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Developing a sustainability indicator set for measuring green infrastructure performance

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Abstract

An urban ecosystem is a dynamic system. Therefore, regular monitoring through the use of measurable indicators will enable an assessment of performance and effectiveness. This paper presents a conceptual framework to facilitate the development of an inclusive model for the sustainability assessment of green infrastructure. The framework focuses on key interactions between human health, ecosystem services and ecosystem health. This study reviews existing models for assessing green infrastructure performance and evaluates these models via a range of selection criteria proposed by the authors based on literature review and interviews with stakeholders. This enables derivation of a novel conceptual framework that identifies and brings together the criteria and key indicators. This integrated framework may then be applied to develop a composite indicator-based assessment model to measure and monitor performance of green infrastructure projects and support future studies.

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Keywords: sustainable development; green infrastructure; urban ecosystem; sustainability indicators; conceptual framework

1. Introduction

Urbanization is a dominant demographic trend and an important component of global land transformation. It is predicted by the United Nations that cities will be saturated from the forecast population growth expected over the

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next four decades (U.N., 2012). This will impose a tremendous ecological burden both locally and globally. The rate of urbanization is directly correlated with increased production and consumption of goods, services and infrastructure. This leads to greater land consumption, landscape fragmentation, biodiversity loss, the creation of urban heat islands, increasing greenhouse gas emissions and the destruction of sensitive ecosystems. The outcomes are a decrease in human health and well-being among other negative impacts on society, which interact with and are exacerbated by climate change (Tzoulas et al., 2007).

As a remedy to some of these negative consequences of urbanization, the installation of green infrastructure as opposed to grey infrastructure is identified as an alternative nature-based and cost-effective solution for improving the sustainability of the urban development. Grey or technical infrastructure refers to the facilities that support social and economic production such as roads, sewerage treatment, water treatment systems, and electricity supply networks (Van de pol, 2010, pp 17). Green infrastructure is described as an integrated network of natural and semi-natural areas and features which deliver a variety of benefits to humans (Naumann et al., 2011). Green infrastructure has become increasingly valued in a wide variety of settings from water purification to climate change adaptation and mitigation. Green infrastructure potentially has lower capital, maintenance and operational costs, has fewer negative impacts on the environment and it significantly reduces carbon emissions compared to grey infrastructure (Benedict & McMahon, 2006; Lafortezza et al., 2013). Where grey infrastructure tends to be designed to perform only single functions, green infrastructure networks serve multiple functions and provide a wide range of engineering, environmental and human services, known as 'ecosystem services' (Ely & Pitman, 2014). Ecosystem services are defined as *'the benefits people obtain from ecosystems'* (MEA, 2005). In this context, integrated networks of green spaces at city scale, or green infrastructure, are seen increasingly as fundamental to the delivery of ecosystem services for human and environmental health.

The ability to assess and regulate the sustainability performance of the built and natural environments, based on measurable criteria at a variety of temporal and spatial scales is critical for sustainable urban development. A range of models that assess the performance of specific aspects and elements specially related to green infrastructure have been developed in response. However, there is no consensus on a model that is comprehensive and integrative across all types and aspects of green infrastructure and ecosystem services.

The purpose of this study is to critically examine the existing frameworks for urban sustainability indicators and to compare the existing green infrastructure conceptual models. This will lead to an outcome that proposes a new framework to facilitate the process of selecting green infrastructure performance indicators to best reflect the comprehensive and integrated function of green infrastructure.

2. Existing frameworks for assessing urban sustainability

Since the concept of sustainable development first became a major concern, a number of methods, frameworks and tools have been developed to assess the state of, or changes to, urban areas in relation to sustainability performance. The method mainly used to assess sustainability is indicator-based assessment, which has been applied to many scientific fields from socio-economic science to environmental sciences. Comprehensive lists of urban sustainability indicators have been developed by international and regional organizations, such as the European Foundation (1998), the European Commission on Science, Research and Development (2000), the UN Habitat (2004), the European Commission on Energy Environment and Sustainable Development (2004), the United Nations (2007) and the World Bank (2008).

