may also offer practical knowledge (educational benefit) for climate change adaptation. We will discuss a set of services and benefits that are reported in literature as essential for climate change mitigation and adaptation. This list is not exhaustive and others exist, e.g. food security benefits of urban agriculture are excluded. However, we categorize the key services and benefits that reflect the role of green urban infrastructure in the context of climate change mitigation and adaptation.

2.1. Physical benefits

2.1.1. CO₂ reduction

Green urban infrastructure contributes to climate change mitigation as it directly removes CO₂ from the atmosphere via photosynthetic uptake during the day and releases CO₂ at night via

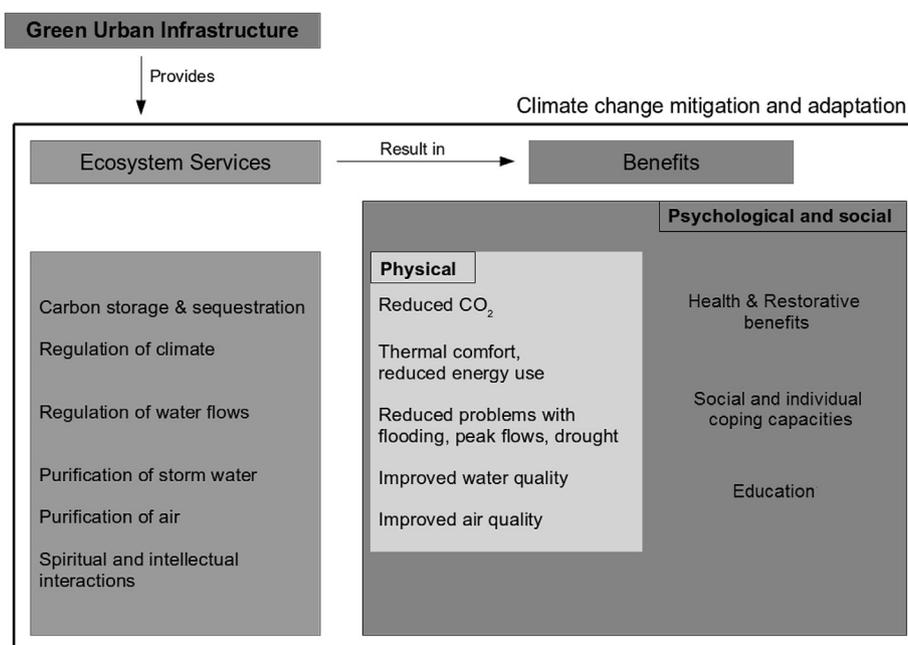


Fig. 1. Green urban infrastructure services and benefits within a climate change mitigation and adaptation framework.

respiration, while additional uptake can occur via below-ground biomass and soils (Velasco and Roth, 2010). The relative strength of all source and sink terms will eventually make up the net urban CO₂ sequestration. For Leicester (the UK), Davies et al. (2011) reported the total average carbon stored within the above-ground vegetation across the city to be 31.6 t C per ha⁻¹ of urban area and 7.6 t C ha⁻¹ alone for domestic gardens. This was similar to the results of Zhao et al. (2010) in the Hangzhou downtown area, where they reported 30.25 t C ha⁻¹ and 1.66 t C ha⁻¹ yr⁻¹ as the average carbon storage and sequestration rate, and a little higher than along three sample transects radiating from the Seattle (the USA) central urban core (18 ± 13.7 t C ha⁻¹) (Hutyra et al., 2011). Carbon storage can also vary considerably like in three cities in South Korea: from 26 to 60 t C ha⁻¹ for natural lands within the cities, and from 4.7 to 7.2 t C ha⁻¹ for urban lands (Jo, 2002). According to Nowak et al. (2013) it varied between 31.4 t C ha⁻¹ for South Dakota (USA) and 141.4 t C ha⁻¹ for Omaha (Nebraska, the USA). The overall carbon storage of urban tree cover among all 28 cities across six US states was 76.9 t C ha⁻¹, with the net carbon sequestration rate 2.05 t C ha⁻¹ yr⁻¹.

Similar CO₂ storage and sequestration can be expected from building green as Ismail et al. (2012) report, measuring daily CO₂ uptake for ten pots of *Ipomoea pes-caprae* showing the annual net photosynthesis rate 2.3 t C ha⁻¹ yr⁻¹. Additional urban carbon storage has been estimated from below-ground biomass and urban soils. A study by Washbourne et al. (2012) across a 10 ha brown-field in Newcastle upon Tyne (the UK) showed that for a soil volume of 1 × 10⁶ t characterized by Ca-/Mg-rich silicate minerals, a total carbon capture potential of 17 × 10³ t C could be achieved. A study of 60 soil cores to a depth of 60 cm in Chuncheon (South Korea) showed an organic carbon storage average of 31 C ha⁻¹ for natural lands and 24 C ha⁻¹ for urban lands (Jo, 2002). In general, green urban infrastructure can be efficient CO₂ reducers as Nordbo et al. (2012) suggest that urban areas have a net sink of CO₂ if their natural fraction exceeds about 80%.

2.1.2. Thermal comfort and reduced energy use

Green urban infrastructure can play a role in climate change adaptation through reducing air and surface temperature by providing shading and enhancing evapotranspiration, which leads to two benefits: reduced energy use and improved thermal comfort. We address the thermal comfort and reduced energy benefits via physical indicators such as ambient temperature, turbulent fluxes and energy savings.

Studies of parks in Singapore (Yu and Hien, 2006) showed that the temperature outside the park's boundary gradually increases when moving further away from the green area. The cooling impact of parks is also reflected in the lower temperatures in the surrounding built environment (the maximal average temperature difference in locations nearby the park: 1.3 °C). A simulation of a cooling energy load in surrounding buildings showed a maximum 10% reduction of energy consumption. Similarly, Shashua-Bar and Hoffman (2000) predicted the cooling effects of small urban green wooded sites in Tel Aviv to be about 2.8 °C; while Nonomura et al. (2009) linked the accelerated temperature increase of 0.16 °C/year (eliminating the background trends) to the decrease of vegetated area in a low populated urban sprawl of Takamatsu, Japan.

As shown by Cameron et al. (2012), domestic gardens play a significant role in climate mitigation, in particular by insulating houses against temperature extremes. Shashua-Bar et al. (2009) concluded that courtyards with shade trees and grass yielded a daytime temperature reduction of up to 2.5 °C. Green roofs often reflect more sunlight than conventional rooftops (Santamouris, 2014), improve rooftop insulation, cool the air via evapotranspiration from plants and evaporation from soils and reduce energy

demands via cooling and insulation (Cook-Patton and Bauerle, 2012). Reporting on green urban infrastructure for various sites across the world, Bowler et al. (2010) concluded that surface temperatures of green roofs are cooler than non-green roofs, even though the actual difference changes according to the time of the day, season, climatic conditions and the volume of water stored.

