An Empirical Environmental Sustainability Index Derived Solely from Nighttime Satellite Imagery and Ecosystem Service Valuation

Paul C. Sutton
University of Denver

This paper describes a crude yet simple Environmental Sustainability Index (ESI) derived solely from the ratio of two classified satellite images with global coverage. An ESI is calculated for each nation of the world by dividing the amount of light energy emitted by that nation as measured by a nighttime satellite image into the total value of that nation's ecosystem services as measured by a land-cover dataset and ecosystem service values estimated by Costanza et. al. (Costanza, d'Arge et al., 1997). The strength of this ESI is its simplicity and global coverage (other ESIs involve hundreds of variables which usually entail many 'data gaps'). The utility of this ESI is not as '*the*' measure of environmental sustainability but as '*a*' measure that can be compared to other ESIs in interesting and informative ways. Measuring environmental sustainability is a difficult challenge that is being undertaken by more and more people and institutions using a wide variety of methods. If independent measures of sustainability do not correspond reasonably well with one another then the practical utility of deriving ESIs will be undermined because the exercise will be perceived as more political than scientific. Two sophisticated ESIs are examined and compared to this simple one: 1) The *2001 Environmental Sustainability Index* derived as an initiative of the Global Leaders of Tomorrow Environment Task Force, World Economic Forum, and 2) *Ecological Footprints of Nations: How much Nature do they use? How much Nature do they have?* developed by Mathis Wackernagel and others as a "Rio + 5" forum study and financed by The Earth Council in Costa Rica. These two indices are a composite of many sub-indices some of which correlate highly; however, the final nationally aggregated figures of the 2001 Environmental Sustainability Index and the comparable Ecological Footprint index do not correlate at all. The Eco-Value/Night Light index described here corresponds strongly with the Ecological Footprint Index and not at all with the Environmental

Please address correspondence to Paul C. Sutton, Department of Geography, University of Denver, Denver, CO 80208; e-mail: psutton@du.edu.

Sustainability Index. Some of the implications of the lack of coherence between these three measures are discussed.

KEY WORDS: sustainability; nighttime imagery; ecosystem services.

INTRODUCTION

The increasing presence of humanity on the earth is presenting itself with ever-increasing ethical, economic, social, ecologic, and environmental challenges. Only recently have we come to question the many faceted implications of our dominant presence on this finite earth. Ideas of "Sustainability" and related terms such as "sustainable development" have only come into common usage in the last two decades. Gro Harlem Bruntland deserves much credit for defining the brilliantly ambiguous concept of "Sustainable Development" ("*Development that meets the needs of the present generation without compromising the ability of the future generations to meet their own needs*"). This simple definition/sentence implicitly contains ideas of economic efficiency, carrying capacity, environmental preservation, and equity. The statement is brilliantly ambiguous in the sense that it is both difficult to disagree with while at the same time imposes many *implicit* constraints as to how development should take place. Consequently, subsequent general agreement with the concept of sustainabile development has spawned research industries, international debates, and considerable attention as to what it really means and how is it measured.

Contradictions and markedly different interpretations of sustainable development often arise because it contains ideas of environmental sustainability, economic efficiency, and human equity (Costanza & Folke, 1997). As a general result environmentalists give greatest importance to sustainability, economists to efficiency, and churches and other human rights groups to equity. It can be argued that environmental sustainability should supercede the efficiency and equity elements of sustainable development because degrading the environment is inequitable to future generations and inefficient. In any case, the ESI's discussed here are all similar in that they attempt to focus on assessing *environmental* sustainability as opposed to the more complex concept of sustainable development. Development of ESIs are a response to a major research question of ecological economics: '*How can we create better systems of national, regional, and global accounting to include natural resource depletion and ecological impacts?*' (Costanza et al., 1991).

Once environmental sustainability is accepted as a collective human objective, it becomes necessary to balance human impacts with the earth's ability to absorb the impact; and human needs for food, water, energy, etc. with the earth's ability to provide food, energy, water etc. Understanding this 'balancing act' is an ongoing research question that is intrinsically involved with the concept of carrying capacity. Identifying, defining and measuring human impacts and the earth's ability to absorb them should (if it isn't already) be a high priority research agenda for the coming decade. An outline for this research agenda has been suggested by Daily and Ehrlich in a paper titled: "Population, Sustainability, and Earth's Carrying Capacity: a framework for estimating population sizes and lifestyles that could be sustained without undermining future generations" (Daily & Ehrlich, 1992).

The Daily and Ehrlich paper provides a conceptual framework for making estimations of regional or disaggregate carrying capacity. The proposed framework breaks the concept of carrying capacity up into at least three distinct entities: 1) Maximum Sustainable Use (MSU), a measurement of the 'interest' on the earth's natural capital (this is essentially an estimate of the food, water, timber, energy, etc. resources that can be harvested on a sustainable basis), 2) Maximum Sustainable Abuse (MSA) of the earth's ecosystems (this is a measure of the ability the various regions and ecosystems of the earth to absorb the impact of human activity), and 3) human environmental impact (this is essentially an I = P*A*T assessment of the impact of human activities (Holdren & Ehrlich, 1974)). It could be argued that human impact should be broken down on the same basis (e.g. Impact (use), and Impact (abuse)). This distinction will be tabled for future research. In many respects the Ecological Footprint calculations of Wackernagel are an attempt to follow up on the suggestions of Daily and Ehrlich.

