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Green Infrastructure in the Space of Flows: An Urban Metabolism Approach to Bridge Environmental Performance and User's Wellbeing

Dr Daniela Perrotti

Universite' Catholique De Louvain

Place du Levant 1/L5.05.02

Louvain-la-Neuve,

Belgium

e-mail: daniela.perrotti@uclouvain.be

Dr Ornella Iuorio

University of Leeds

Leeds

LS2 9JT

United Kingdom

e-mail: o.iuorio@leeds.ac.uk

Abstract Recent research demonstrates that urban metabolism studies hold ample scope for informing more sustainable urban planning and design. The assessment of the flows of resources that are required to sustain the growth and maintenance of cities, can allow gaining a clear picture of how cities operate to comply with environmental performance standard and to ensure that both human and ecosystem health are preserved. Green infrastructure (GI) plays a key role in enhancing both cities' environmental performance and health. GI, indeed, , mitigates Urban Heat Island effect for improved thermal comfort, allows carbon storage and sequestration for climate change mitigation, and reduces PM concentration for healthier air quality. There is a growing evidence that an understanding of provisioning and regulating of ecosystem services can facilitate more environmentally informed GI planning and design. The contribution of GI to enhanced human health and psychological wellbeing is also evidenced in recent studies valuing both material and immaterial benefits provided by urban ecosystems, including cultural ecosystem services. Therefore, the use of ecosystem service frameworks can help reveal and quantify the role of GI in enhancing both urban environmental quality and the wellbeing of human populations. However, there remains little discussion of how human health and wellbeing aspects can be integrated with environmental performance objectives. In this chapter, urban metabolism thinking is proposed as a way forward, providing analytical tools to explore pathways to more sustainable management of natural and anthropogenic resources across the urban scales. Strategies to foster integrated urban metabolism approaches that can inform more holistic GI planning are discussed. Finally future research avenues to incorporate the multiple dimensions of human wellbeing into urban metabolism thinking are highlighted.

1. Introduction

Urban metabolism studies provide a helpful set of tools to assess and analyze the environmental performance of cities, as demonstrated by a growing portfolio of research case studies (Beloin-Saint-Pierre et al. 2017). Urban metabolism is defined as the sum total of the technical and socio-economic processes associated with the production and consumption of key resources (e.g., water, food and energy) that sustain the growth and maintenance of cities (Kennedy at al 2007). Metabolic accounting frameworks enable to quantify resource inputs and outputs to/from the environment and other urban systems, as well as the associated flows of waste and pollutant emissions. Through the assessment of these flows, it is possible to analyse how cities perform to ensure that human health and ecosystems are protected from environmental harm.

A growing evidence base demonstrates that green infrastructure (GI) is a key lever to maximize cities' environmental performance and to enhance health and psychological wellbeing in urban environments. Our working assumption is that these two main areas of interest for GI planning and design are not always systematically considered from an integrated perspective in urban planning. The main ambition of this chapter is therefore to explore pathways to new integrated frameworks that consider human wellbeing and cities' environmental performance synergistically through the adoption of an urban metabolism approach.

2. GI for Cities' Environmental Performance and Human Wellbeing

GI is defined as a spatially and functionally integrated network of urban green and blue areas, including parks, private gardens, woodlands, green corridors, street trees, green roofs and facades, waterways and water bodies (Hansen and Pauleit 2014). These areas conserve natural ecosystem functions and provide complementary environmental and socioeconomic benefits to the public. The concept of "ecosystem service" was created to define the wide-range of benefits humans obtain from ecosystems (Millennium Ecosystem

Assessment 2005). The concept was subsequently employed to quantify and value the benefits that GI provide to urban populations, and facilitate the applications of ecosystem service assessment frameworks in urban planning (Hansen and Pauleit 2014). Among the several ecosystem services provided by GI, provisioning services, as well as air-quality and climate regulating services are key to unravel the contribution of GI to an increased environmental performance and enhanced health and wellbeing in cities.

