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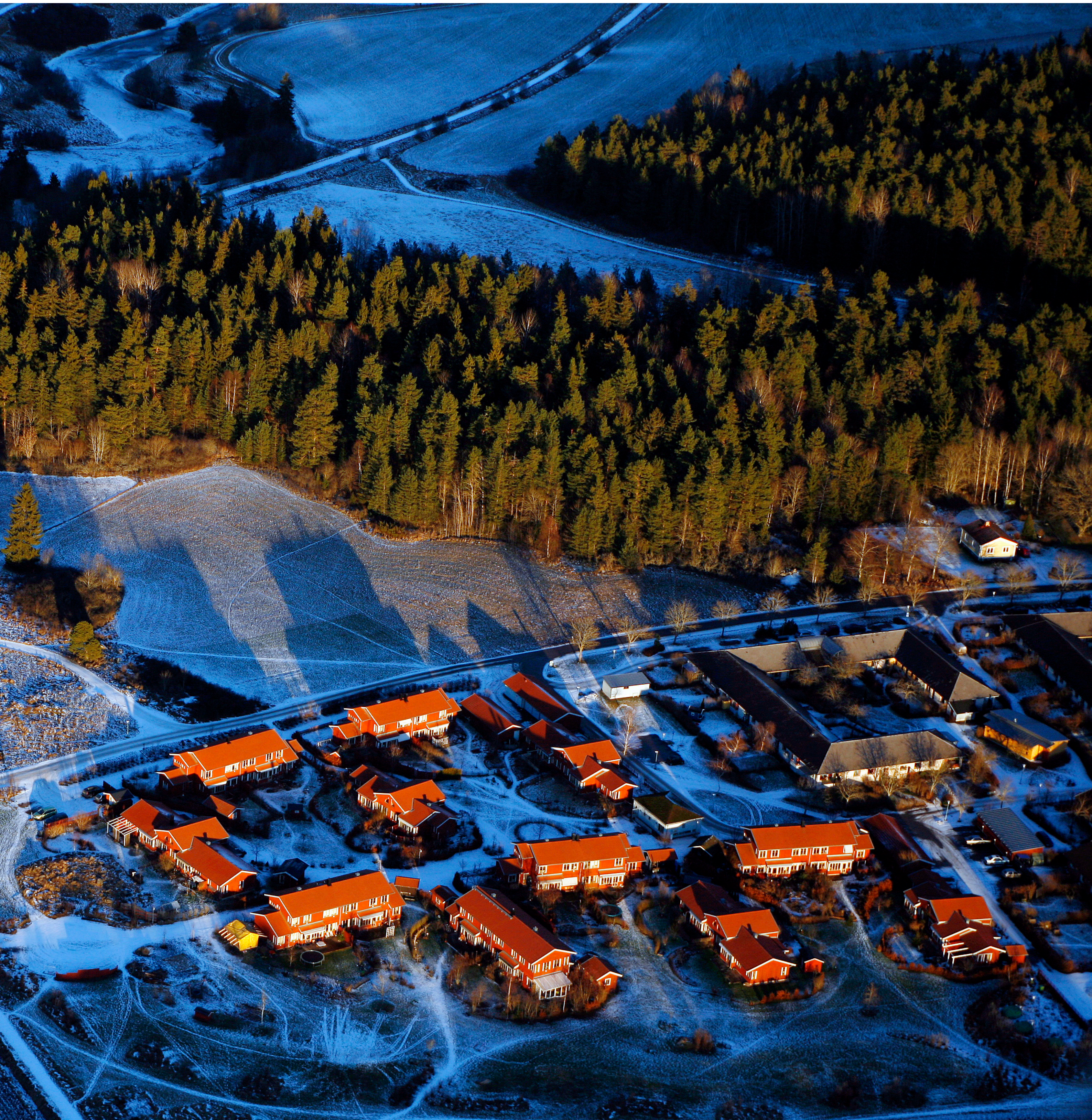

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GREEN INFRASTRUCTURE: FROM GLOBAL TO LOCAL

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URBAN GREEN INFRASTRUCTURE FOR CLIMATE BENEFIT: GLOBAL TO LOCAL

NANCY D. ROTTLE

Abstract

Urban Green Infrastructure can be especially beneficial in addressing climate change challenges to our cities. Five systems of green infrastructure – social, biological, hydrologic, circulatory, and metabolic – provide integrated, multiple benefits. These systems may mitigate anthropogenic impacts to climate through reducing greenhouse gases in the atmosphere while simultaneously helping to reduce the inevitable negative effects that climate change will have on urban environments and populaces. The paper outlines forthcoming climate change challenges and describes the capacity of each of the five systems to provide multiple, overlapping benefits. It then analyzes each system's capacity to contribute to global climate mitigation while diminishing local adverse impacts to urban contexts, supported by relevant projects with examples from North America, Asia and Europe. The paper concludes with propositions for adaptive mitigation and considerations for incorporating green infrastructure in urban planning and design.

Key words:
Green infrastructure, climate mitigation, climate adaptation

Introduction

Climate change has been called the defining issue of the twenty-first century, with cities seen as both solutions for reducing overall greenhouse gas emissions through compact development, as well as the places most dramatically and tragically impacted and therefore most critically requiring adaptive practices. However, for the most part, attention to climate change mitigation has focused on the reduction of greenhouse gas emissions and carbon sequestration at the global scale – most clearly advanced through international agreements such as the Kyoto Protocol – while local climate change policy and plans tend to focus on adaptive responses to predicted climate change impacts, such as sea level rise, water shortages, or compromised gray infrastructure performance. Yet in the urban context at the local level, green infrastructure practices may both protect the overall global climate by mitigating or reducing destructive anthropogenic greenhouse gases while simultaneously providing adaptive buffering from inevitable climate change impacts.

Existing and increasing CO_2 levels in the atmosphere will precipitate inevitable climate change impacts to most parts of the earth. While anticipated impacts vary from region to region around the globe, the International Panel on Climate Change (IPCC) predicts possible scenarios accompanying low, medium and high growth of carbon emissions, with related potential increases in temperatures by the end of the next century ranging between 1.1C and 6.4C. Even with holding CO_2 emissions steady the planet will increase .5C degrees since the greenhouse gases already emitted will remain in the atmosphere and will have a warming effect (IPCC, 2007).

