The nexus between air pollution, green infrastructure and human health

Environment International 133 (2019) 105181

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review article

The nexus between air pollution, green infrastructure and human health

Prashant Kumar[a,b,*], Angela Druckman[c], John Gallagher[b], Birgitta Gatersleben[d], Sarah Allison[e], Theodore S. Eisenman[f], Uy Hoang[g,h], Sarkawt Hama[a], Arvind Tiwari[a], Ashish Sharma[a], K.V. Abhijith[a], Deepti Adlakha[i], Aonghus McNabola[a,b], Thomas Astell-Burt[j,k], Xiaoqi Feng[j,k], Anne C. Skeldon[l], Simon de Lusignan[e,f], Lidia Morawska[m]

[a] Global Centre for Clean Air Research (GCARE), Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, United Kingdom
[b] Department of Civil, Structural & Environmental Engineering, School of Engineering, Trinity College Dublin, Dublin, Ireland
[c] Centre for Environment & Sustainability, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, United Kingdom
[d] School of Psychology, Faculty of Health and Medical Sciences, University of Surrey, Guildford, Surrey, United Kingdom
[e] School of Bioscience and Medicine, Faculty of Health and Medical Sciences, University of Surrey, Guildford, Surrey, United Kingdom
[f] Department of Landscape Architecture and Regional Planning, University of Massachusetts, Amherst, USA
[g] Department of Clinical and Experimental Medicine, University of Surrey, Guildford, Surrey, United Kingdom
[h] Royal College of General Practitioners (RCGP), Research & Surveillance Centre (RSC), Department of Clinical and Experimental Medicine, University of Surrey, Guildford, Surrey, United Kingdom
[i] School of Natural and Built Environment, Queen's University Belfast, Belfast, United Kingdom
[j] Population Wellbeing and Environment Research Lab (PowerLab), School of Health and Society, Faculty of Social Sciences, University of Wollongong, Wollongong, NSW, Australia
[k] Menzies Centre for Health Policy, University of Sydney, Sydney, NSW, Australia
[l] Department of Mathematics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, United Kingdom
[m] International Laboratory for Air Quality & Health, Queensland University of Technology, Brisbane, QLD, Australia

ARTICLE INFO

Handling Editor: Zorana Jovanovic Andersen

Keywords:
Pollution exposure
Physical and mental health
Environmental health
Passive control
City greening

ABSTRACT

Cities are constantly evolving and so are the living conditions within and between them. Rapid urbanization and the ever-growing need for housing have turned large areas of many cities into concrete landscapes that lack greenery. Green infrastructure can support human health, provide socio-economic and environmental benefits, and bring color to an otherwise grey urban landscape. Sometimes, benefits come with downsides in relation to its impact on air quality and human health, requiring suitable data and guidelines to implement effective greening strategies. Air pollution and human health, as well as green infrastructure and human health, are often studied together. Linking green infrastructure with air quality and human health together is a unique aspect of this article. A holistic understanding of these links is key to enabling policymakers and urban planners to make informed decisions. By critically evaluating the link between green infrastructure and human health via air pollution mitigation, we also discuss if our existing understanding of such interventions is sufficient to inform their uptake in practice.

Natural science and epidemiology approach the topic of green infrastructure and human health very differently. The pathways linking health benefits to pollution reduction by urban vegetation remain unclear and the mode of green infrastructure deployment is critical to avoid unintended consequences. Strategic deployment of green infrastructure may reduce downwind pollution exposure. However, the development of bespoke design guidelines is vital to promote and optimize greening benefits, and measuring green infrastructure's socio-economic and health benefits are key for their uptake. Greening cities to mitigate pollution effects is on the rise and these need to be matched by scientific evidence and appropriate guidelines. We conclude that urban vegetation can facilitate broad health benefits, but there is little empirical evidence linking these benefits to air pollution reduction by urban vegetation, and appreciable efforts are needed to establish the underlying policies, design and engineering guidelines governing its deployment.

* Corresponding author at: Global Centre for Clean Air Research (GCARE), Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, United Kingdom.

E-mail addresses: p.kumar@surrey.ac.uk, prashant.kumar@cantab.net (P. Kumar).

https://doi.org/10.1016/j.envint.2019.105181
Received 10 June 2019; Received in revised form 3 August 2019; Accepted 10 September 2019

1. Introduction

Actions to reverse the impacts of anthropogenic sources of air pollution are being undertaken in different ways around the world. However, a dependency on fossil fuels remains to support our transport, industry and energy sectors with 80% of global energy supplies having been produced by fossil fuels in 2018 (EIA, 2019). In conjunction with a demographic shift due to urban migration, with 66% of the global population expected to live in cities by 2050 (UN, 2014), the concentrations of people and pollution coincide. Substantial progress has to be made in decarbonization and climate change mitigation in the provision of services to these ever-growing urban centres. In particular, air pollution in the built environment continues to present a societal challenge and is foreseen to be a problem that may linger for decades to come.

Cities provide opportunities for a large population to access centralized services, yet this often comes with an array of consequences including air, noise and light pollution. Focusing on ambient air quality, exceedances of guidance levels set by the World Health Organization (WHO) are evident and linked with an estimated 6.5 million premature deaths globally each year, the majority of which are suffered by urban populations (Landrigan et al., 2018). Transport emissions are a large contributor to air pollution in cities around the world and contribute to a range of health problems such as respiratory and cardiovascular diseases (Heal et al., 2012). For instance, Karagulian et al. (2015) analysed studies conducted in 529 cities of 51 countries to estimate the global averages of urban PM concentration. They reported that traffic emissions contributed 25% of PM_{10} concentrations, followed by industrial activities (18%). Contributions of traffic emissions and domestic fuel burning constituted shares of 25% and 20%, respectively to urban $PM_{2.5}$ concentrations. This study also mentioned that traffic is the main source of urban $PM_{2.5}$ concentrations in many regions such as India, Southwestern Europe and Brazil and that the domestic fuel burning is an emerging source in some regions like Africa and Central and Eastern Europe. Furthermore, Crilley et al. (2017) carried out a source apportionment study at a roadside environment (Marylebone Road) in central London, UK. They also reported transport emissions as the major contributor, at about 32% of $PM_{2.5}$, followed by secondary inorganic aerosols at about ~21%. Therefore, targeting different methods to control traffic-related air pollution is fundamental in protecting the health of our urban populations (Kumar et al., 2015, 2016).

Green infrastructure is seen as a potential means to mitigate pollution impacts. The definition of the term depends upon the context in which it is used. It can refer to trees and vegetation that provide ecological benefits in urban areas, and also to engineered structures such as sustainable urban drainage systems (Benedict and McMahon, 2006). Here, we use the term to refer to street trees, hedges, bushes, green walls, green roofs and green spaces (parks). The interaction between green infrastructure design (e.g., species selection, spatial positioning) and air pollutants can positively or negatively affect personal exposure and thus human health (Abhijith et al., 2017). The effects depend on the conditions of the surrounding built environment, as well as the type, location, and configuration of GI. The built-environment can be classified into open-road and street canyons type topographies. Open-road environments are roadsides that are not affected by surrounding buildings, having no or low-rise single-storey buildings, and are generally situated in peri-urban and rural areas. On the other hand, street canyons generally have single to multi-storey buildings on both sides of the roads and are situated in urban centres. The wind flow conditions inside the street canyons can be isolated roughness flow, wake interference flow or skimming flow, depending on their aspect ratio i.e. the building height (H) to street width (W) ratio (Oke, 1988). The street canyons can usually be termed as shallow ($H/W \leq 0.5$), deep ($H/W \geq 2$) or in-between ($0.5 < H/W < 2$) (Vardoulakis et al., 2003, Abhijith et al., 2017). When the aspect ratio reaches a certain threshold, tall trees in street canyon environments can increase pollutant concentrations at ground level by restricting dispersion. Since ventilation conditions could differ in different types of street canyons due to wind flow, it is important to make appropriate choices concerning the provision of green infrastructure (GLA, 2019). For example, GI can lead to poor air quality in deep street canyons (Abhijith et al., 2017) as opposed to shallow street canyons, as highlighted in GLA (2019). In open road conditions, roadside vegetation of sufficient height, thickness, and coverage can reduce downwind pollution concentrations through deposition and enhanced turbulence (Abhijith and Kumar, 2019; Deshmukh et al., 2018); while highly porous vegetation with gaps can have no or even increased downwind pollutant concentrations (Baldauf, 2017).

GI and air pollution interactions in street canyons are complex, resulting in a positive or negative impact on air quality based on the aspect ratio and GI types. The pros and cons clearly suggest that particular characteristics of green infrastructure may be sensitive to local environmental and social circumstances. Informed design is key to ensure benefits over adverse impacts, and to maximize the potential for those benefits (Van den Berg et al., 2010). This is highlighted by a range of research studies (Supplementary information, SI, Table S1) and numerous review articles (e.g., Abhijith et al., 2017; Cariñanos and Casares-Porcel, 2011; Gallagher et al., 2015; Lee and Maheswaran, 2011; Shaneyfelt et al., 2017; Eisenman et al., 2019a). Yet there is a lack of consensus on issues related to human health, economics and social co-benefits of air pollution mitigation via green infrastructure (Fig. 1). In particular, the topics that are discussed in this paper need attention, including design guidelines for green infrastructure placement; quantitative assessments of their exposure reduction potential; and the impacts they bring to overall air quality and health outcomes.

A wealth of studies associate the positive impacts of green spaces with health benefits such as enhanced immune functioning and reduced chronic diseases and mental health disorders (Section 2). The relationship between urban greening – defined as organised or semi-organised efforts to introduce, conserve, or manage outdoor vegetation in cities (Eisenman, 2016; Feng and Tan, 2017) – and human health is covered briefly to develop the context of the article. Our main focus lies in presenting a holistic view of the nexus between air pollution, green infrastructure and human health to help fast-track informed decision-making on the exploitation and management of green infrastructure in cities. This can help bridge the gap between research and policy. We present best-practice pathways to inform decision-makers related to green infrastructure interventions in the built environment. Depending on the local (street) and city scales, vegetation types and their placement and density could alter air quality and both increase or decrease public exposure to air pollution. We discuss whether cities have sufficient knowledge to exploit the potential benefits and avoid the undesirable consequences of green infrastructure impacts on human health via air pollution mitigation. By critically evaluating the link between green infrastructure and human health via air pollution mitigation, we consider if our existing understanding of such interventions is sufficient to inform their uptake in practice.

2. The nexus between green infrastructure and human health

Some studies link green infrastructure with health benefits (Suppakittpaisarn et al., 2017), but others have highlighted reservations due to poor study quality and high levels of heterogeneity (Twohig-Bennett and Jones, 2018). The benefits of green infrastructure, while not always claiming direct cause and effect, may include reduced cardiovascular disease, stroke, diabetes and overall mortality (Gascon et al., 2016) as well as reduced circulatory disease (Mitchell et al., 2011), obesity (Sanders et al., 2015), morbidity from respiratory diseases including asthma and other atopic conditions (Lambert et al., 2017), and improved longevity of senior citizens (Takano et al., 2002), pain control (Han et al., 2016), postoperative recovery (Devlin and Andrade, 2017), child cognitive development (Kellert, 2005) and

