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Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI)

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ABSTRACT

The purpose of this paper is to discuss conceptual requirements for a City Sustainability Index (CSI) and to review existing major sustainability indices/indicators in terms of the requirements. The following indices are reviewed: Ecological Footprint (EF), Environmental Sustainability Index (ESI), Dashboard of Sustainability (DS), Welfare Index, Genuine Progress Indicator (GPI), Index of Sustainable Economic Welfare, City Development Index, emergy/exergy, Human Development Index (HDI), Environmental Vulnerability Index (EVI), Environmental Policy Index (EPI), Living Planet Index (LPI), Environmentally-adjusted Domestic Product (EDP), Genuine Saving (GS), and some applications of composite indices or/and multivariate indicators to local or regional context as case studies. The key conceptual requirements for an adequate CSI are: (i) to consider environmental, economic and social aspects (the triple bottom line of sustainability) from the viewpoint of strong sustainability; (ii) to capture external impacts (leakage effects) of city on other areas beyond the city boundaries particularly in terms of environmental aspects; (iii) to create indices/indicators originally for the purpose of assessing city sustainability; and (iv) to be able to assess world cities in both developed and developing countries using common axes of evaluation. Based on the review, we conclude that it is necessary to create a new CSI that enables us to assess and compare cities' sustainability performance in order to understand the global impact of cities on the environment and human life as compared with their economic contribution. In the future, the CSI will be able to provide local authorities with guidance toward sustainable paths.

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1. Introduction

Cities (or urban developed areas with large population) are important worldwide because human social and economic activities have been concentrating there. According to UN-Habitat (2006), there are three important trends in the urbanization processes. First, the biggest cities will be found mainly in the developing world: 'Metacities', massive conurbations of more than 20 million people, are now gaining ground in Asia, Latin America and Africa (UN-Habitat, 2006). Second, more than half of the world's urban population lives in cities of fewer than 500,000 inhabitants, and almost one-fifth lives in cities of between 1 and 5 million inhabitants (UN-Habitat, 2006). Third, cities of the developing world will absorb 95% of urban growth in the next two decades, and by 2030, will be home to almost 4 billion people (UN-Habitat, 2006).

Cities play a significant role in social and economic activities, but they perform poorly in terms of environmental conservation because of externalities. In the Brundtland Report (WCED, 1987), the awareness has grown that many environmental problems have a local origin, while global environmental decay often manifests itself at a local level (Finco and Nijkamp, 2001). It is significant to evaluate sustainability in cities in order to appropriately manage human activities there. Scipioni et al. (2009) mention that the local and the urban dimensions of sustainability are becoming prevalent in international literature and the definition of specific local urban context indicators is of great interest. We are interested in creating a new relevant City Sustainability Index (CSI), which enables us to assess and compare cities' sustainability performances for understanding the local and global impact of cities on the environment and human life as compared with their economic contribution and to potentially help local authorities to obtain political guidance toward possible sustainable paths.

Sustainability assessment has been developed conceptually and through practical applications (George and Kirkpatrick, 2007; Gibson et al., 2005). Pope et al. (2004) conceptually review several approaches of sustainability assessment such as environmental impact assessment (EIA), strategic environmental assessment (SEA), objectives-led SEA, EIA-based integrated assessment, objectives-led integrated assessment, and assessment for sustainability relied on principles-based criteria. In sustainability assessment, the triple bottom line approach, covering environmental, economic and social dimensions, is a starting point (Pope et al., 2004). Sustainability assessment focuses on prospects for lasting net gains and the acceptability of associated trade-offs with generic trade-off rules (Gibson, 2006; Pope et al., 2004; Winfield et al., 2010). The purpose of sustainability assessment is to provide decision-makers with an evaluation of global and local integrated nature-society systems in short and long term perspectives in order to help them to judge which actions should or should not be taken in an attempt to make society sustainable (Devuyst, 2000; Ness et al., 2007). Four major purposes in sustainability assessment are identified: decision making and management, advocacy, participation and consensus building, and research and analysis (Parris and Kates, 2003). Sustainability assessment provides the basic framework of core generic criteria: socio-ecological system integrity; livelihood sufficiency and opportunity; intra- and inter-generational equity; resource maintenance and efficiency; socio-ecological civility and democratic governance; precaution and adaptation; and immediate and long-term integration (Gibson, 2006; Winfield et al., 2010). The framework will be useful for creating a new City Sustainability Index (CSI) in terms of decision-making in reality. CSI tries to evaluate city sustainability as a performance evaluation tool while sustainability assessment in general tries to evaluate sustainability of individual projects, policies, plans and programs as an explanatory or planning tool.

The purpose of this paper is to discuss several conceptual requirements for an appropriate City Sustainability Index (CSI), and to review major sustainability indices/indicators in terms of the requirements. The following indices are reviewed: Ecological Footprint (EF), Environmental Sustainability Index (ESI), Dashboard of Sustainability (DS), Welfare Index (WI), Genuine Progress Indicator (GPI), Index of Sustainable Economic Welfare (ISEW), City Development Index (CDI), Emergy/Exergy, Human Development Index (HDI), Environmental Vulnerability Index (EVI), Environmental Policy Index (EPI), Living Planet Index (LPI), Environmentally-adjusted Domestic Product (EDP), Genuine Saving (GS), and some applications of composite indices or/and multivariate indicators to local or regional contexts as case studies. The structure of this paper is in the following: we discuss conceptual problems to derive requirements for CSI in Section 2; based on them, we review major sustainability indices/indicators in Section 3; we discuss issues relevant to the creation of a new CSI in Section 4, which should be profoundly considered in addition to fundamental conceptual requirements; and finally we provide concluding remarks.

2. Conceptual problems

In this section, conceptual issues on the requirements for the development of an appropriate City Sustainability Index (CSI) are addressed. A discussion on the concept of sustainability is made in order to set-up the general framework and the specific case of city sustainability is discussed in detail later, after discussing cities and their boundaries.

2.1. Concept of sustainability

Sustainability has already been a popular term in the field of environmental economics. However, its definition is still ambiguous. Furthermore, sustainability at the urban level has special characteristics. There are various notions of sustainability sharing several common points.

2.1.1. Definitions of sustainability

The Brundtland Report provides the most popular notion of sustainability (sustainable development): development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). The definition provided by the Brundtland Report is a characteristic definition of sustainability (Bithas and Christofakis, 2006). Based on a review on

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the sustainability concept, there is no consensus regarding the operational content of environmentally sustainable economic development (Bithas and Christofakis, 2006; Fischer et al., 2007). The broad definition of sustainable development gives rise to multiple interpretations (Tanguay et al., 2010). Its proponents differ in their emphases on what is to be sustained, what is to be developed, how to link environment and development, and for how long a time (Parris and Kates, 2003).

Sustainable development is the development that is likely to achieve lasting satisfaction of human needs and improvement of the quality of life under the condition that ecosystems and/or species are utilized at levels and in ways that allow them to keep renewing themselves (Allen, 1980). Allen's definition—the only from the ones revised here that precedes the Brundtland Report—implies but does not emphasize the intergenerational aspect of sustainability. However, it links the quality of life to the preservation of ecosystems, which might be relevant to the discussion of weak and strong sustainability. According to the concept of weak sustainability, substitutability between human and natural capital is acceptable. On the other hand, strong sustainability focuses on the maintenance of natural capital. Although the concepts of weak and strong sustainability are clearly defined, it is practically difficult to make a distinction between the two because the definition of natural capital is not necessarily clear.

Sustainability is a normative notion that indicates the way how humans should act towards nature, and how they are responsible towards one another and future generations (Baumgärtner and Quaas, 2010). The essence of sustainable development is to meet fundamental human needs while preserving the life-support systems of planet Earth (Kates et al., 2001). Both these definitions are in the spirit of ambiguity of the definition in Brundtland Report discussing human needs and intergenerational responsibility.