2.1 Provisioning Ecosystem Services

Research on provisioning ecosystem services offers evidence that GI can optimize the metabolism of cities, through mitigating the water, food and energy demand and reducing the dependence of cities on external catchment areas.

Provision of freshwater, food, as well as renewable energy from locally harvested biomass can enhance cities' self-sufficiency and reduce their dependence on external resource imports; this can additionally result in minimized use of fossil energy for the transport of goods and produces (Pataki et al. 2011). Rainwater collection and treatment contribute to a more circular urban metabolism through maximization of internal recycling and minimization of water imports (Agudelo-Vera et al. 2012). Urban agriculture initiatives optimize local food productivity and reduce the dependence of cities' populations on external imports (Mohareb et al. 2017), facilitating the abatement of transport fuel consumption and greenhouse gases (GHG) emissions associated with the reductions in transportation, cold storage in distribution, and landfill gas emissions from avoided waste along the supply chain (Mohareb et al. 2018). Renewable energy from locally sourced biomass contributes to decrease the share of fossil fuels in the urban energy mix, while minimizing energy imports from external sources (Voskamp et al. 2016).

2.2 Air-Quality and Climate-Regulation Ecosystem Services

GI can uptake gaseous pollutants and intercept larger soluble ambient particulates, resulting in improved air quality. In US cities, the contribution of GI to the reduction of $PM_{2.5}$ concentration has been reported in the range of 0.05-0.24% per year, corresponding to a reduced mortality as high as 7.6 persons/year (Nowak et al 2012). Meanwhile, Tiwary (2002) reports that in London a 10x10 km grid with 25% tree cover is estimated to avoid 2 deaths and 2 hospitalizations per year, through reduced PM_{10} concentration.

GI can also benefit climate regulation, for example, through the mitigation of the Urban Heat Island (UHI) effect. The UHI effect is the embodiment of temperature increase in urban areas in comparison to non-urban areas, culminating in extreme overheating and increased frequency of heat waves in summer (Oliveira et al 2011). The UHI effect has measurable impacts on thermal comfort and, by extension, on the health and vitality of pedestrians in urban spaces as well as on the wellbeing of building inhabitants. Increasing temperature results in higher air-conditioning demand, especially in the summer months, and, consequently, higher electricity consumption and associated costs. GI interventions can significantly contrast UHI, through evapotranspiration and shading provided by trees, grasslands and vegetation. For example, a Singapore-based study by Wong et al (2005) confirmed the moderating potential of green spaces. A temperature test analysis between a vegetated region in the north east of the city and the Central Business District demonstrated significant differences in mean temperatures, which peaked at 4°C. The lowest mean temperature (25°C) of all locations in the entire study area was found in a well-planted part of the city. The tests in Singapore also demonstrated that planted roofs on the top of multi-storey car park facilities effectively improve thermal regulation. Mean temperature reduction improves health and wellbeing, with Chen et al (2014) projecting that increasing the vegetation coverage by 18% within Melbourne could yield a possible decrease in the average heat-related mortality rate up to 28%.

Besides facilitating climate change adaptation, GI also contributes to mitigating the causes of climate change, through the reduction of

GHG concentration. For example, urban forests can minimize carbon dioxide emissions through sequestration and storage of atmospheric carbon in soils and plants, as observed and measured in several North-American cities (Nowak et al 2013 and 2016). Additionally, urban vegetation can decrease the cooling and heating energy demand in buildings (one of the main drivers of anthropogenic carbon emissions), through lowered direct solar radiation, shade and wind-screening effects (Wang et al 2014). For example, modelling of energy savings from tree planting in residential buildings shows annual savings of 2439 kWh per hectare in Toronto (Nowak et al 2013), and nearly double that amount in New York City (4851 kWh/ha/y) (Nowak et al 2007).