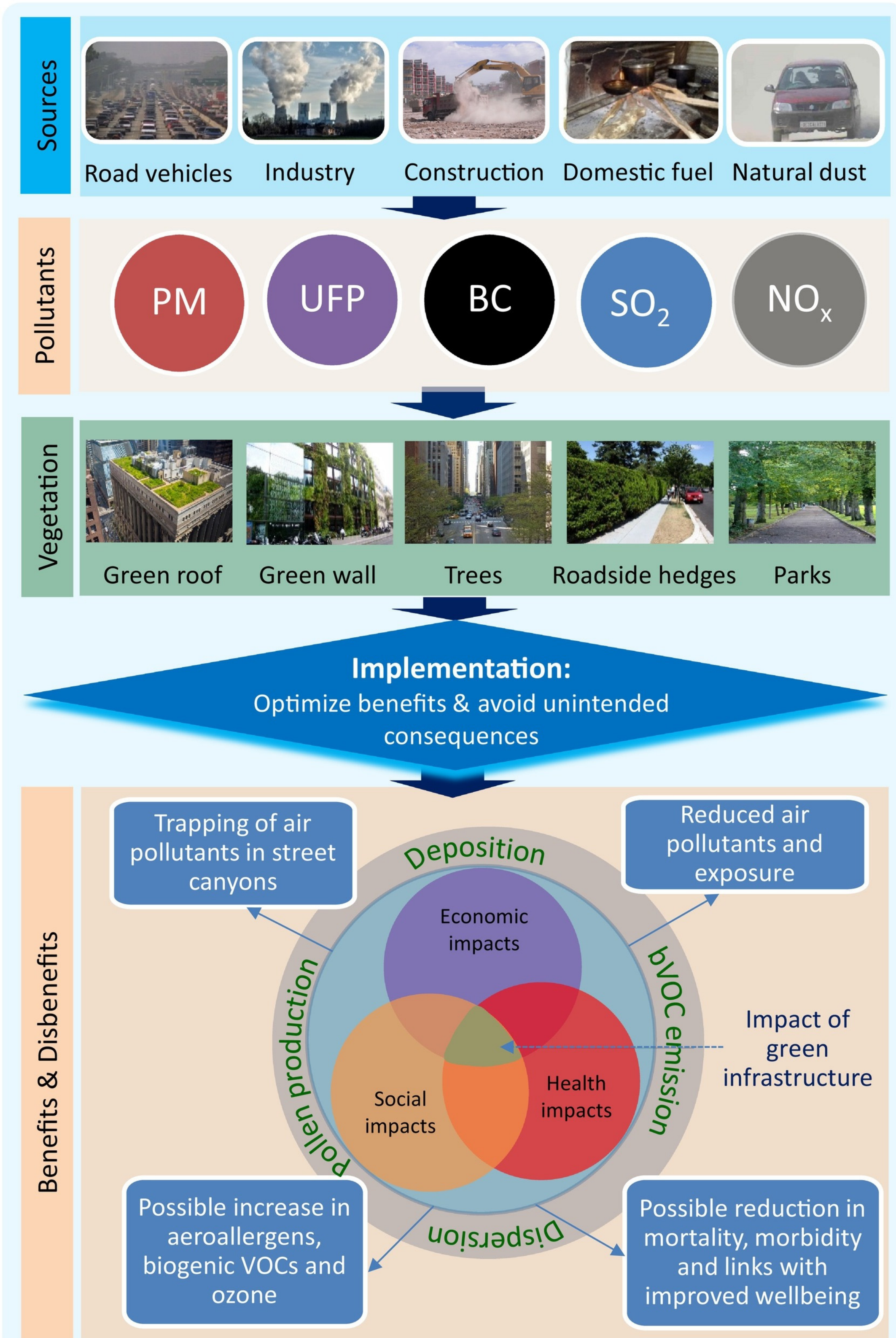

Fig. 1. Conceptual diagram showing the linkages of air pollution sources, greening options, optimised benefits and unintended consequences. This shows (reading from the top to the bottom) linking of mitigation of air pollutants through green infrastructure installations (e.g., trees and hedges) with improved physical and mental health, socio-economic outcomes and unintended consequences. PM: particulate matter ≤ 10 µm (PM_{10}) and ≤ 2.5 µm ($PM_{2.5}$) in diameter; UFP: ultrafine particles (≤ 0.1 µm); BC: black carbon; SO_2: sulphur dioxide; NO_x: nitrogen oxides.

immune function (Hartig et al., 2014). The evidence is not restricted to one part of the world. Pereira et al. (2012) showed an inverse association between levels and variability of neighborhood greenness and coronary heart disease or stroke in Australia. The likelihood of hospitalization and self-reported heart disease was lower for those living in neighborhoods with highly variable greenness compared with those with low variability in greenness. Similarly, researchers from The Netherlands, Australia and the United Kingdom have demonstrated significant associations between neighborhood greenness and reduced likelihood of having type 2 diabetes mellitus (Bodicoat et al., 2014). A longitudinal study of approximately 575,000 adults in Canada associated a reduction in mortality, especially from respiratory diseases, with an increase in residential green space (Villeneuve et al., 2012). Similar results were reported in a larger Canadian study (Crouse et al., 2017) and in the United Kingdom (Mitchell et al., 2011). Access to neighborhood greenness and green space have also been associated with reduced risk of stress, clinical anxiety and depression, psychiatric morbidity, and mortality from circulatory diseases for populations below retiring age (Hartig et al., 2014; Frumkin et al., 2017). Attractive, accessible greenspace can improve community identity and sense of place, improve aesthetics, and provide a place for gathering and social interaction (Wolch et al., 2014). Improved social capital has been linked to reduced stress and improvements in mental health and overall health and well-being (Hong et al., 2018). Cross-sectional studies in the United Kingdom have demonstrated associations between the quality of, and access to, green space with reduced psychological distress in adults (Watts et al., 2013) and reduced depressive symptoms in adolescents and pregnant women (Coombes et al., 2010), with stronger effects in inactive and disadvantaged groups. Evidence from longitudinal research supports the benefit of green space for mental health improvements; for instance, improved alertness in children with attention deficit disorder (Pataki et al., 2011). Evidence for the positive effects of natural environment exposure in later life is also accumulating. A cross-sectional study in the United Kingdom linked a reduction in depression, anxiety symptoms and their co-occurrence in older communities with access to green space (Sugiyama et al., 2008).

A recent report by the WHO (2016) advocates implementation and evaluation of targeted, evidence-based green space interventions to promote health of urban residents. The report underscores that links between green space access and health are likely to be complex and interacting, with variations across developed and developing countries. For example, access to green space may produce health benefits through various pathways, some of which may interact and offer both direct and indirect benefits, and which may have a synergistic effect (WHO, 2016). The potential *mechanisms* underlying links between green infrastructure and human health remain unclear. Researchers have proposed various models to explain the observed relationship (Markevych et al., 2017). Hartig et al. (2014) suggested interacting pathways through which access to green infrastructure could result in improved health outcomes through better air quality, enhanced physical activity, stress reduction, and greater social cohesion. This research is essential for assessing health benefits of urban green spaces in varying global contexts (e.g., high, middle and low income countries) and in cities with different urban design characteristics, to enable the adaptation of context-specific green infrastructure policies and interventions. Lachowycz and Jones (2014) emphasized physical activity, engagement with nature and relaxation, and social activities and interactions as major pathways to health. Villeneuve et al. (2012) proposed a model emphasizing physical activity, respiratory health and resilience to heart-related illness. The authors do not quantify the specific contribution of each pathway, however, poor air quality is known to be linked to adverse health outcomes (HEI, 2019), especially cardiovascular (Requia et al., 2018; Warburton et al., 2019) and respiratory disease (Sciaraffa et al., 2017). Emerging evidence suggests that air pollution may also affect the brain and is possibly linked to dementia (Peters et al., 2019) and cognitive decline (Power et al., 2016). There is also evidence linking air pollution with early-life effects such as low birth weight (Pedersen et al., 2013). Kuo (2015) suggests a central role for enhanced immune functioning as a pathway between nature and health, recognizing that there may be multiple pathways, some of which may interact and offer both direct and indirect benefits (Porcherie et al., 2018). The adverse effects of air pollution may act through similar direct and indirect patho-physiological mechanisms (Chin, 2015). Other possible pathways include improved sleep via reduced noise pollution exposure, stress reduction, improved social support (Linton et al., 2015) and/or increased physical activity (Kredlow et al., 2015). Poor sleep has itself been correlated with a reduction in quality of life, increased risk of chronic diseases such as cardiovascular and respiratory disease and type 2 diabetes, as well as mental health problems and premature death (Cappuccio et al., 2011). However, a major confounder of these studies is sociodemographic and socio-economic differences between populations, with areas where there is more green space often having wealthier, healthier occupants who have healthier lifestyles and/or diets and better access to preventative and curative health care services. Conversely, deprived areas often have less green space and poorer occupants with less access to health care services. Research into the relationship between nearby green space and sleep has been limited to cross-sectional observational studies so far. There are plausible theories as to why green spaces may promote healthier sleep, but more research is needed to draw solid conclusions. For instance, a study of sleep duration in Australia reported that participants with greater amounts of nearby land cover constituting some form of green space generally have a higher number of hours of sleep per night compared with peers in areas with less green cover (Astell-Burt et al., 2013). That result was not explained by measures of psychological distress or physical activity, indicating that the physical removal and/or psycho-acoustic modification of noise via green space may be the dominant pathway. A second study of sleep duration conducted in the United States found similar results (Grigsby-Toussaint et al., 2015). However, a third study in Canada found no association between nearby green space and sleep duration (Chum et al., 2015). In addition to restoration and instoration-based domain pathways, more green space may also reduce exposure to noise and artificial light in the evenings, which are contributors to sleep and circadian disruption (Skeldon et al., 2017). A number of similar examples can also be seen for stress reduction, social cohesion, physical activity and noise reduction in SI Section S1.

The literature on the short- and long-term health consequences of green infrastructure is largely positive but leaves a number of *open questions*. Limited research examines the relative merits of different kinds of green infrastructure for improved health, and only a few longitudinal or interventional studies are available (Nieuwenhuijsen et al., 2017). Systematic reviews on the impact of green infrastructure on chronic health problems are heterogeneous, often using weaker observational designs with short periods of follow-up. Standardized methods for assessing the quality of green infrastructure and evaluations of the effectiveness of green prescriptions - a health professional's written advice to be physically active in nature as part of a person's health management - are needed. Further work is also needed to identify the mechanisms linking observed human health to nature contact, and should look to provide information on susceptible populations who may benefit most from green spaces, and where, when, how much, and what type of green space is needed (Nieuwenhuijsen et al., 2017).

Studies that are on a larger scale, for a wider range of communities, as well as longitudinal, are needed to examine different co-benefits of green infrastructure on human health. There is also little work that examines the influence of urban green space and sense of meaning on nature connectedness and the positive effects on the sense of community. While there is evidence to suggest that green space could benefit physical activity (Coombes et al., 2010), findings are mixed (Hillsdon et al., 2006). This may be partly because many studies focus on narrow geographical areas, self-reported physical activity or health behaviors, and short-term health outcomes. Furthermore, uncertainty still exists regarding the ways in which green space influences physical activity (i.e., the type, access, size and use of green space) and the relationships between green space and context-specific behavior (i.e., physical activity type and intensity). A greater understanding of the ways in which green space influences specific types of physical activity would enable urban designers and landscape architects to design green space that targets specific physical activity behaviors. There is some evidence that green streets encourage active travel (Heath et al., 2006) and reduce roadside pollution (Abhijith et al., 2017), although only a small number of studies have been undertaken that address both factors simultaneously. Importantly, there is little empirical evidence of respiratory or other health benefits owing to air quality improvement via urban trees (Eisenman et al., 2019a; Eisenman et al., 2019b). Therefore, the linkages between green infrastructure and improved health via air quality improvement remain to be adequately quantified. Researchers have highlighted that addressing this gap will aid the development of policy to drive the implementation of green infrastructure for public health improvements and air pollution abatement (Abhijith et al., 2017).

3. The nexus between air pollution, green infrastructure and human health

A general hypothesis exists that green infrastructure affects ambient air quality and thereby human health and wellbeing in both positive and negative ways (Fig. 2). Therefore, it is important to synthesize the evidence relating to green infrastructure's impact on the concentrations of specific pollutants and relate this to human health effects (RCPCH, 2016). Air pollution is a complex mixture of nano to micro-sized particles and gaseous pollutants. Particulate matter of various size ranges (PM_{10}, $PM_{2.5}$, PM_1, ultrafine particles [UFP]) and gaseous pollutants (NO_2, SO_2, CO and O_3) are some of the important pollutants in the urban environment (Fig. 1; SI Table S2). Exposure to these pollutants has been linked with respiratory and cardiovascular diseases (EEA, 2017). The quantification of changes in the air dispersion or chemical reactions of these air pollutants brought about by green infrastructure can allow evaluation of direct or indirect effects of green infrastructure on local and regional air quality.

