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Can measures of well-being and progress help societies to achieve sustainable development?

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ABSTRACT

The search for sustainability and the growing apprehension with environmental degradation are increasingly attracting researchers from around the world, and bringing the need for developing indicators that include the economy, society and environment. This study compares the emergy indices with 10 known indicators taken from the literature: Gross Domestic Product, Gross Domestic Product per capita, Human Development Index, Happiness Index, Life Expectancy, Democracy Index, Ecological Footprint, Surplus Biocapacity, Wellbeing Index and Environmental Sustainability Index 2002. Correlations are made using the Spearman coefficients to verify correlations between the fractions of renewable natural resources, non-renewable natural resources, resources from the economy and the emergy indices with the known indicators, and indexes emerged with the literature indicators. The analysis of the results is made by illustrative matrices and graphs. The results suggest that the combination of socio-economic and biophysical indicators is essential to provide a better understanding of the limits of economic growth and while ensuring sustainable societal well-being.

1. Introduction

The demand for addressing the multitude of environmental, social and economic issues along with concerns of inter or intra-generational equity, generated several indicators that intend to guide the path to sustainability by identifying trends and pointing out the problems that must be addressed with priority. In recent years, several researchers proposed to evaluate and scrutinize the proposed indicators of progress, aligned or not with sustainable development (SD) goals. Extensive research provided suggestions to enhance the assessment progress indicators and the literature provided comprehensive reviews of the various proposed tools as well as the feasibility of incorporating new parameters within an existing framework of evaluation (Giannetti et al., 2014).

Indicators of progress include monetary tools (Costanza et al., 2009; Stiglitz et al., 2010), biophysical models (Wackernagel and Rees, 1996; Odum, 1996), and composite indices (Esty et al., 2005; Prescott-Allen, 2001) that have been developed from the perspective of different disciplines, such as economics, statistics, ecology, engineering and social sciences. Because of the inadequacy of GDP as an indicator of societal health and for the need for comprehensive metrics to measure progress and well-being under the SD perspective, several indicators were proposed based upon studies conducted by multidisciplinary teams of professionals, scholars, governmental agencies, businesses and nonprofit organizations (Esty et al., 2005; Prescott-Allen, 2001). Some proposals were based on the concern that, due to entanglement and, the lack of awareness of the problems that humanity is going through, it is unlikely that a single indicator can cover the needed dimensions to support the development and implementation of an integrated set of indicators is more appropriate in providing information that could result in the better policies and more effective governance (Henderson et al., 2000). However, multi-indicator indices have been criticized because they can be not only troublesome to understand by the general public and stakeholders (Gasparatos et al., 2008, 2009), but can also allow incomplete or biased interpretations by groups with particular interests or limited knowledge. On the other hand, single number indicators are also criticized as they hide important dimensions and could easily be misused (Henderson et al., 2000; El Serafy, 1993).

In a recent paper, the main measures of progress and their respective advantages and disadvantages in apprehending the significant contributions to national progress towards SD were

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reviewed in a comprehensive manner (Giannetti et al., 2014). The positive and negative aspects of a selected group of indicators of progress were discussed, according to Daly's classification of weak, medium and strong sustainability (Daly, 1990, 2008), and the authors concluded that, in spite of the several indices proposed and used, the problem of dealing with the amount of conceptual problems and data collection remains unsolved. However, most of the authors agreed that the adoption of new measures must ensure the link between the economy and intangible variables related to real progress and well-being. This link requires the monitoring of three variables (environmental resources, social structure, and the economy), which must be converted into useful and unambiguous information in order to evaluate alternative policy options (Giannetti et al., 2014).

Several authors have stood up for the inclusion of many overlapping or articulated dimensions into a cohesive structure (Tiezzi et al., 2004; Costanza et al., 2009) since most current approaches tend to underestimate some contributions to progress. Another option is to reach an agreement on a single standardized system of accounts that can inform, directly or indirectly, if society is moving towards SD or not. However, a problem arises because the monetary and biophysical approaches measure progress and sustainability in different ways. If these perspectives were complementary, they could provide a complete picture of the problem, but one can still argue if they actually cover, directly or indirectly, all important aspects of SD.

Several researchers compared a set of proposed indicators and correlated them for establishing which of them would be the most complete (Giannetti et al., 2009, 2010) and which would cover most aspects of sustainability using the largest possible number of countries (Cohen et al., 2006; Wilson et al., 2007). Some articles proposed new indicators aggregating or combining the existing ones (Common, 2007; Burkhardt, 2008), others evaluated how their construction influences the results obtained (Martins et al., 2006; King et al., 2007).

Common (2007) proposed the Happy Life Years index (HLY) as an approach for measuring the progress of a nation, based on non financial figures. This index results from the product between the life expectancy (LY) and the Happiness Score (H). H varies from zero to one, according to citizen's sense of happiness measured with the use of a questionnaire. Development efficiencies were determined by dividing the HLY by the energy use per capita, the Ecological Footprint (EF) and the greenhouse gas emissions for 90 countries. Martins et al. (2006) compared the Human Development Index (HDI) with the Environmental Sustainability Index (ESI-2002) using data from 139 countries, and observed that some developed countries well ranked by HDI occupy intermediate positions in ESI-2002, and that the contrary occurs for Latin American countries. These authors proposed an amendment to HDI by the inclusion of a new dimension, based on ESI-2002, regarding environmental aspects.

The lack of concerns on the limited reserves necessary to support welfare and wellbeing of the established progress/wellbeing measures was evaluated by Tiezzi et al. (2004), who suggested the ratio emergy/ISEW (Index of Sustainable Economic Welfare, proposed by Daly et al., 1989) as an indicator for decision making because it shows how much social or environmental degradation is related to the use of resources to support the local lifestyle. Cohen et al. (2006) showed the importance of natural capital stocks as a resource base for the economy of 134 countries. The loss of natural capital is compared with emergy indices establishing the relationship between the Environmental Sustainability Index (ESI) and the percentage of natural capital as a significant breakthrough. Countries with high or low ESI appear to be protecting their natural reserves while countries with moderate ESI would be depleting their natural capital stock. The authors also compared the percentage loss of natural capital with GDP and found that countries with very high or very low GDP have a low environmental load, while countries with intermediate GDP extensively over-exploit their natural capital. King et al. (2007) proposed a new indicator called Emergy Total Well-being (ETWI) by multiplying the HDI by the countries' percentage of renewable resources. Countries with high ETWI would have a high HDI and a high usage of renewable natural resources. This index was compared with HDI, EF, WI, ESI-2002, the Index of Human Well-Being (HWI) and the Index Environmental Wellness (EWI) for 120 countries. Human well-being and environmental well-being have an inverse relationship, and the WI is not related to the ETWI, although the two combine human and environmental welfare.