2.3 Impacts of GI on Human Health and Psychological Wellbeing

Besides the provision of water, energy and food, and the regulation of air quality and climate, improvements to physical and mental health and the abatement of psychological stresses have been dominant topics in research on GI and its relationship to human wellbeing (Bratman et al 2012).Humans have a longstanding visceral connection to nature and the environment. Octavia Hill, one of the pioneering figureheads behind the foundation of the British National Trust, stated in 1895 that:

> "[…] the sight of sky and of things growing seem human needs, common to all men […]".

Over 120 years later, this intuition is increasingly supported by scientific evidence. A growing body of research now highlights links between a lack of green space and poor health. Several epidemiological studies suggest that depletion of green spaces in cities has created a sense of estrangement and geographical isolation amongst urbanites (Wong et al 2010). It is further noted that reduced contact with natural environments can have a profoundly negative impact on the mental health of city dwellers (Gill et al 2007). Conversely, more green spaces and improved interactions with nature are said to promote a sense of wellbeing, and serve as a means for combating stress and anxiety (Fuller et al 2009). The results of a survey conducted by

De Vries et al (2003) show that the self-reported health of over 10,000 people in the Netherlands was correlated to the quantity of green spaces in the participants' living environment. The investigation found strong relationships between living in a greener area and self-affirmed general health. Mitchell and Popham (2007) made a similar assertion in their England-based study. Through the evaluation of 2001 Census data regarding health compared to land use coverage, the study confirmed high proportions of green space to be associated with healthier populations. Similarly, a South-West England study on blue spaces showed that a higher perceived restorative potential was associated with natural and built scenes containing water, compared to scenes without water (White et al. 2010).
The "Biophilia Hypothesis" proposed by Edward O. Wilson (1984) justifies these relations by describing the innate affiliation humans have for natural environments. By interpretation of evolutionary timelines and trends in urbanisation, most of human evolution and development has occurred in natural regions, whereas only a short period of time has been spent in urbanised landscapes. On this basis, contemporary living, especially in densely built locations, is likely to have an effect on human psychological responses. Moreover, the relationships between views of greenery and improved health appear especially strong (Mitchell and Popham 2007), such that the mere visual presence of green has been cited by many authors to improve health. Some of the most commonly referenced studies provide stark comparisons between a lack of greenery in urban settings and densely vegetated, highly natural scenes (Southon et al. 2018). This approach has highlighted the importance of GI to wellbeing, while also corroborating the counteracting effect of urban built forms.
There is therefore a growing need to examine the preferences for urban green in ordinary day-to-day settings, so that study results can be translated into urban planning. In response to this demand, the Active Perception Technique (APT) was developed by Mirza et al (2012) to help planners better understand the recreational potential of GI and plan urban spaces accordingly.
Some novel psychological implications of green sceneries can also be evidenced in the literature. For example, plants within an office environment and views to green spaces from an office space have been shown to have a positive effect on job satisfaction and, in some

cases, overall quality of life (Dravigne et al 2008). Findings by Kuo (2001) also report that the presence of trees and grass within inner-city precincts can improve residents' sense of safety as well as reduce mental fatigue.

3 Towards Integrated Frameworks to Assess GI Benefits for User's Wellbeing and Cities' Environmental Performance

Notwithstanding recent progress in ecosystem service research, several authors argue the need to consolidate ecosystem service frameworks into integrated GI development and management (Ahern et al., 2014; Grêt-Regamey et al 2016; Hansen and Pauleit, 2014). To this end, one of the most complex challenges is the definition of valuation methods that can effectively translate the benefits provided by GI in a consistent manner across different levels of service provisioning (Kremer at al 2016). This includes the attribution of values also to non-material benefits and cultural ecosystem services, which represents one of the most significant challenges for application-oriented ecosystem service frameworks (de Groot et al 2010).