The removal of atmospheric pollutants by urban vegetation has been of particular interest (Bealey et al., 2007; Litschke and Kuttler, 2008). Vegetation leaves have been shown to remove atmospheric particles by dry deposition onto their surfaces (McDonald et al., 2007; Nowak et al., 2006), and absorb gaseous pollutants through their stomata (Harris and Manning, 2010; Nowak et al., 2006; Yin et al., 2011). Furthermore, vegetation, especially trees, could play a role in improving air quality in urban areas through increased deposition rates of particulate matter and/or absorption of gaseous pollutants. Deposition varies among particles of various sizes, according to the U-shaped parabolic curve of deposition velocity, showing minimum values between 0.1 and 1.0 μm and suggesting that both ultrafine and coarse particles are more susceptible to deposition onto vegetation surfaces (Janhäll, 2015). A review summarising the potential magnitude of air pollution reduction via urban vegetation canopies found that average published deposition values corresponded to an estimated 1% reduction of PM_{10} across urban areas (Litschke and Kuttler, 2008). Urban trees may also indirectly contribute to improved air quality via reduced energy demand, especially when cities energy production is managed using coal as a fuel source, by cutting air conditioning demand in hot weather through the provision of shading and the cooling effects of evapotranspiration (Akbari et al., 1997). However, they may also lead to a reverse effect by increasing the need for heating energy during cold weather conditions (Simpson and McPherson, 1998) and contribute to air pollution by emitting hydrocarbons (Benjamin and Winer, 1998). The reduction in temperature due to increased shade and evapotranspiration promotes chemical reactions to reduce ozone concentrations (Nowak et al., 2000). Previous studies have estimated that about 1 t CO (percentage removal from total CO emissions, 0.03%), 14 t NO_2 (0.50%), 17 t PM_{10} and $PM_{2.5}$ (3.35%), and 1 t SO_2 (0.50%) via 27.8% green space in Strasbourg city (France), and 1320 t PM_{10} and $PM_{2.5}$; 2740 t NO_2 via 8.1% green space in Auckland (New Zealand) are removed annually by vegetation, especially trees (Cavanagh and Clemons, 2006; Selmi et al., 2016). Air pollution removal varies mainly with levels of tree cover and of air pollutant concentrations. Estimates of pollution removal make various assumptions about factors such as deposition rates and leaf surface area, while further studies are still required to provide a comprehensive database for urban areas. This calls for more research to accurately quantify the air quality benefits of different green infrastructure forms at local and regional scales (Pataki et al., 2011; Salmond et al., 2016).

Certain vegetation species can also release significant amounts of reactive gases, known as biogenic volatile organic compound (bVOC) emissions. As discussed in the subsequent text, these compounds can condense and react with other species (hydroxyl ions and nitrate

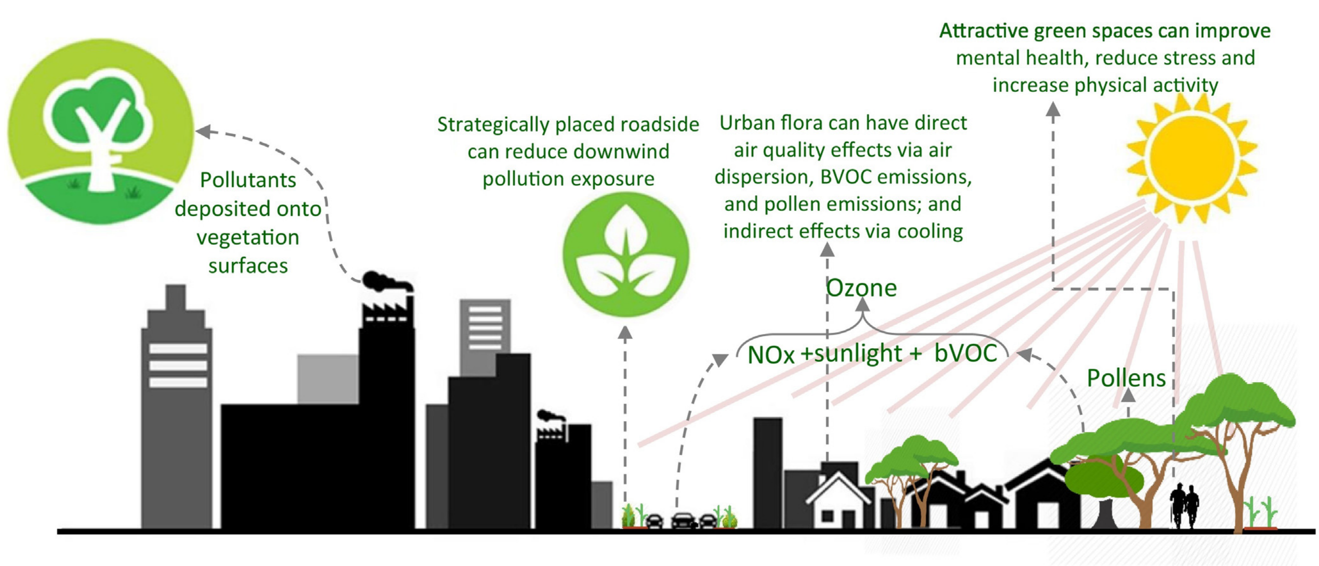

Fig. 2. Schematic diagram showing the air quality benefits and downsides of green infrastructure in the built environment.

radicals) to form small-sized secondary particles that can remain suspended for a relatively long time in the ambient air. These particles can appreciably affect the chemistry of air pollutants in local, regional, and even global scales. The most vital reactive bVOCs are isoprene, monoterpenes, and sesquiterpenes, which can govern the production and loss of ozone and the formation of secondary organic aerosols (Calfapietra et al., 2013). For instance, emissions of isoprene (with substantial levels of NO_X) contribute to the formation of ground-level ozone in urban areas, whereas monoterpenes and sesquiterpenes can increase $PM_{2.5}$ and PM_{10} concentrations (Churkina et al., 2017). Moreover, bVOC emissions from vegetation are highly reactive, with atmospheric lifetimes in the order of seconds to hours. After release into the ambient air, they react rapidly with air oxidants, mainly the hydroxyl ions and nitrate (NO_3) radicals, and also ozone molecules (Churkina et al., 2017). The reactions of bVOCs with these oxidants produce secondary organic compounds such as ozone and stable organic nitrate, which could be transported across great distances (Churkina et al., 2017).

The quantity of bVOC emissions from plants and their reactions in the atmosphere dictate how plants affect atmospheric chemistry. Although it is understood that the short-term retention of atmospheric particles by urban vegetation can reduce ambient pollutant concentrations, the effectiveness of plants as a long-term alternative to other measures is still under debate. Therefore, understanding the role of bVOC emissions in the formation of aerosols in the atmosphere, and understanding the reaction of urban and anthropogenic emissions with bVOC emissions is important for understanding the role of vegetation in urban environments. The bVOC emission potential, as well as the uptake characteristics of vegetation, varies with their size and species. Individual studies have provided information on certain trees and plant species in different parts of the globe (Emmerson et al., 2019; Li et al., 2019). Open-access tools such as i-Tree (Tools for Assessing and Managing Community Forests; https://www.itreetools.org/tools) provide a valuable database on tree species, besides options to quantify benefits and ecosystem services of community trees and forests. While the chemistry is fairly well understood, the quantification of bVOC emissions generated by green infrastructure in specific cities and their contribution to airborne particles is still a grey area in research. In addition, the World Urban Database and Access Portal Tool (WUDAPT; http://www.wudapt.org/wudapt/) is another type of complementary database that provides climate-relevant information on urban centres across the world in the form of local climate zones using remote sensing imagery (Hammerberg et al., 2018). It also captures variations across urbanised landscapes (Ching et al., 2014; Hammerberg et al., 2018). Such a database could complement dispersion modelling, which together with deposition component in the i-Tree model, could support the multidisciplinary assessment of GI impacts on pollutant concentrations at city scale.

There is also much less information on the air pollution health effects mediated by green infrastructure than on green infrastructure and health (Section 2). A widely used approach for estimating human health benefits of air pollution mitigation via vegetation is the deposition component in i-Tree model that can be combined with BenMAP (Environmental Benefits Mapping and Analysis Program) to calculate the number and economic value of air pollution-related deaths and illnesses (EPA, 2018). Using this approach, Hirabayashi and Nowak (2016) at a national scale estimated that the highest reductions in human mortality rates associated with air pollution removal via green infrastructure across the United States were associated with the reductions in $PM_{2.5}$ and O_3. Additional modelling studies of air pollution reduction via green infrastructure estimated one mortality case per year in each of the 10 cities examined in the United States (Nowak et al., 2013), translating to a reduction of 850 mortalities across the country (Nowak et al., 2014). The cumulative reduction of 30 mortality cases each year was estimated in a study of 86 cities in Canada (Nowak et al., 2018), which was proportionally less than previous studies due to lower pollutant concentrations and a shorter in-leaf season for the green infrastructure.

The accuracy and public policy usefulness of results from the modelling studies can, however, be argued, like any other model (Kumar et al., 2011), owing to the assumptions such as the use of relationships developed elsewhere to sites that vary in plant species, site characteristics, climatic and environmental conditions (Saebo et al., 2017). Others have noted concerns pertaining to the propagation of error and marginal magnitude of effect (Pataki et al., 2011; Whitlow et al., 2014). Importantly, citywide deposition modelling does not account for the heterogeneity of urban landscapes and other important mechanisms such as air dispersion, bVOC emissions, pollen production, and synergistic interactions between pollen and air pollution.. However, these modelling assessments offers limited options for estimation of the health benefits associated with green infrastructure interventions via air pollutants reduction. For instance, Tiwari et al. (2019) reviewed the limitations of microscale and macroscale air pollutant dispersion models to evaluate green infrastructure impacts. This work also highlighted an increase in uncertainty, owing to, for example, the combined effects of allergenic pollen and air pollutants on human health (D'Amato et al., 2007), the transformation of air pollutants in the presence of bVOCs (Churkina et al., 2017) and altering exposure in microenvironments (Gallagher et al., 2015), while assessing the holistic effects of green infrastructure and air pollution on human health. Further, a lack of understanding of the combined effects of air pollutants and allergenic pollen, individual's air pollutant exposure and their health data, results in uncertainties in air pollution health risk assessments. These uncertainties restrict planners and policymakers in adopting model-based solutions in the real world.

At a local scale, the placement of green infrastructure between the source (traffic emissions) and receptor (those walking, cycling) along roadsides could act as a natural filtering barrier. In open-road conditions, where either there are no buildings or buildings are at a distance from both sides of the road, a continuous line of thick vegetation barriers is found to reduce downwind pollutant reductions by up to 60% (Abhijith et al., 2017). This reduction depends on several factors, such as the porosity, width, and height of the barrier as well as vegetation species (Baldauf, 2017). However, if there are gaps in such barriers and their porosity is high, for example during leaf-off seasons, it could result in similar or even increased downwind concentrations since pollutants can pass through or move around the gaps (Ghasemian et al., 2017; Hagler et al., 2012). Street canyon conditions, where buildings are in close vicinity to both sides of the road, are more challenging, and the placement of trees becomes critical because they can obstruct the free exchange of polluted air inside the canyon with clean air above. When the height-to-width ratio (aspect ratio) of a street is > 0.5, the use of tall-growing vegetation (trees) is not recommended (Abhijith et al., 2017). Such configurations are commonplace in urban environments and their impact on air quality and human health is rarely considered in practice, most likely due to a lack of awareness of the risks and benefits. Where aspect ratios are < 0.5, a cautious choice should be made between trees and hedges to harvest their best potential and avoid situations of worsened air quality in the street canyon close to ground level (Abhijith et al., 2017). Of course, similar considerations apply for the selection of species that are low pollen and low bVOC emitting (Willis and Petrokofsky, 2017; Kumar et al., 2019).

At the local scale, there is nearly no evidence translating reduced pollution exposure due to vegetation into direct health benefits, and the interpretation of health benefits can only be made by linking them with reduced exposure due to vegetation barriers. For instance, some studies suggest that allergy sufferers require lower concentrations of pollen exposure to trigger allergy symptoms when already exposed to traffic-related air pollution (Emberlin, 1998; Salmond et al., 2016), suggesting that careful thought needs to be given to the species of vegetation used (Cariñanos and Casares-Porcel, 2011; Chen et al., 2017). An increase in vegetation has been linked with a decrease in the prevalence of asthma among children and adults in urban populations (Donovan et al., 2018), but to what extent air quality improvement by vegetation is a mediating mechanism for such links is unclear. For example, this study hypothesizes that observed benefits may be explained by greater and more diverse microbial exposure in vegetated spaces. Furthermore, the complexity of green infrastructure at local scales presents the most obvious challenge in delivering green space for improved air quality, but there is limited evidence to relate local conditions to local benefits in terms of reduced health problems and mortality rates. There is a wealth of evidence linking the exposure to airborne PM and the occurrences of diseases such as cardiovascular (Du et al., 2016) and cerebrovascular (Leiva et al., 2013; Zhang et al., 2011), coronary artery (Ruckerl et al., 2006), respiratory (Zanobetti et al., 2003), ischaemic heart (Burnett Richard et al., 2014), lung cancer mortality (Laden et al., 2006) and cardiopulmonary mortality (Pope III et al., 2002). Populations exposed to PM over the long periods have a much greater incidence rate of cardiovascular diseases and heightened mortality rate (Anderson et al., 2012). For example, Lelieveld et al. (2015) linked 3.3 million premature deaths per year worldwide with the exposure to outdoor $PM_{2.5}$; the highest per capita mortality is found in the Western Pacific region (1.463 million), followed by Southeast Asia (0.65 million) and Eastern Mediterranean (0.286 million). Most health-related policies usually consider such pieces of evidence but policies associating particular interventions (e.g., green infrastructure) with specific health effects are rare. Recently, PHE (2019) carried out a rapid review of air pollution interventions, including green infrastructure, to improve air quality and public health. It also highlighted that sources of outdoor air pollution are well understood and that the reduction in emissions from motor traffic, promotion of active travel and use of green infrastructure would lead to appreciable reductions in the burden of disease and savings to healthcare systems. However, a major gap is that there is little quantification of the impact of such intervention measures.

