LONDON'S GLOBAL UNIVERSITY

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Green Infrastructure for London: A review of the evidence

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Abstract

Green infrastructure is a strategic, planned network of natural, semi-natural and artificial features and networks designed and managed to deliver a wide range of ecosystem services and quality of life benefits (European Commission, 2016; European Commission, 2012; Tzoulas et al., 2007; Bowen & Parry, 2015). In an urban setting, green infrastructure networks may include traditional parks, woodlands, wetlands, rivers, private gardens, street trees, allotments, playing fields, cemeteries and newer innovations such as green roofs and sustainable drainage systems (SuDS) (GLA, 2015a; Wilebore & Wentworth, 2013). This report reviews the benefits, costs and risks of green infrastructure for air quality, surface water management, biodiversity and human health and wellbeing in London.

Green infrastructure can improve air quality by providing barriers to sources of pollution such as busy roads. Plants also remove pollution from the air. Surface water management that aims to reduce local flood risk and water pollution can benefit from green infrastructure which slows down runoff, captures pollutants and increases the amount of water soaking into the ground instead of running into drains. Increasing habitat and connectivity of green spaces in London can encourage greater abundance and diversity of species. A diversity of planting encourages invertebrate diversity, which provides a food source for animals such as birds and bats. Access to green spaces has been demonstrated to improve human physical and mental health. Physical activity may be higher in areas with access to good quality green space. Exposure to nature and a green environment reduces anxiety and improves mental ill-health. Green spaces and infrastructure may also be associated with improved wellbeing, lower crime rates and a stronger sense of place, but this needs to be considered in a social context. ‘Green gentrification’ can benefit wealthier, able-bodied residents to the detriment of more vulnerable groups.

Evaluating the costs and benefits of green infrastructure is complicated by its multi-functional nature. The costs of green infrastructure need to be considered on a project-by-project basis. It is difficult to assign costs to specific services or benefits provided by a green infrastructure component. In addition to economic costs for installation and maintenance there may be other dis-benefits that need to be accounted for and managed. Trees and plants may have negative impacts due to pollen dispersal and emission of volatile organic compounds and ozone which can contribute to air pollution. Tree roots and branches may also damage roads and pavements, and leaves require sweeping. Insects, birds and other species can contribute to increasing the cost of pest control and cleaning.

Not all green infrastructure components are suitable in all conditions. More detailed monitoring of air pollution, biodiversity and surface water is needed to support better prediction of environmental quality and the impact of green infrastructure. There is a risk that green infrastructure components may be implemented inappropriately, undermining benefits and increasing costs and likelihood of failure. There is also the risk that, unless green infrastructure is well integrated into the urban environment, it can become a space that is visited for a specific activity, rather than being used and experienced on a daily basis. There are concerns that infrequent use of green space may reduce its capacity to provide health and wellbeing benefits and limit social cohesion (GLA, 2015a).

Green infrastructure provides considerable benefits to London, and better integration and connection within the city could further enhance London’s ability to respond to these problems. Accounting for the costs and risks associated with green infrastructure, and addressing the need to strengthen the evidence base about its function and impacts alongside its benefits, will allow for more robust decision making and adaptive approaches to planning and management.

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Introduction

Green infrastructure is a strategic, planned network of natural, semi-natural and artificial components designed and managed to deliver a wide range of ecosystem services and quality of life benefits (European Commission, 2016; European Commission, 2012; Tzoulas et al., 2007; Bowen & Parry, 2015). In an urban setting, green infrastructure networks may include parks, woodlands, wetlands, rivers, private gardens, street trees, allotments, playing fields, green roofs and sustainable drainage systems (SuDS) (GLA, 2015a; Wilebore & Wentworth, 2013). By considering these typologies and functions as green infrastructure, its overall protection, design and management can be made more strategically effective.

London is a comparatively green city, with 47% of its total area currently identified as green or blue space (GLA, 2015a). London's population is projected to reach 11 million people by 2050 (ONS, 2016). Accommodating this growth will require extensive development of the city's infrastructure, including the construction of approximately 50,000 homes a year (GLA, 2015a). This growing population will increase pressure on London's biodiversity, air quality and water systems. The development of green infrastructure will be vital to maintain these existing systems, and provide new habitat to conserve London's biodiversity and enhance ecosystem services (GLA, 2015a).

Ecosystem services are the functions provided by green infrastructure and natural systems, which are of benefit to society and the economy, in addition to their intrinsic value. They are described in terms of provisioning, regulating, cultural and supporting services (Hassan et al., 2005). Provisioning services include food, timber, medicines, fibre, fuel and other products. Regulating services include water filtration, climate regulation, crop pollination, disease control and waste decomposition, which provide a healthy environment for people to live in. Cultural services provide spiritual, psychological, educational and aesthetic value. Supporting services are ecological functions that maintain ongoing processes including soil formation, evolution, nutrient cycling and primary production. These benefits vary according to the size, structure, composition, location and purpose of the specific green infrastructure involved. Ecosystem services of particular significance to urban populations include regulating services, such as air pollutant filtration, climate regulation, flood alleviation, and cultural services such as education and recreation opportunities (Alberti, 2010).

A report by the Centre for Sustainable Planning and Environments at the University of the West of England, *The Green Infrastructure Review* (Sinnett et al., 2016) examines non-academic literature to determine the benefits of green infrastructure to provide regulating services such as improving air quality, water and climate regulation, among other things. The review states that there is 'some evidence that the ecosystem services provided by green infrastructure result in economic benefits to society and individuals. This has primarily focussed on the benefits to health and wellbeing… from air quality improvement and physical activity, stormwater management, carbon storage and tourism' (Sinnett et al., 2016:p.2).

Green infrastructure can provide an integrated means for achieving a number of goals and functions of cities. Box 1 outlines some of the potential structural benefits of well-planned and designed green infrastructure, which underpin the delivery of ecosystem services.

Box 1: Benefits of green infrastructure

Flexibility and adaptability

Green infrastructure features can be implemented at different scales: building scale, neighbourhood scale, city scale, catchment scale and across landscapes. Depending on the topography, soil and ground conditions, hydrology and microclimate at the site, the design can be modified to maximise the benefits while reducing risks. Furthermore, while green infrastructure measures can be implemented to treat and control stormwater runoff, improve air quality and biodiversity locally, the effectiveness can increase as a cumulative effect when the green infrastructure measures are used to fully integrate the water cycle, ecosystems and the built environment (Wilebore & Wentworth, 2013).

Multi-functionality

One of the most powerful advantages of green infrastructure is its potential for multi-functionality. By using green infrastructure rather than conventional approaches to managing the built environment, benefits per spatial unit can be maximised (European Commission, 2012). Multi-functional benefits vary between different types of green infrastructure and their primary function. In terms of hydrological benefits, a single green infrastructure measure – if designed and managed effectively - can address both quantity and quality control of surface water runoff. Additional measures can be combined to target a site-specific issue and to deliver wider benefits such as enhanced biodiversity, air quality, urban cooling and recreation. With this flexibility and adaptability green infrastructure can be integrated into urban development where its function can go beyond surface water management, air quality improvement and biodiversity, to improve wellbeing, urban design and social cohesion.

Uses 'wastes' as resources

Rainwater that usually flows directly to the sewage system or a water body can be collected for non-potable uses, or even potable uses if properly treated. By using rainwater harvesting systems as well as other measures such as bio-retention systems, rain gardens and pervious surfaces, surface water runoff can be stored to satisfy future needs. Green infrastructure can also make use of under-utilised land, buildings and neglected urban spaces to provide habitat and connections across the city.

Resilient to climate change

Green infrastructure increases carbon storage in cities, helping to mitigate carbon emissions that contribute to climate change (Rogers et al., 2015). Green infrastructure increases evapotranspiration and shading, cooling urban buildings and spaces and counteracting the urban heat island effect. This in turn can reduce the energy costs associated with cooling. Rainfall may become more extreme and unpredictable due to changes to the climate; therefore, controlling and treating surface water runoff near or at the source using green infrastructure allows the drainage system to be more easily adapted to future hydrologic changes (Ashley et al., 2011). Providing habitat and landscape connectivity may improve the capacity for species to adapt their range and habitat in response to changing climate and habitat fragmentation. In addition, if widely adopted and properly used, the benefits can be long-term and cumulative, city- or even nation-wide (UK Green Building Council, 2015).

Ecologically sound

Using green infrastructure appropriately can protect the natural ecology, morphology, and hydrological characteristics of the sites, and restore or mimic natural evapotranspiration and surface water runoff, and ecosystems (Woods Ballard et al., 2015).

Green infrastructure is not without its costs, risks and uncertainties. The benefits of green infrastructure are widely promoted, but it is important that these are evaluated on the basis of robust evidence which considers potential negative as well as positive impacts. Green infrastructure requires ongoing maintenance and new mechanisms for evaluating economic costs and benefits to enable comparison with more conventional options. Design and maintenance of buildings for closer integration of natural features may change the costs and benefits of development projects. The social and health benefits of green spaces may be enjoyed most by those with relatively high levels of wellbeing, excluding vulnerable groups such as the elderly, young people and people living with disabilities. Trees and vegetation can help to remove pollutants from the air, but species with high pollen production can have negative impacts on people with allergies.

This report evaluates the evidence for green infrastructure in London in relation to air quality, water, biodiversity and health and wellbeing. Each issue is addressed in a separate chapter, and each chapter describes the problem, and the benefits, costs and risks of green infrastructure in addressing it. The evidence is drawn from international studies, as well as London-based experience and case studies. There are significant gaps in both the local and international evidence about green infrastructure, and ongoing research, experimentation and monitoring are required to build knowledge to support decision making, planning and design.

The purpose of this report is to provide a critical evaluation of the evidence for green infrastructure in London. If London is to realise the potential benefits of enhanced green infrastructure it is important that these are understood alongside the risks and costs. A critical and balanced approach will support a more robust approach to enhancing ecosystem services and wellbeing provided by London's buildings, infrastructure and open spaces.

Air Quality

1. Air Quality

There has been popular interest in the impacts of green infrastructure on air quality. The scale of the air pollution problem facing London is vast, and implementing solutions is difficult. Researchers at King's College London estimate that in 2010 up to 9,416 people died in London as a result of nitrogen dioxide (NO_2) and fine particulate ($PM_{2.5}$) pollution (Walton et al., 2015). The King's College study estimated that life expectancy from birth in London is reduced by approximately a year as a result of air pollution.

The prospect of utilising green infrastructure to alleviate the negative consequences of traffic related pollution emissions is very appealing and is often discussed in connection with air quality interventions. In 2013, Transport for London launched a £5 million Clean Air Fund programme, funded by the Department for Transport, to support measures to improve air quality in London. Funded projects included installing green walls in busy, traffic congested areas, such as Edgware Road tube station, and tree planting along several busy roads.

Despite these and other efforts, harmful airborne pollutants remain an issue in many urban areas. Of particular concern are street canyons: areas where tall buildings border both sides of a busy street, trapping in vehicle emissions. While it is possible for wind flow over the building rooftops to help ventilate street canyons, some pollutants are re-circulated, causing their concentrations to build. A general belief is that trees help to absorb pollutants and therefore act as biological sponges to clean the air that people breathe. However, it may be possible that trees act as a wind block, keeping pollutants trapped in the street and raising concentrations. The problem is further complicated by the fact that while trees do absorb some harmful pollutants, they do not absorb others. Trees also emit volatile organic compounds (VOCs, a precursor to ozone) and may act as ventilation blocks in urban street canyons (Buccolieri et al., 2011). Therefore, it is important to take a full inventory of what benefits trees and other vegetation can and cannot provide in terms of better air quality. For instance, it may be better to landscape using shrubs, bushes, flowers, and grasses instead of taller species of plants or to not use plants at all. Given the scale of the problem and the cost of potential solutions it is important to examine the evidence base for decisions to install green infrastructure as a means of reducing air pollution.

What is the problem?

London has some of the highest levels of air pollution of all European cities, with significant health impacts for Londoners, particularly children, the elderly and those with pre-existing medical conditions (London Assembly, 2015). Burning fuels, disturbing dust from construction sites and some biological processes such as pollen shedding release fine particles into the air. Fine particles can be breathed in by people and are related to various respiratory illnesses. Particles (particulate matter, PM) are defined according to their size. PM_{10} refers to particles with a diameter of 10 micrometres or less, and $PM_{2.5}$ particles have a diameter of 2.5 micrometres or smaller.

Combustion, including in car engines, and industrial processes also release gaseous pollutants. These include sulphur dioxide (SO_2), ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2) and nitric oxide (NO) (NO and NO_2 are together referred to as NO_X). Ozone release has also been associated with some tree species (Rogers et al., 2015). NO_2 is a cause for significant concern in London, with pollution levels regularly in breach of EU regulations. Diesel engines in vehicles are a significant source of air pollution, particularly NO_2 and PM_{10}, in London (London Assembly, 2015).

There is some confusion in the professional and policy literature about the definition of 'Air Quality'. Much of the research on Air Quality cited by some government reports, is derived from other reports by urban designers or urban planners, rather than referring directly to the scientific studies. Urban planners often refer to 'Air Quality' in the holistic sense; as a general term encompassing both micro-climate effects such as cooling, shading and humidifying, as well as air pollution removal effects. When these reports are cited, it is important to make the distinction between the two, as the evidence base for mitigating the air pollution in inner city urban settings is weaker than that for improving micro-climate in urban settings.

Street canyons and air quality

Street canyons describe streets that contain buildings continuously lined up on both sides (Nicholson, 1975) and are especially common in central London (Figure 1). They can become pollution hotspots due to increased traffic levels and reduced natural ventilation, leading to trapped air within the street. Street geometry has a significant effect on dispersion of pollution, with overall width of the street, its aspect ratio (Height over Width ratio of the street), and its orientation to background wind all affecting the airflow in the street. Symmetrical street canyons contain buildings that have the same height on either side, whereas asymmetrical canyons have different building sizes on either side (Vardoulakis et al., 2003), which has important implications for influencing airflow (Karra et al., 2017). The climate within a street canyon is controlled largely by micro-meteorological effects rather than those meteorological effects that influence dispersion generally (Hunter et al., 1992).

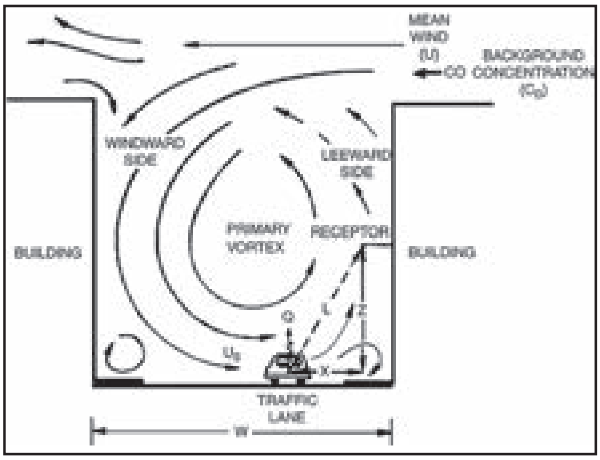

Figure 1: Airflow and circulation between two buildings in a street canyon (source: Dabberdt et al., 1973).

