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REVIEW ARTICLE

Defining and measuring urban sustainability: a review of indicators

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Abstract
Context The sustainability of urban areas is essential to the sustainability of regions, nations, and the world as a whole. Urban sustainability indicators (USIs) can play an important role in advancing the science and practice of sustaining urban systems.
Objectives We review the key concepts of urban sustainability and commonly used indicators for gauging the state and progress of urban sustainability, and discuss how USIs can be further improved from a landscape ecology perspective.
Methods This review is based primarily on peer-reviewed journal papers, as well as books, and documents published by international organizations, governmental agencies, and research institutions. We systematically examine what USIs actually measure and whether they are adequate for gauging urban sustainability, and then discuss major problems and challenges as well as ways forward in developing and applying USIs.
Results Numerous USIs have been developed, including single composite indices and indicator sets. This paper focuses on three indicator sets and ten composite indices. Eight of them cover all the three dimensions of sustainability (environment, economy, and society), and five cover two of the three. Five of them measure strong sustainability, and eight only indicate weak sustainability.
Conclusions Urban sustainability indicators abound, and so do problems with them. These include technical issues of normalization, weighting, and aggregation (upscaling), as well as conceptual issues of indicator selection, boundary delineation, heterogeneity, scale, and strong versus weak sustainability. To overcome these problems, principles and methods in landscape ecology—particularly those of landscape metrics, spatial scaling, and landscape sustainability—have much to offer, and this represents a challenging and fruitful research direction for both landscape and urban scientists in the coming decades.

Keywords Urbanization · Urban sustainability indicators · Indicator frameworks · Sustainable cities · Landscape sustainability

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Introduction

The world has become increasingly urban, and this trend will continue in the foreseeable future. Only 2 % of the world population lived in urban areas in 1800, but this number increased to 14 % in 1900, 29 % in 1950, 47 % in 2000, and over 50 % in 2008 (Wu et al. 2014). The world population is projected to be 70 % urban by 2050 and 100 % urban by 2092 (Batty 2011). While urbanization is often positively correlated with socioeconomic development, it has resulted in a number of environmental problems (Grimm et al. 2008; Pickett et al. 2011; Liu et al. 2014; Wu 2014). As the world continues to urbanize, the sustainability of urban areas must take a central stage in both science and policy arenas. More broadly, sustainability or sustainable development has become the theme of our time, through a series of initiatives by the United Nations, international organizations, and research institutions since the 1970s (Fig. 1). A number of recent attempts have been made to review the historic events and major scientific advances in sustainability research (e.g., Kates et al. 2001; Wu 2013, 2014), and here we briefly discuss several key concepts that are immediately relevant to sustainability indicators.

Widely recognized milestones in sustainability research include: (1) the 1972 United Nations Conference on the Human Environment, at which the international community met for the first time to discuss the global environmental and developmental challenges; (2) the 1987 Brundtland Report (WCED 1987), which offered the most widely used definition of sustainable development; (3) the 1992 Rio Earth Summit, which adopted the Rio Declaration and Agenda 21, calling for developing sustainability indicators; (4) the 1999 US National Research Council Report (NRC 1999), which coined the term "Sustainability Science"; (5) the 2002 Johannesburg Earth Summit, which reaffirmed the implementation of Agenda 21, and (6) the 2012 Rio + 20 Earth Summit, which focused on clear and practical measures for implementing sustainable development.

While sustainability has been defined in many different ways, the Brundtland Report (WCED 1987) captures its essence in broad terms: meeting the needs of people now without devastating the life-supporting ecosystems for future generations. Sustainability is a dynamic process rather than a fixed state: "In essence, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations" (WCED 1987). It is widely accepted that sustainability has "three pillars" or "three dimensions"—environment, economy, and society (also known as the "Triple Bottom Line"). However, their interrelationship, particularly on the degree of substitutability between natural capital and human-made capital, has been at the core of the debate on "weak sustainability" versus "strong sustainability" (Daly 1995; Holland 1997; Ekins 2011; Wu 2013).

Weak sustainability assumes unlimited substitutability between natural capital (i.e., biodiversity and ecosystems) and human-made capital (e.g., machines and urban infrastructure), so that a system is

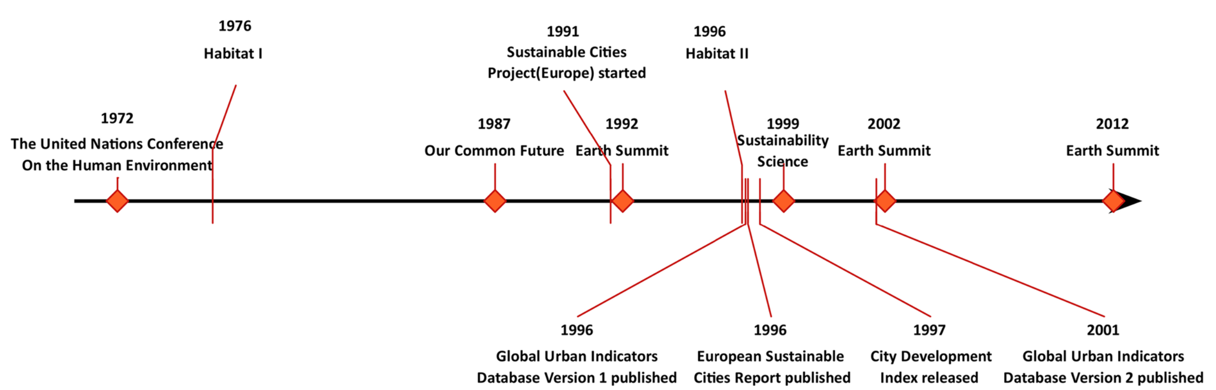

Fig. 1 Timeline of some important events in the history of urban sustainable development, with six marked points indicating widely recognized milestones in the sustainability literature

considered sustainable as long as its total amount of capital stocks is not decreasing (Pearce and Atkinson 1993; Hamilton and Clemens 1999; Pillarisetti 2005; Fischer et al. 2007; Greasley et al. 2014). In other words, depleted natural resources can be replaced with human-made substitutes, and degraded ecosystem services can be replaced by some equivalent forms derived from human-made capital. In this case, rapid urbanization with fast economic growth and declining environmental quality may be considered sustainable. By contrast, strong sustainability assumes that human-made and natural capital are not substitutes but "basically complements" (Daly 1995), or that "substitutability of manufactured for natural capital is seriously limited by such environmental characteristics as irreversibility, uncertainty and the existence of 'critical' components of natural capital, which make a unique contribution to welfare" (Ekins and Simon 1999; Ekins et al. 2003). In this case, urban development cannot be sustainable without a healthy environment.