In addition a number of composite sustainability indices have been developed more recently such as the Environmental Sustainability Index (ESI), the Environmental Performance Index (EPI), the Environmental Vulnerability Index (EVI), the Rio to Johannesburg Dashboard of Sustainability and the Wellbeing of Nations and National Footprint Accounts (Ecological Footprint and Bio-capacity) (SEDAC, 2007).

The development and selection of urban sustainability indicators is a complex process. The most common frameworks for selecting indicators is the Causal Network (CN) method. The CN framework is a combination of a series of causal loops and feedback loops, such as the pressure–state–response (PSR) framework and its transformations: the driving force–state–response (DSR) and the driving force–pressure–state–impact–response

(DPSIR) (Niemeijer and Groot, 2008). The PSR was proposed by OECD (1993) and is based on the pressure indicators that explain the problems caused by human activities, state indicators that monitor the physical, chemical and biological quality of environment and response indicators that indicate how society responds to environmental changes and concerns (Segnestam, 2002).

The European Environment Agency (EEA) extended the PSR framework to 'Driving force-Pressure-State-Impact-Response' (DPSIR) which is now the most internationally recognized framework. The 'Driving force' indicators underlie the causes (economic sectors and human activities) through 'Pressures' (waste, emissions) to 'States' (physical, chemical and biological), and 'Impact' indicators which express the level of environmental harm to human health, ecosystem health and functionality. Ultimately, the setting of indicators, targets and prioritizations are political 'responses' to these environmental problems. These causal networks explain the balanced interaction between human activities and natural resources which demonstrate the sustainability level of urban development. Sustainability assessment provides a fundamental approach to the efficient use of natural resources while adapting to human activities and demands hence provides an essential tool to understand the physical and natural characteristics of urban area and settlements activities in terms of their potential, weaknesses and risks in the urban planning process (Lein, 2003).

Implementing the green infrastructure concept into the urban planning process has important influences. It can increase the resilience of ecosystems, contribute to biodiversity conservation and habitat enhancement and relieve pressures on the environment such as land use change and intensification, fragmentation and climate change resulting from human activities. Figure 1 demonstrates the DPSIR framework of the linkages between human activities and green infrastructure performance. This framework helps to clarify the complex relationship between cause and effect variables as well as understanding the issues that change the performance of green infrastructure and identifying potential solutions. For example, connectivity is a key principle of green infrastructure. Any human activities such as deforestation and land degradation that change the structure of GI will result in increasing the percentage of impervious surfaces and consequently disturbing ecosystem functions and the overall impact on the heath of ecosystem and human.