The vertical concentration of CO and NO_X in street canyons was studied by Zoumakis (1994), who found that these pollutants decreased according to an exponential equation which took atmospheric stability and surface roughness into account. As one moves upward from the street surface, the pollutant concentration decreases exponentially. Another study in Paris found large vertical and horizontal gradients of pollutants in street canyons, as well as a large difference between background pollutant concentrations of benzene and those in the street canyon (Vardoulakis et al., 2002). The Paris team also noted that pollution levels increased with low ambient wind speeds and winds which were almost parallel to the street. This finding may seem counter-intuitive, however near-parallel winds caused more of a build-up in pollutants instead of ventilating them with the effectiveness of perpendicular winds. Elsewhere in France (Nantes in this case), a large group of researchers found that increased traffic volume also led to increased CO and NO_X concentrations and also that wind perpendicular to the street led to higher concentrations on the leeward side (Vachon et al., 2000). Physical modelling showed that this is to be expected in a symmetrical street canyon (e.g. Karra et al., 2017). In results that, at first glance, seem contrary to those mentioned above, Murena, Garofalo and Favale (2008) found no difference in pollution levels between either side of the street in an urban canyon. However, the aspect ratio in their experiment (building height [H] over street width [W]) was 5.8, implying that very deep street canyons are less affected by ambient winds blowing over their tops. Furthermore, Karra et al. (2011) measured higher pollution levels on the windward side in a street in Nicosia, Cyprus, due to the street layout and the position of the traffic lane being closer to the windward side, illustrating the importance of in-street geometry. As far as ventilation is concerned, one study noted that retention times of pollutants in street canyons were 0.7 to 3.8 minutes with ambient winds of 1.7 to 4.5 m/s, and ventilation velocities were 15 to 80 cm/s (DePaul & Sheih, 1985).

There is a large body of research on street canyons in the literature. Some of the main findings relevant to Green Infrastructure and pollution distribution in street canyons can be summarised as follows:

- In most street canyons (with a smaller aspect ratio) pollutant concentrations are higher on the leeward side of the street than the windward side when winds are blowing perpendicular to the street; this may depend on the internal layout of the street and its traffic.
- Pollutant concentrations decrease exponentially in the vertical (depending on surface roughness and atmospheric stability).
- Ambient winds which are parallel to the street and/or low in speed can cause pollutant concentrations to build downwind, as does increased traffic volume.
- Pollutants can ventilate from the street in less than four minutes under typical ambient wind speeds.

How can green infrastructure help?

Green infrastructure can improve air quality by increasing dilution and dispersion of pollution, directly removing pollutants from the air by deposition and absorption on plant surfaces, and counteracting the urban heat island effect. Sinnet et al. (2016) found that 'There is substantial evidence presented in the grey literature that GI, particularly trees, can improve air quality', and that the three types of green infrastructure that are most beneficial are trees, green roofs and open green spaces such as recreational parks. They proceed to report on several case studies and implementations of green infrastructure around the UK and cite the benefits of these projects, but importantly, none were associated with a measurable subsequent reduction in air pollution. Measuring the impact of green infrastructure on air quality in relation to the other elements of the built environment is complex, and considerable uncertainty remains in the underlying science.

Airflow and pollution dispersion

As airflow patterns are influential on pollution dispersion - which are affected by canyon geometry - current research is investigating the implementation of passive controls which can be incorporated into street canyons to manipulate airflow patterns and increase pollutant dispersion (McNabola, 2010; Gallagher et al., 2012). Urban vegetation can act as obstacles in street canyons and therefore influence the dispersion of traffic-induced air pollution by altering airflow patterns, and consequently increasing pollutant concentration (McNabola et al., 2009; Buccolieri et al., 2011; Wania et al., 2012). Street geometry, including aspect ratios, building shape, are all important factors in their influence on airflow and pollution dispersion. However, buildings are not the only obstacles to airflow (Buccolieri et al., 2011). Street features including trees, parked cars and walls disrupt airflow patterns in street canyons (Gallagher et al., 2012), and so do pitched roofs, depending on their height and layout in the street (Wen & Malki-Epshtein, 2018). Investigations, specifically on urban vegetation, have shown that these can influence dispersion of traffic-induced air pollution in a street canyon.

Buccolieri et al. (2011) demonstrate the influence of wind direction on pollutant concentration in street canyons with varying aspect ratios, both with and without vegetation. They concluded that in street canyons with trees, the contribution of trees to the increase in pollutant concentration is larger both when the wind direction is perpendicular to the street and at a 45° incline, compared with no trees at aspect ratios of both W/H = 1 and W/H = 2. This demonstrates that the larger aspect ratio in both the tree-free and tree-lined streets results in larger pollutant concentrations when the wind is perpendicular to the street and vegetation contributes to an increase in pollutant levels - which is consistent with other research (Gromke et al., 2008).

The location of vegetation is an important factor to consider, particularly in street canyons. These are locations where sufficient natural ventilation depends on the width-to-depth aspect ratios of the buildings, which affects airflow mechanisms. Wania et al. (2012), who used the three dimensional microclimate model ENVI-met to simulate street canyons with different aspect ratios and differing vegetation levels, found that pollution concentrations increased with increasing vegetation density, which disrupts wind speed and causes a decrease in ventilation. In contrast to buildings, trees are relatively permeable and some airflows can still penetrate into the tree canopy. However, they found that vegetation reduces wind speed, therefore inhibiting canyon ventilation, and causes an increase in particle concentration (Wania et al., 2012). Vegetation should therefore be relatively widely spaced apart and not occupy large volumes within the canyon, so as not to suppress the ventilating canyon vortex system. Furthermore, tree height should not exceed roof-top level as this leads to a substantial reduction of entrained air (Gromke & Ruck, 2007; Gromke et al., 2008; Ahmad et al., 2005; Wania et al., 2012; Litschke & Kuttler, 2008). A number of computer models and wind tunnel studies have found that tall trees limit ventilation and dilution of the emissions with clean atmospheric air, increasing concentrations of pollutants in the street (Gromke & Blocken, 2015; Gromke & Ruck, 2008; Buccolieri et al., 2009; Buccolieri et al., 2011).

Low-lying vegetation may be preferable; Janhäll (2015) recommends the use of vegetation barriers to reduce exposure to particulate matter (PM). The urban vegetation should be varied in its type and design so as to capture various particle sizes.

Pollution deposition and absorption by plants

Trees and shrubs can act as pollution sinks to reduce the concentration of particles in the atmosphere. The vegetation filters out the particles which are deposited on leaves and branches. Trees also remove gaseous air pollution primarily via leaf-stomata uptake, so these pollutants are absorbed into the tree. Trees have been found to possess optimum characteristics due to their large collecting surface area, increased roughness and the promotion of vertical transport which enhances turbulence (McDonald et al., 2007). There are several aspects of vegetation that influence total pollutant removal and the standard pollutant removal rate per unit of tree coverage (Nowak et al., 2000; Nowak et al., 2006) which include:

- Leaf characteristics
- Weather
- Effect on emissions (through reduced energy use due to lower air temperature and shading of buildings)
- Amount and location of tree cover
- Emission of VOCs that can contribute to the formation of street-level ozone and carbon monoxide

Leaves vary in shape and surface composition. Greater surface roughness of leaves facilitates an intricate pattern of airflow, therefore increasing turbulent deposition of particles and impaction processes by causing localised increases in wind speed (Burkhardt et al., 1995; Chamberlain, 1975). The mechanisms for deposition depend on the size of particle. Finer particles have been found to deposit in the stomatal regions of conifers, therefore the roughness of the surface influences uptake. However, for coarse particles increased stickiness of the surface facilitates greater deposition (Chamberlain, 1975). This is reinforced in a recent study on PM deposition which found that plants with rough wax coated leaves and short petioles accumulate a higher proportion of PM compared to those with long petioles and smoother leaf surfaces (Prajapati & Tripathi, 2008). Plant characteristics are therefore a key variable and have a significant impact on the likelihood of particle deposition. Trees with sticky excretions and rough bark and leaves can extract most types of particulate matter from the atmosphere, whether the particles are fine or coarse (Beckett et al., 1998). Given these criteria, conifers seem to be the best option for cleaning up particulate matter. However, planting the trees in the correct place is important since locating them near sources of particulate matter would likely have a better effect. One study completed in the UK used a deposition model to determine the effect that planting trees in usable space would have on PM_{10} and found that planting up 100% of usable space would reduce PM_{10} levels by up to 30% and (more realistically) planting up 25% of usable space would reduce PM_{10} levels by 10-15% (Bealey et al., 2007). Information such as this is useful to planners who want to determine where to plant trees to help meet air quality standards.

Studies of the impact of green infrastructure and vegetation on removal of particulate matter have focussed mostly on PM_{10} and $PM_{2.5}$ due to concerns about their impacts on health (Tallis et al., 2011; Beckett et al., 1998; Freer-Smith et al., 1997; Tiwary et al., n.d.; Jouraeva et al., 2002). A recent review on urban vegetation and its impact on particulate air pollution was carried out by Janhäll (2015). The review focusses on the two primary physical processes by which vegetation can improve air quality, namely deposition and dispersion of particulate pollutants. It considers studies that carried out on-site measurements, wind tunnel studies and modelling, both for urban street canyons and vegetation barriers. The author refers to previous research on deposition which is derived mainly from forest applications, and states the need for different models to best represent the situation in an urban setting. Most existing studies, which cite PM_{10} reductions of a few per cent due to deposition on urban vegetation, do not account for meteorology and spatial variability.

Deposition of particles largely relies upon sufficient airflow from the pollutant source to the vegetation. Turbulence and the associated tortuous airflow within vegetation is beneficial and has been found to increase the likelihood of particle contact with plant surfaces (Tiwari et al., 2006). However, during exceptionally windy periods, particles can be re-suspended in the atmosphere (Nowak et al., 2006). Other meteorological conditions such as precipitation can also remove particles from the leaf surface, where particles wash off the leaf surface and into the soil (Nowak et al., 2006; Ottelé et al., 2010). Consequently, vegetation acts as a temporary retention site for many atmospheric particles (Nowak et al., 2006).

Freiman et al. (2006) found that PM concentrations were lower in areas with a higher tree cover. In addition to this, a study by Shan et al. (2007) demonstrated a positive correlation between canopy density along a roadside and the total suspended particle (TSP) removal percentage. They concluded that greenbelts along both sides of the road at a 10m width are optimum in removing TSP. This demonstrates a significant role of vegetation as a pollution sink. Cavanagh et al. (2008) further acknowledged the importance of urban forests in mitigating pollution levels. They found a significant decrease in particulate concentration with increasing distance inside the forest due to increased scavenging by the canopy rather than increasing distance from the pollution source (Cavanagh et al., 2008; Raynor et al., 1974). This forest edge effect demonstrates enhanced deposition at forest edges, which is suggested to be due to local advection and enhanced turbulent exchange (Erisman & Draaijers, 2003). The incorporation of urban green spaces could therefore be a useful addition in landscaping to reduce pollution levels.

Gaseous pollutants may be removed from the air by being absorbed by leaf stomata of plants. Absorption of gases by trees and vegetation was studied by Chaparro-Suarez et al. (2011), Alfani et al. (1996), Nowak (1994) and Jouraeva et al. (2002), resulting in many computer modelling studies on the potential of urban forests to remove gaseous pollutants and particulates from the air (Nowak, 2002; Islam et al., 2012).

Several studies have shown that leaves both absorb ozone through pores on their surface called stomata, and emit gaseous chemicals called isoprenoids to scavenge for it in the atmosphere (Velikova et al., 2004). One study found that certain types of isoprenoids can reduce ozone concentrations by up to 35ppb when light, CO_2, temperature, and humidity concentrations are right (Fares et al., 2008). This defensive ability of plants protects them from being harmed by ozone and may contribute to the reduction of ozone from the atmosphere. However, other studies have shown that VOCs emitted by plants may also contribute to ozone pollution in urban areas.

One review by Powe and Willis (2004) quoted several studies which listed the effects of SO_2 absorption by trees:

- McPherson et al. (1994) found that trees removed 3.9 standard tonnes of SO_2 from the Chicago area every day.
- Broadmeadow and Freer-Smith (1996) concluded that the removal rate of forests was 2.1kg of SO_2 per hectare per year.
- McPherson et al. (1998) estimated that pollution reduction per 100 trees was 0.8kg annually. This estimation was based on a 30-year average in a small area, so it may not be applicable elsewhere.

While leaf stomata also absorb NO_2, one study by Fowler et al. (1998) found that even though stomatal absorption was a large sink for NO_2, the deposition rate was still small (1-4ng/m^2/s) and was similar to the soil emission rate of NO_X species, leading to a long lifetime in the atmosphere.

The RE:LEAF partnership has undertaken an urban forest assessment using the i-Tree Eco Tool. Rogers et al. (2015) present the outcome of this assessment, which 'provides a quantitative baseline of the air pollution, carbon storage and sequestration benefits of trees as well as the amenity and stormwater benefits they provide'. They find that London's urban forest consists of over 8.4 million trees, of which 1.6 million trees are located in Inner London, and 6.8 million trees in Outer London. They estimate that the pollution removal by direct air pollution filtration by London's trees in Inner London is 11 tonnes of CO, 288 tonnes of NO_2, 86 tonnes of O_3, 28 tonnes of SO_2, 43 tonnes of $PM_{2.5}$ particulates and 105 tonnes of PM_{10}.

Urban cooling

The Urban Heat Island (UHI) effect refers to the higher temperatures observed in big cities, largely due to heat released from vehicles, power plants, air-conditioning and other urban sources (Rizwan et al., 2008). The adverse effects of UHIs include an increase in energy consumption and ground-level ozone, and a deterioration of the living environment (Rosenfeld et al., 1998; Konopacki & Akbari, 2002). Vegetation can reduce air temperatures through shading and evapotranspiration. Surfaces with a green canopy layer are 5-20 degrees cooler than sunlit surfaces (Shashua-Bar & Hoffman, 2003; Asawa et al., 2000; Lay et al., 2000). Shading can modify building cooling and heating by reducing solar radiation and surface temperature (Robitu et al., 2006) and therefore mitigate the effects of the UHI effect (Tong et al., 2005; Ca et al., 1998).

Strategic planting of trees around buildings is a widely applied mitigation strategy that can reduce energy expenditure of buildings. For example, summer air-conditioning energy reductions of 10-35% were found by Rosenfeld et al. (1995). Furthermore, lower air temperatures can reduce the activity of chemical reactions that produce secondary air pollutants in urban areas (Taha, 1997; Nowak et al., 2000). However, vegetation can reduce wind velocity, therefore reducing natural ventilation and convective cooling of building surfaces (Akbari, 2002). As such, strategic tree planting is vital to optimise the effect of shading on buildings whilst also promoting effective natural ventilation.

Costs

Air pollution benefits of green infrastructure may be achieved by low cost or multi-functional components such as road side hedges and verges, and large open parks and gardens. These can provide barriers to emissions from vehicles and dilution and cooling of polluted air. There is considerable interest in the potential for more intensive, artificial green infrastructure components such as green roofs and walls to remove pollution and protect human health. Whilst green roofs and walls can also deliver benefits for biodiversity and water management, they have much higher capital and maintenance costs than simpler planting schemes and management of parks and open spaces. The multiple benefits of green roofs and walls may justify high costs in localised situations where less expensive options are less viable, but the evidence of their benefits for air pollution alone require caution in analysing relative costs and benefits. Multi-functional benefits, such as the insulation and shading provided by green walls and roofs, may be more easily quantified than air quality benefits.