Since the early 2000s, a transdisciplinary science of sustainability (or sustainability science) has emerged, focusing on the dynamic relationship between nature and society (NRC 1999; Kates et al. 2001; Clark and Dickson 2003; Wu 2013). Sustainability indicators (SIs) are indispensable in the science and practice of sustainability (Wu and Wu 2012). SIs are variables that provide information on the state and performance of human-environmental systems, with time dimension, limits, or targets of their values specified (Meadows 1998). The Rio Summit in 1992 called for the development of SIs, and since then a number of international organizations, governmental agencies, and research institutions have responded, producing a voluminous literature on SIs (Moldan and Billharz 1997; Meadows 1998; Hak et al. 2007; Bell and Morse 2008; Wu and Wu 2012). Most of the SIs have been used at the global, national, and local community levels, without considering spatial patterns of local and regional landscapes.

Sustainability has provided a common theme that unites ecological, geographical, and social sciences, leading to the emergence of landscape sustainability science (Wu 2013) and land system science (Turner et al. 2007, 2013; Verburg et al. 2013). In particular, urban sustainability is becoming "an inevitable goal" of research in landscape and urban studies (Wu 2010). Urban sustainability indicators (USIs) have an important role to play because of their simplicity in math and ease of use. Many USIs exist, but a systematic review from a landscape sustainability perspective is lacking. Thus, the main goal of this paper is to review the progress in the development of urban sustainability measures, discuss the pros and cons of commonly used USIs, and suggest ways to move forward. To achieve this goal, we will address the following specific questions: What does urban sustainability really means? What are the commonly used USIs? What aspects of sustainability do they measure, or are they adequate for gauging urban sustainability? How can we further improve USIs and their applications from a landscape sustainability perspective?

Urban sustainability

As a focus of sustainable development, urban sustainability has become increasingly prominent on political agendas and scientific studies during the recent decades (Fig. 1). Following the 1972 United Nations Conference on the Human Environment, the first United Nations Conference on Human Settlements (Habitat I) was held in Vancouver, Canada in 1976; European Commission initiated the Sustainable Cities Project in 1991; the internationally-known community-based urban sustainability project, Sustainable Seattle, was formed in 1992; the 2nd United Nations Conference on Human Settlements (Habitat II) was held in Istanbul, Turkey in 1996; the European Commission published the European Sustainable Cities Report also in 1996, documenting the past efforts and future visions for promoting sustainability in European urban settings. During the past decade, urban sustainability efforts have mushroomed across the world (Shen et al. 2011; Wu 2014).

How urban sustainability is defined certainly affects how its indicators are derived. Urban sustainability has been defined in various ways, with different criteria and emphases (Table 1). Most of the definitions are derivations from those of sustainability, focusing on the improvement of long-term human wellbeing by balancing the three dimensions of sustainability, minimizing resource consumption and environmental damage, maximizing resource use efficiency, and ensuring equity and democracy. For example, European Environment Agency set five

Table 1 Definitions of urban sustainability

Definition	Source
Five goals that make city sustainable: "minimizing the consumption of space and natural resources; rationalizing and efficiently managing urban flows; protecting the health of the urban population; ensuring equal access to resources and services; maintaining cultural and social diversity"	European Environment Agency (Stanners and Bourdeau 1995)
"Sustainable development of human settlements combines economic development, social development and environmental protection, with full respect for all human rights and fundamental freedoms, including the right to development, and offers a means of achieving a world of greater stability and peace, built on ethical and spiritual vision. Democracy, respect for human rights, transparent, representative and accountable government and administration in all sectors of society, as well as effective participation by civil society, are indispensable foundations for the realization of sustainable development"	United Nations Human Settlements Programme (UN-Habitat) (1996)
"A sustainable city is a city where achievements in social, economic, and physical development are made to last and where there is a lasting supply of the natural resources on which its development depends. Further more, a sustainable city maintains lasting security from environmental hazards that may threaten development achievements by allowing only for acceptable risk"	United Nations Centre for Human Settlements (Habitat) (1997)
"Sustainable urban development may be defined as a process of synergetic integration and co-evolution among the great subsystems making up a city (economic, social, physical and environmental), which guarantees the local population a non-decreasing level of wellbeing in the long term, without compromising the possibilities of development of surrounding areas and contributing by this towards reducing the harmful effects of development on the biosphere"	Camagni (1998)
"A sustainable city is one which succeeds in balancing economic, environmental and socio-cultural progress through processes of active citizen participation"	Mega and Pedersen (1998)
Urban sustainability is "the process of developing a built environment that meets people's needs whilst avoiding unacceptable social or environmental impacts"	Hamilton et al. (2002)
"A city moving toward sustainability improves public health and well-being, lowers its environmental impacts, increasingly recycles its materials, and uses energy with growing efficiency"	Worldwatch Institute (2007)
"A sustainable city is one in which the community has agreed on a set of sustainability principles and has further agreed to pursue their attainment. These principles should provide the citizenry with a good quality of life, in a livable city, with affordable education, healthcare, housing, and transportation"	Munier (2007)
"A sustainable city is one that can provide and ensure sustainable welfare for its residents with the capacity of maintaining and improving its ecosystem services"	Zhao (2011)
Urban sustainability is "an adaptive process of facilitating and maintaining a virtual cycle between ecosystem services and human well-being through concerted	Wu (2014)

urban sustainability goals in 1995 as "minimizing the consumption of space and natural resources; rationalizing and efficiently managing urban flows; protecting the health of the urban population; ensuring equal access to resources and services; maintaining cultural and social diversity" (Stanners and Bourdeau 1995). The United Nations Centre for Human Settlements (Habitat) (1997) defined a sustainable city as "a city where achievements in social, economic, and physical development are made to last and where there is a lasting supply of the natural resources on which its development depends." Local community-based efforts tend to put more emphasis on participation of urban citizens, as illustrated in the definition: "A sustainable city is one in which the community has agreed on a set of sustainability principles and has further agreed to pursue their attainment" (Munier 2007).

Recent urban sustainability studies seem to focus increasingly on the relationship between ecosystem services and human wellbeing (Wu 2010; Elmqvist et al. 2013; Nassauer et al. 2014; Wu 2014). Wu (2014) defined urban sustainability as "an adaptive process of facilitating and maintaining a virtual cycle between ecosystem services and human wellbeing through concerted ecological, economic, and social actions in response to changes within and beyond the urban landscape".

Urban sustainability indicators (USIs)

In the literature of sustainability indicators, a distinction is often made among the terms of data, indicators, and indices, which together form a conceptual hierarchy or an indicator pyramid (Fig. 2). Data are the basic components of an indicator, and multiple indicators comprise an indicator set or a composite index. An indicator is an "operational representation of an attribute (quality, characteristic, property) of a system" (Gallopin 1997), whereas an index is a more complex aggregate variable that combines multiple indicators using various normalization and weighting schemes (Wu and Wu 2012). An indicator set is a group of non-aggregated indicators often organized following a certain indicator framework for a project. An indicator framework is a conceptual structure based on sustainability arguments in order to facilitate indicator selection, development, and interpretation. It is beyond the scope of this paper to review all the sustainability indicator frameworks, which have been discussed in detail elsewhere (Meadows 1998; United Nations 2007; Wu and Wu 2012).