Of course, the ultimate strategy to reduce air pollution *emissions* in cities is to control air pollution at the source. The primary method is through setting vehicle emission standards and standards for other sources in general. However, these can take a long time to implement and are not always as effective as planned, and so other emissions and exposure reduction strategies are also needed. A number of recent and exploratory intervention methods include implementation of source control through low emission zones in cities i.e., placing restrictions on traffic entering an area; (Ellison et al., 2013), restrictions on heavy goods vehicles entering the city centre (Tang et al., 2017), road space rationing schemes such as Rodizo restricting person car use for one-day per week (Rivasplata, 2013) or odd-even car trials restricting personal cars having the last digit of their registration number as even on odd dates and vice-versa (Kumar et al., 2017). Another much more prevalent strategy is the promotion of walking, bicycling, use of public transport, and other non-motorized means of travel, collectively referred to as active commuting or active travel: this can substitute for short car trips, saving emissions from car travel (Neves and Brand, 2019). The adaptive use of obsolete or underused urban infrastructure, such as rail corridors, underutilized back alleys, urban streets, abandoned transport or utility corridors, and remediated brownfields into green infrastructure for walking and biking, informal play and exercise, and social interaction are also effective strategies to reduce air pollution (Wolch et al., 2014). Use of green infrastructure at a local scale can be considered as an *exposure* control strategy via engineering the pathway between the source and receptor. Considering public acceptability, the relative size of the potential health benefits of urban vegetation, the additional co-benefits outside air pollution reduction such as diverse ecological services (Endreny et al., 2017) and natural capital (Chenoweth et al., 2018), suggest that urban green infrastructure should receive due consideration when passive pollutant abatement options are appraised by policymakers. Passive control methods include the use of common urban features such as low boundary walls, trees, on-street parking, hedgerows, green walls, photocatalytic coatings and noise pollution barriers. These methods control air quality through manipulation of natural air pollutant dispersion patterns in built-environments passively, without additional energy requirements. They have the potential to reduce pollution exposure hence improving and protecting human health in urban areas (Gallagher et al., 2015; McNabola, 2010).

There are substantial differences in how natural science and epidemiology approach the topic of green infrastructure and health. As noted in an interdisciplinary review addressing links between urban trees, air quality, and asthma, there are substantial gaps in how natural scientists and public health researchers address this issue: natural scientists tend to focus on air pollution reduction while epidemiologists focus on pollen production. Importantly, there is currently little empirical evidence of asthma reduction or other respiratory health benefits owing to air pollution reduction by urban trees (Eisenman et al., 2019a). Based on these findings, a call for more epidemiological research on links between urban trees, air quality, and asthma has been issued to better inform landscape planning and design (Eisenman et al., 2019b).

4. Informing urban planners of best practice green infrastructure adoption

Effective planning, implementation and preservation of green infrastructure has the potential to lead the way in sustainable urban development by delivering a framework for improved public health and quality of life, while also bringing about nature conservation and other environmental improvements (Tzoulas et al., 2007; Van den Berg et al., 2010). At the city or regional scales, most studies assessing urban vegetation and air quality rely upon models, and further empirical evidence of actual human health benefits is required. At a local scale, the evidence is based on site-specific experimental investigations, where interactions of air pollutants with green infrastructure are assessed and quantified based on the change in concentration of specific pollutants. These experimental investigations allow validation of models that can extrapolate results to similar site conditions at city scales. Consequently, guidance for urban planners should be based on an ever-expanding and more-informed database of results from research investigations, taking into consideration the green infrastructure intervention itself (tree, hedge, green wall or green roof), its characteristics, the pollutants, and the setting (e.g., urban roadside, city park, peri-urban residential area, suburban industrial area).

Efforts to translate research findings into practical guidelines for using GI to improve air quality in near-road environments is evident in recent literature (Baldauf, 2017; Ferranti et al., 2017; GLA, 2019; Hewitt et al., 2019; SMAQMD, 2017). Baldauf (2017) presents favourable physical attributes and vegetation characteristics for improved air quality outcomes in open-road conditions (i.e. highways) using GI in the U.S. In the UK, the GLA (2019) presents broad level recommendations on GI's effectiveness for improving air quality in open-road and street canyon environments for London. The Sacramento Metropolitan Air Quality Management District in California, USA (SMAQMD, 2017) has taken this further by developing their own planning, installation and maintenance documentation based on the EPA guidelines and in-line with local requirements and governing regulations. Their guidance provides detailed vegetation configurations and an extensive species planting list to meet local requirements. Practitioners and policymakers in this setting need to be informed by evidence and guidance such as reported by Ferranti et al. (2017) and Hewitt et al. (2019), as they offer top-down policy, clear interventions and a conceptual framework for GI implementation to improve air quality, with Hewitt et al. (2019) outlining a flow chart of logical pathways to minimise negative feedback and maximize improvements in urban built environment. GLA (2019) also presents a flow chart to identify the most suitable GI for built environment conditions while a most recent document complements it by including advice on plant species selection (Kumar et al., 2019).

In general, these guidelines and decision support tools present the first steps in translating research to practice in the field. It is clear that

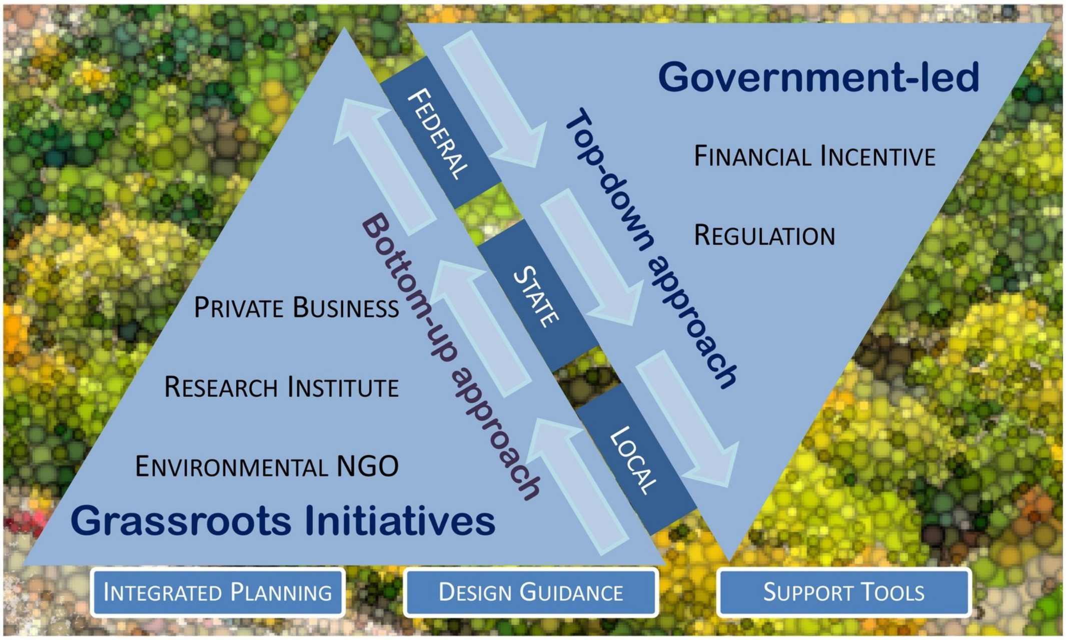

Fig. 3. A conceptual framework showing two ways of promoting green infrastructure initiatives through top-down and bottom-up approaches.

detailed guidance is more advanced for open road conditions (e.g. Baldauf, 2017) than for complex urban built environments (i.e. street canyon conditions). Further research is required to accelerate best practice guidelines for the built environment that can inform and align with local restrictions such as species selection.

4.1. Governance and implementation of green infrastructure interventions

There are essentially two approaches to promoting green infrastructure initiatives: top-down (government-led, through financial support and/or regulation) and bottom-up (grassroots initiatives), as shown in Fig. 3. Both approaches present their own case- and site-specific challenges, relating to the technical, economic, environmental and social considerations for a given project. Therefore, suitable guidance is required to successfully implement a green infrastructure project and ensure a positive outcome and the evidence base is not always available. However, as Slätmo et al. (2019) outlines, and taking Europe as an example, green infrastructure policies are currently available in only 11 of the 32 countries surveyed.

Top-down green infrastructure initiatives can be delivered at various scales, and it is viewed that policies or strategies need to be driven by national governments (Slätmo et al., 2019), but it can be delivered by regional and local authorities or different types of organizations. For example, Mazza et al. (2011) reviewed 100 initiatives from across 27 European Union member states. Of these, 52 initiatives were at a national scale while the remainder were regional or local. Most of the initiatives were led by governments, while 15 were driven by organizations, such as environmental non-governmental organizations, research institutes and businesses (Mazza et al., 2011).

As in traditional infrastructure projects, the key to successful delivery is effective stewardship and financing (Young and McPherson, 2013). For example, a way to encourage uptake of green infrastructure projects is through prioritization of funds by governments at various levels (e.g., federal, state and local levels) (Dunn, 2010). Funding can produce important social co-benefits such as poverty alleviation through the creation of local job opportunities, particularly when allocated to poor localities (Celik and Ogus Binatli, 2018; Dunn, 2010).

Singapore is an exemplary case for the effective planning of green infrastructure. It was referred to as a *City in a Garden* in the 1960s, and more recently as a biophilic city (Ali Cheshmehzangi, 2014; Newman, 2014). The first Singapore Green Plan was released in 1992 by the then Ministry of the Environment, followed in 2002 by a new 10-year national plan, developing a national approach of integrated planning, and subsequent long-term plans including the 2012 National Climate Change Strategy. Green infrastructure planning in Singapore is now well integrated with the planning of the social and economic dimensions of the city, facilitating multi-functional benefits (Newman, 2014). Other initiatives in Singapore include Horticulture Park, which has been set up to demonstrate and experiment with green walls and green roofs, and the Park Connector Network, which is an island-wide network of linear parks that connect major green areas and residential locations (Newman, 2014).

In contrast to Singapore, England's National Planning Policy Framework, which sets out the government's planning policies (DCLG, 2012), makes few references to green infrastructure, with it only being mentioned in passing in relation to adaptation to climate change. Recently, £60 million funding was pledged in the 2019 United Kingdom budget for planting millions of more trees across England, including £10 million for trees in urban streets on the basis of a matching contribution from local authorities, charities and community groups. In addition, at a more local level in England, there are examples of successful green infrastructure planning and implementation. For example, the Cambridgeshire Green Infrastructure Strategy, which sets out local plans for delivering green infrastructure, has comprehensive objectives which include green walls and roofs. It has achieved £21.9 million in direct investment since 2004, out of which £8 million was secured from Government Growth Funding (CCC, 2011; Mell, 2016).

Some green infrastructure policy initiatives have been driven by the associated co-benefits of their implementation rather than air pollution mitigation. This has been seen in the direct application of green roof systems for stormwater management provisions, which has been delivered through the United States Federal Water Pollution Control Act at a national level, and The Seattle City Council Resolution 31,459 (2013) at the state level (SCC, 2015). Other examples exist of design guidance for green streets in Denver, Portland and Philadelphia, as well as incentives in Chicago and Seattle that support the implementation of green infrastructure in the United States (Carter and Fowler, 2008; Dunn, 2010; Newell et al., 2013).