Niccolucci et al. (2012) analyzed the trends of the EF and biocapacity per capita data for 150 countries, between 1961 and 2007, to assess different paths of development. They found that, in all countries, biocapacity is decreasing, but for some the loss is faster. Combining EF and biocapacity with HDI, EPI (Environmental Performance Index) and ESI-2005, the authors highlighted the key role of biocapacity. HDI, EF and biocapacity results were also compared by Moran et al. (2008) for 93 countries, who found that to achieve a minimum sustainability in a country, the ratio EF/biocapacity should be equal or less than 1.0, provided that HDI ≥ 0.8. The only country in this condition was Cuba.

Considering the increasing number of initiatives involving sustainability measures, Wilson et al. (2007) compared six global indices: EF, Surplus biocapacity (SB), ESI-2002, Wellbeing Index (WI), HDI and GDP per capita to examine whether the global indices can be used to guide societies on the SD journey. He divided the information of 132 countries into quintiles and analyzed for inconsistencies among results provided by indices, by highlighting the different interpretations of the sustainability of nations by each indicator used. The variability within the results pointed to a lack of clear directions in approaching SD. Siche et al. (2008) compared SD indicators for twelve countries and discussed the need to develop indicators that include environmental, economic, social, ethical and cultural aspects. These authors observed that ESI-2005 and ESI-2002, in spite of having originated from discussions in academic and policy scales, disregarded the consumption of resources and location in developed countries in the highest rankings while EF and emergy indices ranked the those same countries in the lowest position. The results of the application of ESI-2005 were also criticized by Giannetti et al. (2009), who analyzed the construction of environmental indices based upon expert opinion with paraconsistent logic. They questioned the reliability of the experts' opinions and evaluated the uncertainties due to disagreements among experts, which clearly indicated that the approaches used to measure and monitor SD are insufficient and that there is lack of a solid scientific foundation for sustainability.

Giannetti et al. (2010) compared the results obtained for Mercosur countries using emergy indices and metrics proposed in the literature, including the Ecosystem Services Product (ESP) and the Subtotal Ecological – Economical Product (SEP) proposed by Costanza et al. (1997). Indicators were divided into three groups according to the sustainability dimensions addressed (economic, social and environmental), and the analysis showed that some indicators could be grouped for a more comprehensive result.

All studies revealed that the existing indicators are proxies and may not represent progress in a proper way, either because they are too simple or because they mix so many variables that the final number loses significance.

Bearing in mind that human progress, welfare and well-being are totally interlinked to SD, the objective of this work was to compare measures of well-being and progress in order to identify possible combinations of indicators that could be used to provide information on the progress of society towards SD. For this, indices derived from biophysical models were compared with well known progress indicators based upon their link to sustainability dimensions.

2. Methods

To compare the selected indicators the ranking relative to 106 countries was used. The table of Supplementary materials lists the countries compared and the values of the selected indicators for each country. Comparisons were made among the rankings obtained for each indicator. The degree of correlation between the rankings was analyzed using a matrix that summarizes the results for the countries involved and was represented by graphs that highlight the structural connections and direct and indirect correlations among indicators.

The emergy quantities of renewable (R), non-renewable (N) and purchased resources (F) were collected at the NEAD (2000), and emergy indices were calculated according to Odum (1996) and Brown and Ulgiati (2002). Values for other indicators were obtained from: EF (The Living Planet Report, 2010), SB (Living Planet Report, 2010), HLY (Veenhoven, 2013), LY (Human Development Report, 2010), GDP (Human Development Report, 2010), GDPpc (Human Development Report, 2010), HDI (Human Development Report, 2010), D. Index (Democracy Index Report, 2013), WI (Prescott-Allen, 2001) and the ESI-2002 (Esty et al., 2002).

2.1. Correlation analysis

Correlation analysis is performed from scatter plots and the Spearman correlation coefficient (r_s), which is appropriate for data that do not follow a normal distribution. The Spearman correlation coefficient is a non-parametric measure of correlation between two ordered variables. Thus, correlations are made among the published rankings for each indicator (Equation (1)).

$$r_s = \frac{1 - 6\sum d^2}{n^3 - 3} \quad (1)$$

where r_s is the Spearman correlation coefficient, d is the difference between the posts of each variable in the rank and n is the number of data pairs.

All correlations were based on information from 106 countries. When both variables simultaneously increase, there is a positive correlation that varies between 0 and 1. When there is an inverse relationship, a negative correlation coefficient varies from 0 to -1. For $r_s \geq 0.70$ correlation was considered high or strong, medium for $0.40 \leq r_s < 0.70$, and for $r_s < 0.40$ low or weak correlation. Two different sets of confidence levels were used: $\alpha \leq 0.01$ and for $\alpha \leq 0.05$ (Zar, 1999). Tables 1 and 2 illustrate the procedure adopted to obtain the graphs, showing the correlation matrixes used with values of the coefficient of determination (r^2) and Spearman coefficients (r_s). The r^2 coefficient expresses the relative change of the dependent variable explained by the change of the independent one. $r^2 = 0.54$ indicates that the change of the independent variable explains 54% of the variance of the dependent one. The other 46% may be random or dependent on other factors. Table 2 shows the values of Spearman correlation followed by an asterisk (*), which indicates the significance level lower than 1% ($\alpha \leq 0.01$).

Table 1
The correlation matrix with the coefficients of determination (r^2) between the fractions of resources R, N, F and emergy indices with the known indicators (for 106 countries).

	GDP	GDPpc	HDI	HLY	LY	D. Index	EF	SB	WI	ESI-2002
R	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1
N	0.6	0.2	0.2	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
F	0.9	0.5	0.5	0.5	0.5	0.3	−0.4	−0.3	<0.1	<0.1
EYR	−0.2	−0.4	−0.4	−0.3	−0.4	−0.4	0.3	0.5	- 0.2	<0.1
ELR	−0.2	−0.3	−0.4	−0.2	−0.4	−0.1	0.2	0.5	<0.1	<0.1
ESI	−0.2	−0.4	−0.4	−0.2	−0.4	−0.2	0.3	0.6	<0.1	<0.1

R: renewable natural resources; N: non-renewable resources; F: resources from the economy; EYR: Emergy Yield Ratio; ELR: Environmental Load Ratio; ESI: Environmental Sustainability Index; GDP: Gross Domestic Product (GDP); Gross Domestic Product (GDPpc), HDI: Human Development Index, HLY: Happy Life Years, LY: life years, EF: Ecological Footprint; SB: Biocapacity Surplus; Democracy Index (D. Index); WI: wellbeing Index, ESI-2002: Environmental Sustainability Index-2002.

