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ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 12 (21): 6314-6319, 2013
ISSN 1812-5638 / DOI: 10.3923/itj.2013.6314.6319

Design of Sustainability Indicators System Based on Ecological Footprint with an Application to Guanzhong Region of China

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Abstract: Ecological Footprint (EF) provides an estimate of the land area necessary to satisfy current levels of resource consumption for a defined human population. However, a major difficulty associated with the EF is the reliability to measure progress towards the goal of sustainability. In this study, a new indicators system is designed to bring the EF analysis into the scope of sustainability frameworks. That includes Ecological Pressure Index (EFI), Ecological Occupancy Index (EOI), Ecological-economic Coordination Index (EECI) and Sustainable Development Index (SDI). Furthermore, the consequent assessment of these four indices is based on the time series analysis of ecological footprint, Biological Capacity (BC) as well as ecological budget in Guanzhong region for 1991-2010. And we employ the polynomial regression equations to simulate the dynamic laws. The study results indicate: (1) Per capita EF of Guanzhong increased from 0.9621 gha in 1991 to 1.5177 gha in 2010, while per capita BC decreased from 1.3435 gha to 1.2857 gha during the same period, (2) Per capita ecological budget is positive during 1991-2000, indicating an ecological surplus. Whereas, the ecological deficit occurs in 2001, and rise to 0.3120 by 2010, (3) EFI trends up on the whole, with an increment of 63.19%, which explains the local ecosystem is being heavily burdened more with the increased human consumptions, (4) EOI also presents an ascending tendency approximately with an increment of 55.54%, which demonstrates Guanzhong has an increasing human consumption level compared with the global average, (5) EECI fluctuates in the range of 0.4781 to 0.6152, without outstanding changes, which indicates more efforts need to be made toward the reconciliation of local economic progress and ecological conservation and (6) SDI trends reduced after increasing first, which illustrates the regional sustainability does not progress in a steady level in the past 20 years.

Key words: Guanzhong region in shaanxi province, time series analysis, ecological footprint, sustainability indicators system

INTRODUCTION

Sustainable development remains a challenging problem confronting with many scholars. Recently, the ecological footprint (abbreviated as EF hereafter) is suggested to serve such a purpose as an elegant method (Wackernagel and Rees, 1996). Some scholars regard the EF as a tool to measure sustainability (Templet, 2000; Wackernagel and Silverstein, 2000; Costanza, 2000), while others point out its limitation for policy-making as well as for planning specific steps towards a sustainable future. (Van Den Bergh and Verbruggen, 1999; Opschoor, 2000). It makes the sustainability challenge more transparent. At present, there are not uniform and standard methods or indicators system for sustainable development research, which needs more detailed investigation and precise discussion. Therefore, this paper presents four indices based on the EF and shows how they are applied as a planning and monitoring tool for sustainability by taking Guanzhong basin of Shaanxi Province in China as an example.

MATERIALS AND METHODS

A short explanation of the EF: EF is an area-based indicator, which measure human demand on nature by assessing how much biologically productive land area is necessary to sustain a given consumption pattern. In the last several years, the EF methodology has received much attention (e.g., Bicknell *et al*., 1998; Levett, 1998; Herendeen, 2000; Rapport, 2000; Van Kooten and Bulte, 2000). Although the EF does not serve as an indicator for

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assessing regional sustainability, it dose provide sufficient information about the human impact and appropriation carrying capacity (Costanza, 2000). So far, various modifications to the EF have been made, and many applied research projects have been completed from the global down to the local scale. Examples are estimation of land use changes and ecological potentials in China (Hubacek and Sun, 2001; Ren and Zhang, 2003), further applications of evaluating the environmental impacts of spending options (Lenzen and Dey, 2002), use of input-output analysis methodology (Bicknell *et al*., 1998; Proops *et al*., 1999; McDonald and Patterson, 2004; Suh, 2004a; Wiedmann *et al*., 2006), material flow calculations at the national and international level (Giljum and Hubacek, 2004; Suh, 2004b). Since the EF is a tool still in the process of improvement, and so far, no existing models offer satisfactory explanations for the environmental impacts of different consumer lifestyles (Lenzen and Murray, 2003), so some aspects associated with the potential of the EF need to be perfected continuously.

