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Per capita resource consumption and resource carrying capacity: A comparison of the sustainability of 17 mainstream countries

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ABSTRACT

Sustainability involves aspects of society, economy, and environment. Environmental sustainability is one of the most important factors to support global energy consumption and to absorb the pollution generated by human activities. Because emergy can be used to measure both money and energy flows in the same units, it provides a way to measure the real wealth of both natural and economic systems and the impact of human activities on these systems. A comparison of the carrying capacity of natural resources with the consumption of these resources at regional or global scales can provide a clear image of sustainability. To assess sustainability around the world, we used the National Environmental Accounting Database data for 102 nations (2008 data) to evaluate the resource consumption by 17 mainstream countries. Our results revealed that most of the countries consumed too many resources, thereby decreasing the overall global sustainability of the natural resources that sustain human society. Our results confirm previous predictions that to ensure long-term sustainability, it will be necessary to control population increases, reduce emergy consumption, and promote emergy efficiency.

1. Introduction

In 1987, the Brundtland Report defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Smith and Rees, 1998). This concept means that a nation's social, economic, and natural capital should be preserved for future generations. Contributors to the report believed that sustainable development requires harmonious development of the economy, of society, of natural resources, and of the environment (i.e., four kinds of capital). Economists have defined two levels of sustainability:

1. *Weak sustainability* preserves the total capital, but not necessarily each of the four kinds of capital; that is, the different types of capital are considered to be potentially substitutable for one another. Neoclassical economists tend to maintain that man-made capital can, in principle, replace all types of natural capital and that every technology can be improved upon or replaced as a result of innovation.
2. *Strong sustainability* requires that each type of capital be preserved independently; that is, the different types of capital can complement each other, but cannot substitute for one another. This premise of strong sustainability suggests that those who develop socioeconomic policy have a responsibility to the greater ecological world, and that sustainable development must therefore take a different approach to valuing natural resources and ecological functions.

A resource is any physical or virtual entity of limited availability that must be consumed to obtain a benefit. By definition, the Earth cannot tolerate continued economic and population growth and the consumerism they foster if these processes are unsustainable. Because energy, economic, and environmental constraints operate at all scales to limit future growth, failing to account for these constraints may lead to abrupt and highly disruptive changes instead of a "planned descent" (Brown et al., 2009). Thus, long-term sustainability is defined by the environment's long-term carrying capacity; from an economic perspective, carrying capacity is equivalent to a budget, and it is not possible to spend more than one's budget for more than a short period of time. The concept of carrying capacity for human use of the biosphere is important, since it defines the limits to the biosphere's ability to sustain life, absorb and recycle wastes, and provide resource inputs. There has therefore been renewed

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interest in understanding the relationship between human-dominated systems and their environmental support systems.

Rojstaczer et al. (2001) calculated that the proportion of the biosphere's total net terrestrial primary production carrying capacity being appropriated for human consumption was about 10–55% of terrestrial photosynthetic products. Folke et al. (1997) used estimates of "appropriated ecosystem areas" by cities in the Baltic area as a metric for defining the region's carrying capacity for resource consumption and waste assimilation. Wackernagel and Rees (1996) evaluated the land required to provide resources for urban areas and coined the term "ecological footprint" to describe this impact. Brown and Ulgiati (2001) proposed emergy analysis techniques that could be used to evaluate the environment's carrying capacity for economic development. In this approach, "emergy" represents the "embodied energy" that is contained in flows of energy, materials, or money.

The main energy source of our world comes from the sun. Solar emergy can therefore be used to place a value on natural resources that the economy does not evaluate correctly (e.g., rain, raw materials from nature, water from rivers, biodiversity) and also on resources provided by the human economy, which mainly comprise fossil fuels and their derivatives (the goods and services of industrial economies). Emergy analysis therefore explicitly includes many factors that neoclassical economics treats as externalities. Emergy analysis uses a common unit for all flows, namely the equivalent solar energy Joule (sej). Emergy analysis includes geophysical characteristics to value the amount of energy connected to the production and use of natural resources (Siche et al., 2008). The aim of the methodology is to obtain a thermodynamic measure of the energy used by the production and consumption of a resource (Odum, 1996). Since the early 1990s, emergy and emergy analysis have been widely used to analyze systems as diverse as ecological (Huang, 1998; Campbell et al., 2005), industrial (Brown and Buranakarn, 2003; Johansson et al., 2000; Cuadra and Rydberg, 2006), and economic (Huang and Odum, 1991; Brown et al., 2003; Lei et al., 2010) systems.

The newer interpretation of sustainability is that it implicitly incorporates carrying capacity by suggesting that the long-term greater good of humanity is best maximized by minimizing environmental impacts (ideally, by keeping their magnitude below the environment's carrying capacity) and maximizing useful work. Here, we have built on this assumption by using the per capita emergy consumption of 17 mainstream nations to evaluate their sustainability based on the principle of sustainable use of natural resources and equitable distribution of those resources. In this paper, we base equitability on the assumption that all humans have a right to a similar level of emergy consumption; we have used the global average to define the baseline for equitability.

