An Inclusive Model for Assessing the Sustainability of Cities in Developing Countries – Trinity of Cities' Sustainability from Spatial, Logical and Time Dimensions (TCS-SLTD)

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Abstract: Attaining inclusive, regenerative and sustainable cities for all in the context of unparalleled rates of urbanization, economy-oriented priorities, and chaotic urban development that characterize the developing world is a major challenge. A first step in reaching this goal is to conceptualize an inclusive framework for delineating, assessing and guiding the development of these cities towards sustainability. In this study we outline an inclusive, causal framework for SD assessment, entitled “Trinity of Cities Sustainability from Spatial, Logical and Time Dimensions” (TCS-SLTD). It has been developed for cities in developing countries, and is illustrated using one such city, Xi'an. After reviewing the history and trends of urbanization of cities in Western China, some principles for assessing sustainability of cities in developing countries are suggested, after which the Xi'an case is presented. The urban area of Xi'an has expanded by more than 10 fold during the last quarter century, while arable land has decreased by 39%. In addition to these dramatic changes in land-use, the main axis of urban expansion has shifted from a north-south axial to radial expansion towards all areas around the core city. Over time, urban expansion has followed a “concentrated – deconcentrated - concentrated” trend. Xi'an overall sustainability, as measured by the index we present, has followed an upward – but not monotonic - trend between 1990 and 2010, during which its urbanization rate increased by 30%. On the basis of our multi-dimensional analysis, suggestions are made on how to direct Xi'an toward a more regenerative development path. These include revitalization of the urban system, control of urban form through planning, consulting and informing local communities about sustainable development issues, and achieving efficient functioning and harmonious coordination among different departments and municipal authorities in Xi'an. The TCS-SLTD model, outlined in this

study, is a useful tool for guiding the process of SDI selection, and provides a conceptual framework for holistically assessing the sustainability of city growth and expansion in developing countries. The model can assist urban planners and policy makers in developing countries in the performance of integrated assessments city sustainability, and in the formulation of pragmatic and focused policies to shift cities towards more regenerative and sustainable development trajectories.

Keywords:Trinity of Cities' Sustainability from Spatial, Logical and Time dimensions (TCS-SLTD); Multi-Dimension Framework for Sustainability Assessment (MDFSA); regenerative development; enhanced Drivers-Pressures-States-Impacts-Responses (eDPSIR) framework; cities in developing countries

1. Introduction

Economic growth in the developing world has driven a wave of global urbanization, and most of the world's population growth for the foreseeable future will occur in urban areas in developing countries: almost 64% of population in the developing world will be living in urban areas by 2050 (UN, 2012; Puppim de Oliveira *et al.*, 2013). Given these trends, and given their under-administered political regimes, weak governance and less advanced economies, cities in developing countries are increasingly plagued by various problems in health, quality of life, environmental quality, social cohesion and stability (Cohen, 2005). These problems are often associated with excessive population concentration within or adjacent to urban centers: infrastructure construction has not kept pace with population, especially in megacities often characterized by random, unplanned, urban expansion, poor regional governance and ineffective administrative systems (Cohen, 2005).

Local and international stakeholders have reached a consensus that existing urbanization patterns cannot continue, and agree on the necessity to develop cities in a more coherent and sustainable fashion, as advocated by the United Nations' Millennium Development Goals (MDGs) (Just *et al.* 2010). In order to direct cities towards more sustainable development (SD), sustainable development indicators (SDIs) have been broadly adopted by governmental and institutional organizations (Bossel, 1999, CEC, 2005, Shen *et al.*, 2011) to provide a basis for sustainability-related decision making (UNCED, 1992)

The literature on SDIs proposes a variety of frameworks/models for SDI selection and for the assessment of sustainable development (SD), one of which is the Multi-Dimension Framework for Sustainability Assessment (MDFSA) (Smith and Sheate, 2001, Devuyst *et al.*, 2001, McAllister, 1980). Within this broad framework, specific approaches have been proposed such as the Pressure-State-Response (PSR) framework (UN Commission on Sustainable Development, 2001; Hukkinen, 2003; OECD, 2002), "Vulnerability Framework" (Turner *et al.*, 2003), the CRITINC framework (Ekins *et al.*, 2003), the "Dashboard of Sustainability" (O'Connor and Jesinghaus, 2002, Oras, 2005), *etc.* These MDFSA-based frameworks/models can provide a qualitative way for presenting a large number of SDIs (Olalla-Tárraga, 2006) and facilitate the overall evaluation of SD initiatives, whilst partly uncover relationships hidden within the black box of aggregated indices (Anand and Sen, 1994).

There are, however, some limitations that may jeopardize the applicability and accuracy of MDFSA-based frameworks/models to SDI selection and SD assessment, thereby possibly compromising their impact on decision-making support for cities in developing countries. Indeed, these cities differ from their more developed counterparts in a number of ways. First, they have less developed regional economies

and less educated citizens: it is thus more difficult for their citizens to reach consensus on local SD goals, since economic prosperity is their overriding priority. Second, these cities are often short of specialists with the necessary skills and professional knowledge. Thus, even if SD goals were agreed upon, they would be difficult to achieve due to lack of human capital and know-how. Third, these cities face the problem of incomplete statistical data: there is often insufficient knowledge of major aspects of the social, economic and natural environments, which implies almost insurmountable difficulties for performing SD assessment.

There are two principal limitations to MDFSA based models. One is that the models developed in former studies are mostly focused on evaluating the harm reduction rate, effectiveness and efficiency of interventions: this type of criterion reflects “efficiency thinking” (Sterling, 2003). However, such an approach fails to take the diversified human, social, cultural, and economic elements into account (Elkington, 1997, Suparna, 2013), and contrasts with “whole systems thinking” (Reed, 2007). The other limitation, is that most of these studies are performed in the context of developed countries, which may compromise their suitability when applied to less developed contexts.

Using the city of Xi’an, in Western China, as an example, the purpose of the paper is to consider the principles that should underpin the assessment of SD in cities in developing countries and to outline a flexible framework for assessing SD from a multi-dimensional perspective, one that incorporates – in particular - the spatial aspects of city development.

1.1 Urbanization in Western China

Whereas cities in much of the western world now benefit from balanced and regulated urban processes (Bairoch, 1988), urban areas in developing countries, especially Western China, have experienced rather rapid and chaotic growth. Cities in this region are still – despite their size - in the early stages of urbanization (Puga, 1998), and urban population is over-concentrated in city centers (Henderson, 2002). Urbanization (i.e. the proportion of people living in cities) in Western China soared by 18% (from 17% to 35%) in last two decades (Zhang and Liu, 2004): this is still, however, well below levels in Eastern regions (Maimaitiming *et al*, 2013).

The urbanization process of Western China can be roughly divided into two stages. In stage 1 (from 1949 to 1978), urbanization was dominantly influenced by central government. After the founding of P.R. China in 1949, one acute need was to restore the nation’s heavy industrial production capacity. For security reasons Western China was the first choice for relocating the national defense industry, and this initiated industrialization in the region. The urbanization of Western China, driven by

planned-economy and national development policies (e.g. national “five-year” development plan, national economic plan, *etc*), led to a marked urban-rural divide and to unbalanced regional development: the poor agricultural population was trapped in rural areas, whereas wealthier industrial and administrative workers concentrated in urban areas.