EF assessments allow researchers to analyze whether the amount of biologically productive land available to an economy is equal to or greater than that required to supply all consumed resources and to absorb all generated wastes. This contrast is necessary although not sufficient for sustainability. EF analysis is based on the following two assumptions. First, that it is possible to keep track of most of the resources that a human population consumes and most of the wastes that the population generates. Second, that these resource and waste flows can be converted to a biological productive area necessary to provide the resources and to assimilate the wastes. The biological productive area is termed 'ecological footprint' of the given human population, and the locally available carrying capacity is defined 'biological capacity' (abbreviated as BC hereafter). In the EF analysis, six main categories of biological productive area are distinguished: arable land, forest, pasture, water area, built-up area and fossil-energy area. As the various categories represent great differences in biological productivity, 'equivalence factor' and 'field factor' have been introduced. Combined with these two concepts, the various categories of biological productive area in different regions or nations can be compared with the global average productivity called 'global hectares (gha)'. Once these two factors are determined, each regional EF or BC can be translated in the common measurement unit (Wackernagel *et al*., 2002). Furthermore, the concept of ecological budget is defined as the sum of BC minus EF (Senbel *et al*., 2003). If the ecological budget is negative, it is often interpreted as an ecological 'overshoot' (Haberl *et al*., 2001). That indicates the total area required for supporting the final consumption of a given human population exceeds what is available locally. It would imply that the population satisfies their demands by appropriating the environmental carrying capacity of other regions, i.e. running 'ecological deficit'.

Sustainability indicators system: In order to extend the potential for applying EF methodology to sustainability, we establish a new sustainability framework composed of four indices. The method applied involves the following four steps:

Step 1: The calculation of ecological pressure index (abbreviated as EFI hereafter). It is acknowledged that EF includes renewable resources footprint and non-renewable resources footprint (such as fossil-energy). Towards a certain nation or region, EFI can be defined as the quotient obtained by dividing per capita EF of renewable resources by per capita BC. To some extent, this index reflects the pressure intensity brought by human consumption activities to bear on environment. It is described by Eq. 1:

$$EFI = ef'/bc \quad (1)$$

where, EFI refers to regional ecological pressure index; ef' refers to per capita EF of renewable resources; bc refers to per capita BC.

Step 2: Tthe calculation of ecological occupancy index (abbreviated as EOI hereafter). EOI is defined as the quotient obtained by dividing per capita EF of a given nation or region by per capita EF of the world average. This index presents the proportion of regional EF to global EF, and reflects the regional human consumption levels compared to the global average. Therefore, a higher EOI may be a representative indicator explaining a better economic development situation if it is discussed at national or local scales, especially to developing regions. It is expressed by Eq. 2:

$$EOI = ef / \overline{ef} \quad (2)$$

where, EOI refers to regional ecological occupancy index; ef refers to regional per capita EF; $\overline{ef}$ refers to global average per capita EF at a same period.

Step 3: The calculation of ecological-economic coordination index (abbreviated as EECI hereafter). EECI is defined as the quotient obtained by dividing EOI by EFI. This index reveals the concordant degree of regional economic development and environment improvement. A greater EOI shows a higher consumption pattern than the global average. When the regional population occupies more EF by means of importing resources from elsewhere but not depleting the natural capital stocks within its boundaries, the region is carrying out a high EECI. It is calculated by Eq. 3:

$$\text{EECI} = \text{EOI}/\text{EFI} \quad (3)$$

where, EECI refers to regional ecological-economic coordination index; EOI and EFI are interpreted as the above.

Step 4: The calculation of sustainable development index (abbreviated as SDI hereafter). SDI is associated with the above-mentioned indices. Here, we assume that EFI, EOI, and EECI carry the same weight to SDI. Also, a higher EFI to be an indication of unsustainability, while a higher EOI and EECI to be a favorable token to sustainable development at regional scale. Then, these three indices are standardized according to being positive contribution or negative influence. The model is established as Eq. 4:

$$\text{SDI} = 1/3(P_{\text{EFI}} + P_{\text{EOI}} + P_{\text{EECI}}) \quad (4)$$

$$P_{\text{EFI}} = \begin{cases} 0 & (\text{EFI} \geq \overline{\text{EFI}}) \\ \overline{\text{EFI}}/\text{EFI} - 1 & (\text{EFI} \leq \overline{\text{EFI}}) \end{cases}$$