Although the terminology discussed above is useful, when used broadly, the term "sustainability indicators" may also refer to "sustainability indicator sets" or "sustainability indices". We adopt this usage in this review unless otherwise specified. USIs, as a subset of a much larger body of sustainability indicators, are synoptic measures that provide information on the state, dynamics, and underlying drivers of urban systems, with specifications of time dimension, limits, or targets associated with them. In the following, we review several indicator sets and ten composite indices for gauging urban sustainability. Our selection of these indicators was based on two general criteria: (1) they are relevant to urban sustainability, as defined in the previous section, whether or not they have been used at the urban scale; and (2) they cover more than just one of the three pillars of sustainability (e.g., an urban biodiversity indicator or an urban welfare measure would not qualify). The specific urban indicators that measure the different aspects of the environment, economy, society, and institution are listed in the Appendix from ESM.

Indicator sets for urban sustainability

Indicator sets based on the PSR framework

The Pressure-State-Response framework (PSR), as well as its more elaborated versions, i.e., the Driving

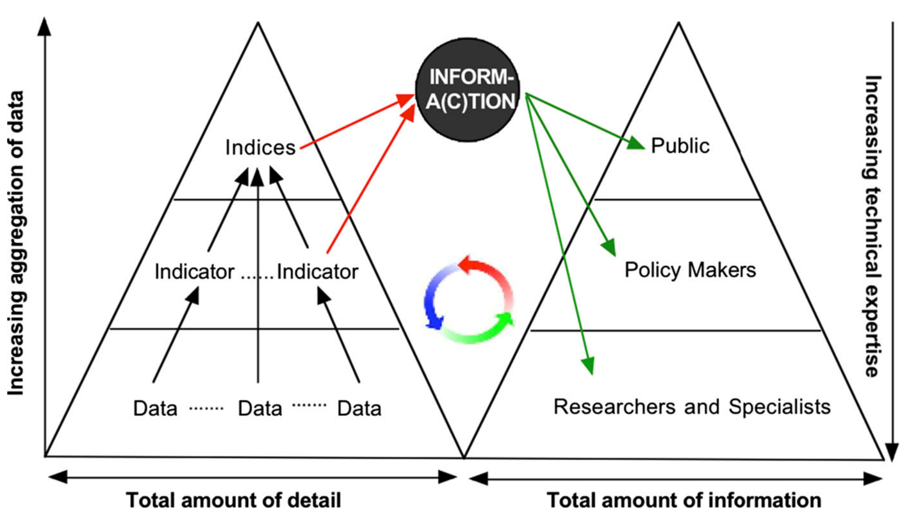

Fig. 2 The indicator pyramid, illustrating the relationship among data, indicators, and indices, as well as their primary user groups (from Wu and Wu 2012; the original figure was based on Braat 1991)

force-State-Response framework (DSR) and the Driving force-Pressure-State-Impact-Response framework (DPSIR), is one of the earliest and most widely used indicator frameworks developed by the Organization for Economic Co-operation and Development (OECD 1993). In this framework, indicators are developed and organized according to pressures or/and driving forces (primarily representing anthropogenic processes), system state or/and impacts (focusing on the current conditions of and impacts on the environment), and responses (pertaining to societal actions and reactions to changes in system state and driving forces). The PSR framework has been used more frequently for developing environment-centered indicator sets.

Most of the earlier efforts for USIs followed the PSR framework by OECD which pioneered in the development of indicators for urban areas (Alberti 1996). Based on the PSR framework, for example, the European Environment Agency (EEA) developed an urban indicator set in 1995, with pressure indicators (e.g., industry, transport, population growth, waste production, and other drivers of change), state indicators (e.g., conditions of the environment and natural resources such as biodiversity and air and water quality), and response indicators (e.g., legislations, regulations, and economic instruments) (http://www.eea.europa.eu/publications/92-826-5409-5). More recent examples of the PSR-based urban indicator sets include those for urban areas in general (Olewiler 2006) and for particular places—such as Taiwan (Huang and Chen 2002) and the Chinese city of Mianyang (Zhao et al. 2014). These indicator sets share many of the same urban indicators, but also have some particularly relevant to the urban area under study.

Indicator sets based on the theme-oriented framework

The theme-based framework is a more flexible conceptual structure that organizes indicators according to four dimensions of sustainability (environment, economy, society, and institutions) and around key themes or issues of policy relevance. Examples of themes include equity, health, and education for the social dimension; biodiversity and air/water quality for the environmental dimension; economic structure and consumption/production patterns for the economic dimension; and institutional frameworks (the systems of formal laws and regulations as well as informal conventions and norms that shape socioeconomic activities) for the institutional dimension. The most influential indicator set based on this framework has been the one developed in 2001 and revised in 2007 by the United Nations Commission on Sustainable Development, which includes 14 themes, 44 subthemes, 50 core indicators, and a total of 96 indicators (United Nations 2007). Although the theme-based framework was originally designed for developing national-level sustainability indicators, it can also be used for gauging urban sustainability on multiple scales.

One of the early indicator sets for sustainable cities developed by the World Health Organization (WHO) in 1994—the Healthy Cities Indicators (HCI)—basically fits the theme-based framework. The HCI set contains indicators pertain to environmental, economic, social, and health-related issues of cities. The European Foundation for the Improvement of Living and Working Conditions (Eurofound; an autonomous body of the European Union) published its urban sustainability indicator set, following a similar framework that considered global change, social justice, economic growth, citizen participation, and urban safety for medium-sized cities in Europe (Mega and Pedersen 1998). The World Bank has established the Global City Indicators Facility (GCIF), consisting of measures of a range of city services and quality of life factors under 20 themes. The United Nations Human Settlements Programme (UN-Habitat) also has established the Global Urban Indicators Database, including indicators of shelter, social development, environmental management, economic development, and governance. In addition, a large number of cities in developed and developing countries have adopted the theme-based framework to develop indicator sets for assessing the sustainability of individual cities and urban regions (Huang et al. 1998; Lee and Huang 2007; Tanguay et al. 2010).

Indicator sets based on the material and energy flow framework

To assess sustainability, it is crucial to keep track of the input, output, and internal dynamics of energy and materials within systems, ranging from a local society to a nation state and the entire world (NRC 2004). To operationalize these accounting procedures, the material and energy flow-based framework of various forms has been developed during the past few decades. The economy-wide material flow accounting (EW-MFA), which came to the fore in the 1990s, provides such a framework based on which indicator sets have been constructed (Eurostat 2001; Bringezu et al. 2003; Haberl et al. 2004; Fischer-Kowalski et al. 2011).