Sustainable growth is described as non-declining consumption while sustainable development is defined as non-declining utility over long term; hence intergenerational equity is considered (Dasgupta, 2001; Pezzey, 1992). However, the term utility does not allow a clear distinction between weak and strong sustainability. Ecologically sustainable economic development is defined as the dynamics in economic activities, human attitudes and human population to maintain an acceptable standard of living for all human beings and to ensure the availability of natural resources, ecosystems and life support systems in the long run (van den Bergh and Nijkamp, 1991). Sustainability is a process in social-ecological linkages including ecological, social and economic dimensions, and implies not challenging ecological thresholds on temporal and spatial scales that will negatively affect ecological systems and social systems (Berkes and Folke, 1998). The sustainability of human–environment systems is determined through three main characteristics: resilience to both natural and anthropogenic disturbances; desirability to human societies; and temporal and spatial scale boundaries (Mayer, 2008). The issue of weak and strong sustainability is not clearly addressed in these definitions either. The attractiveness of the definition of the Brundtland Report lies in its generality leaving issues such as weak and strong sustainability open to interpretations.

The relationship between economic development, life quality and perpetuity of ecosystems and natural resources can be more abstractly addressed through the concept of the triple-bottom line. Sustainability should cover 'the triple bottom line' which considers environmental quality, economic prosperity and social justice (Elkington, 1997). Related to the triple bottom line, biophysical, social and economic considerations represent a nested hierarchy (Fischer et al., 2007). Without a functioning life-support system, societies cannot thrive; without functioning social structures and institutions, economies cannot flourish. This hierarchical nested structure of sustainability is different from the widely held notion of the 'triple bottom line' which treats biophysical (environmental), social and economic considerations as parallel. In order to further reduce the ambiguity created by the relationships between the elements of the triple bottom line, absolute thresholds are needed that will indicate the levels beyond which a system becomes unsustainable. The issue of relative and absolute evaluation is discussed in more detail in Section 4.1.

Several points are shared in a lot of notions of sustainability. Sustainability assessments ought to: (i) integrate economic, environmental, social and increasingly institutional issues as well as to consider their interdependencies; (ii) consider the consequences of present actions well into the future; (iii) acknowledge the existence of uncertainties concerning the result of our present actions and act with a precautionary bias; (iv) engage the public; (v) include both intragenerational and intergenerational equity considerations (Gasparatos et al., 2008). Sustainability assessments have common features: (1) subject focus on the relationship between humans and nature; (2) orientation towards the long-term and inherently uncertain future; (3) normative foundation in the idea of justice, between humans of present and future generations as well as between humans and nature; (4) concern for economic efficiency, understood as non-wastefulness, in the allocation of natural goods and services as well as their human-made substitutes and complements (Baumgärtner and Quaas, 2010). However, despite the common characteristics in the definitions of sustainability, there are no indicator sets that are universally accepted, backed by compelling theory, rigorous data collection and analysis, and influential in policy (Parris and Kates, 2003). Parris and Kates (2003) provide three reasons for this: (a) the ambiguity of sustainable development; (b) the plurality of purpose in characterizing and measuring sustainable development; and (c) the confusion of terminology, data, and methods of measurement.

Based on literature review, we can see that it is difficult to define sustainability precisely and convincingly. Moreover, from this review of definitions, sustainability consists of two main elements: the triple bottom line as an abstract notion of environmental, social and economic processes and over time preservation or intergenerational equity. As a result, we agree to the following points: (1) we should consider the triple bottom line – environmental, economic and social dimensions; (2) we should maintain the equity between current and future generations, among current people and between humans and nature; (3) we should maintain healthy conditions related to (1) and (2) in the long term. These three seem to be fundamental conditions for sustainability as is the distinction between strong and weak sustainability. Bell and Morse (2008) provide a very clear view on the distinction between weak and strong sustainability saying that if one believes in strong sustainability then no exchange between environment and economy can happen.

With regards to city sustainability, the triple bottom line plays an important role because cities mainly contribute to economic and social aspects rather than environmental aspects of sustainability due to environmental externalities. An important requirement is that cities should remain in a healthy condition over time without paralysis and malfunction in terms of environmental, economic and social dimensions (the triple bottom line). In general, most governments consider the triple bottom line. Cities are not exceptions. In fact, there is a strong political desire of governments for the comprehensive assessment of changes in economic, environmental, and social conditions. Böhringer and Jochem (2007) argue that an issue that cannot be clearly measured will be difficult to improve. On the issue of measurement and quantification, Bell and Morse (2008) also point out that "quantification does have limitations, and clearly it is not possible to measure all human experience"; to do so simplifications and assumption are necessary, but "clearly there is a trade-off between necessary simplification and at the same time having SIs [sustainability indicators] that are meaningful" (Bell and Morse, 2008). The process of sustainability assessment itself can help to identify the issues that can be improved, especially when it is conducted in a comparative way (comparison between case studies) and when the elements of sustainability (i.e. indicators) can be distinguished and compared to thresholds.

2.1.2. Weak and strong sustainability

We make a distinction between weak and strong sustainability in more detail here. While weak sustainability focuses on maintaining a combined stock of produced, natural, human and social capital intact, strong sustainability deals with specific environmental functions that ought not to be undermined by economic activity and possible ecological limits to growth (Nourry, 2008). Cities have positive impacts on economic and social aspects of sustainability, but not on environmental ones. Furthermore, they tend to leak environmental externalities to areas out of their boundaries. Therefore, we should evaluate environmental, economic and social dimensions independently without offsetting one aspect by another on the basis of the view of strong sustainability.

According to strong sustainability, natural capital is essentially non-substitutable to produced, human and social capitals. Four key functions of natural capital can be identified: (i) natural capital provides the raw materials for production and direct consumption; (ii) it assimilates the waste products of production and consumption; (iii) it provides amenity services, such as the visual amenity of a landscape; and (iv) it provides the basic life-support functions on which human life depends (Dietz and Neumayer, 2007). Natural capital is not just an inventory of resources, but it includes all those components of the ecosphere, and the structural relationships among them, whose organizational integrity is essential for the continuous self-production of the system itself (Wackernagel and Rees, 1997). However, measurement of natural capital is the challenge for an urban area (Olewiler, 2006). To measure strong sustainability for cities can be complicated because of the actual lack of specific forms of natural capital in the boundaries of urban areas. Nonetheless, strong sustainability is crucial in terms of CSI because external impacts (leakage effects) of cities on areas elsewhere must be considered.

2.1.3. Other attributes of sustainability indices/indicators

In addition to the triple bottom line, we would like to discuss two other attributes on sustainability indices/indicators: top–down/bottom–up approaches and dynamic representation.

Top–down approaches mean that experts and researchers define the framework and the set of indicators while bottom–up approaches feature the participation of different stakeholders in the design of the framework and the indicators selection process (Singh et al., 2009). Bottom–up approaches are suitable for local and regional level studies where a specific problem can be approached. Stakeholder involvement in the conceptualisation and development of indicators is significant (Mascarenhas et al., 2009). On the other hand, bottom–up approaches are unsuitable for studies looking at the broader picture and comparing many different cases. Although the scientifically rigorous indicators used in the top–down paradigm can be objective, they may be difficult for local people to use (Reed et al., 2006).

Dynamic representation is strongly related to intergenerational equity. To be able to understand and explain relationships between different factors and to propose policies towards a more sustainable city, it is important to consider changes over time. However, time series data are often difficult to obtain: moreover, their analysis can complicate the interpretation of the results. Static sustainability indices provide information for a specific point of time without considering changes or relationships over time. In many cases, it is critical to take them into consideration for understanding wider impacts of factors and policies.

Other attributes of sustainability measures to be considered include validity, reliability, comparability, simplicity, and data availability (Singh et al., 2009). Furthermore, simplicity scope, quantification, assessment, sensitivity, and timeliness are discussed (Harger and Meyer, 1996). In many cases, the compliance with the criteria is largely a matter of choice and priorities. In some senses, the construction of sustainability indicators/indices can be considered an art rather than science.

2.2. Boundary of a city

A city is one of the important spatial entities for assessing sustainability and making political decisions based on it. However, it is often problematical to determine the spatial unit or delineate boundaries of cities. How should/can we define cities?

A city can be defined in terms of population and land use: the population density and the ratio of urban developed areas. Certain standards for these variables are needed. The United Nations defines an urban agglomeration as the built-up or densely populated area including the suburbs and continuously settled commuter areas, which may be smaller or larger than a metropolitan area (UN-Habitat, 2006).