Green roofs can significantly reduce energy use (both in summer cooling and winter heating) in buildings with poor insulation systems (Castleton et al., 2010). Under warm and sunny conditions where soil moisture was limited, evapotranspiration from the green roof was low, leading to high sensible heat fluxes during the day. Irrigation improved the performance of the green roof by increasing evapotranspiration. Alexandri and Jones's (2008) study of concrete and green roofs and walls across 9 cities in the world showed that the hotter and drier the climate, the more important the effect of green walls and roofs on mitigating urban temperatures – an energy savings from 32% to 100% can be achieved in cooling buildings. As for green facades, Cheng et al. (2010) concluded that the application of turf as vertical greening reduced the interior surface temperatures by more than 2 °C.

2.1.3. Reduced problems with flooding and improved water quality

Forests, wetlands and floodplains are known buffers of peak flows and also purify water through pollutant removal. These services are relevant to urban areas for adapting to changing weather patterns and the dynamics of human requirements (Farrugia et al., 2013). As the Manning's equation indicates, runoff in urban areas has greater velocity due to smooth impervious surfaces compared to rough natural surfaces (Jacobson, 2011). Therefore, while up to 60% of rainwater becomes runoff in vegetation-free cities, vegetated areas contribute only between 5 and 15%, thereby reducing peak discharge and inducing groundwater recharge (Spatari et al., 2011). However, effective functioning of green infrastructures depends on their location in the urban landscape, and hence should consist of a matrix of corridors and patches in areas with soils having high infiltration capacity (Gill et al., 2007; Ellis, 2012). In the highly flood prone urbanized Como Lake catchment, green areas have reduced stormwater runoff up to 100% during normal precipitation years and 77–88% during high precipitation years (Capitol Region Watershed District, 2012).

Assessment of bioretention cells has shown a reduction in peak flows by at least 96.5% for small to medium-sized storm events (Hunt et al., 2008). Comparison of green and black roof plots indicates similar effects, where precipitation retention for smaller storms (2.5 cm depth) is greater than for large storms (7.6 cm depth) whilst green roofs may reduce the runoff up to 50% (Hall, 2010). A study of Mentens et al. (2006) on intensive green roofs in Germany over a 16-year period demonstrated a runoff reduction of 65–85%. This reduction depends on the green roof structure (layers and depth), climate conditions and the amount of event specific precipitation. Additionally, denser vegetation is known to increase rainwater retention while greater biomass and plant productivity are associated with greater evapotranspiration losses. However, the role of biodiversity in influencing water quantity is unclear (Cook-Patton and Bauerle, 2012).

Besides influencing the quantity and timing of runoff, green urban infrastructure improves the physicochemical characteristics of the water by removing suspended solids, nutrients, hydrocarbons, and heavy metals (Davis et al., 2009). A link between hydrologic performance and water quality has been found: the reduction of peak flows and runoff volumes is associated with the reduction in the Total Phosphorus (TP) and Total Suspended Solids (TSS) (Odefey et al., 2012). While TP and TSS volume reductions are reported at between 65 and 100% (Capitol Region Watershed District, 2012), grass bioretention cells remove nitrate–nitrite by

up to 33%, phosphorus by up to 60% and faecal coliform by up to 100%, which is better compared to the vegetated cells with trees, shrubs and mulch (Passeport et al., 2009). A review by Czemiel Berndtsson (2010) revealed the role of soil material and fertilizers in runoff quality from green roofs to increase phosphorus content. However, modular green roofs, tested by Gregoire and Clausen (2011), reduce overall pollutant loading by acting as a sink and the efficiency of removal depends on the pollutant type, vegetation type, soil properties, fertilizer addition and local climate.

2.1.4. Effects on air quality

Green urban infrastructure affects air quality through the absorption of pollutants like particulate matter (PM₁₀). Some of the particulates, such as black carbon, absorb light and are also called short lived climate pollutants (SLCPs). Urban vegetation absorbing SLCPs has a positive effect on climate change mitigation. However, there is only a limited amount of empirical evidence available and this is mainly related to roadside vegetation. Brantley et al. (2013) have verified reductions in black carbon (indicating traffic exhaust) behind the vegetation barrier; however, they did not see changes in coarse or fine particle levels. Hagler et al. (2012) have noted a variable effect of vegetative barriers also in case of near-road ultrafine particle concentrations (reduction has only been seen in some cases). Similarly, in two northern cities, Helsinki and Lahti, Finland, urban parks and forests have been found to be insignificant in influencing the levels of nitrogen dioxide (NO₂), anthropogenic volatile organic compounds (VOCs) and PM₁₀ (Setälä et al., 2013). In the US, forest edges have been revealed to function as traps for wind-borne pollutants (Weathers et al., 2001).

The evidence based on modeling studies is much broader compared to the results from empirical studies. In London, green areas are estimated to remove 852–2121 tons of PM₁₀ annually, which equates to 0.7–1.4% PM₁₀ reduction (Tallis et al., 2011). Tiwary et al. (2009) have found that a 10 × 10 km grid in London with 25% tree cover could remove 90.4 tons of PM₁₀ per year. A recent analysis in 10 US cities showed that the mass of fine particles (PM_{2.5}) removed by trees annually could be up to 64.5 tons in Atlanta (Nowak et al., 2013). In Guangzhou, China, the annual removal of nitrogen, and sulfur dioxide and total suspended particulates could be 312.03 tons (Jim and Chen, 2008). Nevertheless, the absorption of pollutants varies by vegetation. Freer-Smith et al. (2005) found that coniferous species are able to capture more particles than species with broad leaves. Leaves with complex shape as well as large circumference-to-area ratios, waxy cuticles or ridged hairy leaves collect particles more efficiently (Tiwary et al., 2009). Moreover, green roofs help to reduce air pollution and some of the grasses, such as *Agrostis stolonifera* and *Festuca rubra*, are more effective than *Plantago lanceolata* and *Sedum album* at PM₁₀ capture (Speak et al., 2012). Green walls are even more efficient, potentially reducing NO₂ concentrations by up to 40% and PM₁₀ up to 60% in street canyons (Pugh et al., 2012).

However, large trees on both sides of streets contribute to reduced mixing, and dispersion of air pollutants as well as decrease wind velocity and the related spread of particles (Gromke and Ruck, 2009; Keuken and van der Valk, 2010; Vos et al., 2013). As biogenic volatile organic compounds (BVOC) emitted by trees cause increases in ozone pollution, low BVOC emitting species could decrease the risk of high-ozone episodes in urban areas (Calfapietra et al., 2013). The biogenic emissions model expects an ozone increase of 5–10% in the Northeast area of the USA and a PM_{2.5} decrease of 5% in the Southeast region in 2050 compared to 2000 (Lam et al., 2011). This is an example of a trade-off of short-lived climate pollutants, where concentrations of black carbon decrease, but ozone levels increase. Moreover, effects of climate change can also occur in ozone production due to a change in

temperature, humidity, radiation and transportation of ozone precursors, having different effects throughout Europe (Demuzere and van Lipzig, 2010; Orru et al., 2013).