The Daily and Ehrlich paper also describes some of the difficulties that arise from fundamental differences between renewable and non-renewable resources. They prescribe that renewable resources should not be harvested at rates in excess of their production. Non-renewable resources represent a different challenge. The solution proposed by Daily and Ehrlich is that non-renewable resources should not be used at rates in excess of the rate of the production of substitute resources (e.g., fossil fuels being replaced by solar energy, hydrogen, and hybrid fuel cells). In addition they warn of the difficulties that interactions between MSU and MSA measurements often entail. The lag time between some human activities and their recognition as an environmentally degrading impact (e.g., CFCs and the ozone hole ~50 years, increased CO_2 emissions and global warming ~100 years) is also noted as a complicating factor. Daily and Ehrlich's comments on the social dimensions of carrying capacity focused on the practice of the discounting of environmental values over space and time and problems associated with vast gaps between the rich and the poor nations of the world with respect to how they manage the global commons. The paper admits that it is only a research agenda and:

> We wish to reemphasize that our analyses are necessarily preliminary, intended to provide a framework for subsequent more-detailed and quantitative studies. In particular, central determinants of social carrying capacity lie in the domain of interactions among resources, among sociopolitical and economic factors, and between biophysical and social constraints. However, the complexity of these interactions makes it unlikely that they will be sufficiently well evaluated in the next several decades to allow firm calculations of any carrying capacity. (Daily & Ehrlich, 1992, p. 769)

Despite our inability to make *absolute* measurements of regional carrying capacities in the near future, Daily and Ehrlich assert that making *relative* measures *now* is not only feasible but has the potential to provide important insights with substantial policy implications:

> Global assessments of MSUs and MSAs of critical resources such as forests and the atmosphere should be undertaken immediately, in the tradition already established for greenhouse gases. Such assessments would provide measures of **relative** (my emphasis) contributions of nations to the preservation or destruction of the global commons. They could thus form the basis for international treaties and possible control schemes, such as the issuing of tradable permits for consumption of fractions of global MSUs and MSAs. (Daily & Ehrlich, 1992, p. 769)

This suggestion of measuring relative carrying capacity on a regional basis can be implemented now. The following is a series of suggestions by which these measures can be made.

Global datasets of unprecedented spatial resolution and accuracy are being produced that represent landcover, precipitation, length of growing season, soil, temperature, climate, and more. Producing regionally disaggregated relative measures of 'Maximum Sustainable Use' is a relatively simple task for modern geographic information systems assuming the formulas for measuring them exist and the data is of sufficient quality at appropriate spatial and temporal scales. Admittedly, there is great potential for debate as to the specific formulas for generating such numbers; however, an analysis of sensitivity to formulas may show that the relative numbers do not vary by much. Work by Daily and Costanza (Costanza et al., 1997; Daily, 1997) and others provide preliminary measures of 'Maximum Sustainable Abuse,' particularly with respect to their relative economic value. The results of these efforts could be incorporated into the tradable permit schemes mentioned in the Daily and Ehrlich paper. Spatial separation of production and consumption and other measurement problems makes measurement of regionally disaggregated human impact a bit more problematic.

In the Daily and Ehrlich paper the I = P*A*T formula (Holdren, 1991) was proposed as a measure of human impact. This formula is problematic for several reasons. The role of technology is difficult to parameterize in such an equation. Do technological developments such as improved solar energy panels and hybrid gas-electric powered cars increase the value of 'T' in the equation? Daily and Ehrlich use per capita energy consumption as a surrogate measure of the product of affluence times technology (A*T). One formulation for I = P*A*T could be P = Population, A = GDP/Capita, and T = Total national CO_2 emissions/Total National GDP. Interestingly enough, the arithmetic on this formulation works out to simply be Impact = Total National CO_2 emissions. The measure of impact used in this paper: Nationally integrated measures of a radiance calibrated image of the earth at night does correlate strongly with both national CO_2 emissions and the Ehrlich and Daily idea of Impact = Population * Energy Consumption/Capita (Elvidge et al., 1997). Both crude measures of the complex concept of "Impact," but not necessarily bad ones.

Courtland Smith argues that improved energy efficiency leads to questions about technology as a direct multiplier of population and affluence (Smith, 1995). He argues that technology is a factor that can either magnify or minimize how population and affluence impact the environment. He proposed an alternative version of I = P*A*T in which 'T' is replaced with 'CITE' (the Culture, Institutions, and Technology Effect). In many respects the 2001 Environmental Sustainability Index makes many attempts to capture the 'CITE' ideas of Smith (Samuel-Johnson & Esty, 2001). Despite the difficulty associated with measuring total impact there is little argument that total population is a critical component. The per capita impact is the element that is most problematic in terms of measurement. The nighttime satellite imagery used here may prove useful as an objective and empirical measure of impact.

The generation of national ESIs is a logical follow-up to the suggestions of Daily and Ehrlich with respect to making relative measures of Maximum Sustainable Abuse, Maximum Sustainable Use, and Human impact. The

Ecological Footprint and the 2001 Environmental Sustainability Index are two distinct, independent attempts at making these assessments (Wackernagel et al., 1997; Samuel-Johnson & Esty, 2001). Unfortunately, they do not correlate strongly with one another which raises serious questions with respect to the methods associated with generating them. If measures of this nature fail to eventually converge and correlate with one another 'Sustainability Science' will be increasingly regarded as 'Sustainability Politics' (Kates, C. et al., 2001).