2.2. Selected biophysical indicators

Emergy, EF and SB are non-monetary approaches that provide a measure of the magnitude of human activity in a particular area with respect to environmental energy flows available (Giannetti et al., 2014), in which EF is the most widely used (Morse, 2011). None of the biophysical indicators include the social and economic aspects directly. Although EF accounts for the value originating from the consumer demands and compares them to the present provision of environmental support. The SB results from the difference between a country's EF and its biocapacity. Emergy accounts for the work that is needed by the environment to provide the energy and materials necessary for the progress and well-being, with the advantage of including the free resources that are overlooked by the EF (e.g., sun, rain, soil, wind, etc.). Resources and energy flows are divided into renewable (R), non-renewable (N) and the feedback from the economy (F). Table 3 provides a brief description of the biophysical indicators evaluated.

2.3. Economic and socio-economic indicators

The GDP was chosen to represent economic measures since it is traditionally used to measure countries' economic growth. GDP accounts for the monetary value of all goods and services produced by the economy of the country during a given period, and only includes monetary measures. It is often used to indirectly relate currency circulation to the degree of development. GDP per capita, is the ratio of GDP with the population of a given country.

The Human Development Index (HDI) is accepted worldwide as a socioeconomic index known for assessing the quality of life of populations. It is calculated considering health (measured by life expectancy), education (measured by average years of schooling and expected years of schooling) and income (GDPpc).

2.4. Social indicators

The Democracy Index (D. Index) was published by The Economist to show the relative degree of democracy in 167 countries. This index is based upon five criteria: electoral process and pluralism, civil liberties, governmental functioning, political participation and political culture. Countries are classified into four types of regimes: full democracies, flawed democracies, hybrid regimes and authoritarian regimes (dictatorships). Life Expectancy (LY) is the average number of living years of the country's population. LY is widely used to determine the level of development of countries and as a dimension of HDI and Happy Life Years Index (HLY). The HLY is obtained by multiplying the LY by a happiness score (H), which varies from 0 to 1. This index was designed to translate the number of years of the life of a citizen in which he considers him/herself happy.

Table 2
The matrix of Spearman correlation (r_s) of the fractions of resources R, N, F and emergy indices with the known indicators (for 106 countries).

	GDP	GDPpc	HDI	HLY	LY	D. Index	EF	SB	WI	ESI-2002
R	0.4*	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	0.4*	<0.1	<0.1
N	0.8*	0.4*	0.4*	0.4*	0.4*	0.2*	−0.3*	- 0.2*	<0.1	<0.1
F	0.9*	0.7*	0.7*	0.7*	0.7*	0.6*	−0.6*	−0.5*	0.4*	0.2*
EYR	−0.4*	−0.6*	−0.7*	−0.5*	−0.7*	−0.6*	0.5*	0.7*	−0.4*	−0.2*
ELR	−0.4*	−0.6*	−0.6*	−0.4*	−0.6*	−0.4*	0.5*	0.7*	−0.3*	<0.1
ESI	−0.5*	−0.6*	−0.7*	−0.5*	−0.7*	−0.5*	0.5*	0.8*	−0.3*	−0.1

R: renewable natural resources; N: non-renewable resources; F: resources from the economy; EYR: Emergy Yield Ratio; ELR: Environmental Load Ratio; ESI: Environmental Sustainability Index; GDP: Gross Domestic Product (GDP); Gross Domestic Product (GDPpc), HDI: Human Development Index, HLY: Happy Life Years, LY: life years, EF: Ecological Footprint; SB: Biocapacity Surplus; Democracy Index (D. Index); WI: wellbeing Index, ESI-2002: Environmental Sustainability Index-2002.

2.5. Composite indicators

The Wellbeing Index (WI) is based on the hypothesis that a healthy environment is essential for healthy humans (Prescott-Allen, 2001). It combines two indices, the Human Wellbeing Index (HWI) and Ecosystem Wellbeing Index (EWI). HWI includes population and health parameters, community and equity issues, wealth indicators, knowledge indicators and culture while EWI aggregates land, water and air dimensions, biodiversity issues and resource use indicators. The aggregation of these dimensions is made by a weighted arithmetic mean of variables that are normalized by a proximity-to-target approach of human and ecosystem wellbeing to monitor how close the country is to being sustainable.

The Environmental Sustainability Index (ESI-2002) was designed to measure the global trend towards sustainability by using five components: environmental systems, reducing environmental stresses, reducing human vulnerability, social and institutional capacity, and global responsibility. These components are assessed using 76 variables, which include economic, social and environmental features.

Table 3
A brief description of the biophysical indicators compared with other measures.

Emergy Yield Ratio	EYR	• The EYR = (R + N + F)/F represents the country's ability to use local resources (Odum, 1996), through the relationship between the total resource/energy use and the amount that come from outside the country.
Emergy Loading Ratio	ELR	• The ELR exposes the load that the country's development model imposes on the environment (ELR = (N + F)/R), comparing the use of imported and non-renewable resources with the availability of renewables. A high ELR means a high stress on national environment.
Environmental Sustainability Index	ESI	• The ESI = EYR/ELR, developed by Brown and Ulgiati (2002), links the concept of sustainability to yield maximization coupled with environmental load minimization. The higher the ESI is for the environmental burden, the lower is the sustainability of that country.
Ecological Footprint	EF	• Developed by Wackernagel and Rees (1996) considers all flows of matter and energy needed to sustain the lifestyle and consumption pattern of the population and converts these flows in a standard unit called equivalent hectare.
Surplus Biocapacity	SB	• Results from the difference between a country's EF and its biocapacity. SB indicates how much the consumption pattern of a country depends on resources and ecological services imported from other nations.

2.6. Graphical representation

Graphs were created to represent the interactions among indicators to facilitate interpretation of the results. Each indicator was represented by a point. A link was created for each correlation between indicators. Fig. 1 shows a path analysis diagram (Wright, 1934) derived from the path coefficient calculations illustrated in Table 2. The figure expresses a tentative theoretical model delineating the structural connections and direct and indirect correlation between each indicator (Table 2, line 1) with emergy variables and indices (Table 2, column 1).

Not all indicators had statistically significant direct correlations with emergy variables and indices. The points were shown to be disconnected when there was no correlation between variables. Some weak correlations disappeared after the significance analysis and were not shown in the graphs. To facilitate understanding different line thicknesses were adopted to identify low, medium and high correlations, which were also emphasized by distances from the graph's center. Direct correlations (positive) were represented by straight lines, and inverse correlations (negative) with dashed lines. Fig. 1 shows an example of a graph with all the highlighted characteristics with one of the emergy indices in the central position.