In contrast, the urbanization of cities in Western China during the second stage of development (1979 to today) was driven by a variety of factors (e.g. national and local authorities, marketing activities, *etc*), amongst which promotional activities by local authorities have played a leading role (Zhang and Liu 2004). Thus, the second stage of urbanization has been more decentralized than the first, driven by the enthusiastic adoption, by local governments, of regional economic prosperity as a key objective. Local governments have implemented various measures to stimulate the industrialization of cities, including the encouragement of township enterprises and the setting up of various types of development zones (e.g. High-technology Zones and Economic-development Zones). This more recent stage of urbanization has also been fuelled by migration of the agricultural population from rural to urban areas in search of higher wages and a better life: this has become another key driver of urbanization in Western China.

1.2 Principles for Assessing SD of Cities in Developing Countries

Given this brief overview of Western China’s unique characteristics and recent history, and bearing in mind its low levels of human capital and development, several principles need to be followed while assessing the SD of cities in the region (and, more generally, in developing countries). First, instead of creating a new approach to assessing SD, existing frameworks/models governing SDI collection and SD assessment should be taken as starting points: this ensures cost-efficiency, and also a certain degree of compatibility with existing approaches.

Second, the implementation of these frameworks/models should be easy to understand and simple to follow.

Third, it is crucial that these frameworks/models be able to reveal multi-dimensional relationships within the urban system: they should not only apprehend current social, economic and environmental dimensions, but also spatial, chronological and logical ones.

Last, but not least, local communities should be involved in the process of SDI selection and SD assessment, thereby ensuring that their voices be heard in matters of regional sustainable development. Such involvement will also serve to raise local communities’ awareness of local SD: the assessment process can also serve to promote

124 and enhance SD by informing local communities about sustainability issues.
125
126 In the light of these requirements, an integrative MDFSA-based model, called “Trinity
127 of Cities’ Sustainability from Spatial, Logical and Time Dimensions” (TCS-SLTD),
128 was designed, and will be described below. The model adopts a causal network based
129 framework (the enhanced Drivers-Pressures-States-Impacts-Responses framework-
130 eDPSIR, see Niemeijer and Groot, 2008) as well as an MDFSA approach (UN
131 Commission on Sustainable Development, 2001; Hukkinen, 2003; OECD, 2002). The
132 TCS-SLTD model is specifically designed for SD assessment in cities of developing
133 countries. The eDPSIR framework allows key indicators and cross-boundary issues to
134 be identified within a system, as well as a range of causal relationships
135 between them (Niemeijer and Groot, 2008), while the MDFSA, as previously
136 mentioned, provides a tool for organizing indicators from various fields in order to
137 uncover hidden inter-relations, and to compare different system-level states.
138
139 To demonstrate the steps and methods for implementing the model, and to verify
140 its applicability, a case study of Xi’an, capital of Shaanxi Province and a major
141 primate city in Western China, is presented below.
142
143 The structure of the rest of the paper is as follows. First of all, the TCS-SLTD model is
144 introduced and described in section 2. Then, the research area, method and steps for
145 implementing the TCS-SLTD model are presented in section 3. Following this, the
146 study’s main findings are described in section 4, and suggestions are made on how
147 to further the SD of Xi’an. Section 5 concludes the paper.

148

149 **2. Trinity of Cities’ Sustainability from Spatial, Logical and Time**

150 **Dimensions’ (TCS-SLTD) - Model for Assessing SD of Cities in**

151 **Developing Countries**

152 To delineate the evolution of cities’ sustainability in developing countries, the chosen
153 framework should account for cities’ multi-dimensional natures and evaluate
154 their overall SD trend in a synthetic way. Sustainability implies that citizens live
155 without outstripping their cities’ carrying capacity (social, economic and
156 environmental), and also implies an equitable sharing of resources and opportunities
157 for this and for future generations (Graymore, 2005; Rees, 1996). Cities themselves
158 are heterogeneous entities, mosaics of entwined natural and anthropogenic ecosystems,
159 diversified social groups, and continuous transitions across rural-urban boundaries and
160 land-use patterns (Allen, 2003). Therefore to assess a city’s sustainability,
161 any framework should cover the “triple bottom line” (which considers environmental

quality, economic prosperity and social justice) (Elkington, 1997), should reflect the nested hierarchy of cities' sustainability (Fischer *et al.* 2007), and should also take into account the cities' spatial transformation, as well as variation of the cities' ecosystem services.

Fig. 1. Trinity of cities' sustainability from spatial, logical and time dimensions(TCS-SLTD)

Based on the aforementioned principles, the TCS-SLTD model is designed to apprehend and assess cities' sustainability from three distinct, yet connected, dimensions - space, logic and time - and then to evaluate the overall sustainability of cities by synthesizing values of the three dimensions.

The spatial dimension of the TCS-SLTD model refers to the urban areas' spatial pattern. The "Compact city", as advocated by the European Community (EC), is taken to mean a relatively high-density, mixed-use city, based on an efficient public transport systems and design that encourages walking and cycling (Burton, 2000). Besides the advantages of high density urban areas for environmental sustainability, discussed extensively in former studies (Beatley, 2000; Ewing, 1997; Pope, 1999), high density urban living is also argued to be more socially sustainable (local facilities and services are easier to maintain), and is seen as prerequisite for vitality, vibrancy, cultural activities and social interaction (Williams, 1999).

187 To move towards sustainability, cities' spatial form should move towards compactness.
 188 Compactness can be assessed by the three following standards: i) cities are
 189 functionally "compact" when communication and interaction between citizens are
 190 harmonious and occur within city boundaries, ii) the spatial distribution of
 191 functions can be made more "compact", thereby increasing the carrying capacity of the
 192 urban system; iii) the form of cities can be made more "compact" by optimizing urban
 193 expansion through rational planning and effective development control. A composite
 194 indicator has been chosen—the compact coefficient of urban area (CCUA) (Ding, 2013;
 195 Gasparatos *et al.*, 2008)—for evaluating the spatial sustainability of cities in
 196 developing countries.

$$197 \quad CCUA = k \cdot \frac{NP \cdot LPI \cdot COHESION}{CA \cdot ENN \cdot MN^2} \quad (1)$$

198 Where, k is a normalization factor so that $CCUA$ is between 0 and 1, NP stands for the
 199 number of urban patches, LPI represents the largest urban patch index, $COHESION$ is
 200 the urban patch cohesion, CA stands for the total area of urban patches, ENN represents
 201 Euclidean nearest-neighbor distance between urban patches. We introduce the
 202 equations of five landscape indexes (Appendix 1) into equation (1), and obtain the
 203 formula:

$$204 \quad CCUA = k' \cdot \frac{m^3 \sqrt{Z}}{A(\sqrt{Z} - 1)} \cdot \frac{\max_{j=1}^n(a_j) \cdot \left(\sum_{j=1}^n(p_j^* \sqrt{a_j^*}) - \sum_{j=1}^n p_j^* \right)}{\sum_{j=1}^n a_j \cdot \sum_{j=1}^n (p_j^* \sqrt{a_j^*}) \cdot \left(\sum_{j=1}^n h_j \right)^2} \quad (2)$$

205 Where, k' is a normalization factor so that $CCUA$ is between 0 and 1, a_j is the area of
 206 urban patch j , A is the whole area of urban patches, m is the number of urban patches,
 207 h_j is the Euclidean Nearest-neighbor Distance of urban patch j , p_{ij}^* is the perimeter of
 208 urban patch j in terms of cell surface, a_{ij}^* is the area of urban patch j in terms of
 209 number of cells, Z is the total number of cells of urban area. Since $CCUA$ is positively
 210 correlated with NP , LPI and $COHESION$, and negatively correlated with CA and ENN ,
 211 $CCUA$ is a positive volume index (PVI), which means that a city is more "compact" as
 212 the score of $CCUA$ increases.