Politically-based boundaries such as countries, counties and cities may have an advantage in terms of the application of policies. Sustainability assessment based on them is helpful for decision-makers and policy-makers to decide which actions they should and should not take in an attempt to make society more sustainable (Devuyst, 2001). It is, however, pointed out that politically-based boundaries can be arbitrary and geographically irrelevant for evaluating sustainability. In the context of the analysis of ecological footprint, Fiala (2008) mentions that cross-country comparisons rely on boundaries that are arbitrary, and are thus potentially meaningless. This criticism can be relevant to any definitions that rely on national boundaries (Fiala, 2008). Holistic systems management and sustainability assessment are hindered by the difference between boundaries for administration and natural resource management because data for social and ecological indicators describe different regions (Graymore et al., 2010).

Nonetheless, we need relevant data for assessing sustainability in a target spatial entity. Then, we rely on the data provided by politically-based boundaries more or less. 105 countries base their urban data on administrative criteria, limiting it to the boundaries of state or provincial capitals, municipalities or other local jurisdictions; 100 countries define cities by population size or population density, with minimum concentrations ranging broadly, from 200 to 50,000 inhabitants; 25 countries specify economic characteristics such as the proportion of the labour force employed in non-agricultural industries as significant in defining cities; 18 countries count the availability of urban infrastructure in their definitions, including the presence of paved streets, water supply systems, sewerage systems, or electric lighting; 25 countries provide no definition of “urban” at all; and 6 countries regard their entire populations as urban (UN-Habitat, 2006). Sustainability data tend to be fairly complete at coarse spatial scales for politically-bounded systems, but sparse at smaller scales and for non-politically-defined systems because fewer data are available for units with non-politically-based boundaries, such as biomes, ecoregions and hydrologic drainage systems (Mayer, 2008). Many data are collected for politically-defined systems, but political boundaries may be irrelevant or misleading for sustainability research (Mayer, 2008).

As mentioned above, the definition of city is complicated. It is difficult to determine ideal boundaries of cities to assess sustainability in world cities. Particularly, it is too difficult to use some ideal non-politically-based boundaries, considering the data availability for sustainability assessment. In the end, we should ideally define cities by the population density, the ratio of urban developed areas and so on, but we are in reality interested in politically-based administration boundaries in terms of policies and data collection for sustainability. Perhaps, we will try to create appropriate boundaries of target cities by combining existing politically-based administration ones. We will define their boundaries by some relevant factors in terms of city

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sustainability so that we can use available data provided in politically-based administration boundaries.

2.3. City sustainability

As we discussed in Section 2.1, sustainability has several conditions that are commonly shared and agreed by different definitions. City sustainability should also satisfy the conditions. However, the notion of urban sustainability has become popular, but its meaning remains vague (Finco and Nijkamp, 2001). Thus, we discuss the concept of city sustainability assessment in this section.

The assessment system of city sustainability has not been well established, because the required conditions for city sustainability assessment are still ambiguous. Tanguay et al. (2010) surveyed 23 studies of the use of urban sustainable development indicators (SDI) in developed western countries. In total, 72% of the indicators apply to only one or two studies, and very few indicators are found in more than five studies (Tanguay et al., 2010). This might show the tendency to focus on indigenous contexts and properties more than necessary, because core requirements for city sustainability have not been sufficiently clarified. It is difficult to define sustainability indicator-based on information at different spatial and temporal scales (Putzhuber and Hasenauer, 2010).

The sustainability of cities is inextricably linked to the integrity and sustainability of the rural hinterland—global sustainability, because human beings remain dependent on the environment even as urbanization is accelerated (Rees, 2001). This is the central notion of city sustainability. Based on it, we think that there are two core conditions for city sustainability assessment: to judge whether cities are sustainable in terms of environmental, economic and social dimensions respectively; and to evaluate both direct and indirect external impacts and dependencies of a city on other areas beyond the city boundaries. We will explain them in more detail in the following.

Cities are mainly the urban developed areas that are densely populated, and pursue economic and social benefits rather than environmental ones. The major reason for the advent of cities is the positive agglomeration effects, which may be more than the costs of excessive concentration such as environmental degradation, pollution, living stress and so on. Cities attract a growing number of humans and anthropogenic assets while natural elements suffer a decrease almost equivalent to the increase in humans and man-made assets (Bithas and Christofakis, 2006). Urban growth rests on a trade-off between agglomeration economies or economies of scale and scope, and diseconomies such as population excessive concentration and environmental decay. Environmental quality problems are likely to become severer with urban size although factors such as land use, transportation system and spatial layout of a city are critical factors for determining the urban environmental carrying capacity (Munda, 2006). Based on the feature of cities, it is necessary to assess both positive and negative agglomeration effects in terms of environmental, economic and social aspects respectively. Cities are confronted with the problem of trade-offs between them. We should avoid offsetting positive economic benefits and negative environmental impacts each other from the perspective of strong sustainability. If we excessively weigh the economic performance of a city, its sustainability will be biased toward over-evaluation. If we excessively evaluate the environmental aspects of a city, its sustainability will be biased toward under-evaluation. The more diffused and common interpretation of a sustainable city as a city in which natural environmental aspects are given first priority in urban policy is somehow a limited interpretation, since it would underestimate the positive aspects related to the agglomeration advantages in the city (Camagni et al., 1998). In the concept of city sustainability assessment, it is crucial to take the triple bottom line into consideration from the perspective of strong sustainability. Sustainable cities are the ones to develop economic activities within the carrying capacity of the local ecosystem so that the local population can benefit as a whole (Devuyst, 2001).

Evaluating environmental aspects, we have to consider external impacts and dependencies of a city on other areas beyond the city boundaries, because a city concentrates on economic development within it and at the same time depends on other areas for supply of resources and food, disposition of wastes, emission of pollutants, indirect use of ecosystem services, and so on. Cities are open systems that have impacts on all other areas and on the earth as a whole (Munda, 2006). Cities are different from countries and regions because the latter include many non-urban areas. Cities cannot independently function and make a living. Cities are inherently unsustainable because of their dependence upon the existence of importing resources, many of them non-renewable, and exporting waste, some of it non-assimilable in the ecological perspective (Camagni et al., 1998). The natural and biological functions that are necessary to cities are supported by ecosystems mainly outside the realm of urban space while the natural elements that exist within the urban space merely play a marginal and complementary part in the maintenance of the bio-natural status of urban systems (Bithas and Christofakis, 2006). Furthermore, it ought to be recognized that the claim on external resources may be higher in a relatively small urban area, so that a situation of local sustainability may be achieved but it may be detrimental to other areas (Finco and Nijkamp, 2001). The external impact is also called 'leakage'. The leakage implies that some local systems can appear to be sustainable due to large inflows of resources from other systems at rates which are unsustainable for those areas (Mayer, 2008).

In particular, it is critical to assess indirect as well as direct external impacts and dependencies of cities on the outside. Economic activities in a spatial entity directly and indirectly have negative external impacts on other areas through trade and movements of physical materials. Through trade, the social and environmental impacts of human activities across boundaries cause a local sustainability to be dynamically linked to that of other areas (Graymore et al., 2010). Trade enables local people to sustainably exceed local carrying capacities, which has a negative impact on the earth because all accounts must globally balance as a whole (Daily and Ehrlich, 1992). The Ecological Footprint (EF) tries to capture such external impacts. The EF measures the total consumption of goods and services and the amount of waste assimilated by the global hectare (a unit of measure) of bioproductive lands (Rees, 1992; Rees and Wackernagel, 1996; Wackernagel and Rees, 1997). Then, it is possible to measure its external impacts by the difference (ecological deficit) between the measured hectares (ecological footprint) and the bioproductive lands (biocapacity) in a target city (Bagliani et al., 2008; van den Bergh and Verbruggen, 1999; Wackernagel et al., 2006). The notion of the EF is too aggregate, although it evaluates both direct and indirect impacts. When all the direct and indirect consumptions are summed up, a fixed rate of substitution is implicitly assumed between different ecological impacts (van den Bergh and Verbruggen, 1999). The notion of virtual water is also useful for evaluating indirect external impacts. For instance, imports of agricultural products imply those of water at the same time. The notion is applicable to the external dependencies about other significant environmental resources and indirect impacts of pollutants implicitly moved through trade. The water footprint concept is rooted in the search to illustrate the hidden links between human consumption and water use and between global trade and water resources management (Hoekstra, 2009).

