EMERGY SYNTHESIS 4:
Theory and Applications of the Emergy Methodology

Proceedings from the Fourth Biennial Emergy Conference,
Gainesville, Florida

Edited by
Mark T. Brown
University of Florida
Gainesville, Florida

Managing Editor
Eliana Bardi
Alachua County EPD,
Gainesville, Florida

Associate Editors
Daniel E. Campbell
US EPA
Narragansett, Rhode Island

Shu-Li Haung
National Taipei University
Taipei, Taiwan

Enrique Ortega
Centre for Sustainable Agriculture
Uppsala, Sweden

Torbjorn Rydberg
Centre for Sustainable Agriculture
Uppsala, Sweden

David Tilley
University of Maryland
College Park, Maryland

Sergio Ulgiati
University of Siena
Siena, Italy

December 2007

The Center for Environmental Policy
Department of Environmental Engineering Sciences
University of Florida
Gainesville, FL

4

Comparative Analysis of Indicators of Well-being Using Environmental Accounting

Danielle DeVincenzo King, Matthew J. Cohen, Sharlynn Sweeney, and Mark Brown

ABSTRACT

Despite the abundance of sustainable development research and literature, there is a need to substantiate and quantify the links between human well-being and the environment. The National Environmental Accounting Database (NEAD, Sweeney et al. 2007, these proceedings), which quantifies the resource basis of 134 nations (ca. 2000), was used to provide a uniform set of indicators of resource use, partitioning, trade, and environmental condition. These indices, such as percent renewable and non-renewable emergy use per capita, were compared to social, political, economic, and environmental indicators of welfare. The emergy indices were also compared to popular composite welfare and sustainability indices including the Yale Environmental Sustainability Index (YESI) and the United Nations Development Program's Human Development Index (HDI). An inverse relationship was found between human well-being and environmental well-being. In particular, a strong negative association was observed between the percent of total emergy from renewable sources and HDI, and a strong positive association was observed between non-renewable emergy use per capita and HDI. This suggests that countries with a high proportion of their resource use coming from non-renewable sources have greater human welfare. A new indicator, termed the Emergy Total Well-being Index (ETWI), is proposed that integrates human welfare and resource sustainability by minimizing the percent of resource use that comes from non-renewable resources and maximizing human well-being as measured by HDI. Countries with high ETWI include Iceland, Argentina, and Suriname. The results of this study enhance sustainability assessment by providing data on relationships between the resource basis of an economy and patterns of national welfare.

INTRODUCTION

Social equality, economic stability, environmental conservation, and global carrying capacity, which are all part of the broader concept of sustainable development (Munasinghe and McNeely 1995), have become familiar issues in contemporary society. Researchers monitor various indicators of ecological, economic, and social condition in order to compare well-being and progress towards sustainability between nations. Examples of these include international debt, Gross Domestic Product (GDP), and carbon dioxide emission rates, as well as popular aggregated indices such as Yale's Environmental Sustainability Index (YESI) and the United Nations Development Programme's Human Development Index (HDI). However, there is no single index that serves as a universally accepted measure of sustainability (Kaufmann and Cleveland 1995, Hanley 2000). Indicators such as GDP are criticized for being one dimensional and, therefore, inadequate predictors of total well-being (Steer and Lutz 1993). Likewise, many researchers are unsatisfied by popular aggregated indices. YESI is criticized for its subjective methodology and for combining too many disparate variables (The

Ecologist 2001, Morse 2004, Morse and Frasier 2005), masking more relationships than it reveals. HDI is criticized for its inclusion of GDP as a component of well-being and for not including a measure of happiness or sustainability (Van Den Berg 2002, Morse 2004; for suggested modifications see Ivanova et al. 1998, Noorbakhsh 1998, Anad and Sen 2000, Lind 2003, Morse 2003). Despite advances in sustainability and well-being research, there is a great need to quantify links between environmental sustainability, human well-being, and non-economic resource flows.

This study addresses the above issues using environmental accounting (EA), also known as emergy synthesis. Environmental contributions to economies or individuals are not adequately captured in monetary terms (Odum 1996). By expressing both economic and environmental flows in common units, EA permits meaningful comparison of resource requirements for national economic processes, and, consequently, a means to monitor and compare sustainability. Ecosystem services at the national level were evaluated using EA and synthesized into indices of sustainability and environmental contributions in the National Environmental Accounting Database (NEAD, Sweeney et al. 2007, these proceedings). To better understand indices of well-being that are commonly used by researchers and their relationship to quantitative measures of resource use, several indices of well-being were compared to each other and to these EA indices for 134 nations. Specifically, the following questions were addressed:

1. How are the emergy indices related to each other and can they be used to rank the so called sustainability of nations?
2. How are the commonly used well-being and sustainability indicators related to each other, why do they disagree, and are their criticisms valid?
3. How do emergy indices and the above mentioned well-being and sustainability indices relate, and what can an evaluation of the resource basis of a nation tell us about the welfare of the people and the environment?
4. Which countries create high welfare (as measured by the above mentioned well-being and sustainability indices) with sustainable practices (as measured by the emergy indices)?

METHODS

For this study, emergy indices previously calculated for 134 nations were reduced to their latent variables using principle components analysis (PCA - StatSoft 2004); PCA is a matrix-rotation method that consolidates information from numerous co-linear variables into a set of orthogonal composite variables (principal components). Since the original variables are co-linear, it is generally possible to use only a small set of the composite variables to capture most of the variance in the original data set; further, since the first composite variable, by definition, captures the largest fraction of the original variance and is orthogonal (uncorrelated) to all subsequent variables, the order in which the PCs are extracted is informative. PCA permits examination of the structuring relationships among the original data (PC loadings) and, most importantly, a smaller number of variables to represent the original data set. Pearson correlations (ρ) were used to compare indicators of human and environmental well-being/sustainability to each other and to the emergy indices.

Emergy Indices

National level emergy flows and aggregate indices were calculated for 134 nations for the year 2000 (see Sweeney et al. 2006 for definitions of flows, indices, and analysis methods) within the NEAD. Due to the large number of emergy indices, correlations were calculated for normalized emergy indices to eliminate redundancy. If two indices were correlated with an R of 0.8 or above (significant at .01 level, 2-tailed), the one less commonly used in interpretation or less insightful for national comparisons was dropped from the analysis. Exceptions were made for emergy indices that, although highly correlated with other indices, have individual importance in interpreting results of an emergy analysis.