213
 214 The logical and time dimensions of the TCS-SLTD model are the two sides of the
 215 same coin. Given the multi-factor nature of cities, the primary goal for assessing cities'
 216 sustainability is to select representative sustainable development indicators (SDIs),
 217 which can logically represent most aspects of the spectrum of cities' development, and
 218 are collectable from official statistical materials or related authorities.

219
 220 For the logical dimension, a causal network-based framework – the eDPSIR
 221 framework – guides SDI selection. Since SDIs characterize the status of the
 222 system (Jackson *et al.*, 2000), determining the validity of these indicators requires a

robust selection methodology (Dale and Beyeler, 2001). Widely applied to various managerial problems for assessing decision making and policy recommendations, system approaches provide a framework for indicator selection (Bossel, 2001). The eDPSIR framework, rooted in causal chain networks, provides conceptual guidance for understanding the real world and helps to achieve a relatively systematic and transparent process of indicator identification (Niemeijer and de Groot, 2008).

Turning to the time dimension, eight thematic aspects of SDIs, respectively belonging to the five dimensions of the eDPSIR framework (drivers, pressures, states & impacts, and responses), are collected in time series. SDIs, collected in order to represent the complex interrelationships between various factors that impact cities' sustainability, are grouped into the following dimensions: population growth, economic development, requirements for improving social well-being, thriving business, industrial optimization, future proofing, environmental impacts, and residents' life quality. The indicator that represents environmental impacts (ecosystem services) is calculated by adopting the equivalent weighting factors for ecosystem service per hectare for terrestrial ecosystems in China (Xie *et al.*, 2003) as well as land-use change detection (Foody and Mathur, 2004). The other indicators are collected directly from local official statistical resources.

Since a factor that cannot be clearly measured will be hard to act upon (Bohringer and Jochem, 2007), stakeholders in cities in developing countries require synthetic assessments of changes in the economic, environmental, urban form, and social (including institutional) dimensions of cities. Based upon the general approach we have outlined, the comparative sustainability of cities can be calculated using methods of remote sensing, GIS, ecosystem service evaluation, combined with the multivariate analysis of SDIs: methodological details are provided in the next section.

3. Method

3.1 Research Area

Situated between 33°42'N (UTM 3782579.08 m) and 33°45'N (UTM 3813622.30 m), 107°40'E (UTM 296635.96 m) and 109°49'E (UTM 340906.54 m), Xi'an is the capital of Shaanxi Province in Western China (Fig.2). Influenced by the East Asian monsoon, Xi'an enjoys a semi-arid, continental climate with four distinct seasons. By the end of 2010, the population of Xi'an was 8.47 million, with 5.62 million living in urban districts. Xi'an's total area is 10,108 km² (XABS, 2011), and population density—in urban areas—is 774 person/km². As a sub-provincial city, it has direct jurisdiction over 9 districts (Beilin, Yanta, Weiyang, Baqiao, Xincheng, Lianhu, Changan, Yanliang, and Lintong) and 4 counties (Lantian, Huxian, Zhouzhi and Gaoling).

Fig.2. Location of research area

As one of the “Four Great Ancient Capitals of China”¹, Xi’an has re-emerged as an important cultural, industrial and educational center in Western China. Initiated by the “First Five” Plan², Xi’an’s urbanization process began with a period of “laying the foundations” (1966-1976) resulting from the third front construction policy³. Following this, industrialization and urbanization proceeded apace between 1977 and 2000: the city benefitted from its human capital resources and from flourishing electronics, machinery, chemical, materials, reconnaissance, automation control, aerospace and aviation industries. Over the course of the last fifty years, Xi’an has become one of the biggest cities along the “Longhai-Lanxin” railway line in China⁴, and has been nominated as a key hinterland open city⁵ by the State Council.

1 The Chinese phrase ‘Four Great Ancient Capitals of China’ traditionally refers to Beijing (the current capital of the People’s Republic), Nanjing, Luoyang, and Chang’an (Xi’an).

2 China’s five-year plans are a series of social and economic development initiatives. The economy was shaped by the Communist Party of China (CPC) through the plenary sessions of the Central Committee and national congresses. The First Plan was undertaken from 1953 -1957.
http://en.wikipedia.org/wiki/Five-year_plans_of_China

3 Led by the government of People’s Republic of China, a large amount of national defense infrastructure, defense-related science and technology, heavy industries and transportation infrastructure was initiated in the 13 provinces of Western China, beginning in 1964, guided by the ideology of combat readiness.

4 Situated in the central China, the “Longhai-Lanxin” railway line has a total length of 4101 km. It is composed of two main railway lines— ‘Longhai’ railway line and “Lanxin” railway line. “Longhai” railway line runs 1759 km from Liangyugang in its west to Lanzhou in its east. The “Lanxin” railway is 2342 km long and connects Lanzhou in Gansu province with Urumchi in Xinjiang province. As a major element of the ‘western development policy’, the construction of “Longhai-Lanxin” railway line has stimulated the economy of Western China.

5 In order to develop the local economy through the effective use of foreign investment and the introduction of advanced technologies and scientific management methods, cities in China’s hinterland are encouraged to take a series of measures, including implementing a certain type of institutional regime to facilitate the formation of an international investment environment, speeding up local infrastructure construction, promoting conversion to the market system (by planning and fostering development), and implementing multi-level preferential policies.

Notwithstanding the growing economy and booming fiscal revenue, rapidurbanization hasput enormous pressure on the city’s fragile ecosystem (Lu and Chen, 2006).Not only is this pressure attributable to urban expansion (and to concomitant land consumption and building),Xi’an is also facedwith urban environmental problemssuch as domestic garbage, air- and noise-pollution (Lu and Chen, 2006).Likewise, the thriving tourist sector has also put pressure on local environmental carrying capacity.

3.2 Materials and Method for Land-use Change Detection

The five steps proposed by Saadat et al. (2009) for classifying of LANDSATE ETM+ were adopted.Changes of fourland-use categoriesfrom 1988 to 2010, namely built-up land, arable land⁶,forest, and water body (Table 1), were detected through analysis ofLANDSATE TM satellite datasets for 1988, 1995, 2006 and 2010, and LANDSATE ETM+ satellite datasets for 2000.Other supplemental materials were also used, such as a detaileddigital land-use map, at the 1:25 000 scale, derived from the Survey of Xi’an city for the years 1990 and 2000.