In the urban context, the inflows, outflows, and internal flows of material and energy in a city have often been referred to as "urban metabolism" (Wolman 1965). Comparing urban material dynamics to organismic (or ecosystem) metabolism echoes the long tradition of the city-as-organism analogy (going through the birth-growth-maturation-death cycle) in urban ecology. While criticized by some (Golubiewski 2012), the urban metabolism approach has been widely used in urban ecology and industrial ecology as it provides a useful framework for analyzing resource consumption and waste production in urban systems, as well as facilitating the linkage between the environment and economy (Decker et al. 2000; Huang and Hsu 2003; Kennedy et al. 2011; Pincetl et al. 2012). Compared to MFA, urban metabolism is a more specific form of the material and energy flow framework with an explicit focus on cities. It has been used as a conceptual basis for developing USIs, such as urban ecological footprints (Rees and Wackernagel 1996) and urban metabolic indicator sets (Kennedy et al. 2014).

Also consistent with the material and energy flows framework, Life Cycle Assessment (LCA) is a systems approach to assessing the environmental impacts associated with a product or service, from raw material extraction, through production and use, to waste disposal (Finnveden et al. 2009; Baumann 2010). The methodology of LCA was mainly developed in the 1990s in the engineering community, but has become increasingly cross-disciplinary by incorporating elements from social, economic, environmental, and management sciences (Finnveden et al. 2009; Baumann 2010; Powers et al. 2012). LCA provides a framework for developing specific indicators related directly to the different phases in the life cycle of a product or service, following a cradle-to-grave accounting of resource use and environmental impacts. An important recent development in LCA, particularly relevant to urban sustainability, is the integration of the techniques of LCA with the conceptual model of urban metabolism (Chester et al. 2012; Pincetl et al. 2012; Goldstein et al. 2013). Also, incorporating land use and land cover change explicitly in LCA is another promising research area which will make LCA-based methods more effective for landscape and regional sustainability analysis (Eddy and Gergel 2015).

Single composite indices

Ecological Footprint

Ecological Footprint (EF) is an area-based indicator that focuses on the environmental dimension of sustainability, implying that a sustainable society should operate within its environmental carrying capacity (Rees 1996). Specifically, EF is defined as the land (and water) area that is needed to provide all the energy and material resources consumed and to absorb all the wastes discharged in order to support a population or an activity, given prevailing technology and resource management practices (Rees 1996; Wackernagel and Rees 1996). Comparing the actual EF to the available biocapacity of a place of concern provides an indication of whether the environmental carrying capacity of that place is exceeded. To quantify both the demands and supplies of the renewable resources generated by land and water, a productivity-weighted areal unit—the "global hectare"—is used in the calculation of EF (Table 2). One global hectare is a normalized value based on the average productivity of all biologically productive land and water of the world in a given year. The consumption of natural resources of different kinds, from energy to biomass, can be converted to global hectares.

Since the early 1990s, EF has become a widely used indicator of human impacts on the environment across a wide range of scales, from individual humans and activities to the entire world (Wackernagel and Rees 1996; Luck et al. 2001; Wieldmann and Barrett 2010). For example, based on a global-level EF analysis Wackernagel et al. (2002) reported that human demands for ecosystem goods have exceeded the earth's regenerative capacity since the 1980s onward, overshooting the global biocapacity by 20 % in 1999. EF has had a long tradition of focusing on cities since its inception (Rees and Wackernagel 1996). At the urban scale, EF can keep track of a city's demands for food, water, and other natural resources as well as its natural capital, providing a useful measure of its

Table 2 Mathematical formulations of composite sustainability indictors discussed in this paper (see the main text for references)

Indicator	Formula
Ecological Footprint (EF)	EF = P/YN × YF × EQF, where P is the amount of product harvested, YN is the average yield for P, and YF and EQF are the yield factor and equivalence factor
Green City Index (GCI)	GCI = CO_2 emissions + energy + buildings + land use + transport + water and sanitation + waste management + air quality + environmental governance
City Development Index (CDI)	CDI = (Infrastructure index + Waste index + Health index + Education index + Product index)/5, where:
	Infrastructure = 25 × Water connections + 25 × Sewerage + 25 × Electricity + 25 × Telephone,
	Waste = Wastewater treated × 50 + Formal solid waste disposal × 50,
	Health = (Life expectancy − 25) × 50/60 + (32 − Child mortality) × 50/31.92,
	Education = Literacy × 25 + Combined enrolment × 25, and
	Product = (log City Product − 4.61) × 100/5.99
Environmental Performance Index (EPI)	EPI = *f*(Environmental Health, Ecosystem Vitality), in which 20 indicators representing 9 issue areas are aggregated through an unequal weighting scheme
Genuine Progress Indicator (GPI)	GPI = C_{adj} + G_{nd} + W − D − E − N, where C_{adj} is personal consumption expenditures adjusted for income inequality, G_{nd} is non-defensive government expenditures, W is nonmarket contributions to welfare, D is defensive private expenditures, E is the costs of environmental degradation, and N represents depreciation of the natural capital base
Genuine Savings (GS)	GS = Gross domestic savings − Consumption of fixed capital (Depreciation) + Education expenditure − Air pollution costs − Water pollution costs − Depletion of nonrenewable natural resources − CO_2 damage costs
Human Development Index (HDI)	HDI (1990–2009) = 1/3(Life Expectancy) + 1/3(Education index) + 1/3(GDP per capita, adjusted for purchasing power parity), in which Education index is a combination of adult literacy rate and enrollment ratio
	HDI (2010–) = (Life Expectancy)$^{1/3}$ × (Education index)$^{1/3}$ × (GNI per capita, adjusted for purchasing power parity)$^{1/3}$, in which Education index is a combination of mean years of schooling and expected years of schooling
Happy Planet Index (HPI)	HPI = Happy life years/Ecological Footprint, where Happy life years is the product of Life expectancy and Experienced well-being which is obtained from surveys
Wellbeing Index (WI)	WI = 1/2(Ecosystem Wellbeing Index + Human Wellbeing Index), where EWI = 1/5(land + water + air + species and genes + resource use), and HWI = 1/5(health and population + wealth + knowledge and culture + community + equity)
Sustainable Society Index (SSI)	SSI = Human Wellbeing + Environmental Wellbeing + Economic Wellbeing, or
	SSI = 1/7(Basic Needs + Health + Personal & Social Development + Natural Resources + Climate & Energy + Transition + Economy)

environmental sustainability. A number of case studies of sustainability assessment using EF on national, regional, municipal, and local scales have been compiled by the Global Footprint Network (http://www.footprintnetwork.org).

The popularity of EF has been met with criticisms, pointing to the abstraction of the area-based measurement, the demarcation of spatial boundaries, and the lack of consideration of technological change, equity issues, and policy prescriptions (van den Bergh and Verbruggen 1999; Ayres 2000; Moffatt 2000; Fiala 2008; van den Bergh and Grazi 2010). In response to some of the criticisms, Rees (2000) admitted that “certainly eco-footprinting is not all-inclusive” and “does not produce a complete picture of ecological sustainability”. He concluded that the limited scope of EF does not invalidate the method for what it does measure; but rather it only suggests that EF calculations most likely underestimate the actual human appropriations of ecosystem goods (Rees 2000).