Risks

There is considerable uncertainty and relatively sparse evidence in the science of urban air pollution and its interaction with green infrastructure. London-wide monitoring by the Clean Air London network hosted at King's College London provides robust monitoring across the city, and demonstrates the scale of the problem with some spatial variation. Air pollution is experienced by London citizens at a very personal scale – on the journey to work or school, waiting at the bus stop, walking to the shops, jogging or cycling near busy roads, or through the front doors and windows of homes and businesses. For this reason, citizen scientists have been undertaking their own measurements of air pollution at locally significant sites, and have revealed much higher concentrations of pollution than those recorded by the official monitoring network. Citizen science data has also demonstrated lower pollution levels near green spaces, and may also provide important data for monitoring the impact of new green infrastructure installations. Data collected by citizen scientists needs to be carefully vetted to ensure data quality is sufficient and methods employed are robust. There are issues with handheld monitoring devices consistently showing higher measurements than fixed monitoring stations such as those set up by the London Air Quality Network (LAQN).

More detailed monitoring of air pollution is needed to support better modelling and prediction of air pollution in general, as well as providing more evidence for the impact of green infrastructure. Much of the basic science of the interaction between air pollution and green infrastructure is developed based on a diverse set of studies in rural or forested landscapes, wind tunnels and laboratory studies. While these studies are important, their results may not be directly applicable to urban applications of green infrastructure in contexts which are much more complex and subject to variability in weather, climate and other environmental conditions. Indirect evidence of pervasive pollution levels within London can also be obtained through ecological analysis: for example, monitoring the presence - or absence - of lichen intolerant to SO_2 inside London, can be illuminating and complementary to direct chemical measurements of SO_2 on streets (APIS, 2014). Better monitoring of air quality impacts of existing and new green infrastructure in the London (or broader urban) context will improve modelling and evidence for decision making about the most effective measures to take in different situations.

Several studies discuss the beneficial influence of tree planting in urban areas on air quality (McDonald et al., 2007; Nowak et al., 2000, 2006; Freiman et al., 2006; McPherson et al., 1997; Currie & Bass, 2008; Powe & Willis, 2004). However, studies have also demonstrated that vegetation can inhibit ventilation through acting as obstacles to airflow, leading to a negative impact on air quality at specific locations (Buccolieri et al., 2011; Litschke & Kuttler, 2008; Wania et al., 2012; Salim et al., 2011). Furthermore, little is known about the influence of vegetation in higher-density, built-up environments and the main influencing parameters (Wania et al., 2012).

While trees play an obvious role in cleaning the air humans breathe, they also can be a source of pollutants, a ventilation block, or may not absorb pollutants fast enough. A small number of epidemiological studies are found in the literature, on the association between vegetation cover, and especially trees, and health benefits, in particular relating to respiratory health effects such as development of asthma, wheeze, rhinitis and allergic sensitization (Lovasi et al., 2008). However, the same author finds in subsequent research the contradictory evidence that trees were associated with a higher prevalence of asthma and childhood allergic sensitization to tree pollens (Lovasi et al., 2013). Strategic planting is important since blind planting based on aesthetic appeal and not the greatest air quality effects may contribute to increased health problems in the population.

It is therefore important to examine the influence of trees on such locations, particularly because air quality is significantly compromised due to increased energy consumption and traffic-induced emissions. This involves collecting field measurements to investigate the effects of different street configurations containing varying vegetation levels to quantify the overall effect of vegetation on street scale pollutant concentration.

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Water

2. Water

Urban surface water refers to rainwater that falls on city surfaces, including ground, streets, roofs, parks, and gardens (GLA, 2015b). Surface water runoff, or stormwater runoff, is surface water before it enters a watercourse, drainage system or public sewer (Defra, 2010a). Surface Water Management (SWM) is the management of surface water flood risk by employing a combination of structural and non-structural measures (Walesh, 1989). The Department for Environment, Food and Rural Affairs (Defra) defines surface water flooding as 'flooding from sewers, drains, groundwater, and runoff from land, small water courses and ditches that occurs as result of heavy rainfall' (Defra, 2010b). SWM aims to reduce flooding by storing or infiltrating rain where it falls, and slowing down the flow of surface water to reduce downstream flooding. SWM addresses water quality issues by removing surface water pollutants in order to improve the health of rivers and other water bodies; as well as alleviating the impacts of drought by retaining and harvesting rainwater for later use.

In cities such as London, changes in landscape due to urban development can increase flood risks and exacerbate water pollution (GLA, 2015b). London is a region of high water stress, meaning that demand for water is a high proportion of the water that is available from rainfall (EA, 2013a). This problem is particularly acute during times of drought, when rainfall is below average for an extended period. Green infrastructure based approaches to urban drainage can bring solutions to the urban surface water problems of flooding and water pollution.

What is the problem?

Unlike the ground surfaces in natural environments, urban surfaces tend to be impervious and have less vegetation cover. In conventional urban surface water management, the runoff is drained away from urban surfaces as quickly as possible using engineered drains, sewers and channels. This infrastructure is typically buried below ground, so that maintenance is difficult, problems can go unseen and people have limited knowledge of where water flows in the city. These drainage networks result in high volumes of polluted runoff that is discharged to receiving water bodies or transferred to sewage treatment works. Urban runoff may carry high phosphorus and nitrogen loads that can contribute to pollution of water bodies and lead to algal blooms and ecological imbalances. Toxic metals as well as bacteria and pathogens may also be present in high concentration in urban runoff, which can impair the aquatic habitat as well as impact human health (Erickson et al., 2013).

Population growth will increase stress on local water resources and the volume of wastewater flowing through the sewers. Construction of new homes, schools and infrastructure could add further pressure on the drainage system by reducing permeable surfaces and increasing the volume of stormwater runoff (GLA, 2016b).

The sewerage network in central London is mostly a combined sewer system, where household and industrial wastewater is combined together with surface water runoff in a single pipe system to be conveyed to sewage treatment plants (CIWEM, 2004). While a separate piped system for each type of flow has become the norm for newer development in outer London, the combined system dominated the network up until mid-20th century.

While the combined sewage system functions well under normal conditions, problems arise when the volume of water in the sewers exceeds their capacity. This usually occurs during a heavy storm event, when surface water runoff fills the sewers. The result is that the sewers overflow into local rivers, such as the Lea and the Thames, discharging untreated stormwater and wastewater into the environment (US EPA, 2016). The process described is called Combined Sewer Overflow (CSO), and it acts as an emergency discharge valve that prevents bursting of pipes or backflow during prolonged or heavy rainfall. Currently in London CSO discharge occurs more than 50 times a year, and on average 20 million tonnes of untreated sewage is discharged into the Tidal River Thames (ICE, 2016). CSO discharge can contain high levels of suspended solids, pathogenic microorganisms, toxic pollutants, oxygen-demanding organic compounds, oil and grease, and other pollutants (United States Environmental Protection Agency, 1994).

In London the Tideway Tunnel is under construction as the primary solution to CSOs. This project commenced construction in 2017 and is due to be completed by 2023, at an estimated cost of £4.1 billion. It will involve a 25km long 'super-sewer' running from Acton, under the Thames to Beckton. Water from CSOs will overflow into the tunnel to be stored and transferred for treatment at the Beckton sewage treatment works, instead of overflowing into the river. This 'grey infrastructure' solution will improve the safety, ecology and aesthetics of the River Thames, but it will be complemented by green infrastructure to achieve multiple benefits for surface water management and to improve sewer capacity across London.

Parts of London are at high risk of surface water flooding, which occurs when rain falls faster than it can drain away or soak into the ground. Surface water flooding can occur very quickly in heavy storm events without adequate drainage or space for water to flow in to, leading to flash flooding. Areas that are close to the route of London's 'lost rivers', such as the Fleet, the Effra, and the Westbourne, are prone to surface water flooding due to the natural topography of the landscape. In combined sewer areas, surface water flooding is more likely where sewers are operating close to capacity, with little room to convey additional water from runoff.

Climate change is predicted to increase the intensity of rain storm events in London, leading to increased surface water runoff during storms (Forest Research, 2010a). Furthermore, flooding can cause health and safety hazards, economic losses and inconvenience to local residents and businesses (Susdrain, 2016).

How can green infrastructure help?

On the city and catchment scale, a network of green infrastructure can improve overall water quality and maintain stream form and function (US EPA, 2017). In the UK, Sustainable Drainage Systems (SuDS) is an approach used to manage surface water that aims to mimic natural hydrology and minimise surface water runoff into sewers and drains (Woods Ballard et al., 2015). SuDS is considered 'green' infrastructure, or sometimes 'blue' infrastructure as its main function is water management (Wilebore & Wentworth, 2013). The techniques used include both natural and artificial components in the design.

Properly functioning SuDS will have the ability to:

1. Mimic natural infiltration to delay and reduce discharges and reduce concentration/volume of pollutants
2. Attenuate peak surface water flows to reduce flood risks
3. Capture and store stormwater for future uses

By incorporating green infrastructure in the drainage system, rainwater can be retained and re-harvested while surface water runoff can be reduced. This alleviates the stress on the piped sewage system and reduces the frequency and volume of sewer flooding and CSOs. At the catchment scale the health and function of rivers and streams can be restored and maintained. SuDS may include natural green spaces, as well as semi-natural spaces such as rain gardens, bioswales, planter boxes and bioretention ponds. In addition, 'grey' measures such as permeable pavements and downspout disconnection are also used in sustainable drainage systems.

Green infrastructure installed as part of sustainable drainage systems and natural flood risk management approaches can control the quantity and speed of stormwater runoff and thereby manage the impact of flooding on people and the environment (The Wildlife Trust, n.d.). Contrary to conventional drainage systems that are designed exclusively for conveyance of stormwater runoff to the downstream, green infrastructure techniques can be used to help capture, use, retain, and delay discharge of rainwater (GLA, 2015b).

Retaining rainwater may be used in sustainable drainage systems to slow down surface water runoff and can have additional benefits to water supply. Rainwater harvesting provides temporary, local storage of water that can be reused instead of running off into the sewer. Infiltration of rainwater into the ground, instead of running off, can replenish ground water supplies and soil moisture.

Green infrastructure has the ability to physically remove and chemically or biologically treat pollutants from stormwater runoff using soils and vegetation. Vegetated surfaces not only can reduce runoff volume, they also can provide some treatment to the stormwater by removing sediments and pollutants from the still or slow-moving water. While certain measures, such as green roofs and urban canopies, can perform sediment trapping alone or in combination with other techniques, bio-retention systems (such as bio-swale, raingarden, planter box, anaerobic bio-retention), ponds and wetlands are generally implemented when reduction in pollutant load is needed in stormwater management.

There is a wide range of water quality treatment processes that can be designed into a green infrastructure. Most commonly the effectiveness of treatment is linked to the velocity control, retention time, choice of plant species and the filtration media used (Payne et al., 2014; Woods Ballard et al., 2015). Sedimentation and filtration usually occur by slowing down the runoff flow, allowing sediments and particulate-bound pollutants to be removed; while dissolved contaminants may require a combination of settling, adsorption, and other biochemical processes. In addition, nutrients, metals, and other organic pollutants can be absorbed by plants, especially in ponds and wetlands. To manage surface water as well as groundwater pollution risks, green infrastructure can provide natural treatment by reducing the pollutants to environmentally acceptable levels, though the effectiveness of treatment varies depending on the specific component used as well as the specific pollutants needing to be removed.

Green roofs and walls

Roofs can account for 40-50% of impermeable surfaces in an urban area, therefore there are major opportunities in reducing runoff by retrofitting roofs (Lamond et al., 2015). Green roofs can reduce runoff volume by intercepting and retaining rainwater in the vegetation and soil, as well as evaporation and transpiration of precipitation (European Commission, 2012).

There are two main types of green roofs. Extensive roofs consist of shallow growing medium of three to six inches that can support shallow rooted or short plants, and are rather inexpensive to install and usually inaccessible to the public; while intensive roofs have thicker (more than six inches) growing medium and are capable of supporting a greater variety and size of plants (GSA, 2011; Murphy, 2015). When choosing the type of green roof, the irrigation and growth needs of the vegetation, as well as the loading on the roof structure must also be taken into consideration (Woods Ballard et al., 2015).

In a study by Gill et al. (2007), the surface runoff model predicted that by adding green roofs to all buildings in town centres, retail, and high density residential areas in Greater Manchester, the runoff for an 18mm rainfall event is reduced by 17.0-19.9%, and for the 28mm event by 11.8-14.1%. The performance of green roofs in reducing runoff frequencies and volume depends on depth of the substrate and its degree of saturation, the slope of roof, and the type of vegetation, and the attenuation effects will reduce as the duration and depth of storm increases (Woods Ballard et al., 2015; European Commission, 2012). Figure 2 presents a summary of available evidence of the performance of green roofs in runoff interception as a function of substrate depth.

Reference	Interception provided by green roofs[1]	Substrate depth
GSA (2011)	12.5 – 19 mm (USA)	Substrate depth 75 – 100 mm
Stovin et al. (2012)	About 12 – 15 mm (estimated based on 100% retention of rainfall for 1:1 year, 1 hour event in Sheffield, UK and 72% retention for 1:1 year 24 hour event)	80 mm substrate
Fassman-Beck and Simcock (2013)	About 20 mm (most frequent result was 0 mm runoff for events up to 20 mm)	100 - 150 mm substrate
Paudel (2009)	16.5 mm (Detroit, Michigan, USA)	100 mm substrate
Martin (2008)	About 10 mm (Ontario, Canada)	100 mm substrate

[1] I.e. no runoff for majority of events up to these depths.

Figure 2: Performance of green roofs in runoff interception as a function of substrate depth (Woods Ballard et al., 2015)

The efficiency in runoff retention and reduction of peak flow also depends on seasonal change (temperature), amount of rainfall, duration of storm, how long since last storm, as well as the roof size (GSA, 2011). The highest retention rates have been recorded in the summer, when storms tend to be shorter and the soil moisture deficit tends to be higher (GSA, 2011; Woods Ballard et al., 2015). The study by GSA (2011) has shown that a 75,000 square foot green roof on a Walmart in Chicago was able to delay peak runoff for nearly two hours, which was longer than what was observed with smaller sized green roofs.

In terms of treatment of pollutants in the runoff, green roofs' performance could vary. In areas where acid rain (precipitation with pH below 5.6) is a common problem, the growth medium (pH from 7 to 8) of the green roofs can neutralise the acid rain for 10 years or more (GSA, 2011). By reducing the volume of runoff and through a series of physical, biological, and chemical processes, the amount of pollutants (sediments, organic compounds, heavy metals) in the rainwater can be reduced (Woods Ballard et al., 2015; Ahmed, 2011). However, there are mixed results regarding the green roofs' ability to reduce pollution level in the runoff. Green roofs may become a source of pollution by releasing nutrient pollutants such as nitrogen and phosphorus from the growth medium or fertilizer to the runoff, but a study has shown that improvement could be made by including 7% biochar in the growth medium (Barr et al., 2017; GSA, 2011; Lamond et al., 2015).

Green walls or living walls are those covered in some form of vegetation such as climbing plants. They include traditional green walls such as those covered in ivy, wall ferns and spleenworts, as well as more intensely designed and engineered structures that include irrigation systems. They could provide various benefits such as thermal insulation, cooling benefits to the building, noise attenuation, and biodiversity; but there is lack of evidence in their contribution towards storm peak attenuation (Design for London et al., 2008). Green walls that are not properly managed can damage the wall surface and structure. Maintenance of green walls is a very important consideration in their long-term effectiveness and viability.

Rainwater harvesting

Rainwater harvesting (RWH) is a green infrastructure system that can be used to collect runoff from roofs or surrounding surfaces within the boundary of a property before it reaches the ground, which is an advantage since one of RWH's main functions is to store rainwater for future uses (Woods Ballard et al., 2015). Collected water is usually stored in tanks, rain barrels, rainwater butts or cisterns, which can conserve water during dry periods, as well as ensure attenuation capacity by releasing the water before storms (GLA, 2015b; US EPA, 2017). The performance, however, will depend on the volume of storage provided and the design of the system (Lamond et al., 2015). If designed appropriately, runoff volumes from impermeable surfaces can be reduced by 37% to 77% depending on the storage size, and long term performance of rainwater harvesting systems is excellent (Blanc et al., 2012).