Table.1 Land use classification scheme

Land use category	Brief description
Arable land	Agricultural land is used for cultivation, mainly for growing crops, and occasionally for planting fruit trees, mulberry trees and woods. It includes cultivated land, reclaimed land, and fallow field.
Forest land	Forest Lands have a tree-crown areal density (crown closure percentage) of 10 percent or more, are stocked with trees capable of producing timber or other wood products, and exert an influence on the climate or water regime. Lands from which trees have been removed to less than 10 percent crown closure but which have not been developed for other uses are also included (Anderson et al, 1976).
Built-up land	Built-up land is comprised of areas of intensive use with much of the land covered by structures. This category includes cities, towns, villages, strip development along highways, transportation, power, and communication facilities, and areas such as those occupied by mills, shopping centers, industrial and commercial complexes, and institutions that may, in some instances, be isolated from urban areas (Anderson et al, 1976).
Water body	This category includes water area, shoal, canals, ditches, and so forth ⁷ .

Two hundred ground truthing points were collected by using global positioning

⁶ Since there is little green land in the city, and since it has the same spectral characteristics as cultivated land, both are classified as arable land.

⁷The national standards of “classification of land use survey” in China (GB/T 21010-2007)

system (GPS) in April and May 2013: half were used for sampling and the other half for assessing the classification's accuracy. The total accuracy of the Landsat-derived land-use data by Kappa accounts were 86.34%, 85.47%, 85.94%, 89.84% and 87.92% respectively, corresponding to the standard accuracy of 85-90% for LULC mapping studies recommended by Anderson et al. (1976).

3.3CCUA and Ecosystem Services Value (ESV) Evaluation

Using changes in built-up land detected in 3.2, the geography and spatial characteristics of the five indexes of landscape ecology - *CA*, *NP*, *LPI*, *ENN* and *COHESION* - are assessed using Arcgis 9.3 and Fragstate 3.3 (McGarigal *et al.*, 2012). With this information, the *CCUA* (see equation 1) of Xi'an in 1988, 1995, 2000, 2006 and 2010 is calculated. *CCUAs* for other years are derived by linear interpolation (Dyn *et al.*, 1990).

Changes in the four land-use categories are used to estimate variations of the ecosystem services value (ESV) of Xi'an between 1988 and 2010: note that the ecosystem service value of built-up land is zero.

The ESV of land in any particular category is based on the nearest equivalent ecosystem (Table 3). In accord with Costanza *et al.*'s (1997) parameters, and in keeping with the results of a survey of 200 Chinese ecologists, Xie *et al.* (2003) have extracted the per hectare equivalent factor weight of ecosystem service of terrestrial ecosystems (Table 2). A factor weight of 1 is equivalent to the economic value of natural food production of arable land, per hectare, per year. Xie *et al.* (2003) proposed that it be equated to 1/7 of actual food production. To estimate the ecological service value of our research area more precisely, the economic value of average natural food production is evaluated by using the data collected from local statistical resources, with national average prices of grain types collected from the China Rural Statistical Yearbook in 2011. The ecosystem service value of a hectare of unit weighted land in the research area is estimated at 1649.66 Yuan/hectare (Xie, *et al.*, 2003).

Table 2 - Equivalent factor weight of ecosystem services per hectare of terrestrial ecosystem in China (Xie *et al.*, 2003)

	Forest	Grassland	Arable land	Wetland	Water body	Barren land
Gas regulation	3.5	0.8	0.5	1.8	0	0
Climate regulation	2.7	0.9	0.89	17.1	0.46	0
Water supply	3.2	0.8	0.6	15.5	20.38	0.03
Soil formation and retention	3.9	1.95	1.46	1.71	0.01	0.02
Waste treatment	1.31	1.31	1.64	18.18	18.18	0.01
Biodiversity protection	3.26	1.09	0.71	2.5	2.49	0.34

	Forest	Grassland	Arable land	Wetland	Water body	Barren land
Food	0.1	0.3	1	0.3	0.1	0.01
Raw material	2.6	0.05	0.1	0.07	0.01	0
Recreation and culture	1.28	0.04	0.01	5.55	4.34	0.01
Total	21.85	7.24	6.91	62.71	46.01	0.42

Table 3 – Ecosystem service value of unit area of different land use categories in Xi'an city (Yuan/km²·a)

	Forest land	Cropland	Water body	Built-up land
Gas regulation	577381	82483	0	0
Climate regulation	445408	146820	75884	0
Water supply	527891	98980	3362007	0
Soil formation and retention	643367	240850	1650	0
Waste treatment	216105	270544	2999082	0
Biodiversity protection	537789	117126	410765	0
Food	16497	164966	16497	0
Raw material	428912	16497	1650	0
Recreation and culture	211156	1650	715952	0
Total	3604507	1139915	7590086	0

Given the ecosystem service value of each land use category, the service value for each category, and service function is given in equations (3) to (5).

$$ESV_k = \sum_f A_k \times VC_{kf} \quad (3)$$

$$ESV_f = \sum_k A_k \times VC_{kf} \quad (4)$$

$$ESV = \sum_k \sum_f A_k \times VC_{kf} \quad (5)$$

ESV_k , ESV_f and ESV refer to the ecosystem service value of land use category “ k ”, of ecosystem function type “ f ”, and the total ecosystem service value respectively. A_k is the area of land use category “ k ” and VC_{kf} the value coefficient (Yuan/ha • year) for land use category “ k ”, ecosystem service function type “ f ”.

3.4 Sustainable Development Indicators (SDIs) Selection and Comparative

Sustainability Assessment

Based on the eDPSIR framework (Niemeijer and Groot, 2006), a straightforward causal network of Xi'an development is used to structure the selection of SDIs. To accomplish this, two important elements need to be identified, namely

“pressure interface” and “key nodes”. The term “pressure interface” refers to the economic sector or human activity that exerts pressure on the environment, which in this study is the funnel through which a range of driving forces exert pressure. “Key nodes”, as components of the causal network, can be classified into three types: root nodes, central nodes and end-of-chain nodes (Niemeijer and de Groot, 2008). Root nodes are nodes that have many outgoing arcs (the arcs diverge from these nodes). Central nodes are those that have many incoming and/or outgoing arcs (converging and diverging arcs). End-of-chain nodes typically have multiple incoming arcs. With these elements, the causal network of Xi’an development can be drawn.

In order to summarize the multiple factors that drive regional urbanization, as well as their impacts on regional sustainability, the root nodes that have been chosen are population growth and economic development. The central nodes are: the need to improve social wellbeing, thriving business, industrial optimization, future proofing, environmental impacts, and residents’ quality of life. The end-of-chain nodes, selected because they relate to a large number of issues that surround the development of Xi’an, are represented by indicators drawn from local statistical resources corresponding to the central nodes: they are treated as SDIs for Xi’an.

Given this general framework, SDI selection follows a two-step process. For step 1, field research was carried out in Xi’an from June to July 2013. 30 stakeholders connected to the development of Xi’an were convened, from local government, research institutes, universities, and other key administrative authorities, and their opinion on drivers, pressures, states and responses corresponding to local sustainability were gathered. For step 2, indicators, as end-of-chain nodes of the DPSIR framework, were selected as SDIs for the research area. A pool of indicators was first collected from local official statistical resources (i.e. Xi’an city Statistical Yearbook, Xi’an city Yearbook, *etc.*). Then, a group of experts from relevant research domains (i.e. major players in the regional economy, urban ecology, regional sustainable development, *etc.*) were invited to pick indicators from the pool. Finalized SDIs were decided upon based on experts’ choices, as well as availability and continuity of these data from 1990 to 2010.

It is vital to guarantee the completeness and continuity of time series data used for SD assessment. Therefore, aside from the estimated value of ecosystem services of Xi’an city from 1988 to 2010, all indicators of central nodes and other SDI related data were selected - under the guidance of the eDPSIR framework - from local statistical sources.