3.1 The Example of the UK Corporate Natural Capital Account

An example of multi-layered ecosystem valuation frameworks is the UK Corporate Natural Capital Account (CNCA) and its pilot application in the London Borough of Barnet (Eftec and Jon Sheaf Associates 2017). The CNCA aims to capture the annual economic values of benefits provided by GI in the borough, and to model GI management and maintenance costs over time as well as potential returns on investment. The CNCA framework is built around a five-step methodology (Table 1). First, the borough's green spaces are classified by habitat type and their specific qualities (Natural Capital Assessment Register). Benefits provided by each habitat type (e.g., recreation, physical health, property value uplift, and climate regulation) are quantified (Physical Flow Account), and monetary values attributed to them (Monetary Flow Account). For example, visits to the local green spaces provide approximately 30% of the Barnet population's physical activity requirements, and the value of avoided health costs due to inactivity is estimated at over £19 million per year. In terms of climate regulation, the total value of carbon sequestered is estimated at £0.1 million per year. In parallel to the monetary benefits, maintenance costs and the on-going liability costs of sustaining these benefits in perpetuity are assessed (Maintenance Cost Account). Finally, benefits in perpetuity are expressed against maintenance costs under liability (Natural Capital Balance Sheet), which assists with the identification of strategies to optimize the ratio between costs and benefits and to maximize returns on investment. The value of benefits such as climate regulation or positive health outcomes can be translated into new investment programmes for further development and maintenance of GI over time.

Table 1 Five-step methodology used in the Corporate Natural Capital Account (CNCA) framework, after Eftec and Jon Sheaf Associates 2017.

Step	Question	Scope
1. Natural Capital Asset Register	Which natural capital assets does the local authority hold responsibility for?	Extent, condition and quality of all the natural capital asset stocks relevant to the accounts.
2. Physical Flow Account	What flows of benefits are provided by those assets to the local authority or the wider society?	Flows of goods (public/private) and services that are dependent on the natural capital asset stocks identified in Step 1 (Natural Capital Asset Register).
3. Monetary Flow Account	Which monetary value do those benefits have?	Monetary value of the flows of goods and services captured in Step 2 (Physical Flow Account).
4. Maintenance Cost Account	What is the cost to maintain the natural assets and their flows of benefits?	Costs of current and future activities scheduled to maintain the natural capital asset stocks identified in Step 1 (Natural Capital Asset Register).
5. Natural Capital Balance Sheet	What is the costs-benefits ratio? How to maximize returns on investment?	Benefits in perpetuity against maintenance costs under liability identified in Step 4 (Maintenance Cost Account).

Overall, the results of the Natural Capital Balance Sheet show that the net value of natural capital assets is estimated at over £1.8 billion and the benefits provided by the local green spaces are over ten times the costs of maintaining them in perpetuity (Eftec and Jon Sheaf Associates 2017). This way of presenting the benefits provided by GI in cities can assist local authorities with building a better case for further investment in GI development and maintenance over time. The relevance of monetary flow accounting for decision-making is proved by the growing popularity of the CNCA in the UK, and its application at different spatial scales (Landscape Institute 2018). The CNCA has been, for example, used to assess and value the recreation, amenity and physical health benefits provided by the Beam Parklands, a green space in the London Borough of Barking and Dagenham (Eftec 2015). This approach ultimately provides a valuable baseline to facilitate GI conservation policy, and to align local strategies for GI development and management with values attached to ecosystems. Pressures on ecosystems can be modified or managed accordingly, in order to preserve benefits that are most valued by society.