While predicted impacts vary by region, increased temperatures worldwide in both summers and winters are anticipated, with exaggerated effects at the higher and lower latitudes. Temperature rise will cause increased soil evaporation, the likelihood for summer drought, and accompanying demands for water use; in regions that rely upon snowpack for water supply, less winter snow accumulation will reduce the amount of available summer water needed for irrigation, plant survival and human comfort. This change in temperature and water regimes will add stress to ecosystems such as forests, wetlands, and streams and the species that are adapted to existing environmental conditions, reducing overall biodiversity, favoring pest invasions, and especially impacting sensitive species. In addition, higher summer temperatures will be exacerbated in urban areas, where the «urban heat island effect» (UHI) already raises temperatures. In addition to the warmth-retaining mass and surfaces in cities, waste heat emitted from industrial operations, vehicles, and air conditioning raises temperatures in urban areas. The UHI can have dire implications for urban populations, especially the many with vulnerabilities and without mechanical cooling; humans are able to survive only within a narrow range of body temperatures, as became apparent in the

2003 heat wave, or «Canicule», in Europe which was responsible for the loss of over 70,000 lives. Not only is the number of extreme heat days in cities increasing, but they are predicted to cluster in heat waves that disallow the periodic cooling required for human health and survival.

Stronger storms and wetter winters are also predicted with a warming climate, bringing increased flooding as well as river and stream erosion, further threatening human health and biodiversity. Sea levels are conservatively predicted to rise .18 to .59 meters (IPCC, 2007) within the next century, inundating productive lowlands and coastal cities housing a significant portion of the world's population, as well as exacerbating storm flooding and causing sewer back-ups in urban areas. It is worth noting that the 2007 IPCC estimate does not account for potential ice sheet flows or climate-carbon feedbacks, and more recent estimates of sea level rise by 2100 is one to two meters. In a world where over half of the population lives in urban areas, and with this fraction growing, climate change is certain to dramatically impact the lives of significant numbers of people, as well as the organisms and systems upon which they depend. The question is not whether there will be adverse environmental and human consequences, but how extreme they will be.

Despite these predicted impacts and the clear scientific consensus that climate change is at least in part anthropogenic, global attention and action to minimize the intensity of altered conditions and to prepare for their inevitable effects is stalled. Obstacles to action by both the populace and their governments include the gradual timeframe and uncertainty of the severity of future impacts; the enormity, complexity and variability in projected impacts that make future conditions difficult as well as unpleasant to consider; the potential near-term costs coupled with the non-immediacy of the problems; doubt about anthropogenic genesis of climate change propagated by purposeful climate sceptics; stalemates between governments that disagree on the actions that need to be taken; and the generally depressing prospect of so much damage that is being wrought by our individual and collective actions, which discourages many people from engaging the issue. With such looming grand challenges, and so many seemingly insurmountable obstacles, how might Urban Green Infrastructure benefit our global and local climates? I assert that, while it is by no means a panacea by itself, green infrastructure can contribute positively, adding to a suite of practices that must be taken up in order to reduce the severity of climate change in the next century, as well as to aid urban populations in adapting to its inevitable negative effects. In this paper, I argue that Urban Green Infrastructure (UGI) has two inherent attributes that recommend it as an important component in addressing climate change. First, UGI serves multiple functions, making it cost-effective, aesthetic, and desirable regardless of its relationship to climate change, and thereby potentially much less politically charged, costly or unpleasant to undertake. Second, green infrastructure can simultaneously address both *mitigation* – reducing the overall degree of global climate change – and *adaptation,* that is, helping humans to cope with some of the impacts of a warming climate that are already upon us. This paper examines these two perspectives in its contention that Urban Green Infrastructure is an important land-based strategy that should be employed as cities are planned, designed and retrofitted. I define green infrastructure operationally as a set of five systems: social, biological, hydrologic, circulatory, and metabolic. The research question is: What is the capacity of each of the five systems of Urban Green Infrastructure to provide multiple, overlapping benefits, and what are each system's potential for addressing both climate change protection (mitigation) and adaptation? The paper ends with propositions and considerations for employing green infrastructure as a critical strategy for addressing climate change challenges in the urban environment.

Urban Green Infrastructure Providing Multiple Benefits

The definition of green infrastructure has evolved from primarily signifying large scale, undeveloped spaces surrounding communities – greenbelts, greenways and agricultural lands that provide ecosystem services, as first described by Benedict and McMahon (2006)[1] – to its application to cities as articulated by Girling and Kellett (2005): «*the entirety of urban green spaces*» that *«performs a multitude of vital environmental services in cities»*. Green infrastructure is also a term used to signify a natural-systems approach to utilities, which employs natural forms and processes such as detaining and filtering stormwater in vegetated swales and reducing impervious surfaces to increase infiltration; terms such as «high performance infrastructure» (New York City and Design Trust, 2005) and «green stormwater infrastructure» (Seattle, Green Stormwater Infrastructure, 2012) are synonymous to this connotation. A European team reviewed literature on green infrastructure and summarized it in a definition that encompasses urban to rural networks that comprise both built and natural ecological systems, where green infrastructure is: *«…considered to comprise of all natural, semi-natural and artificial networks of multi-functional ecological systems within, around and between urban areas, at all spatial scales»* (Tzoulas, et al., 2007). In this paper I use this comprehensive spatial and system definition, adding to it the recognition that green infrastructure provides services that benefit both humans and other species:

> *All natural, semi-natural and artificial networks of multi-functional ecological and low-impact systems within, around and between urban areas that provide services while promoting the health of humans and their related environments.* (Rottle and Maryman, 2012).

1 Benedict and McMahon first described green infrastructure as «the interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife» (2006, p. 1).

Further, Urban Green Infrastructure can be identified as five critical systems: social, biological, hydrologic, circulatory and metabolic, with all referring to the outdoor spatial and physical environment of the city. I describe each of these systems below:

The Social System is comprised of the community outdoor spaces, especially public, that provide places to play, meet, celebrate, exercise, eat, drink, express, debate, and reflect. They are the portions of the public realm that bring comfort, delight, connection and health to urban dwellers; they are the spaces that make us want to live in cities, which in turn aids us in minimizing our personal ecological footprints compared to suburban and rural living. It is a commonly held notion that compact cities are more sustainable than sprawling metropolitan regions, since residents in compact settlements typically consume fewer resources; yet, a system of accessible, highly functioning community spaces is essential to attracting residents from the suburbs and making a city livable and lovable, critical qualities of a truly sustainable city.

The Biological System provides spaces and qualities that support multiple species, enhancing a region's characteristic biodiversity. Often built in former biologically rich environments, cities typically degrade ecological integrity and impede critical flows; however greenbelts and continuous tree canopies, riparian corridors and shorelines, large patches of native vegetation, and even small scale plantings and water flows can provide essential ecological connectors through urban areas. Taking steps to fortify the biological health of the urban environment can reduce the inherent urban stresses on life forms, which are exacerbated by the effects of climate change such as increased heat and altered water regimes; urban forests not only provide shelter and food but also act as temperature regulators. Biologically rich landscapes and the species they support also afford human contact with nature in the city, providing significant restorative and educational benefits through these experiences.