3. Results and discussion

Several authors emphasized the lack of concern on the limited reserves necessary to support welfare and wellbeing of the conventional progress/wellbeing measures (Tiezzi et al., 2004; Cohen et al., 2006; King et al., 2007). Section 3.1 presented the correlation of the indicators evaluated with the fraction of available resources and the emergy indices to assess the influence of the natural capital stocks on each indicator. Since only a few authors

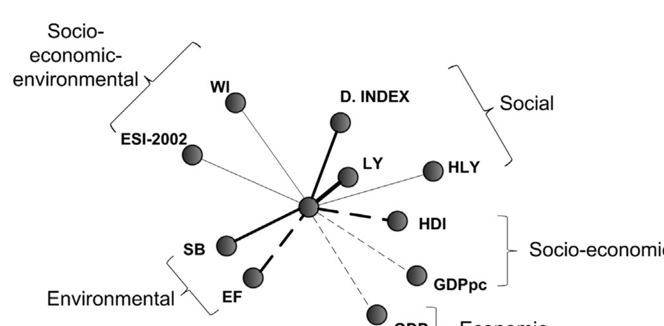

Fig. 1. Example of graph with links that represent weak, medium, and strong correlation according to their line thickness and their distance from the graph center. The emergy indices placed in the central position were compared with GDP, GDPpc, HDI, HLY, LY, D. Index, WI, ESI-2002, EF, and SB. Direct correlations were shown as (—) and inverse correlations were shown as (- -).

considered the particular characteristics of each country or group of countries (Giannetti et al., 2010; Niccolucci et al., 2012; Brizga et al., 2014) a sensitivity analysis (Section 3.2) regarding important features of national development was performed to determine the influence on correlations of geographic location, political regime and the HDI, in evaluating the measure of development.

3.1. Correlation of the indicators evaluated, the fraction of available resources and emergy indices

The renewable, non-renewable and purchased inflows that contribute to a country's activities and progress were accounted for in emergy terms. The R flows represented the free resources that are overlooked by other metrics (e.g., sun, rain, soil, wind, etc.). The N inputs to a country are resources extracted from the local environment at rates greater than they are replenished and by their very definition cannot be depended on in the long term (e.g., minerals, soils, fossil fuels, wood, etc.). Purchased inputs (F) are materials, energies and services that are imported from outside the country.

Fig. 2 shows that, except for GDP and SB, there is no correlation between the renewable fraction, R, and the ten indicators evaluated, which indicates that none of them considers the availability of renewable resources that the country needs to support its development. The correlations between R and SB were expected since both indicators deal with the natural resources availability. The correlation between R and GDP suggests an indirect relationship between economic growth and the availability of renewable resources.

It was found that N correlates with all the indicators, except for the WI and the ESI-2002, which indicates that the composite indices do not adequately assess the availability of local resources. There is a low inverse correlation with EF and SB, a direct medium correlation with the D Index, HLY and LY, and a high positive correlation with GDP. The direct correlations show that almost all indicators take into account the availability of non-renewable resources (such as minerals or fossil fuels), reinforcing the premise that they are based on the concept that development; progress and wealth depend on the quantity of resources that the country has available to underpin its economic growth (Giannetti et al., 2012).

Most of the ten indices have high or medium correlation with F, except for the ESI-2002. The correlation with F, which represents the share of resources that come from outside the countries' borders and GDP and GDP_{pc} was expected. However, the correlation with indices such as the HDI, HLY, LY, EF, SB and D. Index, revealed that these indicators, despite their proposed functions as alternative measures for development, are still heavily dependent on the values associated with economic growth. This result reinforces the idea that economic values have a strong influence in the conception, construction and composition of indices designed to meet, at least in theory, the social understanding of the state of the world. All ten indices studied consider, in one or another way, the economic resources that are necessary for the countries' welfare and sustainability. Thus, the strongest direct correlations were associated with GDP, GDP_{pc}, HDI, HLY and LY. In the case of HDI and LY, it was found to show the importance of a healthy economic system to ensure human development and the life expectancy of the average citizen. In regard to the D. Index and WI, it was clear that a healthy economy was considered to be necessary, but not as important. For EF and SB, the correlation was negative, which confirms that the development, as is currently thought, does not take into consideration the available natural resources (SB) or the rate of their consumption (EF).

The emergy indices combined the three types of resources inflows (R, N, and F) to assess the sustainability of the system. Results clearly showed that the indicators to measure development were designed without considering the availability/usage of renewable resources. Thus, as the R fraction was included, the correlations of all of them were found to be negative with emergy indices, except for SB and EF (Fig. 3).

The results shown in Fig 3 found that most indices consider the availability of resources to the development and/or sustainability, but do not differentiate between the types of resource (whether renewable or not), except for SB and EF. These results suggest that economic/social measures, despite being considered to be dependent upon the availability of resources, do not take into account their availability in the long term, which would only be possible with the use of renewable resources. These indices may assess short term progress, but fail to evaluate SD.

A summary of the correlations found among the indices is shown in Table 4, taking into account the dimensions considered by each metric. Despite the fact that emergy accounting does was not designed to measure the social or economic relationships and wellbeing, it does show a high or an average correlation with social, economic indicators, confirming that the environmental support is directly related to the results expected in the social and economic areas.

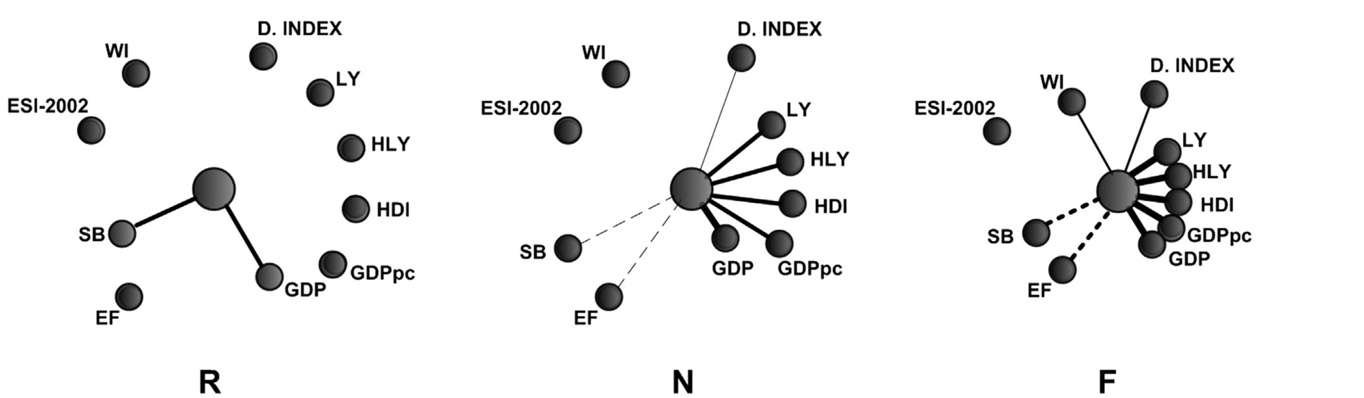

Fig. 2. The Spearman correlation among the ten indices and the available R, N and F resources of 106 countries. Direct correlations are shown as (—) and inverse correlations are shown as (- - -). The links represent weak, medium, and strong correlations according to their thickness and their distance from the graph center. In this context, R refers to renewable natural resources; N refers to non-renewable resources; F refers to resources from the economy; EYR refers to Emergy Yield Ratio; ELR refers to Environmental Load Ratio; ESI refers to Environmental Sustainability Index; GDP refers to Gross Domestic Product; GDPpc refers to Gross Domestic Product, HDI refers to Human Development Index, HLY refers to Happy Life Years, LY refers to life years, EF refers to Ecological Footprint; SB refer to Biocapacity Surplus; D. Index refers to Democracy Index; WI refers to Wellbeing Index, ESI-2002 refers to the Environmental Sustainability Index-2002.