In brief, we have to pay special attention to the two critical conditions for city sustainability assessment, considering essential characteristics of cities. First, we have to evaluate the triple bottom line in terms of strong sustainability. Second, we must consider external impacts and dependencies (leakage effects) of cities on areas elsewhere particularly in environmental aspects, because cities depend on non-urban areas elsewhere through both direct and

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indirect trade and movements of physical materials. The point is that cities are independently non-sustainable.

2.4. Gap between developed and developing countries

We should avoid the problem that sustainability indices/indicators tend to over- or under-estimate developed countries as compared with developing countries. For example, the Environmental Sustainability Index (ESI) favours developed countries due to their economic status and environmental pollution control supported by their high income (Esty et al., 2005). We observe a similar trend in the Environmental Policy Index (EPI) as well. Unlike the category of 'ecosystem vitality' in EPI, the category of 'environmental health' is highly correlated with wealth, indicating that many of the low-performing countries have not made the investments necessary to curtail environmental pollutants or to provide adequate water and sanitation to their citizens (Esty et al., 2008). The problem is related to the distinction between weak and strong sustainability. If sustainability indices/indicators are based on the notion of weak sustainability, good performances in economic aspects can offset bad performances in environmental dimensions, and vice versa. It is likely that developed countries tend to be highly evaluated because of high income. There is a huge gap in GDP per capita between developed and developing countries. This discussion is also valid for city sustainability assessment.

In this discussion, we can obtain important implications from the Environmental Kuznets Curve (EKC). The EKC postulates an inverted-U-shaped relationship between different pollutants and per capita income, which represents a long-term relationship between environmental impact and economic growth (Dinda, 2004). We should note that no single EKC relationship fits all pollutants and that we have no evidence to support the EKC hypothesis for gases such as carbon dioxide in particular (Yandle et al., 2002). Nonetheless, it seems that economic growth can be a solution for problems on environmental degradation for select pollutants, although the resolution of the problems cannot be automatically realized without relevant environmental policies (Yandle et al., 2002). This implies that developing countries should pursue economic growth although environmental problems transiently become more serious in the initial stage. However, we have ecological thresholds in the local and global systems. It is unknown whether we can accept the situation that environmental and ecological conditions degenerate in all the developing countries in the world. Moreover, negative environmental impacts are often accumulated. If we highly evaluate developed countries merely because of high income, this will imply that all the developing countries have only to follow the development paths through which developed countries have grown. We, however, want or/and might need to show another sustainable path to cities in developing countries through a new appropriate system of City Sustainability Index (CSI).

There is essentially a difference in development stages between developed and developing countries. In developed countries, the sustainability discussion focuses on environmental topics, while in developing countries the issues of poverty and equity are equally important (Kemmler and Spreng, 2007). Regarding social equity, for example, we cannot set a common definition of poverty rate in developed and developing countries. In developing countries, the standard that the daily income is equal to or less than 1 USD will be meaningful, but the same standard is meaningless in developed ones. Certainly, the standard of absolute poverty is important, but we would rather focus on 'equity' in individual societies. Issues of sustainability have been addressed differently in different parts of the world, according to the policymaking and environmental priorities of cities and countries (UN-Habitat, 2006). To give another example, in cities of the developed world, energy consumption remains a major concern, and many urban areas have been redeveloped with an emphasis on compact neighbourhoods, clean transportation options and the use of green technologies (UN-Habitat, 2006).

Furthermore, the leakages between developed and developing countries are creating serious problems, and thus should be adequately considered. Leakages occur when wealthy countries with strict environmental protection laws import raw materials and pollution-intensive products, and export wastes, thereby keeping their domestic environment in better condition (Mayer, 2008).

Based on the abovementioned points, we need a new City Sustainability Index (CSI) that can assess world cities in both developed and developing countries in the same system without bias. We should avoid highly evaluating cities in developed countries solely due to their large income in order to provide cities in developing countries with a new sustainable path.

3. Review of sustainability indices and indicators

We provide a critical review on major sustainability indices and indicators in terms of city sustainability, discussing them from the aforementioned perspectives. (i) We evaluate whether indices/indicators can satisfy the two important conceptual requirements. First, we evaluate whether they can assess external impacts (leakage effects) of cities on outer areas such as peripheral areas, outer non-urban zones and other cities from which the cities under assessment import goods, resources and services. Second, we consider whether they cover the triple bottom line of sustainability. (ii) We discuss the methodology by which indicators and indices are created and structured: indicator-based indices and single-unit indices. We divide indices/indicators into the categories of strong and weak sustainability. As we discussed in the previous section, a new CSI should take the viewpoint of strong sustainability. (iii) We evaluate to what extent major indices and indicators can assess the sustainability of world cities in both developed and developing countries. We categorize them using two axes: the original spatial unit of analysis and the applicability to the comparison of sustainability among world cities.

3.1. Consideration of external impacts and the triple bottom line

We discuss whether major sustainability indices/indicators can satisfy the two conceptual requirements: consideration of the external impacts (leakage effects) and coverage of the triple bottom line. Table 3-1 shows the results on the evaluation. As a result, there is no index/indicator that satisfies both of the conditions.

3.1.1. Coverage of both the triple bottom line and leakage

There is no index/indicator in the top-left cell in the table. This implies that there is no index/indicator that measures the external environmental impacts of a city on other areas beyond the city boundaries and considers the triple bottom line of sustainability. That is why we need to create a new relevant City Sustainability Index (CSI) in this respect.

3.1.2. Consideration of leakage without covering the triple bottom line

Indices/indicators in the top-right cell in Table 3-1 can capture external environmental impacts, but do not consider all the environmental, economic and social dimensions of sustainability. They are Ecological Footprint (EF), night-time satellite imagery sustainability (satellite-based sustainability), emergy/exergy and Water Footprint (WF).

The Ecological Footprint (EF) measures the total consumption of goods and services produced and the amount of waste assimilated by the global hectare of bioproductive lands (Rees, 1992; Rees and Wackernagel, 1996; Wackernagel and Rees, 1997). The EF assesses environmental burdens whereas it does not explicitly consider economic aspects and does not take account of social equity at all.

On the other hand, the EF is conceptually discussed in the context of cities or urban areas (Rees, 1992; Rees and Wackernagel, 1996). Through trade and natural flows of ecological goods and services, all urban regions appropriate the carrying capacity of distant areas elsewhere, creating dependencies that may not be ecologically or geopolitically stable or secure. In addition, this situation applies not only to commercial trade but also to the unmonitored flow of goods and services provided by nature, but typical urban development policies ignore the fact that the city's role in wealth creation depends on the continuous production of ecological goods and services somewhere else (Rees, 1992; Rees and Wackernagel, 1996). However, the EF cannot sufficiently capture the external impacts of the target spatial entities on other areas because it does not consider technological changes and land degradation (or soil erosion) with intensive production growth (Fiala, 2008; van den Bergh and Verbruggen, 1999; van Kooten and Bulte, 2000). Then, Fiala (2008) derives the implication that a country that would look positive with regards to its ecological footprint could in fact have a very high rate of land degradation and so is consuming its land faster and in more harmful ways than countries that are more careful with land. This shows the difficulties in the measurement of external impacts by the EF. Furthermore, the EF does not include irreversibility or threshold effects concerning the fundamental concept of sustainability (Nourry, 2008).

The night-time satellite imagery sustainability (satellite-based sustainability) is derived solely from the ratio of two classified satellite images with global coverage (Sutton, 2003). The satellite-based sustainability is calculated for each nation of the world by dividing the amount of light energy emitted by that nation as measured by a night-time satellite image by the total value of that nation's ecosystem services as measured by a land-cover dataset and ecosystem service values. This indicator does not consider economic and social aspects at all. However, the excess amount of energy used as compared with ecosystem service values is treated as the external impacts on the other areas that provide ecosystem services.