Technology and building standards can support important policy options to promote green infrastructure implementation (Carter and

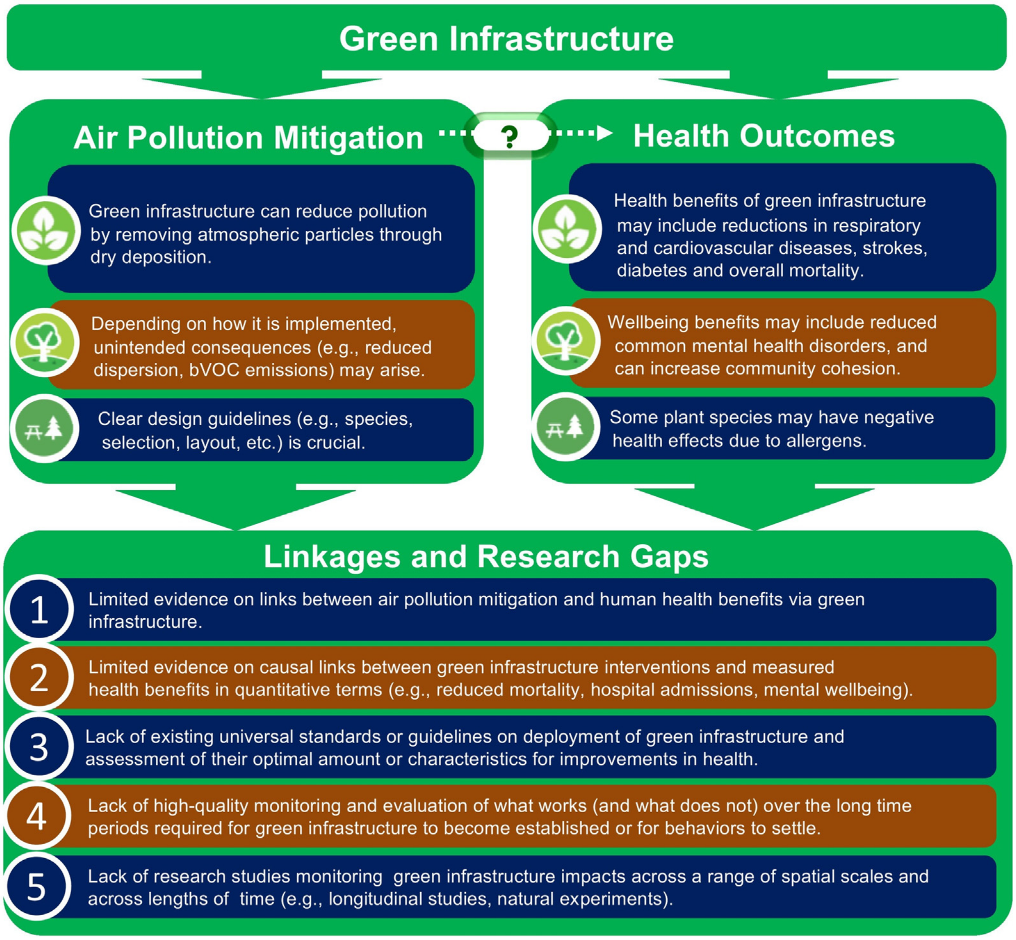

Fig. 4. Summary of purported linkages and research gaps between green infrastructure, air pollution and human health.

Fowler, 2008; Weber et al., 2006). For instance, building codes in Tokyo (Japan), Linz (Austria) and Basel (Switzerland) require new private/public buildings and car parks to have a percentage of their rooftops greened (Carter and Fowler, 2008; Ngan, 2004).

Various tools have also been developed to facilitate the embedding of green infrastructure initiatives in urban planning. For example, Weber et al. (2006) developed a tool to help prioritize areas of highest ecological significance and vulnerability to development, identifying and ranking elements at multiple spatial scales to help decision-making about conservation, restoration and development in the state of Maryland, United States (Benedict and McMahon, 2012; Weber et al., 2006).

In summary, government-sponsored schemes for green infrastructure projects in polluted localities have the potential to yield multiple co-benefits, such as poverty alleviation by generating employment. A dedicated land area for green infrastructure and formal planning programs with community input are required for this to succeed (Schilling and Logan, 2008). The successful widespread uptake of green infrastructure initiatives relies largely on government support, whether at federal, state or local levels (Irga et al., 2017). This can be through financial incentives or through regulations, but whichever route is taken, adequate funding needs to be prioritized for city greening projects.

4.2. Research to policy: continuously bridging the knowledge gap

Cities are constantly evolving and so are the differences in living conditions within and between them. In parallel, the knowledge base of evidence for implementing green infrastructure interventions is also increasing. Yet, in some other cases, planning policy is key to protecting existing green infrastructure (McWilliam et al., 2015). Planners and practitioners need to access data, in a suitably digestible form, which can inform their decisions on placing green infrastructure in a new setting, or indeed on managing existing green spaces. Examples such as GLA (2019) and Baldauf (2017), from the United Kingdom and the U.S.A. respectively, have taken steps towards transforming knowledge generated from research to practical guidance in design and implementation. However, the availability of data surrounding green infrastructure's impacts on air pollution mitigation and human health and wellbeing is not well documented and does not translate for all scenarios. It varies considerably between urban areas, and no universal standards exist to detail the optimal amount or characteristics of vegetation, leaving practitioners in a difficult position.

The global policies and initiatives for encouraging green infrastructure best practices show that governments at federal, state and city levels have a critical role in implementing green infrastructure in urban town planning (Slätmo et al., 2019), and facilitating opportunities for integrating urban development, public health promotion and wider environmental benefits (Mell et al., 2017). The availability of integrated tools that could allow assessment of green infrastructure for pollution reduction and health benefits is limited; some early examples exist but need to be disseminated (Isely et al., 2010). In addition, some tools that can support the planning and implementation of green infrastructure have been identified by Slätmo et al. (2019) but they are not universally recognised or applied in an effective manner. There is also a need to develop flexible guidance that can address localized requirements rather than generalized best practice (Madureira and Andresen, 2014). These tools and policies are required simultaneously, and the validation of their potential should be measured as they support the design of green and pollution-resistant urban environments.

4.3. Research gaps in the current knowledge base

The health, social, economic and environmental benefits of green infrastructure for urban areas are well-documented, as is the potential for green infrastructure to mitigate air pollution at a local scale if designed and implemented properly. However, the economic impacts relating to green infrastructure and human health needs further research to support the economic case to drive changes in planning and policy (Bowen and Lynch, 2017). Implementing green infrastructure can lead to multiple socio-economic and environmental impacts which include increasing property values, reducing the risk of local flooding and increasing biodiversity. The benefits of green infrastructure dominate the rationale for several cities implementing greening policies. Importantly, there is evidence to support substantial reductions in urban runoff, local atmospheric cooling, and improvements in human health that do not appear to be related to pollutant concentrations (Pataki et al., 2011). What is currently lacking is a clear understanding of the complex relationship of air pollution health effects mediated by green infrastructure, which may not always present a positive outcome and validates gaps in knowledge in this area (Fig. 4).

With the ongoing focus on case studies in the field of green infrastructure research (iSCAPE, 2019), there is a growing awareness of the need for improved understanding of its impact on air pollution and human health. There is an abundance of literature linking green infrastructure, especially parks and green spaces, with human health and wellbeing, and the interlinkage between trees and hedges with air pollution. However, there is limited evidence of the causal links between green infrastructure interventions and measured health benefits in quantitative terms (e.g., reduced mortality, hospital admissions, life years, and mental disorders). There is scant attention on the development of rigorous models in order to predict the real-time impacts of vegetation on air quality at different stages, time points and across geographical scales. However, the lack of validated models capable of predicting air quality impacts from varying green infrastructure designs restricts researchers' ability to quantify the associated health impacts (Tiwari et al., 2019). Therefore, integrated models are required that can simulate the holistic impact of green infrastructure on air quality for quantifying their health benefits. The role of green infrastructure interventions in human health needs to be prioritized as a research area. In addition, future work needs to cohesively attain knowledge in this field at local, regional and global scales. Firstly, there is a lack of existing universal standards or guidelines on the deployment of green infrastructure and the assessment of optimal amounts or their characteristics for improvements in health. Secondly, there is a lack of high-quality monitoring and evaluation of what works (and what does not) over the long periods that it can take for green infrastructure to become established and for behaviors to settle. Thirdly, there are nearly no research studies that have monitored green infrastructure impacts across a range of spatial scales and across lengths of time (e.g., longitudinal studies and natural experiments).

5. Actions to maximize successful knowledge exchange

To ensure effective knowledge exchange is achieved relating to green infrastructure, air pollution abatement and improving human health, the following actions have been outlined to extend the impact of green infrastructure beyond its current economic, environmental and societal functions.

- Informing practitioners, urban planners and policymakers about the role of green infrastructure interventions on air pollution mitigation and human health is key for the dissemination, implementation and uptake of scientific research into practice. The development of research briefs based on research findings and simple guidance to support effective implementation (e.g. design characteristics for green infrastructure by Baldauf (2017)), can give key stakeholders confidence in the delivery of green infrastructure solutions to air quality and health. Presenting the evidence from scientific case studies in a manner that can be easily applied in practice will encourage uptake of local air pollution mitigation measures at the local scale. This evidence also needs to be provided in an open-access database with contextual classifications (pollutant and climatic characteristics based on geographical location) can maximize the effectiveness of such interventions. Furthermore, the co-benefits of green infrastructure must be considered in the modes of communication to key stakeholders.
- Develop tools and services to support practitioners to achieve best practice in the selection and positioning of green infrastructure (e.g. decision-making flowchart for positive air quality interventions by Hewitt et al. (2019)). This can be achieved by ensuring the multiple benefits of green infrastructure are considered in the early design phase of projects to maximize its potential for increasing recreation, urban heat island mitigation, place-making and aesthetic impacts of green infrastructure. It may also be useful to consider the potential of how the impacts of green infrastructure are incorporated into educational programming, economic development, public health, and community building initiatives, to enhance knowledge exchange and consider the direct and indirect benefits of green infrastructure on human health.
- A continuation of research on the inter-relationship between green infrastructure and air pollution is important to fill scientific research gaps (Section 4.3). Recent studies by Deshmukh et al. (2018), Abhijith and Kumar (2019) and Eisenman et al. (2019a) are examples of progressive research which is improving our understanding of interactions between green infrastructure and air pollutants, to inform better design and lead to better health outcomes. In doing so, documenting environmental characteristics affecting dispersion and plant characteristics influencing deposition will provide a more robust evidence base to inform strategies to improve urban air quality.

Taken together, this three-pronged approach can offer the promise of enhancing human health and wellbeing and reducing pollution.

6. Conclusions and future outlook

Green infrastructure such as trees and green roofs are instrumental for health, socio-economic and environmental benefits; and air pollution mitigation is one of the most commonly cited benefits. This may explain why cities are revisiting traditional practices of implementing greening into their landscapes. Yet, green infrastructure can present some downsides in relation to air quality when positioned in the wrong place or planting the wrong species, from the perspective of air pollution dispersion and bVOC/pollen emissions, respectively. Therefore, planners and practitioners need clear and practical guidance in a suitably digestible form that can inform their decisions on green infrastructure selection and design of new projects, or indeed managing existing green spaces to ensure positive outcomes are achieved. Two questions that remain: (i) how can green infrastructure effectively mitigate air pollution exposure and lead to health improvements in polluted locations, and (ii) have policymakers and urban planners sufficient information to implement green infrastructure strategies to ensure improved air quality?

A holistic approach is presented here for the nexus between air pollution, green infrastructure and health, topics usually studied in isolation, but which together are key to enabling policymakers and urban planners to make informed decisions. The availability of data surrounding green infrastructure's impact on air pollution mitigation is not well documented and does not translate for all scenarios. Despite recent examples of advancements in research in the field and the emergence of design guidelines for effective green infrastructure design and implementation in different contexts for urban air pollution mitigation, significant work is still required to generate best practice that has transferability to local requirements. Green infrastructure guidelines in terms of species selection vary considerably within urban areas, and no universal standards exist to detail optimal amounts, types and locations of vegetation, leaving practitioners in a challenging position.

While a wealth of studies relate the positive impacts of green spaces with health benefits such as enhanced immune functioning and reduced chronic diseases and mental health disorders, the underlying pathways linking green infrastructure and human health remain unclear. Importantly, there is little empirical evidence that these positive health outcomes are related to air pollution reduction through urban vegetation. At roadside locations where people are directly exposed to emissions, vegetation has been found to have mixed effects, with reductions and increases in pollution under different conditions. As such, the development of decision support tools and services can help ensure a positive outcome based on green infrastructure interventions that have universal recognition, and ensuring a positive outcome in decision-making will help build confidence in driving top-down initiatives by national governments.

