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Green infrastructure of cities: an overview

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Abstract

With growing urbanization cities are increasingly suffering due to the abundance of built-in spaces, concrete, mortar and tarmac, urban heat islands, increasing frequency of extreme heat events and climate change. The sustainable development goal 11, emphasizes on developing green infrastructure which could minimize the environmental footprint of the cities. In this paper, we discuss the role of green infrastructure in carbon sequestration, mitigating atmospheric pollution, moderating temperature and mitigating climate change, and management of storm water. We also discuss biodiversity of green infrastructure and the latter as habitat of organisms, and provide an overview of economic value of trees in the urban areas.

Keywords: Green infrastructure, carbon sequestration, urban heat island, pollution abatement, urban biodiversity.

Introduction

World is undergoing rapid urbanization. United Nations (1991) figures indicate that in 1990 only 37% of the total population of developing countries was urbanized, it is predicted that by the year 2025 the proportion will be 61%. While in mid-1990, 45% (2.4 billion) of the people of the world were living in towns or cities, this will increase to 51% in 2000 and 65% in 2025. The rate of urbanization is remarkably high in the developing world. India is also becoming increasingly urbanized. By 2050 it is estimated that 50% of population in India will become urbanized (Mell, 2015). It is frequently stated that climate change and biodiversity loss in cities go together with growing urbanization (Nagendra and Mundoli, 2019). According to the latest air quality database, compared to 49% in high-income countries, 97% of cities in “low- and middle- income countries with more than 100,000 inhabitants do not meet WHO air quality guidelines” (WHO, 2018). For example, Delhi is found to be the most polluted city in the world (WHO, 2018).

Cities are usually founded in species-rich areas where environment is congenial to life, however, cities are now suffering due to the abundance of built-in spaces, concrete and tarmac and also global warming. Nagendra and Mundoli (2019) argue that environmental footprint of the cities needs to be reduced by careful planning of the green spaces as envisaged in the Sustainable Development Goal 11 (https://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-11- sustainable-cities-and-communities.html) which focuses on building sustainable cities and communities. In this connection, developing green infrastructure in cities is an important task though it has been frequently “ignored because while urban planners focus on built-up space, the ecologists focus on forest and protected areas and miss the biodiversity within the cities” (Nagendra and Mundoli, 2019). Realizing the importance of urban vegetation, Nerlekar *et al* (2019) have indeed pleaded for long-term biodiversity monitoring in urban landscapes.

Urban green infrastructure (UGI) can be defined as “the network of planned and unplanned green spaces, spanning both the public and private realms, and managed as an integrated system to provide a range of benefits” (Norton *et al.,* 2015); in fact, it can be visualized as an interconnected network of green spaces that conserves natural ecosystem values and functions and provides associated benefits to human populations (Benedict and McMahon, 2002).

According to Chenoweth *et al.* (2018), the green infrastructure of a city comprises various "natural and semi-natural green spaces, including parks and gardens, amenity green space, allotments and city farms, cemeteries and churchyards, green corridors such as rivers or railway embankments, conservation and nature reserves, and archaeological sites". The concept of green infrastructure covers the quality and quantity as well as the multifunctional roles of urban and peri-urban green spaces, and emphasizes the importance of interconnections between habitats (Turner, 1996; Rudlin and Falk, 1999; Sandströ m, 2002; Van der Ryn and Cowan, 1996). According to Tzoulas *et al*. (2007), a well-planned green infrastructure can provide both a framework for economic growth and nature conservation. The objectives of developing green infrastructure include improving human health and wellbeing, urban aesthetics, biodiversity conservation, water management, sustainable land management, climate change mitigation and adaptation, job creation, and urban regeneration (Chenoweth *et al*., 2018). Urban green spaces are also important for developing pro-environment attitudes among people as found out by an interesting survey in Pune (Budruk *et al*., 2009).

In this paper, we discuss the role of green infrastructure in mitigating atmospheric pollution, carbon sequestration, moderation of temperature and mitigation of climate change, and management of storm water. We also discuss biodiversity of green infrastructure and the latter as habitat of organisms, and provide an overview of economic value of trees in the urban areas.