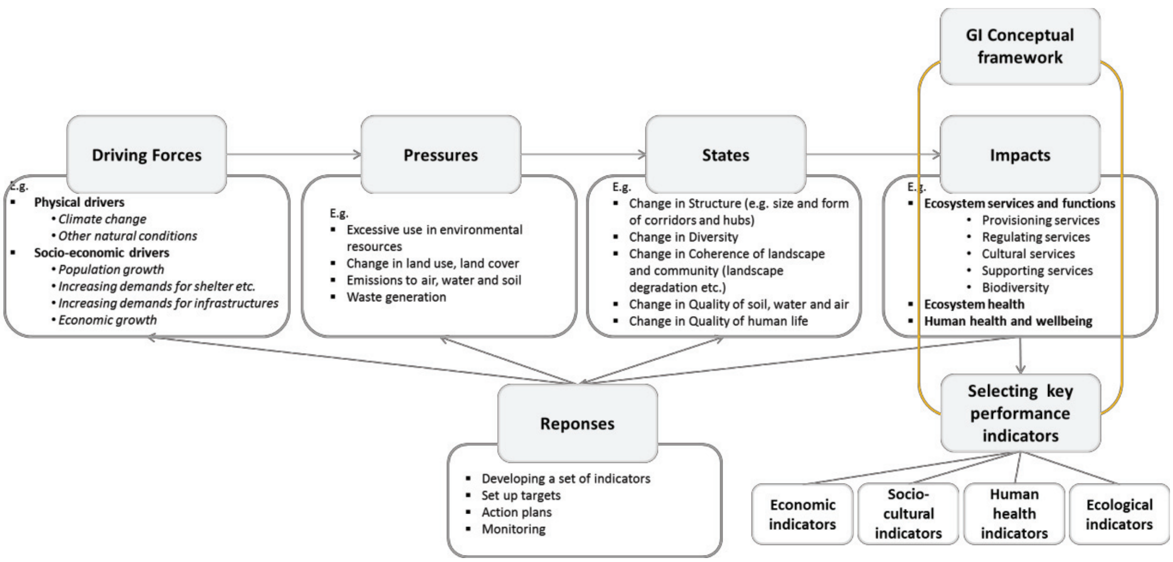

Figure 1 DPSIR framework of linkage between human activities and green infrastructure performance (Source author).

3. Existing green infrastructure conceptual models

Numerous social science research models address the environmental effects on human mental and physical health (Table 1). The clear consensus is that green open space and biodiversity contribute positively to improving mental and physical health for urban residents.

Pickett et al. (1997; 2001) proposed an integrated human ecosystem framework for analyzing urban systems in relation to their social, biological and physical aspects. The two interconnected parts of this framework are: (1) The human-social system, which includes social institutions and cycles; (2) The resource system, which consists of cultural and socio-economic resources, and ecosystem structure and processes. Grimm et al. (2000) revised Pickett's human ecosystem framework based on outcomes of land use and land cover changes on the interactions between social and ecological systems. Even though these two models help to explain the concept of green infrastructure in general, they do not clearly address the relationships between ecosystems and public health (Tzoulas et al., 2007).

Another integrated framework named the "arch of health" was developed by the World Health Organisation (WHO, 1998). This model illustrates the environmental, cultural, socio-economic, working and living conditions, community, lifestyle and hereditary factors of public health. Paton et al. (2005) combined the "arch of health" model with developmental principles (social, environmental, organisational and personal factors) and systems theory to enhance application within organizations.

In 2003, the Millennium Ecosystem Assessment body established a framework for assessing global ecosystem changes and their impacts on human and ecosystem health. This framework links ecosystem services and human wellbeing through socio-economic factors. Ecosystem services were classified into four categories: provisioning, regulating, supporting and cultural; and human well-being was classified into five categories: security, access to basic resources, health, good social relations and freedom of choice (MEA, 2003,pp 78). Even though this framework is very broad and includes many parameters, it does not 'explicitly distinguish between the biological, psychological and epidemiological aspects of health' (Tzoulas et al., 2007, pp 21).

A comprehensive and complex model developed by Van Kamp et al (2003) synthesized various factors that affect the quality of life including personal, social, cultural, community, natural environment and built environment as well as economic factors. However, the interrelationships between these factors were not clear. Tzoulas et al. (2007) proposed a framework for green infrastructure in urban areas that provided the ground for linking ecological concepts such as ecosystem health to social concepts such as individual or community health. On this basis, Lafortezza et al. (2013) described a framework for green infrastructure planning with five interlinked conceptual components: (1) ecosystem services; (2) biodiversity; (3) social and territorial cohesion; (4) sustainable development, and (5) human well-being. In 2010 Abraham et al. conducted a scoping study reviewing over 120 studies examining the health-promoting aspects of natural and designed landscapes. The authors identified three dimensions of human health linked to Green Infrastructure: (1) Mental well-being: landscape as a restorative environment; (2) Physical well-being: walkable landscapes; (3) Social well-being: landscape as a bonding structure. Table-1 summarizes the most recent frameworks which link ecosystem and human health.