Since urbanization is the population shift from rural to urban areas, together with accompanying transformations in life style, the equation for quantifying the urbanization process of Xi’an is formulated as follows:

$$PU_i = U_i / P_i \times 100 \quad (6)$$

Where i represents the year (between 1990 and 2010), U_i represents the amount of urban household population in year i , P_i is the total population of Xi'an city in year i , PU_i stands for the urbanization rate of Xi'an city in year i .

The $CCUA$ score, calculated from equation (1), is treated as the city's spatial sustainability score. The scores of the five factors of the eDPSIR framework (drivers, pressures, states & impacts, and responses) are evaluated by Principal Component Analysis (PCA) (Pearson, 1901; Hotelling, 1933; Jolliffe, 2002) from the data collected from local statistical resources (excepted the measure of "environmental impacts" represented by the ESV). Since the units and scale of SDIs are different, the indicators are standardized using Z-scores.

Based upon these indicators the comparative sustainability of Xi'an from 1990 to 2010 is assessed by equation (7). Since there are causal relationships between the six factors mentioned above, their weights are assigned the value of 1 and their contribution to local sustainability are treated as equal.

$$I_i = CCUA_i + Yd_i - Yp_i + Ys_i + Yi_i + Yr_i \quad (7)$$

Where i indicates the year (between 1990 and 2010), I_i stands for the sustainability score in year i , $CCUA_i$ is the compactness coefficient for Xi'an in year i , Yd_i is the score for drivers in year i , Yp_i is the score for pressures in year i , Ys_i is the score for states in year i , Yi_i is the score for impacts in year i , and Yr_i is the score for responses in year i .

4. Results and Discussion

In this section, the land-use changes and landscape pattern transformation Xi'an's urban area between 1988 and 2010 are described. Then, the SDIs of Xi'an are selected based on the eDPSIR framework's causal network, and evolution of the research area's sustainability from 1990 to 2010 is assessed by applying the TCS-SLTD model.

4.1 Land-use Changes and Landscape Pattern Transformation of Urban Area

in Xi'an

Fig.3. Land-use changes of Xi'an between 1988 and 2010

Over the past 23 years, the area of built-up land in Xi'an has sharply expanded while the area of the arable land experienced an opposite trend (Fig.3). From 1988 to 1995, the area of built-up land in Xi'an increased by 150%: together with the main southward swathe of urbanization, the central urban area of Xi'an had entirely covered the downtown area (mainly concentrated within the city wall), the western industrial district and eastern 'Fangzhi city'⁸ emerged, and the urbanization process in Lintong and Yanliang districts (respectively located in Northwestern and Northeastern Xi'an city) were initiated.

From 1995 to 2000, the area of built-up land in Xi'an expanded by 21%, and the central urban area had entirely covered the downtown area, eastern 'Fangzhi City', the western industrial district, as well as the newly developed urban area in Southern Xi'an. Since 2000, Northern Xi'an has become the hot spot of urbanization, and the city witnessed an increase of its built-up land of 171.72 km² between 2000 to 2006, accompanied with accelerating urbanization processes in Lintong and Yanliang districts.

From 2006 to 2010, built-up land in Xi'an has rapidly expanded from the central city to its surrounding areas, with a net increase of 931.95 km² (almost doubling in size).

⁸With a distance of 12 kilometers to the central city, it is located in the east part of Xi'an city. From 1954, it has become the location of key provincial textile industries base with a series of national textile enterprises and subsidiary bodies. The area of 'Fangzhi city' is 5 km².

Conversely, Xi'an's arable land has dramatically shrunk, losing 39% between 1988 and 2010, an annual decrease of $55.24 \text{ km}^2 \cdot \text{year}^{-1}$. Most of this was converted to built-up land and forest. The forested area of Xi'an, has, somewhat counterintuitively, grown, with a totally increase of 393.99 km^2 in the past 23 years.

The landscape pattern of Xi'an has also been transformed (Table.4). First, the new urban areas, mainly converted from arable land for industrial, residential and public utilities, are randomly distributed, following no apparent pattern. This is evidenced by the 64% increase of *NP* (indicator of urban patches). Second, the dominance of certain urban areas in Xi'an has increased during the urbanization process: the *LPI* has increased more than 10-fold over the 23 year period (from 0.67% in 1988 to 9.78% in 2010). Third, urban areas in Xi'an have also become more concentrated, clumped and aggregated, since the *ENN* of urban patches has decreased by 38% while *COHESION* increased by 1.5%.

Table 4. Landscape transformation and CCUA of urban area in Xi'an between 1988 and 2010

Year	CA (sq.km)	NP	LPI (%)	ENN (m)	COHESION	CCUA
1988	93.30	1944.00	0.61	323.02	98.41	11987.4
1995	234.46	2570.00	1.80	296.47	98.89	22198.71
2000	283.36	4398.00	1.60	233.04	98.84	45196.88
2006	455.08	2658.00	3.91	263.48	99.59	32761.55
2010	931.95	3196.00	9.78	199.93	99.84	83772.53

Looking at the *CCUA*'s evolution between 1988 and 2010, the spatial sustainability of Xi'an has followed an upward trend. With a sharp rise of 277% between 1988 and 2000, the expansion of built-up land and the increasing fragmentation and dominance of urban patches are the main reasons for this growth. Yet the spatial sustainability of this city declined by 28% between 2000 and 2006 due to a decline in the number of urban patches and increased average distance between them. Between 2006 and 2010, the spatial sustainability of Xi'an increased considerably (by 250%) benefiting from increases in the dominance of certain urban patches as well as decreasing average distance between them.

4.2 The Causal Network and SDIs of Xi'an

4.2.1 Root Nodes

Two factors, namely urban population growth and regional economic prosperity, are identified as the main drivers of urbanization in Xi'an. These two drivers have largely stimulated the urbanization process: they have also, inevitably, put intense pressure on the city's natural environment. Therefore, indicators representing the drivers of

urbanization, namely total population in urban areas, urban population density, annual population growth rate, GDP, per capita annual living expenditure of urban households, and disposable income of urban households, are used to represent the root nodes of the eDPSIR framework's causal network for Xi'an.

4.2.2 Key Nodes, Central Nodes and End-of-Chain Nodes

In the eDPSIR framework's causal network, indicators representing drivers and responses are used as central nodes, while indicators representing pressures, and states and impacts are treated as end-of-chain nodes.

Urban population growth and regional economic prosperity display, unsurprisingly, positive correlation with the improvement of social wellbeing, economic prosperity, and industrial development. However, these factors are also the main reasons for regional environmental degradation, and have exerted great pressure on local ecosystems.

Therefore, indicators that represent quality of environment, residents' lives and functionality of the urban area's ecosystem, are treated as "states & impacts" in the eDPSIR framework. Meanwhile, indicators representing countermeasures applied for eliminating pressures and negative impacts on the city's ecosystem and social status are collected and treated as "responses".