The Hydrologic System encompasses water as a resource as well as the health of aquatic environments. Five «waters» can be considered for these purposes: clean water source for drinking; stormwater, or rainwater that falls on urban surfaces; greywater, which is water that has been used for functions such as washing and is easily recycled for other uses; black water, or sewage; and aquatic environments. The first four can be seen as resources, reducing demand through reclamation and providing redundant urban water sources. If not managed well, these waters can have deleterious effects on aquatic environments through pollution, scarcity and altered hydrologic regimes, while on the other hand, they can be used to enhance aquatic habitats through ecological design. A green infrastructure approach to the hydrologic system implies that we can apply new ways of harvesting, re-using and treating water, especially as it becomes a scarcity, while also minimizing impacts to and enhancing habitats as well as providing aesthetic amenities.

Considering water as part of a «closed-loop» system where it is recycled and re-used can be a helpful framework for hydrologic resource conservation.

Active transport is the green infrastructure focus of the Circulatory System. This system includes cycling networks and facilities, and pedestrian environments that encourage walking and lingering in the urban public realm. If designed well, both of these modes also serve to connect people from their homes to work and school and to public transit nodes, creating safe and more inviting environments and flexible, well-connected networks of movement through the city. Use of active transport rather than automobiles can not only increase health of the environment and atmosphere, but, importantly, can also contribute to human health by engaging people in daily physical activity. Recreational bicycling and walking trail networks are also important parts of the system, significantly adding to a city's liveability and desirability, as confirmed by their current popularity demonstrated by real estate values and sales of housing near to these amenities.

The Metabolic System consists of energy-producing elements that have minimal impacts to the Earth's deteriorating climate. In the Urban Green Infrastructure rubric this includes elements such as small-scale energy generators that harness natural processes and which can be used in the urban environment, such as wind turbines on buildings and in parks, solar hot water heating and cooling, and photovoltaic mechanisms. Such generators can also potentially send energy back to the grid. Importantly, this category also features the urban food system, which supplies the food that we metabolize for our personal energy with minimal atmospheric impacts of transport, processing and packaging. The urban food system includes urban and community gardens, farmland on the urban fringe, and farmer's markets that bring local food from the grower to the consumer.

While each of these systems can provide numerous human and environmental benefits, the hallmark of Urban Green Infrastructure is its multifunctional performance. Where traditional infrastructure typically addresses a single system with a sole function, green infrastructure most often serves multiple functions and provides more than one ecological service. An example of this multi-functionality is urban forests, which simultaneously yield several benefits: delivering climate control through shading buildings, streets and people; providing habitat for birds and other arboreal species; reducing stormwater runoff and erosion by intercepting rain and evapotranspiring it; improving air quality by removing particulates; and enhancing the aesthetics, spatial definition and comfort of urban community spaces. Like urban forests, other green infrastructure features – on scales from park systems, to pedestrian and cycling streets, to living roofs – address multiple systems and values simultaneously. In this way, they are cost effective approaches to not only solving environmental issues, but also providing the amenities that people enjoy and want to support. Green infrastructure systems are also often less expensive than their gray counterparts; a study by American Rivers and partner organizations determined that green infrastructure techniques can be less costly to implement while also reducing stormwater treatment, energy, flooding and public health expenses (American Rivers, et al., 2012). If the finances now spent to build and maintain gray infrastructure such as pipes, vaults, and transmission lines, to repair flood damage, and to provide health services related to sedentary lifestyles and contaminated water were instead spent on implementing green infrastructure, our cities could be rendered more ecologically sound, healthful for people, and environmentally legible and delightful.

A corollary to the affordability of green infrastructure is that it often augments rather than replaces gray infrastructure, reducing scale costs and providing redundancy in a system that therefore lends it resiliency in severe situations. For example, cities may still require pipes to carry the highest stormwater flows in heavy storms, but the use of rain gardens, street trees and permeable surfaces can reduce the size of these expensive pipes and vaults and decrease the number and severity of flooding events. Similarly, allocation of street lanes to cycling and safe, enjoyable pedestrian environments can reduce the wear and tear and accompanying costs that vehicles generate, while also providing an alternate mode of mobility when traveling by motorized means might be constrained by weather or catastrophe. With such redundancy, if one system is hindered another can take over without losing essential function, imparting resiliency in a city's infrastructure.

With these multiple overlapping benefits, it can be seen that regardless of political persuasion or climate change beliefs, it is advantageous to plan, design and implement Urban Green Infrastructure to render cities safe, livable, and healthy, with potential secondary benefits to the global atmosphere and towards resiliency to climate change impacts.

Addressing Climate Change Mitigation and Adaptation

In their 2007 article Swart and Raes posited, *«the question is not whether the climate has to be protected from humans or humans from climate, but how both mitigation and adaptation can be pursued in tandem»* (p. 301). Discovering and implementing methods for adapting to climate impacts while also reducing the severity of those impacts – e.g. mitigating the degree of human-caused climate change – is a critical planning principle to address climate change in the built environment. The IPCC defines *mitigation* as «*anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases,*» while *adaptation* is the «*adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities, that is, how organisms can cope with the actual impacts of climate change such as increased heat, floods, drought, and rising seas* (IPCC, 2007, p. 869). Practices that protect the climate, especially through reduction of greenhouse gases, tend to affect the global environment, while adaptive strategies are more likely to operate at the local level.

In his book *The City and the Coming Climate* (2012) Brian Stone argues that the IPCC definition of mitigation lacks inclusion of land-based strategies that can help to minimize climate change impacts, and contends that such strategies are significant in their potential to decrease the overall severity of climate change as well as its deleterious impacts on human health and well-being, going so far as to say *«land-surface changes are the single most effective option available to cities to counteract the very real threats of climate change in the next half-century»* (p. 99). Robust systems of Urban Green Infrastructure provide land-based strategies that will typically simultaneously address both mitigation and adaptation, and therefore this rubric provides a powerful and easily deployed conceptual tool for guiding planning and design policies. Below I examine each of these systems separately to evaluate if and how they might help to protect the climate, and how they can help humans adapt to climate change impacts. I first examine each system's capacity to *mitigate* the severity of future climate change, primarily through reduction of greenhouse gases, and then survey the capability for green infrastructure to decrease or help humans *adapt* to the negative effects of irreversible impending climate patterns.