2.2. Psychological and social benefits

In addition to the focus on physical benefits, some studies consider social benefits (James et al., 2009; Perring et al., 2012) indicating that the proximity of urban ecosystems provides a range of recreational and psychological benefits, as well as opportunities for community bonding and education to adapt to climate change.

2.2.1. Health and restorative benefits

Green urban infrastructure has health benefits, as it increases residents' participation in physical, leisure and social activities, leading to relaxation, comfort and satisfaction (Mazlina et al., 2012). Studies indicate that green urban infrastructure encourages more active and healthier forms of travel such as walking and cycling (Coombes et al., 2010), and as a result can help to mitigate climate change as it can reduce carbon emissions. A review by Tzoulas et al. (2007) suggested, however, that despite accumulating evidence on the relationships between components of green urban infrastructure and health, causal relationships are not easy to establish. Good access to urban green spaces is associated with higher physical activity levels, and a lower likelihood of being overweight or obese (Coombes et al., 2010). Maas et al. (2009) demonstrated how the annual prevalence rate of 15 of the 24 disease clusters was lower in living environments with more green space in a 1 km radius. The relation was strongest for anxiety disorder and depression, and stronger for children and people with a lower socio-economic status. Illness or impairment is considered as a key impediment for taking adaptive measures in case of weather extremes (Tzoulas et al., 2007).

Neighborhood green space enhances health by mitigating stressful life events, e.g. at times of social and environmental perturbations (van den Berg et al., 2010). A link between the need for restoration (worries and stress), the use of environmental self-regulation strategies (favorite places), and restorative outcomes has been demonstrated (Korpela et al., 2010). While evidence suggests that an increase in average global temperature is likely to be accompanied by an increase in aggressive feelings (Hsiang et al., 2013), the use of urban green spaces has been examined to alleviate thermal discomfort during periods of heat stress (Lafortezza et al., 2009). According to Thorsson et al. (2007), the number of people seeking shade in green areas increases rapidly with thermal conditions. Analogously, Lin et al. (2012) and Lenzholzer (2012), emphasized the importance of tree shade and accessible water to improve thermal comfort and parks' attendance. As Tzoulas et al. (2007) suggest, future research should clarify the positive or negative health outcomes from different types and configurations of green urban infrastructure.

2.2.2. Social and individual coping capacities

Coping capacities refer to the inner strengths and coping resources for necessary adaptation to situational demands such as climate change (Swim et al., 2009). In this respect, existing literature shows how green urban infrastructure may promote individual as well as community level coping capacities. On the individual level, the perceived ability or inability to take corrective action and to affect the outcomes can support climate change adaptation or mitigation activities (Lertzman, 2012). People acting as stewards of their environment through community gardening, park management or watershed restoration (Krasny and Tidball, 2009) may contribute to the feeling of self-efficacy in making the environmental conditions more favorable around them. Evidence from

climate education programs shows that participants gain in self-efficacy, social competence, and a sense of civic responsibility (Johnson et al., 2007). In turn, a stronger place attachment – the feeling of ownership and responsibility promotes climate-positive behavior, as individuals are more likely to act carefully in a place they value (Gifford, 2008).

On the level of communities, studies suggest that in high density urban areas, green space can improve social interaction, community bonding and satisfaction, and can contribute to the resilience of communities in the face of environmental extremes, floods or conflicts (Krasny and Tidball, 2009). Opportunities to socialize in green areas may be particularly important for more vulnerable societal groups, e.g. the elderly, those in poor health, or those with young children that tend to have limited access to social networks (Kazmierczak, 2013). Analysis by Laforteza et al. (2009) showed that during thermal stress people living alone reported higher benefits from green urban infrastructure than people living in families. In addition, existing literature (Kazmierczak and Carter, 2010) shows that visitors engage in social activities (by parks of good quality) and tend to form more extensive social ties.

2.2.3. Education

Psychological studies show that ignorance and uncertainty, besides the effects of denial and habit, can be considered primary psychological obstacles to taking adaptive or mitigation actions toward climate change (Swim et al., 2009). Instead of focusing on factual knowledge, more practically-oriented and hands-on learning curricula enable people to better understand the depth and delicate balance of cause and effect relationships between their own actions and the urban ecosystem (Dearborn and Kark, 2010; Hashimoto-Martell et al., 2012). Allotment gardens foster experiential learning about local ecosystems, providing social-ecological memories of gardening skills, local climate variability and other ecological conditions for gardening (Barthel et al., 2010). By contrast, public-access community gardens are more open to the general public and interactive methods of managing a local green area and enable to create more heterogeneous learning about environmental and social pressures that condition the creation and maintenance of green urban infrastructure (Krasny and Tidball, 2009).

3. Synthesis of GUI evidence and spatial scales, co-benefits and trade-offs

3.1. Dealing with complexity by identification of relevant spatial scales

Planning and managing green urban infrastructure and climate change mitigation and adaptation needs to be approached holistically, taking into account diverse spatial-temporal dynamics including the interactions between services (Fisher et al., 2009). One way to deal with these complexities is to analyze the benefits in relation to different spatial scales. The scalar differentiation can help in identifying the particular biophysical characteristics that matter in the benefit production and thereby could be taken into consideration in decision-making related to regional, city-scale and site-specific spatial plans (Niemelä et al., 2010; Scholes et al., 2013; Sternlieb et al., 2013). Focusing on spatial scales can also help to link activities and capacities of various local actors to support the holistic management of green infrastructure regionally (Wyborn and Pixler, 2013).

To address green urban infrastructure as the source of services and benefits, we summarize the evidence in terms of their spatial scales and the relevance of the benefits (Fig. 2). Acknowledging that appropriate scales for an analysis depend on the particular issue at hand (Sayre, 2009; Scholes et al., 2013; Villarroel Walker et al., 2014), we chose a scale set (city-region, neighborhood-district,

site-block) that considers scalar aspects of each benefit, but is simple enough to allow generalization. Adaptation benefits vary greatly by local conditions and related vulnerabilities (Biesbroek et al., 2010; Heidrich et al., 2013) and urban areas will need to adjust adaptation-oriented scalar frameworks for their specific local purposes. This general scale set can provide inspiration for discussing usable scales and analysis approaches in different regions.