2. Methods

2.1. The principle of environmental sustainability

To operationalize the concept of strong sustainability, Daly (1991) defined four operational principles (Gudmundsson and Höjer, 1996): (1) The main principle is to limit the human scale (throughput) to a level that, even if it is not optimal, is at least within the environment's carrying capacity and is therefore sustainable. (2) Technological progress should increase efficiency rather than throughput. (3) Renewable resources should be exploited on the basis of a profit-maximizing sustained yield to avoid depleting a resource. (4) Nonrenewable resources should be exploited, but at a rate equal to the creation of renewable substitutes.

In the extensive discussion and use of the concept since then, there has generally been a recognition of three aspects of sustainable development: (1) An *economically sustainable* system must be able to produce goods and services on a continuing basis, to maintain manageable levels of government and external debt, and to avoid extreme sectoral imbalances that can damage agricultural or industrial production. (2) A *socially sustainable* system must achieve distributional equity, adequate provision of social services (including health and education), gender equity, and political accountability and participation. (3) An *environmentally sustainable* system must also include the maintenance of biodiversity, atmospheric stability, and other ecosystem functions that are not ordinarily classified as economic resources. The concept of sustainable development is therefore inherently intertwined with the concept of carrying capacity. When the consumption of natural resources exceeds nature's ability to replenish these resources, the carrying capacity is exceeded, the environment becomes increasingly degraded, and the system is not sustainable. The long-term consequence of continuing environmental degradation is the Earth's inability to sustain human life; in economic terms, unsustainable spending results in bankruptcy.

Emergy consumption can be used to determine how much energy is needed at each point in a system (Brown et al., 2009). The per capita emergy consumption value is a suitable indicator of resource utilization and an indicator of whether consumption is balanced with the per capita carrying capacity; in addition, it serves as an indicator of the equitability of emergy consumption by allowing a comparison of how much emergy is available to each person to use. The interface between the resources supplied by the environment and the resources consumed by the ecological economy can be compared among countries using per capita indices of resource use intensity, energy-based trade balances, and the sustainability of production (Brown et al., 2003); the advantage of this approach is that it can simultaneously provide insights into both sustainability and equitability issues.

Energy is required for all processes in an ecosystem, and resource consumption can be described using an emergy diagram that shows the relationship between population and per capita emergy use (Fig. 1). In the context of the present paper, the renewable resource carrying capacity defines the basis for strong sustainability, and the available renewable resources should be consumed equitably by all citizens of the world (following the

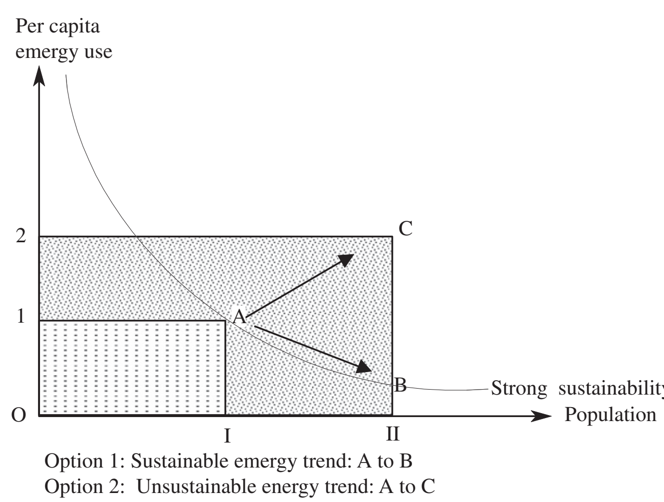

Fig. 1. The relationship between population and per capita emergy use as a function of socioeconomic development. The strong sustainability line represents the condition of strong sustainability, in which the consumption of all resources must be sustainable.

equity principle of sustainable development). Since the available resources cannot increase, an increasing population will decrease the amount of emergy available for use by each person. As development progresses from point *A* to point *B* in Fig. 1, per capita emergy use must follow the sustainability curve *AB*, and the area under *AB* represents the range of sustainable combinations of population and per capita emergy use under the constraint of strong sustainability. The area *A*–*I*–*O*-1 represents the sustainable resource consumption (i.e., the range of sustainable combinations of population and per capita emergy use) for the whole world at development stage A. If the world's population increases, then less emergy is available for each person's use (distance *B*-II is smaller than distance *A*–I), and per capita emergy use must decrease to maintain sustainability.

In reality, however, development often follows a path from *A* to *C* (Fig. 1): as the population increases from I to II, resource consumption (represented by per capita emergy use) increases from 1 to 2, and because the new rate of consumption is above the sustainability line, this creates a deficit in sustainable resource use represented by the area above the strong sustainability line from 1 to 2 and from I to II. This deficit must be filled by the consumption of nonrenewable resources. Since this will decrease the remaining store of nonrenewable resources, future generations will be required to use less resources to achieve sustainability, and this resource consumption strategy is therefore unsustainable.

2.2. Resource consumption and carrying capacity

The biosphere is driven by fluxes of renewable energies in the form of sunlight, tidal momentum, and deep earth heat. Human society draws energy directly from the environment by withdrawing the energy from short-term storage (typically considered to be from 10- to 1000-year turnover times), such as wood, soil, and groundwater, and from long-term storage, such as fossil fuels and minerals (Brown and Ulgiati, 1999). Ultimately, the global carrying capacity for humanity is a kind of budget that is determined by the planet's annual emergy income from both renewable sources (such as sunlight, rain, wind, waves, and tide) and dispersed nonrenewable sources (such as fisheries, forestry, soils, and water extraction), which are referred to as "free" emergy. (In this paper, "dispersed" refers to resources that are spread over large areas and that therefore have a low density compared with concentrated resources such as a coal or oil deposits.) By comparing a country's available support emergy with its emergy consumption, we can determine whether the country's socioeconomic activity is sustainable.