Climate Change Mitigation

First, in examining the Social System for its ability to protect climate, I have reasoned in the preceding section of this paper that community and open space supports livable, compact urban form. Such compactness of settlement is required to feasibly support public transport systems and can generate close-knit social communities, enabling people to drive less and thereby reduce carbon emissions. Providing access to amenities such as gathering spaces, play areas and contact with the natural world in the urban context attracts people to choose this compact form, to live in cities, generating smaller individual «ecological footprints» that can be achieved through shared residential housing as well as from use of public transit and active transport. Open space advocate Mike Houck from the Portland Green spaces Institute has reversed Thoreau's famous aphorism about wilderness, quipping, *«In livable cities lies the preservation of the world.»* Cities such as Amsterdam and Copenhagen have recognized the import of green space in their «finger plan» growth planning, with both cities designating urban development to occur along fingers of transit corridors separated by generous green space in the «webbing» between the urbanized fingers, providing easy access to open spaces from cities and towns. Copenhagen's 1947 Regional Plan (or «The Five Finger Plan») is based upon goals that the public should be able to easily access nature as well as transportation infrastructure. A contemporary summary of the plan describes its intent that «*People should have the possibility to enjoy forests and lakes, agricultural landscapes, rivers, streams and fjords and still benefit from the close proximity to the city centre.»* (Copenhagen Capacity, 2012). Contemporary Vancouver, B.C. is a model of a dense residential city center with ample open space, from large forest reserves to small pocket parks, connected by a continuous public shoreline and bicycle trail, which together with protection of views between thin residential towers provides the context for an exceptionally high quality of compact urban life.

The Biologic System directly contributes to climate mitigation through carbon sequestration in soils and vegetation, and indirectly by cooling buildings and cities so that fewer fossil fuels are used for air conditioning. Mature, large trees have been found to proportionally sequester more carbon than newly planted small trees (Nowak and Crane, 2002). One 12" diameter tree sequesters an average of 17 pounds of carbon per year (equivalent to an average of 63 passenger car miles), while a 30"

Figure 1
Vancouver, B.C. Canada is regularly rated one of the world's most livable cities, with high-density podium towers, carefully planned views and connected green spaces and a continuous public shoreline.
PHOTO: NANCY ROTTLE

diameter tree will sequester 92 pounds of CO_2 annually, or equivalent to the carbon emitted in 337 vehicle miles. Planted areas, including the organic components of soil, and green roofs can also contribute to carbon sequestration in the city. A study of a dozen extensive (thin substrate) green roofs over two years found that the carbon dioxide sequestered in both above and below ground biomass averages 375 g carbon per sq. meter (Getter, et al., 2009). In addition to removing greenhouse gases from the air, a large tree shading a western wall can save 268 kWh of electricity per year in the Midwestern US, and 3,430 kBtu annually for heating and cooling (McPherson, et al., 2006), with concomitant reduction in carbon emissions that would otherwise be produced through burning of fossil fuels to produce that energy. The vegetation and soils in green roofs and walls can also help to reduce energy consumption in buildings by insulating them from heat, cold, and solar radiation. One study modeling energy consumption in Houston buildings found that green roofs in that city could reduce natural gas consumption by 11 %, due primarily to cooling (Sailor, 2008).

Carbon is also stored in the wetland, stream and «green stormwater» environments of the Hydrologic System, both above ground in the bodies of aquatic plants, and in the organic, humus-rich wetland soils that retain carbon. Additionally, use of green stormwater infrastructure can significantly reduce the CO_2-intensive manufacturing process of concrete catch basins, pipes and vaults, while infiltrating water and using the microbes in soils and plants to treat water close to where it falls can reduce energy required to pump stormwater to a receiving water treatment plant. In a study of energy used to treat wastewater in Illinois, it was estimated that 1,300 kWh of electricity is required for treatment of each million gallons of wastewater (NRDC, 2009). When stormwater is harvested for onsite re-use, energy required to pump potable water from afar can also be significantly reduced. The energy to convey, treat, and distribute water in Southern California is calculated at 12,700 kWh per million gallons of water used (California Energy Commission, 2005); replacing transported water with that from water harvested from rainwater, graywater (such as air conditioning condensate) and wastewater could significantly lower that carbon-generating energy footprint.

Seattle's Residential Rainwise program is an example of simultaneously reducing stormwater in the combined sewer system while also promoting rainwater harvest and re-use. Residents living in prioritized combined sewer basins are eligible to receive monetary assistance of up to US$ 3.50 per square foot of impervious surface managed by installing rainwater cisterns to collect and hold rooftop water and by collecting runoff in «raingardens» that infiltrate stormwater which would otherwise flow to the wastewater treatment plant (Seattle Rainwise, 2012).

In the Circulatory System, the carbon reduction benefits of walking and cycling compared to driving personal vehicles are obvious. A conservative estimate of the amount of CO_2 emissions saved through cycling rather than taking car trips in the EU is 11 million tons (European Cycling Federation, 2011). Well-designed pedestrian environments also encourage use of public transit. The environmental conditions of the «walksheds» around transit stations can encourage or deter use of buses, trolleys and trains: streets that are human-scaled, safe, protected from unpleasant elements of weather and noise, and that offer comfort, interest and delight best support walking and transit use. Cycling facilities such as bicycle parking, and buses and train cars that accommodate bicycles, further support the use of active transport for commuting. Copenhagen's traffic division prioritizes the bicycle as the form of urban transport, with over 50 % of all trips within the city taken by bicycle (City of Copenhagen, 2011a). With over 35 % of commute trips taken by bicycle, the region's planners have instituted Cycle Superhighways connecting regional towns to the city, to raise the mode split in further favor of daily bicycle trips to work and school. New York City's closure of over a mile of Broadway has been enormously successful in accommodating and spurring greater pedestrian and bicycle use in the center of Manhattan. Within the first year after street improvements were made, not only did pedestrian use increase while injuries were reduced, but travel speeds for vehicles also improved (New York City, 2012). Such shifts in conditions to favor walking and cycling can significantly reduce the carbon emissions generated in a metropolitan region.

Energy production by alternative local sources in the Metabolism System also has clear climate benefits. Well-functioning small scale, in-place energy production such as solar and photovoltaics, micro-hydro, wind turbines, and heat from burning urban forest waste can be used efficiently without loss of energy from transmission, with ample reduction in greenhouse gas emissions potentially achieved compared with burning coal and oil. Climate protection can also be significant through sourcing food – which provides human energy – through local urban agriculture systems compared to industrial agriculture; fewer «food miles» and less fossil fuels used for pesticides, herbicides and packaging produce fewer greenhouse gases, while support of local agriculture through farmer's markets, allotment gardens and farmland preservation measures can preserve and build carbon sequestering soils.

Providing opportunities for residents to grow food, to engage in urban agriculture, and to purchase locally produced agricultural products in an accessible urban food system can therefore contribute to climate mitigation. Seattle's «P-Patch» program and its numerous Farmer's Markets provide such an example of a robust local food system. The city's P-Patch program makes available over 75 community garden spaces located throughout the city's urban neighborhoods which residents rent to grow food and flowers, with over 20,000 pounds of excess produce donated to local food banks in 2011 (Seattle P-Patch, 2012). The most recent «Upgarden» has been built upon the top of a 1960s parking garage in the city center, providing over 30,000 square feet of gardening space for neighborhood residents. The City also sponsors several market gardens, where gardeners, many who are immigrants, grow produce that is sold as community supported agriculture (CSA) subscriptions to augment personal incomes (Seattle Market Gardens, 2012). Over a dozen farmer's markets spread throughout the city provide access to local food while supporting livelihoods of urban and rural small-scale farmers.