Fig. 2 synthesizes our findings; a benefit was defined as *relevant* on a scale when the evidence included from several studies' arguments showed that this scale required attention in the planning of green urban infrastructure because 1) the benefit is dependent on green urban infrastructure components or characteristics on this scale, and 2) this scale enables the consideration of the relevant green urban infrastructure components and characteristics better than some other scales. A benefit was marked as *not defined* when the evidence was conflicting or unclear or if the evidence was lacking. A benefit was defined as *less relevant* when there were arguments from several studies showing that there are other scales that are clearly more useful than this one.

The evidence discussed above is not all-encompassing but it covers the essential part of empirical evidence found in the literature (Fig. 2). Based on the evidence, the following benefits/benefit sets are relevant on all the three scales (city-region, neighborhood-district, site-block): improved water quality, reduced problems with flooding, peak flows and drought, and health and restorative benefits, social and individual coping capacities and education. Water related benefits arise from services linked to a regionally functioning water system, whereby ignoring the regional scale could lead to management degrading the system as a whole. Ignoring the smaller scales, in turn, could lead to land use and management solutions altering water connections within the sub catchments and thereby, for example, preventing storm water from flowing to a green area in which it could be purified.

Evidence for green urban infrastructure on health and restorative benefits, social and individual coping capacities and education differs from the evidence on the other benefits addressed by the complexity of human experiences and behavior, e.g. variation of

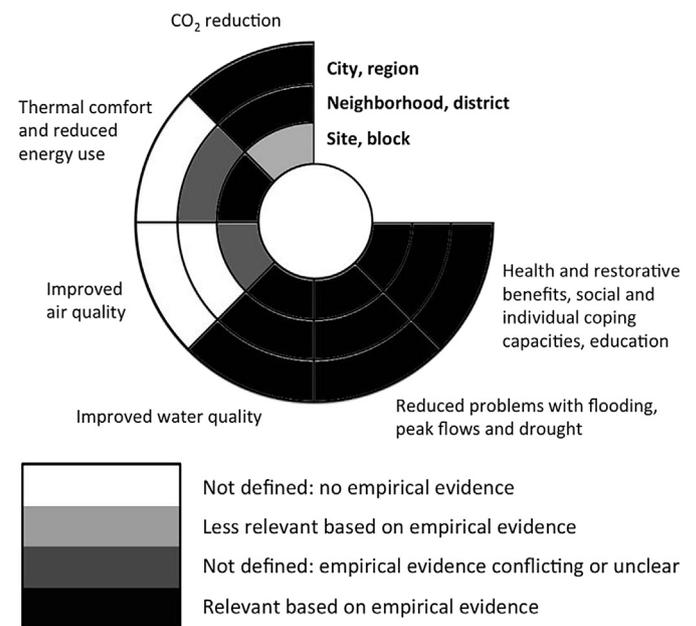


Fig. 2. Relevance of the benefits from green urban infrastructure for climate change adaptation and mitigation on three spatial scales, based on the evidence discussed above.

cultures, lifestyles, mobility habits and place relations of urban inhabitants. The spatial scale set is not sensitive to social scales such as the individual, a family or a group; however, it enables a general level consideration of the psychological and social benefits together with other benefits as part of a holistic approach. The psychological and social benefits are relevant on all three scales: on the site/block scale possibly because the site characteristics define how the environment can be experienced; on the neighborhood/district and city/region scales these benefits are important because accessibility of opportunities to specific experiences is dependent on land use solutions on these scales.

Thermal comfort is a benefit with which it is possible to define one scale as especially important, the scale of site/block. The cooling effect of a green area beyond its boundary is supported by few studies; most of them are simulations, especially those referring to the whole city/region scale. Effects of green urban infrastructure on thermal comfort and reduced energy use are linked to the characteristics of vegetation and vegetated surfaces, e.g. in urban street canyons and parks and on buildings. However, these benefits may be relevant on the neighborhood/district scale as well.

Improved air quality was the most unclear of the benefits studied. Air purification services can vary significantly by detailed characteristics of green spaces such as tree type and the location of

vegetation in relation to buildings, and effects of this service have been demonstrated only on a site/block scale. However, the evidence is not particularly strong as it is dependent on case-specific local characteristics and general conclusions are difficult to justify.

CO₂ reduction was the only benefit for which it was possible to define a less important scale. The site/block scale is less relevant because the benefit makes sense when the volume of CO₂ sequestration and storage is large, and for this, large green areas are important and a single site less significant. If large areas are lost by lack of attention to wider scales, the lost volumes are impossible or at least difficult to compensate for with site/block scale solutions.

3.2. Co-benefits and trade-offs

Our review suggested that there are relevant co-benefits and trade-offs that require attention in addressing the production of services and benefits. Fig. 3 illustrates the co-benefits between different services, based on the examples of the types of green infrastructure that favor the benefit (trees, green roofs, etc).

The grade of the co-benefit observed is the result of the analysis of published studies that provide empirical evidence (total 86 papers). This analysis has been accomplished by linking the green urban infrastructure (e.g. green roofs) and the benefit (e.g. CO₂