Pollution mitigation and Carbon sequestration

Urbanization degrades the environment by replacing natural landscapes, with manmade materials (Nowak, 2006). Heat, and emissions of various kinds associated with urbanization, affect not only the local and regional landscape but also the health of local people (Nowak, 2006). Urban vegetation can positively affect the local and regional air quality by removing air pollutants and altering the urban atmosphere. Urban trees remove air pollution primarily through uptake via leaf stomata and other parts of the plant surface (Mullaney *et al*., 2015). An increase in percent tree cover is reported to enhance air quality (Lenschow, 1986), improvement in air quality by trees is, however, size-dependent as McPherson *et al* (1994) have reported that "large healthy trees can remove 60 - 70 times more air pollution than smaller trees". Nowak *et al.* (2006) estimated air pollution removal by trees in cities: Szeged 6.5 $g\ m^{-2}$ of canopy cover, Charleston 6.7 $g\ m^{-2}$, Minneapolis 6.2 $g\ m^{-2}$, Victoria 10.9 $g\ m^{-2}$, Barcelona 9.3 $g\ m^{-2}$. Transport is a major source of air pollution in Bangaluru, yielding a pollution load of 54.4 tons day^{-1} of suspended particulate matter below 10 mm (PM10), 217.4 tons $day-^{1}$ of NOx and 14.6 tons $day-^{1}$ of SO_2.

The urban forest can provide pollution reduction benefits, but certain urban tree species can also contribute to the problem (Livesley *et al*., 2016), for example, certain species emit biogenic volatile organic compounds that can lead to the formation of smog or ozone (Chameides *et al*., 1992; Calfapietra *et al*., 2013; Dunn-Johnston *et al*., 2016). It is known that ozone is harmful in the urban atmosphere, particularly in warm climates. Urbanized catchments usually experience greater nitrate, phosphate, sulfate, carbon, and heavy metal pollution in waterways as compared to unurbanized catchments (Bernhardt *et al*., 2008; Kaushal and Belt, 2012). According to Livesley *et al*. (2016), urban tree and soil systems could substantially reduce the nutrient concentrations in the run-off from urban catchment. Also trees can sequester substantial amounts of carbon (C) from CO_2. The US national average urban forest carbon storage density is 25.1 t C ha^{-1} (Nowak and Crane, 2002), Singh *et al* (2019) estimated carbon storage of street trees from the Banaras Hindu Campus, Varanasi and reported the highest amount of carbon storage (kg $tree^{-1}$) in *Madhuca longifolia*, that is 9.0×10^3 followed by *Tamarindus indica* (7.7×10^3), *Tectona grandis* (7.0 ×

10^3), *Mangifera indica* (5.9×10^3), *Syzygium cumini* (5.3×10^3). Differences between species in carbon sequestration and storage capacity are mainly determined by the differences in size distribution of trees (Kiss *et al*., 2015; Deb *et al*., 2016) and the fertility status of the soil (Singh *et al*., 2019).