Green City Index

Green City Index (GCI) was developed by the Economist Intelligence Unit in cooperation with Siemens (EIU-Siemens) for assessing and comparing the world cities in terms of their "environmental performance" (http://www.siemens.com/entry/cc/en/greencityindex.htm). Since 2009, the EIU-Siemens project has assessed more than 120 cities around the world, and produced a series of reports with GCI rankings of these cities by region (African Green City Index, Asian Green City Index, European Green City Index, German Green City Index, Latin American Green City Index, and U.S. and Canada Green City Index). The cities were chosen on the basis of their size and prominence, most of which are national capitals and metropolises with large populations and business centers.

GCI includes about 30 indicators of 9 categories, including CO_2 emissions, energy, buildings, land use, transport, water and sanitation, waste management, air quality, and environmental governance (Table 2). About half of the indicators in GCI are quantitative based on data usually from official public sources (e.g., CO_2 emissions, water consumption, air pollution), and the other half are qualitative assessments of environmental policies (e.g., investment in renewable energy, traffic-congestion-reduction policies, and air quality codes). The specific formulation of GCI varies somewhat between the regions, accounting for data availability and unique challenges in each region. The European Green City Index was developed earlier, consisting of 16 quantitative and 14 qualitative indicators, and its methodology was then adapted for developing the GCI of the other regions. Different from the European GCI, the African GCI includes indicators measuring access to electricity, potable water, and information. So far, GCI has been promoted almost exclusively by the EIU-Siemens project, and is yet to be taken up by other researchers.

Environmental Performance Index

Environmental Performance Index (EPI), formerly called Environmental Sustainability Index (ESI), was developed by the Center for Environmental Law and Policy at Yale University and Columbia University's Center for International Earth Science Information Network, in collaboration with the World Economic Forum and the European Commission's Joint Research Center (http://epi.yale.edu). EPI is constructed based on two broad themes (or policy objectives): protection of human health from environmental harm and protection of ecosystems, with 9 issue areas (i.e., agriculture, air quality, biodiversity and habitat, climate and energy, fisheries, forests, health impacts, water resources, and water and sanitation). Altogether, 20 indicators are used to quantify the 9 issue areas of the two themes, and then aggregated into one single index of EPI (Table 2). In the process of aggregation, the weights of the indicators, issue areas, and overall policy objectives are determined according to their relevance to policy issues and data quality: higher relevance corresponds to higher weights and less reliable data to lower weights (Hsu et al. 2014).

EPI has been used to measure how well different countries are meeting internationally established targets and how they compare with each other. It focuses on the environment dimension of sustainability, as the name itself suggests, but has a strong emphasis on policy issues that cut across social and institutional dimensions. Although EPI has been used primarily at the national level, it can be used for assessing the sustainability of cities and urban regions after the issue areas and associated indicators are properly modified to address urban issues. However, this is yet to be done.

Genuine Progress Indicator

Recognizing that GDP is an indicator of economic growth but not sustainable development, efforts to "green" GDP mushroomed since the early 1990s (Wu and Wu 2010; Kubiszewski et al. 2013). In addition to economic activities, resource consumption and environmental damage, completely ignored in GDP, are explicitly considered in the formulations of Green GDP measures. A prominent sustainability indicator of this kind is Genuine Progress Indicator (GPI), which is composed of more than 20 individual indicators covering the environmental, economic, and social dimensions of sustainability (Talberth et al. 2006). GPI accounts for both conventional economic transactions and nonmarket natural and social benefits, explicitly distinguishing between positive and negative impacts of economic activities on human wellbeing (Table 2; Posner and Costanza 2011). GPI is the revised version of Index of

Sustainable Economic Welfare (ISEW), proposed by Daly and Cobb (1989). Both GPI and ISEW are derived from the national accounts of the transactions deemed directly relevant to human wellbeing, including the positive economic contributions of household and volunteer work and the negative influences of pollution, commuting, crime, and family breakdown. The main differences between the two are related to data availability and users' preferences for valuation methods (Lawn 2003). In recent years, however, GPI has been used more frequently than other Green GDP measures (Lawn 2003; Kubiszewski et al. 2013).

Although ISEW and GPI were originally designed to measure progress at the national level, they have been used at multiple scales (Posner and Costanza 2011). For example, as the first user of Green GDP at the national level, China released its environmentally adjusted GDP in 2006, concluding that the economic loss of environmental damages accounted for 3 % of its total GDP in 2004 (Wu and Wu 2010). The State of Maryland of the United States has adapted GPI to measure how development activities impact long-term prosperity (http://www.dnr.maryland.gov/mdgpi/). GPI has also been applied at the city level, including several American cities (Costanza et al. 2004; Venetoulis and Cobb 2004), Chinese cities (Wen et al. 2007; Zhang et al. 2008), and Canadian cities (Anielski and Johannessen 2009).

Genuine savings

Genuine savings (GS) were proposed as an indicator of sustainable development, based on the idea that "the level of overall capital stock should be non-decreasing" for a sustainable nation state (Pearce and Atkinson 1993). The wealth of a country can only be increased by net savings, not necessarily by GDP, and the calculation of net savings must consider resource depletion and environmental degradation, as well as changes in technologies and human resources. Thus, GS measures the net change in the whole range of assets important for economic development, including produced assets, natural resources, environmental quality, human resources, and foreign assets (Table 2; Hamilton and Clemens 1999; Pillarisetti 2005; Dietz and Neumayer 2007; Greasley et al. 2014).

GS represents another way of "greening" GDP or national accounts by subtracting the values of natural resource consumption and depletion, costs of pollution damages (including those related to human health), and deducting net foreign borrowing, as well as by treating expenditures on education as saving rather than as consumption (increasing human capital) (World Bank 1997). GS and GPI are conceptually similar, but technically different. GPI focuses on the "flows" of transactions, whereas GS measures changes in stocks or different kinds of capital, showing the resources available for the future (Rogers and Srinivasan 2007). Although not as widely as GPI, GS has also been used in assessing urban sustainability, including a number of cities in China, India, and the United States (Wen et al. 2005; Rogers and Srinivasan 2007; Zhang et al. 2008).

Human Development Index

Human Development Index (HDI) was developed by the United Nations Development Programme (UNDP) in the 1990s to assess the levels of human and social development of different countries around the world (http://hdr.undp.org/en/content/human-development-index-hdi). As a composite index, HDI is computed as the arithmetic mean or geometric mean of three normalized sub-indices: life expectancy, education and standard of living (Table 2). Since 1990, UNDP has released the Human Development Report annually, with all countries ranked by their values of HDI. HDI is arguably the most widely used among all sustainability indicators so far because it captures the most essential elements of human wellbeing and because it is easy to compute and interpret. Its mathematical formulation clearly indicates that HDI considers the economic and social dimensions, but omits the environmental dimension. As a measure of human wellbeing, however, HDI has been quite popular (e.g., Leigh and Wolfers 2006; Raudsepp-Hearne et al. 2010). In addition to its widespread applications at the national level, HDI has also been used for assessing the sustainability or "prosperity" of major cities around the world during the recent years (UN-Habitat 2012).