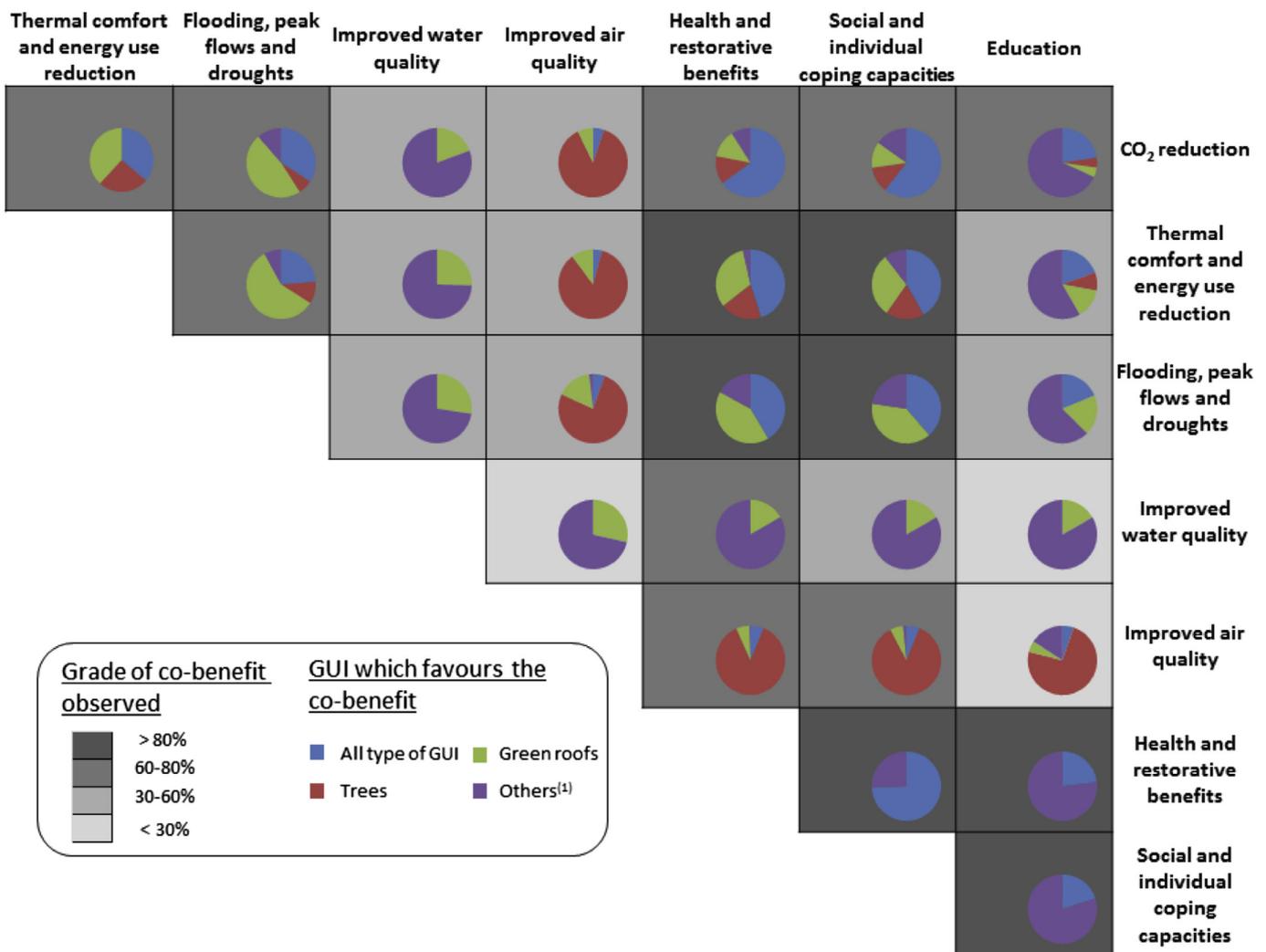


Fig. 3. Co-benefits caused by green urban infrastructure. ⁽¹⁾ Other green urban infrastructure can refer to: rain gardens (flooding, peak flows and droughts and water quality), allotment gardens (health and restorative benefits, social and individual coping capacities and education), bioswales and wetlands (water quality). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reduction) they have generated, and assessing if this green urban infrastructure also favors other benefits (e.g. thermal comfort). For example, based on our analysis of the literature we can affirm that health and restorative benefits have a high grade of co-benefit (above 80%) with social and individual coping capacities. These co-benefits are supported by all types of green urban infrastructure, but also by others, in this case allotment gardens. From Fig. 3, it can be concluded that physiological and social services favor co-benefits with other services. This is because almost all types of green urban infrastructure can benefit health, coping capacities and education. More detailed descriptions and interpretations of the benefits and tradeoffs are provided in the supplementary material. In summary, in addition to the mentioned co-benefits, the following trade-offs were identified:

- Maintenance activities: various maintenance and construction activities (Carter and Keeler, 2008) emit carbon back into the atmosphere via fossil-fuel combustion (e.g. construction, transport). Fertilization can also be a problem, for example, when an intensive green roof requires frequent fertilization which reduces the quality of stormwater runoff (Berndtsson, 2010).
- Tree shade: very important in cold climates, as shade can reduce solar radiation penetration, increasing winter heating demand and reducing thermal comfort in streets and parks (Lin et al., 2012; Maher, 2013).
- Large street trees: large trees on both sides of streets could also contribute to reduced mixing, dispersion, and wind velocity and thereby increase air pollution levels at the street-level (Gromke and Ruck, 2009; Keuken and van der Valk, 2010; Vos et al., 2013).
- Density and mobility: if a city has extended green areas, the population density generally reduces, increasing mobility and fuel consumption.
- Animals and insects in green areas: may be a nuisance or pose a health hazard as carriers of diseases (e.g. Lyme disease); increased use of pesticides may in turn lead to reduced air and water quality.

4. Conclusion

This article demonstrated that an increasing body of knowledge related to the estimation of the benefits provided by green urban infrastructure to climate change mitigation and adaptation is available. The topic is clearly gaining momentum and many studies provide empirical evidence that can be used to design green infrastructure to decrease the vulnerability of urban areas to climate change. However, the analysis also showed that it remains difficult to draw unambiguous conclusions regarding the actual contribution of green urban infrastructure. The main reason for this is that in many cases it is not clear how the evidence obtained in specific conditions and spatial spheres could be reproducible in other conditions and spheres. Future research should provide such important disclaimers and general conclusions. Nevertheless, the potential of green urban infrastructure across scales is very beneficial, particularly with respect to:

- The role of green urban infrastructure in contributing to climate change mitigation and offsetting urban carbon emissions. Specifically, potential CO₂ storage and sequestration of unconventional green space, such as green roofs and green facades, for which robust data are still lacking;
- The impact of greening interventions on thermal comfort in a wider urban area;
- The cooling effect of green roofs in different types of buildings and in different seasons;

- The absorption of air pollutants by different types and composition of green urban infrastructure;
- The cumulative effect of green urban infrastructure on runoff, groundwater recharge and evapotranspiration, considering local physiographic, climatic and biotic aspects;
- The vulnerable social groups that could benefit the most from the health and restorative benefits offered by green urban infrastructure;
- The characteristics of green areas which bring the most social and psychological benefits at times of climate-related environmental extremes;
- Co-benefits and trade-offs between the provision of physical and social benefits of green urban infrastructure in response to climate change effects;
- Complex stakeholder relations behind the provision of green urban infrastructure services and benefits in different societal and climatic contexts.

Concerning the analysis of trade-offs and co-benefits, it can be concluded that many green urban infrastructure elements can provide multiple benefits for urban areas. This should be taken into account in planning and design, e.g. in assessing the usability of specific greening techniques in different types of areas. Consideration of the multi-functionality is particularly important as the case of looking at one benefit only could, in turn, be detrimental from another point of view (trade-offs).

Defining the scales of benefits carries several practical advantages. First, on the individual level, indicating the specific benefits of green urban infrastructure for climate change adaptation and mitigation will reduce the uncertainty of climate change and the global nature of its potential effects that are recognized as the universal barriers to effective behavioral responses. Evidence on the spatially defined benefits of green urban infrastructure measures for climate change adaptation can motivate citizens to undertake often costly or difficult changes in behavior.

Second, on the level of political and administrative decision-making, a better understanding of the spatial scales of green urban infrastructure benefits lies in the improved ability to set policy objectives and responsibilities at appropriate administrative levels. A more systematic understanding of the bio-physical and social processes defining the various services from green urban infrastructure enables to target the stressors hampering the provision and quality of these services. Understanding the benefits of greenery allows employing specific competences of regional and local level authorities, e.g. in urban greening initiatives.