We conclude that urban greening can generate potentially broad health benefits such as reduced chronic diseases, the risk of stress and psychiatric morbidity and can offer diverse ecosystem services. However, there is little empirical evidence linking these health outcomes to air pollution reduction from urban vegetation, and optimal guidelines for its deployment in the built environment are yet to be established. Therefore, further research and an international and collaborative approach to advancing this field are necessary to accelerate the successful development of tools and services, implementation of guidance and policy, and promotion of green infrastructure as a mechanism to improve human health through air pollution mitigation.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgements

This work has been supported by the EPSRC funded project Health assessment across biological length scales for personal pollution exposure and its mitigation (INHALE; Grant No. EP/T003189/1), GREENMASS (Green Infrastructure and Health Mapping Alliance of Surrey Academics) project that is supported by the University of Surrey's Urban Living Award; and the iSCAPE (Improving Smart Control of Air Pollution in Europe) project, which is funded by the European Community's H2020 Programme (H2020-SC5-04-2015) under the Grant Agreement No. 689954.

Author contributions

PK secured funding, conceptualized the idea, wrote (and revised) the manuscript by coordinating inputs from co-authors who contributed to specialized topic areas and helped shape the direction of the manuscript. The author contributions to particular sections included: Introduction (all), the nexus between greenness and human health (BG, SA, UH, SdL, TA-B, XF, DA), the nexus between air quality, greenness and human health (PK, JG, AM, AKV, AT, SH, TSE), Informing urban planners of best practice green infrastructure adoption (AD, JG, PK, AS) and Actions to maximize successful knowledge exchange (JG, PK, TSE, LM). All the authors commented on the entire manuscript, contributed to the conceptual development of figures and the overall cohesiveness and proofreading of the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105181.

References

Abhijith, K.V., Kumar, P., 2019. Field investigations for evaluating green infrastructure effects on air quality in open-road conditions. Atmos. Environ. 201, 132–147.

Abhijith, K.V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S., Pulvirenti, B., 2017. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – a review. Atmos. Environ. 162, 71–86.

Akbari, H., Kurn, D.M., Bretz, S.E., Hanford, J.W., 1997. Peak power and cooling energy savings of shade trees. Energy and Buildings 25, 139–148.

Ali Cheshmehzangi, C.J.G., 2014. Development of green infrastructure for the city: a holistic vision towards sustainable urbanism. Architecture & Environment 2, 13–20.

Anderson, J.O., Thundiyil, J.G., Stolbach, A., 2012. Clearing the air: a review of the effects of particulate matter air pollution on human health. Journal of Medical Toxicology 8, 166–175.

Astell-Burt, T., Feng, X., Kolt, G.S., 2013. Does access to neighborhood green space promote a healthy duration of sleep? Novel findings from 259,319 Australians. BMJ Open 3, e003094.

Baldauf, R., 2017. Roadside vegetation design characteristics that can improve local, near-road air quality. Transp. Res. Part D: Transp. Environ. 52, 354–361.

Bealey, W.J., McDonald, A.G., Nemitz, E., Donovan, R., Dragosits, U., Duffy, T.R., Fowler, D., 2007. Estimating the reduction of urban PM10 concentrations by trees within an environmental information system for planners. J. Environ. Manag. 85, 44–58.

Benedict, M.A., McMahon, E.T., 2006. Green Infrastructure: Linking Landscapes and Communities. Urban Land (vol. June). ISBN-10: 1559635584, p. 1559635320.

Benedict, M.A., McMahon, E.T., 2012. Green Infrastructure: Linking Landscapes and Communities. Island Press.

Benjamin, M.T., Winer, A.M., 1998. Estimating the ozone-forming potential of urban trees and shrubs. Atmos. Environ. 32, 53–68.

Bodicoat, D.H., O'Donovan, G., Dalton, A.M., Gray, L.J., Yates, T., Edwardson, C., Hill, S., Webb, D.R., Khunti, K., Davies, M.J., Jones, A.P., 2014. The association between neighbourhood greenspace and type 2 diabetes in a large cross-sectional study. BMJ Open 4.

Bowen, K.J., Lynch, Y., 2017. The public health benefits of green infrastructure: the potential of economic framing for enhanced decision-making. Curr. Opin. Environ. Sustain. 25, 90–95.

Burnett Richard, T., Pope, C.A., Ezzati, M., Olives, C., Lim Stephen, S., Mehta, S., Shin Hwashin, H., Singh, G., Hubbell, B., Brauer, M., Anderson, H.R., Smith Kirk, R., Balmes John, R., Bruce Nigel, G., Kan, H., Laden, F., Prüss-Ustün, A., Turner Michelle, C., Gapstur Susan, M., Diver, W.R., Cohen, A., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ. Health Perspect. 122, 397–403.

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.

Cappuccio, F.P., Cooper, D., D Elia, L., Strazzullo, P., Miller, M.A., 2011. Sleep duration predicts cardiovascular outcomes: a systematic review and meta-analysis of prospective studies. Eur. Heart J. 32, 1484–1492.

Cariñanos, P., Casares-Porcel, M., 2011. Urban green zones and related pollen allergy: a review. Some guidelines for designing spaces with low allergy impact. Landsc. Urban Plan. 101, 205–214.

Carter, T., Fowler, L., 2008. Establishing green roof infrastructure through environmental policy instruments. Environ. Manag. 42, 151–164.

Cavanagh, J.-A.E., Clemons, J., 2006. Do urban forests enhance air quality? Australasian Journal of Environmental Management 13, 120–130.

CCC, 2011. Cambridgeshire Green Infrastructure Strategy. Cambridge City Council, pp. 176. Available: https://www.cambridge.gov.uk/media/2557/green-infrastructure-strategy.pdf (accessed 25.09.2018).

Celik, S., Ogus Binatli, A., 2018. Energy savings and economic impact of green roofs: a pilot study. Emerg. Mark. Financ. Trade 54, 1778–1792.

Chen, L., Liu, C., Zhang, L., Zou, R., Zhang, Z., 2017. Variation in tree species ability to capture and retain airborne fine particulate matter (PM2.5). Sci. Rep. 7, 3206.

Chenoweth, J., Anderson, A.R., Kumar, P., Hunt, W.F., Chimbwandira, S.J., Moore, T.L.C., 2018. The interrelationship of green infrastructure and natural capital. Land Use Policy 75, 137–144.

Chin, M.T., 2015. Basic mechanisms for adverse cardiovascular events associated with air pollution. Heart 101, 253.

Ching, J., See, L., Mills, G., Alexander, P., Bechtel, B., Feddema, J., Oleson, K.L., Stewart, I., Neophytou, M., Chen, F., Wang, X., Hanna, A., 2014. WUDAPT: facilitating advanced urban canopy modeling for weather, climate and air quality applications. In: 94th American Meteorological Society Annual Meeting 2–6 February, Georgia, USA.

Chum, A., O'Campo, P., Matheson, F., 2015. The impact of urban land uses on sleep duration and sleep problems. The Canadian Geographer/Le Géographe Canadien 59, 404–418.

Churkina, G., Kuik, F., Bonn, B., Lauer, A., Grote, R., Tomiak, K., Butler, T.M., 2017. Effect of VOC emissions from vegetation on air quality in Berlin during a heatwave. Environmental Science & Technology 51, 6120–6130.

Coombes, E., Jones, A.P., Hillsdon, M., 2010. The relationship of physical activity and overweight to objectively measured green space accessibility and use. Soc. Sci. Med.