Any definition of sustainability must include a time factor. What is sustainable in one time period may not be sustainable in the long run. For example, Fig. 2 illustrates the growth and decline of an economy. Practices and processes that are characteristic of the growth phase may be sustainable initially, but become unsustainable during the transition phase, when the per capita emergy use exceeds the value in the two lowest sustainability lines. This leads to a decline phase because the economy increasingly requires the consumption of a diminishing store of nonrenewable emergy. On the other hand, practices that are sustainable during the decline phase because they do not rely on the consumption of nonrenewable emergy are probably not competitive with faster-growing economies under the dog-eat-dog competition that is characteristic of an economy in its rapid growth phase (Brown and Ulgiati, 1997).

Sweeney et al. (2007) summarized socioeconomic development of 134 nations in a standardized database that compiled data on Earth's material, energy, and money flows, aggregated at a national scale for the year 2000. The result is the National

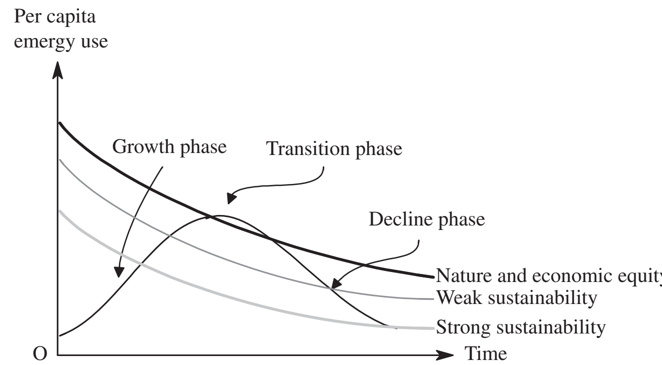

Fig. 2. The development stages of an economy in relation to its resource consumption levels and resource carrying capacity.

Environmental Accounting Database (NEAD) research, which provides this data using standardized conversion factors. We used the average per capita emergy consumption in 2008 as the benchmark for per capita emergy consumption, because 2008 is the most recent year for which NEAD data is available, and is provided by Dr. S. Sweeney (S. Sweeney, University of Florida, Gainesville, communication, 2011). Previous research estimated that the total global input of renewable emergy was 15.83×10^{24} sej/yr (Brown and Ulgiati, 2004), so we have used the same value here for consistency. The total per capita free emergy in 2008 was calculated by adding the renewable resource emergy ($R=6.94\times10^{15}$ sej) and the dispersed nonrenewable emergy ($N_0=0.60\times10^{15}$ sej), for a total of 7.54×10^{15} sej. This represents the strong sustainability curve in Fig. 2. Since we consume nonrenewable emergy to maintain our high quality of life, the average per capita natural emergy (renewable plus nonrenewable resources$=R+N$) produces a higher curve that represents weak sustainability at a total emergy value of 25.20×10^{15} sej in 2008.

Because most nations use both their internal resources and goods, minerals, and fuels imported from other countries, as well as the results of human labor from other countries, they are import-driven economies, and the total of these values represents "economic emergy" ($F_{(i)}+G_{(i)}+P_2I$), which represents the uppermost line in Fig. 2. Similarly, for an economy driven by resource exports, the nation will export large quantities of non-renewable resources; for example, Saudi Arabia exports oil and oil products and Australia exports iron minerals. The total export of these goods and human labor is also "economic emergy", but even though it is calculated differently ($F_{(e)}+G_{(e)}+P_1E$), it also represents the uppermost curve in Fig. 2. The sum of a country's natural and economic emergy equals its total emergy consumption. For some countries, this will equal total emergy use, but for resource-exporting countries, the value of total emergy consumption will be greater than the total emergy use.

The global average per capita emergy consumption represents the benchmark for equitable natural and economic emergy consumption. In 2008, this equaled 49.35×10^{15} sej per capita. If a nation's per capita emergy consumption is greater than this value, its consumption is not equitable, and all emergy consumption above this level must be met from one of three sources: goods and services obtained by trade with other nations; emergy taken from the past (e.g., fossil fuels); and emergy borrowed from the future in the form of unsustainable resource use (e.g., by overexploitation of forests and fisheries). However, a nation that is rich in emergy resources may combine sustainable consumption with inequitable consumption if it consumes more emergy than the global average while still meeting the conditions for strong sustainability within that nation.

3. Results and discussion

In this paper, we have focused our analysis on humanity's place in the biosphere and the consequences of continued population growth accompanied by increased consumption of natural resources. Using data from a variety of sources, the NEAD team of the University of Florida calculated the socioeconomic development of 102 nations in a standardized database at a national scale for the year 2008. The database represents the most comprehensive list of countries and their emergy flows that is currently available, so we have used it in our analysis. The database contains data for nations with a total population of 5.88×10^9, which amounted to 86.1% of the world's population with 6.83×10^9 in 2008 (United Nations, 2009). To simplify our comparison, we used the average values of the emergy parameters for all 102 nations to approximate the global average, and this served as our benchmark value. Table 1 defines the key emergy parameters that we compiled in this study, and Table 2 presents the values for the 17 countries that we chose to compare in this study.