This article has proposed a green urban infrastructure assessment framework and quantifies some of the benefits and trade-offs of green infrastructure with regard to climate change mitigation and adaptation. Our suggestion of identifying benefits from green urban infrastructure across three different scales can hopefully help to assess, develop and interpret green urban infrastructure as a part of climate-proof urban areas.

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Appendix A. Supplementary material

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References

- Alexandri, E., Jones, P., 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Build. Environ.* 43 (4), 480–493.
- Barthel, S., Folke, C., Colding, J., 2010. Social-ecological memory in urban gardens—retaining the capacity for management of ecosystem services. *Glob. Environ. Change* 20 (2), 255–265.
- Berndtsson, J., 2010. Green roof performance towards management of runoff water quantity and quality: a review. *Ecol. Eng.* 36, 351–360.
- Biesbroek, G., Swart, R., Carter, T., 2010. Europe adapts to climate change: comparing national adaptation strategies. *Glob. Environ. Change* 20 (3), 440–450.
- Bowler, D., Buyung-Ali, L., Knight, L., Pullin, A., 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landsc. Urban Plan.* 97 (3), 147–155.
- Brantley, H., Hagler, G., Deshmukh, P., Baldauf, R., 2013. Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. *Sci. Total Environ.* 468–469, 120–129.
- Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G., Loreto, F., 2013. Role of biogenic volatile organic compounds (BVOC) emitted by urban trees on ozone concentration in cities: a review. *Environ. Pollut.* 183, 71–80.
- Cameron, R., Blanuša, T., Taylor, J., Salisbury, A., Halstead, A., Henricot, B., Thompson, K., 2012. The domestic garden – its contribution to urban green infrastructure. *Urban For. Urban Green.* 11 (2), 129–137.
- Capitol Region Watershed District, 2012. BMP performance and cost-benefit analysis: Arlington Pascal project 2007–2010. Retrieved from: http://www.capitolregionwd.org/wp-content/uploads/2012/09/2007_2010_BMP_Performance_MainBody.pdf.
- Carter, T., Keeler, A., 2008. Life-cycle cost–benefit analysis of extensive vegetated roof systems. *J. Environ. Manag.* 87 (3), 350–363.
- Castleton, H., Stovin, V., Beck, S., Davison, J., 2010. Green roofs: building energy savings and the potential for retrofit. *Energy Build.* 42 (10), 1582–1591.
- Chan, K., Satterfield, T., Goldstein, J., 2012. Rethinking ecosystem services to better address and navigate cultural values. *Ecol. Econ.* 74, 8–18.
- Cheng, C., Cheung, K., Chu, L., 2010. Thermal performance of a vegetated cladding system on facade walls. *Build. Environ.* 45 (8), 1779–1787.
- Cook-Patton, S., Bauerle, T., 2012. Potential benefits of plant diversity on vegetated roofs: a literature review. *J. Environ. Manag.* 106, 85–92.
- Coombs, E., Jones, A., Hillsdon, M., 2010. The relationship of physical activity and overweight to objectively measured green space accessibility and use. *Soc. Sci. Med.* 70 (6), 816–822.
- Czemieli Berndtsson, J., 2010. Green roof performance towards management of runoff water quantity and quality: a review. *Ecol. Eng.* 36 (4), 351–360.
- Davies, Z., Edmondson, J., Heinemeyer, A., Leake, J., Gaston, K., 2011. Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale. *J. Appl. Ecol.* 48 (5), 1125–1134.
- Davis, A., Hunt, W., Traver, R., Clar, M., 2009. Bioretention technology: overview of current practice and future needs. *J. Environ. Eng.* 135 (3), 109–117.
- Dearborn, D., Kark, S., 2010. Motivations for conserving urban biodiversity. *Conserv. Biol.* 24 (2), 432–440.
- Demuzere, M., van Lipzig, N., 2010. A new method to estimate air-quality levels using a synoptic-regression approach. Part I: Present-day O₃ and PM₁₀ analysis. *Atmos. Environ.* 44 (10), 1341–1355.
- Ellis, J., 2012. Sustainable surface water management and green infrastructure in UK urban catchment planning. *J. Environ. Plan. Manag.* 56 (1), 24–41.
- European Environment Agency (EEA), 2012. Urban adaptation to climate change in Europe. Retrieved from European Environment Agency website: <http://www.eea.europa.eu/publications/urban-adaptation-to-climate-change>.
- Faehnl, M., Söderman, T., Schulman, H., Lehvavirta, S., 2014. Scale-sensitive integration of ecosystem services in urban planning. *GeoJournal*, 15 pp. (published online 12 June, 2014).
- Farrugia, S., Hudson, M., McCulloch, L., 2013. An evaluation of flood control and urban cooling ecosystem services delivered by urban green infrastructure. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* 9 (2), 136–145.
- Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. *Ecol. Econ.* 68 (3), 643–653.
- Freer-Smith, P., Beckett, K., Taylor, G., 2005. Deposition velocities to Sorbus Aria, Acer Campestre, Populus Deltoides X Trichocarpa 'Beaupre', Pinus Nigra and X Cupressopyris Leylandii for coarse, fine and ultra-fine particles in the urban environment. *Environ. Pollut.* 133, 157–167.
- Gifford, R., 2008. Psychology's essential role in alleviating the impacts of climate change. *Can. Psychol.* 49 (4), 273–280.
- Gill, S., Handley, J., Ennos, A., Pauleit, S., 2007. Adapting cities for climate change: the role of the green infrastructure. *Build. Environ.* 33 (1), 115–133.