The simple measure of environmental sustainability described in this paper measures human impact by a simple integration of the amount of light energy emitted from each nation of the world from a nighttime satellite image and merges the conceptions of maximum sustainable use and maximum sustainable abuse into nationally aggregate measures of ecosystem service value based on a global landcover dataset. A similar analysis was conducted in which nighttime emissions and ecosystem services were used to map 'marketed' and 'non-marketed' economic activity at the nationally aggregate levels (Sutton & Costanza, 2002). Unfortunately it was determined that nighttime emissions are not correlated strongly enough with national GDP to use as a direct proxy of 'marketed' economic activity. This analysis differs in that it uses aggregate measures of nighttime emissions for each nation in the index. Measuring Environmental Sustainability on a per capita basis (sometimes called Eco-Footprinting) is a controversial undertaking. The logic of Eco-Footprinting and the relative merits of perfoming Eco-Footprint analyses on agricultural capacity or energy consumption have been discussed extensively (Ferguson, 1999; 2001). The purpose of the measure described here is not as an alternative to previous attempts at measuring the eco-footprints of nations. The purpose of this measure is to provide a measure that is conceptually simple enough, and hopefully theoretically robust enough, to use as a tool to evaluate the utility of these more sophisticated measures of sustainability.

DATA AND METHODS

Three ESIs were used in this study. The two sophisticated datasets ('2001 Environmental Sustainability Index' and the 'Ecological Footprint of Nations') were derived by others and obtained from the world wide web (Wackernagel et al., 1997; Samuel-Johnson & Esty, 2001). The simpler ESI proposed here (Eco-Value/Nighttime Light Energy) was derived using two global datasets in a geographic information system. A brief description of these datasets and the methods used to develop them follows.

2001 Environmental Sustainability Index

The 2001 Environmental Sustainability Index (2001 ESI) was developed as an initiative of the Global Leaders of Tomorrow Environment Task Force of the World Economic Forum. The Yale Center for Environmental Law and Policy (YCELP) and the Center for International Earth Science Information Network (CIESIN) contributed to the development of this index. The 2001 ESI attempts to develop a '*transparent, interactive process that draws on rigorous statistical, environmental, and analytic expertise to quantify environmental sustainability*.' According to the main report of the 2001 ESI document the Key Results are: 1) Environmental Sustainability can be measured, 2) The Index creates benchmarks of environmental conditions that can influence decision making, 3) Serious 'data gaps' for many nations of the world should be filled, 4) Economic conditions affect, but do not determine, environmental conditions; and, policy regarding these conditions are separate choices. The 2001 ESI is derived by averaging five key 'core' components (parenthetical key: *Component [# of Indicators]*: Environmental Systems [5], Reducing Stresses [5], Reducing Human Vulnerability [2], Social and Institutional Capacity [7], and Global Stewardship [3]). The 'Indicator' variables that constitute the five key components are themselves derived from 67 specifically measureable and nationally aggregate variables. Examples of a few of the 67 fundamental variables are: "Urban SO_2 concentraion," "Total Fertility Rate:," "Scientific and Technical articles per million of population:," and "Number of memberships in environmental intergovernmental organizations." One of the variables used in the 2001 ESI that measured anthropogenic impact on the land was in fact derived from a composite nighttime satellite image and a similar global land cover dataset (Elvidge et al., 1995). Needless to say, the arithmetic associated with merging these 67 variables into single numerical measures of national ESIs is difficult to appreciate. Nonetheless, the 67 variables chosen all seem reasonable in light of the environmental sustainability index they are trying to measure. How they should be weighted is a complex question which the 2001 ESI report reasonably avoids. The 'weighting' question is undoubtedly an element of the 'interactive' nature of developing indices for which there will be a consensus. One notable result of the arithmetic involved in generating the 2001 ESI's is the fact that the aggregate national numbers correlate strongly with nationally aggregate measures of GDP/Capita. The

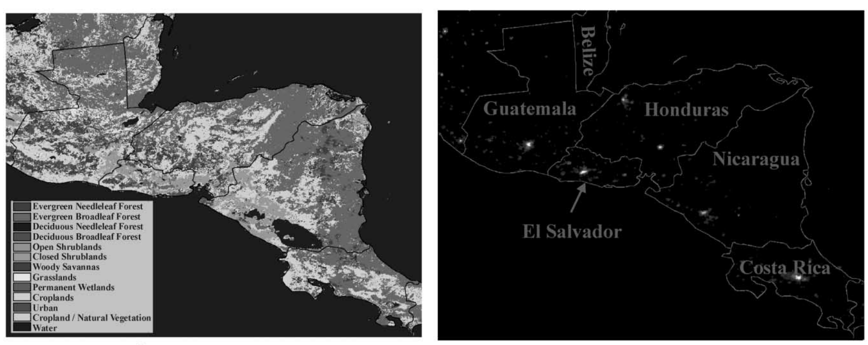
2001 ESI was calculated for 122 nations. According to this measure the most sustainable nations were: Norway, Finland, and Canada. The least sustainable were: Burundi, Ethiopia, Haiti, Saudi Arabia, and Libya. The 2001 ESI is a truly independent, and perhaps theoretically distinct, measure of 'environmental sustainability' than the 'Ecological Footprint.' The following will hopefully clarify these distinctions.

The Ecological Footprint of Nations

The 'Ecological Footprint' index of environmental sustainability is probably more narrow in scope than the 2001 ESI in that it is less influenced by 'local' environmental quality and less influenced by the cultural and institutional elements that are involved with both local and global environmental quality. In this sense the 'Ecological Footprint' more closely attempts to measure the MSU, MSA, and I = P*A*T described by Daily and Ehrlich. "*Ecological Footprint analysis is an accounting tool that enables us to estimate the resource consumption and waste assimilation requirements of a defined human population or economy in terms of corresponding productive land area*" (Wackernagel & Rees, 1996). Nonetheless, the 'Ecological Footprint' is as much an 'Environmental Sustainability Index' as the 2001 ESI. The 'Ecological Footprint' ESI is also a composite index involving many variables. However, in contrast to the 2001 ESI these variables focus on the nature and productivity of land resources, variability of human consumption patterns, and the energy accounting of each nation's international trade. The land variables focus on areal extent, biological productivity, and waste absorption capacity. The consumption variables characterize and account for the differing ecological impact of human consumption throughout the nations of the world. Finally, the ecological footprint index tries to capture the separation of production and consumption by looking at the import and export goods of each nation to see who is actually consuming the energy associated with manufacturing, agriculture, etc. Wackernagel's index calculated the following measures for 52 nations of the world: Total Ecological Footprint (a measure of impact), Available Ecological Capacity (a measure that merges the concept of MSU and MSA), Ecological Deficit (an ESI that results from the difference between the two). The most sustainable countries according to this ESI were: Australia, Finland, Peru, Colombia, and Brazil. The least sustainable were: Belgium, The Netherlands, Singapore, and the United States. Surprisingly there is no correlation between the Ecological Deficit and the 2001 ESI. This is one reason for developing the simple ESI described below.