Temperature moderation, Climate change mitigation

In urban areas vegetated surfaces are replaced with impervious built surfaces, as result shading, evaporative cooling, rainwater interception, storage and infiltration functions of vegetation are diminished; but green spaces within the built environment allow such processes to occur (Whitford *et al*., 2001). In urban areas, energy exchanges are modified so as to create an urban heat island (UHI), where air temperatures are several degrees warmer than in the adjoining rural areas (Wilby, 2003; Graves *et al*., 2001). "UHI occurs because of the modification of energy balance on account of the presence of urban canyons, thermal properties of the building materials, presence of impervious surfaces, and reduced albedo" (Singh *et al*., 2018). The UHI is a very real phenomenon that confronts people living in towns and cities with increased exposure to heat stress and potential heat stroke (Livesley *et al*., 2016). However, there is a lack of research on the amplification of climate change effects by urban heat island (Emmanuel and Loconsole, 2015).Warming associated with urbanization will increase in future as a result of global climate change. The urban warming, particularly in summer, is of concern because of its relation with human comfort and wellbeing (Svensson and Eliasson, 2002; Eliasson, 2000). According to Gill *et al.* (2007), "air temperature provides a simple estimator of human thermal comfort". Extreme heat events (EHE) are more common in warm and dry climates, and as argued by Norton *et al* (2015), development of an urban green infrastructure (street trees, parks, green facades, etc.) can reduce temperature in urban areas. For example, in the city of Gaborone, in Botswana at midday, densely vegetated areas were up to 2°C cooler than the adjoining rural sites (Singh *et al*., 2018). Emmanuel and Loconsole (2015) argue that green infrastructure could play a significant role in reducing the urban overheating in the future global warming scenario and thus developing green infrastructure could be an important adaptation feature of cities. Fig. 1 includes examples of green infrastructure of a city. The urban vegetation improves the quality of life of the urban population by mitigating stress from overheating and increased frequency of occurrence of extremely high temperatures, through shading and evapotranspiration (Kiss *et al*., 2015), and can also improve the environmental quality around an urban area (Nowak, 2006). It has been reported that extreme heat events (EHE) cause increased mortality and morbidity in city populations (Norton *et al*., 2015), and the frequency, intensity and duration of EHEs are projected to increase with climate change (Alexander and Arblaster, 2009).The benefits of urban trees include *inter alia* (i) improvement in air and water quality, (ii) energy conservation in buildings, (iii) cooler atmosphere, (iv) reduction in ultraviolet radiation, (v) carbon sequestration and removal of air pollutants, (vi) reduction in storm water runoff, apart from aesthetic and ecophysiological benefits (Nowak and Dwyer, 2000; . O'Campo *et al*., 2009; Tyrväinen *et al*., 2003; Jim and Chen, 2008; Kirnbauer *et al*., 2013; Nowak *et al*., 2013). The poor in the cities often depend on the city trees for fuel, food and medicine (Nagendra and Mundoli, 2019) (Fig. 2). Given the rapid growth of urbanization and increasing global warming, much of the adaptive action should occur in the cities. In fact, Goal 11 of the Sustainable Development Goals (https://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-11-sustainable-cities-and-communities.html) emphasizes on building sustainable cities wherein environmental footprint is reduced by developing and enlarging the green infrastructure. Increasing the amount of green infrastructure in cities is among the important ways to reduce the variations and maxima of urban air and surface temperatures (Norton *et al*., 2015). However, much action-oriented research and policy planning is needed to (a) ameliorate the urban heat island (UHI) effect, and (b) to use UHI mitigation as part of climate change adaptation, particularly in developing countries.

According to Nowak *et al*. (2013) and US EPA (2013), in the contiguous United States alone, urban trees store over 708 million tons of carbon (approximately 12.6% of annual carbon dioxide emissions in the United States) and capture an additional 28.2 million tons of carbon (approximately 0.05% of annual emissions) per year. The value of urban carbon sequestration is substantial: approximately $2 billion per year, with a total value of current carbon storage over $50 billion (Nowak *et al*., 2013). Sun *et al*. (2019) estimated the total amount of carbon stored in the urban green spaces of Beijing at 956.3 Gg (1 Gg = 109 g) for the year 2014; the spatial heterogeneity in vegetation carbon density varied from 0 to 68.1 Mg C ha^{-1}, with an average density of 7.8 Mg C ha^{-1}. Beijing is the second highest energy consuming city of China, with the total CO_2 emissions in 2030 estimated to be 0.43 times higher than that of 2005 (Feng *et al*., 2013). According to the carbon emission reduction target of "the 13rd Five-Year Plan of Beijing (2016–2020)", the CO_2 emissions per unit of GDP in 2020 is to be decreased by 20.5% compared with that in 2015 and the year 2020 is supposed to be the peak for total CO_2 emissions, which is a big challenge for Beijing (Liu *et al*., 2014).