The emergy/exergy tries to value the economy on the same basis as the work of the environment by the unit of energies (Siche et al., 2008). The emergy is the embodied energy and expresses all numbers in one kind of energy (for example, solar energy) required to produce designated goods and services, while the exergy is defined as the sum of available energies of all kinds (Odum and Odum, 2000). Exergy is simply the value of available energy as work (Balocco et al., 2004); it is useful for assessing energy scarcity or availability and energy efficiency in the extraction of natural resources (Hoang and Rao, 2010; Warr et al., 2008). Obviously both emergy and exergy do not take economic and social aspects into consideration, although we may be able to apply the notion of emergy/exergy to the analyses of economic and social problems (Gasparatos et al., 2008). On the other hand, the emergy/exergy can assess external impacts of a city on other areas beyond the city boundaries. Once system boundaries are established, flow charts are used to follow the movement of emergy through the system. Emergy flowing into or out of the system without an identified source or sink is identified quickly, and in this respect the index can identify "leakage" flows (Mayer, 2008).

The Water Footprint (WF) of an individual or a community is the total volume of freshwater that is used to produce the goods and services consumed by the individual or community (Hoekstra, 2009; Hoekstra and Chapagain, 2007). The WF measures the extent of human economic activities' dependency on water, a crucial environmental resource. Thus, the WF does not assess economic and social aspects. One of the important purposes of the WF, however, is to figure out the external impacts in terms of water. The WF illustrates the hidden links between human consumption and water use and between global trade and water resources management (Hoekstra, 2009). The total water footprint of a country is made up of the internal and external water footprints: the internal water footprint is the volume of water needed to grow and provide the goods and services which are produced and consumed inside that country, whereas the external water footprint results from consumption of imported goods or water that is used for the production of goods in the exporting country (WWF, 2008). The external water footprint is often referred to as 'virtual water (trade)' (Chapagain et al., 2006; Chapagain and Hoekstra, 2007; Hoekstra and Chapagain, 2007).

Table 3-1
Consideration of triple bottom line and external impacts.

		Coverage of triple bottom line	
		Yes	No
Inclusion of external impacts	Yes	None	EF Satellite-based sustainability Emergy/exergy WF
	No	DS ESI WI ISEW GPI Applications of composite indices to local contexts	CDI HDI EVI EPI LPI EDP (Green GDP) GS

3.1.3. *Coverage of the triple bottom line without considering leakage*

Indices/indicators in the bottom-left cell in Table 3-1 consider all the environmental, economic and social dimensions of sustainability, while they cannot capture external environmental impacts. They are Dashboard of Sustainability (DS), Environmental Sustainability Index (ESI), Well-being Index (WI), Index of Sustainable Economic Welfare (ISEW), Genuine Progress Indicator (GPI), and some applications of composite index to local and regional contexts.

The Dashboard of Sustainability (DS) is a mathematical and graphical software program designed to integrate the complex influences of sustainability by creating concise evaluations (Scipioni et al., 2009). It is a tool for considering the economic, social, and environmental conditions of development and incorporating ad hoc set indicators in order to evaluate sustainability. The DS in itself does not provide an ideal set of indicators for assessing sustainability. Therefore, it does not take account of external impacts, although it is possible to capture them if relevant input indicators are created.

The Environmental Sustainability Index (ESI) assesses individual country's sustainability based on 5 major components such as environmental systems, reducing environmental stresses, reducing human vulnerability, social and institutional capacity and global stewardship (Esty et al., 2005). The five components are composed of 21 indicators, and 21 indicators are decomposed into 76 variables. The indicators and variables included in the ESI reflect the concept of the triple bottom line. As for the assessment of external impacts, although Sutton (2003) claims that the 2001 version of the ESI does not address leakage effects, the 2005 ESI identifies some leakage in the component of global stewardship, specifically through the SO_2 exports and the imports of polluting goods and raw materials as percentage of total imports of goods and services (Esty et al., 2005). However, the following criticism is still valid. The ESI downplays or ignores transboundary or spillover effects of northern countries' unsustainable consumption (Morse and Fraser, 2005).

The Well-Being Index (WI) is derived from the mean of a Human Well-being Index (HWI) and an Ecosystem Well-Being Index (EWI) (Böhringer and Jochem, 2007; Prescott-Allen, 2001). The HWI and EWI respectively consist of five sub-indices. More specifically, the HWI comprises indices of health and population, welfare, knowledge, culture and society, and equity. The EWI comprises indices for land, water, air, species and genes, and resources deployment. The five dimensions of the HWI are based on 36 indicators, and those of the

EWI on 51 indicators. They cover economic, environmental and social aspects of sustainability. However, the WI does not take the leakage effects into consideration (Mayer, 2008).

The Index of Sustainable Economic Welfare (ISEW), the Genuine Progress Indicator (GPI) and the Sustainable Net Benefit Index (SNBI) are all formulated in a way to better approximate the sustainable economic welfare of a given population and specifically to provide an alternative to other national account measures such as the Gross Domestic Product (GDP) that are deemed to be inadequate for capturing human welfare (Dietz and Neumayer, 2007; Gasparatos et al., 2008). They are fundamentally modified GDP (monetary) measures, considering environmental and social factors that often have a trade-off relationship with economic development or GDP growth. Differences between the ISEW and the GPI are due to the revision of the methods of computation and concern the treatment of public and private defensive expenditures on health and education and also the incorporation of cost estimates of welfare losses such as loss of leisure time and underemployment (Nourry, 2008). They cannot explicitly evaluate the external effects (Mayer, 2008).

There are many applications of a composite index or multivariate indicators to local or regional contexts as case studies (Ferrarini et al., 2001; Graymore et al., 2009; Kondyli, 2010; Lee, 2007; Mascarenhas et al., 2009; van Dijk and Mingshun, 2005). Lee (2007) elicit 51 sustainability indicators from a case study of Taipei city in Taiwan, and divide them into four categories such as environment, economy, society and institution. They analyse the trend of the indicators in each category and a composite sustainability index into which the four categories are integrated for 11 years (1994–2004). Mascarenhas et al. (2009) develop a conceptual framework to select common local sustainability indicators in a regional context by use of a participative approach that can consider local stakeholders' interests, and apply the framework to the Algarve region in Portugal. Ferrarini et al. (2001) assess 45 municipalities within the province of Reggio Emilia in Italy in terms of sustainability, selecting 25 indicators. Kondyli (2010) applies composite sustainability indicators to the islands of the north Aegean region in Greece, covering economic, social and environmental factors in terms of policies. Graymore et al. (2009) apply the MCA-based (Multiple Criteria Analysis based) indicators to the South West region of Victoria in Australia at the regional to sub-catchment scale, considering economic, environmental, social and institutional elements.

3.1.4. No coverage of both the triple bottom line and leakage

Indices and indicators in the bottom-right cell in Table 3-1 do not cover the triple bottom line of sustainability and external leakage impacts. They are City Development Index (CDI), Human Development Index (HDI), Environmental Vulnerability Index (EVI), Environmental Policy Index (EPI), Living Planet Index (LPI), environmentally-adjusted net product (EDP or Green GDP), and Genuine Saving (GS).

The City Development Index (CDI) is a single measure of the level of development in cities, which is calculated by five sub-indices such as city product, infrastructure, waste, health and education (UN-Habitat, 2001).

The Human Development Index (HDI) is a summary measure of a country's human development. The HDI measures the average achievements in a country in three basic dimensions: life expectancy at birth; adult literacy rate with gross enrolment ratio in education; and GDP per capita in purchasing power parity (PPP) US dollars (Nourry, 2008; UNDP, 2009).

The Environmental Vulnerability Index (EVI) assesses the vulnerability of physical environment in the unit of country (SOPAC, 2005). The EVI is composed of 32 indicators of hazards, 8 of resistance and 10 that measure damage. In this respect, causal relations among variables are not clear in the EVI. This index provides an absolute evaluation on the indicators in which we can set standards or thresholds. Its raison d'être is to provide a rapid and standardised method for characterising vulnerability in an overall sense and to identify issues that may need to be addressed within each of the three pillars of sustainability, namely environmental, economic and social aspects of a country's development" (SOPAC, 2005). However, the EVI has been designed to reflect the extent to which the natural environment of a country is prone to damage and degradation. Thus, it does not address the vulnerability in the social, cultural and economic dimensions (SOPAC, 2005).