Figure 2
Seattle's new «Upgarden» is a community garden created on the roof of a 1960s parking garage in the city center, with a vintage car serving as a planter. The garden is one in a system of over 75 urban community gardens.
PHOTO: NANCY ROTTLE

To summarize the above analysis, practices within each of the five green infrastructure systems can effectively contribute to climate change mitigation, lowering the amount of greenhouse gases in the atmosphere and therefore potentially easing the future adverse conditions that climate change will produce. With such practices taken up worldwide, and combined with other significant measures to reduce greenhouse gas emissions, we might expect to cope with low-emission rather than high-emission scenarios, which vary dramatically in anticipated temperature and sea level rises.

Climate Change Adaptation

Next, this examination takes a similar approach to evaluating the value of each of the five green infrastructure systems for climate *adaptation*, briefly assessing each system's utility in mollifying local and regional impacts that are predicted to occur, whether within the current concentrations of CO_2 in the atmosphere in low-impact scenarios, or with an increase in atmospheric greenhouse gases that will result in higher-impact scenarios. Incorporated in these analyses is the likelihood of a robust green infrastructure system to imbue resilience in a metropolis, which will be required to cope with extreme events such as high heat – already an issue with growing urban heat island effects – as well as the gradual degradation of ecosystem health.

First, can the Social green infrastructure system help us to adapt to, or minimize the consequences of climate change? If the global population continues its predicted pattern to inhabit cities, then social space may provide significant benefits, especially in aiding the urban populace to cope with extreme heat events. Without air conditioning – which many will lack due to the cost of energy, or blackouts precipitated by extreme heat – outdoor spaces may provide refuge from the stifling heat that can accrue in indoor spaces, and therefore save lives. Social space may also facilitate neighborhood residents in coming to know each other, thereby building community strength that is critical in coping with catastrophic events such as high heat, flooding, and power failures. Interpersonal relationships can be especially important to the elderly and infirm who rely on special services to survive; attention from neighbors in the absence of these services can be a matter of life and death. In the European heat wave of 2003, it is thought that many elderly died not only as they lacked air conditioning to cool nights, but also because their families were away on holiday and therefore unable to check on them (Stone, 2012).

Many cities are incorporating water features in new public parks and plazas, recognizing the aesthetic draw of water as well as the relief it provides in high summer heat. For example, Jamieson Park in the city center of Portland, Oregon overflows with families and children playing in the shallow water fountains on warm sunny days, serving as a hub for this new urban residential neighborhood. In Copenhagen, Islands Brygge waterfront park is an achievement by local residents to claim outdoor recreational space on the harbor, serving as a living room for the dense residential district, and its floating swimming platform has become a popular draw and icon for the city's renowned public life culture.

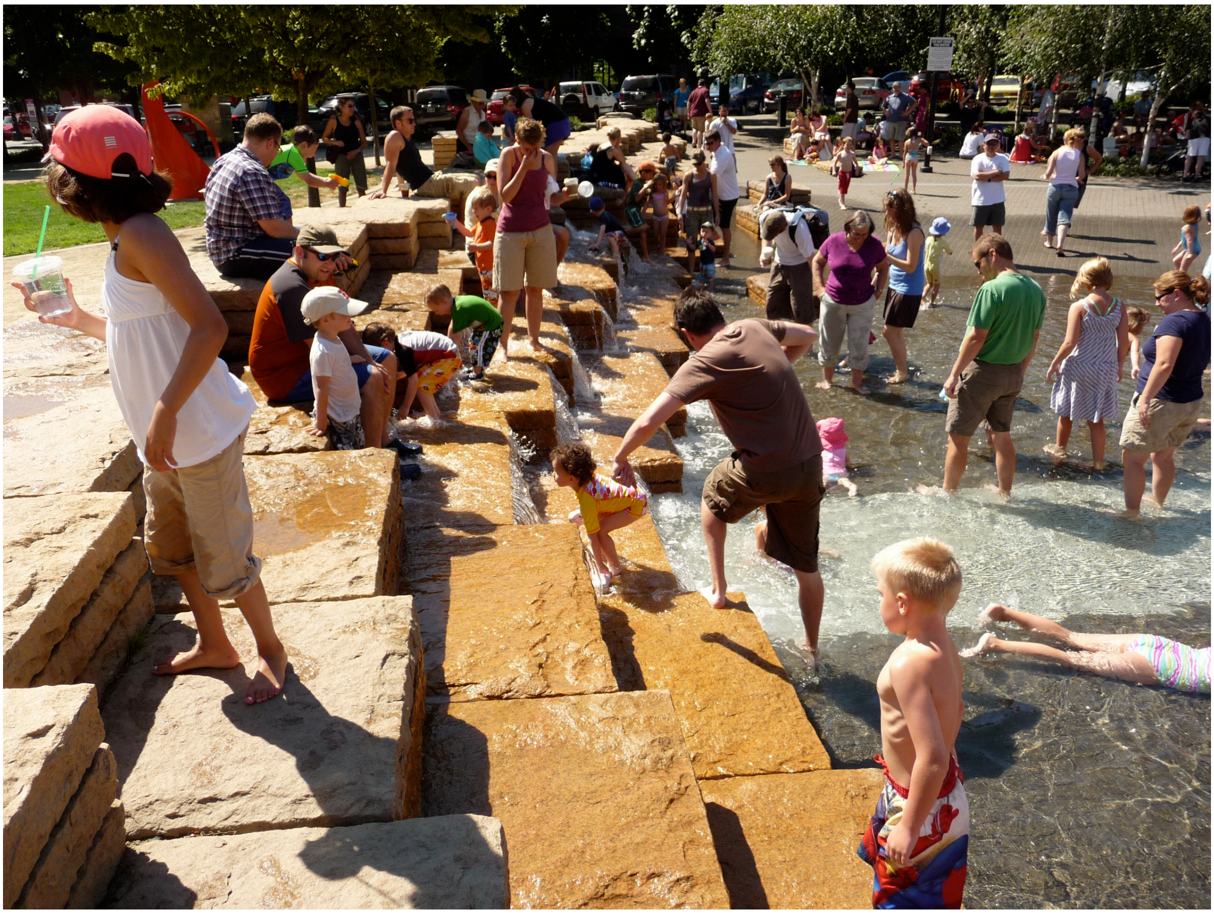


Figure 3
Jamieson Park in Portland's Pearl District provides an urban gathering space that is especially popular with children on hot days. The urban park spaces in this new downtown district invite families to live in a more compact, urban setting.
PHOTO: NANCY ROTTLE