The water from RWH is mostly intended for non-potable uses, which includes irrigation, toilet flushing, car washing, etc., and appropriate treatment is usually applied. Depending on the intended purpose – residential or commercial use and water conservation or surface water management, design specifications such as tank and pump size are modified to suit the need (Woods Ballard et al., 2015).

Infiltration systems

An important step in stormwater runoff control is infiltration. Infiltration components are designed to mimic and enhance the natural infiltration process to reduce runoff rates and volumes, and their performance depends on the infiltration capacity (permeability) of the surrounding soils and the local groundwater level (Lamond et al., 2015; Woods Ballard et al., 2015). Areas where the water table is close to the surface or with impermeable soils such as London clay are unlikely to be suitable for infiltration measures. Infiltration components are designed to temporarily store runoff while allowing it to percolate into the ground, and may include soakaways, infiltration trenches, infiltration basins, infiltration blankets; while bio-retention systems as well as permeable pavement can be designed to allow infiltration from their bases (Blanc et al., 2012; Woods Ballard et al., 2015).

It is generally accepted that infiltration devices can contribute greatly to reducing stormwater runoff and increasing groundwater recharge, though the long-term performance and functionality are still uncertain (Blanc et al., 2012). There is strong evidence that infiltration devices can reduce surface runoff volume as well as attenuate runoff peaks, as shown in Figure 2. However, the performance of infiltration largely depends on the soil saturation and the level of the groundwater table prior to storm event, as well as seasonal changes in the hydraulic conductivity and seasonal groundwater level (Lamond et al., 2015; Blanc et al., 2012).

There is limited data on the performance of pollutant reduction, but properly designed and maintained infiltration systems should be able to remove a wide variety of pollutants in stormwater through chemical and bacterial degradation, sorption, and filtering (Minnesota Pollution Control Agency, 2016a). Based on the US National Pollutant Removal Performance Database (2000) prepared for the EPA Office of Science and Technology, the medium pollutant removal (%) of infiltration systems is the following: TSS (95), TP (70), Soluble P (85), TN (51), NOx (82), Cu (N/A), and Zn (99). For TSS, Soluble P, NO_X, and Zn, the data were based on fewer than five data points.

Permeable surfaces

London, as a highly urbanised metropolitan area, has a high proportion of impermeable surfaces (GLA, 2015b). Pervious surfaces and the associated subsurface structures are an efficient system to tackle this problem. These surfaces are suitable for pedestrian and/or vehicular traffic, and can be used to replace traditional impervious surfaces such as car parks, low-speed roads, sidewalks, patios, etc. (Woods Ballard et al., 2015; Minnesota Pollution Control Agency, 2016b). Pervious surfaces function by intercepting runoff, reducing the volume and frequency of runoff, and providing treatments through filtration, adsorption, biodegradation, and sedimentation (Woods Ballard et al., 2015).

Based on the materials used, there are two main types of pervious surfaces. Porous surfacing allows for infiltration across the entire surface material, and permeable surfacing usually are formed of material that is itself impervious to water but allows for infiltration through gaps in the surface. The materials most appropriate for a project should be decided by considering the expected traffic loadings, the visual appearance required, and the underlying soil conditions (Woods Ballard et al., 2015).

Compared to conventional materials, results from many studies suggest that pervious surfacing has positive results in reducing surface runoff volume (runoff reduction varied from 10% to 100%), and lowering and delaying total stormwater runoff peaks (peak flow reductions from 12% to 90%) (Blanc et al., 2012). The performance of the system varies from site to site, but in general the infiltration rate through the various layers of the system as well as the rainfall intensity are the major controlling factors. In addition, pervious pavements that are not properly installed or maintained are prone to clogging, which leads to reduction in system performance. When clogging occurs, there could be loss of 60% to 90% of the initial infiltration rate depending on the material used (Woods Ballard et al., 2015). Therefore, sedimentation control or pre-treatment from contributing areas should be required (Minnesota Pollution Control Agency, 2016b). Competent installation and adequate maintenance are important to maintain the performance of permeable pavements.

Filter strips and drains

Filter strips are vegetated gentle slopes designed to treat runoff from adjacent impermeable areas through sedimentation, filtration, and infiltration, and can often be used as a pre-treatment process before swales and bio-retention systems (Woods Ballard et al., 2015). In addition to slowing runoff velocities, well designed filter strips can effectively remove total suspended solids and total heavy metals. A study by Schmitt et al. (1999) investigating the performance of filter strips in relation to the vegetation and filter strip width revealed that the settling, infiltration, and dilution processes can account for the performance differences on the design's impacts on different contaminant types. Both 7.5m and 15m wide filter strips downslope can greatly reduce sediment concentrations in runoff (76-93%), as well as the concentration of contaminants that are strongly associated with sediment (as opposed to dissolved contaminants) (Schmitt et al., 1999). The reduction in dissolved contaminants concentration was largely due to dilution, while the reduction of contaminants mass exiting the filter strips was due to infiltration. It was also found in this study that doubling the filter strip width also doubled infiltration and dilution while sediment settling showed no improvement.

Filter drains are usually implemented downstream of a pre-treatment system such as filter strips, and these shallow trenches can help with peak attenuation as well as reduction in fine sediments, metals, hydrocarbons, and other pollutants (Woods Ballard et al., 2015).

Bio-retention systems

Bio-retention systems are shallow landscaped depressions that tend to have multiple benefits due to their attractive vegetated landscape features. In regard to surface water management, their main functions are reduction of runoff rates and volumes, as well as treatment of pollutants through the vegetation and soil (Woods Ballard et al., 2015). Rain gardens are less engineered than full bio-retention systems, and they can be designed as a small system to be used on a single property and are generally more flexible in size and design.

Studies have shown that correctly designed and maintained bio-retention systems can effectively remove pollutants (Roy-Poirier et al., 2010, Woods Ballard et al., 2015). Another study used synthetic runoff to test the performance of a rain garden installed in Bloomington, Minnesota. The synthetic runoff represents runoff volume from rainfall events up to 2.5 inches (6.35 cm) in depth, which accounts for 99% of rainfall events and 98% of the total precipitation depth in a normal year in the test area (Erickson & Gulliver, 2011). Since there was no outflow observed from the synthetic runoff events, the rain garden was expected to achieve 98% total volume reduction as well as capture or infiltrate at least 95% of dissolved phosphorus and total suspended solids. Once more it is difficult to directly compare across sites, but the performance of a rain garden or bio-retention system generally will depend on the permeability of the filter medium, vegetation used, the sizing, and other specifications such as pre-treatment when sediment loadings are high (Erickson & Gulliver, 2011; Hunt et al., 2012; Woods Ballard et al., 2015).

Detention basins

Detention basins are easy to construct and maintain landscape features that are usually either vegetated or hard-landscaped depressions designed to store and sometimes infiltrate rainwater (Woods Ballard et al., 2015; GLA, 2015b). The basin remains dry and is filled up with water during a storm event. Its primary function is peak flow reduction by delaying the runoff from being released to streams, while sediment and pollutant removal can be enhanced if detention period is prolonged and a permanent pool is added (Woods Ballard et al., 2015; Dauphin County Conservation District, 2013). Modelled results on the performance of a system of detention ponds revealed that without the system, peak discharge would be 48% to 50% higher in a given storm event (Lamond et al., 2015).

Swales

Swales are planted, flat bottomed, shallow channels designed to convey, treat, and attenuate surface water runoff. They can be used to drain roads, paths or parking lots, and can replace conventional pipework to convey runoff (Woods Ballard et al., 2015). Their main functions are reduction of total runoff volume and peak flows, and pollutants removal via filtration or sedimentation (Blanc et al., 2012; Stagge et al., 2012). The main types of swales are: standard conveyance swales, dry swales, and wet swales. The first two types are effective at runoff volume reduction, and all three types have good potential for peak flow reduction.

Studies on performance of swales have found that the mean volume reduction of runoff was reported from as low as 0% to as high as 87%, however any direct comparison across projects would be difficult since methodologies used for analysis and reporting were very different (Blanc et al., 2012). As for peak flow, a reduction of from 27% to 100% was reported by different studies, but again several assessment methodologies were used. Long-term performance is still uncertain, but it can be assumed that clogging due to aging of the structure and saturation levels of underlying soils may have a negative influence on performance.

Costs

Financial costs

Financial costs consist of one-off costs on research surveys and mapping, land purchase, and compensation to create, restore, and enhance green infrastructure features, as well as recurrent costs in maintenance and monitoring, evaluation, and communication activities (European Commission, 2012).

Costs and benefits analysis is needed for each project because the calculations vary according to the sites, specific problems addressed, the characteristics of the locality, and stakeholders involved. For example, the capital cost estimation could vary between sites due to different site conditions (e.g. land contamination, soil strength, high groundwater level, etc.) (WSP UK Ltd., 2013).

Some green infrastructure features require constant maintenance to ensure proper function, water quality management, and pollution prevention. However, maintenance of SuDS measures won't be excessive compared to traditional systems, but the approach will be different since the SuDS systems contain less pipe networks but more soft landscaping features (GLA, 2015b). Some systems are susceptible to clogging from sediments such as infiltration devices and permeable paving; in these cases pre-treatment should be considered and regular maintenance should be enforced.

Opportunity costs

Opportunity costs are the economic opportunities foregone as a result of green infrastructure, which would be higher at areas where there are high rates of development or productive agricultural land (European Commission, 2012). However, these costs are difficult to estimate since green infrastructure projects are often well integrated or dovetailed into other planning or architectural projects.

As a result, it is important to understand the benefits of green infrastructure. However, the benefits may be less quantifiable and more variable than the costs for various reasons. Moreover, the value of green infrastructure is assigned subjectively and can be influenced by people's background, cultural perception, and past experience with green infrastructure (Forest Research, 2010a).

Attraction to the green infrastructure sites can generate multiple other benefits, including economic benefits (Wilebore & Wentworth, 2013). However, due to the multi-functional nature of green infrastructure, there is difficulty in assigning costs and values to each service provided or benefit associated with each green infrastructure feature (GLA, 2015a). While some sustainable drainage benefits are quantifiable, such as improvement in water quantity and quality control, values of social benefits may be less obvious. In The SuDS Manual produced by CIRIA (2015), several costs of sustainable drainage are outlined. They include feasibility, appraisal and design costs, construction costs, operation and maintenance costs, monitoring costs for certain projects, end of life disposal and decommissioning costs, as well as costs avoided and opportunity costs. In addition to the cost and benefit analysis methods discussed in The SuDS Manual (2015), Defra and HM Treasury also provides a few supporting documents for how to assess costs and benefits.

Risks

Long term planning as well as careful and rigorous design, implementation, and maintenance are required in order to avoid improper functioning of the system. Moreover, the lack of proper maintenance may lead to health and safety risks. For example, fertilising vegetated surfaces such as green roofs and infiltration basins as well as the use of herbicides should be avoided or carried out with good care, to prevent contaminants from leaving the system or entering the groundwater. Green infrastructure systems need to be carefully monitored and maintained to ensure removal of pollutants and to avoid re-entrainment of pollutants during severe storm events. Pollutants captured by green infrastructure systems may be washed back into the environment, or re-released as plants die and decay if the system is not actively managed.

Furthermore, it should be recognised that not all green infrastructure techniques are suitable for surface water management in all sites. Constraints on ground permeability and saturation as well as groundwater vulnerability should be considered before deciding to use infiltration techniques (EA, 2013b). Other environmental factors should be taken into consideration as well, including neighbouring landscapes, seasonal variabilities, prevailing climate, length of any preceding dry period, and characteristics of a rain event (e.g. intensity, duration and temporal spacing of multiple events) (Blanc et al., 2012). A review of several US studies showed very wide variation in the performance of different green infrastructure components for reducing runoff and improving water quality, recommending that groups involved in implementing green infrastructure take a conservative approach in their estimation of benefits for surface water management (Driscoll et al., 2015).

Climate-proofing social housing landscapes in Hammersmith and Fulham

The London Borough of Hammersmith and Fulham, Groundwork and the office of the Mayor of London, supported by funding from the EU Life+ programme, implemented a programme of 'climate proofing' on three social housing estates – Queen Caroline Estate, Cheeseman's Terrace, and Richard Knight House and neighbouring houses (GLA, 2016a; Connop & Clough, 2016). The three estates cover an area of five hectares and are home to 700 households. All three estates are located in Critical Drainage Areas and are prone to localised surface water flooding.

A mix of SuDS measures were installed across project sites. Rain gardens, permeable paving, and green roofs are present in all three estates, while other measures (grassed basin, stony basin, swale, downpipe disconnection, gravel lawn, and trench tree pit) were installed in specific sites due to particular constraints. The SuDS measures are designed to drain an area of hard surfaces of 3,360 m^2 (0.3 hectares), and to hold 110 m^3 of water. The total cost for installation was £450K.

Monitoring devices were installed including time-lapse cameras, flow meters and weather stations, and showed that the installed systems performed well during storm events. From 16th October 2015 to 31st May 2016, ground level SuDS diverted 100% of the rainfall away from the storm drain system, and green roofs absorbed an average of 84 % of rainfall (estimated based on average attenuation for the five largest storm events during the monitoring period). From the sites monitored, the total value of rainfall retained and diverted away from the storm drain system was 479,300 litres, and the total across all sites was estimated to be 1,286,800 litres.

Find out more:

https://www.groundwork.org.uk/Sites/london/pages/lifeplus-lon

Residential de-paving in Kennington

Lambeth is a central London borough, characterised by highly urbanised areas served by Victorian sewer systems, and historically has been affected by flooding since 1911 (URS Infrastructure & Environment UK Limited, 2013a). Front gardens were de-paved at 50 and 60 Reedworth Street, Kennington (Susdrain, 2012; TfL, 2016). Reedworth is a residential street, consisting of social housing ranging from 1960s tower blocks to 1930s flats as well as a variety of local shops and businesses. The project aimed to increase the permeability of the front gardens and to demonstrate how this could be achieved without affecting car parking.

Sections of paving, concrete and tarmac were reduced and replaced with a permeable surface such as gravel or soil (URS Infrastructure & Environment UK Limited, 2013b). In agreement with the residents, two strips of paving slabs, or 40% of paving were removed. Lambeth Council provided basic materials, tools, and contractors to help the resident volunteers to de-pave their gardens. No other costs were incurred except for the volunteers' time and labour. Maintenance required only weeding and planting.

Find out more:

http://www.susdrain.org/case-studies/case_studies/kennington_residential_de-pave_retrofit_london.html

Figure 3: 50 Reedworth Street before and after de-paving (Susdrain, 2012)

Lost River Effra

The River Effra is one of London's 'lost rivers'. The source of the Effra is in Westow Park, Upper Norwood, and it ran through South London to discharge into the Thames at Vauxhall. The river was culverted and converted into a sewer in the nineteenth century as part of the construction of London's major sewers. It still forms part of the sewer network today, buried beneath streets, buildings and parks. Although it no longer functions as a river, the path of the Effra influences the local landscape and surface water flows. As a result, areas near the route of the river are more prone to surface water flooding than other places in the local region.