3.2 The Challenge of Valuing Cultural Ecosystem Services and their Integration in Assessment Frameworks

The increasing attention paid nowadays to monetary translation methods, as the one adopted in the CNCA, raises the question of whether monetary metrics can capture the whole range of benefits provided by GI. Effective business cases need to be made to sustain the viability of GI development and maintenance given the finitude of financial resources. Therefore research into alternative valuation methods is critical to enhance the applicability of the ecosystem concept into decision-making and urban planning (Kremer at al 2016). Expanding integrated ecosystem service frameworks beyond monetary values requires gaining bottom-up understanding and acknowledgment of values assigned by inhabitants to the non-material benefits obtained by GI. These include, for example, place-making, beautification, enhanced sense of community and safety, which routinely fall within the cultural ecosystem service category (de Groot et al 2010). More generally, cultural services refer to the enhancement of human capabilities and experiences resulting from human-ecosystem relationships (Chan et al 2012). They arise from human perceptions of ecosystems, rather than from the ecosystem itself, which is different from all other ecosystem services (Buchel and Frantzeskaki 2015).

Because valuations are subjective between users, classification of cultural ecosystem services and elaboration of effective valuation systems are particularly complex tasks, especially when aiming to integrate them within comprehensive assessment frameworks rather than using distinct valuation methods (Daniel et al 2012). Acknowledgment of plurality in value dimensions (Chan et al 2012) can facilitate more comprehensive valuing approaches and methods, including moral, aesthetic or spiritual aspects, alongside monetary metrics. Investigation into user's experiences of urban green spaces can be used to better capture the value of services resulting from the perception of nature and its effect on user's wellbeing. For example, Buchel and Frantzeskaki (2015) propose a method to translate the concept of ecosystem services to GI users, in order to assess and value their recognition and appreciation of GI benefits. Questionnaires and interviews in the three most visited urban parks in Rotterdam were used to evaluate intangible and non-monetary values as perceived by users, and consequently inform GI design. Social setting, sense of place and aesthetic appreciation were among the most valued non-monetary benefits across different user profiles (39 respondents in total, with gender, age group and residence region used as main variability factors). Complementarily, Langemeyer et al. (2015) proposed a framework to assess cultural ecosystem services both in monetary and non-monetary terms in the Montjuïc park in Barcelona. Results of a survey conducted with nearly 200 users showed, for example, that environmental learning benefits generate low monetary values but high non-monetary values. The survey also aimed at linking the provisioning of cultural ecosystem services more directly to land-uses and management regimes. For example, respondents associated stronger place values with low management regimes, while higher values for tourism and cultural land-uses activities were attributed to high management regimes.

As showed in these studies, integrated assessment methods combining monetary and non-monetary valuations of physical and intangible benefits of GI can inform better tailored management strategies across natural capital assets or within the same green area.

4 An Urban Metabolism Approach to Foster Integrated Frameworks for GI Planning and Design

Integrated ecosystem service frameworks can play a substantial role in the planning and design of cities in which environmental performance is not prioritised over more immaterial benefits for human wellbeing (e.g., user's perception, aesthetic, cognitive and spiritual enrichment). Such frameworks can inform more holistic GI planning approaches, taking into account the impacts of ecosystems on both environmental performance dynamics (provisioning and regulating services) and the multiple physical and psychological dimensions of human wellbeing (cultural services).

However, the translation of scientific knowledge into policy and practice has thus far proved challenging (Grêt-Regamey et al 2016), and more application-oriented approaches are needed to generate greater impetus for GI practices.