- Gregoire, B., Clausen, J., 2011. Effect of a modular extensive green roof on storm-water runoff and water quality. *Ecol. Eng.* 37 (6), 963–969.
- Gromke, C., Ruck, B., 2009. On the impact of trees on dispersion processes of traffic emissions in street canyons. *Boundary-Layer Meteorol.* 131, 19–34.
- Hagler, G., Lin, M., Khlystov, A., Baldauf, R., Isakov, V., Faircloth, J., Jackson, L.E., 2012. Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions. *Sci. Total Environ.* 419, 7–15.
- Hall, A., 2010. Green infrastructure case studies: municipal policies for managing stormwater with Green Infrastructure. Retrieved from United States Environmental Protection Agency: <http://rfcd.pima.gov/pdd/lid/pdfs/40-usepa-gi-case-studies-2010.pdf>.
- Hashimoto-Martell, E., McNeill, K., Hoffman, E., 2012. Connecting urban youth with their environment: the impact of an urban ecology course on student content knowledge, environmental attitudes and responsible behaviors. *Res. Sci. Educ.* 42, 1007–1026.
- Heidrich, O., Dawson, R.J., Reckien, D., Walsh, C.L., 2013. Assessment of the climate preparedness of 30 urban areas in the UK. *Clim. Change* 120 (4), 771–784.
- Hsiang, S., Burke, M., Miguel, E., 2013. Quantifying the influence of climate on human conflict. *Science* 341, 6151.
- Hunt, W., Smith, J., Jadlovec, S., Hathaway, J., Eubanks, P., 2008. Pollutant removal and peak flow mitigation by a bioretention cell in urban charlotte, N.C. *J. Environ. Eng.* 134 (5), 403–408.
- Hutyra, L., Yoon, B., Alberti, M., 2011. Terrestrial carbon stocks across a gradient of urbanization: a study of the Seattle, WA region. *Glob. Change Biol.* 17 (2), 783–797.
- Ignatieva, M., Stewart, G., Meurk, C., 2011. Planning and design of ecological networks in urban areas. *Landsc. Ecol. Eng.* 7 (1), 17–25.
- Ismail, A., Samad, M., Rahman, A., Yeok, F., 2012. Cooling potentials and CO₂ uptake of Ipomoea Pes-Caprae installed on the flat roof of a single storey residential building in Malaysia. *Proc. Soc. Behav. Sci.* 35, 361–368.
- Jacobson, C.R., 2011. Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review. *J. Environ. Manag.* 92 (6), 1438–1448.
- James, P., Tzoulas, K., Adams, M., Barber, A., Box, J., Breuste, J., Elmqvist, T., Frith, M., Gordon, C., Greening, K., Handley, J., Haworth, S., Kazmierczak, A., Johnston, M., Korpela, K., Morettin, M., Niemelä, J., Pauleit, S., Roeq, M., Sadler, J., Thompson, W., 2009. Towards an integrated understanding of green space in the European built environment. *Urban For. Urban Green.* 8 (2), 65–75.
- Jim, C., Chen, W., 2008. Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China). *J. Environ. Manag.* 88, 665–676.
- Jo, H., 2002. Impacts of urban greenspace on offsetting carbon emissions for middle Korea. *J. Environ. Manag.* 64 (2), 115–126.
- Johnson, L., Johnson-Pynn, J., Pynn, T., 2007. Youth civic engagement in china: results from a program promoting environmental activism. *J. Adolesc. Res.* 22 (4), 355–386.
- Kazmierczak, A., 2013. The contribution of local parks to neighborhood social ties. *Landsc. Urban Plan.* 109, 31–44.
- Kazmierczak, A., Carter, J., 2010. Adaptation to Climate Change Using Green and Blue Infrastructure. A Database of Case Studies. The University of Manchester, Manchester.
- Keuken, M., van der Valk, K., January, 2010. The effects of trees and hedges on air quality in a street-canyon in Amsterdam. Paper presented at the CLIMAQS Workshop Local Air Quality and its Interactions with Vegetation, Antwerp, Belgium.
- Korpela, K., Ylén, M., Tyrväinen, L., Silvennoine, H., 2010. Favorite green, waterside and urban environments, restorative experiences and perceived health in Finland. *Health Promot. Int.* 25, 200–209.
- Krasny, M., Tidball, K., 2009. Applying a resilience systems Framework to urban environmental education. *Environ. Educ. Res.* 15 (4), 465–482.
- Laforcezza, R., Carrus, G., Sanesi, G., Davies, C., 2009. Benefits and well-being perceived by people visiting Green spaces in periods of heat stress. *Urban For. Urban Green.* 8 (2), 97–108.
- Lam, Y., Fu, J., Wu, S., Micklely, L., 2011. Impacts of future climate change and effects of biogenic emissions on surface ozone and particulate matter concentrations in the United States. *Atmos. Chem. Phys.* 11, 4789–4806.
- Lenzholzer, S., 2012. Research and design for thermal comfort in Dutch urban squares. *Resour. Conserv. Recycl.* 64, 39–48.
- Lertzman, R., 2012. The myth of apathy: psychoanalytic explorations of environmental degradation. In: Weintrobe, S. (Ed.), *Engaging with Climate Change: Psychoanalytic and Interdisciplinary Perspectives*. Routledge, London, pp. 117–133.
- Lin, T.-P., Tsai, K.-T., Hwang, R.-L., Matzarakis, A., 2012. Quantification of the effect of thermal indices and sky view factor on park attendance. *Landsc. Urban Plan.* 107, 137–146.
- Maas, J., Verheij, R., de Vries, S., Spreeuwenberg, P., Schellevis, F., Groenewegen, P., 2009. Morbidity is related to a green living environment. *J. Epidemiol. Commun. Health* 63, 967–973.
- Maher, J., 2013. Measuring the energy savings from tree shade. Paper presented at the Agricultural & Applied Economics Association's 2013 AAEE & CAES Joint Annual Meeting. Washington, DC. Retrieved from: http://ageconsearch.umn.edu/bitstream/150567/2/Maher_AAEE_P3348_TreeShade.pdf.
- Mazlina, M., Said, I., Mohamad, I., 2012. Experiential contacts with green infrastructure's diversity and well-being of urban community. *Proc. Soc. Behav. Sci.* 49, 257–267.