National Ecosystem Service Value/National Nighttime Image Integrations

This measure of environmental sustainability is quite simple and is referred to from here on as the Eco-Value/Night Light Energy ESI. An ESI is calculated for each nation of the world by dividing the amount of light energy emitted by that nation as measured by a nighttime satellite image into the total value of that nation's ecosystem services as measured by a land-cover dataset and ecosystem service values estimated by Costanza et al. (1997). The nighttime satellite image is a global dataset derived from mosaicing hundreds of orbits of the Defense Meteorological Satellite Program's Operational Linescan System (DMSP OLS). This image has been screened for clouds and ephemeral lights such as lightning, forest fires, gas flares, and lantern fishing (Elvidge et al., 1998) (Figure 1). Studies of this imagery have correlated it with the extent of urban land cover, population density, energy consumption, greenhouse gas emissions and other socioeconomic parameters (Elvidge et al., 1997; Imhoff et al., 1997; Sutton et al., 1997; Doll et al., 2000). The image is radiance calibrated so an integra-



Global 1 km² IGBP Land-Cover Dataset **DMSP-OLS 'Earth at Night' dataset**

Country	Population (1996)	Eco-Value/Night Light	Local Rank
Belize	224,000	261,306	6
Nicaragua	4,351,000	184,308	5
Honduras	5,751,000	97,093	4
Guatemala	11,241,000	62,085	3
Costa Rica	3,466,000	24,959	2
El Salvador	5,935,000	9,896	1

FIGURE 1. A representation of the datasets used to calculate Eco-Value and impact from around Central America.

tion of the values of the pixels over the land of a nation is a measure of light energy. This measure is used as a proxy for 'Impact' in the I = PAT sense. It has been suggested that the extremely rich and the extremely poor people of the world have the greatest per capita impact on the earth's environment. With this in mind it is likely that the Night Light proxy of impact is biased toward capturing the environmental impact of the extremely wealthy more than the extremely poor.

The second dataset used in this ESI is a global land-cover dataset developed by the United States Geological Survey and available on the web (http:/edcdaac.usgs.gov/glcc/glcc.html) (Figure 1). The International Geosphere Biosphere Program participated in developing a version of this dataset with seventeen land-cover classes representing the major biomes of the world. These classes were matched to the corresponding ecosystem service values calculated by Costanza et al. (1997) to calculate the total annual value of each nation's ecosystem services. This measure is intended to be a merged proxy of the MSU and MSA outlined by Daily and Ehrlich. Ecosystem services are not measured perfectly by global maps of landcover (Pimentel, 1988; Farber, 2002); nonetheless, this dataset was the most useful for this purpose. The value of the maritime ecosystem services, including coral reefs, sea grass beds, etc. were not included in this measurement. According to the methods of Costanza et al. the value of maritime ecosystem services account for about two thirds of the earth's ecosystem services. Incorporating these values into this analysis would have most reasonably been accomplished using a dataset of the Exclusive Economic Zone boundaries of the world's nations (Solutions 2000). This omission may be fortunate in that most of the world's Net Primary Productivity and biodiversity exists in the terrestrial environment anyway. The total value of ecosystem services does correlate strongly with NPP on a per biome basis (Costanza et al., 1998) and spatially explicit global maps of NPP may in fact be a better measure of MSU and/or MSA and/or ecosystem service value. In any case, this Eco-Value/Night Light measure is in some sense an adjusted measure of land per person in which the land figure is adjusted by its ecological value and the per person figure is adjusted by a proxy measure of per capita consumption.

The most sustainable nations according to this index were: Madagascar, Mongolia, and numerous small island nations and protectorates. The least sustainable were: Kuwait, Singapore, Belgium, Luxemborg, and the United Arab Emirates. Nations in the Oil producing regions of the Middle East did not fare will by this index. One reason for this is that separating gas-flares from city lights can be difficult if they are spatially intermingled at the 1 km^2 scale. Recall, that the nighttime light dataset used in this analysis used only non-ephemeral lights so fires, gas flares, etc. were excluded.

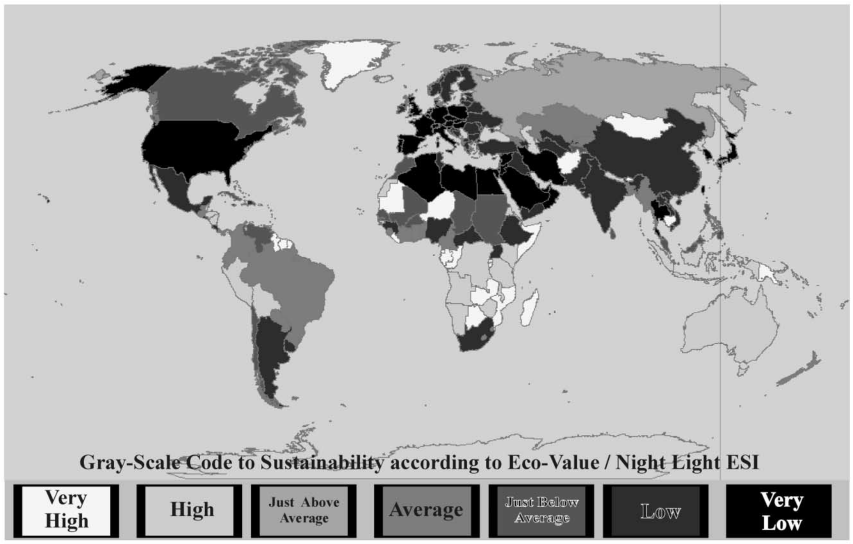
Also, the Eco-Value/Nighttime Light ESI was calculated for 210 nations and protectorates; consequently, in our subsequent analyses comparisons of highest and lowest rankings between these ESIs were limited to nations for which all three ESIs were measured (N = 48).