The Environmental Performance Index (EPI) focuses on the impacts of countries on the environment, which is mainly composed of indicators on environmental health and environmental vitality (Esty et al., 2008). The EPI includes 25 indicators. It builds on measures relevant to two core objectives: (i) reducing environmental stresses to human health (the Environmental Health objective); and (ii) protecting ecosystems and natural resources (the Ecosystem Vitality objective) (Esty et al., 2008).

The Living Planet Index (LPI) assesses the impacts of human activities on ecosystems in themselves or/and ecosystem functions, referring to indicators of biodiversity (WWF, 2008). The LPI of global biodiversity is measured by populations of 1686 vertebrate species across all regions of the world (WWF, 2008).

The environmentally-adjusted net product (EDP or Green GDP) is a modified GDP measure, which is derived by deducting the depreciation of produced capital and the amount of resource depletion and environmental degradation from GDP (Böhringer and Jochem, 2007; Dietz and Neumayer, 2007; Mayer, 2008). The Genuine Saving (GS) is derived from EDP minus consumption (Dietz and Neumayer, 2007).

3.2. Methodology and strong sustainability

In this section, we review major sustainability indices/indicators, focusing on the methods that have been used to construct them. They are divided into two categories: indicator-based indices and single-unit indices. We discuss the potentials of each methodological approach in terms of the criterion of weak/strong sustainability, based on the discussion in Section 2.1. In Table 3-2, major sustainability indices/indicators are divided into categories according to two axes: methodological approaches and weak/strong sustainability. Indicator-based indices can be used to measure strong sustainability. However, the combination of different indicators into a composite index needs to be carefully made in order to consider the preservation of natural capital. A multi-criteria analysis (MCA) may be a potential candidate for a relevant City Sustainability Index (CSI). If we synthesize and evaluate multidimensional nature of complexity, a multi-criteria framework is a very efficient tool to operationalise the Neurath's idea 'orchestration of sciences' (Munda, 2006).

3.2.1. Indicator-based indices

Indicator-based indices refer to the indices structured by combining different indicators that represent different processes. The main criticisms against them have to do with the subjectivity of the choice of variables and the weighting of the indicators. Several indices/indicators belong to this category: the City Development Index (CDI); the Dashboard of Sustainability (DS); the Environmental Sustainability Index (ESI); the Environmental Vulnerability Index (EVI); the Environmental Policy Index (EPI); the Wellbeing Index (WI); the Human Development Index (HDI); the Living Planet Index (LPI); and the night-time satellite imagery sustainability (satellite-based sustainability).

The EVI and EPI take the view of strong sustainability although they do not cover the triple bottom line. Both of them focus only on environmental aspects. The EVI assesses the vulnerability of physical environment (SOPAC, 2005). The EPI focuses on reducing environmental stresses to human health and protecting ecosystems and natural resources (Esty et al., 2008).

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Table 3-2
Methodological approaches and weak/strong sustainability.

	Strong sustainability	Partly strong, partly weak sustainability	Weak sustainability	Unknown
Indicators-based Index	EVI	DS	CDI	HDI
	EPI	ESI	WI	Satellite-based sustainability
	LPI			
Single-unit Index	EF		ISEW	
	WF		GPI	
	Emergy/exergy		EDP	
			GS	

The DS and the ESI take only partly the viewpoint of strong sustainability, as the summarized outputs are provided by a composite index that is based on weak sustainability. The DS is a mathematical and graphical tool that assesses environmental, economic and social dimensions of sustainability (Scipioni et al., 2009). The ESI provides assessments of environmental, economic and social dimensions of sustainability as intermediate outputs. At these intermediate evaluations, the three dimensions are considered unexchangeable (Esty et al., 2005). However, the summarized final outputs are given by a composite index in which capitals in the three dimensions are considered substitutable.

The CDI and the WI are both composite indices, and take the viewpoint of weak sustainability. The CDI is the composite index that is composed of five sub-indices such as city product, infrastructure, waste, health and education (UN-Habitat, 2001). Thus, capitals in the five distinct categories are offset one another, which shows the view of weak sustainability. The WI is the composite index provided by the mean of the Human Well-being Index and the Ecosystem Well-Being Index. In the process of calculation, various types of capitals are considered substitutable.

The HDI measures the average achievements in three basic dimensions: life expectancy at birth; adult literacy rate with gross enrolment ratio in education; and GDP per capita. It does not deal with environmental aspects and natural capitals at all. Thus, we cannot exactly judge whether the HDI takes the view of strong sustainability.

Indices with a limited number of variables covering specific aspects of sustainability should be lead or flagship indicators because they cannot comprehensively measure sustainability—flagship indicators have more promise (Kemmler and Spreng, 2007). The Living Planet Index (LPI) (WWF, 2008) and the satellite-based sustainability (Sutton, 2003) are such indices. The LPI is based on strong sustainability because it focuses on the impacts of human activities on ecosystems and ecosystem functions referring to a measurement of biodiversity, although it does not cover the triple bottom line (WWF, 2008). It is difficult to judge whether the satellite-based sustainability is based on strong sustainability. This indicator is provided by dividing the amount of light energy emitted by that nation, as measured by a night-time satellite image, by the total value of that nation's ecosystem services as measured by a land-cover dataset and ecosystem service values (Sutton, 2003). It measures the relative status of economic activities to the values of ecosystem services.

3.2.2. Single-unit indices

Single-unit indices aim to represent the balance between economic activities and the environment. In general, they tend to be restricted in terms of the economic, social and natural processes they consider when measuring sustainability because of the conversion to a single unit (bioproductive land, water, energy etc.). Single-unit indices cannot consider as many processes as indicator-based ones can, but they provide a clear picture of the relationships between economic activities and the environment. In addition, several assumptions need to be made in order to take account of the processes that are not directly related to the reference unit. Economic indices are a subcategory of single unit indices as they value the impacts on the environment and society in monetary terms. Several indices/indicators are included in this category: Ecological Footprint (EF); Water Footprint (WF); Index of Sustainable Economic Welfare (ISEW); Genuine Progress Indicator (GPI); Environmentally-adjusted Domestic Product (EDP or Green GDP); Genuine Saving (GS); satellite-based sustainability; and emergy/exergy.

The EF and the WF are based on strong sustainability, but they do not cover the triple bottom line. Both of them measure the stresses of human activities on the environment. The EF is an indicator of strong sustainability that assumes substitutability of different forms of natural capital, because it assumes different natural capital goods are additive in terms of land area (Dietz and Neumayer, 2007). The WF addresses the preservation of natural capital representatively indicated by water. The emergy/exergy is based on strong sustainability. The emergy/exergy measures the environmental burdens of economic activities by the solar energy terms.

The EDP and the GS take the viewpoint of weak sustainability. They are the modified GDP measure, which is derived by deducting the depreciation of produced capital and the amount of resource depletion and environmental degradation (and consumption) from GDP. In the calculation method, different types of capitals are considered substitutable. The ISEW and the GPI intended to take the view of strong sustainability, but they are a measure of weak sustainability by assuming that the diverse components of comprehensive utility can be simply added together in order to estimate an overall indicator (Dietz and Neumayer, 2007).

3.3. Applicability to cities

In this section, we categorize major sustainability indices/indicators by the original spatial unit of analysis, and discuss whether they are applicable to world cities in an equitable manner. Table 3-3 shows the summary of the discussion. Consequently, only the City Development Index (CDI) is originally created for evaluating city sustainability. Only a few indices/indicators can compare sustainability among world cities in both developed and developing countries using common axes of evaluation.

3.3.1. Original unit of analysis

The vertical axis in the table represents the original spatial unit of analysis. Only the CDI has originally been created for cities (UN-Habitat, 2006). All the rest have been created for assessing, analysing and comparing sustainability among countries. It is easier to obtain necessary data at a national level than at lower aggregation levels such as biosphere, regions, catchments, municipalities, and cities. The fundamental spatial units of analysis in the Living Planet Index (LPI) are the globe and biospheres such as terrestrial, marine, freshwater, tropical forest, dryland ones and so on (WWF, 2008). Therefore, we need to create sustainability indices or indicators that will address the characteristics of cities as discussed in Section 2.