In order to compare nations using a practical number of measures, dimension-reducing techniques were required. Specifically, because many national level indicators are correlated, a smaller number of composite latent variables could be extracted using a principal components analysis (PCA). This was done using emergy indices for 120 nations (out of 134) in the NEAD; 14 nations were not included in the PCA because one or more of the emergy indices could not be calculated due to missing data. Before the PCA was performed, indicators that were identical or very similar to others by definition were eliminated. For example, because Percent of Use Free and Fraction of Use Purchased are by definition complimentary, Fraction of Use Purchased was removed from the PCA.

Well-Being and Sustainability Indices

Composite indices of human, economic, and environmental sustainability, as well as many social, economic, governmental, and environmental indicators that are either common in the literature or are currently receiving much global media attention (Flanders and Ross-Larson 2002, Cheru 2002, Poku 2002, York et al. 2003) were compared to each other and emergy indices in order to test questions one through four above. The comparison of well-being and sustainability indicators was carried out on seven overall groups of indicators (Table 1), which were selected as follows.

Group 1: Aggregate indices, so termed because they are each composed of several metrics, were chosen because they have become popular in the literature for describing and comparing nations. These include the ecological footprint (EF), Yale Environmental Sustainability Index (YESI), the United Nation's Development Program's Human Development Index (HDI), Well-being Index (WI), Ecosystem Well-being Index (EWI), and Human Well-being Index (HWI). Definitions and sources for these indices can be found in Appendix A. Some indices, such as the Genuine Progress Indicator (GPI) and the Gross National Happiness (GNH), could not be analyzed because they have not been computed for many countries.

Groups 2-5: To select a manageable set of social, economic, governmental, and environmental indicators to evaluate from a population of over 1200 indicators with global data coverage, a process of eliminating obscure or redundant indicators was conducted. First, approximately 50 indicators were selected based on their frequency of citation in the literature and the degree of global media attention they are receiving (Flanders and Ross-Larson 2002, Cheru 2002, Poku 2002, York et al. 2003). Then, this first group of 50 indicators was correlated (Pearson) against

Table 1. Indicator groups.

Group #	Group Type	Description	# of Indicators
1	Aggregate indices	Indices composed of several metrics	6
2	Social well-being indicators	Quality of life and health, education, labor, demographics	20
3	Govt. & political indicators	Economic freedom, civil freedom, quality of governance, risk to finance & investment	24
4	Economic indicators	Income, use of money, military, tourism, technology, debt, aid	18
5	Environmental indicators	Land use, fertilizer use, deforestation, water quality, air quality, energy	13
6	YESI component indices		26
7	HDI component indices		3

the entire population of 1200 indicators. Any of the indicators from the population that were not correlated with the original 50 with an R of 0.8 (significant at .01 level, 2-tailed) or above were also selected.

Groups 6 and 7: Metrics within the YESI and HDI were selected for evaluation in order to clarify apparent discrepancies between sustainability indices and explore criticisms of these indices.

A complete list of indices, their definitions and sources can be found in DeVincenzo King (2006). All data were from the year 2000 when available. This final list was then organized into the thematic groups and sub-groups found in Table 1 to simplify interpretation of the analysis. To prepare them for analysis, all indices and indicators were evaluated for normality and transformed where appropriate.

In order to elucidate overlap and inconsistencies between the various indices and to provide insight regarding which countries are providing for the well-being of their population and environment, Pearson correlations between all indicators and emergy indices were conducted.

A regression analysis was performed to identify those countries whose human well-being, as measured by HDI, was higher or lower than would be predicted based on their non-renewable emergy use per capita. A new index was proposed that combined HDI and emergy percent renewable. Based on the premise that environmental sustainability can be defined as minimizing the percent of resource use that comes from non-renewable resources, and human sustainability can be defined as maximizing human well-being as measured by HDI then a new indicator of total well-being can be derived. The formula for this new indicator, the Emergy Total Well-being Index (ETWI) is

$$ETWI = HDI * \%R$$

where *HDI* is the Human Development Index, and *%R* is the percent of a nation's total emergy use that comes from renewable sources. To determine its utility as a well-being indicator, ETWI was correlated to aggregate indices.

RESULTS

This section presents results of dimensionality reduction of emergy indices, followed by correlations among aggregate indices, between the aggregate indices and emergy indices/principle components, and between other well-being indicators and emergy indices/principle components.

Emergy Principle Component Analysis

Standard emergy analysis results in over 30 indices. Data compression of the emergy indices of 120 nations using PCA yielded five principal components (Table 2), selected because they accounted for 76 percent of the variability in the dataset.

Comparative Analysis of Aggregate Indices (Group 1)

Table 3 is a correlation matrix showing the relationships between aggregate indices of environmental and/or human well-being. Notably, the Yale Environmental Sustainability Index (YESI) is significantly positively correlated with ecological footprint (EF). YESI is also strongly correlated with measures of human well-being, such as the Human Development Index (HDI) and Human Well-being Index (HWI), as well as the Well-being Index (WI), which is an average of the Ecosystem Well-being Index (EWI) and HWI. Conversely, relationships between the other indicators suggest that as measures of environmental well-being increase, measures of human well-being decrease. For example, HDI and HWI are both positively correlated with the EF and negatively correlated with the EWI.

Table 2. Emergy principle components.

Principle Component (PC)	Name	Variability Explained
PC 1	Magnitude of the Economy	39%
PC 2	Magnitude of Natural Resource Base	18%
PC 3	Per Capita Emergy Intensity	7%
PC 4	Raw Resource Export	7%
PC 5	Non-Renewable (Natural Capital) Intensity	5%

Table 3. Correlation matrix of aggregate indices.

Index	(LN) EF	YESI	HDI	WI	HWI	EWI
Natural Log LN Total Ecological Footprint (EF)	1					
Yale Environmental Sustainability Index (YESI)	0.408(**)	1				
Human Development Index (HDI)	0.855(**)	0.417(**)	1			
Well-being Index (WI)	0.630(**)	0.723(**)	0.644(**)	1		
Human Well-being Index (HWI)	0.880(**)	0.519(**)	0.931(**)	0.795(**)	1	
Ecosystem Well-being Index (EWI)	-0.600(**)	0.140	-0.645(**)	0.067	-0.552(**)	1

** Correlation is significant at 0.01 level (2-tailed). * Correlation is significant at 0.05 level (2-tailed).

Table 4 shows the strongest correlations between the aggregate indices and the emergy indices and demonstrates the following relationships:

1. As resource based measures of sustainability increase (percent renewable [R/Use] and the emergy sustainability index), environmental well-being as indicated by the EF and EWI increases and human well-being as indicated by the HDI and HWI decreases.
2. As resource use intensity increases (emergy use/area, emergy use/capita, non-renewable emergy use/capita and the emergy investment ratio), environmental well-being, as indicated by the EF and EWI, decreases and human well-being, as indicated by the HDI and HWI, increases.