Storm Water Management

Increases of impervious surfaces in cities results in increased runoff, and the disposal of storm water directly into surrounding waterways is detrimental to the aquatic environment. Urbanization increases impervious surface area and causes soil compaction thus reducing water infiltration into the soil. For example, urban run-off in Manchester, UK from rainfall was much higher from asphalt (62%) than from surfaces with tree pits (20%) or turf (<1%) (Armson *et al*., 2013). Roy *et al.* (2014) argue that "large volumes of runoff may lead to flooding, sewer system malfunction, and impairment of surface and subsurface water resources". The storm water runoff pollutes surface waters, accelerates stream flows and destroys urban aquatic habitats (Nowak, 2006). Urban trees can reduce storm water flow and therefore developing urban forests can potentially reduce the sediment and pollution load from the storm flow systems. According to the United States Department of Agriculture, trees planted over open, impervious surface such as parking lots could reduce storm water runoff by as much as 20%, and 15% of the total rainfall can be captured and reduced by branches and stem. A large tree can capture and retain as much as 332 gallons of water. The estimate assumes the widest part of the tree's crown at 33 feet (https://www.srs.fs.usda.gov/compass/2018/01/11/urban-forests-stormwater-management/).

Sustainable storm water management should provide for the hydrological patterns of urban areas to closely mimic those of natural areas (Denman *et al*., 2011). Bio-filtration systems are being increasingly used as part of water sensitive urban design (WSUD) to improve the quality as well as to reduce the quantity of storm water run-off by directing the storm water run-off into a treatment area with plants growing in a moderately permeable soil. Most bio-filters use grasses, sedges and rushes but in extremely urbanized area, like streets, trees may be more suitable (Denman *et al*., 2011). Green infrastructure science largely focuses on technologies to facilitate infiltration of storm water using rain gardens, bio-swales, and permeable pavements so as to increase the ground storage of water.

Habitat for Organisms

Urban green spaces nurture a variety of fauna such as squirrels, monkeys, birds, and insects (Cornelis and Hermy, 2004), and some of these organisms "are so well-adapted to the urban environments that they are more abundant in cities than in surrounding natural vegetation" (Mullaney *et al*., 2015). Street trees also provide connectivity between urban forest patches and between the urban forest and surrounding rural vegetation and thus provide corridors for the dispersal of small mammals, birds, butterflies, moths and beetles, etc (Mullaney *et al*., 2015). The physical characteristics of street trees influences faunal abundance and diversity, and therefore, to avoid homogenization of fauna, planting a diversity of native tree species is often recommended (Alvey, 2006). For example, the Australian cities with high proportions of native trees are reported to have high bird diversity and native-bird abundance than unurbanised areas (Mullaney *et al*., 2015). In residential parts of California and Nicaragua, native tree species are widely utilized by bats and iguanas respectively (Mullaney *et al*., 2015).

Several forms of public green space are candidates for pollinator conservation. Recommendations to maximize the quality of these green spaces for bees often focus on reducing management frequency or intensity, as well as increasing the abundance of flowering vegetation (Turo and Gardiner, 2019).

Economic Value of Urban Trees

In order to attract attention of city planners and managers, it is important to assign monetary value to urban greenery. Street trees of cities support healthy urban communities and boost property values (Mullaney *et al*., 2015). Willis and Petrokofsky (2017) have forcefully argued that trees are indeed natural capital assets for cities as they provide immense benefits and ecosystem services for the wellbeing of city dwellers. "Trees that line our streets, fill our parks and shade our houses make up an urban forest" (Killicoat *et al*., 2002), which provides a variety of economic, social and environmental benefits**.** Green spaces enhance home values (Luttik, 2000) and businesses revenues (Wolf, 2003), reduce cooling-related energy costs (McPherson *et al*., 1997), moderate ambient air temperatures, reduce carbon emissions, and improve water and air quality (McPherson, 1994; Nowak *et al*., 2006). Vailshery *et al* (2013) have reported that street stretches with trees had afternoon temperatures lower by 5.6 ^{0}C and road surface temperature lower by 27.5^{0}C than exposed road surfaces in Bangaluru. Paradoxically, unlike conventional forestry and fruit trees, urban street trees usually do not have a market value (Pandit *et al*., 2012) and therefore, they are viewed more as liabilities than assets (McPherson, 2007). Several authors have documented the potential energy savings gained by planting street trees (McPherson *et al*., 1994; Donovan and Butry, 2009; Pandit and Laband, 2010). For example, a 10% increase in tree cover is found to reduce total heating and cooling energy use by 5–10%, and a single tree can reduce annual heating cost by 1.3% and cooling cost by 7% (McPherson *et al*., 1994). Urban street trees generate significant economic benefits for communities as per the examples reported in Table 1.