4.2.3 The Causal Network of the eDPSIR Framework

Fig.4. The causal network of eDPSIR framework of Xi'an

The causal network of Xian's eDPSIR framework is shown in Figure 4. In the framework, direct relationships, represented by full lines, indicate that central nodes have direct impacts on the end of chain nodes, or that end of chain nodes can immediately respond to central nodes. Indirect relationships, represented by dotted lines, indicate that central nodes have indirect impact on the end of chain nodes, or that end of chain nodes respond to central nodes indirectly.

i) *Drivers of pressure*: urban population growth and regional economic prosperity, as the main drivers that stimulate urbanization, are root nodes in the causal network. Indicators of total population in urban areas as well as annual population growth are directly related to the urban population growth. They have indirect influence on urban households' disposable income, which reflects improvement in household living standards. Economic development not only directly stimulates regional GDP growth and local economic prosperity, but also has indirect influence on urban households' disposable income.

Five indicators, namely freight traffic, passenger traffic, volume of industrial wastewater, total volume of industrial waste gas emission, and volume of industrial solid waste, represent pressure within the eDPSIR framework. The first two indicators are not only the result of economic prosperity, but also contribute directly to local Green House Gas (GHG) emission. The other three are directly caused by industrial development.

ii) *Drivers of States & Impacts*: Acting as end of chain nodes, the states of the natural environment and of the quality of residents' life are directly influenced by the drivers of the eDPSIR framework, represented by seven indicators from local statistical resources. These are: total area of parks, gardens and green space, per capita area of roads, per capita public green area, per capita area of living space, number of public vehicles per 10,000 population, annual number of traffic accidents, and number of registered cases. What needs to be stressed was that the ESV variation of Xi'an was estimated and treated as an indicator to represent impacts of urbanization on local ecosystem in Xi'an.

iii) *Responses to Pressure and States & Impacts*: Measures are taken for eliminating negative impacts on the states of the city due to pressures & impacts, which are represented by the following indicators: percentage of volume of industrial solid waste that is recycled, percentage of industrial waste water meeting discharge standards, and percentage of cleared up cases. Two of these are used to represent the countermeasures for mitigating industrial pollution, while the other is a precaution taken for guaranteeing high quality of living standard for local residents.

547

548 4.3 Urbanization and Its Impacts on SD of Xi'an

549

550 **Fig.5. Urban form transformation of Xi'an city between 1988 and 2010**

551

552 Historical and administrative factors have influenced the urbanization process of Xi'an.

553 For various reasons (detailed in section 3.1.2), most research institutes and

554 universities in Xi'an are located in Southern city, endowing this region with potential

555 for future industrialization and urbanization. Especially after approval of

556 Xi'an's High-Tech Industries Development Zone by the State Council in 1991, this

557 region has become the rapidly urbanizing in Xi'an (Fig.5). With an accelerating

558 urbanization process in Xi'an after 1991, Southern Xi'an has experienced strong

559 pressure on its natural environment and continuous degradation of its business

560 environment (i.e. growing operating costs for medium and small companies), due

561 to congestion and other costs linked with the dense agglomeration of companies in this

562 region. Thus, Northern Xi'an, which used to be dominated by arable land, has become

563 a more environmentally attractive and cost-effective location for enterprises and

564 public institutions. Especially after the approval of the Xi'an Economic-Technological

565 Development Zone by the State Council in 1993, Northern Xi'an became the next hot

566 spot for industrialization and urbanization. This process has promoted a more spatially

567 balanced urbanization process in Xi'an. After 2006, urbanization in

568 Xi'an has spread radially, with its urban area sprawling towards surrounding zones along

569 major transport axes.

570

571 Xi'an's urbanization rate has increased rapidly from 1990 to 2010.

Administrative factors have had some influence on the process. With adoption of the policy “transforming counties into urban districts”, Lintong County and Changan County became urban districts in 1997 and 2001 respectively, contributing net increments of urban population of 55,800 and 244,488 to the city.

Fig.6. Scores of the sustainability of Xi'an city and its constitution

The SD of Xi'an has followed an uneven growth trend (Fig. 6 – see also equation 6). The comparative sustainability score increased by 205% between 1990 and 2010, but the trend has fluctuated rather than followed a monotonic increase.

Fig.7. Comparing study of urbanization process and overall sustainability of Xi'an city from 1990 to 2010

Among the six factors taken for assessing SD of Xi'an city (equation 6), CCUA, drivers, pressures, states, and responses have followed an upward trend, whilst impacts have followed an opposite trend (Fig. 7b). The drivers indicator displays a sharp and almost

monotonic increase between 1990 and 2010, due to urban population growth and economic prosperity. The pressure indicator, which increased by 457%, provides evidence of the enormous environmental pressures caused by the urbanization process in Xi'an. Meanwhile, factors of states & responses have showed a modest upward trend with twists and turns, since the "states" of the city was multi-factors determined and countermeasures were restrained by a series of factors, i.e. the level of infrastructure construction, social awareness of environmental problems, local governance of research area, etc. Furthermore, the implementation of the policy of "transforming counties into urban districts" have significant impact on the spatial pattern of urban area, and the CCUA of Xi'an has showed U-bend pattern from 2001 to 2010.

As with the urbanization rate of Xi'an has kept a continued upward trend between 1990 and 2010 with an annual increasing rate of $0.55\% \cdot \text{year}^{-1}$, while SD of this city has demonstrated a fluctuated increasing trend in the same time frame (Fig. 8a). The main reason for such circumstance was rooted in the rapid urbanization in Xi'an has not only brought this city intensive population concentration in urban centre, but also sharp expansion of urban area. These newly developed urban areas were generally lack of necessary infrastructures and adequate public service facilities. Even in some cases, these urban areas were under intensive industrialization and environmental degradation. Although detailed urban planning formulated for these regions have always under the guidance of classical urban planning theory and modern ideas of sustainable development and circular economy, it still need to take 2-3 years to catch up the pace of former urbanized area, and turn to bring positive contributions to SD of the city.

4.4 Discussion

Decision-makers, stakeholders, and local communities agree that the present mode of city development in developing countries is unsustainable (Zhang *et al.*, 2013). Approaches need to be found to shift these cities towards sustainable development paths. One way of doing so is to recognize that cities are systems of interconnected processes, and to implement the rational coordination of the multi-dimensional interactions inherent to such systems. The objective would be to improve environmental and human conditions by revitalizing the urban system, controlling urban form, and involving local communities in city development. However, the obtaining the know-how to implement such "regenerative sustainability" of cities, especially in less developed contexts, is a daunting task as much for stakeholders, as for scholars, scientists, and officials working in the related fields.

In this study, we have examined the relationship between the transformation of urban form, variations in social-economic-environmental indicators, and fluctuations of

631 overall sustainability of Xi'an. Based on this, we now make some suggestions on how
632 to pursue regenerative sustainable development in Xi'an (Geng *et al.*, 2014), which
633 may be instructive for other cities in developing countries with similar social-economic
634 contexts, development paths or historical and geographical characteristics.