However, the relationships between emergy indices and environmental well-being were not found to be true for YESI. Of all aggregate indices tested, YESI had the weakest correlations with emergy indices. This suggests that YESI may not be exclusively measuring environmental sustainability, as its name suggests.

Table 4. Correlation matrix of aggregate indices and key emergy indices.

	LN EF	YESI	HDI	WI	HWI	EWI
R/Use	-0.567(**)	0.089	-0.612(**)	-0.163	-0.530(**)	0.648(**)
LN Use/Area	0.560(**)	0.081	0.689(**)	0.426(**)	0.712(**)	-0.586(**)
LN Use/Capita	0.768(**)	0.539(**)	0.748(**)	0.676(**)	0.768(**)	-0.333(**)
LN NonRenewable /Capita	0.554(**)	0.220(*)	0.593(**)	0.331(**)	0.511(**)	-0.387(**)
LN Emergy Investment Ratio	0.555(**)	0.124	0.577(**)	0.360(**)	0.585(**)	-0.467(**)
LN Emergy Sustainability Index	-0.589(**)	0.082	-0.628(**)	-0.200(*)	-0.559(**)	0.644(**)

** Correlation is significant at 0.01 level (2-tailed). * Correlation is significant at 0.05 level (2-tailed).

Table 5 is a correlation matrix showing the relationship between aggregate indices and emergy principle components. In general, the correlations in Table 5 suggest the following relationships:

1. As magnitude of the economy (PC1) increases, environmental well-being as indicated by the EF and EWI decreases, human well-being as indicated by the HDI and HWI increases, and overall well-being as indicated by the WI increases.
2. As per capita emergy intensity (PC3) increases, environmental well-being as indicated by the EF decreases, human well-being as indicated by the HDI and HWI increases, and overall well-being as indicated by the WI increases.
3. As raw resource export (PC4) decreases, environmental well-being as indicated by the EF decreases, human well-being as indicated by the HDI and HWI increases, and total well-being as indicated by the WI increases.

Again, the relationships between emergy principle components and environmental well-being were not found to be true for YESI. To explore these discrepancies with YESI, as well as some of the criticisms of YESI and HDI found in the literature that were briefly mentioned in the introduction, the components of YESI and HDI were also analyzed (results presented later in this paper).

Table 5. Correlation matrix between aggregate indices and emergy principle components

	LN EF	YESI	HDI	WI	HWI	EWI
PC1 – Magnitude of the Economy	0.776(**)	0.118	0.832(**)	0.381(**)	0.784(**)	-0.798(**)
PC2 – Magnitude of Natural Resource Base	-0.080	0.099	-0.074	-0.105	-0.111	0.044
PC3 – Per Capita Emergy Intensity	0.331(**)	0.243(*)	0.257(**)	0.319(**)	0.242(*)	0.027
PC4 – Raw Resource Export	-0.262(**)	-0.419(**)	-0.292(**)	-0.474(**)	-0.407(**)	0.041
PC5 – Non-Renewable (Natural Capital) Intensity	0.054	0.228(*)	0.068	0.115	0.022	0.119

** Correlation is significant at 0.01 level (2-tailed). * Correlation is significant at 0.05 level (2-tailed).

(a)