$$P_{\text{EOI}} = \begin{cases} 0 & (\text{EOI} \leq \overline{\text{EOI}}) \\ \text{EOI}/\overline{\text{EOI}} - 1 & (\text{EOI} \geq \overline{\text{EOI}}) \end{cases}$$

$$P_{\text{EECI}} = \begin{cases} 0 & (\text{EOI} \leq \overline{\text{EOI}}) \\ \text{EECI}/\overline{\text{EECI}} - 1 & (\text{EOI} \geq \overline{\text{EOI}}) \end{cases}$$

where, P_{EFI}, P_{EOI} and P_{EECI} represent the characteristic factors for manifesting regional (un) sustainable development at a certain aspect; $\overline{\text{EFI}}$, $\overline{\text{EOI}}$, as well as $\overline{\text{EECI}}$ refers to the average of regional EFI, EOI and EECI for 1991-2010, respectively. Obviously, we regard the average for a long period of time as the reference standard. Towards the negative index such as EFI, if the value in some year exceeds the secular average, it implies an increased pressure on ecosystems has been caused by human consumption, which goes against the regional sustainability. As a comprehensive index, SDI revels the relation between the level of economic activity and its corresponding impact on the environment.

FRAMEWORK APPLICATION TO GUANZHONG REGION

A brief introduction of study area: Guanzhong basin is located in the center of China (Fig. 1). The terrain in this region descends from west to east with mean altitude of 325-900 m, and it is correspondingly flat and low in the central section. The mean annual precipitation is 600-700 mm, and it belongs to temperate semi-humid continental monsoon climate. The population in this region has reached 25.07 million by 2010.

Considering the overall arrangement for regional development in China, it occupies the predominant location that connects all directions and it is the crucial point to propel industry and agriculture development in Shaanxi province. However, because of the complicated terrain and environmental status, appending the intensive and extensive influence of human activities, some ecological issues including soil and water loss, land degradation, disafforestation and disaster happened severely. So it is significative to evaluate the sustainability of this region for driving economic development of Shaanxi province, furthermore, accelerating the advancement in the west or mid-east of China.

Calculation and analysis of EF and BC of Guanzhong for 1991-2010: In EF calculation, we mainly consider three items: (1) biological resource consumption primarily

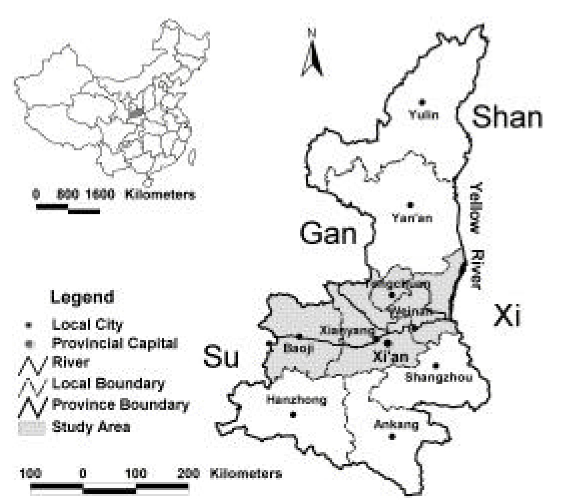

Fig. 1 Sketch map of study area

including agricultural products, forest products, animal products etc., (2) fossil-energy consumption involving coal, oil, electric power and natural gas and (3) trade between regions and countries by adding imports to local production and subtracting exports. All regional data for 1991-2010 are obtained from Shaanxi Yearbook published by China Statistics Press.

Per capita EF, BC and ecological budget of Guanzhong for 1991-2010 have been calculated shown in Table 1. Per capita EF of study area increased from 0.9621 gha in 1991 to 1.5177 gha in 2010, while per capita BC decreased from 1.3435 gha to 1.2857 gha during the same period. Per capita ecological budget is positive during 1991-2000, indicating an ecological surplus. Whereas, ecological deficit occurs in 2001, and rise to 0.3120 by 2010. In effect, overshoot means spending nature's capital faster than it is being regenerated.

Figure 2 shows the development trend of per capita EF, BC and ecological budget. Further, we employ the polynomial regression analysis to simulate the dynamic laws of these indices. They are expressed by the following three quadratic polynomials as Eq. 5-7:

$$Y_E(t) = -0.0003t^2+0.0353t+0.9218\ R_E^2 = 0.9517 \quad (5)$$

$$Y_B(t) = -0.0004t^2+0.0011t+1.3682\ R_B^2 = 0.9159 \quad (6)$$

$$Y_{eb}(t) = -0.0001t^2+0.0342t+0.4553\ R_{eb}^2 = 0.9670 \quad (7)$$

where, for instance, t = 1 means the year of 1991; R_E^2, R_B^2 as well as R_{eb}^2 refers to, respectively, the determination coefficients of these trend lines equations.