To capture a range of environmental, resource, and economic conditions, we chose the G7 countries (the United States, Japan, Germany, the United Kingdom, France, Italy, and Canada), the BRICS countries (Brazil, Russia, India, China, and South Africa), and some several additional countries whose economy is driven by resource exports (labor for Mexico, Thailand, and Indonesia; natural resources for Australia and Saudi Arabia). We then compared the emergy parameters for these 17 countries using the methods described in Section 2.

3.1. Emergy consumption by the 17 nations

In the rest of Section 3, we will focus on the data in Table 2, but we have presented graphs of this data as Online Supplemental Figure S1 to facilitate comparisons between nations.

Renewable resources are those that can be easily replenished or reproduced. Some, like sunlight, air, and wind, are continuously available and their quantity is not affected by human consumption. Other renewable resources can be depleted by human use, but can also be replenished, thus maintaining a balance. Some of these, like agricultural crops, take a short time for renewal; others, like water, take a longer time, and others, like forests, take even longer. All of these resources are considered to be ''free'' because they can renew themselves at no cost without human intervention if the resources are managed sustainably. Large countries tend to have a richer store of renewable resources. Brazil had the highest total use of renewable emergy, followed by China, Canada, and Russia (Table 2, Supplemental Fig. S1a).

Nonrenewable resources form over very long (geological) periods. Minerals and fossil fuels are included in this category. Since their rate of formation is extremely slow, they cannot be replenished on a human time scale once they are depleted. Some of these substances, such as metals, can be reused by recycling them, but others, such as coal and petroleum, cannot be recycled. Although nonrenewable resources take a long time to form, they have a high energy quality and a correspondingly high transformity (Odum, 1996). The United States had the highest consumption of nonrenewable emergy, followed by the China, Russia, Australia and India (Table 2, Supplemental Fig. S1b). Saudi Arabia consumed a surprisingly high amount of nonrenewable resources (driven primarily by consumption to exploit the fossil fuels that are the country's primary exports). However, Saudi Arabia is rich in oil and related products, and exported most of these resources.

The United States had the highest total use of economic emergy, followed by China, Germany, Russia and Japan (Table 2, Supplemental Fig. S1c). Germany 's high rank (driven primarily by imports) is somewhat surprising, but could perhaps be explained by the amount of manufacturing it performs for the world market.

Thailand had the highest total emergy money ratio (EMR), followed by Indonesia, Russia, Saudi Arabia, India, China and South Africa (Table 2, Supplemental Fig. S1d). Japan ranked last because its economy is driven primarily by imported resources consumed to produce exported products.

When expressed in terms of EMR, the most industrialized nations have the lowest ratios, suggesting that less emergy is consumed per unit of GDP in developed economies than in developing economies. On the other hand the countries with the highest ratios had the smallest GDPs, and higher EMR values indicate greater vulnerability of an economy to resource imperialism by developed economies, which all have lower EMR. These were often countries that supply raw resources to world markets instead of developing their own domestic industrial infrastructure (Brown et al., 2009). However, as Brown et al. (2003) noted, the currencies of developed economies have greater buying power in developing economies, thus capital investment flows continuously from developed economies to developing ones to pay for imports of resources by the developing nations.

The United States had the highest total emergy use, followed by China, Russia and India (Table 2, Supplemental Fig. S1e). The fact that Russia ranked third duo to its rich natural resources. For the total emergy consumption (natural+economic), the United States ranked first, followed by China, Russia, Brazil, Australia and Canada (Table 2, Supplemental Fig. S1f). The fact that Russia

Table 1
Definitions of the emergy parameters used in the data in Table 2.

Parameter	Variable name	Description
R	Renewable emergy flows	The largest terrestrial renewable flow+tide
N	Total nonrenewable emergy flows	The sum of extraction of indigenous nonrenewable resources
N_0	Dispersed nonrenewable flows	The sum of forestry, fisheries, soil, and water resource extraction
N_1	Concentrated nonrenewable flows	The sum of fuel, metal, and mineral production minus N_2
N_2	The portion of N_1 exported without use	The sum of raw fuel, metal, and mineral exports
$F_{(i)}$	Imports of fuels, metals and minerals	The sum of fuels, metals, and minerals that are imported
$G_{(i)}$	Imports of goods and electricity	The sum of other imported goods and electricity
I	Dollars paid for imports	Services included in imports ($ value)
P_2I	Emergy of services in imports	Services in imports ($) $\times$ world emergy per dollar ratio
$F_{(e)}$	Exports of fuels, metals and minerals	The sum of the fuels, metals, and minerals exported ($ value)
$G_{(e)}$	Exports of goods and electricity	The sum of other exported goods and electricity
E	Dollars received for exports	Services received in exchange for exports ($ value)
P_2	World emergy money ratio (EMR)	Total global emergy use/gross world product
P_1	National emergy money ratio (EMR)	National emergy use/gross domestic product

Note: The factor definitions were obtained from Sweeney et al. (2007). For *R*, only the largest flow is included to avoid double-counting.

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Table 2
Emergy consumption data for 17 mainstream nations and for all 134 nations in the University of Florida database[a].