ANALYSIS AND RESULTS

There were some questions associated with respect to which datasets to use. The Ecological Footprint data of Wackernagel and others was posted on the web for 1993 and 1997 calculations. The 1997 data for the 52 nations reported was used here. The 2001 ESI was produced as a pilot measure in 2000 and as a more substantial measure in 2001 (Samuel-Johnson, 2000). We used the 2001 data for 122 nations. In addition, the 2001 ESI published within its report a measure of Ecological Deficit measured along the lines of Wackernagel's Ecological Footprint methods for 118 nations. The source cited for these 'Eco-Deficit' calculations was the *Living Planet Report* of the World Wide Fund for Nature (WWF), Gland Switzerland. The 'Eco-Deficit' reported in the 2001 ESI report only correlated with the '97 Eco-Deficit of Wackernagel with an R^2 of 0.13. This may be due to differences in number of nations for which it was measured; nonetheless, it raises questions regarding what numbers to use. In general, the numbers used in this analysis were: 1) Empirically derived Eco-Value/Night Light Energy (N = 210); 2) Eco-Deficit numbers from Wackernagel (1997) (N = 52), and 2001 ESI numbers from World Economic Forum (N = 122).

Using the absolute scores for these various ESIs is problematic for statistical reasons. All correlations reported are based on the *ranks* of the figures reported. This means that the regressions are non-parametric in nature. This is appropriate in the sense that we are more likely to be successful at measuring *relative* rather than *absolute* environmental sustainability as suggested by Daily and Ehrlich. Also, The 2001 ESI figures were converted to a standard normal ditribution or 'normalized' after the final means of the five 'core' sub-endices were calculated. Assumption of a normal distribution of ESIs for the nations of the world is dubious at best. The non-parametric methods used here lack the potential statistical power of using the absolute numbers reported; however, the results are more robust and less influenced by outliers in the data. Figure 2 summarizes the results for the common 48 nations to all these endices with a cartographic representation of the Eco-Value/Night Light Energy ESI for 210 nations and protectorates.

One of the observations that motivated this study was the fact that the 'Eco-Deficit' of Wackernagel's method did not correlate significantly to the



Country	Eco-Value/ Night Light	Rank	Eco-Deficit Wackernagel (97)	Rank	2001 ESI	Rank		Country	Eco-Value/ Night Light	Rank	Eco-Deficit Wackernagel (97)	Rank	2001 ESI	Rank
Argentina	19,732	34	0.7	40	62.5	35		Japan	3,270	11	-3.4	7	60.6	32
Australia	103,836	48	5.0	48	70.7	44		Jordan	4,768	21	-1.8	16	40.1	6
Austria	4,409	20	-1.0	23	67.8	43		Malaysia	39,385	41	0.4	38	49.7	19
Bangladesh	62,156	43	-0.2	34	39.5	5		Mexico	11,844	29	-1.2	19	45.3	13
Belgium	283	2	-3.7	2	44.1	11		Netherlands	1,154	5	-3.6	3	66.0	40
Brazil	82,652	46	3.6	47	57.4	29		New Zealand	70,878	44	12.8	50	71.3	45
Canada	46,681	42	1.9	44	78.1	48		Nigeria	11,673	28	-0.9	25	31.8	2
Chile	29,932	38	0.7	41	56.6	27		Norway	12,453	30	0.1	37	78.2	49
China	27,401	37	-0.4	30	37.6	4		Pakistan	6,048	23	-0.3	31	43.6	10
Colombia	81,204	45	2.1	45	54.8	25		Peru	155,224	49	6.1	49	54.3	24
Costa Rica	24,959	36	0.0	35	58.8	30		Philippines	38,006	40	-0.6	28	35.7	3
Czech Republic	1,143	4	-0.5	29	57.2	28		Poland	3,443	14	-2.1	14	47.6	17
Denmark	4,343	19	-0.7	27	67.0	42		Portugal	3,686	16	-0.9	24	61.4	34
Egypt	1,637	6	-1.0	21	46.5	15		Singapore	162	1	-7.1	1	46.8	16
Ethiopia	16,841	32	-0.3	33	31.2	1		South Africa	14,385	31	-1.9	15	51.3	21
Finland	10,611	26	2.6	46	80.5	50		South Korea	1,930	8	-2.9	10	40.3	7
France	2,745	10	0.1	36	65.8	39		Spain	3,442	13	-1.6	17	59.5	31
Germany	1,741	7	-3.4	6	64.2	38		Sweden	9,124	24	1.1	42	77.1	47
Greece	10,813	27	-2.6	12	53.1	22		Switzerland	4,339	18	-3.2	8	74.6	46
Hungary	3,349	12	-1.0	22	61.0	33		Thailand	5,545	22	-1.6	18	45.2	12
India	10,390	25	-0.3	32	40.9	8		Turkey	20,340	35	-0.8	26	46.3	14
Indonesia	183,129	50	1.2	43	42.6	9		United Kingdom	4,028	17	-3.5	5	64.1	37
Ireland	17,393	33	0.6	39	64.0	36		United States	3,565	15	-3.6	4	66.1	41
Israel	1,045	3	-3.1	9	49.5	18		Venezuela	36,059	39	-1.1	20	50.8	20