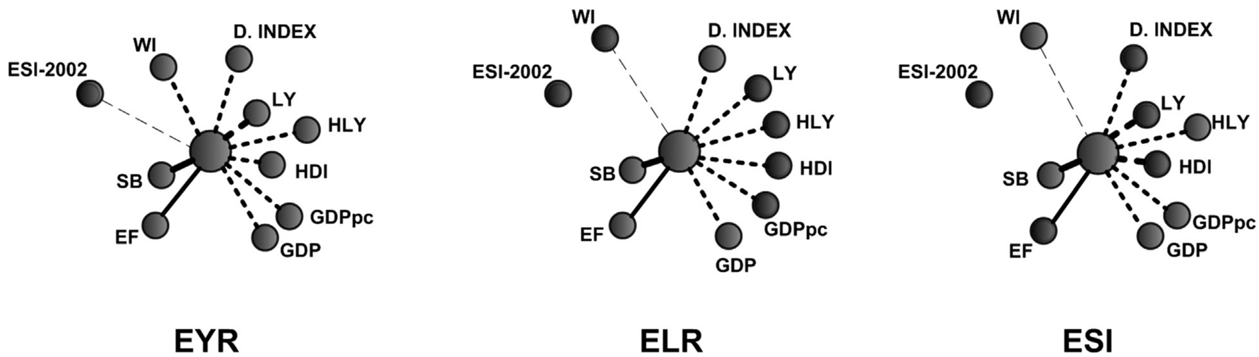

Fig. 3. The Spearman correlations among the ten indices and the emergy indicators of 106 countries. Direct correlation (—) and inverse correlation (- - -). The links represent weak, medium, and strong correlation according to their thickness and their distance from the graph center. Where: R: renewable natural resources; N: non-renewable resources; F: resources from the economy; EYR: Emergy Yield Ratio; ELR: Environmental Load Ratio; ESI: Environmental Sustainability Index; GDP: Gross Domestic Product (GDP); Gross Domestic Product (GDPpc), HDI: Human Development Index, HLY: Happy Life Years, LY: life years, EF: Ecological Footprint; SB: Biocapacity Surplus; Democracy Index (D. Index); WI: Wellbeing Index, ESI-2002: Environmental Sustainability Index-2002.

Directly or indirectly, the emergy indicators (EYR, ELR and ESI) correlated with all indices studied, suggesting that, if used alone, they could act as an acceptable proxy to sustainable societal and economic development.

3.2. Sensitivity analysis highlighting regional, political and social characteristics

The majority of the studies assess the use of progress indicators and the correlations among them deal the largest possible number of countries to guarantee the statistical representativeness of their analyses. However, this approach disregards regional characteristics, local social organization and development levels. SD in a social system or in a country is related to the capacity of ecosystems to regenerate materials and assimilate wastes. SD in a territory also depends on the consumption that can occur within the limits of their own resources (renewable or not). Biophysical indicators can be used to help to quantify the biocapacity available for each country, and also in global terms.

The separation into continents, political regimes and human development groups resulted in finding lower correlations than what was obtained for the whole set of countries. The lower values may be partly explained by the decrease of the sample size and partially by the accentuation of each sample's characteristics, such as the geographic features that join countries with a similar environment (climate, longitude, latitude, cultural values, and so forth).

Fig. 4 shows the correlations with ESI by continent. Correlation values for other emergy indices are available in the Supplementary Materials (Tables S2–S5). The strongest correlations among the countries of the different continents were observed with EYR, which does not differentiate the type of resource used. The introduction of renewable resources to calculate ESI as a requirement to ensure SD makes correlations with all indices decrease or disappear. These results are in agreement with the findings of researchers who observed that the limit of the reserves that support wellness and well-being are not considered by most indices (Cohen et al., 2006; King et al., 2007; Siche et al., 2008).

ESI-2002 and WI do not correlate with any of the emergy indices for Africa and Asia (see Fig. 4 for ESI and Tables S2–S5 for the other indices), and this result suggested that these composite indicators might not capture the development models practiced in these two continents. The correlation of ESI-2002 and WI also disappears when the United States and Canada are separated from the other American countries. This result may be interpreted in the light of three points. The first is that significant information is lost during the aggregation step in composite indices. The second is that these indices are built upon premises that reflect how development is understood by their designers. The choice of metrics and tools depend on the context and the characteristics that the analyst seeks to highlight (Gasparatos et al., 2008). The third is that people assigned to select the most representative variables to compose the final indices do not necessarily agree on the relative importance of one among others (Giannetti et al., 2009). Thus, variables and

Table 4
Classification of selected indices, including the dimensions of sustainability of each and of their correlation coefficients (r_s).

Indicator	Sustainability dimension			Degree of correlation		
	Economic	Social	Environmental	High $r_s \geq 0{,}7$	Medium $0{,}4 \leq r_s < 0{,}7$	Low $r_s < 0{,}4$
GDP	★			F, N	R, EYR, ELR, ESI	–
GDPpc	★	★		F	N, EYR, ELR, ESI	–
HDI	★	★		F, EYR, ESI	N, ELR	–
HLY		★		F	N, EYR, ELR, ESI	–
LY		★		F, EYR, ESI	N, ELR	–
D. Index		★			F, EYR, ELR, ESI	N
EF			★	–	F, EYR, ELR, ESI	N
SB			★	EYR, ELR, ESI	R, F	N
WI		★	★		F, EYR	ELR, ESI
ESI - 2002	★	★	★			F, EYR

R: renewable natural resources; N: non-renewable resources; F: resources from the economy; EYR: Emergy Yield Ratio; ELR: Environmental Load Ratio; ESI: Environmental Sustainability Index; GDP: Gross Domestic Product (GDP); Gross Domestic Product (GDPpc), HDI: Human Development Index, HLY: Happy Life Years, LY: life years, EF: Ecological Footprint; SB: Biocapacity Surplus; Democracy Index (D. Index); WI: Wellbeing Index, ESI-2002: Environmental Sustainability Index-2002.