- Mentens, J., Raes, D., Hermy, M., 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landsc. Urban Plan.* 77 (3), 217–226.
- Naumann, S., Gerardo, A., Gerdes, H., Frelüh-Larsen, A., McKenna, D., Pam, B., Burch, S., Sanders, M., 2010. Assessment of the Potential of Ecosystem-based Approaches to Climate Change Adaptation and Mitigation in Europe. Final report to the European Commission, DG Environment, contract no. 070307/2010/580412/SER/B2. Ecologic Institute and Environmental Change Institute, Oxford University Centre for the Environment. Retrieved from: http://ec.europa.eu/environment/nature/climatechange/pdf/EbA_EBM_CC_FinalReport.pdf.
- Niemelä, J., Saarela, S.-R., Söderman, T., Kopperoinen, L., Yli-Pelkonen, V., Väre, S., Kotze, D., 2010. Using the ecosystem services approach for better planning and conservation of urban green spaces: a Finland case study. *Biodivers. Conserv.* 19 (11), 3225–3243.
- Nonomura, A., Kitahara, M., Masuda, T., 2009. Impact of land use and land cover changes on the ambient temperature in a middle scale city, Takamatsu, in Southwest Japan. *J. Environ. Manag.* 90 (11), 3297–3304.
- Nordbo, A., Järvi, L., Haapanala, S., Wood, C.R., Vesala, T., 2012. Fraction of natural area as main predictor of net CO₂ emissions from cities. *Geophys. Res. Lett.* 39 (20).
- Nowak, D., Greenfield, E., Hoehn, R., Lapoint, E., 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environ. Pollut.* 178, 229–236.
- Odefey, J., Detwiler, S., Rousseau, K., Trice, A., Blackwell, R., O'Hara, K., Buckley, M., Souhlas, M., Brown, S., Raviprakash, P., . Banking on Green: A Look at How Green Infrastructure Can Save Municipalities Money and Provide Economic Benefits Community-wide. A Joint Report by American Rivers, The Water Environment Federation, The American Society of Landscape Architects, ECONorthwest. Retrieved from: http://www.asla.org/uploadedFiles/CMS/Government_Affairs/Federal_Government_Affairs/Banking%20on%20Green%20HighRes.pdf.
- Orru, H., Andersson, C., Ebi, K., Langner, J., Astrom, C., Forsberg, B., 2013. Impact of climate change on ozone-related mortality and morbidity in Europe. *Eur. Respir. J.* 41, 285–289.
- Passeport, E., Hunt, W., Line, D., Smith, R., Brown, R., 2009. Field study of the ability of two grassed bioretention cells to reduce storm-water runoff pollution. *J. Irrigat. Drain. Eng.* 135 (4), 505–510.
- Pauleit, S., Liu, L., Ahern, J., Kazmierczak, A., 2011. Multifunctional green infrastructure planning to promote ecological services in the city. In: Niemela, J., Breuste, J., Guntenspergen, G., McIntyre, N., Elmqvist, T., James, P. (Eds.), *Urban Ecology: Patterns, Processes, and Applications*. Oxford University Press, Oxford, pp. 272–286.
- Perring, M., Manning, P., Hobbs, R., Lugo, A., Ramalho, C., Standish, R., 2012. Novel ecosystems: intervening in the new world order. In: Higgs, E., Hobbs, R., Hall, C. (Eds.), *Novel Ecosystems*. Wiley Press, London, pp. 310–325.
- Pugh, T., Mackenzie, R., Whyatt, J., Hewitt, C., 2012. Effectiveness of green infrastructure for improvement of air quality in urban street canyons. *Environ. Sci. Technol.* 46 (14), 7692–7699.
- Santamouris, M., 2014. Cooling the cities – a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* 103, 682–703.
- Sayre, N.F., 2009. Scale. In: Castree, N., Demeritt, D., Liverman, D., Rhoads, B. (Eds.), *A Companion to Environmental Geography*. Wiley, Chichester, England, pp. 95–108.
- Scholes, R.J., Reyers, B., Biggs, R., Spierenburg, M., Duriappah, A., 2013. Multi-scale and cross-scale assessments of social–ecological systems and their ecosystem services. *Curr. Opin. Environ. Sustain.* 5 (1), 16–25.
- Setälä, H., Viippola, V., Rantalainen, A.-L., Pennanen, A., Yli-Pelkonen, V., 2013. Does urban vegetation mitigate air pollution in northern conditions? *Environ. Pollut.* 183, 104–112.
- Shashua-Bar, L., Hoffman, M., 2000. Vegetation as a climatic component in the design of an urban street: an empirical model for predicting the cooling effect of urban green areas with trees. *Energy Build.* 31 (3), 221–235.
- Shashua-Bar, L., Pearlmutter, D., Erell, E., 2009. The cooling efficiency of urban landscape strategies in a hot dry climate. *Landsc. Urban Plan.* 92 (3–4), 179–186.
- Spatari, S., Yu, Z., Montalto, F., 2011. Life cycle implications of urban green infrastructure. *Environ. Pollut.* 159 (8–9), 2174–2179.
- Speak, A., Rothwell, J., Lindley, S., Smith, C., 2012. Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmos. Environ.* 61, 283–293.
- Sternlieb, F., Bixler, R.P., Huber-Stearns, H., Huayhuaca, C., 2013. A question of fit: reflections on boundaries, organizations and social–ecological systems. *J. Environ. Manag.* 130, 117–125.
- Swim, J., Clayton, S., Doherty, T., Gifford, R., Howard, G., Reser, J., Stern, P., Weber, E., 2009. Psychology and Global Climate Change: Addressing a Multi-faceted Phenomenon and Set of Challenges. American Psychological Association's Task Force on the Interface Between Psychology and Global Climate Change, Washington, DC.
- Tallis, M., Taylor, G., Sinnett, D., Freer-Smith, P., 2011. Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landsc. Urban Plan.* 103, 129–138.
- Thorsson, S., Honjo, T., Lindberg, F., Eliasson, I., Lim, E.-M., 2007. Thermal comfort and outdoor activity in Japanese urban public places. *Environ. Behav.* 39 (5), 660–684.
- Tiwary, A., Sinnett, D., Peachey, C., Chalabi, Z., Vardoulakis, S., Fletcher, T., Leonardi, G., Grundy, C., Azapagic, A., Hutchings, T.R., 2009. An integrated tool to assess the role of new planting in PM10 Capture and the human health benefits: a case study in London. *Environ. Pollut.* 157, 2645–2653.
- Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., James, P., 2007. Promoting ecosystem and human health in urban areas using Green Infrastructure: a literature review. *Landsc. Urban Plan.* 81 (3), 167–178.
- van den Berg, A., van Winsum-Westra, M., de Vries, S., van Dillen, S., 2010. Allotment gardening and health: a comparative survey among allotment gardeners and their neighbors without an allotment. *Environ. Health* 9 (1), 74.
- Velasco, E., Roth, M., 2010. Cities as net sources of CO₂: review of atmospheric CO₂ exchange in urban environments measured by Eddy covariance technique. *Geogr. Compass* 4 (9), 1238–1259.
- Villarreal Walker, R., Beck, M.B., Hall, J.W., et al., 2014. The energy-water-food nexus: strategic analysis of technologies for transforming the urban metabolism. *J. Environ. Manag.* 141, 104–115.
- Vos, P.E., Maiheu, B., Vankerkm, J., Janssen, S., 2013. Improving local air quality in cities: to tree or not to tree? *Environ. Pollut.* 183, 113–122.
- Washbourne, C.L., Renforth, P., Manning, D., 2012. Investigating carbonate formation in urban soils as a method for capture and storage of atmospheric carbon. *Sci. Total Environ.* 431, 166–175.
- Weathers, K.C., Cadenasso, M.L., Pickett, S.T.A., 2001. Forest edges as nutrient and pollutant concentrators: potential synergisms between fragmentation, forest canopies, and the atmosphere. *Conserv. Biol.* 15 (6), 1506–1514.
- Wyborn, C., Pixler, R.P., 2013. Collaboration and nested environmental governance: scale dependency, scale framing, and cross-scale interactions in collaborative conservation. *J. Environ. Manag.* 123, 58–67.
- Yu, C., Hien, W., 2006. Thermal benefits of city parks. *Energy Build.* 38 (2), 105–120.
- Zhao, M., Kong, Z.-H., Escobedo, F.J., Gao, J., 2010. Impacts of urban forests on offsetting carbon emissions from industrial energy use in Hangzhou, China. *J. Environ. Manag.* 91 (4), 807–813.