Contribution to biodiversity

Contrary to general belief, the urban systems are considerably rich in species diversity. Being novel ecosystems, they provide a diversity of habitat for plants and animals such as lawns, wastelands, herbaceous borders, shrubberies and hedges, parklands, gardens, street trees, and pavement cracks and walls (see ref Singh *et al*., 2018 for details). For example, because of high temperature, city is suitable for thermophilic species of plants, digger wasps, long horned beetles, rove beetles and glow worms and springtails (Mabelis, 2005). Due to Higher temperature of city, birds can produce more eggs per year (Klausnitzer, 1989). Mabelis (2005), has recorded a “shift from hygrophilic species to dry-tolerant species from the outskirts of the city to the centre in Warsaw for several groups of animals: worms, spiders, harvest-spid, springtails, carabid beetles, lady beetles, flies, scorpion flies, ants and parasitic wasps” and has explained the high density of some mammal and bird species in the city by the availability of plenty of food. City supports relatively more granivorous birds and omnivorous birds, than insectivorous and carnivorous birds (Tomiałojć and Profus, 1977).

Avian migration is a global phenomenon with movements spanning thousands of kilometers through diverse environments (Newton, 2003). Natural and anthropogenic obstacles abound during migration, including predation, habitat degradation and destruction, collisions with structures (e.g., buildings, communication towers, wind turbines), and attraction to artificial light at night (Horton *et al*., 2019). In addition to these factors, another fundamental challenge for migratory birds is shifts in resource availability induced by global climate change, which has the potential to affect all aspects of their annual life cycle, including migration (Møller *et al*., 2010).

Interestingly, economic profile of the residents often determines the kind of vegetation developed in their area. Gopal *et al.* (2015) found that in the slums of Bangaluru, most plant species have economic, food, medicinal or cultural value, while species planted in the richer residential areas are largely ornamental, and frequently non-indigenous. Paul and Nagendra (2015), found that core area of Delhi (older part of Delhi) has greater amount of green space and stable vegetation (as the Central Ridge Forest falls within this zone and also abundance of avenue trees of the Lutyen’s Delhi) than other areas, particularly the rapidly expanding periphery. In fact, as argued by Singh *et al.* (2018), establishment of urban nature reserves to create space for biodiversity to flourish and to promote wellbeing of city dwellers, needs to be made mandatory while planning a city.

Although we acknowledge the central role of large, permanent green spaces, here we draw attention to the emerging opportunity presented by small-scale, short-lived green spaces such as pop-up parks (PUPs) to synergistically enrich urban nature for the benefit of biodiversity and people (Mata *et al*., 2019). PUPs may help people rekindle their connections with nature, socialize, spend time outdoors, and experience positive short-term body and mind states. Such parks offer not only insight into how small, temporary green spaces can complement permanent green spaces in incorporating nature into cities but also provide a platform for addressing targeted research questions related to green space design.

Marine urbanization is another growing problem. Marine urbanization is often associated with negative ecological and economic impacts, including decline in water quality and habitat productivity, spread of invasive species, and proliferation of jellyfish and toxic algal blooms (Malerba *et al*., 2019).Changes in physical conditions contribute to these impacts and affect communities that colonize artificial and natural habitats (Connell, 2001; Glasby and Connell, 2001). One general but rarely recognized effect of marine urbanization is that most artificial structures increase the proportion of shaded and vertical-facing substrata compared to natural habitats (Malerba *et al*., 2019).

The abnormal increase in encrusting (fouling) biomass favored by marine urbanization is likely to affect coastal food webs. By reducing light availability, the construction of artificial structures creates new shaded environments in which energy-producing autotrophic organisms are replaced by energy-consuming heterotrophic species (Malerba *et al*., 2019).