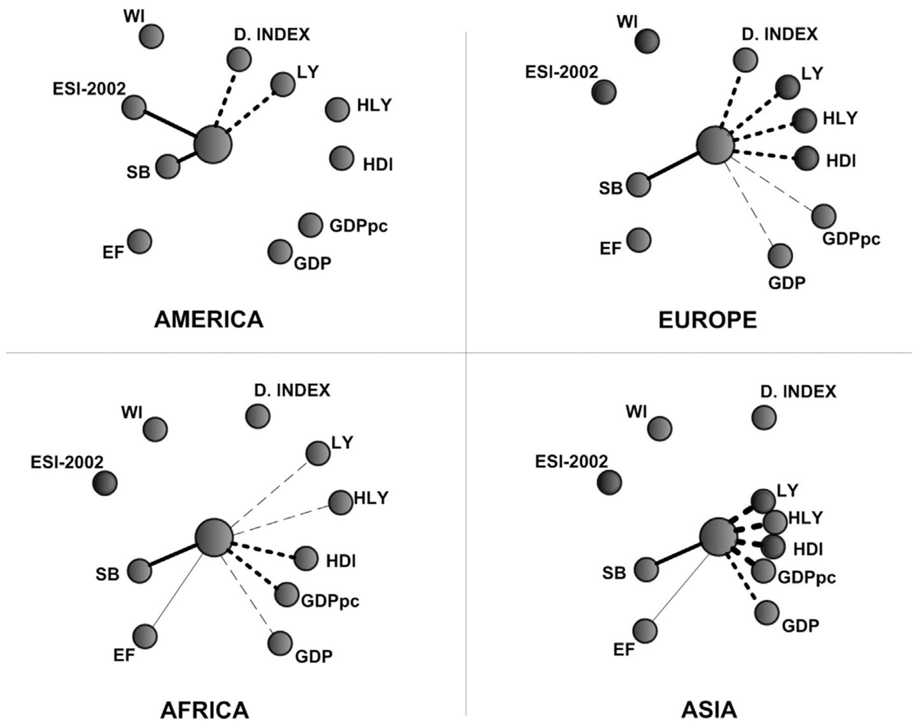

Fig. 4. The Spearman correlation among the ten indices and the ESI for America, Europe, Africa and Asia. Direct correlation (—) and inverse correlation (- - -). The links represent weak, medium, and strong correlations according to their thickness.

premises, on which these composite indices are designed, may not be suitable for application in all countries.

Fig. 5 shows the correlation for the 106 countries divided into groups as established by the Democracy Index (full democracy, imperfect democracy, hybrid and authoritarian regimes). The Spearman correlation coefficients (r_s) for the other emergy indices are shown in Tables S6–S9, which are available in the Supplementary Materials. For all political regimes, correlations with the R

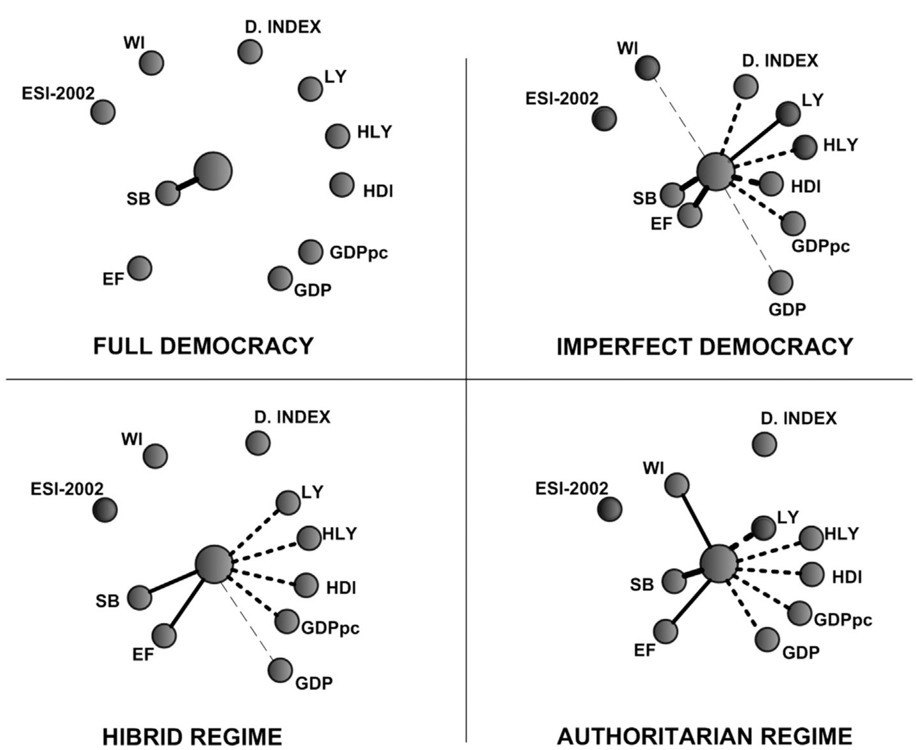

Fig. 5. The Spearman correlation among the ten indices and the ESI according to the political regime. Direct correlation (—) and inverse correlation (- - -). The links represent weak, medium, and strong correlations according to their thickness.

fractions were similar regardless of the democratic regimes considered. There was also a strong correlation between the F and N fractions with GDP for all regimes, which were similar to those found for the world (Table 4), except for the full democracy where medium correlations with ESI-2002 and WI were found. The same pattern was observed for correlations with the emergy indices. EYR correlated with biophysical and socio-economic indices, which reinforced the idea that it could indirectly cover aspects that are evaluated by both types of indices. It as found that ELR correlated with SB, which confirmed its usefulness to assess the availability of environmental resources.

Except for the countries with full democracy, ESI correlated with environmental indicators (EF and SB), and socio-economic indicators (Fig. 5). The similarity found among the correlations for countries separated by the types of political regimes and those found for all countries suggested that these indicators are not sensitive to the governmental structure.

Fig. 6 showed that correlations were found when the countries were separated according to HDI classification, which combines traditional socio-economic development (GDP_{pc}) with the social wellbeing (represented by the health and education). The Spearman correlation coefficients (r_s) compared with the other emergy indices are shown in Tables S10–S13, which are available in the Supplementary Materials. The medium correlations among ESI, ESI-2002 and WI disappeared except for countries with low human development level, and while correlations with socio-economic indicators dropped or disappeared.

The lack of correlations with the R fraction for all groups confirmed the well-known criticism that HDI disregards environmental issues (Sagar and Najam, 1998; Gasparatos, 2008). It was noteworthy that, only for countries with very high human development, all correlations were positive. The inverse or non-existent correlations with EF were expected since this indicator penalizes the high resource consumption of the population associated or not with improved socio-economic indicators.