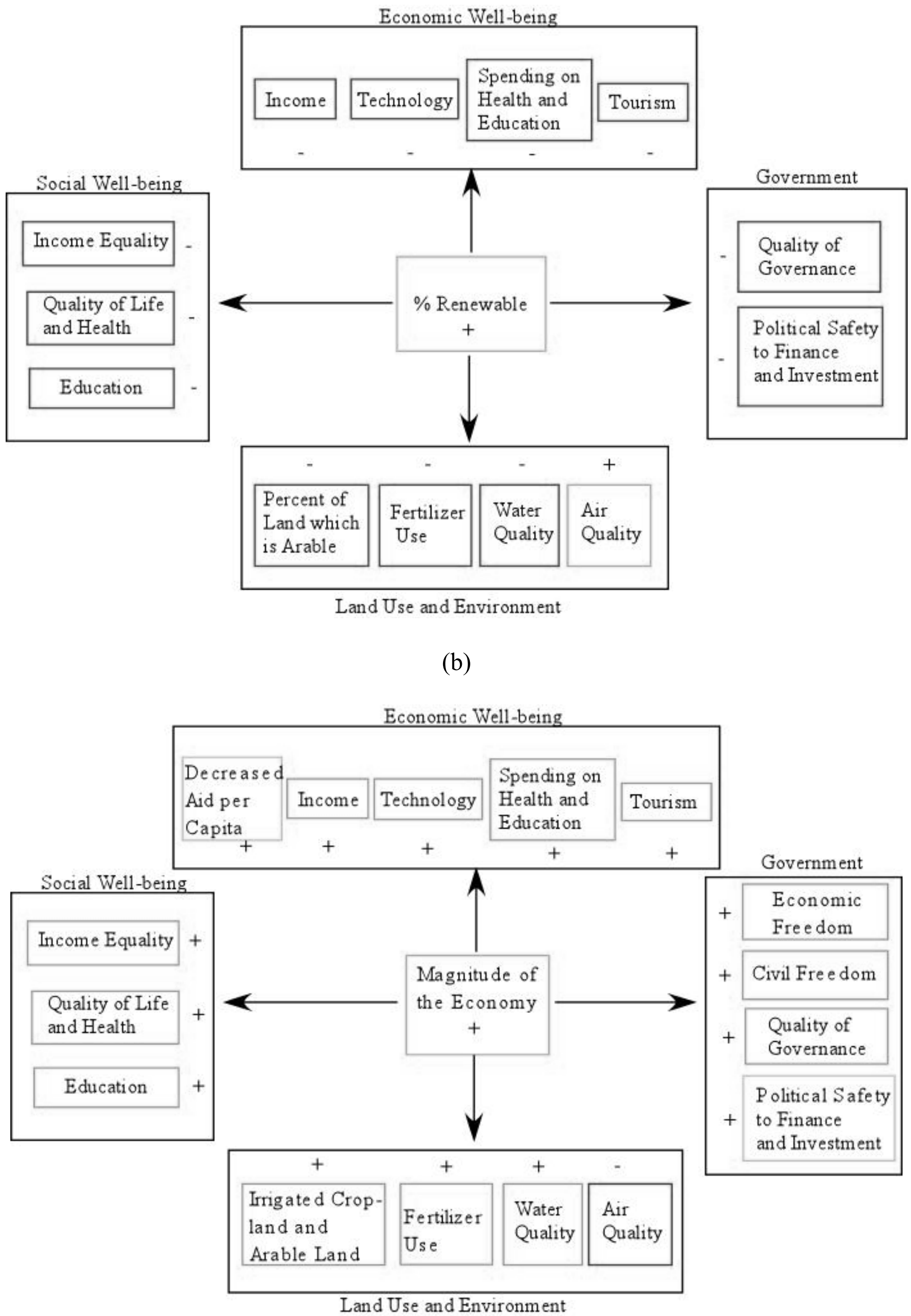


Figure 1. *Summary diagrams of the relationships between well-being and percent renewable (a) and magnitude of the economy (b).*

Comparative Analysis of Miscellaneous Well-Being Indicators (Groups 2-5)

Complete results of the individual social, political, economic, and environmental well-being indicators analyzed in this study can be found in DeVincenzo King (2006). Figure 1 summarizes the strongest relationships found between these various components of human well-being and the emergy indices. As environmental sustainability (as measured by percent renewable) increases, social well-being, economic well-being, and governmental well-being decrease. Inversely, as economic development increases (as measured by magnitude of the economy), social well-being, economic well-being, and governmental well-being increase.

Comparative Analysis of Aggregate Indices' Components (Groups 6 and 7)

Yale Environmental Sustainability Index (YESI)

Table 6, a correlation matrix of the components of YESI, shows that the Reducing Environmental Stresses (RES) component is negatively correlated with EF and positively correlated with the EWI (as would be expected of an environmental well-being indicator), whereas the Reducing Human Vulnerability (RHV) and Social and Institutional Capacity (SIC) components are strongly positively correlated HDI (see explanation of HDI in Appendix A), HWI, GDP, and the GDP Index (GDP Index is the United Nations Development Programme's adjusted GDP per capita). These two components are also negatively correlated with EWI and positively correlated with EF. This suggests that these two components, which make up 1/3 of YESI, may be better indicators of human well-being than environmental well-being.

As illustrated by Figure 2, YESI also shows no relationship to the percent of emergy from renewable resources (also called percent renewable), a resource based measure of environmental sustainability. Table 7 presents the strongest correlations between the emergy indices and YESI components. Ten of the 21 YESI indicators are uncorrelated or significantly negatively correlated with percent renewable (R/U). The difference between YESI and percent renewable is particularly interesting in Sub-Saharan African nations in Figure 2 below. While YESI defines these nations as unsustainable, by emergy measures they have relatively low non-renewable emergy use per capita and a large percent of their total emergy use comes from renewable sources.

Likewise, as is shown in Table 7, eight of the 21 indicators which make up the YESI have a strong and significant positive correlation to magnitude of the economy (PC1). Interestingly, YESI and the environmental governance indicator are significantly negatively correlated with raw resource export (PC4). These relationships and the nature of the indicators showing surprising correlations (such as reducing population pressure, human sustenance, and science and technology) suggest that the YESI may be partially measuring economic development, as well as environmental conditions. Also, YESI is significantly positively correlated to total emergy use per capita (R = 0.54) and fuel use per capita (R = .23). This again is the opposite of what one would expect of an environmental sustainability indicator.

Human Development Index (HDI)

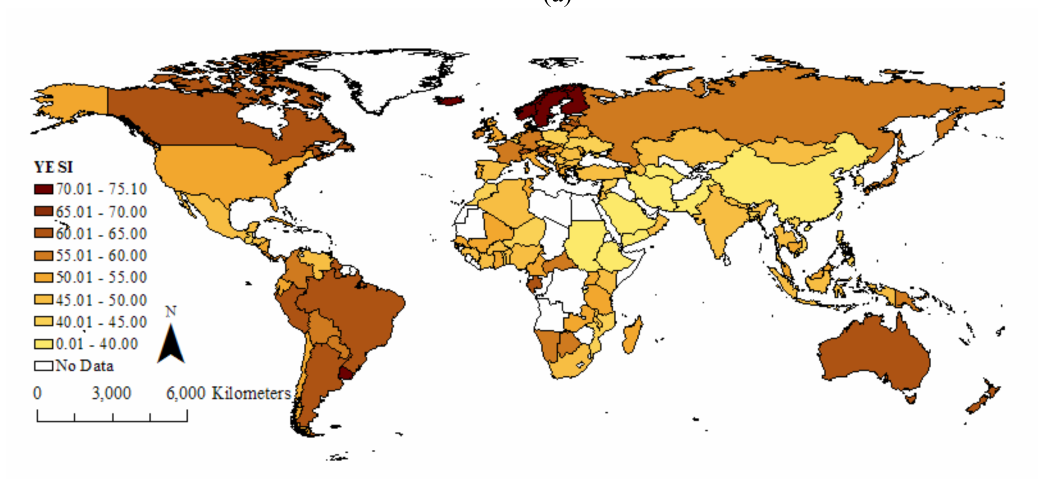
Results show that the Human Development Index (HDI) is significantly positively correlated with non-renewable emergy use per capita (R = 0.59) and total emergy use per capita (R = .75), as well as PC1 – Magnitude of the Economy. Figure 3 is a graph of the residuals from the regression analysis predicting HDI from non-renewable emergy use per capita. Countries with high positive residuals, including France, Lebanon, Moldova, Paraguay, and Switzerland, have better human welfare (as measured by the HDI) than would be predicted based on their non-renewable resource use per capita. Countries with high negative residuals, including Burkina Faso, Mozambique, Niger, Senegal and Uganda, have lower human welfare than would be predicted based on their non-renewable resource use per capita. This may suggest an efficiency of resource use index that can be used as a measure of a human dimension

Table 6. Correlation matrix of aggregate indices including YESI components.