Malerba et al (2001) estimate that the fouling biomass on artificial structures consumes 25,148 megajoules (MJ) and produces 2.46 metric tons of CO2 daily, with a carbon flux of 1.45 g C m−2 day−1 (7.6 × 106 MJ and 898 metric tons of CO$_2$ annually)in Port Phillip Bay but In

Moreton Bay, the fouling biomass on artificial structures consumes 10,878 MJ of energy and produces 1.06 metric tons of CO_2 daily, with a carbon flux of 1.254 g C m−2 day−1 (3.97 × 106 MJ and 388 metric tons of CO_2 annually).

Conclusion and Future perspectives

It is clear from the foregoing that green infrastructure of urban areas provides all the four kinds of ecosystem services (provisioning, regulating, supporting and cultural) recognized by the Millenium Ecosystem Assessment, encompassing multifunctional benefits such as social, economic, cultural and environmental, in an integrated and interconnected manner (Figure 3). The components of green infrastructure contribute to stabilization and regulation of weather conditions and preservation of the ecosystem services in the urban areas. It is also clear that much more information is available from developed temperate regions than that from developing tropical regions. Nevertheless, the available findings could provide valuable insights for green infrastructure planning and biodiversity conservation in tropical urban areas. It is recognized that the underlying mechanisms in the relationships between the degree of urbanization and biodiversity (native and exotic) are little known.

Further research is required in the following areas:

1. Identification of possible data sources and data gaps.
2. Identification of approaches for developing smart-compact green cities focusing on multifunctionality at different scales.
3. Developing short- and long-term solutions to alleviate urban poverty through appropriate greening.
4. Understanding the optimal mix of species suitable for planting in tropical cities.
5. Developing strategies and tools for educating public, planners and decision makers regarding the desirability of green infrastructure and nature conservation within urban areas

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Figures

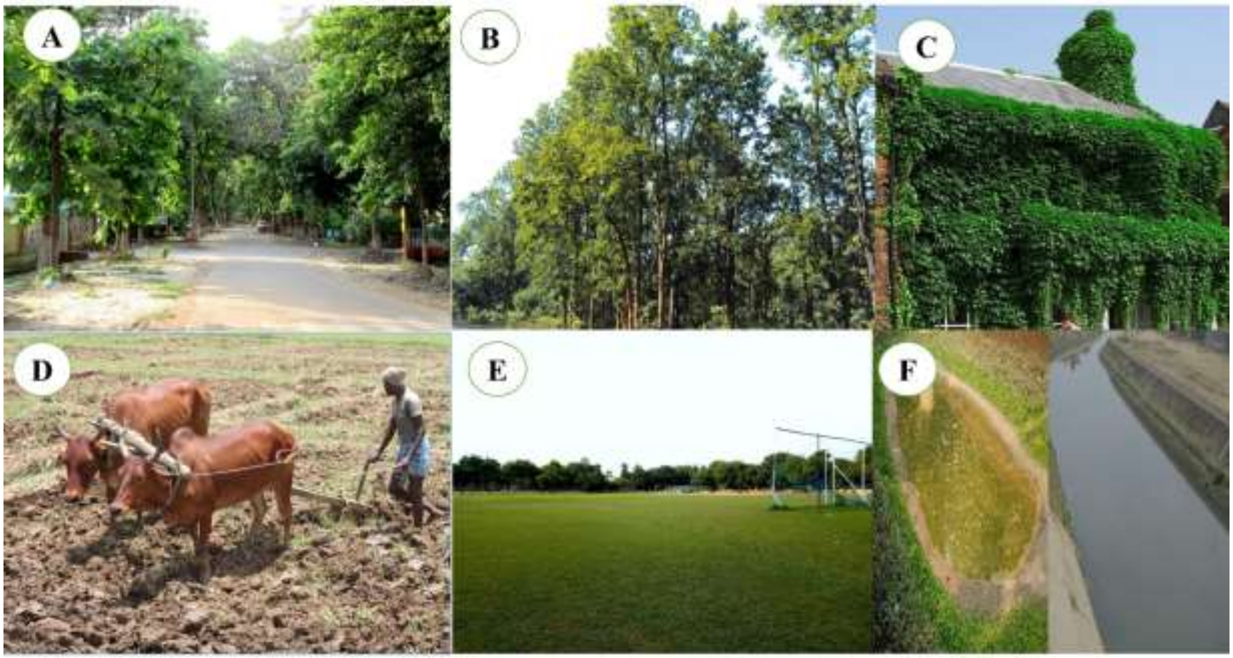

Figure 1: Examples of green infrastructure in cities (A) street trees, (B) city forest, (C) green façade (wall covered with climbing plants), (D) agriculture, (E) unpaved grassy field, and (F) pond and rive

Figure 2: Collection of (A): fuel wood, (B): leaf fodder, and (C) fruits and (D) edible flowers.