In 2013 the London Wildlife Trust was commissioned by the Department of Environment, Food and Rural Affairs (Defra) and the Carnegie Trust to empower local communities to create green infrastructure features to improve local neighbourhoods and resilience to climate change along the route of the lost River Effra. Thames Water, the Greater London Authority and Lambeth Council have provided further support for the project. Working with LWT, communities have installed green roofs and rain gardens, and de-paved surfaces to improve infiltration and provide new green spaces and habitats. The initiatives vary in scale, from individual planter boxes to restoration of the Ambrook, one of the original tributaries of the River Effra. The project demonstrated the value of reconnecting current community efforts to improve the urban environment through water management and local environmental history.

Find out more:

http://www.wildlondon.org.uk/lost-effra

Further information

Susdrain: **http://www.susdrain.org/**

London Sustainable Drainage Action Plan: **https://www.london.gov.uk/WHAT-WE-DO/environment/environment-publications/london-sustainable-drainage-action-plan**

Living with Rainwater: **http://www.wildlondon.org.uk/news/2014/12/15/living-rainwater-londoners-taking-simple-steps-reduce-flood-risk**

Biodiversity

3. Biodiversity

Biodiversity is defined as diversity within species, between species, and of ecological communities - ecosystems (Convention on Biological Diversity, 2015). The global decline in biodiversity has been strongly associated with, amongst other things, the rapid growth of human populations, natural habitat destruction, and increasing urbanisation (Grimm et al., 2008; Mcdonald et al., 2008; Dirzo et al., 2014; Newbold, 2015). Urbanisation in particular has been associated with declines in species richness, diversity and abundance of terrestrial species (Faeth et al., 2011). As the human population is projected to reach 9.7 billion by 2050 (UN-DESA, 2015), the conflict between humans and biodiversity will intensify (Hahs et al., 2009; Alberti, 2010).

Green infrastructure creates opportunities to preserve biodiversity in urban environments, and counteract some of the negative ecological impacts of urbanisation. Effective planning for biodiversity in cities relies on protective planning policies and the development of green infrastructure initiatives to maintain existing habitat and create new opportunities for biodiversity in urban areas (Norton et al., 2016). The importance of green infrastructure for preserving biodiversity has led it to be included as a critical part of the UK National Planning Policy Framework (Department for Communities and Local Government, 2012), and it also plays a significant role in globally meeting the Aichi targets set by the Convention on Biological Diversity strategic plan (2011-2020). While the development of green infrastructure has positive impacts on urban biodiversity, there is still a need to establish what types and characteristics of green infrastructure are most effective, and provide the greatest benefit (Snäll et al., 2016).

What is the problem?

Global shifts towards urbanisation will see at least 60% of the world's human population living in urban areas by 2030 (UN-DESA, 2016). In general, the development of urban environments is characterised by the transformation of natural green spaces into grey infrastructure comprised of substantial expanses of impervious surfaces (Aronson et al., 2014). As a result, urban biodiversity is typically restricted to highly fragmented, disturbed and degraded habitat patches. This leads to an overall reduction in native biodiversity (species richness and evenness), as the remaining habitat is unable to support complex ecological communities, due to disruption of ecological processes from lack of resources and barrier effects of grey infrastructure (Grimm et al., 2008; Shochat et al., 2010).

The ecological footprint of urbanisation often extends beyond municipal boundaries and impacts can be felt at regional and global scales (Grimm et al., 2008). Species may be differentially impacted by urbanisation, where species that are more sensitive to habitat loss and fragmentation will be most affected, including some amphibians (Hamer & McDonnell, 2008) and some bat species (Russo & Ancillotto, 2015). In contrast, more urban-tolerant species often increase in richness and abundance (Francis & Chadwick, 2012). This means that ecological communities within urban areas often show overall patterns of low species richness but high abundance, reflecting increases in populations of urban-tolerant species and a loss of sensitive species (Faeth et al., 2011). Non-native species (species outside their native geographic range), often occur in urban areas and have an additional impact on native wildlife in urban ecosystems through competition for resources with native species, predation, disease transmission, and habitat alteration (Manchester & Bullock, 2000).

Conserving urban biodiversity and maintaining the ecological integrity of urban ecosystems is important to the provision of many vital ecosystem services. Loss of urban biodiversity is also leading to the 'extinction of experience' for people living in urban areas due to a lack of interaction with the natural world. Disconnection from nature can result in apathy towards wider environmental issues (Miller, 2005). As human populations become more urbanised, it will be increasingly difficult for people to interact with nearby nature, and there will be considerable conflict between developers and conservationists over use of increasingly valuable land in cities.

How can green infrastructure help?

Although biodiversity in urban areas faces numerous challenges, the level of predicted global urbanisation provides restoration opportunities through the provision of well-designed and implemented green infrastructure, creating biodiversity ‘hotspots’ within human-dominated environments (Farinha-Marques et al., 2011). Green infrastructure is generally understood to support urban biodiversity by providing vegetated natural and semi-natural habitats and increasing habitat connectivity allowing species to move through the urban environment (Forest Research, 2010a). There are numerous types of urban green infrastructure as reviewed in Braquinho et al. (2015). The National Ecosystem Assessment presents the state of urban green infrastructure in relation to biodiversity (Davies et al., 2011) and the London Mayor’s 2002 Biodiversity Strategy describes the specific types of green infrastructure that characterise London (GLA, 2002). Some of the more common types of urban green infrastructure in London are discussed below.

Semi-natural green spaces

Semi-natural green spaces are the remnants of natural land cover that remain after urban development and include habitats such as woodland, wetland, grassland and heathland. Typically, these green spaces are managed with biodiversity as a high priority and may or may not be designated as nature reserves. In London, these sites form the majority of the 1,574 Sites of Importance for Nature Conservation (SINCs) that were originally identified in policy in 1985 (Greater London Council & Department of Transportation and Development, 1985). Information on priority habitats for biodiversity in London is held by GiGL (**http://www.gigl.org.uk/london-bap-priority-habitats/**). Hampstead Heath provides an example of a semi-natural green infrastructure site and is characterised by large areas of both dense woodland and open grassland with a number of large ponds. A number of nationally protected species have been recorded at Hampstead Heath including seven species of bats, numerous bird species and stag beetles. The site has been designated a Site of Metropolitan Importance for Nature Conservation, and a section of the site has been designated as a Site of Special Scientific Interest (City of London & Land Use Consultants, 2008).

Parks and commons

Parks can act as important refuges for species sensitive to urbanisation, such as bumblebees (McFrederick & LeBuhn, 2006) and amphibians (Hamer & McDonnell, 2008). However, parks can differ significantly in ecological value due their habitat composition and complexity, as well as their management regimes (CABE Space, 2006a). Some parks in London have been designated as SINCs and therefore are managed with biodiversity as a high priority. The size of urban parks is also positively correlated with increasing biodiversity. Larger parks can comprise a vast mosaic of different habitats, providing resources and refuges for a large number of species, and are therefore more beneficial for urban species richness (Aida et al., 2016). Small parks can act as vital ‘stepping-stones’ or ‘corridors’ between larger, isolated urban habitats (Cornelis & Hermy, 2004), allowing species to move and disperse between sites, thereby improving connectivity between sites (Beninde et al., 2015). As pressure for development on larger areas of land intensifies with increasing urban populations, land for the creation of new large urban parks is scarce, and strategies to conserve biodiversity must therefore focus on preserving existing large urban parks and improving the ability for species to move between these large habitat patches through the creation of green corridors (Beninde et al., 2015). This has been policy and practice in London since 1985 (Greater London Council & Department of Transportation and Development, 1985). Regent’s Park in the London Borough of Camden is an example of a large urban park in London. It is heavily managed, consisting mainly of mown grassland and planted flowerbeds. However, the park has been found to support a small population of hedgehogs, a UK Biodiversity Action Plan Species (The Royal Parks, 2017).

Domestic gardens

In many cities, a large proportion of green infrastructure is comprised of domestic garden space. London is no exception and 24% of the Greater London area is estimated to be private, domestic garden space (Smith et al., 2010). However, only 14% of this land is estimated to be vegetated (lawn, tree canopy, other vegetation). Between 1998 and 2007, 3,000 ha of vegetated land cover was lost from London’s gardens. A number of citizen science biodiversity monitoring schemes have focussed on the potential of domestic gardens to provide habitat for wildlife, such as the British Ornithological Organisation’s Garden BirdWatch (**https://www.bto.org/volunteer-surveys/gbw**) and the RSPB’s Big Garden Birdwatch (**https://ww2.rspb.org.uk/get-involved/**

activities/birdwatch). In addition, the RSPB's 'Homes for Nature' Initiative encourages homeowners to alter their gardens to support greater biodiversity by adding features such as bird feeders, nest boxes, garden ponds and compost heaps. Urban parks and gardens provide key areas for human-biodiversity interactions that are crucial in combatting the 'extinction of experience' and promoting a connection to nature and also afford opportunities for environmental education and citizen science (Gaston et al., 2007; Palliwoda et al., 2017).

Urban waterways

Urban waterways, such as rivers, streams, canals, lakes and ponds are not only fundamental to the existence of freshwater biodiversity in urban areas, but they also support terrestrial biodiversity. Urban waterways act as corridors in heavily built-up environments and provide key foraging areas for many species including bats (Lintott et al., 2015). In London, urban waterways have historically been focussed on human uses, and management of their biodiversity was neglected up to the 1990s. The Environment Agency has since led a renaissance of enhancement works, captured by many partners in the London Rivers Action Plan (GLA et al., 2009) and given further impetus through the Water Framework Directive (JNCC & Defra, 2010). Restoration of urban waterways includes reconfiguration of channels, bank stabilisation, replanting of riparian vegetation and stormwater management (Bernhardt & Palmer, 2007). Funk et al. (2009) indicated that extending and enhancing existing water channels, and improving groundwater connectivity would have a positive impact on freshwater biodiversity, increasing mollusc and dragonfly abundance and species richness, which is the prime focus of the London Wildlife Trust's Water for Wildlife programme (**http://www.wildlondon.org.uk/water-for-wildlife**).

Green roofs and walls

Green roofs now number over 700 in central London alone (GLA, 2017a) and there exists a body of evidence for how they perform for biodiversity (Williams et al., 2014). In comparison, biodiverse walls have a much shorter history of use in London and there exists much less evidence on their ecological performance. Therefore, these features are discussed together in the following section as the lack of information on wall features precludes any further comparison with roof features. A range of terminology is used to describe these design features including biodiverse, green, vegetated and living roofs/walls. Due to the focus of this report on green infrastructure, we refer to these features as green roofs/walls.

Where competition for space is high, green roofs and walls provide alternatives for the creation of urban biodiversity habitats (Francis & Lorimer, 2011). Green roofs can vary considerably in their design, with extensive roofs typically consisting of shallow substrate and low-lying vegetation while intensive roofs typically consist of deeper substrate and more complex vegetation structures (Braquinho et al., 2015). In addition, brown roofs typically use rocky substrate to create habitats similar to brownfield sites (Bates et al., 2015). The majority of green roofs in the UK are installed in London (42%) (Moulton & Gedge, 2017) which is driven by London's specific green roof planning policies (GLA, 2016c). Green walls are essentially green roofs in a vertical orientation, and more commonly contain climbing plants or require greater structure to provide a substrate for plants to grow (GLA, 2008). Green roofs and walls are generally inaccessible to the public, leaving them relatively undisturbed compared to other types of green infrastructure. The availability of undisturbed habitat is vital for many species including microorganisms, insects and nesting birds (Getter & Rowe, 2006; Oberndorfer et al., 2007). Green roofs and walls can facilitate species dispersal and movement through urban landscapes (Williams et al., 2014). They can be designed to provide specific ecological functions that may be missing in surrounding urban environments, such as planting high nectar yielding plants (e.g. thyme) for pollinators, or providing nesting sites for birds and bats (GLA, 2008).

Despite the potential benefits of utilising green roofs or walls for urban biodiversity, most investigations have not explicitly examined this. For example, a review of green roof projects by Williams et al. (2014) found that only 8% of a total of 1,824 projects formerly assessed cited aims for biodiversity conservation or mentioned any related benefits to urban biodiversity. In the few ecological studies that have focussed on the biodiversity impacts of biodiverse roofs and walls, evidence suggests that green roofs support greater biodiversity than conventional roofs and provide habitat for generalist and some rare species including black redstarts (Baumann, 2006) and bee species of conservation significance (Brenneisen, 2006). Green roofs are particularly important for habitat provision for invertebrates, for example 136 different species of invertebrate were found in just 8 London green roofs (Jones, 2002), and specifically 59 species of spiders (9% of the UK total) were found in just 10 green roofs (Kadas, 2006). However, it is important to caution that recorded presence of a species on green roofs may only establish the species ability to disperse there and does not necessarily indicate that the species benefits in any way from the presence of the structure. It is currently unclear whether green roofs and walls can support similar levels of biodiversity to ground level green infrastructure or replicate ground level communities.

Grass verges

Grass verges are an often overlooked example of green infrastructure, but potentially play an important role in habitat connectivity, due to their spatial extent and ubiquity. If planted with suitable vegetation these spaces can provide valuable habitat for pollinators (Hopwood, 2013). Due to their proximity to road traffic they are also well placed to provide other ecosystem services, including air quality enhancement, carbon sequestration and noise reduction (O'Sullivan et al., 2017). However, their proximity to roads can make them unsuitable habitat for some species due to elevated levels of noise, light and air pollution.

Artificial structures

There is growing recognition of the potential of 'greening' existing 'grey' infrastructure such as roads, railways, bridges and garden walls to provide extra habitat for biodiversity in cities (see University of Glasgow-led NERC-funded project 'A Decision Framework for Integrated Green Grey Infrastructure'). Artificial structures can provide extra habitat in cities for nesting, feeding and movement with design features such as nest boxes, feeding structures and artificial corridors. Artificial corridors are more common in Northern Europe and America to facilitate the movement of large mammals. However, small-scale artificial nesting and feeding habitats are commonly used in domestic gardens in the UK, the use of which has recently been promoted by the RSBP's 'Homes of Nature' initiative. Such features have also been designed into a number of larger-scale green infrastructure projects in London. For example, a range of artificial biodiversity habitat structures have been integrated onto grey infrastructure at the Queen Elizabeth Olympic Park as part of the site's Biodiversity Action Plan (London Legacy Development Corporation, 2013). Installations or modifications to human-made structures and buildings on the site include bird boxes, bat boxes and voids, bee hotels, insect boxes and habitat walls. The current challenge for park managers is to understand whether these artificial structures are being used by wildlife, and this challenge is being tackled with traditional and innovative biodiversity assessment at the site (see the Nature-Smart Cities project, **www.naturesmartcities.com**). There is currently a lack of evidence for how well artificial structures are used by wildlife, and monitoring is essential to understand how best to design them for biodiversity (Bat Conservation Trust, 2017).

Costs

Economic costs

Public funding for maintaining urban green spaces has been cut significantly since 1979 (CABE Space, 2006b) which has led to a decline in the condition and accessibility of urban green infrastructure in the UK (Davies et al., 2011). Unfortunately, green infrastructure is not a statutory service, meaning local authorities are not legally required to provide it. In local authorities with shrinking budgets other statutory services such as waste management have been maintained while funding for green infrastructure management has declined. In relation to the management of green infrastructure for biodiversity, the horticultural skills within local authorities has also been in decline, meaning that the professionals responsible for managing green infrastructure do not necessarily have the skills to manage appropriately for biodiversity. A review of the UK's parks recently concluded that numbers of park staff have been declining over the past few years (Heritage Lottery Fund, 2016). In addition, many local authorities have over-stretched or non-existent in-house ecological expertise (UK Parliament, 2013) which hinders the ability of local authorities to manage green infrastructure appropriately for biodiversity.