	YESI	ES Component	RES Component	RHV Component	SIC Component	GS Component
Yale Environmental Sustainability Index (YESI)	1					
ESI - Environmental Systems (ES) Component	0.691(**)	1				
ESI - Reducing Environmental Stresses (RES) Component	0.156	0.353(**)	1			
ESI - Reducing Human Vulnerability (RHV) Component	0.482(**)	0.076	-0.312(**)	1		
ESI - Social and Institutional Capacity (SIC) Component	0.652(**)	0.134	-0.510(**)	0.622(**)	1	
ESI - Global Stewardship (GS) Component	0.282(**)	-0.045	-0.021	-0.356(**)	0.160	1
Natural Log Total Ecological Footprint	0.408(**)	0.164	-0.448(**)	0.811(**)	0.657(**)	-0.397(**)
HDI	0.417(**)	0.101	-0.412(**)	0.839(**)	0.684(**)	-0.371(**)
Well-being Index	0.723(**)	0.387(**)	-0.222(*)	0.617(**)	0.738(**)	0.044
Human Well-being Index	0.519(**)	0.103	-0.477(**)	0.836(**)	0.821(**)	-0.208(*)
Ecosystem Well-being Index	0.140	0.367(**)	0.484(**)	-0.535(**)	-0.341(**)	0.408(**)
Natural Log GDP	0.132	-0.213(*)	-0.532(**)	0.545(**)	0.605(**)	-0.182(*)
GDP Index	0.445(**)	0.120	-0.496(**)	0.850(**)	0.747(**)	-0.323(**)

** Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).

(a)



(b)

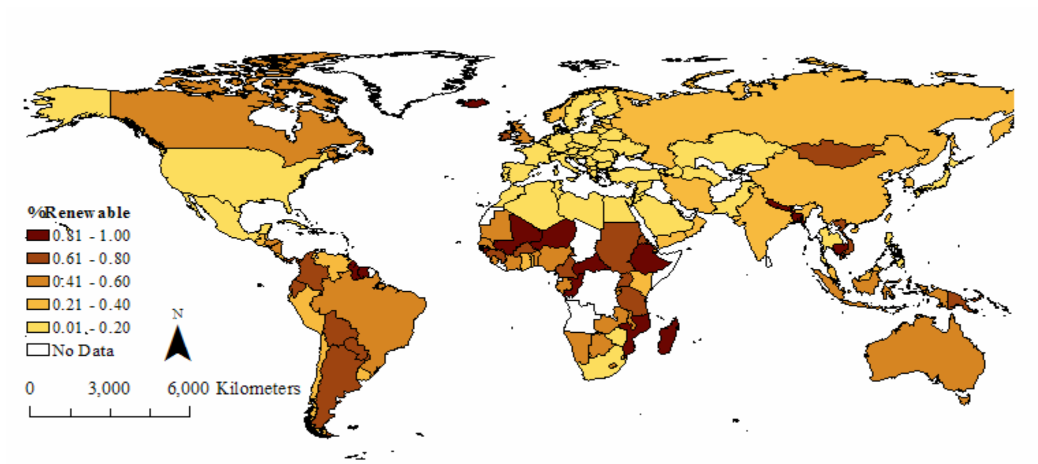


Figure 2. *Maps of sustainability indices (a) Map of the Yale Environmental Sustainability Index. Data from Esty et al. 2005 (b) Map of emergy percent renewable.*

of sustainability. HDI has been criticized as a human well-being indicator because it is partially composed of GDP per capita (Steer and Lutz 1993). However, relationships were also observed between individual components of the HDI (Table 8). This suggests that despite inclusion of GDP per capita, HDI adequately captures human well-being as measured by its other two components (life expectancy and education).

Emergy Total Well-being Index (ETWI)

Based on the above analysis of HDI, the Emergy Total Well-being Index (ETWI), the product of HDI and emergy percent renewable, may capture total well-being. Figure 4 is a map of the new ETWI, with national rankings found in Table 9. Both HDI and the percent of emergy use from renewable resources are on 0-1 scales, so their product has a maximum of 1 and a minimum of 0. Countries with a high ETWI have both high HDI (human welfare) and high percent of emergy use from renewable resources (environmental sustainability).

Table 10 shows the correlations between ETWI and the aggregate indices. Interestingly, ETWI is not correlated with WI, which should also be a measure of total well-being. Also, while ETWI is positively correlated with measures of environmental well-being, it is negatively correlated with measures of human well-being such as HDI and HWI.

Table 7. Correlations of YESI components.

	R/Use	PC1 - Magnitude of Economy	PC4 – Raw Resource Export
Environmental Sustainability Index (ESI)	0.089	0.118	-0.419(**)
ESI - Environmental Systems (ES) Component	0.386(**)	-0.260(**)	-0.189
ES - Air Quality Indicator	-0.454(**)	0.394(**)	-0.147
ES - Biodiversity Indicator	0.285(**)	-0.430(**)	0.162
ES - Land Indicator	0.529(**)	-0.483(**)	0.194(*)
ES - Water Quality Indicator	0.110	0.129	-0.429(**)
ES - Water Quantity Indicator	0.479(**)	-0.267(**)	-0.270(**)
ESI - Reducing Environmental Stresses (RES) Component	0.351(**)	-0.566(**)	0.159
RES - Reducing Air Pollution Indicator	0.578(**)	-0.783(**)	0.255(**)
RES - Reducing Ecosystem Stress Indicator	0.043	-0.089	0.113
RES - Reducing Population Pressure Indicator	-0.599(**)	0.740(**)	-0.342(**)
RES - Reducing Waste and Consumption Pressures Indicator	0.195(*)	-0.363(**)	0.257(**)
RES - Reducing Water Stress Indicator	0.610(**)	-0.731(**)	0.092
RES - Natural Resource Management Indicator	0.260(**)	-0.462(**)	0.241(*)
ESI - Reducing Human Vulnerability (RHV) Component	-0.626(**)	0.752(**)	-0.219(*)
RHV - Environmental Health Indicator	-0.501(**)	0.770(**)	-0.377(**)
RHV - Basic Human Sustinence Indicator	-0.637(**)	0.796(**)	-0.123
RHV - Reducing Env-Related Nat. Disaster Vulnerability Ind.	-0.289(**)	0.156	0.039
ESI - Social and Institutional Capacity (SIC) Component	-0.270(**)	0.615(**)	-0.496(**)
SIC - Environmental Governance Indicator	-0.317(**)	0.582(**)	-0.513(**)
SIC - Eco-Efficiency Indicator	0.532(**)	-0.490(**)	-0.171
SIC - Private Sector Responsiveness Indicator	-0.381(**)	0.677(**)	-0.304(**)
SIC - Science and Technology Indicator	-0.524(**)	0.790(**)	-0.381(**)
ESI - Global Stewardship (GS) Component	0.405(**)	-0.386(**)	-0.209(*)
GS - Participation in International Collaborative Efforts Indicator	-0.072	0.400(**)	-0.336(**)
GS - Greenhouse Gas Emissions Indicator	0.629(**)	-0.629(**)	-0.132
GS - Reducing Transboundary Environmental Pressures Indicator	0 .233(*)	-0.414(**)	-0.043

Highlighted correlations are those discussed in the text.