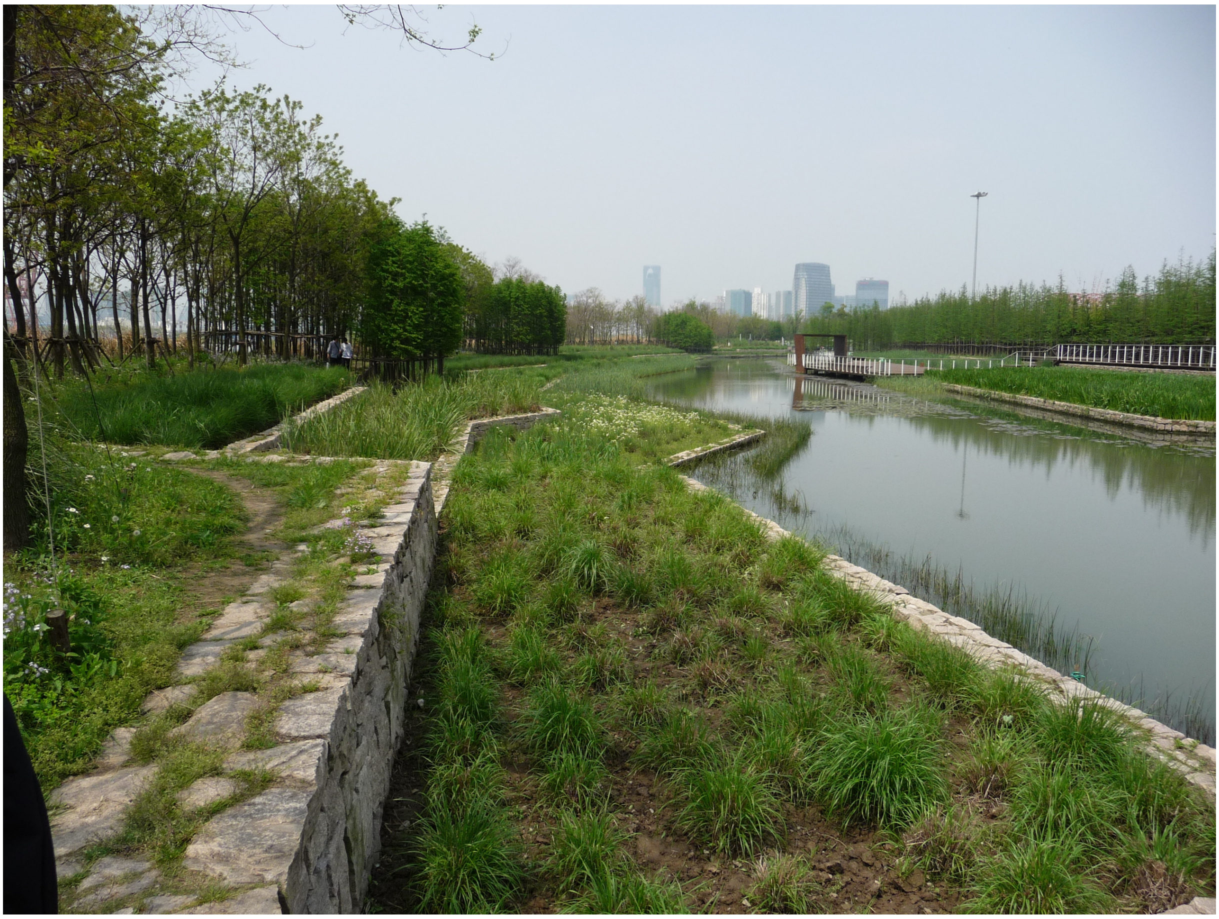
The Biological System has great capacity to aid cities in coping with the impacts of climate change, especially in mollifying heat island effects and increased stormwater impacts, for both human well-being as well as survival of cool-temperature species such as salmon. Forests, trees, riparian zones, and green roofs and walls generally cool and add moisture to the overall environment. A number of studies confirm that trees can reduce outside temperatures significantly; McPherson, et al., found the variation between green/non-green city centers to be as much as 9 °F (2006). Irrigated green roofs can help to cool air and building temperatures, through evaporative cooling and reduction of surface albedo, providing relief in heat events. A study for Toronto estimated that greening 50 % of the surface area of the city's downtown flat roofs with irrigated green roofs would produce cooling of the city by approximately 2 degrees Celsius (Liu and Bass, 2005). Cooling the overall environment can reduce the amount of air conditioning needed for individual buildings, with the double benefit of both climate mitigation and adaptation. In a study to assess potential adaptation benefits of green infrastructure over the next century in Manchester, England, the University of Manchester developed computer models for future climate change scenarios which indicated that adding ten percent tree cover in urban areas could maintain urban surface temperatures at or below 1990 levels. In contrast, the study predicted rises of 1.7 C degrees by 2080 with only maintenance of the current tree canopy, or, worse still, a 5+ C degree rise if ten percent of the tree coverage were lost in the town center, even for a low-emissions future scenario. In that same study, models indicated that greening all roofs would maintain temperatures below 1990 for all scenarios and land cover types, as opposed to temperatures as much as 7.6 C higher if roofs were not greened in the town centers, in the high-emissions scenario (Gill, et al., 2007).

Urban greening also provides significant potential benefits for supporting biodiversity in the face of climate change, both in its provision of continuous habitat along continental and regional migration routes for seasonal species, and in enhancing overall biodiversity within cities. In addition to reducing higher temperatures caused by the urban heat island effect, connected, diverse and especially native vegetative habitat will generally contribute to native species' health, helping to build resilience to stressful new conditions caused by climate change. Such resilience may include resisting negative impacts of exotic and pest invasions. Riparian vegetation in connected stream, lake and river corridors will help cool water, to help salmon and other cold-water species to survive. Connected corridors of canopies and ground level vegetation not only cool cities, but also provide shelter, food, nesting and movement opportunities for birds, mammals, amphibians and insects that are stressed by both urban conditions as well as climate change impacts. Green roofs may also aid in providing habitat: a study in Berlin found 7 % of regional species on one small roof (Kohler, 2006), while in Greater London researchers found 10 % of species classified as «nationally rare and scarce» on the city's green roofs (Kadas, 2006).

Hydrologic green infrastructure – sometimes called «Green Stormwater Infrastructure (GSI)», «Low Impact Development (LID)» and «Sustainable Urban Drainage (SUDS)» – can be especially effective in helping people and their environments to adapt to climate change impacts. Green stormwater practices that strive to infiltrate rainwater where it falls will help cities to cope with increased precipitation and storm intensity, manage flooding, and reduce pollution and temperature stresses to aquatic environments. As summer climates become hotter and drier, water harvest and re-use will become more important both for direct consumption and to maintain vegetation so that it survives and can provide full climate-mitigation and adaption functions. Collected and re-used water can replenish or reduce demand on limited water and energy resources, assure adequate water supply for domestic, industrial and agricultural needs by providing a redundant source in times of shortages, and forestall need for costly and often environmentally damaging water supply plant expansions.