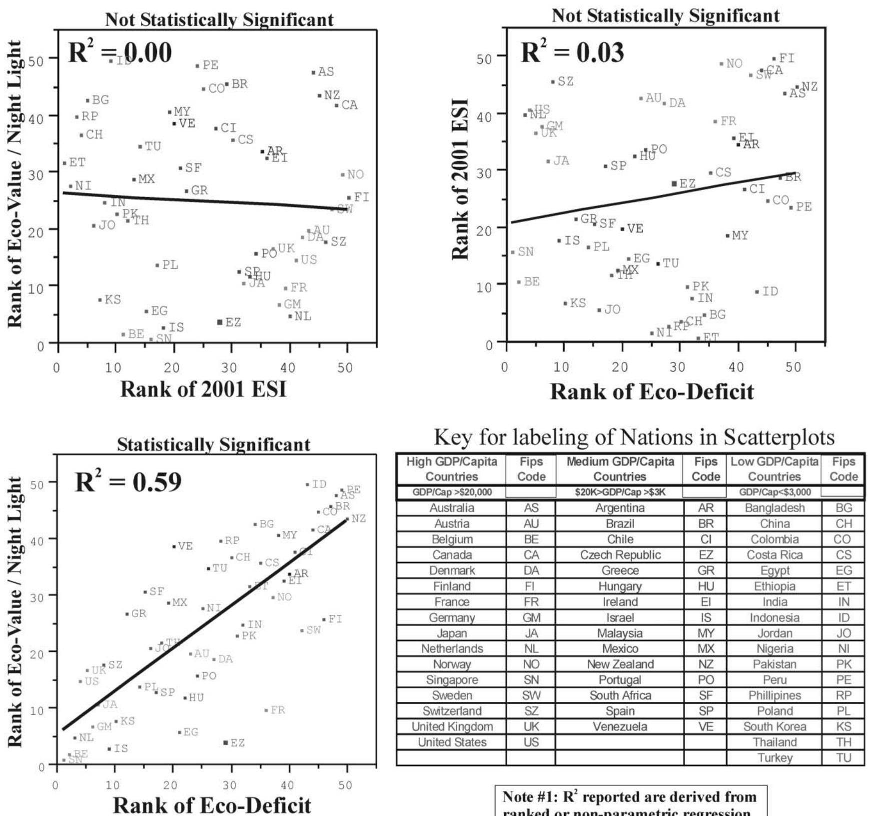
FIGURE 2. Map of Eco-Value/Night Light ESI with table comparing actual values and ranks to 2001 ESI and Ecological Footprint for 48 nations.

2001 ESI. Table 1 is a correlation matrix of the three variables and their ranks in addition to other variables of interest such as GNP/Capita and population density (Table 1 is based on an N = 47 because the WWF Eco-Deficit number was not available for Belgium). The ranks were ordered so that higher ranks indicated higher levels of sustainability for all indices. These correlations will not agree exactly with all previously published correlations (particularly those in the 2001 ESI report) because they have a smaller sample size. Nonetheless, the majority of the world's population is accounted for in these 47 nations, and, the correlations are not much different anyway. Some interesting things to note in this table are that population density correlates negatively with all the ESIs except the Eco-Deficit of the World Wide Fund for Nature. In other words, high national population densities tend to have lower environmental sustainability. GDP per capita on the other hand correlates positively with both the 2001 ESI and Wackernagel's '97 Ecological Footprint but negatively with all other ESIs. It should be noted here that Wackernagel's Ecological Footprint is a measure of Impact, not an ESI. The Eco-Deficit number is the difference between the Ecological Capacity and the Ecological Footprint and is one of the ESIs that did correlate negatively with GDP per capita. Table 6 of the 2001 ESI report presented 'Correlations Between the 2001 ESI and Other Comparative Measures.' This table reported a correlation (R) of 0.60 with the Ecological Footprint. This is inappropriate in that the Ecological Footprint is not a 'comparable measure'. The Ecological Footprint is a measure of impact rather than sustainability which is measured by the Eco-Deficit.

Figure 3 summarizes the three critical comparisons buried in Table 1 as scatterplots in which the coding of the points represents the 48 nations for which numbers were available for all three indices. The essence of this figure demonstrates that there is no statistically significant relationship between the proposed Eco-Value/Night Light Energy ESI and the 2001 ESI, nor is there any significant relationship between Wackernagel's Eco-Deficit ESI and the 2001 ESI; however, the correlation between the Eco-Value/Night Light Energy ESI and Wackernagel's Eco-Deficit is both positive and statistically significant. The coding of the points sheds light on how the 2001 ESI is strongly correlated to GDP per capita whereas the other two ESIs have countries of all income levels with high measures of sustainability. Higher GDP per capita countries tended to dominate the lower levels of both the Eco-Deficit and the Eco-Value/Night Light Energy ESIs. Aggregate national population density seems to be a significant contributor to this effect in that the only high GDP per capita nations with high ESIs according to the both the Eco-Deficit and the Eco-Value/Night Light Energy were Canada and Australia.

DISCUSSION

Measuring environmental sustainability should be a major research question for the foreseeable future. The 2001 ESI and the Ecological Footprint analyses are laudable preliminary attempts at doing just that. However, the absence of any correlation whatsoever between these measures raises questions as to whether one or both of these measures are grossly inadequate or whether they are merely measuring environmental sustainability in profoundly different ways.