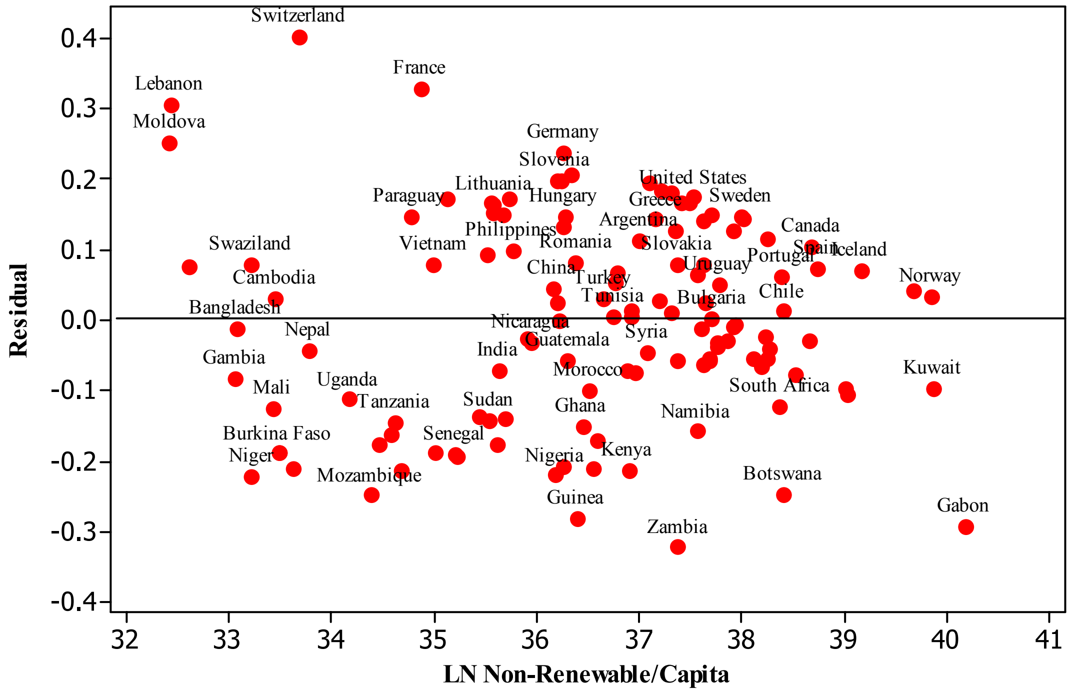


Figure 3. *Graph of regression residuals of prediction of HDI from LN non-renewable emergy use per capita*

Table 8. Correlation matrix of HDI components and emergy indices. **

	HDI	Life Expectancy Index	Education Index	GDP Index	LN Use/ Capita	LN Non-Renewable/ Capita	PC1 - Magnitude of the Economy
HDI	1						
Life Expectancy Index	0.927	1					
Education Index	0.926	0.774	1				
GDP Index	0.935	0.813	0.802	1			
LN Use/Capita	0.748	0.605	0.695	0.789	1		
LN Non-Renewable/Capita	0.593	0.510	0.554	0.594	0.711	1	
PC1 – Magnitude of Economy	0.832	0.774	0.729	0.837	0.513	0.563	1

** All correlations were significant at the 0.01 level (2-tailed).
versus LN non-renewable emergy use per capita.

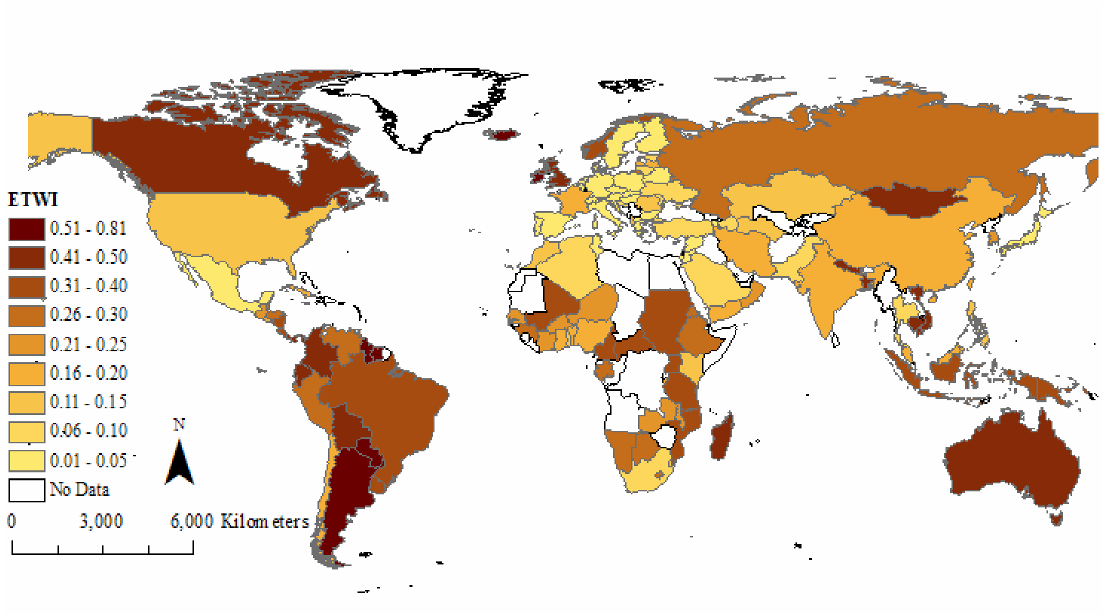


Figure 4. *Map of the Emergy Total Well-being Index (HDI * percent of emergy use from renewable resources).*

DISCUSSION

By providing data on relationships between the resource basis of an economy and patterns of national welfare, this study contributes to sustainability assessment. The correlations between aggregate indices in Table 3 and Table 4 suggest that human well-being and environmental well-being have an inverse relationship. Relationships between miscellaneous well-being indicators (groups 2-5) and emergy indices reinforce this finding. The only well-being indicator that increases with environmental sustainability and decreases with economic development is air quality (see Figure 1). However, the only air quality indicator included in this study was carbon dioxide emissions per capita. From a resource use perspective (Table 5), nations that maximize the magnitude of their economy and their per capita emergy intensity have higher human well-being and lower environmental well-being. Those nations with high raw resource export appear to have low human well-being and environmental well-being.