Table 1 Models and theories linking ecosystem and human health aspects (Source: Tzoulas 2007; revised by author).

Author	Model/theory	Green infrastructure aspect	Human health aspect
Freeman (1984)	Model of Environmental Effects on Mental and Physical Health	Physical, social and cultural factors	Nervous system and illness
Henwood (2002)	Psychosocial Stress and Health Model	Physical poor environment	Chronic anxiety, chronic stress and high blood pressure
Pickett et al. (1997, 2001), Grimm et al. (2000)	Human Ecosystem Framework	Ecosystem structure and processes and cultural and socio-economic resources	Socio-ecological systems

WHO (1998)	Arch of Health	Environmental, cultural, socio-economic factors	Working and living conditions, community, lifestyle and hereditary factors
Paton et al. (2005)	Healthy living and working model	Environmental, cultural, socio-economic factors	Living and working conditions
Millennium Assessment (2003)	Links between ecosystem services and human well-being	Provisioning, ecosystem services, regulating and cultural	Security, basic resources, health, social relationships, and freedom of choice
Macintyre et al. (2002)	Framework based on basic human needs	Air, water, food, infectious diseases, waste disposal, pollution	Health and human needs (biological, personal, social, and spiritual)
van Kamp et al. (2003) and Circerchia (1996)	Domains of liveability and quality of life	Natural environment, natural resources, landscapes, flora and fauna, green areas	Health all aspects (physical, psychological, social)
TEP (2008)	Life support system and sustainable growth	high-quality natural environment (environmental capacity), Managing surface waters ; biodiversity; climate change adaptation	Movement network(Active travel mode and impacts on human health and wellbeing); productivity (Sustaining jobs)
Tzoulas et al. (2007) and Austin (2014)	Conceptual framework integrating Green Infrastructure, ecosystem and human health.	Ecosystem services and functions (air and water purification, climate and radiation regulation, etc.) and ecosystem health (air quality, soil structure etc.)	Socio-economic, community, physical and psychological health
Abraham et al. (2010)	Human health and wellbeing benefits of green infrastructure	Accessibility, walkability, Aesthetically appealing rural green, environmental aspects (air quality and noise reduction), Biophilia, restorative, social and cultural interactions	Physical, psychological and social health and wellbeing

4. Developing a conceptual framework

The DPSIR framework (Figure 1) conceptualizes the interaction between human activities and green infrastructure structure and performance. This framework provides the basis to establish a composite indicator-based model for assessing green infrastructure performance (Figure 2).Frequently in green infrastructure literature, the concept of ecosystem services is adopted to replace and explain the functions and benefits of green infrastructure from the global to the local scales (Tzoulas, 2007; Mazza et al., 2011; Lovell et al., 2013; Austin, 2014; Hansen et al., 2014; Ely & Pitman, 2014). The combination of both green infrastructure and ecosystem services theories into a unified framework seems promising.

Figure 2 demonstrates the links between human health and wellbeing, ecosystem health and ecosystem services. This model respects both philosophical anthropocentrism and ecocentrism. The link between these three systems is very clear. A healthy ecosystem within a green infrastructure environment has the ability to increase the delivery of ecological and cultural services to improve human health and wellbeing at both individual and community scales. This conceptual framework proposed in figure 2 helps to identify relevant indicators for assessing the performance of green infrastructure.

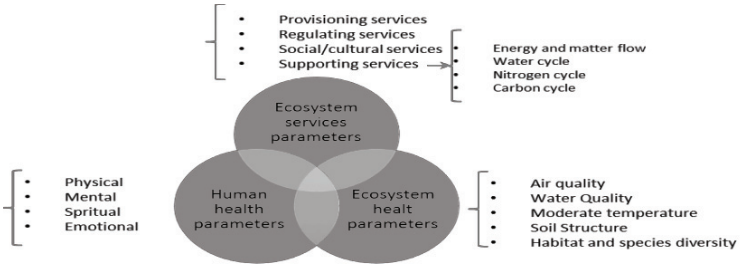

Figure 2 Conceptual framework of green infrastructure proposed by the author, derived from the integration of the approaches set out in Table 1 and the DPSIR framework in Figure 1.