Key for labeling of Nations in Scatterplots

High GDP/Capita Countries	Fips Code	Medium GDP/Capita Countries	Fips Code	Low GDP/Capita Countries	Fips Code
GDP/Cap >$20,000		$20K>GDP/Cap >$3K		GDP/Cap<$3,000	
Australia	AS	Argentina	AR	Bangladesh	BG
Austria	AU	Brazil	BR	China	CH
Belgium	BE	Chile	CI	Colombia	CO
Canada	CA	Czech Republic	EZ	Costa Rica	CS
Denmark	DA	Greece	GR	Egypt	EG
Finland	FI	Hungary	HU	Ethiopia	ET
France	FR	Ireland	EI	India	IN
Germany	GM	Israel	IS	Indonesia	ID
Japan	JA	Malaysia	MY	Jordan	JO
Netherlands	NL	Mexico	MX	Nigeria	NI
Norway	NO	New Zealand	NZ	Pakistan	PK
Singapore	SN	Portugal	PO	Peru	PE
Sweden	SW	South Africa	SF	Phillipines	RP
Switzerland	SZ	Spain	SP	Poland	PL
United Kingdom	UK	Venezuela	VE	South Korea	KS
United States	US			Thailand	TH
				Turkey	TU

Note #1: R^2 reported are derived from ranked or non-parametric regression

Note #2: Higher ranks in all cases suggest higher sustainability

FIGURE 3. Correlations and scatterplots between ranked values of Eco-Footprint, Environmental Sustainability Index, and Eco-Value/Night Light endices.

The variables used as input to both measures seem entirely appropriate indicators of various aspects of sustainability. For this reason it seems clear that the 2001 ESI and the Eco-Deficit are measuring fundamentally different aspects of environmental sustainability. The diverging influence of GDP per capita on these two measures suggests that the Eco-Deficit analysis captures more of the impact that is non-local to the nation in question. In other words, when people talk about the 'separation of production and consumption' (Chisolm, 1990) they are in some part recognizing that some countries of the world can enjoy the consumption of some goods and services while farming the environmental degradation necessary to create those goods out to less developed countries. It could be argued that an equitable measure of environmental sustainability should account for the spatial mis-match of production and consumption and allocate the impact of production to the location of the consumption. The energy analysis of the imports and exports of each nation that is incorporated into the Eco-Deficit analysis suggests that this ESI captures this separation of production and consumption in ways that the 2001 ESI does not. The night light measure of the Eco-Value/Night Light Energy probably captures a major portion of this separation also, which may explain its high correlation with the Eco-Deficit index. This distinction between the 2001 ESI and the Eco-Deficit ESI suggests that the Eco-Deficit is measuring environmental sustainability more within the conceptual framework involving MSA, MSU, and I = P*A*T suggested by Daily and Ehrlich.

In contract, the 2001 ESI seems to capture more of the "Culture, Institutions, and Technology effect" described by Holdren. The 2001 ESI is more a measure of how the environment of a particular nation is doing without attempting to allocate the impacts (both good and bad, but mostly bad) of the environmental degradation that is occurring back to their consumption source. For example, the United States performed quite well on the 2001 ESI but rather poorly on both the Eco-Deficit and the Eco-Value/Night Light Energy indices. The culture, institutions, and technology of the U.S. (and its affluence) allow for greater monitoring and mitigation of environmental degradation locally. However, the U.S. is not as concerned about environmental degradation outside its own back yard even if U.S. consumption is the primary cause of that degradation.

Thus, there is a marked contrast between these independent measures of environmental sustainability. The Eco-Deficit is a more measure of environmental sustainability while the 2001 ESI is more a local measure of local environmental quality. The Eco-Deficit is more able to allocate environmental impact to distant spatial sources of consumption and is consequently a better indicator of the sustainable behavior of the people's of the nations it calculates an index for. In contrast, the 2001 ESI seems to be more of a measure of local environmental quality. The 2001 ESI would probably be useful if you wanted to choose what country to live in based on environmental quality. However, some statements in the 2001 ESI report suggest that this distinction is not fully appreciated. For example, *Annex 3: Frequently Asked Questions* of the 2001 ESI answers the question: '*Isn't Singapore's score too low?*':

> Singapore, widely considered to be a well-managed, prosperous country, received a relatively low score. . . . Some commenta-

TABLE 1

Correlation Matrix of Both the Ranks and Absolute Value of Various ESIs and Other Relevant Aggregate National Statistics

Variable	GDP/ Capita	Population Density	Eco- Value/ Night Light	Rank Eco- Value/ Night Light	Ecodeficit '93 (Wackernagel)	Rank EcoDeficit '93 (Wackernagel)
GDP/Capita	1.00	0.23	–0.20	–0.29	–0.28	–0.33
Population Density	0.23	1.00	–0.12	–0.29	–0.37	–0.29
Eco-Value/Night Light	–0.20	–0.12	1.00	0.75	0.35	0.42
Rank Eco-Value/Night Light	–0.29	–0.29	0.75	1.00	0.58	0.66
Ecodeficit '93 (Wackernagel)	–0.28	–0.37	0.35	0.58	1.00	0.93
Eco-Footprint '97 (Wackernagel)	–0.33	–0.29	0.42	0.66	0.93	1.00
Eco-Footprint '97 (Wackernagel)	0.19	–0.07	–0.04	–0.05	–0.10	–0.07
Rank Eco-Footprint '97 (Wackernagel)	–0.05	–0.19	0.11	0.06	–0.14	–0.06
Eco-Deficity '97 (Wackernagel)	–0.14	–0.38	0.63	0.69	0.79	0.71
Rank Eco-Deficit '97 (Wackernagel)	–0.21	–0.30	0.63	0.78	0.76	0.81
2001 ESI	0.57	–0.15	–0.05	–0.06	0.20	0.04
Rank 2001 ESI	0.59	–0.14	–0.06	–0.08	0.16	0.00
EcoDeficit (WWF)	–0.38	0.01	0.51	0.61	0.34	0.45
Rank EcoDeficit (WWF)	–0.37	0.07	0.52	0.59	0.41	0.54