Name	Renewable emergy	Non renewable	Free	Nature	Imported	Exported	Economy[b]	EMR	Population	Total use	Total consumption
Calculation	R	$N_0+N_1+N_2$	$R+N_0$	$R+N$	$F_{(i)}+G_{(i)}+P_2I$	$F_{(e)}+G_{(e)}$ $+P_1E+$tourism	High value of Imported or Exported	Total use / GDP		$R+N_0+N_1$ +Imported	Nature +Economy
All 102 nations	3.73×10^{25}	1.11E+26	4.08E+25	1.48E+26	1.25E+26	1.42E+26	1.42E+26	4.48E+12	5.88E+09	2.60E+26	2.90E+26
United States	2.28E+24	1.95E+25	2.40E+24	2.18E+25	1.26E+25	6.47E+24	1.26E+25	2.38E+12	3.04E+08	3.41E+25	3.43E+25
China	3.35E+24	1.79E+25	3.53E+24	2.13E+25	9.79E+24	5.89E+24	9.79E+24	6.82E+12	1.32E+09	3.08E+25	3.10E+25
Russia	2.60E+24	9.54E+24	2.75E+24	1.21E+25	1.78E+24	6.92E+24	6.92E+24	7.20E+12	1.41E+08	1.20E+25	1.91E+25
Canada	3.07E+24	3.27E+24	3.09E+24	6.34E+24	2.34E+24	3.72E+24	3.72E+24	5.23E+12	3.32E+07	7.83E+24	1.01E+25
Brazil	3.53E+24	4.52E+24	4.12E+24	8.05E+24	1.21E+24	3.05E+24	3.05E+24	4.52E+12	1.96E+08	7.40E+24	1.11E+25
Mexico	4.08E+23	2.30E+24	4.75E+23	2.71E+24	2.83E+24	1.73E+24	2.83E+24	4.64E+12	1.10E+08	5.05E+24	5.54E+24
Australia	2.36E+24	5.05E+24	2.39E+24	7.41E+24	1.05E+24	3.59E+24	3.59E+24	5.68E+12	2.10E+07	5.91E+24	1.10E+25
Japan	1.99E+23	1.80E+24	2.06E+23	1.99E+24	5.72E+24	2.63E+24	5.72E+24	1.57E+12	1.27E+08	7.68E+24	7.72E+24
United Kingdom	2.38E+24	1.75E+24	2.40E+24	4.14E+24	3.49E+24	2.33E+24	3.49E+24	2.75E+12	6.19E+07	7.33E+24	7.62E+24
India	1.51E+24	4.95E+24	2.02E+24	6.46E+24	2.33E+24	1.44E+24	2.33E+24	6.88E+12	1.14E+09	8.35E+24	8.79E+24
Indonesia	1.78E+24	1.76E+24	1.88E+24	3.54E+24	1.10E+24	1.73E+24	1.73E+24	8.08E+12	2.38E+08	4.13E+24	5.27E+24
Germany	5.21E+22	8.03E+23	6.73E+22	8.56E+23	7.03E+24	3.92E+24	7.03E+24	2.15E+12	8.24E+07	7.81E+24	7.88E+24
Italy	6.75E+22	4.63E+23	7.55E+22	5.30E+23	3.78E+24	1.70E+24	3.78E+24	1.87E+12	5.82E+07	4.30E+24	4.31E+24
France	6.18E+23	1.77E+23	6.27E+23	7.95E+23	4.15E+24	1.86E+24	4.15E+24	1.72E+12	6.26E+07	4.91E+24	4.95E+24
South Africa	1.64E+23	1.77E+24	1.97E+23	1.93E+24	5.64E+23	1.49E+24	1.49E+24	6.35E+12	4.88E+07	1.76E+24	3.42E+24
Thailand	1.89E+23	1.85E+24	2.24E+23	2.04E+24	1.20E+24	2.61E+24	2.61E+24	1.15E+13	6.62E+07	3.14E+24	4.65E+24
Saudi Arabia	8.03E+22	4.17E+24	1.18E+23	4.25E+24	6.80E+23	4.34E+24	6.80E+23	7.17E+12	2.49E+07	3.41E+24	4.93E+24

Notes: Countries are arranged in order of decreasing total emergy consumption.

[a] Data provided by Dr. S. Sweeney (University of Florida, Gainesville, personal communication, 2011).
[b] Whether imported or exported emergy is higher determines the main direction of an economy and can therefore be used to represent the economy's emergy. See Section 2.2 for details.

ranked third was surprising, but this was undoubtedly driven primarily by its huge area and rich natural resources.

The ratio of economic emergy to natural emergy is a measure of economic efficiency, but also indicates the pressure on a nation's resources. If the ratio is greater than 1, this means that local sources of emergy are insufficient to sustain its economy's activity. That is, since economic emergy measures the sum of *F*, *G*, and imports or exports (whichever of the two is greater), it is a measure of the emergy in imports that can be "purchased" by sales of emergy. If a nation imports raw resources and exports finished products, then the efficiency ratio will be higher because, dollar for dollar, the emergy in finished products is lower than that in raw resources.

The developed industrial countries (Germany, Italy, France, Japan, Thailand and Mexico) had a ratio of economic emergy to natural emergy greater than 1 (Table 2, Supplemental Fig. S1g). Those with little or no resource base import large quantities of emergy while exporting far less emergy, and thus place high pressure on their resources. Germany places the greatest pressure on its resources. The export-driven countries (Saudi Arabia, India, Brazil, China, Australia, Indonesia, Russia, United States, Canada, South Africa and United Kingdom) have an efficiency ratio less than 1. The average ratio of the 102 nations was 0.96.