Happy Planet Index

Happy Planet Index (HPI) was first developed in 2006 by the New Economics Foundation (NEF), which directly relates human wellbeing to human consumption of natural resources (http://www.happyplanetindex.org/).

The index is calculated as the ratio of Happy Life Years (happiness-adjusted life expectancy) to environmental impact (measured by Ecological Footprint), and essentially measures "the ecological efficiency with which human wellbeing is delivered" (New Economics Foundation 2009). The formulation of HPI is based on the assumption that human wellbeing should be measured not only in terms of longevity but also quality of life, and that a sustainable world can only be achieved by simultaneously increasing human wellbeing and reducing human ecological footprints (Table 2). NEF, the creator of HPI, has computed HPI for 143 countries, covering 99 % of the world's population. The results show that richer developed nations tend to have higher HPI values, and that some less wealthy countries also are quite "happy", but with a much smaller per capita ecological footprint (New Economics Foundation 2009). While HPI has been used only on the national level, as Mega (2013) suggested, it can, and should, be used for assessing urban sustainability. Its simple mathematical formulation seems readily applicable to cities or urban regions.

Wellbeing Index and barometer of sustainability

Wellbeing Index (WI), also known as the Barometer of Sustainability, was developed as a tool for measuring and communicating a society's wellbeing and progress toward sustainability through the sponsorship of World Conservation Union (IUCN) in the 1990s (Prescott-Allen 1997, 2001). Different from the three- or four-dimensional framework, WI is based on a dual framework that has only two dimensions—people and ecosystems—which are considered equally important, so that the wellbeing of a human-environment system is determined simultaneously by the wellbeing of both people and the ecosystems that people depend on. This dual framework is based on the assumption that dividing the people component further unjustifiably reduces the weight of the environment—for example, "the triple framework reduces the weight of the environment to a third; the quadruple framework reduces it to a quarter" (Prescott-Allen 2001, pp. 291). The WI framework was often explained through the metaphor of the Egg of Wellbeing: "The ecosystem surrounds and supports people much as the white of an egg surrounds and supports the yolk. Just as an egg can be good only if both the yolk and white are good, so a society can be well and sustainable only if both people and the ecosystem are well" (Prescott-Allen 2001, pp. 4–5).

Thus, WI is a compound index with two components: Human Wellbeing Index (HWI) and Ecosystem Wellbeing Index (EWI) (Table 2). HWI is the average of indicators measuring the wellbeing of people from five aspects: health and population, wealth, knowledge and culture, community, and equity. HWI reflects socioeconomic conditions more realistically than monetary indices such as GDP and represents human wellbeing more comprehensively than HDI. EWI is the average of indicators measuring the ecosystem conditions in terms of land, water, air, species and genes, and resource use. The result of WI can be presented as a single value (i.e., the arithmetic average of EWI and HWI) or, more meaningfully, as a two-dimensional graph, with EWI as the X-axis and HWI as the Y-axis. Both axes are scaled from 0 to 100 and divided into five equal bands: Bad, Poor, Medium, OK, and Good. The overall wellbeing of a system is indicated by the intersection between EWI and HWI, and this plot is called the "Barometer of Sustainability" (Prescott-Allen 2001). On the barometer, the axis with the lower score always overrides the other axis, meaning that the overall wellbeing is determined by either EWI or HWI whichever is lower. In other words, no tradeoff or substitution is allowed between human wellbeing and ecosystem wellbeing.

As the first global assessment of sustainability, the WI method was used to compare the wellbeing of 180 countries (Prescott-Allen 2001). The method can be used at any level, ranging from a municipality to the entire world. However, WI has not been widely used in the past decade when many new sustainability indicators have mushroomed.

City Development Index

City Development Index (CDI) was developed in 1997 by the Urban Indicators Programme of the United Nations Human Settlements Programme (UN-Habitat), in order to rank cities of the world according to their level of development (UN-Habitat 2002). CDI is composed of five sub-indices: Infrastructure, Waste, Health, City product, and Education (Table 2). Each sub-index is further composed of multiple indicators: (1) Infrastructure that considers water availability, sewerage, access to electricity, and telephone availability; (2) Waste that includes wastewater treatment and solid waste disposal; (3) Health that considers life expectancy and child mortality; (4) City product which is analogous to GDP at the city level; and (5) Education that combines literacy and school enrollment. All the indicators are aggregated using weights that are determined by Principal Component Analysis and experts' opinions (UN-Habitat 2002).

CDI is a measure of urban development and access to urban facilities by individuals, and seems effective to evaluate urban poverty and urban governance. In particular, the components of health, education and infrastructure are useful for measuring poverty outcomes, and the components of infrastructure, waste and city product are pertinent to the effectiveness of urban governance. The result of CDI can be presented as a radar diagram to visually show how well the different components do, and also to facilitate comparisons among different cities and regions. The United Nations Human Settlements Programme has computed CDI for 232 cities in 113 countries around the world to assess the urban conditions and trends between 1993 and 1998 (UN-Habitat 2002). The developer of CDI has regarded it as "the best single measure of the level of development in cities" (UN-Habitat 2002, p. 3).

Sustainable Society Index and Sustainable City Index

Sustainable Society Index (SSI) is a highly aggregated sustainability index which was developed in 2006 by the Sustainable Society Foundation, a non-profit organization based in the Netherlands (http://www.ssfindex.com). The original formulation of SSI includes 22 indicators under 5 categories: personal development, clean environment, well-balanced society, sustainable use of resources, and sustainable world (Van de Kerk and Manuel 2008). The latest version of SSI now is organized hierarchically according to 3 "wellbeing dimensions", 7 categories, and 21 indicators (http://www.ssfindex.com) (Table 2). The three wellbeing dimensions (and categories) are Human Wellbeing (Basic needs, Health, and Personal and social development), Environmental Wellbeing (Natural resources, and Climate and energy), and Economic Wellbeing (Transition and Economy). Each category has 2 or 3 indicators which are aggregated into a single index. SSI was originally developed and has been used for national-level analysis (computed for more than 150 countries), but recent efforts have been made to apply it at regional and local levels (http://www.ssfindex.com/about-ssf/).