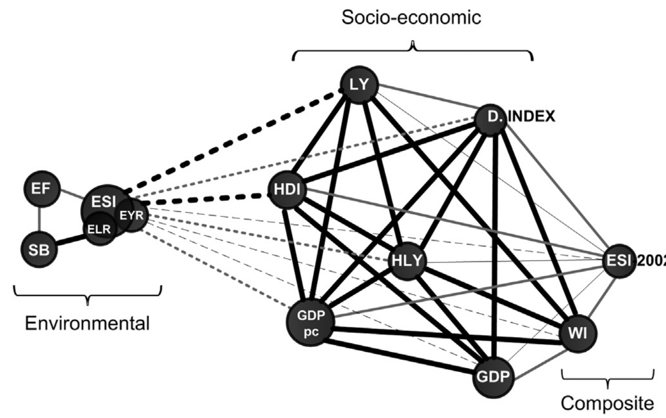

Fig. 7. The Spearman correlations among the ten indices and the emergy indices for 106 countries. Direct correlation (—) and inverse correlation (- - -). The links represent weak, medium, and strong correlations according to their thickness.

4. Comparing all ten indices

By the correlations among ten selected indices and the emergy indices it was possible to assess the capacity of each one to measure the SD of nations. It was also possible to determine which indicators would be redundant (such as ESI-2002 and WI) and which would be complementary (such as SB and GDP).

The set of emergy indicators (EYR, ELR and ESI) correlated directly or inversely with all indicators. The socioeconomic and composite indicators, in general, showed low or inverse correlations with biophysical indicators, indicating that not only the lack of concern on the biosphere limits, but also the high demand for non-renewable resources to achieve the social needs and goals (Fig. 7). It was also clear that the composite indices with a large number of variables do not represent the biophysical or the

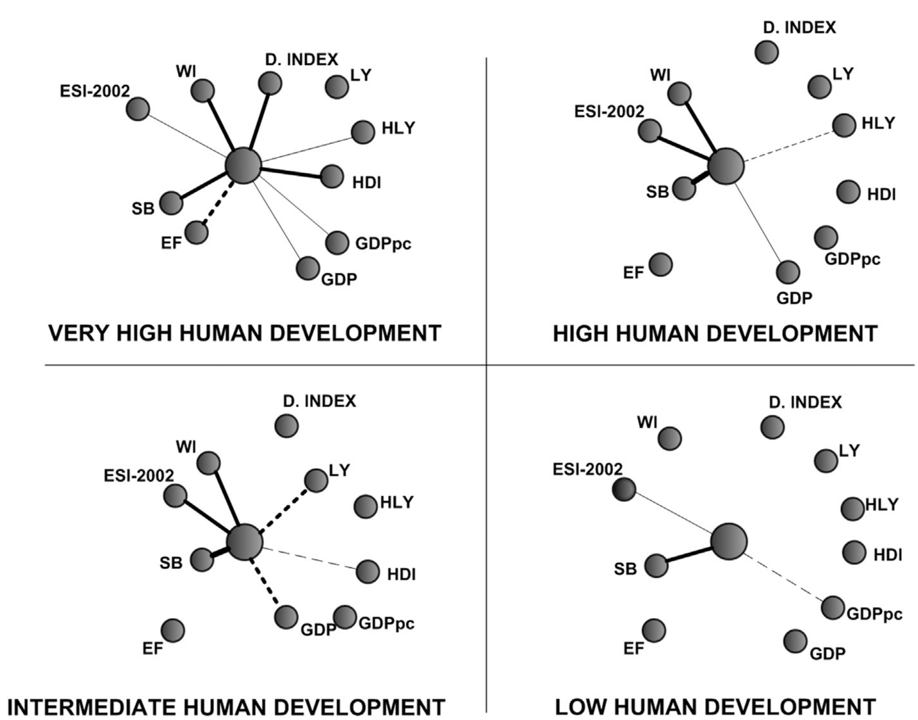

Fig. 6. The Spearman correlations among the ten indices and the ESI according to the development level. Direct correlation (—) and inverse correlation (- - -). The links represent weak, medium, and strong correlations according to their thickness.

socioeconomic goals. Use of ESI-2002 evidenced medium correlations with socio-economic indicators and weak correlations with environmentally-oriented indicators. It was found that WI, showed a high correlation with socio-economic indicators but does not correlate with biophysical indicators.

The emergy indices effectively showed correlations between environmental and socioeconomic indices by considering not only the countries' contributions to the world economy (via EYR), but also the environmental stresses caused by each nation via ELR. ESI, which combined EYR and ELR, was the index that showed lower differences among the results obtained from the total sample and for its subsets. Hence, this index should, at least for now, be used as a good proxy to measure progress towards SD with attribute that it is not heavily affected by the context of the assessment, and of integration of biospheric limits into the current anthropogenically centered frameworks. However, it must be recognized that none of these indices encompass the complete range of perspectives that need to be embraced to help to guide societies on the path to SD.

The assessment of countries with the use of biophysical indicators made it clear that all activities and demands of socio-economic dimensions require materials and energy (Fig. 8). Social and economic activities require support and maintenance, and to assess enduring development models, the index must provide information on the environmental component that provides the flows that ensure fuels, electricity, materials, food, clean air and water, and so forth.

Fig. 8 illustrates the capacity of each index to measure the SD of nations and to make clear that only biophysical indicators (Odum, 1996; Wackernagel and Rees, 1996) can provide information on the limits of the natural capital (carrying capacity) to be used to support societal economic growth and social welfare. The cycle shown on the right side of Fig. 8 is not feasible without the support of the environment, and the more one invests to satisfy the demands for improving the socio-economic conditions, the higher will be pressure on the environment. Information, health and education produced within the socio-economic sphere are totally dependent upon the capacity of the natural environment for their essential resources. Thus, every improvement in this dimension increases pressure on the environment. For example, since the energy and monetary expenses of supporting healthy population, rises as a consequence of the populations growth, additional maintenance is required when the average age of the population increases and expensive medical technology is required for supporting the older people. Economic and social growth may be achieved if there are available resources to support expanding development, but once installed; maintenance systems must provide efficient services. Evaluation of maintenance alternatives can improve management choices at the moment and in periods of low energy. The graphs in Fig. 8 show that current indices, except for the biophysical ones, consider availability of resources to be essential to development and to sustainability, but do not differentiate between the types of resources (whether renewable or not).

5. Conclusions

Human decisions determine the use of the main flows of the economy and environment. Indices for monitoring progress toward SD have been developed based upon concepts and relationships that must be learned and accepted by people as the bases for them to conduct their lives within the eco-system upon which they are totally interdependent.