636 **4.4.1 Urbanization Process and Existing Countermeasures for Future-proofing** 637 **Xi'an**

638 The transformation of Xi'an's urban form can be described as
639 "concentration–deconcentration–concentration". The transformation can be divided
640 into three stages: ① *The preliminary stage*. Xi'an's initial spatial growth was
641 concentrated. The city, composed of downtown (within the city walls built in Ming
642 Dynasty), the western industrial base (mostly defense industries), and eastern
643 "Fangzhi city" (dominated by several state-owned textile enterprises), grew because it
644 had been chosen as the preferred location for heavy industries, especially the national
645 defense industry. Its form was determined by administrative location decisions.
646 ② *The developing stage*. This stage was roughly after the initiation of reforms and of
647 China's opening-up policy. Two main factors influenced Xi'an's urbanization process
648 during this stage. One was the implementation of the policy – "transforming counties
649 into urban districts" in Lintong and Changan counties in order to facilitate urban
650 governance. The other was the emergence of market-driven development zones around
651 the city: these officially sanctioned special areas were destined to upgrade the region's
652 industrial structure and stimulate economy prosperity. The setting up of Xi'an's
653 High-Tech Development Zone in 1991 and its Economic and Technological
654 Development Zone in 1993 have radically altered the thrust of urbanization, from
655 west-east to south-north. The foundation of Xi'an City Chan-Ba Ecological District⁹ in
656 2004 has refocused urbanization to Eastern Xi'an, after decades of rapid
657 urbanization in Southern and Northern Xi'an led to environmental pressures in these
658 regions.
659 ③ *The revitalization stage*. Newly urbanized areas, especially development zones, are
660 generally quite remote, and often lack infrastructure and public services. Most
661 residents of these regions are also short of necessary education and knowledge to adapt
662 to urban-style life. Like many cities in developing countries, Xi'an has experienced a
663 rapid pace of urbanization, extensive population concentration, an accelerated
664 physical expansion of urban areas, leading to severe environmental pressure on its
665 ecosystem. The third stage is characterized by a quest for regional development: this
666 entails not only economy prosperity, but also environmental protection and social
667 wellbeing, and cannot be achieved without taking the whole urban system into
668 account.

9 Learning from the development experience of cities at home and abroad, the CPC Xi'an Municipal Committee and Xi'an Municipal Government established the Chan-Ba Ecological District in 2004. As an ecological urban district, the Chan-Ba Ecological District incorporates ecological control into urban construction.

669
 670 The main stakeholders in Xi'an have reached consensus that the existing pattern of
 671 development can be neither sustainable nor regenerative unless a series of
 672 countermeasures are taken, by local communities as well as local
 673 authorities, to "future-proof" the city.
 674
 675 First, in order to ensure the comparative advantage of Xi'an's industry, policies have
 676 been formulated to orientate leading industries towards advanced manufacturing, such
 677 as aerospace, electronic information and components, power transmission equipment,
 678 motor vehicle parts and components, and modern service industries, such as tourism,
 679 culture, commercial logistics, exhibition consulting, and outsourcing services.
 680 Objectives have been set taking into account existing industries, as well as
 681 socio-economic development plans at larger scales, such as the "Guanzhong-Tianshui
 682 Economic Zone Plan"¹⁰.
 683
 684 Meanwhile, "Innovation development", aimed at encouraging the productivity and
 685 competitiveness of local knowledge resources and at building potential for future
 686 growth, has been advocated by the local government, since Xi'an has the third largest
 687 concentration of research institutions and universities in Mainland China.
 688
 689 Furthermore, three administrative measures (reform of the "urban village"¹¹,
 690 upgrading public infrastructure and services, zoning regulations), have been
 691 implemented by local government in order to optimize the city's spatial form and
 692 governance. The reform of the "urban village" consists in the revitalization of central
 693 districts, where used to be characterized by transient population, various old and
 694 un-renovated buildings, and poor public infrastructure. This measurement has
 695 improved the urban form's 'compactness' and has improved local governance. The
 696 carrying capacity of the urban system and the living standards of residents have
 697 been improved through the upgrading public infrastructure services, i.e. public transit
 698 system, public green space system, etc. Xi'an's zoning regulations have been
 699 upgraded under the proactive guidance of local government. Overall, the central
 700 downtown area, which used to be the center of regional administration,
 701 industrialization and transportation, has shifted towards business, recreation (public

10 Approved by the State Council, the "Guanzhong-Tianshui Economic Zone Development Planning" was set in accordance with "People's Republic of China National Economic and Social Development the Eleventh Five-year Planning" and "Western Development the Eleventh Five-year Planning", with planning period from 2009 to 2020. This plan has identified the development objectives as: overall economic strength to achieve a new breakthrough.

11 Urban villages (literally: 'village in city') are villages that appear on both the outskirts and the downtown segments of major Chinese cities, including Beijing, Shenzhen and Guangzhou. They are surrounded by skyscrapers, transportation infrastructures, and other modern urban constructions. Urban villages are a unique phenomenon that formed part of China's urbanization efforts. Urban villages are commonly inhabited by the poor and transient, and as such they are associated with squalor, overcrowding and social problems. However, they are also among the liveliest areas in some cities and are notable for affording economic opportunity to newcomers to the city.

green space), and residential utilities, while municipal government facilities and factories have been intentionally relocated to more remote sites, in order to stimulate development in urban fringe area.

However, these three administrative measures are piecemeal, focused on solving specific problems and lacking overall coherence. Furthermore, these measures are temporally and spatially mismatched: the reform of the “urban village” was carried out at the street scale and with a time frame of about 5 years, while the upgrading the public infrastructure services was carried out on larger spatial scale, i.e. districts or several roads, and over a shorter time frame, i.e. 1-2 years. Meanwhile, the zoning of urban areas, undertaken under the aegis of urban planning, was carried out at the city level and is expected to roll out over several decades.

4.4.2 Suggestions on SD of Xi'an

The key suggestion, one that underpins this paper's central argument, is the need to shift from one-dimensional piecemeal countermeasures to a holistic approach to organizing city development. The urban system (and systems) as a whole need to be revitalized, with coordinated interventions on urban form, on the community's ideas about city development, and on harmonizing coordination between different municipal authorities and departments.

In order to revitalize the urban system, the local government should advocate “human centered” urbanization policies, which recognize that all citizens should have equal access to public services regardless of their residence permits. The city requires better urban planning that can meet citizens' diverse interests and needs. For this to occur, institutional innovation, with focus upon city governance, is urgently needed. This should include reform of the household registration system by removing barriers to labor mobility between rural and urban areas, as well as the support of a mobile and versatile labor force with equal access to public services. It should also ensure that the idea of “regenerative development” be incorporated into future urban planning, in order to prevent Xi'an's rapid urbanization from jeopardizing the fragile urban ecosystem, from endangering the quantity and quality of arable land, thereby avoiding the vicious circle of growth and degradation that characterizes cities in developing countries.

To control the urban form, countermeasures should focus on enhancing urban planning and design, regulating land-use control, and ensuring that local authorities have the means and capacity to oversee the process. Furthermore, market-oriented zoning regulations are desirable in order to optimize land-use. By adopting more flexible zoning, urban areas in Xi'an will in all likelihood see smaller plots and some land-use diversification. In addition to these local interventions, cross-departmental joint

meetings need to be convened by high-rank authorities (e.g. provincial government of Shaanxi Province) to identify and address supra-regional or cross-sectoral land-use issues.

To facilitate the identification and advancement of community ideas on city development, it is important to gradually transform the traditional decision-making process on issues of city development: this entails shifting the local governance process from a top-down and government-mandated model to a more balanced bottom-up and top-down model. This will involve both seeking-out of community opinion by local and regional authorities, and information sessions by these authorities in order to inform the community of city-wide sustainability issues. Consensus on city growth in Xi'an can only be achieved when local communities are informed about, and take part in, the process of decision-making: in the long run this will facilitate the execution and implementation of decisions, thereby accelerating the roll-out of actions that will improve SD and minimize the impacts of rapid urbanization.