3.2. *Per capita emergy consumption for the 17 nations*

The values of the per capita emergy consumption parameters can indicate the sustainability of a nation when these values are compared with the corresponding resource carrying capacity. Table 3 presents the data for the 17 nations, and Fig. 3 presents the values visually to facilitate comparisons with the average value, represented by the horizontal line.

One measure of a nation's natural richness is the per capita free emergy that is available from renewable resources and dispersed nonrenewable sources. Although the renewable resources can be replenished easily, or remain continuously available (e.g., sunlight, air, wind), they have a low energy quality and a lower emergy transformity (Odum, 1996). Fig. 3(a) shows the per capita free emergy of the 17 countries. Large flows of renewable emergy dominated the countries with high per capita free emergy, with the greatest value for Australia, followed by Canada. Both countries have large areas but sparsely populated interiors, and gain nearly 40% of their total use per capita emergy from renewable sources. Eight countries had a per capita free emergy greater than the global average level, which means that they consume a disproportionate share of the world's renewable emergy sources. Italy, Japan, India, and China had very low per capita free emergy resources.

The renewable environmental energies such as wind, geothermal, and tidal energy only occur at intensities sufficient to provide net energy in limited areas of the planet, thus their total contribution will not replace a large proportion of current global energy needs. These dispersed renewable resources therefore cannot be efficiently utilized based on current technology, and countries with abundant renewable resources such as Australia and Canada, despite their high per capita free resource carrying capacity, waste or underutilize most of these resources because of the difficulty of economically exploiting them.

Fig. 3(b) shows the per capita natural emergy for the 17 countries. The countries with the highest per capita natural emergy are countries that have a large area, relatively large stores of nonrenewable flows, and relatively small population densities. This is why Australia has the highest per capita natural emergy, followed by Canada and Saudi Arabia; the latter's high value is driven primarily by the country's rich fossil fuel resources. Nine countries have a per capita natural emergy above the global average, which means that they consume a disproportionally high proportion of global natural resources, thereby weakening overall sustainability. India, Italy, Germany, France, Indonesia, and China consumed much less natural resources per capita than the other countries.

Fig. 3(c) shows the per capita economic emergy values for the 17 countries. The countries with the highest per capita economic emergy are industrialized countries with relatively small population densities. Thirteen countries had a per capita economic emergy greater than the global average, which means that their economy was too dense and exerted too much pressure on the global environment. India, Indonesia, and China consumed much less economic emergy per capita than the other countries.

Fig. 3(d) shows the total per capita emergy use for the 17 countries. The countries with the highest total per capita emergy use are countries with a large area, relatively large flows of

Table 3
Per capita emergy consumption by the 17 nations compared in the present study. Data provided by Dr. S. Sweeney (University of Florida, Gainesville, personal communication, 2011).

	Emergy category (per capita sej)					
	Free	Nature	Economy	Total use	Total consumption	Total use/Total consumption
All 102 nations	6.94E+15	2.52E+16	2.41E+16	4.42E+16	4.93E+16	0.90
United States	7.90E+15	7.15E+16	4.13E+16	1.12E+17	1.13E+17	0.99
China	2.68E+15	1.61E+16	7.43E+15	2.34E+16	2.36E+16	0.99
Russia	1.95E+16	8.63E+16	4.92E+16	8.53E+16	1.35E+17	0.63
Canada	9.31E+16	1.91E+17	1.12E+17	2.36E+17	3.03E+17	0.78
Brazil	2.10E+16	4.10E+16	1.55E+16	3.77E+16	5.65E+16	0.67
Mexico	4.32E+15	2.46E+16	2.57E+16	4.59E+16	5.03E+16	0.91
Australia	1.14E+17	3.53E+17	1.71E+17	2.81E+17	5.24E+17	0.54
Japan	1.62E+15	1.57E+16	4.49E+16	6.04E+16	6.06E+16	1.00
United Kingdom	3.87E+16	6.68E+16	5.63E+16	1.18E+17	1.23E+17	0.96
India	1.77E+15	5.66E+15	2.04E+15	7.32E+15	7.71E+15	0.95
Indonesia	7.92E+15	1.49E+16	7.29E+15	1.74E+16	2.22E+16	0.78
Germany	8.17E+14	1.04E+16	8.53E+16	9.48E+16	9.57E+16	0.99
Italy	1.30E+15	9.12E+15	6.49E+16	7.39E+16	7.40E+16	1.00
France	1.00E+16	1.27E+16	6.63E+16	7.84E+16	7.90E+16	0.99
South Africa	4.04E+15	3.96E+16	3.05E+16	3.60E+16	7.01E+16	0.51
Thailand	3.38E+15	3.08E+16	3.94E+16	4.74E+16	7.02E+16	0.68
Saudi Arabia	4.72E+15	1.71E+17	2.73E+16	1.37E+17	1.98E+17	0.69

Notes: Countries are arranged in order of decreasing total emergy consumption.