3.3.2. Applicability to comparison among world cities

We discuss the applicability of indices/indicators to the comparison of sustainability among world cities. Several indices/indicators rank developed countries higher than developing ones by ignoring the unsustainable path they have followed to achieve economic growth.

Table 3-3
Original unit of analysis and the applicability to world cities.

		Applicability to comparison of sustainability among world cities	
		Yes but conditional	No
Original unit of analysis	Global		LPI
	Country	CDI	ESI
		DS	HDI
		WF	EVI
		EF	EPI
		GPI	Satellite-based
		ISEW	sustainability
		GS	WI
		EDP (Green GDP)	
	Region or Local		Applications of composite indices to local contexts
	City	CDI	
	Other	WF	LPI
		Emergy/exergy	

We would like to avoid this because the same path should not be followed by developing countries. The Environmental Sustainability Index (ESI) favours developed countries by including too many measures of capacity and favouring technological innovation over indigenous or local knowledge which are highly related to income (Esty et al., 2005). Except for Uruguay, the countries in the top ranks are highly developed ones endowed with natural resources, strong economies, and low population densities. Industrialized countries have substantial pollution stresses, but they can afford to manage their environmental challenges well because of their high income as the Environmental Kuznets curve (EKC) tells. The Environmental Policy Index (EPI) provides partly similar results. Esty et al. (2008) have found that there is a strong positive correlation between environmental health and wealth but that there is no correlation between environmental vitality and wealth. The Human Development Index (HDI) also tends to place much value on advanced countries, because all the three indicators included are intimately related to the standard of income: life expectancy at birth; adult literacy rate with gross enrolment ratio in education; and GDP per capita (Nourry, 2008; UNDP, 2009).

Several indices/indicators include the variables that are meaningless in the context of city sustainability. The Environmental Vulnerability Index (EVI) has been designed to reflect the extent to which the natural environment of a country is prone to damage and degradation. However, it does not address the environment that has become dominated by human systems such as cities and farms (SOPAC, 2005). Human impact is considered an exogenous factor, and human systems are not the recipients of the impact (Pratt et al., 2004). Many indicators focusing on natural phenomena and pure environmental issues are irrelevant for cities: high winds, dry, wet and hot periods, sea temperatures, volcanoes, tsunamis, ecosystem imbalance, endangered species, vegetation cover, marine reserves and so on. This is because cities are densely populated urban developed areas and ecological conditions within cities do not matter so much. We need to evaluate human impacts of cities on the environment particularly in the outside of them. The Living Planet Index (LPI) cannot be applied to cities because it is an index of biodiversity, measured by populations of 1686 vertebrate species across all regions of the world. The satellite-based sustainability cannot capture the differences among world cities because satellite images cannot measure small subtle differences among them. There is no big difference in night-time satellite images among cities. In fact, it may be difficult even to distinguish cities in developed countries from those in developing ones because cities are urban developed areas with large population concentrated in both developed and developing countries. Particularly for countries in which GDP per capita exceeds a certain standard, the quantity of night-time light emissions per spatial unit may not sufficiently differ. The Well-Being Index (WI) specialises in assessing sustainability in countries. Thus, it includes several irrelevant indices for city sustainability: indices for land, species and genes.

Finally, we may be able to use some indices/indicators if we can contrive relevant variables or/and methods. The CDI has originally been created for evaluating city sustainability, but it has serious limitations when it comes to the comparative analysis among world cities (see Table 3-1). The Dashboard of Sustainability (DS) does not provide an ideal set of indicators for assessing sustainability. If we can create appropriate indicators and collect data for city sustainability, we will be able to use the DS for the comparison among world cities. The DS can be used at a local level to compare the sustainability of a local context to other local context, although this is the direction taken in the last applications of the DS (Scipioni et al., 2009). Several applications of composite indices or multiple indicators to local or regional contexts as case studies are too specific to be applied to the comparison among world cities (Ferrarini et al., 2001; Graymore et al., 2009; Kondyli, 2010; Lee, 2007; Mascarenhas et al., 2009). The Water Footprint (WF) can be used as one of the relevant indicators for conducting a comparative analysis of sustainability among world cities because the external WF can assess the leakage impacts of a city on other areas beyond the city boundaries in terms of fresh water, one of the crucial life-supporting environmental resources. However, the WF is insufficient because it does not cover the triple bottom line (see Table 3-1). The Ecological Footprint (EF) can be assessed for persons, activities or regions, from a city to the world at large (van den Bergh and Verbruggen, 1999). This indicator is conceptually discussed in the context of cities or urban areas (Wackernagel et al., 2006). It can be one of the useful indicators for assessing city sustainability in comparison, but it does not cover the triple bottom line and it has some serious limitations discussed in the previous sections. The Index of Sustainable Economic Welfare (ISEW) and the Genuine Progress Indicator (GPI) are applied to cities. For example, Costanza et al. (2004) carry out the first multi-scale application of the GPI at the city, county and state levels in Vermont, USA. They show that it is feasible to apply the GPI approach at smaller spatial scales and to compare across scales and with the national average. Pulselli et al. (2006) apply the ISEW to the Province of Siena, Central Italy, and show that the application of this index at a local level is feasible. Wen et al. (2007) apply the GPI to four cities in China. Thus, the ISEW and the GPI can be applied to the comparison of sustainability among world cities, but they have serious limitations, as mentioned in the previous sections. The Genuine Saving (GS) and the Environmentally-adjusted net product (EDP or Green GDP) are modified measures of GDP, and they can be applied to compare city sustainability in the world, although they also have limitations (see Table 3-1). The emergy and exergy measure human economic activities in energy terms. They can in principle be applied to compare world cities. Balocco et al. (2004) apply the exergy to evaluate the sustainability of an urban area, taking account of the mean life-time cycle of buildings. However, single indices like the emergy and the exergy cannot sufficiently capture city sustainability because they do not cover the triple bottom line.

4. Further discussion towards a new CSI

In this section, we discuss a few important points or requirements for creating a new City Sustainability Index (CSI) briefly.

4.1. Relative and absolute evaluation

All the indices/indicators discussed in this paper except for the Environmental Vulnerability Index (EVI) provide a relative evaluation among target spatial entities, mainly countries. However, sustainability should be judged by certain standards like biophysical or ecological thresholds. Sustainability is not a relativistic concept, since the biophysical limits to sustaining life on Earth are absolute (Fischer et al., 2007). A sustainable development indicator should make it possible to assess whether a country is on a sustainable growth path, but indicators such as the ISEW and GPI do not give this indication because no benchmark value for a sustainable state exists (Nourry, 2008). Relative positions among the spatial entities do not tell us whether they are sustainable or not. Even though a country is considered sustainable in a relative evaluation, it may be non-sustainable in absolute terms. Measuring relative performance is meaningless if all countries are on unsustainable trajectories (Esty et al., 2005). Moreover, relative evaluation depends on the input data. Unless we have data about some entities, we do not consider them in the evaluation. This tends to bring about biased assessments. Thus, it is ideal to provide absolute evaluation where possible. For this purpose, we should try to set certain threshold values or ranges in individual indices/indicators.

In terms of city sustainability, absolute evaluations are crucial. Bithas and Christofakis (2006) explain the decisive difference between relative and absolute evaluation of sustainability in the context of cities. "Practically, fundamental disturbances of the biological functions in cities occur once a certain biological element has deteriorated beyond some crucial levels. These levels could be considered to be the limits that preserve a minimum acceptable ecological balance and evolution and through them a minimum level of environmental sustainability. These crucial environmental limits should be defined in relation to the health of humans within the city. . . . These levels set certain absolute reference limits. . . . As long as the biological and ecological limits are not overstepped, the relative ratio, 'positive outcome/negative effect', offers an essential tool for the evaluation of city sustainability. In contrast, when these limits are violated, and the biological balance has been fundamentally disturbed, there is no point in performing an evaluation based on the relative ratio" (Bithas and Christofakis, 2006). Measurable indicators, including minimum performance levels and critical threshold levels, must be defined, estimated and used in order to improve awareness of sustainable development issues of modern cities (Finco and Nijkamp, 2001).