If one accepts the premise that HDI accurately reflects human well-being, the regression graph in Figure 3 and the proposed Emergy Total Well-being Index (ETWI) provide a measure of the efficiency of resource use. Nations who have a high ETWI score (which include Iceland, Argentina, Suriname, Guyana, and Ireland) are generating human welfare on a more renewable resource basis.

Interestingly, ETWI is not correlated with the Well-being Index (WI), although both combine human well-being and environmental well-being, and therefore should be measures of total well-being. This is especially surprising since the individual components of WI appear to be adequate measures of human and environmental well-being, respectively (see Table 3 and Table 4). The Human Well-being Index (HWI) is significantly positively correlated with HDI and the Ecosystem Well-being Index (EWI) is significantly negatively correlated with the Ecological Footprint (EF). One reason for this discrepancy between the ETWI and the WI is that the WI is an average of human and environmental well-being, whereas the ETWI is a product of the two, making it more sensitive to extreme values. This may make ETWI more useful than WI for identifying nations with high total well-being, as nations must score high in both components to receive a high total score, whereas an average may mask a deficiency in one category.

Table 9. National rankings and values for Emergy Total Well-being Index (ETWI).

Rank	Nation	ETWI	Rank	Nation	ETWI	Rank	Nation	ETWI
1	Iceland	0.805	43	Belize	0.265	85	Azerbaijan	0.076
2	Argentina	0.673	44	Gabon	0.257	86	Croatia	0.076
3	Suriname	0.633	45	Peru	0.256	87	Moldova	0.075
4	Guyana	0.615	46	Botswana	0.253	88	Turkey	0.073
5	Ireland	0.585	47	Guinea	0.250	89	Saudi Arabia	0.067
6	New Zealand	0.584	48	Guatemala	0.243	90	Lithuania	0.062
7	Paraguay	0.541	49	Senegal	0.240	91	South Africa	0.055
8	Colombia	0.478	50	Oman	0.235	92	Ukraine	0.054
9	Panama	0.478	51	Niger	0.233	93	Slovenia	0.050
10	Canada	0.477	52	Burkina Faso	0.232	94	Belarus	0.050
11	Vietnam	0.469	53	Zambia	0.226	95	Bulgaria	0.047
12	Australia	0.461	54	Malawi	0.221	96	Sweden	0.047
13	Ecuador	0.444	55	Cote dIvoire	0.217	97	Syria	0.042
14	Cambodia	0.439	56	S. Korea	0.208	98	Denmark	0.041
15	Mongolia	0.436	57	Benin	0.195	99	Netherlands	0.039
16	Nepal	0.428	58	China	0.191	100	Finland	0.038
17	Bolivia	0.412	59	Malaysia	0.190	101	Portugal	0.037
18	Bangladesh	0.407	60	Nigeria	0.189	102	Mexico	0.035
19	Madagascar	0.407	61	Yemen	0.175	103	Macedonia	0.035
20	UK	0.406	62	Ghana	0.170	104	Lebanon	0.031
21	Indonesia	0.396	63	Chile	0.168	105	Austria	0.029
22	Sudan	0.391	64	India	0.165	106	Greece	0.029
23	Cameroon	0.388	65	Albania	0.165	107	Switzerland	0.028
24	Brazil	0.383	66	Latvia	0.164	108	Tunisia	0.028
25	PNG	0.382	67	Burundi	0.160	109	Japan	0.026
26	Nicaragua	0.375	68	Iran	0.157	110	Trinidad	0.025
27	CAR	0.362	69	El Salvador	0.155	111	Poland	0.022
28	Tanzania	0.352	70	Cuba	0.151	112	Spain	0.022
29	Mali	0.325	71	France	0.150	113	Jamaica	0.022
30	Uruguay	0.320	72	Philippines	0.142	114	Slovakia	0.021
31	Norway	0.309	73	Kenya	0.135	115	Armenia	0.019
32	Costa Rica	0.308	74	Kazakhstan	0.123	116	Hungary	0.017
33	Gambia	0.308	75	Swaziland	0.122	117	Italy	0.015
34	Uganda	0.304	76	Morocco	0.116	118	Cyprus	0.015
35	Mozambique	0.302	77	United States	0.114	119	Czech Rep.	0.011
36	Eritrea	0.298	78	Togo	0.110	120	Kuwait	0.010
37	Venezuela	0.294	79	Romania	0.107	121	Germany	0.009
38	Lesotho	0.292	80	Turkmenistan	0.107	122	Jordan	0.009
39	Honduras	0.290	81	Algeria	0.085	123	Israel	0.003
40	Ethiopia	0.286	82	Pakistan	0.085	124	Belgium	0.003
41	Namibia	0.285	83	Estonia	0.083			
42	Russian Fed.	0.274	84	Thailand	0.080			

Table 10. Correlations between ETWI and aggregate indices.

Metric	ETWI
EF	-0.305(**)
ESI	0.304(**)
HDI	-0.217(*)
WI	0.086
HWI	-0.203(*)
EWI	0.451(**)

** Correlation is significant at the 0.01 level (2-tailed).* Correlation is significant at the 0.05 level (2-tailed).

REFERENCES

Anad, S., and A. Sen, 2000. The Income Component of the Human Development Index. Journal of Human Development, 1(1): 83-106.

Cheru, F., 2002. Debt, Adjustment and the Politics of Effective Response to HIV/AIDS in Africa. Third World Quarterly, 23(2): 299-312.

DeVincenzo King, D. M. 2006. Emergy Accounting of the Resource Basis of Nations, Human Well-being and International Debt. University of Florida Masters Thesis.

Esty, D.C., M. Levy, T. Srebotnjak, and A. de Sherbinin. 2005. *2005 Environmental Sustainability Index: Benchmarking National Environmental Stewardship.* Yale Center for Environmental Law and Policy, New Haven, CT. Available online at www.yale.edu/esi Accessed April 20, 2005.

Flanders, S., and B. Ross-Larson, eds., 2002. *The Human Development Report 2002.* Oxford University Press, Inc., New York, NY.