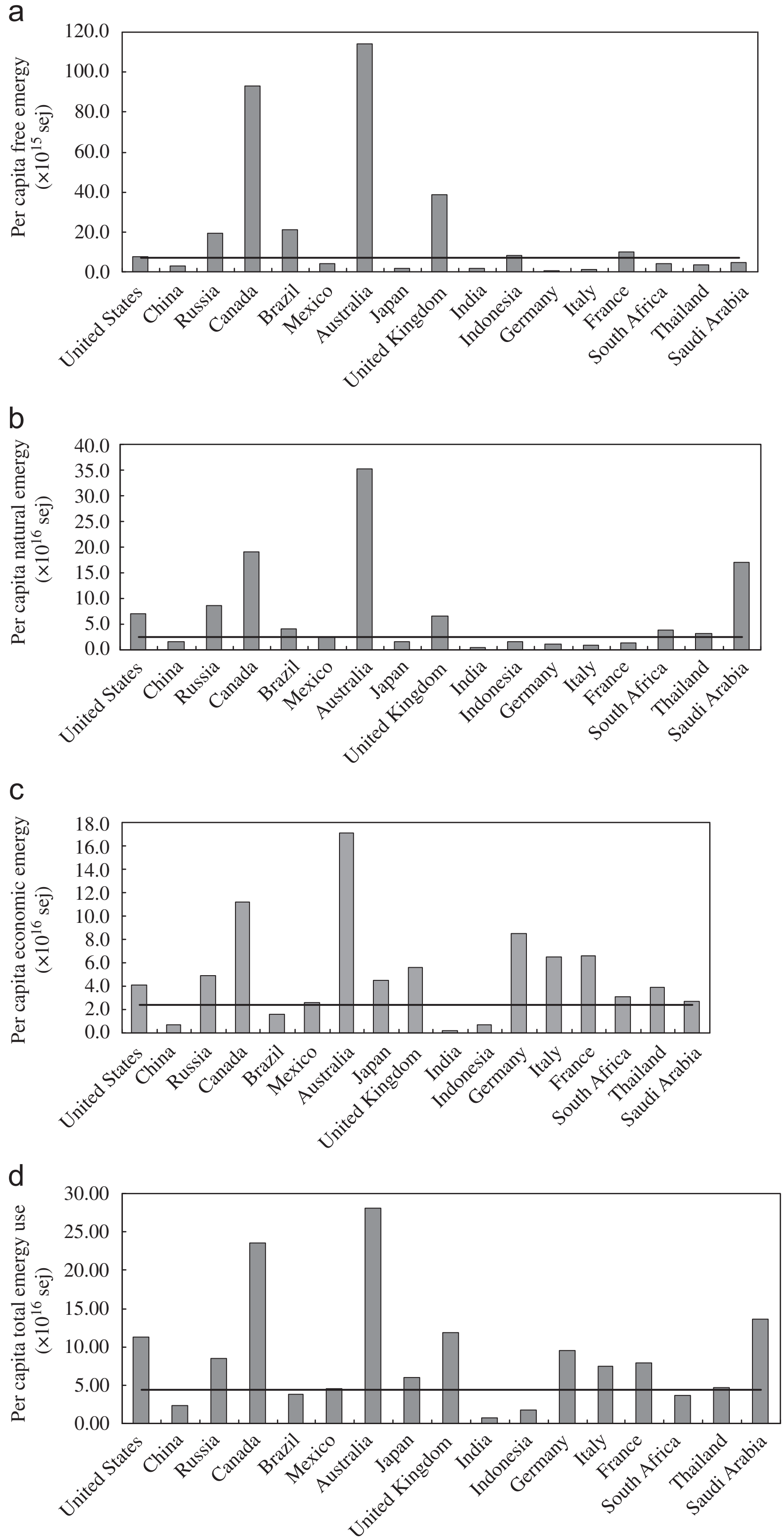

Fig. 3. (a) Per capita free emergy values for the 17 nations. The horizontal line represents the mean value for the 102 nations in the NEAD database. (b) Per capita natural emergy values for the 17 nations. The horizontal line represents the mean value for the 102 nations in the NEAD database. (c) Per capita economic emergy values for the 17 nations. The horizontal line represents the mean value for the 102 nations in the NEAD database. (d) Per capita total emergy use values for the 17 nations. The horizontal line represents the mean value for the 102 nations in the NEAD database.

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nonrenewable emergy, and relatively small population densities. Twelve countries had a total per capita emergy use greater than the global average, with Australia highest, followed by Canada and Saudi Arabia. This means that they consume too much emergy compared with citizens of other countries. India, Indonesia, and China had lower total per capita emergy use than the other countries.

It is increasingly being suggested that humanity should shift the global economy's driving energies from fossil fuels to more renewable forms of energy such as solar, wind, tidal, or biomass energy. Unfortunately, each of these renewable resources is less concentrated than fossil fuels and therefore has lower energy quality. To utilize these resources to power the complex tasks required by modern information and industrial economies will require that these energies be upgraded to a quality commensurate with the economy's requirements (i.e., technology must be improved sufficiently that these sources can replace nonrenewable sources in the quantities that are currently consumed). Many analyses (e.g., Brown et al., 2009) of the emergy available from renewable resources suggest that we cannot shift to renewable resources and still provide enough energy to meet current demand, much less the projected future demand created by increasing populations and consumer-driven demand for improved quality of life. Biomass energy is a particular problem because it requires large areas of arable land and huge quantities of water, and thereby increases competition for these resources between food and energy crops.