5. Performance indicators of green infrastructure

Indicators reduce the complexity of data, simplify interpretations and assessments and facilitate communication between experts and non-experts (Segnestam, 2002). Therefore, indicators can be used to highlight key information concerning ecosystem structure, function and services.

Ely and Pitman (2014) tabulate the ecosystem services that can be provided by green infrastructure based on the "triple bottom line" of sustainable development, which represents the benefits of green infrastructure across the categories of environmental, social and economic (Table 2).

Table 2 Ecosystem services that can be provided by green infrastructure (Source: Ely & Pitman 2014, p.28).

Theme	Categories	Sub-categories
Environmental	Climatic modification	Temperature reduction (Shading; evapotranspiration)
		Wind speed modification
	Climate change mitigation	Carbon sequestration and storage
		Avoided emissions (reduced energy use)
	Air quality improvement	Pollutant removal
		Avoided emissions
	Water cycle modification	Flow control and flood reduction (Canopy interception; Soil infiltration and storage)
		Water quality improvement
	Soil improvements	Soil stabilization
		Increased permeability
		Waste decomposition and nutrient cycling.
	Biodiversity	Species diversity
		Habitat and corridors
	Food production	Productive agricultural land
		Urban agriculture
Social	Human health and well-being.	Physical
		Social and psychological
		Community
	Cultural	
	Visual and aesthetic	
Economic	Commercial vitality	
	Increased property values	

	Value of ecosystem services

However, Austin (2014) explained the contribution of green infrastructure to ecosystem services by demonstrating the interlinkages between ecosystem health and human health and wellbeing through the framework proposed by Tzoulas et al. (2007). This framework has been further developed by the author by adding the natural processes (energy, carbon, water etc.) as supporting functions and fundamental elements in providing services to humans and nature (Table 3).

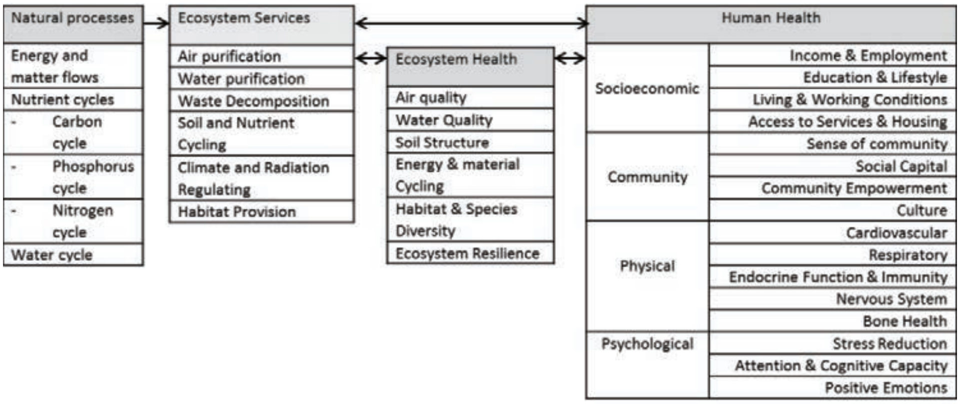

Table 3 Green infrastructure contributions to ecosystem and human health through ecosystem services. (Source: Noss and Cooperrider 1994; Tzoulas et al. 2007 and Austin 2014 ; revised by author).