As the public fiscal support for green infrastructure declines, other economic models have been developing. Volunteers play an increasingly important role in the maintenance and stewardship of urban green spaces in London. Organisations such as The Conservation Volunteers (TCV, **www.tcv.org.uk**) are responsible for the management of a number of green spaces in London, and coordinate a network of volunteers to support the on-going maintenance of many of London's green spaces. Mixed models of public, private, trust and charity partnerships are an alternative means of funding green infrastructure development and management (CABE Space, 2006b; Wallis, 2015). Large-scale projects, such as Walthamstow Wetlands (see case study), receive financial support from multiple sources, making it possible to develop large green infrastructure projects that would probably be unfeasible within the budgets of local authorities. Greater reliance on philanthropy to fund green infrastructure development and long-term management, similar to philanthropic models popular in the US, has been proposed as another alternative funding model for urban green space in the UK (GLA, 2015a).

Biodiversity dis-benefits

There is a lack of literature addressing the negative aspects of increased biodiversity, and yet it is important to consider these potential costs or 'ecosystem disservices' when implementing urban green infrastructure (Lyytimäki & Sipilä, 2009). Direct costs of urban biodiversity are mainly focussed on damage to physical structures, such as tree roots damaging roads and pavements, bird excrement causing corrosion of metal structures and acceleration of decomposition of wooden structures due to increased microbial activity. Economic losses can also be incurred through pest damage to garden plants and allotment crops, and through the cost of controlling such pests (Baker & Harris, 2007). Urban biodiversity costs are incredibly difficult to value and predict, as damage can vary considerably within and among cities, depending on the type of green infrastructure and the species present (Lyytimäki & Sipilä, 2009). However, in London these costs are mainly associated with a small number of invasive species such as Japanese knotweed (*Fallopia japonica*), buddleia (*Buddleja* spp.) and the Chinese mitten crab (*Eriocheir sinensis*). The London Invasive Species Initiative (**www.londonisi.org.uk/**) works to reduce the environmental and economic problems caused by invasive species in London.

Risks

Green infrastructure may not always be as valuable to urban biodiversity as is often portrayed. There is uncertainty over whether any particular green infrastructure component, in and of itself, necessarily supports biodiversity in any significant way (Hostetler et al., 2011). Further research is required to assess the ecological value of different types of green infrastructure, particularly newer structures such as green walls, as well as the features of green infrastructure that are most beneficial to biodiversity including connectivity, habitat size and habitat quality. It will be important to consider these factors when designing green infrastructure for biodiversity, to meet targets and have a significant impact on urban biodiversity levels.

Currently there is a risk that the focus on green infrastructure could act as a conceptual trap that may divert funding from more specific conservation actions that could provide better outcomes for urban biodiversity (Garmendia et al., 2016). Conserving and monitoring urban biodiversity is likely to require long-term investment and immediate results are unlikely, and this should be reflected in the planning process. To be effective for biodiversity in the long-term, urban green infrastructure will in many cases require a systems-based approach, including the engagement of local communities and the complementary management of built areas (Hostetler et al., 2011).

Central to the concept of green infrastructure is a multi-functional planning approach with multiple goals beyond just biodiversity conservation (Garmendia et al., 2016). Seeking to achieve multiple goals in green infrastructure planning involves trade-offs (Maes et al., 2015) and achieving biodiversity conservation or avoiding negative biodiversity impacts may not always be possible (Hirsch et al., 2011; Redpath et al., 2013). The goals of any given green infrastructure project may not include biodiversity conservation, nor should it necessarily require it. However, the implications of not considering biodiversity in a green infrastructure project need to be considered and justified. Urban planners need to promote urban green infrastructure that provides multiple functions including direct human benefits (e.g. outdoor sports facilities and amenity green space), storm water management and air quality regulation alongside supporting biodiversity.

201 Bishopsgate

A new build development in the City of London, 201 Bishopsgate was designed to incorporate an extensive biodiverse roof specifically aimed at promoting high levels of biodiversity (City of London Corporation, 2011). The biodiverse roof was completed in 2009 and has a total area of 2,200 m^2 with 34% vegetation coverage. The initial plan was to plant a basic sedum roof containing only 12 plant species, however this was expanded late in development to include another 20 species of wildflower to increase the ecological value of the biodiverse roof. It was hoped the roof would provide foraging habitat for bats, house sparrows, house martins and swifts. The roof has already shown good potential for wildlife, with multiple bee, butterfly and hoverfly species recorded in its first year. Black redstarts have also been recorded in the surrounding roof area and it is thought that they use the roof for foraging. This project also had the additional benefit of improving the aesthetic quality of the building to the surrounding overlooking buildings.

London Ecology Masterplan

Individual small-scale green infrastructure projects are valuable, but larger-scale initiatives are required to increase overall habitat area and habitat connectivity. In 2015, the Crown Estate launched an initiative known as the London Ecology Masterplan (**www.wildwestend.london**). The main focus of the project is to establish a green corridor through the west end of London linking St James' Park and Regent's Park. A corridor of significant patches of green infrastructure (100 m^2 or larger) with a maximum separation between patches of 100 m has been delineated. The aim of the project is to create a series of sites of high ecological value, acting as green stepping stones that provide a range of habitats for plants and insects, as well as nesting and foraging areas for birds. This should enable wildlife to move more freely between two of the major urban parks in London. This project will include the installation of a variety of green infrastructure including: biodiverse roofs and walls, community gardens and pocket habitats as well as installing bird boxes, bat boxes and beehives. This project will involve long-term monitoring of biodiversity to assess the project's success and has begun with baseline bat and bird surveys prior to the commencement of development. The London Ecology Masterplan has now led to the Crown Estate collaborating with other West End property owners to launch the Wild West End project to further promote biodiversity in the surrounding area.

Walthamstow Wetlands

Walthamstow Wetlands (**www.walthamstowwetlands.com**) is Europe's largest urban wetlands site. This large-scale urban green infrastructure regeneration project has restored the habitat of a 211 ha fully operational reservoir site owned by Thames Water to a valuable habitat for local and migratory wildlife. In October 2017 it was made publically accessible and offers a Visitor Centre, café and viewing platform. The regeneration project was funded through a public-private-charity partnership between the Heritage Lottery Fund, Thames Water, the London Borough of Waltham Forest, London Wildlife Trust and the GLA.

Crane Valley Restoration Project

The Crane Valley Project is a large-scale river restoration project to restore the habitat and improve accessibility of the 66 km River Crane Thames tributary. With support from five London boroughs, public, voluntary and private stakeholders, the London Wildlife Trust are leading on a wide range of works aimed at restoring the river. In 2013, the London Wildlife Trust published the Crane Valley Catchment Plan (London Wildlife Trust, 2013) which identified the five main issues affecting the river as invasive species, heavily modified channels, pollution, flooding risk and restricted access. Ongoing projects along the River Crane are tackling these issues, including invasive species removal, river and floodplain enhancement, meander restoration, and assessment of the ability of fish to pass the river catchment.

Health and Wellbeing

4. Health and Wellbeing

While green infrastructure has documented benefits on biodiversity, drainage, flood prevention and air quality (Rolls & Sunderland, 2014), it has also been linked to positive effects on human health and wellbeing (Morris, 2003b). The World Health Organisation defines health as 'a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity' (WHO, 2017). Health can be divided into three concepts: physical, mental and social (Naylor et al., 2016). The natural environment is considered to be beneficial for all aspects of human health, and is often used as a quality of life indicator (Fuller & Gaston, 2009), prompting a UK government initiative to provide cleaner, safer and greener public spaces (Morris, 2003b). However, the strength of this association has yet to be fully established and the perceived positive association is purely correlative; identifying causal mechanisms is particularly challenging and understudied (Keniger et al., 2013).

What is the problem?

There is a global demographic trend towards urbanisation, with 69.6% of the population expected to live in urban environments by 2050 (U.N., 2015) leading to greater isolation and disconnection from nature (Fuller et al., 2007; Gaston et al., 2007). The Department for Environment and Rural Affairs (Defra) noted a greater association for ill health in urban communities, relative to rural (Hunt et al., 2000; Defra, 2002, 2003). Urban populations display a higher incidence of illness, including coronary heart disease (CHD), asthma, dementia, and depression (Hunt et al., 2000).

London is the third largest city in Europe, with a population of 8.6 million (GLA, 2015a). London has many serious health concerns; for example, it has the highest rate of childhood obesity of any major global city (London Health Commission, 2014) and, compared to other regions of the UK, has the largest proportion of the population reporting high levels of anxiety (GLA, 2014).

Physical health

Urban residents face several unique health challenges, including high levels of air pollution. Research on the Global Burden of Disease for the WHO in 2010 found that 48,016 deaths in the UK were attributed to air pollution (Murray et al., 2012). Defra estimate air pollution costs the UK £8.6 to £18.6m per annum through hospital admission and reduced life expectancies (Defra, 2010c). Urban residents face additional threats due to the urban heat island effect, as prolonged periods of high temperature can result in excess deaths, particularly in the elderly and infirm (Met Office, 2012; GLA, 2015a).

Physical inactivity is a major contributor to many health conditions, including coronary heart disease (CHD), obesity, type-2 diabetes, and mental health problems (Rolls & Sunderland, 2014). The WHO estimates 31% of adults over the age 16 are insufficiently active, leading to 3.2 million deaths a year. Inner cities and poorer and disadvantaged populations report lower participation in outdoor recreational activities (Lee & Maheswaran, 2011; Hillsdon et al., 2008).

In London, 1.8 million adults report they do less than 30 minutes of moderately intense physical activity a week, leading to problems such as CHD and obesity (London Health Commission, 2014). It is estimated 3.8 million Londoners are overweight or obese, including more than 1 in 4 under the age of six. Reports indicate that an increase in levels of physical activity could prevent the deaths of up to 4,100 Londoners a year (London Health Commission, 2014) yet only 13% of Londoners walk or cycle to work, despite 50% living in close proximity to their workplace (GLA, 2015a).

Mental health

Mental ill health is the leading cause of disability in the UK, with 1 in 4 adults a year suffering from a form of mental illness (McManus et al., 2009). Poor mental health can affect an individual's education, employment, physical health and personal relationships (GLA, 2014). The economic costs of mental ill-health in the UK total approximately £105 billion annually (Centre for Mental Health, 2010; Alcock et al., 2014). Urban environments are associated with higher incidences of anxiety and depression; however, mental ill health is complex and poorly understood, and stigmatization has often led to poor reporting rates (Mental Health Taskforce, 2016). The inherent variability of mental health therefore makes quantifying its effects difficult.

Of the 1 in 4 people in London suffering from mental ill health, one third suffer from two diagnosable mental conditions simultaneously, and 1 in 10 children suffer clinically significant mental health problems (GLA, 2014). This high rate of mental ill health has strong economic implications for the city, costing £7.5b a year in health and social care, education and the criminal justice system. In addition, London employers lose £1.1b a year due to stress, anxiety or depression of staff (London Health Commission, 2014).

How can green infrastructure help?

Green infrastructure includes numerous features, from parks to green walls and street verges, providing many benefits; and is increasingly thought of as a way to improve human health in cities (Rolls & Sunderland, 2014) by creating an opportunity for urban residents to interact with nature (Dallimer et al., 2012). Ward Thompson et al. (2012) identified three mechanisms by which natural spaces improve human wellbeing: the restorative power of nature, and providing space for physical activity and for social interaction. This positive association between access to nature and human wellbeing has promoted advancement of green infrastructure development, especially in urban areas where green space may be lacking (Morris, 2003b). This has been reflected in a policy commitment in London, as part of the 'London Plan, improving access to nature'. This initiative looked to identify regions within London deficient in greenspaces and develop new, and restore existing greenspaces to improve access for Londoners across boroughs (GLA, 2008; GIGL, 2017).

While there is a considerable amount of literature demonstrating the benefits of green spaces with regards to health and wellbeing, the quantitative evidence of what forms of green infrastructure may be best is lacking. As such, many of the benefits of implementing green infrastructure are qualitative (Bowen & Parry, 2015).

According to the London Green Infrastructure Task Force report (GLA, 2015a), proximity to green space could improve Londoners' health, for example by encouraging more regular cycling and walking. The group propose green infrastructure should make up at least 50% of the city by 2050, which could encourage 80% of Londoners to walk, jog or cycle for at least 2 miles per day (GLA, 2015a). As the impacts of green infrastructure on human health are still not fully understood, if public health is to become a primary justification for investment in green infrastructure in London, its design and management must be able to deliver observable positive health outcomes for target groups (GLA, 2015a).

Physical health

Numerous studies have demonstrated accessibility to green spaces as a key factor in influencing activity (Lee & Maheswaran, 2011; McMorris et al., 2015; Irvine et al., 2013). For example, Bauman and Bull (2007) found proximity to recreation facilities, attractive destinations and urban walkability scores were all strongly correlated with physical activity. Similarly, Mytton et al. (2012) found people living in greener areas were 24% more likely to achieve recommended levels of physical activity. A study in Bristol also found those who reported difficulty in accessing local green space were 22% less likely to participate in physical activity and residents who lived close to green space were 48% more likely to achieve recommended levels of physical activity (Hillsdon et al. 2011). Additionally, physical activity in children has been linked to access to green space (Almanza et al., 2012; Coombes et al., 2013).

However, the link between green space and activity is mixed: while the majority of studies show a positive association between accessibility, provision etc. some studies show no significant relationship (Hillsdon et al., 2008). This may be due to the community structure, for example ethnic minorities, people with disabilities, the elderly, and teenagers are less likely to use green spaces (Morris, 2003a; Abercrombie et al., 2008; Trost et al., 2002).

Air pollution contributes to almost 50,000 deaths in the UK, attributable to 7% of adult deaths in London (Murray et al., 2012). A large body of evidence demonstrates the ability for green infrastructure to mitigate air pollution in highly polluted cities such as Shanghai (Yin et al., 2011). In London, Tallis et al. (2011) found the Greater London Authority's (GLA) urban tree canopy removes between 852 and 2,121 tonnes of PM_{10} per annum, and increasing canopy coverage by 10% of the current GLA land area would remove 1,109-2,379 tonnes of PM_{10} from the atmosphere by 2050. Quantitative evidence of the health benefits of reducing air pollution is difficult to identify, however Tiwary et al. (2009) evaluated the role of using natural vegetation and modelled the health outcomes and estimated that only a modest 2 premature deaths and 2 hospital admissions could be averted annually in a $10km^2$ area of east London if vegetation cover was increased. However, the study did not account for non-hospital-related health benefits.

Numerous studies have found increasing green space had a protective effect for some diseases such as coronary heart disease (CHD), asthma (Sandifer et al., 2015; Hanski et al., 2012), chronic obstructive pulmonary disease (COPD) (Maas et al., 2006), diabetes mellitus (Tamosiunas et al., 2014), blood pressure (Ulrich, 1984) and those associated with income deprivation (Mitchell & Question, 2016). Restoration of biodiversity and management of natural sites has also been associated with disease management (Secretariat of the Convention on Biological Diversity, 2012). However, the specific features of green infrastructure that appear to be influencing these health benefits are difficult to identify due to confounding variables including income deprivation and age (Villeneuve et al., 2012; Richardson et al., 2012; Bixby et al., 2015).

There is a gap in the literature concerning the positive observable effects of developing green walls and roofs. Several studies have identified positive links with health and viewing the natural environment, including reducing blood pressure (Hartig et al., 2003), lower cortisol concentration and pulse rate (Song et al. 2014) and assisting patient recovery (Nakau et al., 2013; Raanaas et al., 2012). This apparent positive association between viewing nature and improved health may be influential when considering green walls and roofs, as urban residents gain a visual benefit from these structures.