In particular, based on SSI, the Sustainable Society Foundation developed the Sustainable City Index (SCI) in January of 2014, which had the same 3 wellbeing dimensions, 7 categories, and 16 indicators. SCI has recently been revised, with modified dimensions, categories, and indicators (www.gdindex.nl). The revised SCI 2.0 now has 9 categories: Basic needs, Personal development, and Social development (the dimension of Human wellbeing), Environment and nature, Resource efficiency, Energy efficiency, and Transport efficiency (the dimension of Environmental wellbeing and resource circularity), and Work and Public finance (the dimension of Economic wellbeing). There are 24 indicators associated with the 9 categories which emphasize personal and social development, environmental quality, resource and energy use efficiency, and several other prominent issues in cities. The indicators are aggregated into the single index of SCI through a geometric averaging scheme. The range of values of SCI goes from 1 to 10. SCI has been used to rank all 403 cities in the Netherlands in 2014. Of all these cities, the highest score is 5.8, the lowest score is 3.1, and the average score is 4.8, suggesting there is much room for sustainability improvements (http://www.gdindex.nl).

Discussion

From the above review, it is clear that there is no lack of USIs, which have been developed from different conceptual frameworks and for different purposes. In this section, we discuss several issues on the problems, challenges, and ways forward in the use of USIs, particularly from the perspective of landscape sustainability science (Wu 2013).

What do USIs really measure?

By definition, USIs are supposed to gauge the state and processes of urban sustainability. But do they each measure all the three dimensions of sustainability? What kind of sustainability do they actually measure: weak sustainability or strong sustainability? Of all the USIs reviewed in this paper, eight of them cover all the three dimensions, and five consider only two of the three dimensions (Fig. 3). Specifically, indicator sets

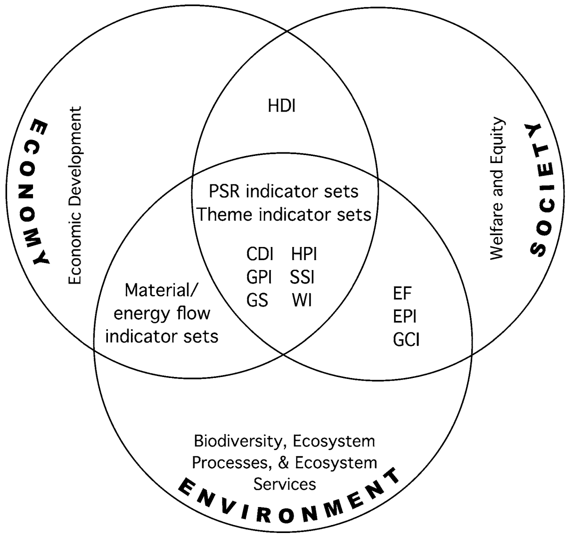

Fig. 3 Venn diagram of urban sustainability indicators in relation to the three dimensions of sustainability. Four types of urban sustainability indicators are distinguished

developed from the PSR framework and the theme-based framework and six composite indices (CDI, GPI, GS, HPI, SSI, and WI) cover all the three dimensions of sustainability; indicator sets derived from the material/energy flow framework cover the economic and environmental dimensions; three indices (EF, EPI, and GCI) cover the environmental and social dimensions; and HDI covers the social and economic dimensions (Fig. 3). Most of these USIs assign equal weights to the different dimensions, and thus they are fundamentally measures of weak sustainability. Only five of the indices or indicator sets examined in this study (i.e., EF, EPI, GCI, PSR-based indicator sets, and certain material/energy flow indicator sets) may be considered as measuring strong sustainability (Table 3).

The scope of USIs in terms of the three dimensions is important both theoretically and practically. Urban sustainability is fundamentally a dynamic process of harmonizing the environment, economy, and society in an urban area through design, planning, and institutional activities. Thus, measuring all the sustainability dimensions is often necessary to satisfy the needs for theoretical comprehensiveness and for diagnostic analysis of policy action areas. To do that, one can either develop an indicator set based on the PSR framework or the theme framework, or use composite USIs that cover the three dimensions. Using different kinds of indicators in concert or combining single indices with indicator sets in the same assessment can also provide useful information for confirmation and comparison of results.

Urban boundary and spatial scale

Urban sustainability focuses on human wellbeing which depends, fundamentally, on the flows of ecosystem services (provisioning, regulating, and cultural) derived from natural capital (biodiversity and ecosystems) locally and from afar (Wu 2010, 2013, 2014). USIs have been used mostly for individual cities, ranging from small municipalities to large metropolises. However, urban areas are spatially nested hierarchical landscape systems, as local cities form metropolitan regions which in turn comprise urban agglomerations. These urban systems interact with each other across organizational levels and spatial scales. Cities function as energy and material sucking funnels, importing resources from and exporting wastes to places far beyond their physical boundaries (Luck et al. 2001). As "environmental limits represent a nested set of rather different constraints at the local through global levels" (Moldan et al. 2012), it is more meaningful to assess urban sustainability on multiple scales using USIs.

A city that derives most of its ecosystem services from other regions nationally or internationally is subject to myriad environmental and sociopolitical uncertainties and thus hardly sustainable in the long run. A city that prospers by continuously increasing its material and energy consumption at the expense of its environment cannot possibly be sustainable. From a strong sustainability perspective, a sustainable city or urban region must maintain a "critical" level of local and regional biodiversity and ecosystem functioning so as to provide the most of the essential ecosystem services required for human wellbeing. While making individual cities sustainable on their own may be formidable or even impossible, making urban regions sustainable with limited externalities is not only possible but also desirable (Forman 2008; Wu 2013, 2014). Using USIs on multiple scales, or linking local indicators with regional indicators, can certainly help address these issues on strong versus weak sustainability in an urban context. For example, this can be done by adopting the hierarchical patch dynamics framework, in which a series of urban hierarchical

Table 3 Classification of urban sustainability indicators based on the weak and strong sustainability criteria that are centered on substitutability between natural and human-made capital

Sustainability criteria	Weak sustainability indicator	Strong sustainability indicator
Indicator Sets	Theme-based indicator sets	PSR-based indicator sets
		Material and energy flow indicator sets
Composite Indicators	City Development Index (CDI)	Ecological Footprint (EF)
	Genuine Progress Indicator (GPI)	Environmental Performance Index (EPI)
	Genuine Savings (GS)	Green City Index (GCI)
	Happy Planet Index (HPI)	
	Human Development Index (HDI)	
	Sustainable Society Index (SSI)	
	Wellbeing Index (WI)*	

* WI can be considered as a strong sustainability indicator if the result is presented in the form of Barometer of Sustainability (see the main text for more detail)

levels (e.g., single city—city cluster—urban region—nation state) is explicitly identified, and USIs are applied at each and every hierarchical level (Wu 1999; Li et al. 2013). Such multi-scale analysis not only provides deeper insight into the sustainability of individual urban systems, but also critical information for urban and regional planning across scales.