4.4.3 The Adoption of TCS-SLTD Model

Some features of this study of SD in Xi'an have wider relevance, and address questions of sustainability in other developing countries.

First, most of the frameworks/models used for assessing SD in cities have multi-dimensional/hierarchical structures, in order to reflect the complex nature of cities and of sustainability. Generally, these frameworks/models are either formulated by adopting the three-pillars of "sustainability" – environmental, economic and social (institutional) (Sun, *et al.*, 2010; Li, *et al.*, 2012), or are based on the driving force/pressure state/effect (DPSE) model (Fan & Qi, 2010). However, models developed using the three-pillar approach are not well adapted to analyzing the relationships between: they often lack a dynamic element and do not usually explicitly incorporate interdependencies and causal relationships amongst factors. Models or frameworks of the DPSE type are better suited to analyzing causal links between these dimensions, but can benefit from incorporating the variety of factors that three-pillar approach considers.

Second, therefore, to assess the overall sustainability of cities through multi-dimensional/hierarchical models requires identifying and synthesizing impacts from a wide variety of spheres that contribute to city development. However, the problem of prioritizing and weighting indicators remains: this relates to the Multi Criteria Decision Making (MCDM) problem (Drake, 1998). One possible solution is to adopt an Analytical Hierarchical Process (AHP) to determine the weight of different sustainable development indices (Zhou *et al.*, 2007; Yue *et al.*, 2010). However, the deficiency of this method, although it has often been used in the public and private

sectors (Hartwich, 1999), is that it does not provide guidance about structuring the problem to be solved. Furthermore, as the levels of hierarchy increase, so does the difficulty and time it takes to synthesize weights (Hartwich, 1999).

Third, although several studies have emphasized the connection between SD and spatial patterns of development (Gao, *et al.*, 2011), none have developed an index for evaluating the spatial sustainability of an urban region, nor has the spatial scale been integrated into the comprehensive assessment of the overall sustainability of cities.

In light of the above, the TCS-SLTD model developed in this study contributes to better assessing the SD of cities in developing countries. By adopting of the eDPSIR framework, TCS-SLTD model is capable of including all major factors associated with the overall sustainability of cities, and provides guidance to policy-makers pursuing regenerative sustainability (Du Plessis, 2012; Zhang, 2014). The comparative level of sustainability of cities calculated in using the TCS-SLTD model only indicates the overall trend of cities' development, but can also be decomposed along the dimensions of the eDPSIR framework (drivers, pressure, states, impacts and responses). This capacity to decompose the SD index is important, since the underlying rationale of the framework is to improve the overall sustainability of cities by increasing the positive contribution (or by decreasing the negative contribution) of all six of the framework's underlying dimensions. Furthermore, the TCS-SLTD model also synthesizes a city's spatial configuration – through the CCUA – allowing it to be integrated into the SD assessment: this dimension is not addressed in former studies.

5. Conclusions

Attaining inclusive, regenerative and sustainable cities for all in the context of unparalleled rates of urbanization, economy-oriented priorities, and chaotic urban development that characterize the developing world is a major challenge. A first step in reaching this goal is to conceptualize an inclusive framework for delineating, assessing and guiding the development of these cities towards sustainability.

In this study we outline an inclusive, causal framework for SD assessment, entitled “Trinity of Cities Sustainability from Spatial, Logical and Time Dimensions” (TCS-SLTD). It has been developed for cities in developing countries, and is illustrated using one such city, Xi'an. After reviewing the history and trends of urbanization of cities in Western China, some principles for assessing sustainability of cities in developing countries are suggested, after which the Xi'an case is presented.

The urban area of Xi'an has expanded by more than 10 fold during the last quarter century, while arable land has decreased by 39%. In addition to these dramatic changes

in land-use, the main axis of urban expansion has shifted from a north-south axial to radial expansion towards all areas around the core city. Over time, urban expansion has followed a “concentrated–deconcentrated–concentrated” trend. Xi’an overall sustainability, as measured by the index we present, has followed an upward – but not monotonic - trend between 1990 and 2010, during which its urbanization rate increased by 30%. On the basis of our multi-dimensional analysis, suggestions are made on how to direct Xi’an toward a more regenerative development path. These include revitalization of the urban system, control of urban form through planning, consulting and informing local communities about sustainable development issues, and achieving efficient functioning and harmonious coordination among different departments and municipal authorities in Xi’an.

The TCS-SLTD model, outlined in this study, is a useful tool for guiding the process of SDI selection, and provides a conceptual framework for holistically assessing the sustainability of city growth and expansion in developing countries. The model can assist urban planners and policy makers in developing countries in the performance of integrated assessments of city sustainability, and in the formulation of pragmatic and focused policies to shift cities towards more regenerative and sustainable development trajectories. Furthermore, with the advancement of technologies and the proliferation of new forms of data (e.g. social networking data, GPS tracts, satellite data set, etc.), the data required for applying the TCS-SLTD model will become more easily available, and more complete, over time. The TCS-SLTD framework is flexible: the paper’s major contribution is to provide a conceptual framework that can structure city-level SD assessment (including its geographic and spatial dimensions) together with an example of the way it can be applied.

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 1001

1002 Appendix 1

1003 Selected landscape indicators for quantifying the spatial characteristics of cities

1004 (McGarigal et al. 2012)

1005

Index	Formula	Unit	Range	Function
	$CA = \sum_{j=1}^n a_{ij} \left(\frac{1}{10,000} \right)$			It is a measure of
Total (class)	a_{ij} = area (m ²) of patch ij .	Hectares	CA > 0,	landscape composition,
area (CA)			without limit	specifically, how much
				of the landscape is
				comprised of a single
				patch type
	$NP = m_i$			NP of a particular patch
	m_i = number of patches in the landscape of			type is a simple measure
Number of	patch type (class) i .	None	NP ≥ 1,	of the extent of
patches (NP)			without limit	subdivision or
				fragmentation of the
				patch type
	$LPI = \frac{\max_{j=1}^n(a_{ij})}{A} (100)$			LPI is a simple measure
Largest patch		Percent	0 < LPI ≤ 100	of dominance
index (LPI)	a_{ij} = area (square meters) of patch ij , A =			
	total landscape area (square meters)			
	$ENN_MN = \frac{1}{n} \sum_{j=1}^n h_{ij}$			ENN_MN is the measure
Mean Euclidean				to quantify the average
nearest neighbor	h_{ij} is the edge to edge distance from class i	Meters	ENN > 0,	patch of class i isolation
distance (ENN)	patch j to its nearest neighboring patch of		without limit	level at the
	the same class.			class/landscape level

					$COHESION = \left[1 - \frac{\sum_{j=1}^n p_{ij}^*}{\sum_{j=1}^n p_{ij}^* \sqrt{a_{ij}^*}} \right] \left[1 - \frac{1}{\sqrt{Z}} \right]^{-1} \quad (100)$		Patch cohesion index
Patch cohesion					$0 \leq$		
(COHESION)	p_{ij}^* = perimeter of patch ij in terms of number	None		$COHESION <$			measures the physical
	of cell surfaces, a_{ij}^* = area of patch ij in						connectedness of the
	terms of number of cells, Z = total number of				100		corresponding patch type
	cells in the landscape						

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