To derive a draft indicator set from the above conceptual model, a series of 21 semi-structured interviews were conducted with Australian representative experts. Interviewees were asked to identify the main benefits of green infrastructure. There was a strong recognition of the social and cultural role of green spaces in human health and wellbeing, emphasizing that it:

- is an imperative for national, regional and local policy regarding sustainable development
- brings economic and health benefits
- contributes to climate change mitigation and adaptation
- can offset the negative environmental and social effects of development
- improves the quality of life and the quality of place

Analyzing and coding the interviewees' responses revealed nine major concepts and themes that were consistent across all interviewees: These nine concepts can be classified into three categories: economic growth; environmental sustainability; and health and wellbeing.

- Concept 1: Climate change adaptation and mitigation
- Concept 2: Human health and wellbeing
- Concept 3: Healthy ecosystem
- Concept 4: Biodiversity
- Concept 5: Economic benefits
- Concept 6: Alignment with political issues and city strategies
- Concept 7: An active travel network
- Concept 8: Water management
- Concept 9: Food production

Based on the literature review and interviews, a set of 30 indictors in four categories including ecological indicators, health indicators, socio-cultural indicators and economic indicators has been proposed (Table 4).

6. Conclusions

According to DSE (2007) sustainability assessment is ‘a generic term for a methodology that aims to assist decision making by identifying, measuring and comparing the social, economic and environmental implications of a project, program, or policy option’ (DSE, 2007,pp1). Green infrastructure performance indicators play an important role in successfully achieving the urban sustainability targets. They can be used for the proposing new sustainable urban development plans and for improving the decision-making process based on the pre-established benchmarks. This will allow the comparison of different practices and facilitate the identification of best practices among various urban development scenarios.

This paper has proposed a conceptual framework which links green infrastructure performance into ecosystem services, ecosystem health and human health and wellbeing. This framework (Figure 2) provides a conceptual basis to establish a composite indicator-based model for assessing green infrastructure sustainability performance, which are identified in Table 4. These 30 indicators have been selected (as shown in table 4) based on literature review and semi-structure interview with 21 stakeholders in Australia. The proposed variables or the indicators are both qualitative and quantitative

This research is essentially exploratory; the development of GI sustainability performance indicators, which in future studies further investigation, is required in terms of the scale and applicability of these indicators in various GI typologies, and also assigning weight to indicators based on the stakeholders’ perspective.

Table 4 Proposed green infrastructure performance indicator set

CATEGORIES	PERFORMANCE INDICATORS		REFERENCES	
ECOLOGICAL INDICATORS	C1	Climate and microclimatic modifications *(e.g. Urban Heat Island effect mitigation; temperature moderation through evapotranspiration and shading; wind speed modification)*	*Regulation of solar radiation*	*(Armson et al., 2012; Picot, 2004; Streiling & Matzarakis, 2003; Akbari et al., 2001)*
			Lowering air temperature through evapotranspiration	*(Heidt & Neef, 2008; Rosenfeld et al., 1998)*
			Wind breaking	*(Duryea et al., 1996)*
	C2	Air quality improvement *(e.g. Pollutant removal; Avoided emissions)*	*(CNT 2010; Nowak et al. 2006)*	
	C3	Carbon Emissions *(e.g. direct carbon sequestration and storage; avoided greenhouse gas emissions through cooling)*	*Direct carbon storage and sequestration*	*(CNT 2010; Nowak & Crane, 2002)*
			Controlling carbon dioxide emissions by cooling effect	*(CNT 2010; Akbari, 2002)*
	C4	Reduced building energy use for heating and cooling *(through e.g. shading by trees; covering building by green roof and green walls)*	*(Akbari & Taha, 1992)*	
	C5	Hydrological regulation *(e.g. flow control and flood reduction; regulation of water quality; water purification)*	*Regulation of water quality problems*	*(Sanders, 1986)*
			Increased rainwater retention and flooding	*(CNT 2010; Xiao et al., 2000; Grimmond et al., 1994)*
	C6	Improved soil quality and Erosion prevention *(e.g. soil fertility; soil stabilization)*	*(McKinney, 2006; Zhu & Carreiro 2004)*	
	C7	Waste decomposition and nutrient cycling	*(Astbury and Rogers 2004)*	