Indicator selection

Using USIs involves the selection of individual indicators to measure specific aspects of each sustainability dimension. A large pool of such urban indicators for different themes is available for selection, many of which have been used in a number of case studies (Appendix from ESM). The choices of the component indicators for a particular sustainability index or indicator set directly affect the results and conclusions. Unfortunately, the selection process is "inherently very subjective" and "much depends upon a value judgment as to what is important" (Morse et al. 2001). To reduce arbitrariness in the selection process, we recommend that the PSR and theme-based frameworks be followed. In addition to covering the three pillars, project objectives, scale, and strong versus weak sustainability also need to be considered. Given the subjective nature of selecting indicators, urban sustainability assessment should emphasize the use of widely recognized urban indicators, with clearly articulated justifications.

USIs based on the Triple Bottom Line and, more generally, multi-dimensional concepts of sustainability may be considered as fundamentally measuring weak sustainability. But this does not have to be the case. The recognition of multiple dimensions of sustainability itself, without assigning equal weights to them, is not necessarily a weak sustainability perspective. In fact, the strong sustainability perspective cannot be articulated without invoking multiple types of capital or sustainability dimensions. Nevertheless, the distinction between weak and strong sustainability has important implications for urban sustainability assessment because whether or not a USI or a group of USIs is adequate depends on what kind of sustainability is intended to be achieved. As discussed earlier, weak sustainability is eventually not sustainable (Daly 1995; Wu 2013), although weak sustainability indicators can be useful. To avoid misleading interpretations, however, we argue that an urban sustainability assessment should include at least one strong sustainability indicator (e.g. EF or GCI). Thus, the concept of the "Critical Natural Capital" and the associated "sustainability gap" approach (also Ekins and Simon 1999; Ekins et al. 2003; Ekins 2011) are quite useful in urban sustainability assessment.

Weighting and aggregation

Using USIs also involves a series of technical steps from the acquisition and processing of data to the computation and presentation of the indicator results (Fig. 2). The values of component indicators usually are normalized for compatibility (e.g., everything is monetized in GPI and GS, but standardized to the unit of global hectares in EF), and then weights are assigned to indicators which are aggregated into theme indicators (or sub-indices). In the case of composite indices, such as those in Tables 2 and 3, sub-indices are further aggregated into single values (Fig. 2).

The technical details of weighting and aggregation can also affect the calculation of USIs, often presenting methodological challenges. Published indicator studies have used various methods for weighting and aggregation (see Table 4), making inter-study comparison difficult. In many cases, simplistic methods such as equal or arbitrary weighting schemes were used because they are "transparent and easy to understand" (Esty et al. 2005). A number of more rigorous statistical methods have been proposed for aggregating sustainability indicators, including regression analysis, Principal Component Analysis, Factor Analysis, Data Envelopment Analysis, Analytic Hierarchy Process, and Conjoint Analysis (Krajnc and Glavi 2005; Nardo et al. 2005; Jollands 2006; Bohringer and Jochem 2007). Whenever possible, these quantitative methods should be preferred. Also, as indicator aggregation involves scaling in space and across hierarchical levels, several scaling approaches in landscape ecology may prove useful in the future (Wu 1999).

Spatializing urban sustainability indicators

Urban sustainability assessment using USIs has mostly treated cities as social-economic-ecological systems that are internally homogeneous in space. However, urban systems represent the most spatially heterogeneous of all landscapes, composed of patches

Table 4 Comparison of selected sustainability indicators that have been, or can be, used for assessing urban sustainability

Indicator	Publication year	Developer	Normalization method*	Weighting method*	Aggregation method*	Scale originally intended	Applied at urban scale?
City Development Index (CDI)	1997	UN-Habitat	Distance from mean	PCA or experts' opinions	Weighed average	Urban	Yes
Ecological Footprint (EF)	1992	Wackernagel and Rees	Global hectares	Equal	Summation	Local to global	Yes
Environmental Performance Index (EPI)	By-yearly since 2006	Yale University and Columbia University	(0, 100)	PCA or experts' opinions	Weighed average	Global, National	Not yet
Genuine Progress Indicator (GPI)	1994	Redefining Progress	Monetized	Equal	Summation	Global, National	Yes
Genuine Savings (GS)	1999	World Bank	Monetized	Equal	Summation	Global, National	Yes
Green City Index (GCI)	2009	Economic Intelligence Unit and Siemens	(1, 10)	Equal	Average	Urban	Yes
Human Development Index (HDI)	Yearly since 1990	United Nations Development Programme	(0, 1)	Equal	Average	Global, National	Yes
Happy Planet Index (HPI)	2006	New Economics Foundation	(0, 100)	–	–	Global, National	Not yet
Sustainable Society Index (SSI)	2006	Sustainable Society Foundation	(0, 10)	Unequal	Weighted average	Global, National	Yes
Wellbeing Index (WI)	2001	IUCN and International Development Research Centre	(0, 100)	Unequal, categorical	Weighed average	Global, National	Not yet

* For details on the methods of normalization, weighting and aggregation, see Nardo et al. (2005), Jollands (2006), and Bohringer and Jochem (2007)

and corridors of different kinds and sizes (e.g., backyards, parking lots, parks, central business districts, residential areas, schools, rivers, and roads). Urban systems are patchy not only environmentally but also economically and socially. To accurately assess urban sustainability, therefore, spatial heterogeneity within a city and the broader urban region needs to be considered (Wu 2010). In other words, USIs need to be "spatialized".

How does the spatial pattern of cities and metropolitan regions affect the sustainability of these urban systems? This is an important question for urban ecologists and planners as well as landscape and sustainability scientists. Numerous studies in the landscape ecology literature have shown that the composition and configuration of urban landscapes both may have substantial influences on ecological and socioeconomic processes, or vice versa. To help spatialize USIs, we need to further integrate USIs with landscape pattern analysis, with an emphasis on ecosystem services and human wellbeing in changing landscapes (Wu 2013, 2014). There are two simple ways to move forward: computing USIs with spatially explicit data representing the spatial patterns of environmental, economic, and social conditions; and combining landscape metrics with USIs in the same assessment. There are examples of both approaches (e.g., Morse et al. 2011; Jones et al. 2013; Potschin and Haines-Young 2013; Iverson et al. 2014), and more studies are needed.

Conclusions

Urban sustainability indicators include both indicator sets and composite indices that are suitable for assessing the sustainability of urban systems. While there seems no lack of USIs, their applications have suffered from both technical and conceptual inconsistencies. To move forward with urban sustainability assessment using USIs, we make the following suggestions: (1) Use the PSR or theme-based frameworks to guide the selection of urban indicators, and cover all three dimensions of sustainability with generally accepted urban indicators; (2) Be clear about what kind of sustainability—weak or strong sustainability—is being gauged; (3) Include at least one strong sustainability indicator in the assessment by combining indicator sets and composite indices; (4) Follow rigorous procedures for normalization, weighting, and aggregation; (5) Adopt a multi-scale strategy to consider hierarchical linkages between local cities and urban regions; and (6) Spatialize USIs to consider landscape patterns and the flows of ecosystem services in changing environments.

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