We should note that it is difficult to set such absolute limits in decision-making on the basis of ecological and environmental thresholds, although they are critical for assessing city sustainability. First, the difficulty lies in determining the limits of human economic activities in cities indirectly through their negative impacts on the environment. It is necessary to convert ecological and environmental thresholds into the amount of human economic activities, but this is complex and requires many assumptions. Second, it is complicated to concretely link activities in a city to ecological and environmental systems on which they have negative external impacts. We need to specify the range of the ecological and environmental systems when we consider ecological and environmental thresholds. It is almost impossible, considering their externalities on the global scale. Third, we still have difficulty imposing absolute limits in each city even if we certify what range of ecological and environmental systems we should consider. This is because we need to evaluate the total amount of external impacts that multiple cities make on an environmental and ecological system. It is quite hard to ascribe the compound or accumulated external impacts of multiple cities to each individual city, and to fix an absolute limit respectively considering the thresholds. Fourth, decision-makers may not be able to obtain public acceptance of such absolute limits in reality, because they sacrifice pecuniary economic benefits in the short run.

The upshot is that it is crucial to provide an absolute evaluation with a certain standards or thresholds as long as it is possible. In terms of a new appropriate CSI, it will be worthwhile to consider the following three types of standards at least: (i) (general or scientific) thresholds, (ii) global standards (common in the world or international agreements) and (iii) local standards (relative evaluation in an individual country) for mainly considering the differences between developed and developing countries.

4.2. Total environmental impact and eco-efficiency

Population size matters in itself. Environmental impact is determined by the multiplication of population, affluence (amount of resource consumption per capita) and technology, which is denoted by $I = PAT$ (Daily and Ehrlich, 1992; Ehrlich and Ehrlich, 1990; Ehrlich and Holdren, 1971). Based on the equation, if population size (P) is substantially large, environmental impact (I) will become considerably large even though A and T are small. In this case, it may not be so meaningful to consider only the size of A, which indicates eco-efficiency. This is because the total environmental impact is still large due to large population (P).

Thus, it is important to distinguish between the total environmental impact and eco-efficiency, depending on environmental indicators. The total environmental impact matters when eco-toxicity has been accumulating over time or/and when the impact concentrates in a small geographical area. In this case, we need to measure the total (accumulated) amount of environmental burden rather than the flow of environmental pollution. Even if economic activities in a city are eco-efficient, serious problems may occur if the total environmental impact is large or accumulated to a large extent. In industrial countries, for example, energy consumption per unit of production in the chemical industry has fallen by 57% since 1970 while the output has more than doubled in the same period (Schmidheiny, 1992). To give another example, in West Germany, the chemical industry managed to cut emissions of heavy metals by 60–90% between 1970 and 1987, whereas it boosted output by 50% (Schmidheiny, 1992). In these cases, we should carefully assess the environmental performances, considering both the eco-efficiency and the total environmental impact.

In brief, environmental serious problems will happen due to large environmental impact or/and eco-inefficiency. Even if a city is environmentally sustainable in terms of the amount of pollution per capita (eco-efficient), for example, the total environmental impact may bring about a serious environmental problem because of large population size. That is why it is necessary to consider both of them, depending on environmental indicators in a new CSI. In general, we have to consider both stocks and flows on sustainability indicators.

4.3. Method of comparison among world cities

We should avoid ranking world cities by a synthesized index, a composite index or a single indicator. It is appropriate to compare environmental, economic and social aspects respectively among cities at least, because the aspects are complex complement or trade-off relationships and because a composite index often implies weak sustainability. One index is inappropriate for fully understanding the sustainability of a system, and therefore several indices used in combination are required (Mayer, 2008). It is more useful to look directly at sustainability measures such as land degradation and CO_2 aggregations, rather than using a footprint that at best poorly captures the sustainability problems (Fiala, 2008). For example, the fact that densely populated countries, regions and cities show large ecological footprints is not necessarily a sign of non-sustainability, but rather the outcome of particular spatial allocation factors and specialisation patterns (van den Bergh and Verbruggen, 1999). In other words, the measure of ecological footprint is a composite index that indicates both environmental and economic situations, and then we cannot merely conclude that large ecological footprints imply non-sustainability. Moreover, it may be inappropriate to rank or compare world cities using each indicator. Probably, it is better to conduct pairwise comparison among world cities with individual indicators directly considered and compared.

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4.4. An agent-based model for city sustainability assessment

In Section 3, we review major sustainability indicators/indices, but we have found a different interesting approach for city sustainability assessment. It is the Urban Sustainability Assessment Framework for Energy (USAFE), an agent based model which is combined with an information index in order to measure the level of sustainability of urban systems in simulations (Zellner et al., 2008). Agent-based models have the advantage of explicitly modelling economic, social and environmental processes and of representing the interactions between agents in much detail. Zellner et al. (2008) discuss that too much detail in the model can lead to over-complication, but that luck of detail can lead to poor representation of the modelled system. In their conclusion, determining the right balance between realism and interpretability in any modelling endeavour is an art and it is a creative process that requires continuous exploration, experimentation and adjustment within the specific context (Zellner et al., 2008). The main problem of agent-based models is that they require a large amount of data. Thus, if we apply the agent-based modelling approach to a large number of cities for their comparison, the application will be time-consuming. Stochasticity can be another problem when a policy is tested by the comparison of pre- and post-policy runs of agents-based models.

5. Conclusion

In this paper, we review major sustainability indices/indicators in terms of their applicability to city sustainability: Ecological Footprint (EF), Environmental Sustainability Index (ESI), Dashboard of Sustainability (DS), Welfare Index, Genuine Progress Indicator (GPI), Index of Sustainable Economic Welfare, City Development Index, emergy/exergy, Human Development Index (HDI), Environmental Vulnerability Index (EVI), Environmental Policy Index (EPI), Living Planet Index (LPI), Environmentally-adjusted Domestic Product (EDP), Genuine Saving (GS), and some applications of composite indices or/and multivariate indicators to local or regional context as case studies. We conclude that we need to create a new appropriate City Sustainability Index (CSI) because no major index/indicator that has been developed for the assessment of sustainability in countries can satisfy the following four requirements for an ideal CSI. First, it must consider the triple bottom line of sustainability from the viewpoint of strong sustainability. Second, it has to capture leakage effects on areas elsewhere in the environmental dimension. Third, it ought to be created originally for the purpose of assessing city sustainability. Fourth, it has to be able to assess world cities in both developed and developing countries in an equitable manner. Then, we have found that there is no index/indicator that satisfies all the four requirements. In particular, it is interesting that no index/indicator can cover the triple bottom line and treat external impacts beyond city boundaries at the same time (see Table 3-1). That is the reason why we need to create a relevant new CSI system in order to assess and compare cities' sustainability performance and to provide local authorities with guidance toward sustainable paths.

In addition to the four requirements above, we should carefully consider the three important notions as far as the evaluation methodology is concerned. To begin with, we should rely on absolute criteria as far as possible, considering scientific thresholds, global standards based on international agreements, and local standards. Sustainability should be judged by certain standards such as biophysical or ecological thresholds, because sustainability is not a relativistic notion. Nevertheless, it is difficult to set absolute limits in decision-making on the basis of ecological and environmental thresholds, mainly because we need to measure such limits of economic activities in cities indirectly through their negative external impacts on the environment. Next, we should use both/either total environmental impact and/or eco-efficiency as a threshold or a criterion according to indicators. It is significant to distinguish between total environmental impact and eco-efficiency. This is because total environmental impact may still matter because of large population even if environmental impact per capita is small. Finally, we should avoid a synthesized composite index because the evaluation is offset among environmental, economic, and social dimensions. This implies weak sustainability. It is appropriate to compare the three dimensions respectively among cities at least, because they have complex complement or trade-off relationships.

In this paper, we do not discuss how an appropriate system of CSI should be used in decision-making. Our future research is to concretely provide a new system of CSI and discuss how to use the CSI for both comparing world cities and considering decision-making of policies.

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