The range of possible forms of green stormwater infrastructure is limited only by the imagination. Biological systems can be used to clean water, to minimize stresses that polluted water impinge on aquatic environments and to allow reclaimed water to be re-used as a resource. Houtan Park in Shanghai, China, is an example of a park design that moves severely polluted water through a series of wetland pools, cleansing the water from a Grade V to a Grade II, after which it is used to irrigate the park (Landscape Architecture Foundation, 2012). In Portland, Oregon and Seattle, Washington, streetside «raingardens» are used to detain, infiltrate and clean dirty stormwater from vehicle-traveled surfaces before it drains into streams, rivers and bays. In two years of monitoring of Seattle's «SEA Streets» these biofiltration swales reduced the amount of runoff by 99 %, while a second design using cascading ponds on a steep hillside was found to substantially reduce pollutant levels in the stormwater (Horner, Lim and Burges, 2004; Chapman and Horner, 2010). Urban forests are an important component in green stormwater infrastructure in temperate and tropical climates, since trees help to intercept, absorb, and evapotranspire rainwater, as well as facilitate infiltration of rainwater into the soil. A study on the effects of tree canopy in the US Pacific Northwest estimated an average of 30 % reduction in stormwater runoff due to interception and transpiration of conifer trees (Herrera, 2008). Green

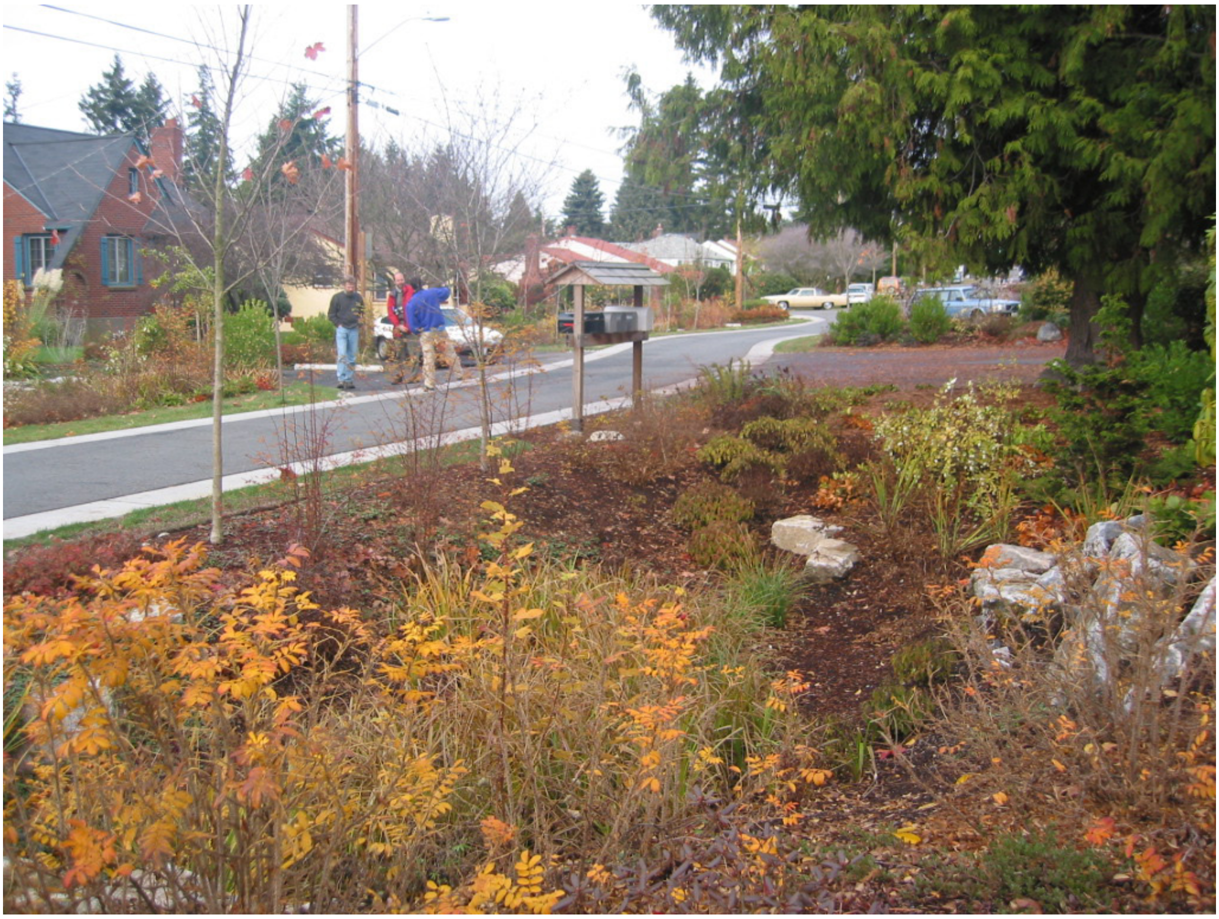
Figure 4
Houtan Park in Shanghai, China, purifies polluted river water in a series of wetlands so that it can serve as an urban amenity as well as be re-used to irrigate the extensive plantings in the riverside park. Design by Turenscape.
PHOTO: NANCY ROTTLE



roofs have been shown to retain and evapotranspire 40–80 % of annual precipitation, depending upon roof depth, substrate, and climate (Carter and Rasmussen, 2006; Deutsch, et al., 2007). In the Manchester study cited above, Catherine Gill and her research partners projected that increasing tree cover and adding green roofs would reduce projected higher stormwater runoff, though not sufficiently to handle all of the anticipated future increase in precipitation due to climate change (Gill, et al., 2007).

In the Circulatory green infrastructure system, active transport not only mitigates climate change through reducing carbon emissions, but also can influence immediate local conditions by reducing the substantial waste heat burden that motor vehicles contribute to the urban heat island effect. In addition, air pollution is exacerbated by heat, so walking and cycling instead of driving may help to lessen the unhealthful conditions that extreme heat events produce. Indirectly, active transport can provide resiliency to a city coping with climate change impacts: walking and cycling provide a form of transport redundancy that can be undertaken even in times of fuel shortages, storm damage or other catastrophic events. Engaging in active transport can also build personal resilience to cope with climate chaos events through the documented benefits of physical and mental health enhancement that are gained through

Figure 5
Streetside «Street Edge Alternative (SEA Street)» biofiltration raingardens in Seattle have proven to both detain and infiltrate water as well as cleanse it of pollutants.
PHOTO: NANCY ROTTLE



regular exercise. Walking and cycling, and the environments that support these forms of movement, also foster conviviality in the public realm and therefore interpersonal and cultural ties, building the social resiliency that is necessary to ensure that all are cared for in extreme events. Building the infrastructural networks that support active transport also can enable all citizens adequate mobility, promoting a more democratic and therefore potentially more resilient society.