	C8	Noise level attenuation	*(CNT 2010; Islam et al., 2012; Nettle 2009)*	
	C9	Biodiversity-protection and enhancement *(e.g. Communities; species; genetic resources; habitats)*	*Promoting conservation*	*(Adams, 1994)*
			Harbouring wildlife	*(Dunster, 1998)*
HEALTH INDICATORS	C10	Improving physical well-being *(e.g. physical outdoor activity; healthy food; healthy environments)*	*(Schipperijn et al., 2013; Li et al., 2011; Kent, Thompson et al. 2011;; Abraham et al. 2010;; Wilbur et al. 2002; Ulrich, 1984)*	
	C11	Improving social well-being *(e.g. social interaction; social integration; community cohesion)*	*(Peschardt et al., 2012; Wood et al. 2010; Maller et al. 2006;Frumkin et al. 2004)*	
	C12	Improving mental well-being *(e.g. reduced depression and anxiety; recovery from stress; attention restoration; positive emotions)*	*Reduction of mental fatigue*	*(Arnberger & Eder, 2012; Kuo & Sullivan, 2001; Kaplan & Kaplan, 1989;)*
			Emotional and spiritual benefits	*(Abraham et al. 2010; Milligan and Bingley 2007; Chiesura, 2004)*
SOCIO-CULTURAL INDICATORS	C13	Food production *(e.g. urban agriculture; kitchen gardens; edible landscape and community gardens)*	*(Clark & Nicholas, 2013)*	
	C14	Opportunities for recreation, tourism and social interaction *(community livability)*	*(Gobster & Westphal, 2004; Nowak et al., 2001)*	
	C15	Improving pedestrian ways and their connectivity *(e.g. increasing safety; quality of path; connectivity and linkage with other modes)*	*(Turrell 2010; Leslie et al. 2005; Titze et al. 2005)*	
	C16	Improving accessibility	*(Rundle et al. 2013)*	
	C17	Provision of outdoor sites for education and research	*(McDonnell et al., 1997)*	
	C18	Reduction of crimes and fear of crime *(comfort; amenity and safety)*	*(Kuo & Sullivan, 2001)*	
	C19	Attachment to place and sense of belonging *(cultural and symbolic value)*	*(Kent, Thompson et al. 2011; Cohen et al. 2008)*	
	C20	Enhancing attractiveness of cities *(e.g. enhancing desirable views; restricting undesirable views)*	*(Manning, 2008)*	
ECONOMIC INDICATORS	C21	Increased property values	*(Donovan & Butry 2010; Shoup and Ewing 2010)*	
	C22	Greater local economic activity *(e.g. tourism, recreation, cultural activities)*	*(Wolf, 2004 ; McPherson & Simpson, 2002)*	
	C23	Healthcare cost savings	*(Shoup and Ewing 2010; Bauman et al 2008)*	
	C24	Economic benefits of provision services *(e.g. raw materials; timber; food products; biofuels; medicinal products; fresh water etc.)*	*(Baines, 2000)*	
	C25	Value of avoided CO2 emissions and carbon sequestration	*(CNT 2010; Scott et al., 1998)*	
	C26	Value of avoided energy consumption *(e.g. reduced demands for cooling and heating)*	*(CNT 2010; Akbari & Taha, 1992)*	

	C27	Value of air pollutant removal/avoidance	*(McPherson et al., 1999)*
	C28	Value of avoided grey infrastructure design*(construction and management costs)*	*(CNT 2010; Girling & Kellett, 2002)*
	C29	Value of reduced flood damage	*(Wong 2011; CNT 2010; Xiao et al., 2000)*
	C30	Reducing cost of using private car by increasing walking and cycling (e.g. shifting travel mode)	*(McPherson & Muchnick, 2005)*

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