According to these regression equations, we can estimate the local per capita EF, BC and ecological deficit will reach 1.7018, 1.0412 and 0.6607 in 2020, respectively, if the improvements in technology and resource management will steadily increase the bioproductivity at a rate similar to that of the last 20 years. That reveals the conflicts between the EF and BC will become acute year by year.

Assessment of the sustainability of Guanzhong: Based on the statistics of the global per capita EF and BC for 1991-2010 offered by WWF (http://en.wikipedia.org/wiki/World_Wide_Fund_for_Nature) in the 'Living Planet Report 2010', as well as the results of regional per capita EF and BC, we calculate the EFI, EOI, EECI and SDI of Guanzhong during this period by using the models 1-4 (Table 1).

Figure 3 shows the time series of EFI, EOI, EECI and SDI of Guanzhong for 1991-2010. It is obvious, EFI trends up on the whole, with an increment of 63.19% during the past 20 years. That explains the local ecosystem is being heavily burdened with the increased human consumptions gradually. Meanwhile, EOI also presents an increasing tendency approximately with an increment of 55.54 %. That demonstrates Guanzhong has an increasing human consumption level compared to the global average with the passage of time. In addition, it is worth emphasizing that the growth range of EOI is less than that of EFI, which illustrates per capita EF may be due to more depleting local natural resources but not imports, with associated ecological impacts within its borders. EECI fluctuates between 0.4781 and 0.6152 with no outstanding changes. All of the results indicate the growing consumption of Guanzhong relies on more natural resources produced within the local region and more imports from elsewhere. The ecological appropriation is

Table 1: The per capita EF, BC, Ecological budget, EFI, EOI, EECI and SDI of Guanzhong for 1991-2010

Year	Global per capita EF	Regional per capita EF	Regional per capita BC	Ecological budget	EFI	EOI	EECI	SDI
1991	2.1692	0.9621	1.3728	0.4107	0.8001	0.4435	0.5543	0.0914
1992	2.1874	1.0023	1.3712	0.3689	0.8002	0.4582	0.5726	0.1006
1993	2.1884	1.0415	1.3741	0.3326	0.8001	0.4759	0.5948	0.1139
1994	2.2154	1.0830	1.3690	0.2860	0.8200	0.4889	0.5962	0.1044
1995	2.2660	0.9602	1.3635	0.4033	0.8300	0.4237	0.5105	0.0761
1996	2.3026	1.1145	1.3578	0.2432	0.8100	0.4840	0.5976	0.1104
1997	2.2857	1.1299	1.3517	0.2218	0.8035	0.4943	0.6152	0.1244
1998	2.2433	1.1567	1.3454	0.1887	0.8996	0.5156	0.5732	0.0541
1999	2.2224	1.2089	1.3387	0.1298	1.0104	0.5440	0.5384	0.0030
2000	2.1805	1.2221	1.3261	0.1040	1.0125	0.5605	0.5536	0.0023
2001	2.1724	1.3244	1.3242	-0.0002	1.1523	0.6096	0.5291	0.0267
2002	2.1664	1.3098	1.3095	-0.0003	1.1542	0.6046	0.5238	0.0237
2003	2.1975	1.3264	1.3091	-0.0173	1.2626	0.6036	0.4781	0.0231
2004	2.2070	1.3842	1.3216	-0.0626	1.2052	0.6272	0.5204	0.0371
2005	2.1973	1.3723	1.3210	-0.0512	1.1004	0.6245	0.5676	0.0418
2006	2.1743	1.4662	1.3121	-0.1541	1.1106	0.6743	0.6072	0.0949
2007	2.1653	1.3943	1.2853	-0.1090	1.1046	0.6439	0.5829	0.0624
2008	2.1960	1.4226	1.2687	-0.1539	1.2006	0.6478	0.5396	0.0493
2009	2.1902	1.4688	1.2366	-0.2322	1.2065	0.6706	0.5558	0.0627
2010	2.2000	1.5177	1.2057	-0.3120	1.3057	0.6899	0.5284	0.0741