While green infrastructure components in the Metabolic System may be most effective in reducing climate change through reduced carbon emissions, elements in this system can also foster resiliency through providing alternative energy supply, whether to cope with increased temporary demand – such as cooling needs during heat events – or seasonal reduced supply, such as when hydroelectric flows become low through drought. Similarly, while local food systems can reduce carbon emissions, they also enhance supply in times of shortages that might be caused by extreme or unexpected climate patterns, supplementing food sources from other regions that might be impaired by storm or drought. Here again, the social resiliency formed through community gardening and local farmer's markets can become an important factor in helping people to cope with local disasters and shortages wrought by climate change.

Analysis

Table I summarizes the above analysis of the capacity of green infrastructure to mitigate climate change (or, protect climate) at the global level, and to help the human populace and other species to adapt locally to the inevitable impacts of increased greenhouse gases in the atmosphere. It can be seen that implementation of each of the five green infrastructure systems can contribute to both mitigation and adaptation. Moreover, many of the components of these systems can provide multiple benefits, such as urban forests and green roofs helping to reduce energy use needed for cooling while also providing habitat, or use of collected water to generate electricity while also reducing demands on potable water supplies. Additionally, many of the system components can be spatially combined: for example, community space can support urban forests, green stormwater treatment, habitat, and pedestrian and cycling networks if planned and designed well.

Table 1
The table summarizes the analysis investigating the capacity of each of the five green infrastructure systems to mitigate and/or provide adaptive advantages to climate change impacts.

	Mitigate – Global (reduce energy usage, store carbon)	**Adapt – Local** (reduce stresses of extreme weather & resource shortages, community resilience)
Social: Community Space		
Urban Amenities support Compact Form	x	x
Urban Social Space, Nearby Nature	x	x
Circulatory: Active Transport		
Pedestrian Environments, Connections to Transit	x	x
Cycling Networks	x	x
Hydrological: Five Waters		
Water Supply: Harvest and Re-use (rain, greywater, blackwater)	x	x
Green Stormwater Treatment – Biofiltration, Green Roofs, Tree Canopy	x	x
Aquatic and Coastal Environments	x	x
Biological: Habitat		
Urban Forests, Connected Habitats, Corridors	x	x
Habitat Patches, Green Roofs, Green Walls	x	x
Metabolism: Energy		
Local Food Systems: Community Gardens, Urban Farms, Farmers' Markets	x	x
Small-scale Energy Production	x	x

Discussion: Adaptive Mitigation

While many adaptive strategies can be employed to help the human race cope with the impacts of climate change within growing urban populations, many of these strategies may only exacerbate the situation, producing ever more greenhouse gases which will then precipitate more dramatic changes and more severe conditions to which we must then find adaptation mechanisms, in a downward spiraling feedback loop. For example: coping with higher temperatures will require more energy-intensive air conditioning, and add more waste heat to the urban environment; lack of potable water supplies will stimulate energy-intensive desalinization; and flooding from bigger storms will suggest that larger (greenhouse-gas emitting) concrete detention and conveyance systems be built. Those who are able may elect to move out of hot cities to the countryside, triggering increased burning of fossil fuels for transportation and heating. Some adaptive actions will have secondary negative impacts – for example, coastal cities may build high levies along their shorelines for protection from rising seas, severing their populace from the elements that both cool the air and provide high quality livability, and, adding insult to injury, reducing shoreline habitat and biodiversity and the aquatic resources they support.

Therefore, it is paramount to identify actions that provide local protection from climate change impacts while also serving to minimize future impacts through reducing greenhouse gas emissions. Brian Stone calls these actions «*adaptive mitigation*»: *«climate management activities designed to reduce the global greenhouse effect, through the control of gaseous and/or land-surface drivers, while producing regional benefits in the form of heat management, flood management, enhanced agricultural resilience, or other adaptive benefits.»* (2012, p. 147).

Adaptive mitigation also implies that climate protection efforts should not exacerbate the adverse immediate impacts of climate change. While exceptionally dense cities may have decreased fossil fuel consumption in the short term, without the cooling advantages of urban greening they may become untenable without heat-producing and carbon intensive artificial air conditioning. In the same vein, some «compact» urban form patterns such as tall towers may block sunlight and cooling breezes, or generate excess turbulence at their bases, creating inhospitable conditions for good outdoor community space, and thereby potentially inhibiting the social cohesion important for resilience in extreme climate events.

Copenhagen's recent award-winning Climate Adaptation Plan is exemplary in setting out integrated strategies that will equip the city to cope with existing and predicted storm intensity and resultant flooding, while also providing climate mitigation benefits. These strategies feature green-and-blue infrastructure improvements, including continuous corridors of gardens, parks, nature areas and schoolyards, living roofs, facades and parking lots, planting of broad-crowned street trees, incorporating water storage in parks and courtyards, and expanding green transport links such as vegetated off-road bikeways. These adaptive features are presented as opportunities to simultaneously raise the quality of life for Copenhageners, recognizing that «*a green approach may have a broad and wide multidimensional effect, and can solve several problems of climate adaptation, as well as improving Copenhageners' health and well-being.*» (City of Copenhagen, 2011b).

From the above analysis it should be clear that green infrastructure offers multiple forms of adaptive mitigation. Each of the systems possesses the capacity to simultaneously contribute to climate protection as well as adaptation to climate change impacts. Still, the systems and their components need to be carefully integrated into the urban environment, and considered for their contributions to both climate change mitigation and adaptation. The appropriate quantity, placement and design of applied green infrastructure must be incorporated with adaptive mitigation in mind. Too much green in a city might compromise compactness, whereas not enough would be ineffective. Design solutions must be region and place-specific; for example, stormwater treatment, water harvesting and urban greening in arid regions look and function very differently from that of temperate and tropical climates. And of course, detailed study, design and application of evidence-based design is necessary, to understand and model the potential success and actual environmental services that green infrastructure can be expected to provide in future climate conditions: for example, stormwater calculations need to take predicted future storm patterns into account; plant species able to thrive in future conditions should be included in planting schemes; and designers need to be aware that some trees species can accelerate ozone formation in high heat events. Still, green infrastructure should be among the measures used in the first line of defending our global climate, and in promoting the health and survival of citizens who must deal with the acute conditions that inevitable changed climatic patterns will instigate. Brian Stone (ibid., p. 102) suggests that: «*[Tree planting] will come to be viewed as a down payment on the massive program of climate management soon to be undertaken by cities – the beginnings of an inland seawall to guard against the rising tide of heat.*» With its inherent efficiency, multiple benefits, affordability, quality of life advantages, and dual effectiveness of addressing both climate mitigation and adaptation, the integrated systems of Urban Green Infrastructure are vital tools to employ as we confront the climate change challenges ahead.

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Current Research

Current research projects include testing of stormwater quality treatment in multifunctional urban waterfront spaces; green wall and water harvesting design, construction and monitoring; investigation on climate benefits of green infrastructure; leadership on regional green infrastructure planning; and pedestrian and cycling infrastructure design and communication.