The correlations among the socio-economic indices revealed that they account for the availability of non-renewable resources (such as minerals or fossil fuels), to support, progress and wealth generation. However, there was no correlation with the use of the renewable resources, which indicates a lack of concern with the availability of environmental support resources to ensure development in the long term.

The combined usage of biophysical and socioeconomic indices could improve the quality of information provided. Additional research is needed to combine the socioeconomic and biophysical information differently from that proposed by the existing indices,

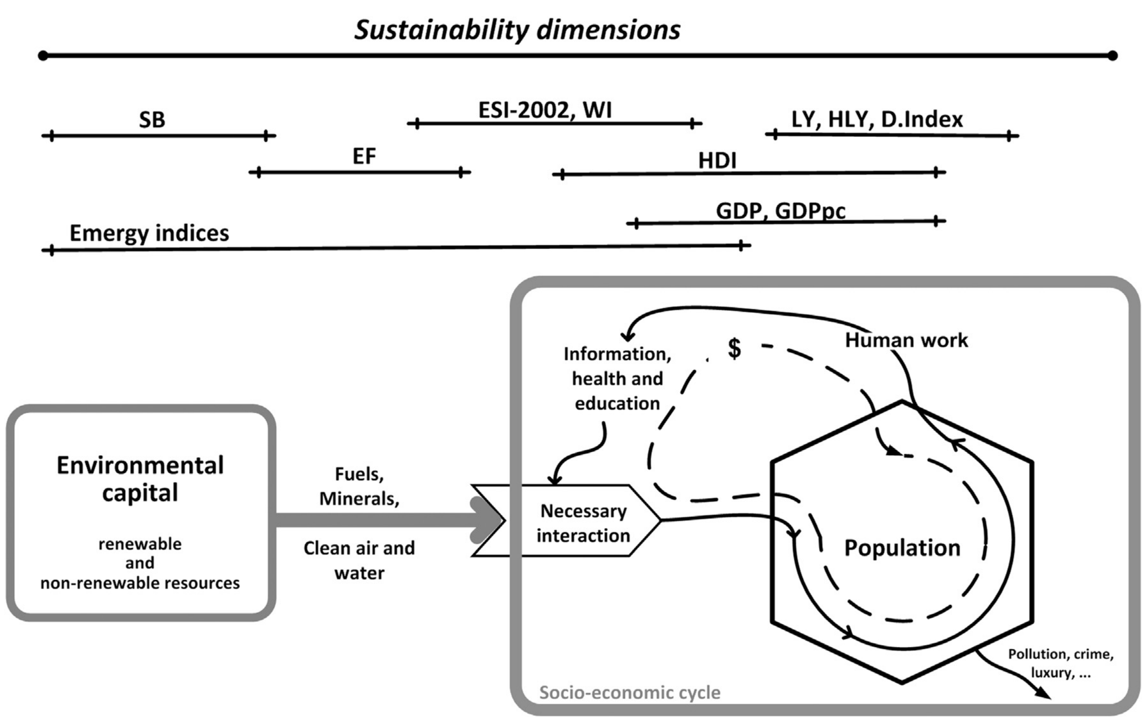

Fig. 8. Structure of human social organization that operates within the environment and economy, with a highlight on the extent of each indicator to measure SD.

considering that more environmental support is required for organizing society and that this support must be used with greater efficiency in preserving materials, energy and ecological services. This conclusion is in agreement with the findings of King et al. (2007) who proposed a new indicator derived by multiplying the HDI of the countries' by the percentage of their renewable resources as a way to combine human and environmental welfare.

Through the analyses of the correlations of the findings among the selected indices it was possible to determine which indices are redundant and which are complementary (Table 5). At this time, if one decides to use a single index, the ESI, which combines the biosphere limits with the current anthropogenic centered framework, was the index, which provided more medium and strong correlations with the socio-economic ones, and thereby could be useful to monitor societal progress towards SD. However, according to the correlations shown in Fig. 7, the combination of several socio-economic indices with the biophysical ones would provide similar results.

The indices listed in Table 5 can be used to evaluate progress based on past data, but a time series is needed to establish trends upon which future strategies, targets and timetables can be developed and implemented. This need may be responsible for the resistance to adopting new indices because in order to document their validity requires several years of measurements.

The GDP provides information on economic activities and criticisms to this indicator are well known (Giannetti et al., 2014). Social indicators can establish whether society's needs are being met. Indirectly, socio-economic indicators correlate with the amount of resources and energy being moved from the environment to the economy and are being used to meet the basic conditions required by a healthy society. Among these indicators, the HDI is reasonably satisfactory in combining economic and social aspects, with a strong inverse correlation with the biophysical indices.

The biophysical indicators provide information on how much environmental resources are being used by the socio-economic cycle. Indirectly, they correlate with the intensity of economic activities and with the actions being taken to promote wellness. Among these indicators, the ESI is reasonably satisfactory in providing information about the use of renewable resources, and in correlating with economic and social aspects.

If sustainability is recognized as the final goal of societies, none of the indices evaluated in this study were found to be capable of encompassing all of the significant aspects of economic, social and environmental well-being. Additionally, none of them provides adequate information about the efficiency of usage of the resources. Thus, a temporary solution may be to complement the information of socio-economic indices with those provided by the biophysical ones. However, these combinations of socio/economical/biophysical indices may be expanded upon and used jointly to more effectively estimate the availability of environmental resources and be used to help societies to live within planetary boundaries for the short and long-term.

The indices that have been developed and tested for this paper contribute much to the dialogue and help us to see that GDP is inadequate for monitoring sustainable societal development. In order for societies to become truly sustainable, much more work is needed to help to accelerate the transition to equitable, post-fossil carbon societies, as rapidly as possible. The authors of this paper invite your comments, suggestion and collaboration in jointly moving forward with the work started within it.

Table 5
Classification of selected indices based upon their complementarity or redundancy, according to the correlations shown in Fig. 7. The authors did not include ESI-2002 because it does not provide strong correlations with any of the other indices. Non-renewable and imported resources (F) were considered redundant with socio-economic indicators, as shown in Fig. 2.

	Redundancy	
	Socio-economic	Biophysical
Complementarity	GDP	R
	GDPpc	
	HLY	EF
	LY	SB
	D. Index	EYR
	HDI	ELR
	WI	ESI

Where: R: renewable natural resources; N: non-renewable resources; F: resources from the economy; EYR: Emergy Yield Ratio; ELR: Environmental Load Ratio; ESI: Environmental Sustainability Index; GDP: Gross Domestic Product (GDP); Gross Domestic Product (GDPpc); HDI: Human Development Index, HLY: Happy Life Years, LY: life years, EF: Ecological Footprint; SB: Biocapacity Surplus; Democracy Index (D. Index); WI: Wellbeing Index.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.11.076.

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