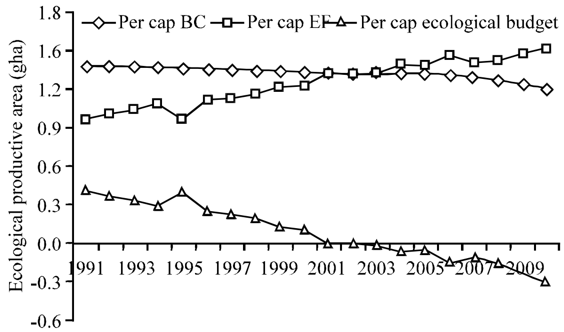

Fig. 2: Time series of per capit EF, BC and ecological budget of Guanzhong for 1991-2010

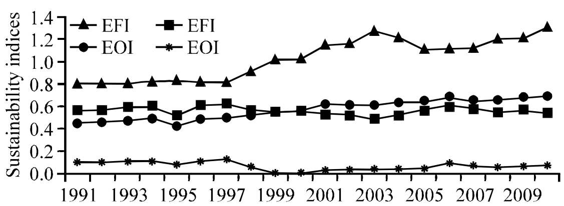

Fig. 3: Time series of EFI, EOI, EECI and SDI of Guanzhong for 1991-2010

mainly achieved at the expense of environment carrying capacity, i.e. economic progress does not coordinate with the ecological protection smoothly. Owing to the changes of these three indices, SDI trends reduced after increasing first compared with itself in a long run. Its value is correspondingly higher for 1991-1997, while it descends during the time of 1998-2005 only with an average of 0.2188, and finally, it regains a relatively finer condition after 2006.

However, it is necessary to emphasize the ecological deficit has been growing ever since 2001 on the whole. While it does not correspond to the situation that regional sustainability has been declining. As far as this point, we can conclude the sustainability should not be measured simply relying on the EF.

RESULTS AND DISCUSSION

In this study, per capita EF and BC of Guanzhong for 1991-2010 are firstly calculated. By moving beyond single-year assessments and analyzing the time series, such accounts can reveal whether we are marching towards or away from the ecological overshoot (Wackernagel *et al.*, 2004). Comparing the human demand with the nature's supply, we can conclude that in the past 20 years, per capita EF presents a descending trend, which is almost opposite to that of per capita BC. In 2001, overshoot occurs, which means that the people's demands for natural resources have exceeded the supply from the ecosystem since that time. If keeping the consumption and bioproductivity increased at a rate similar to that of the past 20 years, the conflict between the EF and BC will be aggravated much more.

In order to strengthen the completeness of the EF methodology, we present a new sustainability indicators system composed of four indices, which are EFI, EOI, EECI as well as SDI. The results indicate in the last 20 years, EFI of Guanzhong region represents an ascending trend in principle. That implies the growing pressure on ecosystems is causing habitat destruction or degradation and permanent loss of productivity, threatening both biodiversity and human well-being. Otherwise, EOI also has been increasing at a restively slow rate. That demonstrates although Guanzhong has developed a higher consumption level, yet its increased EF may be rely more on depleting the local natural resources but not imports from elsewhere. EECI changes in the range of 0.4781 to 0.6152. This indistinct fluctuation indicates the local economic progress and ecological conservation does not move toward a more harmonious way. Owing to the changes in these three indices over a long period of time, SDI trends reduced after increasing first. That explains the local sustainability does not progress in steady steps. Therefore, some pertinent policies should be proposed.

These suggestions include expanding the population size reasonably to control the total consumption footprint; improving technology and resource management scheme to increase per area bioproductivity; making good use of various ecological productive resources to avoid excess expenditure; adding extra support to conserve the local natural capital; developing cycle economy to boost potential profitability. Thus, the EF moves from being merely a theoretic tool to become a strategic tool for policy analysis. We hope this comprehensive supplement of the EF is helpful to give direction for regional efforts to close the sustainability gap.

ACKNOWLEDGMENTS

This study was supported by "National Natural Science Foundation of China" (No.41001374, 41272246, 51009008, 41371220)and "Fundamental Research Funds for the Central Universities" as well as the project "Subjects Innovation and Talents Introduction Plan of Colleges and Universities" (B08039), which is fund by State Foreign Affairs Bureau and Ministry of Education, China.

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