Note: These correlations are based on the 47 nations for which numbers existed for all variables. The Eco-Deficit Numbers with 'WWF' were obtained from the 2001 ESI report which cited the World Wide Fund for Nature's *Living Planet Report*

> tor's suggested that Singapore's unexpectedly low score reflected a flaw in the ESI's methodology. . . . We do not agree with these suggestions. There are compelling analytical reasons to believe that small islands with large populations and considerable economic activity will approach, if not exceed, the limits of environmental sustainability. We do not wish to "control" for such factors; in fact we wish to do precisely the opposite: to illuminate cases where such limits are being approached. (2001 ESI, p. 32)

This is an unusual defense of Singapore's low score in light of the fact that Singapore was a profound outlier in the relationship between GDP per capita and the 2001 ESI scores. Japan had a high 2001 ESI score despite their high levels of consumption and the fact that Japan's population of over 125 million lives on a few islands the size of California. Japan's 2001 ESI score is a more typical 2001 ESI score in that it is a measure of environmental quality rather than sustainability. Most people would choose to live in Japan over Indonesia for environmental quality reasons; in addition as a

Eco-Footprint '97 (Wackernagel)	Rank Eco-Footprint '97 (wackernagel)	Eco-Deficity '97 (Wackernagel)	Rank Eco-Deficit '97 (Wackernagel)	2001 ESI	Rank 2001 ESI	EcoDeficit (WWF)	Rank EcoDeficit (WWF)
0.19	–0.05	–0.14	–0.21	0.57	0.59	–0.38	–0.37
–0.07	–0.19	–0.38	–0.30	–0.15	–0.14	0.01	
	0.11	0.63	0.63	–0.05	–0.06	0.51	0.52
–0.05	0.06	0.69	0.78	–0.06	–0.08	0.61	0.59
–0.10	–0.14	0.79	0.76	0.20	0.16	0.34	0.41
–0.07	–0.06	0.71	0.81	0.04	0.00	0.45	0.54
1.00	0.58	–0.16	–0.20	–0.03	–0.01	–0.20	–0.20
0.58	1.00	–0.14	–0.16	–0.23	–0.22	0.10	0.08
–0.16	–0.14	1.00	0.85	0.25	0.24	0.37	0.36
–0.20	–0.16	0.85	1.00	0.17	0.15	0.56	0.59
–0.03	–0.23	0.25	0.17	1.00	0.99	–0.15	–0.13
–0.01	–0.22	0.24	0.15	0.99	1.00	–0.18	–0.16
–0.20	0.10	0.37	0.56	–0.15	–0.18	1.00	0.92
–0.20	0.08	0.36	0.59	–0.13	–0.16	0.92	1.00

Japanese citizen you would probably be more likely to consume the hardwoods of Indonesia's rainforests. In any case, Singapore has an anomalously low score in the 2001 ESI. The 2001 ESI report's defense of this low score confuses the distinction between measuring environmental quality and environmental sustainability.

This confusion is one good reason for creating simple indices of environmental sustainability such as the Eco-Value/Night Light Energy ESI. Simple indices can be used as a cross check on more sophisticated measures such as the 2001 ESI and the Eco-Deficit analyses. The simplicity of this measure enables comprehension for a greater number of people and its use as a comparison tool sheds light on the nature of the differences between more sophisticated ESIs such as the Ecological Footprint and the 2001 ESI.

Measuring environmental sustainability is a daunting task. Both the 2001 ESI and the Ecological Footprint analyses shed important light on different aspects of sustainability. As the practice of measuring sustainability evolves it is hoped that there will be greater agreement as to what environmental sustainability means and between various attempts to measure it. Issues of scale are formidable with respect to this task and the authors of both the 2001 ESI report and the Ecological Footprint analyses were careful to note this. The Eco-Value/Night Light Energy ESI is also subject to problems of scale. Calculating the total value of the Ecosystem Services of a nation is profoundly dependent upon the spatial resolution at which you measure and classify land cover types (Konarska, 2000). Measurement units raise additional questions. Some might argue that the watershed rather than national administrative boundaries are the appropriate unit of analysis for any assessments of environmental sustainability. Finally, issues associated with the separation of production and consumption must be resolved. These issues are at the core of questions involving local to global linkages and necessitate more appropriate accounting for the historically ignored social, ecologic, and economic costs and benefits associated with international and inter-regional trade.

CONCLUSION

Achieving environmental sustainability is increasingly being recognized as important human objective. The difficult task of defining and measuring environmental sustainability is the logical next step. Hopefully this will occur as an iterative, interactive, and transparent process in which consensus and consilience are achieved within and between the nations of the world. The Eco-Value/Night Light Energy ESI proposed here is intended as a contribution to the process of assessing environmental sustainability. It correlates strongly with the Eco-Deficit analysis of Wackernagel yet weakly with the 2001 ESI of the World Economic Forum. This is probably because it is more likely to incorporate issues of separation of production and consumption in the Eco-Deficit index that are absent in the 2001 ESI. The nature of the difference between the Eco-Deficit index and the 2001 ESI will probably be a component of future debates about measuring environmental sustainability. Simple indices such as the Eco-Value/Night Light Energy ESI can assist in clarifying the distinctions between different measures and help non-scientists comprehend the nature of the indices being calculated.

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