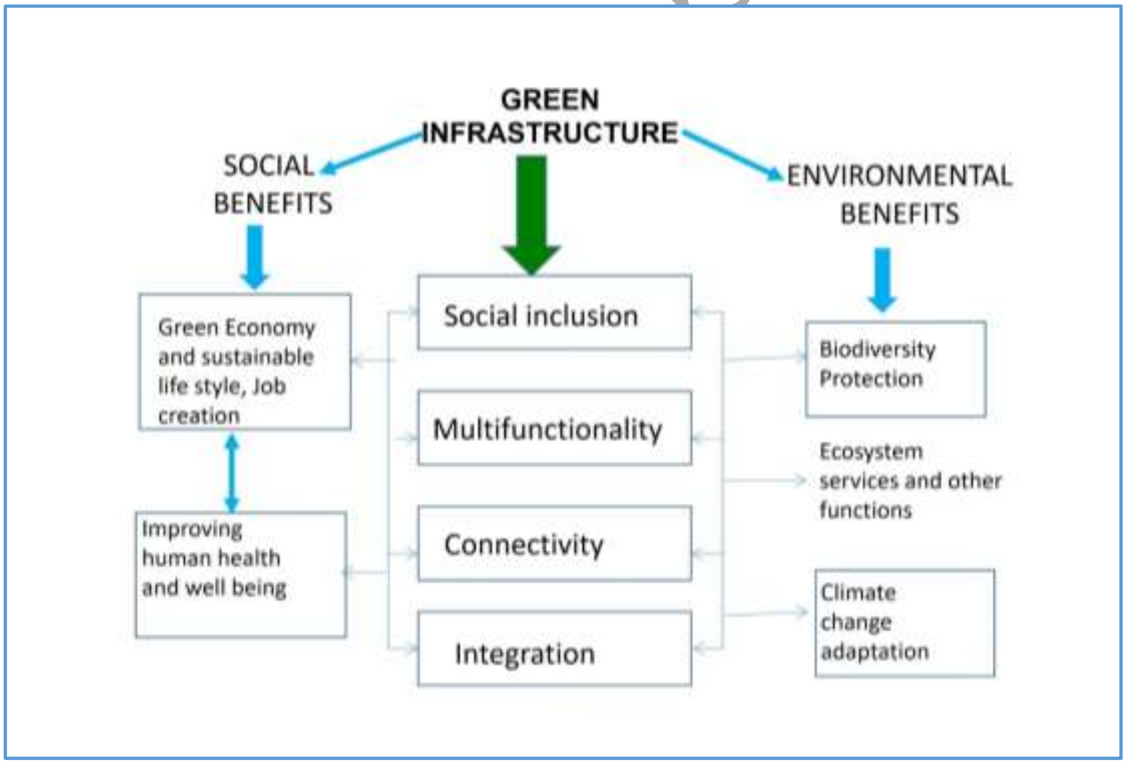

Figure 3: Social and environmental benefits of green infrastructure (See also Hansen *et al*, 2017)

Table 1: Examples of estimated annual values of environmental, social and economic benefits of a street tree.

	Annual benefit per tree (US $)				
	Storm water	Air pollution	CO_2 reduction	Energy saving	Overall economic benefits
Modesto (USA) (McPherson *et al.* , 1999)	6.76	15.82	4.93	10.97	54.4
Adelaide (Australia) (Killicoat *et al.* 2002)	6.85	34.50	1.71	64.00	171.00
Bismarck (USA) McPherson *et al.* , 2005)	27.83	0.28	1.53	31.03	71.50
Lisbon (Portugal) (Soares *et al.*, 2011)	47.80	5.40	0.33	6.16	159.00