70, 816–822.
Crilley, L.R., Lucarelli, F., Bloss, W.J., Harrison, R.M., Beddows, D.C., Calzolai, G., Nava, S., Valli, G., Bernardoni, V., Vecchi, R., 2017. Source apportionment of fine and coarse particles at a roadside and urban background site in London during the 2012 summer ClearfLo campaign. Environ. Pollut. 220, 766–778.
Crouse, D.L., Pinault, L., Balram, A., Hystad, P., Peters, P.A., Chen, H., van Donkelaar, A., Martin, R.V., Ménard, R., Robichaud, A., Villeneuve, P.J., 2017. Urban greenness and mortality in Canada's largest cities: a national cohort study. The Lancet Planetary Health 1, e289–e297.
D'Amato, G., Cecchi, L., Bonini, S., Nunes, C., Annesi-Maesano, I., Behrendt, H., Liccardi, G., Popov, T., van Cauwenberge, P., 2007. Allergenic pollen and pollen allergy in Europe. Allergy 62.
DCLG, 2012. Department for Communities and Local Government. National Planning Policy Framework. Ministry of Housing, Communities & Local Government, London SW1E 5DU, pp. 65.
Deshmukh, P., Isakov, V., Venkatram, A., Yang, B., Zhang, K.M., Logan, R., Baldauf, R., 2018. The effects of roadside vegetation characteristics on local, near-road air quality. Air Qual. Atmos. Health 12, 259–270.
Devlin, A.S., Andrade, C.C., 2017. In: Fleury-Bahi, G., Pol, E., Navarro, O. (Eds.), Handbook of Environmental Psychology and Quality of Life Research. International Handbooks of Quality-of-life Springer, Cham Quality of the hospital experience: impact of the physical environment. In.
Donovan, G.H., Gatziolis, D., Longley, I., Douwes, J., 2018. Vegetation diversity protects against childhood asthma: results from a large New Zealand birth cohort. Nature Plants 4, 358–364.
Du, Y., Xu, X., Chu, M., Guo, Y., Wang, J., 2016. Air particulate matter and cardiovascular disease: the epidemiological, biomedical and clinical evidence. Journal of Thoracic Disease 8, E8–E19.
Dunn, A.D., 2010. Siting green infrastructure: legal and policy solutions to alleviate urban poverty and promote healthy communities. BC Envtl. Aff. L. Rev. 37, 41.
EEA, 2017. Air quality in Europe. In: EEA Report No 13/2017, pp. 80. Available online: https://www.eea.europa.eu/publications/air-quality-in-europe-2017 (accessed 2018.2009.2018).
EIA, 2019. Global Energy & CO2 Status Report: The Latest Trends in Energy and Emissions in 2018. International Energy Agency (IEA). Available at: https://webstore.iea.org/global-energy-co2-status-report-2018 (accessed 16.07.2019).
Eisenman, T.S., 2016. Greening cities in an urbanizing age: the human health bases in the nineteenth and early twentyfirst centuries. Change Over Time 69. http://scholarworks.umass.edu/larp_faculty_pubs/69.
Eisenman, T.S., Churkina, G., Jariwala, S.P., Kumar, P., Lovasi, G.S., Pataki, D.E., Weinberger, K.R., Whitlow, T.H., 2019a. Urban trees, air quality, and asthma: an interdisciplinary review. Landsc. Urban Plan. 187, 47–59.
Eisenman, T.S., Jariwala, S.P., Lovasi, G.S., 2019b. Urban trees and asthma: a call for epidemiological research. Lancet Respir. Med. 7, e19–e20.
Ellison, R.B., Greaves, S.P., Hensher, D.A., 2013. Five years of London's low emission zone: effects on vehicle fleet composition and air quality. Transp. Res. Part D: Transp. Environ. 23, 25–33.
Emberlin, J., 1998. The effects of air pollution on allergenic pollen. Eur. Respir. Rev. 8, 164–167.
Emmerson, K.M., Palmer, P.I., Thatcher, M., Haverd, V., Guenther, A.B., 2019. Sensitivity of isoprene emissions to drought over south-eastern Australia: integrating models and satellite observations of soil moisture. Atmos. Environ. 209, 112–124.
Endreny, T., Santagata, R., Perna, A., Stefano, C.D., Rallo, R.F., Ulgiati, S., 2017. Implementing and managing urban forests: a much needed conservation strategy to increase ecosystem services and urban wellbeing. Ecol. Model. 360, 328–335.
EPA, 2018. U.S. Environmental Protection Agency. Environmental Benefits Mapping and Analysis Program (BenMAP). Retrieved November 18, 2018, from. https://www.epa.gov/benmap.
Feng, Y., Tan, P.Y., 2017. Imperatives for greening cities: a historical perspective. In: Tan, P.Y., Jim, C.Y. (Eds.). Greening Cities: Forms & Functions. Springer, Singapore, pp. 41-70.
Ferranti, E.J.S., MacKenzie, A.R., Ashworth, K., Hewitt, C.N., 2017. First Steps in Urban Air Quality. A Trees and Design Action Group (TDAG) Guidance Document. UK: London. Available from: http://epapers.bham.ac.uk/3069/ (accessed 01.08.2019).
Frumkin, H., Bratman, G.N., Breslow, S.J., Cochran Jr., B., Lawler, P.H.K., Levin, J.J., Tandon, P.S., Varanasi, U., Wolf, K.L., Wood, S.A., 2017. Nature contact and human health: A research agenda. Environ. Health Perspect. 125, 075001. https://doi.org/10.1289/EHP1663.
Gallagher, J., Baldauf, R., Fuller, C.H., Kumar, P., Gill, L.W., McNabola, A., 2015. Passive methods for improving air quality in the built environment: a review of porous and solid barriers. Atmos. Environ. 120, 61–70.
Gascon, M., Triguero-Mas, M., Martínez, D., Dadvand, P., Rojas-Rueda, D., Plasència, A., Nieuwenhuijsen, M.J., 2016. Residential green spaces and mortality: a systematic review. Environ. Int. 86, 60–67.
Ghasemian, M., Amini, S., Princevac, M., 2017. The influence of roadside solid and vegetation barriers on near-road air quality. Atmos. Environ. 170, 108–117.
GLA, 2019. Greater London Authority, 2019. Using Green Infrastructure To Protect People From Air (April 2019). Available at. https://www.london.gov.uk/WHAT-WE-DO/environment/environment-publications/using-green-infrastructure-protect-people-air-pollution (access date 14.07.2019).
Grigsby-Toussaint, D.S., Turi, K.N., Krupa, M., Williams, N.J., Pandi-Perumal, S.R., Jean-Louis, G., 2015. Sleep insufficiency and the natural environment: results from the US behavioral risk factor surveillance system survey. Prev. Med. 78, 78–84.
Hagler, G.S.W., Lin, M.-Y., Khlystov, A., Baldauf, R.W., 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.
Hammerberg, K., Brousse, O., Martillic, A., Mahdavi, A., 2018. Implications of employing detailed urban canopy parameters for mesoscale climate modelling: a comparison between WUDAPT and GIS databases over Vienna, Austria. Int. J. Climatol. 38, 1241–1257.
Han, J.-W., Choi, H., Jeon, Y.-H., Yoon, C.-H., Woo, J.-M., Kim, W., 2016. The effects of forest therapy on coping with chronic widespread pain: physiological and psychological differences between participants in a forest therapy program and a control group. Int. J. Environ. Res. Public Health 13, 255.
Harris, T.B., Manning, W.J., 2010. Nitrogen dioxide and ozone levels in urban tree canopies. Environ. Pollut. 158, 2384–2386.
Hartig, T., Mitchell, R., De Vries, S., Frumkin, H., 2014. Nature and health. Annu. Rev. Public Health 35, 207–228.
Heal, M.R., Kumar, P., Harrison, R.M., 2012. Particles, air quality, policy and health. Chem. Soc. Rev. 41, 6606–6630.
Heath, G.W., Brownson, R.C., Kruger, J., Miles, R., Powell, K.E., Ramsey, L.T., the Task Force on Community Preventive Services, 2006. The effectiveness of urban design and land use and transport policies and practices to increase physical activity: a systematic review. J. Phys. Act. Health 3, S55–S76.
HEI, 2019. Health Effects Institute. 2019. State of Global Air 2019. Special Report. (2578-6873)Health Effects Institute, Boston, MA (accessed 02.08.2019).
Hewitt, C.N., Ashworth, K., MacKenzie, A.R., 2019. Using green infrastructure to improve urban air quality (GI4AQ). Ambio 1–12. https://doi.org/10.1007/s13280-019-01164-3.
Hillsdon, M., Panter, J., Foster, C., Jones, A., 2006. The relationship between access and quality of urban green space with population physical activity. Public Health 120, 1127–1132.
Hirabayashi, S., Nowak, D.J., 2016. Comprehensive national database of tree effects on air quality and human health in the United States. Environ. Pollut. 215, 48–57.
Hong, A., Sallis, J.F., King, A.C., Conway, T.L., Saelens, B., Cain, K.L., Fox, E.H., Frank, L.D., 2018. Linking green space to neighborhood social capital in older adults: the role of perceived safety. Soc. Sci. Med. 207, 38–45.
Irga, P.J., Braun, J.T., Douglas, A.N.J., Pettit, T., Fujiwara, S., Burchett, M.D., Torpy, F.R., 2017. The distribution of green walls and green roofs throughout Australia: do policy instruments influence the frequency of projects? Urban For. Urban Green. 24, 164–174.
iSCAPE, 2019. iSCAPE, 2018. Improving the Smart Control of Air Pollution in Europe. Retrieved on 10 July 2019 from. https://www.iscapeproject.eu/.
Isely, E.S., Isely, P., Seedang, S., Mulder, K., Thompson, K., Steinman, A.D., 2010. Addressing the information gaps associated with valuing green infrastructure in west Michigan: INtegrated Valuation of Ecosystem Services Tool (INVEST). J. Great Lakes Res. 36, 448–457.
Janhäll, S., 2015. Review on urban vegetation and particle air pollution – deposition and dispersion. Atmos. Environ. 105, 130–137.
Karagulian, F., Belis, C.A., Dora, C.F.C., Prüss-Ustün, A.M., Bonjour, S., Adair-Rohani, H., Amann, M., 2015. Contributions to cities' ambient particulate matter (PM): a systematic review of local source contributions at global level. Atmos. Environ. 120, 475–483.
Kellert, S.R., 2005. Building for Life: Designing and Understanding the Human-Nature Connection. Island Press, Washington, DC, pp. 2005.
Kredlow, M.A., Capozzoli, M.C., Hearon, B.A., Calkins, A.W., Otto, M.W., 2015. The effects of physical activity on sleep: a meta-analytic review. J. Behav. Med. 38, 427–449.
Kumar, P., Ketzel, M., Vardoulakis, S., Pirjola, L., Britter, R., 2011. Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environment - a review. J. Aerosol Sci. 42, 580–603.
Kumar, P., Khare, M., Harrison, R.M., Bloss, W.J., Lewis, A.C., Coe, H., Morawska, L., 2015. New directions: air pollution challenges for developing megacities like Delhi. Atmos. Environ. 122, 657–661.
Kumar, P., Andrade, M.F., Ynoue, R.Y., Fornaro, A., de Freitas, E.D., Martins, Martins, J.L. D., Albuquerque, T., Zhang, Y., Morawska, L., 2016. New directions: from biofuels to wood stoves: the modern and ancient air quality challenges in the megacity of São Paulo. Atmos. Environ. 140, 364–369.
Kumar, P., Gulia, S., Harrison, R.M., Khare, M., 2017. The influence of odd–even car trial on fine and coarse particles in Delhi. Environ. Pollut. 225, 20–30.
Kumar, P., Abhijith, K.V., Barwise, Y., 2019. Implementing Green Infrastructure for Air Pollution Abatement: General Recommendations for Management and Plant Species Selection. https://doi.org/10.6084/m9.fi gshare.8198261.v1.
Kuo, M., 2015. How might contact with nature promote human health? Promising mechanisms and a possible central pathway. Front. Psychol. 6. https://doi.org/10.3389/fpsyg.2015.01093.
Lachowycz, K., Jones, A.P., 2014. Does walking explain associations between access to greenspace and lower mortality? Soc. Sci. Med. 107, 9–17.
Laden, F., Schwartz, J., Speizer, F.E., Dockery, D.W., 2006. Reduction in fine particulate air pollution and mortality. Am. J. Respir. Crit. Care Med. 173, 667–672.
Lambert, K.A., Bowatte, G., Tham, R., Lodge, C., Prendergast, L., Heinrich, J., Abramson, M.J., Dharmage, S.C., Erbas, B., 2017. Residential greenness and allergic respiratory diseases in children and adolescents – a systematic review and meta-analysis. Environ. Res. 159, 212–221.
Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N., Baldé, A.B., Bertollini, R., Bose-O'Reilly, S., Boufford, J.I., Breysse, P.N., Chiles, T., Mahidol, C., Coll-Seck, A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K.V., McTeer, M.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potočnik, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk, W.A., van Schayck,