Hanley, N., 2000. Macroeconomic Measures of 'Sustainability'. Journal of Economic Surveys, 14(1): 1-30.

Ivanova, I., F.J. Arcelus, and G. Srinivasan, 1999. An Assessment of the Measurement Properties of the Human Development Index. Social Indicators Research, 46: 157-179.

Kaufmann, R.K. and C.J. Cleveland, 1995. Measuring Sustainability: Needed – An Interdisciplinary Approach to an Interdisciplinary Concept. Ecological Economics, 15: 109-112.

Lind, N., 2004. Values Reflected in the Human Development Index. Social Indicators Research, 66: 283-293.

Loh, J., and M. Wackernagel, 2004. Living Planet Report 2004. World Wide Fund for Nature, Gland, CH. Available online at www.panda.org Accessed April 20, 2005.

Morse, S., 2003. For Better or for Worse, Till the Human Development Index Do Us Part? Ecological Economics, 45: 281-296.

Morse, S., 2004. *Indices and Indicators in Development: An Unhealthy Obsession with Numbers.* Earthscan Publications, Sterling, VA.

Morse, Stephen, and Evan D.G. Frasier, 2005. Making 'Dirty' Nations Look Clean? The Nation State and the Problem of Selecting and Weighting Indices as Tools for Measuring Progress towards Sustainability. Geoforum, Vol. 36: 625-640.

Munasinghe, Mohan, and Jeffrey McNeely, 1995. Key Concepts and Terminology of Sustainable Development. In: Munasinghe, M. and W. Shearer, (Eds.). *Defining and Measuring Sustainability: The Biogeophysical Foundations.* The World Bank, Washington, D.C.

Noorbakhsh, F., 1998. A Modified Human Development Index. World Development, 26(3): 517-528.

Odum, H.T., 1996. *Environmental Accounting. Emergy and Environmental Decision Making.* John Wiley & Sons, NY.

Poku, N., 2002. Poverty, Debt and Africa's HIV/AIDS Crisis. International Affairs, 78(3): 531-536.

Prescott-Allen, R., 2001. *The Well-being of Nations: A Country-by-Country Index of Quality of Life and the Environment*. Island Press, Washington, DC.

StatSoft, Inc. 2004. STATISTICA (data analysis software system), version 6. www.statsoft.com.

Steer, A., and E. Lutz, 1993. Measuring Environmentally Sustainable Development. Finance & Development, 30(4): 20-23.

Sweeney, S., M.J. Cohen, D.M.D. King, and M.T. Brown. *In Press*. Creation of a Global Emergy Database for Standardized National Emergy Synthesis. Proceedings of the 4th Biennial Emergy Research Conference. Gainesville, FL

The Ecologist (Eds.), 2001. Keeping Score. The Ecologist, 31(3): 44-47.

Van Den Berg, H., 2002. Does Annual Real Gross Domestic Product per Capita Overstate or Understate the Growth of Individual Welfare over the Past Two Centuries? The Independent Review, 7(2): 181-196.

York, R., E.A. Rosa, and T. Dietz, 2003. STIRPAT, IPAT and ImPACT: Analytic Tools for Unpacking the Driving Forces of Environmental Impacts. Ecological Economics, 46: 351-365.

APPENDIX A

Ecological Footprint

The Ecological Footprint (EF) is a national index of natural resource consumption reported in the number of global hectares (a hectare with the average biological productivity for a hectare on Earth) it would take to support one person from that nation. The Total EF includes the amount of built up land, the amount of water withdrawn, and the area required to provide and absorb the waste from food, timber and energy consumption. For example, the EF for a country includes the biocapacity needed to sequester the carbon produced by that country from the burning of fossil fuels. The EF does not include waste flows for which there is no limit considered sustainable (e.g., heavy metals, plutonium, CFCs, dioxins) or for which there is currently no reliable data on the wastes impact (e.g. acid rain). A higher EF corresponds to a higher consumption of resources per person (Loh and Wackernagel 2004). This index and its component indicators were calculated using data from the year 2001.

Ecosystem Well-being Index

See description of the Well-being Index.

Human Development Index

The Human Development Index (HDI) is a measure of a country's average achievement in human development based upon a long and healthy life (life expectancy at birth), knowledge (adult literacy rate and gross enrolment ratio) and standard of living (Gross Domestic Product per capita). Each indicator's range is transformed to a scale from zero to one, with zero being the minimum value and one being the maximum value for each indicator for a specific year. Countries are given a score in each of the three categories (Life Expectancy Index, Education Index and GDP Index). These scores are then averaged to determine the HDI. The higher a country's HDI, the higher its level of human development. Countries are also ranked and classified by their HDI as countries of "high" (reclassified as 3), "medium" (reclassified as 2) or "low" (reclassified as 1) human development (Flanders and Ross-Larson 2002). This index and its component indicators were calculated using data from the year 2000.

Human Well-being Index

See description of the Well-being Index.

Well-being Index

The Well-being Index (WI) is similar to ESI. It is based on the concept that ecosystem well-being and human well-being should be measured separately, then equally weighted and considered together. Countries are given performance scores from zero to 100 for both aspects of well-being. These performance scores are separately called the Human Well-being Index (HWI) and Ecosystem Well-being Index (EWI). HWI is a composite of indicators in the five categories of health and population; wealth; knowledge; and culture, community, and equity. EWI is composed of indicators in the five categories of land, water, air, species and genes, and resource use. HWI and EWI are then averaged to determine a country's WI. A high WI corresponds to a high total well-being (Prescott-Allen 2001). These indices were calculated using data from the most recent year available.

Yale Environmental Sustainability Index

The Yale Environmental Sustainability Index (YESI) is a measure of a country's environmental health and history, resource use, and institutional mechanisms to change society's environmental and resource use trajectory. The index is based on five components (state of environmental systems, stress on those systems, human vulnerability to environmental change, social and institutional capacity to cope with stresses, and contribution to global stewardship) derived from 21 indicators considered fundamental to sustainability (e.g., water quality, reducing air pollution, basic human sustenance, science and technology). Seventy-six variables are transformed to comparable scales, then aggregated and used to score countries in these 21 indicator categories. The 21 indicators are weighted equally and then averaged to determine a country's ESI. The ESI score is meant to quantify a country's ability to avoid environmental deterioration. The higher a country's ESI score, the more likely it is to maintain environmental health and resources in the future (Esty et al. 2005). This index and its component indicators were calculated using data from the most recent year available.