Urban metabolism approaches present a strategy. Inputs-outputs models, such as Material Flow Analysis (MFA), have been increasingly employed in recent years to provide key environmental performance data and policy guidelines for local planning agendas (Beloin-Saint-Pierre et al. 2017). The growing popularity of MFA applications suggests that urban metabolism represents a promising method, holding ample scope in the future for informing more sustainable urban planning and design (Kennedy et al. 2011). MFA applications currently extend from infrastructure systems (e.g., water and energy supply, waste disposal) to neighbourhood planning and housing developments (e.g., Chrysoulakis et al. 2013; Roy et al. 2015). Building on previous research experiences, MFA application in GI planning and design represents a new frontier in urban metabolism research (Perrotti and Stremke 2018). MFA studies can reveal the contribution of GI towards an optimized performance of cities and increased health of urban populations. As discussed in section 2, GI strategies can mitigate resource demand and reduce the magnitude of waste flows that are rejected to the environment, resulting in a more resource-efficient and less carbon- and pollutant-intensive metabolism of urban systems. GI strategies include, for example, retrofitting buildings with green roofs/facades to improve insulation, densifying wind-screening vegetation to lower heating demand, producing crops in domestic gardens and collecting and treating rainwater for garden irrigation. Ultimately, deeper knowledge of GI benefits gathered through urban metabolism assessments can assist decision-making with outlining strategies and principles for GI development geared toward identified local needs and targets. However, a better articulation between efficient resource management and enhancement of population's health and wellbeing are critical to meaningful applications of metabolic analysis in GI planning and design (Fig. 1). Future research should therefore concentrate on the development of new urban metabolism frameworks that will be able to fully incorporate aspects of user's wellbeing with sustainable urban metabolism objectives.

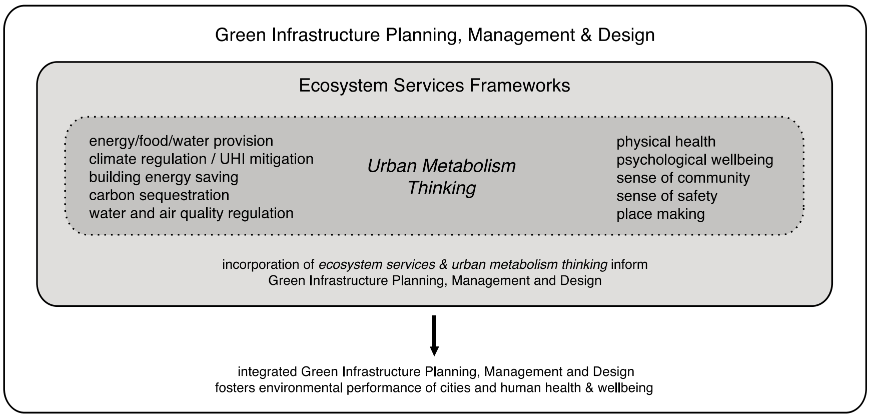

Fig. 1 Proposed conceptual framework to inform integrated Green Infrastructure Planning, Management and Design, which can foster environmental performance of cities and human health and wellbeing

Finally, new integrated frameworks can also foster a more holistic understanding of the notion of urban metabolism, including considerations of immaterial and non-monetary aspects associated with the management of flows of natural and anthropogenic resources in cities. In line with the emergent field of study of Political-Industrial Ecology (Newell et al. 2017), this would foster a more interdisciplinary dialogue in the urban metabolism research community, which could ultimately inform more comprehensive and inclusive policy-making.

Conclusion

Throughout this chapter, we have argued that GI can play a central role in improving urban environmental quality and enhancing health and wellbeing in cities. By making use of the ecosystem service concept, we have discussed the contribution of GI in improving environmental performance of cities, including optimized resource provisioning (e.g., more circular water, energy and food flow management), healthier air quality (e.g., reduction of $PM_{2.5}$ concentration) and effective climate regulation (e.g., UHI mitigation through cooling effects). The chapter also discusses the positive impacts of GI on physical and mental health, through its demonstrated capacity to promote a sense of wellbeing and combat mental stress. However, although a strong evidence base demonstrates the wide range of benefits provided by GI, the implementation of scientific findings in policy and planning is still limited. This can be due to the complexity in capturing all GI values and benefits and translating them in a consistent manner. Even the most recent trends that adopt monetary metrics seem not being able to express the whole range of material and non-material benefits. Therefore, an urban metabolism approach is proposed as a way forward to capture the capacity of GI to both increase the urban environmental quality and enhance people's health. Finally, we have suggested that effective GI strategies serving both purposes rely on the development of new integrated urban metabolism frameworks, which can also express and reveal the immaterial benefits and non-monetary values of GI.

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