Mental health

As with physical activity, green infrastructure helps to reduce stress by increasing the rate of decline in the stress hormone cortisol. An exploratory study in a disadvantaged area of Dundee found saliva cortisol levels declined faster in those living in areas with more green space (Ward Thompson et al., 2012; Rolls & Sunderland, 2014). This is in keeping with Ulrich's stress reduction theory whereby green space stimulates the parasympathetic nervous system, reducing stress levels (Ulrich et al., 1991).

Many studies use self-reported improvement in mental health when discussing the benefits of green space (Cohen-Cline et al., 2015; Sturm & Cohen, 2014; Nutsford et al., 2013) including reduction in stress and anxiety when moving to greener areas (Alcock et al., 2014; White et al., 2013), improvements in mood, and lower frustration when walking through green areas (Aspinall et al., 2013; Berman et al., 2012) and a reduction in prescription of antidepressants with increased tree coverage (Taylor et al., 2015).

The strength of the association between green infrastructure and human health has led to the spread of 'green care' which uses nature-based interventions for mental and physical care using farming, horticulture and conservation (GLA, 2015a; Bragg & Atkins, 2016). Many of these 'social prescribing' programmes can be specifically targeted to suit the needs of patients (Mind, 2013; Bragg et al., 2015). Social and therapeutic green care has been highly successful in the UK, with over 1,000 projects focusing on learning difficulties and mental health (Sempik et al., 2003). Care Farms are an example of therapeutic care using horticultural practices and landscapes (Care Farm, 2016a), spreading around the UK with approximately 240 farms, including in London - such as Stepney City Farm. Social Return on Investment studies on a number of green care programmes have demonstrated considerable savings to NHS budgets through decreased admission (Bragg & Leck, 2017).

Social wellbeing

Social cohesion is important to the health and wellbeing of people in a community. Improved and increased interactions between residents can help reduce crime and create a sense of safety (Armour et al., 2016; Kuo & Sullivan, 2001). Many studies have shown being in a natural environment encourages social interaction (Ward Thompson et al., 2012). Green infrastructure provides a space for residents to meet and interact, thereby acting as a 'green magnet' (Gobster, 1998) by drawing members of the community together. Peters et al. (2010) found that while most park visitors did not intend to meet new people, small talk and incidental interactions occurred, improving community trust. Development of green infrastructure also provides an opportunity for community projects and engagement such as community gardens. The New York City 'High Line' (Lindquist, 2012), Melbourne 'Dig In' community garden project (Kingsley & Townsend, 2006; Armstrong 2000) and the 'Philadelphia Green Program' (Armour et al., 2016) all rely on community engagement, from planning and development, maintenance and technical assistance, to promoting networking among community members and improving community wellbeing (GLA, 2015a).

Crime rates are important when considering human wellbeing as they link with perceptions of safety. Crime prevention through environmental design is an approach that implements green infrastructure to build secure and resilient communities, by developing visually attractive green infrastructure and thereby improving public perception of the surrounding environment (Kuo & Sullivan, 2001). The mechanism behind reduction in crime and green infrastructure development is not clearly identified; however, it is likely linked to increased vigilance, community pride, and better social ties within the community (Armour et al., 2016). Well-maintained green infrastructure can help reduce gun crime (Raanaas et al., 2012), robbery, and assault (Wolfe & Mennis, 2012).

Tree coverage appears to be a strong factor influencing social cohesion, and appears to facilitate reduction in crime, particularly in poor, inner-city neighbourhoods (Troy et al., 2012). Kuo and Sullivan (2001) concluded that an increase in green space contributed to improved social cohesion, increased vigilance and discouraged crime. Residents of the Chicago Robert Taylor Housing Project in greener areas felt safer, reporting 48% fewer property crimes and 56% fewer violent crimes. This study strongly advocates for the importance of improving green infrastructure owing to its influence in improving social wellbeing. The results were so significant that city government was prompted to spend $10 million planting 20,000 trees.

There is a strong argument for the positive benefits of improved green infrastructure for all aspects of human wellbeing, the focus of which has been parks and tree coverage, and providing space for members of urban communities to socialise, engage in physical activity, and promote green care facilities. However, the majority of all studies have provided correlational evidence for the benefits of green infrastructure, and very little has identified the causal mechanisms behind improved health and wellbeing with development of green infrastructure.

Dose-response modelling is a process used in medical sciences, and provides a potential technique to generate informed nature-based health interventions based on quantifiable nature-based health benefits (Barton & Pretty, 2010; Cox et al., 2017). Shanahan et al. (2015) identified three measures of 'nature dose' to begin to identify causal relationships between nature and human health: quality and quantity of nature, frequency of exposure, and duration of exposure. By assessing nature-dose responses, the development of new green infrastructure can be targeted to maximize human benefits (Cox et al., 2017). For example, Shanahan et al. (2016) found that increasing frequency and duration of visits to green spaces reduced incidences of depression and high blood pressure, leading to the conclusion that visiting outdoor green space for at least 30 minutes a week can reduce the prevalence of depression by 7% and high blood pressure by 9%.

Built environment aesthetics

Green infrastructure plays a role in shaping the aesthetics of the urban environment, and the presence of green infrastructure is typically viewed as having a positive effect on the character of urban spaces. In London, the Victoria Business Improvement District is investing in improving green infrastructure to enhance the built environment in the Victoria area. One rationale behind this investment is the belief of local businesses that the positive effect green infrastructure has on the human experience will promote customer spending and motivate staff (Cross River Partnership & Natural England, 2016). The presence of urban green infrastructure has been shown to have a positive effect on house prices (Liebelt et al., 2017). Although increasing house prices may not be a long-term desirable outcome of urban green infrastructure and may contribute to 'green gentrification' (Natural England, 2014), the evidence that green infrastructure does have a positive impact on property values highlights the effect green infrastructure has on improving the liveability of urban environments.

Local food production

Urban green infrastructure can support the local production of food, typically in allotments and domestic and community gardens. This reduces reliance on food production systems outside of the city, increases access to locally produced food, and supports the creation of new businesses (Poulsen, Neff & Winch, 2017; White & Bunn, 2017). In the UK, interest in domestic food production is increasing (Davies et al., 2011). London supports a number of urban farms including Hackney City Farm (**http://hackneycityfarm.co.uk/**) and the Mudchute (**https://www.mudchute.org**), and in combination with allotments and community gardens, these spaces make up 995 ha of land cover in Greater London (Greenspace Information for Greater London CIC, 2015). An innovative example of urban food production is the Global Generation Skip Garden (**https://www.kingscross.co.uk/skip-garden**), now located at Lewis Cubitt Park, which was situated in various locations across King's Cross during the King's Cross regeneration project. Food was grown in skips, which could be easily transported around the site to make use of 'meanwhile' space awaiting development. The initiative supported an on-site café, outreach work with local schools, and provided space for rest, relaxation and connection to food production for the local community.

Skills and employment

Urban green infrastructure and the biodiversity it supports offer a wide range of opportunities to develop skills and employment opportunities in London. Green infrastructure provides the spaces for people to interact with biodiversity and learn skills to utilise nature in the urban environment. For example, Walworth community garden in the London borough of Southwark (**http://walworthgarden.org.uk**) offers horticulture and bee-keeping training courses which can be used to further careers in these areas. Walthamstow Marshes in the London borough of Waltham Forest provides the space to learn about medicinal herbs, where local herbalists lead walking tours of the area, teaching about the medicinal properties of plants on the site (**http://www.hedgeherbs.org.uk**).

Nature tourism and leisure activities

Offering space for biodiversity can also attract economic activity from a range of nature tourism and leisure activities (Natural Economy Northwest, 2008). In 2016, the Royal Botanic Gardens at Kew was the third most visited paid attraction in the UK, with over 1.8 million visitors (Visit England, 2017). The site is designated a UNESCO world heritage site, and offers attractions in their extensive grounds which support a wide range of native and exotic plant and tree species, such as botanical glasshouses, exhibitions and one of the world's most comprehensive herbariums. Urban green infrastructure also provides space for recreation activities. The Queen Elizabeth Olympic Park is home to a number of sports facilities that were constructed for the 2012 London Olympic Games and are now open to the public.

Human health and wellbeing

Urban green infrastructure provides space for city dwellers to spend time outdoors in semi-natural environments. Access to green infrastructure has a number of human health and wellbeing benefits such as increased levels of physical activity, reduced symptoms of poor mental health and stress, increased levels of communal activity, and greater opportunities for active transport (Faculty of Public Health, 2010). Human contact with biodiversity in green infrastructure habitats may have additional health benefits if exposure to environmental microorganisms modifies the human microbiome and regulates immune function, although the evidence for this remains limited (Flies et al., 2017). The All London Green Grid (ALGG) provides planning policy to promote a network of green infrastructure in London, connecting otherwise fragmented green spaces to provide routes for wildlife and recreation (GLA, 2012). The ALGG aims to promote human health and wellbeing by increasing access to open space and nature, promoting cycling and walking and encouraging healthy living. An example of how this is being achieved is through the improvement of existing green infrastructure in London such as the South East London Green Chain (**www.greenchain.com**). This network of green infrastructure provides walking links between numerous green spaces in south-east London. Plans of the ALGG include enhancing the existing network by adding new connections to areas of deficiency, and enhancing the existing green infrastructure (GLA, 2011). A review of ALGG policy uptake reports that at least half of London boroughs make specific policy commitments to the ALGG (CPRE London & Neighbourhoods Green, 2014).

Biophilia is the concept that humans possess a need and desire to have contact with the natural world (Wilson, 1984). This concept has recently been integrated into thinking about how to design cities to facilitate human contact with nature by the Biophilic Cities project (**biophiliccities.org/**). Through this project, a network of cities is growing that are actively encouraging urban design to support biodiversity and increase human contact with nature. The only UK city currently in the network and classified as a 'Biophilic City' is Birmingham.

Costs

Evidence suggests that low-impact development, including the integration of green infrastructure into grey infrastructure, can significantly lower construction costs and add property value (Gensler and Urban Land Institute, 2011). Scottish National Heritage (2014) claimed on average, developers would be willing to pay at least 3% more for land in close proximity to green space and an additional £800k - £2m in council tax could be generated by improved green space. At present there is a lack of peer-reviewed literature and no defined method of assessing the economic value of green infrastructure on human health. This limits our ability to systematically compare monetary estimates that have been made, and as a result economic value is generally calculated as absence costs and money saved from other services.

Assigning an economic cost to green spaces is notoriously difficult and many of the observed benefits are difficult to assign an economic value, including social wellbeing and mental health. However, many studies have noted improvements to local economies in regions where parks have been developed or improved upon, as attractive greenspaces bring local residents and visitors into a local area. For example, in Glasgow, businesses in close proximity to the Glasgow Green felt that the regeneration of the green improved morale and retention of staff, whilst also providing an attractive location for customers (HLF, 2016) . Green spaces, particularly public parks, are important recreational centres both for socializing and engaging in physical activity, with 57% of the UK population in 2016 reporting that they visit their local park at least once a month (HLF, 2016). Bird (2004) estimated that urban parks alone annually save the national economy £1.6m to £8.7m, including savings to the NHS of £0.3m to £1.8m. One mechanism through which this is thought to occur is the increase in physical activity associated with green space (Rolls & Sunderland, 2014). It is also estimated that if green space can facilitate an increase in physical activity such that there is a proportional 1% decline in the sedentary population, the resulting savings in health costs could reach £1.44b per annum (Bowen & Parry, 2015).

Urban green infrastructure can also contribute to economic benefits for London businesses through the improved wellbeing of staff (Lee & Maheswaran, 2011). Viewing natural elements in the workplace can improve cognitive function of employees, increasing attention span and productivity and reducing stress (Lee et al., 2015). Additionally, it is estimated people who work in buildings overlooking visible green spaces take a quarter less time off work than those who do not (Armour et al., 2016). London employers lose an estimated 6.63 million working days a year due to stress, anxiety or depression, equating to output losses of £1.1 billion annually, and an average London firm loses £4,800 each week due to sickness absence (London Health Commission, 2014).

Risks

There is a need for data collection and sharing with regards to green infrastructure to ensure successful techniques are replicated and developments remain economically and socially useful. However, this evidence for best practice is still lacking and many of the risks are still poorly understood and planned for.

London's existing green infrastructure is highly variable with regards to quality, spatial provision, connectivity and accessibility. Green spaces are often larger and of better quality in affluent areas and are not always easily accessible for the old, infirm, some ethnic minorities and, increasingly, children and young people. Urban greening can also increase property prices, associated with 'green gentrification' which entrenches urban environmental injustice (Wolch et al., 2014). In addition, park quality, maintenance and congestion is often poorer in communities with lower socioeconomic backgrounds and ethnic minorities (Pearsall, 2010). With the mounting evidence supporting the health benefits associated with improved access to green infrastructure, greater emphasis is being placed to counteract environmental injustice. For example, from 2003 to 2011, property prices surrounding the New York High Line rose by 103%. This may mean that local residents in vulnerable populations are displaced to less desirable locations in order to find affordable housing (Wolch et al., 2014). This can create new social tensions over residential developments and increase resentment within communities, thereby reducing social cohesion, increasing individuals' sense of isolation and reducing social wellbeing.

There is also the risk that, unless green infrastructure is in close proximity, it can become a space that is visited for a specific activity, rather than being experienced on a daily basis. There are concerns that irregular use of green space may reduce its capacity to provide health and wellbeing benefits and limits social cohesion (GLA, 2015a). To ensure usage by all community members and to reduce the risk of failure of uptake, and lost health benefits, the implementation of green infrastructure needs careful planning to account for local needs and cultural preferences (Özgüner, 2011). There is evidence that at-risk groups, such as the disabled, elderly, teenagers and ethnic minorities are less likely to use green spaces (Morris, 2003a). It is therefore important that new green infrastructure is developed with these groups in mind, in order to encourage its use, leading to greater physical activity and social cohesion.

There is a need to maintain green infrastructure to avoid it falling into disrepair. If sites are poorly maintained, fewer people may visit and sites may fail in their aims to improve wellbeing (Rolls & Sunderland, 2014). It is important to consider the management of all risk factors, and responsibilities for ensuring success must be made clear (GLA, 2015a).

Though green spaces have been noted as being largely beneficial to human health, there are concerns in some cases that green infrastructure can be associated with health problems such as allergies, hay fever, injury and asthma (Morris, 2003b). While there is no significant link between green space and the risk of asthma, increased allergic sensitisation has been documented (Lovasi et al., 2013).

Most studies are correlative in design, social science focused, suffer sampling bias (often relying on in situ recruiting), of short duration and lack a control group, making it very difficult to identify which factors influence human health and wellbeing (Shanahan, Lin et al., 2015; Keniger et al., 2013). Without understanding the mechanisms behind improved human health (species richness, vegetation composition, accessibility and size) and how these may vary with different cultures, regions, socio-economic groups and what the long-term effect of exposure to nature may be, it is difficult to develop green infrastructure which will reliably provide health benefits to the community (Shanahan, Lin et al., 2015). In addition, there is a research bias towards traditional green space. To further support the planned expansion of green infrastructure, more needs to be done to investigate how alternative forms of green infrastructure (including green walls and roofs) may benefit communities' health and wellbeing (Armour et al., 2016).