O.C.P., Yadama, G.N., Yumkella, K., Zhong, M., 2018. The lancet commission on pollution and health. Lancet 391, 462–512.
Lee, A.C.K., Maheswaran, R., 2011. The health benefits of urban green spaces: a review of the evidence. J. Public Health 33, 212–222.
Leiva G, M.A. Santibañez, D.A. Ibarra, E, S., Matus C.P., Seguel, R., 2013. A five-year study of particulate matter (PM2.5) and cerebrovascular diseases. Environ. Pollut. 181, 1–6.
Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 525, 367–371.
Li, L., Guenther, A.B., Xie, S., Gu, D., Seco, R., Nagalingam, S., Yan, D., 2019. Evaluation of semi-static enclosure technique for rapid surveys of biogenic volatile organic compounds (BVOCs) emission measurements. Atmos. Environ. 212, 1–5.
Linton, S.J., Kecklund, G., Franklin, K.A., Leissner, L.C., Sivertsen, B., Lindberg, E., Svensson, A.C., Hansson, S.O., Sundin, Ö., Hetta, J., 2015. The effect of the work environment on future sleep disturbances: a systematic review. Sleep Med. Rev. 23, 10–19.
Litschke, T., Kuttler, W., 2008. On the reduction of urban particle concentration by vegetation a review. Meteorol. Z. 17, 229–240.
Madureira, H., Andresen, T., 2014. Planning for multifunctional urban green infrastructures: promises and challenges. Urban Des. Int. 19, 38–49.
Markevych, I., Schoierer, J., Hartig, T., Chudnovsky, A., Hystad, P., Dzhambov, A.M., de Vries, S., Triguero-Mas, M., Brauer, M., Nieuwenhuijsen, M.J., Lupp, G., Richardson, E.A., Astell-Burt, T., Dimitrova, D., Feng, X., Sadeh, M., Standl, M., Heinrich, J., Fuertes, E., 2017. Exploring pathways linking greenspace to health: theoretical and methodological guidance. Environ. Res. 158, 301–317.
Mazza, L., Bennett, G., De Nocker, L., Gantioler, S., Losarcos, L., 2011. Green Infrastructure Implementation and Efficiency. Final Report for the European Commission DG Environment on Contract ENVB2SER20100059.
McDonald, P.J., Aptaker, P.S., Mitchell, J., Mulheron, M., 2007. A unilateral NMR magnet for sub-structure analysis in the built environment: the surface GARField. J. Magn. Reson. 185, 1–11.
McNabola, A., 2010. New directions: passive control of personal air pollution exposure from traffic emissions in urban street canyons. Atmos. Environ. 44, 2940–2941.
McWilliam, W., Brown, R., Eagles, P., Seasons, M., 2015. Evaluation of planning policy for protecting green infrastructure from loss and degradation due to residential encroachment. Land Use Policy 47, 459–467.
Mell, I., 2016. Global Green Infrastructure: Lessons for Successful Policy-making, Investment and Management. Routledge.
Mell, I., Allin, S., Reimer, M., Wilker, J., 2017. Strategic green infrastructure planning in Germany and the UK: a transnational evaluation of the evolution of urban greening policy and practice. Int. Plan. Stud. 22, 333–349.
Mitchell, R., Astell-Burt, T., Richardson, E.A., 2011. A comparison of green space indicators for epidemiological research. J. Epidemiol. Community Health 65, 853–858.
Neves, A., Brand, C., 2019. Assessing the potential for carbon emissions savings from replacing short car trips with walking and cycling using a mixed GPS-travel diary approach. Transp. Res. A Policy Pract. 123, 130–146.
Newell, J.P., Seymour, M., Yee, T., Renteria, J., Longcore, T., Wolch, J.R., Shishkovsky, A., 2013. Green alley programs: planning for a sustainable urban infrastructure? Cities 31, 144–155.
Newman, P., 2014. Biophilic urbanism: a case study on Singapore. Australian planner 51, 47–65.
Ngan, G., 2004. Green Roof Policies: Tools for Encouraging Sustainable Design. Landscape Architecture Canada Foundation.
Nieuwenhuijsen, M.J., Khreis, H., Triguero-Mas, M., Gascon, M., Dadvand, P., 2017. Fifty shades of green: pathway to healthy urban living. Epidemiology 28, 63–71.
Nowak, D.J., Civerolo, K.L., Rao, S.T., Sistla, G., Luley, C.J., Crane, D.E., 2000. A modeling study of the impact of urban trees on ozone. Atmos. Environ. 34, 1601–1613.
Nowak, D.J., Crane, D.E., Stevens, J.C., 2006. Air pollution removal by urban trees and shrubs in the United States. Urban For. Urban Green. 4, 115–123.
Nowak, D.J., Hirabayashi, S., Bodine, A., Hoehn, R., 2013. Modeled PM2.5 removal by trees in ten U.S. cities and associated health effects. Environ. Pollut. 178, 395–402.
Nowak, D.J., Hirabayashi, S., Bodine, A., Greenfield, E., 2014. Tree and forest effects on air quality and human health in the United States. Environ. Pollut. 193, 119–129.
Nowak, D.J., Hirabayashi, S., Doyle, M., McGovern, M., Pasher, J., 2018. Air pollution removal by urban forests in Canada and its effect on air quality and human health. Urban For. Urban Green. 29, 40–48.
Oke, T.R., 1988. Street design and urban canopy layer climate. Energy and Buildings 11, 103–113.
Pataki, D.E., Carreiro, M.M., Cherrier, J., Grulke, N.E., Jennings, V., Pincetl, S., Pouyat, R.V., Whitlow, T.H., Zipperer, W.C., 2011. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. Front. Ecol. Environ. 9, 27–36.
Pedersen, M., Giorgis-Allemand, L., Bernard, C., Aguilera, I., Andersen, A.-M.N., Ballester, F., Beelen, R.M.J., Chatzi, L., Cirach, M., Danileviciute, A., Dedele, A., Eijsden, M.v., Estarlich, M., Fernández-Somoano, A., Fernández, M.F., Forastiere, F., Gehring, U., Grazuleviciene, R., Gruzieva, O., Heude, B., Hoek, G., Hoogh, K.d., van den Hooven, E.H., Håberg, S.E., Jaddoe, V.W.V., Klümper, C., Korek, M., Krämer, U., Lerchundi, A., Lepeule, J., Nafstad, P., Nystad, W., Patelarou, E., Porta, D., Postma, D., Raaschou-Nielsen, O., Rudnai, P., Sunyer, J., Stephanou, E., Sørensen, M., Thiering, E., Tuffnell, D., Varró, M.J., Vrijkotte, T.G.M., Wijga, A., Wilhelm, M., Wright, J., Nieuwenhuijsen, M.J., Pershagen, G., Brunekreef, B., Kogevinas, M., Slama, R., 2013. Ambient air pollution and low birthweight: a European cohort study (ESCAPE). Lancet Respir. Med. 1, 695–704.
Pereira, G., Foster, S., Martin, K., Christian, H., Boruff, B.J., Knuiman, M., Giles-Corti, B., 2012. The association between neighborhood greenness and cardiovascular disease: an observational study. BMC Public Health 12, 466.
Peters, R., Ee, N., Peters, J., Booth, A., Mudway, I., Anstey, K., 2019. Air pollution and dementia: a systematic review. J. Alzheimers Dis. 1–19. https://doi.org/10.3233/JAD-180631.
PHE, 2019. Review of interventions to improve outdoor air quality and public health. Public Health England London SE1 8UG. Available at: https://www.nature.com/articles/nature15371?platform=oscar&draft=journal (accessed 15.07.2019).
Pope III, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287, 1132–1141.
Porcherie, M., Lejeune, M., Gaudel, M., Pommier, J., Faure, E., Heritage, Z., Rican, S., Simos, J., Cantoreggi, N.L., Le Gall, A.R., 2018. Urban green spaces and cancer: a protocol for a scoping review. BMJ Open 8, e018851.
Power, M.C., Adar, S.D., Yanosky, J.D., Weuve, J., 2016. Exposure to air pollution as a potential contributor to cognitive function, cognitive decline, brain imaging, and dementia: a systematic review of epidemiologic research. NeuroToxicology 56, 235–253.
RCPCH, 2016. Every Breath we Take: The Lifelong Impact of Air Pollution. Royal College of Physicians, London, pp. 123. Available. https://www.rcplondon.ac.uk/projects/outputs/every-breath-we-take-lifelong-impact-air-pollution (accessed 118.109.2018).
Requia, W.J., Adams, M.D., Arain, A., Papatheodorou, S., Koutrakis, P., Mahmoud, M., 2018. Global association of air pollution and cardiorespiratory diseases: a systematic review, meta-analysis, and investigation of modifier variables. Am. J. Public Health 108, S123–S130.
Rivasplata, C.R., 2013. Congestion pricing for Latin America: prospects and constraints. Res. Transp. Econ. 40, 56–65.
Ruckerl, R., Ibald-Mulli, A., Koenig, W., Schneider, A., Woelke, G., Cyrys, J., Heinrich, J., Marder, V., Frampton, M., Wichmann, H.E., Peters, A., 2006. Air pollution and markers of inflammation and coagulation in patients with coronary heart disease. Am. J. Respir. Crit. Care Med. 173, 432–441.
Saebo, A., Janhäll, S., Gawronski, S., Hanslin, H.M., 2017. Urban forestry and pollution mitigation. In: Ferrini, F., Konijnendijk van den Bosch, C., Fini, A. (Eds.), Routledge Handbook of Urban Forestry. Routledge, London, pp. 112–122.
Salmond, J.A., Tadaki, M., Vardoulakis, S., Arbuthnott, K., Coutts, A., Demuzere, M., Dirks, K.N., Heaviside, C., Lim, S., Macintyre, H., McInnes, R.N., Wheeler, B.W., 2016. Health and climate related ecosystem services provided by street trees in the urban environment. Environ. Health 15, 36.
Sanders, T., Feng, X., Fahey, P.P., Lonsdale, C., Astell-Burt, T., 2015. Greener neighbourhoods, slimmer children? Evidence from 4423 participants aged 6 to 13 years in the longitudinal study of Australian children. Int. J. Obes. 39, 1224.
SCC, 2015. Green Stormwater Infrastructure in Seattle Implementation Strategy 2015–2020. Seattle City Council, pp. 80. Available: http://www.seattle.gov/Documents/Departments/OSE/GSI_Spreads_v82_July_2015_WEB.pdf (accessed 2020.2009.2018).
Schilling, J., Logan, J., 2008. Greening the Rust Belt: a green infrastructure model for right sizing America's shrinking cities. J. Am. Plan. Assoc. 74, 451–466.
Sciaraffa, R., Borghini, A., Montuschi, P., Gerosa, G., Ricciardi, W., Moscato, U., 2017. Impact of air pollution on respiratory diseases in urban areas: a systematic review: Daniele Ignazio La Milia. Eur. J. Pub. Health 27.
Selmi, W., Weber, C., Rivière, E., Blond, N., Mehdi, L., Nowak, D., 2016. Air pollution removal by trees in public green spaces in Strasbourg city, France. Urban For. Urban Green. 17, 192–201.
Shaneyfelt, K.M., Anderson, A.R., Kumar, P., Hunt, W.F., 2017. Air quality considerations for stormwater green street design. Environ. Pollut. 231, 768–778.
Simpson, J.R., McPherson, E.G., 1998. Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento. Atmos. Environ. 32, 69–74.
Skeldon, A.C., Phillips, A.J.K., Dijk, D.-J., 2017. The effects of self-selected light-dark cycles and social constraints on human sleep and circadian timing: a modeling approach. Sci. Rep. 7, 45158.
Slätmo, E., Nilsson, K., Turunen, E., 2019. Implementing green infrastructure in spatial planning in Europe. Land 8, 62. https://doi.org/10.3390/land8040062.
SMAQMD, 2017. Sacramento metropolitan air quality management district, California. Landscaping guidance for improving air quality near roadways, plant species and best practices for the Sacramento region (February). Available at. http://www.airquality.org/LandUseTransportation/Documents/LandscapingGuidanceDraft2017-Feb23.pdf (access date 14.07.2019).
Sugiyama, T., Leslie, E., Giles-Corti, B., Owen, N., 2008. Associations of neighbourhood greenness with physical and mental health: do walking, social coherence and local social interaction explain the relationships? J. Epidemiol. Community Health 62, e9.
Suppakittpaisarn, P., Jiang, X., Sullivan, W.C., 2017. Green infrastructure, green Stormwater infrastructure, and human health: a review. Current Landscape Ecology Reports 2, 96–110.
Takano, T., Nakamura, K., Watanabe, M., 2002. Urban residential environments and senior citizens' longevity in megacity areas: the importance of walkable green spaces. J. Epidemiol. Community Health 56, 913–918.
Tang, J., McNabola, A., Misstear, B., Caulfield, B., 2017. An evaluation of the impact of the Dublin Port Tunnel and HGV management strategy on air pollution emissions. Transp. Res. Part D: Transp. Environ. 52, 1–14.
Tiwari, A., Kumar, P., Baldauf, R., Zhang, K.M., Pilla, F., Di Sabatino, S., Brattich, E., Pulvirenti, B., 2019. Considerations for evaluating green infrastructure impacts in microscale and macroscale air pollution dispersion models. Sci. Total Environ. 672, 410–426.
Twohig-Bennett, C., Jones, A., 2018. The health benefits of the great outdoors: a systematic review and meta-analysis of greenspace exposure and health outcomes. Environ. Res. 166, 628–637.

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, 167–178.

UN, 2014. United Nations - world urbanization prospects 2014. Available from: https://esa.un.org/unpd/wup/publications/files/wup2014-highlights.pdf (accessed 19.06.2018).

Van den Berg, A.E., Maas, J., Verheij, R.A., Groenewegen, P.P., 2010. Green space as a buffer between stressful life events and health. Soc. Sci. Med. 70, 1203–1210.

Vardoulakis, S., Fisher, B.R.A., Pericleous, K., Gonzalez-Flesca, N., 2003. Modelling air quality in street canyons: a review. Atmos. Environ. 37, 155–182.

Villeneuve, P.J., Jerrett, M., Su, J.G., Burnett, R.T., Chen, H., Wheeler, A.J., Goldberg, M.S., 2012. A cohort study relating urban green space with mortality in Ontario, Canada. Environ. Res. 115, 51–58.

Warburton, D.E.R., Bredin, S.S.D., Shellington, E.M., Cole, C., de Faye, A., Harris, J., Kim, D.D., Abelsohn, A., 2019. A systematic review of the short-term health effects of air pollution in persons living with coronary heart disease. J. Clin. Med. 8, 274.

Watts, P., Phillips, G., Petticrew, M., Hayes, R., Bottomley, C., Yu, G., Schmidt, E., Tobi, P., Moore, D., Frostick, C., Lock, K., Renton, A., 2013. Physical activity in deprived communities in London: examining individual and neighbourhood-level factors. PloSOne 8, e69472.

Weber, T., Sloan, A., Wolf, J., 2006. Maryland's green infrastructure assessment: development of a comprehensive approach to land conservation. Landsc. Urban Plan. 77, 94–110.

Whitlow, T.H., Pataki, D.E., Alberti, M., Pincetl, S., Setälä, H., Cadenasso, M.L., McComas, K., 2014. Response to authors' reply regarding "Modeled PM2.5 removal by trees in ten U.S. cities and associated health effects" by Nowak et al. Environ. Pollut. 191, 258–259.

WHO, 2016. World Health Organisation. Urban green spaces and health - a review of evidence. Available at. http://www.euro.who.int/_data/assets/pdf_file/0005/321971/Urban-green-spaces-and-health-review-evidence.pdf (accessed 03.08.2019).

Willis, K.J., Petrokofsky, G., 2017. The natural capital of city trees. Science 356, 374–376.

Wolch, J.R., Byrne, J., Newell, J.P., 2014. Urban green space, public health, and environmental justice: the challenge of making cities 'just green enough'. Landsc. Urban Plan. 125, 234–244.

Yin, S., Shen, Z., Zhou, P., Zou, X., Che, S., Wang, W., 2011. Quantifying air pollution attenuation within urban parks: an experimental approach in Shanghai, China. Environ. Pollut. 159, 2155–2163.

Young, R.F., McPherson, E.G., 2013. Governing metropolitan green infrastructure in the United States. Landsc. Urban Plan. 109, 67–75.

Zanobetti, A., Schwartz, J., Samoli, E., Gryparis, A., Touloumi, G., Peacock, J., Anderson Ross, H., Le Tertre, A., Bobros, J., Celko, M., Goren, A., Forsberg, B., Michelozzi, P., Rabczenko, D., Hoyos Santiago, P., Wichmann, H.E., Katsouyanni, K., 2003. The temporal pattern of respiratory and heart disease mortality in response to air pollution. Environ. Health Perspect. 111, 1188–1193.

Zhang, P., Dong, G., Sun, B., Zhang, L., Chen, X., Ma, N., et al., 2011. Long-term exposure to ambient air pollution and mortality due to cardiovascular disease and cerebrovascular disease in Shenyang, China. PLoS One 6, e20827 doi:20810.21371/journal.pone.0020827.