There is extensive evidence indicating a positive association between the development of green infrastructure and improved physical, mental and social health and wellbeing. However, this evidence is predominantly correlative, with very little research identifying causal evidence for the mechanisms and features of green infrastructure contributing to improved public health and wellbeing (Sandifer et al., 2015; Shanahan et al., 2016; Keniger et al., 2013). Future research needs to focus on the quantification of health outcomes, concentrating on causality, assessing dose-response relationships and using longitudinal studies to identify the long-term effects of green infrastructure on human wellbeing (Shanahan, Fuller et al., 2015; Shanahan, Lin et al., 2015). This will require collaboration across disciplines incorporating health scientists and practitioners, social scientists, ecologists and landscape planners (Dallimer et al., 2012; Jorgensen & Gobster, 2010) to ensure the correct application and implementation of green infrastructure to provide effective, long-term health and wellbeing benefits (Shanahan, Lin et al., 2015).

Beam Parklands, Dagenham

Beam Parklands is a multi-functional, award winning wetland park in east London forming a boundary between the London boroughs of Barking & Dagenham and Havering (Beam Parklands, 2017). The site's primary function was to provide flood defence, but the community was involved throughout design and development to create a local asset of safe, high quality green space. Funding was provided by the European Regional Development Fund (£1.5 million), Environment Agency (£0.5 million), Veolia Havering Riverside Trust (£250,000) and Big Lottery Fund (£174,000) (The Land Trust, 2017). The 'Friends of Beam Parklands' community group was set up to consult with stakeholders and planners to ensure site development included local values and encouraged community participation, including local children and parents helping to plant trees, shrubs and reeds.

Since opening in 2011, the 53 ha site has helped regenerate a deprived area. The 8 km of pathways have encouraged recreation and activity within the area and created an important link between previously fragmented communities at Dagenham village and Mardyke estate in Rainham. It is estimated the site will contribute £770,000 in community benefits through recreation, community engagement, improvements in health and reduction in community severance. The continued management of this project has been assured through the addition to the Land Trust's investment of £1.9m from the Homes and Communities Agency's Parkland allocation for the East London Green grid (Natural England, 2013).

Green Gym

The Green Gym scheme is a programme run by 'The Conservation Volunteers' (TCV) using free outdoor sessions to engage participants in physical activity through practical conservation projects (TCV, 2017). A recent study on the Social Return on Investment (SROI) found the physical health of participants rose on average by 33%. An evaluation of TCV Green Gym in 2008 estimated for every £1 invested, £2.55 would be saved in treating illness due to inactivity, clearly demonstrating the health benefits to individuals and reducing strain on health services (TCV, 2008).

Sessions are designed to include participants of different ages and abilities, bringing community members together, reducing social isolation. Green Gym activities build personal resilience and social networks through education and development of new skills. A study by the SROI of Green Gyms in 2014 found social isolation reduced by 80% and greatly improved social wellbeing worth £400,000 (Bragg & Leck, 2017). There is growing demand for Green Gyms, with more projects each year, particularly in urban areas including London to tackle the rise in physical inactivity and social isolation in urban areas (Bragg & Leck, 2017).

Putting Down Roots

The Putting Down Roots (PDR) project run by St Mungo's Broadway provides social and therapeutic horticulture to support the recovery of the homeless with mental health problems in London. Participants from St Mungo's are referred by the charity's mental health team and take part in informal sessions tailored to the needs of the participants. PDR uses gardening activities and horticultural training within St Mungo's housing projects, local allotments and community gardens, building social contacts and helping to break down the stigma associated with homelessness and mental health problems. Participants typically suffer depression (54%), schizophrenia (50%) and anxiety (40%) in addition to low literacy and substance abuse. PDR provides participants with skills and support enabling them to move into further employment. In 2012 an evaluation of PDR revealed 37% of participants gained a qualification and/or moved on to further education, employment or volunteering (St Mungo's, 2017). To continue the success of PDR, the project has expanded into local communities, further developing green infrastructure within these communities and providing long-term training and therapy for participants with enduring mental health problems (Mind, 2017).

Further information

Natural Estates: **http://www.wildlondon.org.uk/natural-estates**

Budding Together: **http://www.wildlondon.org.uk/budding-together**

Growing Out: **http://www.wildlondon.org.uk/growing-out**

Design and Management

5. Design and Management

Achieving the benefits and managing the risks associated with green infrastructure requires good design and management, underpinned by knowledge of local conditions as well as relevant science and engineering. Green infrastructure requires long-term management and maintenance, which should be considered at the earliest stages of design and planning.

Design

Given the complex and multidimensional nature of green infrastructure, how best to design cities and urban green infrastructure to optimise benefits is a rapidly developing field. However, there are some fundamental ecological principles that can be drawn on to inform the design of green infrastructure to maximise the environmental performance.

Vegetation structure

The structure and complexity of vegetation in urban environments has been shown to influence the biodiversity that can persist in cities. A recent study by Threlfall et al. (2017) assessed the response of a diverse range of taxa to key urban vegetation attributes. This study found that an increase in understory vegetation volume of 10-30% resulted in an increase of 30-120% in occupancy levels of bats, birds, beetles and bugs. In domestic gardens, it has been found that the three-dimensional structure and complexity of vegetation influences the diversity of a range of species (Goddard et al., 2010). As vegetation structure and complexity is directly influenced by human management, there has been interest from a number of NGOs in encouraging homeowners to alter their gardens to support greater biodiversity. This includes the RSPB's 'Homes for Nature' initiative, the London Wildlife Trust's 'Garden for a Living London' project and the 'Wild About Gardens' campaign run by the Royal Horticultural Society in collaboration with The Wildlife Trusts. Vegetation choice also affects the air pollution impacts of green infrastructure, with some plants contributing to pollution, while others reduce it. Similarly, the water quality performance of SuDS depends on the choice of vegetation.

Scale

Green infrastructure projects can vary widely in scale, from a green roof on a residential building measuring only a few square meters, to a masterplan-scale restoration project such as the Queen Elizabeth Olympic Park development. Green infrastructure sites make up part of a larger network of green space that weaves through the grey landscape of cities. The amount of green infrastructure in a city, and how well-connected this network is, will determine what biodiversity can persist in cities. Species' ability to survive in a city is determined by how much habitat they require to survive and by how able they are to move through the urban landscape (Davies et al., 2011). For example, flying species such as birds and bats are much more able to travel across the grey urban landscape to access unconnected green infrastructure habitats than smaller-bodied species such as bugs and beetles. The amount and connectivity of green infrastructure should be considered when developing urban green infrastructure for biodiversity.

Character

The Natural England National Character Areas (NCA) use characteristics of the landscape and biodiversity, among others, to subdivide England using natural, rather than administrative, boundaries. The aim of this work is to inform decision-making on the natural environment, using areas that are more appropriate to the natural environment than administrative areas. The Greater London Area is made up of a number of NCAs, and the location of developments within the NCA boundaries should be considered when planning green infrastructure developments.

Management

Green infrastructure presents challenges for management, to achieve multiple benefits and minimise risks. Maintenance of sites and components is important to ensure long-term performance, which requires knowledge and skills as well as funding. Many of the benefits of green infrastructure may not be realised by the owners and managers of the sites themselves. For instance, a water manager may invest in SuDS to improve surface water management, and neglect opportunities to achieve air quality benefits if they increase the costs or complexity. Achieving integration requires new ways of working across sectors, professions and institutions.

Strategic actors

Management and ownership of green infrastructure in London is complex and involves numerous public and private actors. Public actors include the 32 London boroughs, the City of London, Transport for London, the Royal Parks Agency, the Lee Valley Regional Park Authority, the London Legacy Development Corporation (LLDC), and over 20 separate park trusts (GLA, 2015a). The declining availability of public funding to London's local authorities means that the ownership and management of green infrastructure is being increasingly transferred to the private sector, community groups, NGOs and community interest companies. Large-scale private owners of green infrastructure in London include Thames Water and Crown Estates. Thames Water and private developers also work with local community groups and schools on funding, implementing and maintaining green infrastructure. Green infrastructure projects may be funded through planning gain from local development, such as Section 106 funds or Community Infrastructure Levies.

The development of new green infrastructure habitats typically involves a number of built environment professionals including architects, landscape architects, engineers and ecologists, who advise on design with respect to biodiversity. Ecologists must be involved in green infrastructure development from an early stage to maximise the potential of new green infrastructure habitats to provide valuable habitat for wildlife. Local authority ecologists should advise on planning applications and track developments once they are built. Unfortunately the ecological expertise within local authorities has been declining, with some London boroughs having no in-house ecological expertise (UK Parliament, 2013).

Long-term management

Outreach and education is fundamental to long-term biodiversity conservation efforts. Positive connections with urban biodiversity are important, since economic and political influence is focussed in cities (especially so for the UK with London), and it is where public policy on biodiversity conservation is formed (Dearborn & Kark, 2010). Green infrastructure is not a fixed asset like grey infrastructure; it is a living and growing environment that changes over time. Trees grow bigger, new plant species colonise grasslands, river banks erode. This needs to be considered during green infrastructure design, and management plans need to be sympathetic to these changes while ensuring that it can still support other intended functions such as safe human use. Management plans need to be flexible to accommodate changing needs of green infrastructure features, and management demands are likely to decrease once green infrastructure habitats have settled and established.

Conclusions

Strategically-planned, well-designed and maintained green infrastructure has the potential to deliver multiple benefits to London's environment and residents. This report addressed the costs, benefits and risks of green infrastructure for London. It reviewed scientific, professional and policy-based literature in relation to air quality, water, biodiversity and health and wellbeing. While the report focussed on each component of the environment separately, green infrastructure has the potential to deliver multiple, simultaneous benefits.

What is the problem?

London faces serious environmental problems, including air and water pollution and flooding. London is in breach of international standards for air quality and urban water quality. The city provides important habitat for plants and animals, but these habitats may be threatened by urban development to meet the needs of a growing population. Invasive species also dominate London's ecology, and abundance of particular species may be at the detriment of biological diversity.

Londoners' physical and mental health is influenced by their environment. London has the highest rate of childhood obesity of any major global city (London Health Commission, 2014) and, compared to other regions of the UK, has the largest proportion of the population reporting high levels of anxiety (GLA, 2014). 1 in 4 people in London suffer from mental ill-health and 1 in 4 children under 6 years old are obese. Air pollution is estimated to reduce life expectancy from birth in London by 1 year (Walton et al., 2015).

How can green infrastructure help?

Green infrastructure can be beneficial in absorbing polluting gases and filtering particles from the air, slowing down and cleaning up rainwater that runs off surfaces, providing habitat for wildlife, and improving mental and physical health. In addition, urban green infrastructure has several potential benefits that cut across different components of the environment.

An economic valuation of London's 8.4 million trees has estimated that ecosystem services provided by London's trees are worth £133 million per year (i-Tree, 2015). This is a conservative estimate as the survey did not measure or value additional important ecosystem services provided by urban trees such as physical and mental health and wellbeing benefits. At a smaller scale, the Victoria Business Improvement District (VBID) has conducted an audit and economic valuation of the trees, green spaces and other green infrastructure assets in the Victoria area (Rogers et al., 2012). In an area prone to flooding, the survey and valuation estimated that existing green infrastructure diverts 112,400 cubic meters of storm water from the local sewer system annually at an estimated value of between £20,638 and £29,006 in reduced CO_2 emissions and energy savings every year.

Costs

Evaluating the costs and benefits of green infrastructure is complicated by its multi-functional nature. The costs of green infrastructure need to be considered on a project-by-project basis. It is difficult to assign costs to specific services or benefits provided by a green infrastructure feature. For instance, the cost of installing a SuDS system may be evaluated according to the surface water benefits it delivers, but benefits to health and wellbeing and biodiversity may not be included if these are not the accountability of the project owner.

In addition to economic costs for installation and maintenance, there may be more generic dis-benefits that need to be accounted for and managed. Trees and plants may have negative health impacts through exacerbating allergies. Trees may also emit volatile organic compounds and ozone which can contribute to air pollution. Tree roots and branches may damage roads and pavements. Other costs of increased biodiversity can include corrosion and cleaning costs from bird droppings and accelerated decomposition of wooden structures as a result of increased microbial activity. Insects, birds and other species can contribute to plant damage and crop losses in gardens and allotments, and may increase the cost of pest control.

Risks

Not all green infrastructure techniques are suitable in all conditions. Ground permeability, soil conditions, local geology, water table dynamics, the condition of existing buildings and structures, microclimates, proximity to green space and waterways, as well as sources of pollution, runoff and threats to biodiversity, must all be considered in determining which technique to implement. There is a risk that green infrastructure components may be implemented inappropriately, undermining benefits and increasing costs and likelihood of failure.

More detailed monitoring of air pollution is needed to support better modelling and prediction of air pollution and the impact of green infrastructure. Existing studies and models based on studies in rural or forested landscapes or under laboratory conditions may not be applicable in urban contexts. There is also a risk that air pollution modelling does not adequately account for local weather and micro-climate.

There is uncertainty over whether any particular green infrastructure component in and of itself necessarily supports biodiversity in any significant way (Hostetler et al., 2011). Increasing biodiversity in urban areas could have risks for local wildlife and human health. For example, improvements to green infrastructure with the aim of benefiting native species could also aid the spread of invasive species (Faeth et al., 2011). There are also concerns that higher urban biodiversity could contribute to a higher likelihood of disease transmission within wild and domestic animal populations and increased potential for zoonotic disease transmission (Lyytimäki & Sipilä, 2009).

Most studies of the benefits of green infrastructure and health have established correlations rather than causation. There is a risk that evidence of correlations between green infrastructure and good health may be the result of confounding factors such as income and socio-economic status, and this should be considered in evaluating the data. Most studies are correlative in design, social science focused, suffer sampling bias (often relying on in situ recruiting), of short duration and lack a control group, making it very difficult to identify which factors influence human health and wellbeing (Shanahan, Lin et al., 2015; Keniger et al., 2013).

Green infrastructure for London

In evaluating the evidence relating to green infrastructure for London this report has drawn on a range of scientific, professional and policy-based studies. Evidence for green infrastructure is emerging as it rises up the policy agenda and more projects are implemented. The evidence base is far from complete, particularly considering multiple and synergistic impacts, and decision making about green infrastructure involves trade-offs and uncertainties.

Gaps in evidence present two contrasting risks in relation to green infrastructure policy and implementation. Firstly, green infrastructure solutions may be considered to be higher risk than conventional options for urban infrastructure and development. Qualitative evidence of benefits may be ignored or downplayed in decision-making processes that are focused on economic costs and benefits. Evidence from case studies may be dismissed as irrelevant to new circumstances in particular places. Secondly, decisions to implement green infrastructure may be based more on hype and fashion than evidence or analysis. This could lead to higher costs and missed opportunities for achieving more robust solutions to environmental issues in London, and ultimately undermine the credibility of green infrastructure.

If green infrastructure is to be part of integrated solutions to the pressing environmental problems facing London, it needs to be integrated within strategic and local plans. Moving beyond small pilot projects and case studies to a strategic and integrated plan for green infrastructure requires collaboration across local and central government, with community groups and citizen scientists, and academics and professionals from different disciplines. There is sufficient evidence of the benefits of green infrastructure in addressing environmental problems to warrant large scale planning implementation, and an integrated approach should allow for ongoing monitoring and adaptive management.

London faces serious challenges to its environment and the health and wellbeing of residents. Green infrastructure provides considerable benefits to London, and better integration and connection could further enhance London's ability to respond to these problems. Accounting for the costs and risks associated with green infrastructure and the need to strengthen the evidence base about its function and impacts, alongside its benefits, will allow for more robust decision making and adaptive approaches to planning and management.

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