3.3. National emergy consumption and sustainability conditions

The per capita total emergy consumption measures human consumption in terms of the solar energy needed to create the natural resources and sustain the global economy. Fig. 4 concisely summarizes the sustainability of per capita emergy consumption for the 17 nations compared with the mean strong, weak, and economic sustainability levels based on the global average emergy values. The strong sustainability line represents the average per capita free emergy of the 102 nations in the NEAD database in 2008, whereas the weak sustainability line represents the average per capita natural emergy in 2008 and the economic equity line represents the average per capita total emergy consumption in 2008. We found that all 17 countries had consumption greater than the strong sustainability line, which means that their style of emergy consumption is unsustainable in the long term. India, Indonesia and China had consumption values below the weak sustainability line, which means that both countries consume less natural emergy than the global average. The United States, Russia, Canada, Brazil, Mexico, Australia, Japan, the United Kingdom, Germany, Italy, France, South Africa, Thailand, and Saudi Arabia also consumed more than the economic equity line. Australia consumed the most emergy per capita, followed by Canada, Saudi Arabia, and the Russia. We found that the Asian countries used less emergy per capita than Australia, North American and European countries. Although China used the third-lowest total per capita emergy per year, this is because the nation's high population decreased the average per capita emergy consumption.

In 2008, the global per capita emergy consumption was 49.35×10^{15} sej, which was 1.96 times the global per capita natural ($R+N$) carrying capacity (25.20×10^{15} sej). This indicates that humans are not living within the planet's natural resource carrying capacity.

One important solution will be to reduce total emergy use in developed economies. Reducing emergy consumption per capita means reducing total emergy use, and this will require a change in consumption habits to avoid waste and the development of more efficient technologies. Without such measures, emergy constraints will increasingly slow GDP growth. The competitive stance of economies that do not change their structure fast enough to avoid this problem will decline in comparison with their competitors unless all developed economies agree to decrease their total resource consumption equally. This was one of the intended consequences of the Kyoto Protocol, but unless all the major developed economies implement the measures specified by this international treaty, they will see their competitive advantage and their economy decline.

Our comparison of the per capita emergy consumption in the 17 countries reveals which nations are on sustainable resource utilization trajectories and which ones will exacerbate the current global resource squeeze. Only 3 of the 17 countries consume less per capita emergy than the global average per capita natural carrying capacity. Only one country (India) is on a strongly sustainable road.

3.4. Comparison the value of per capita emergy category between 2000 and 2008

The International Energy Agency (IEA) regularly publishes a report on world consumption for most types of primary energy resources. According to IEA total world energy supply was 102,569 TWh (*i.e,*

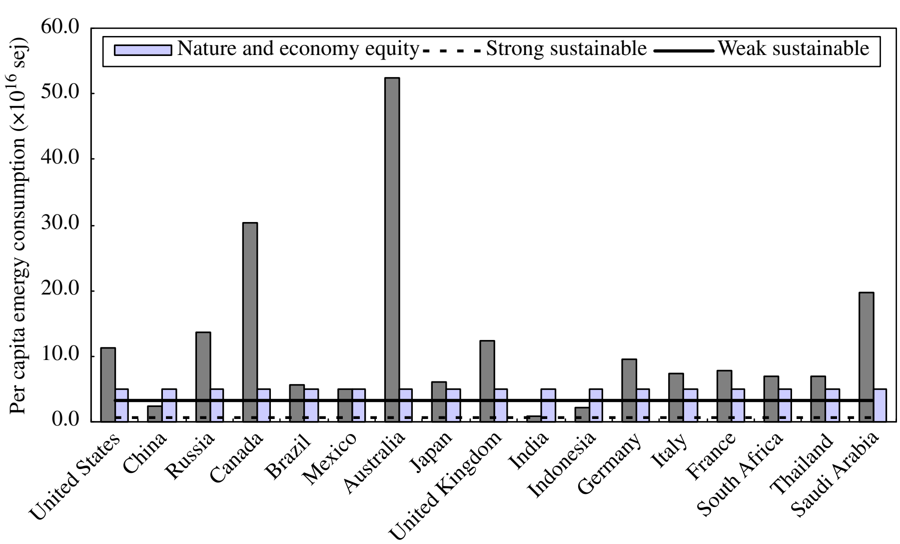

Fig. 4. National per capita total emergy consumption and the resulting level of sustainability.

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Table 4
Comparison of per capita emergy category between 2000 and 2008 in the present study.

	Emergy category (per capita sej)				
	Free	Nature	Economy	Total use	Total consumption
All 102 nations of 2008	6.94E+15	2.52E+16	2.41E+16	4.42E+16	4.93E+16
All 134 nations of 2000	7.66E+15	1.85E+16	1.69E+16	2.79E+16	3.54E+16
Ratio of 2008 to 2000	0.91	1.36	1.43	1.58	1.39

Notes: All 134 nations data of 2000 are from Sweeney et al. (2007), all 102 nations data of 2008 are provided by Dr. S. Sweeney, University of Florida, Gainesville, personal communication (2011).

terawatt hour, 1 TWh $=10^{12}$ Wh) (1990), 117,687 TWh (2000) and 143,851 TWh (2008). World oil prices raised in the past 10 years, oil consumption continued to grow to meet rising demand.

In 2008, total worldwide energy consumption was 474×10^{18} J. From 1990 to 2008 the average use of energy per person as IEA data increased 10% and the world population increased 27%, that result the energy use grew from 1990 to 2008 increased to 39% in the world (The International Energy Agency, 2011).

National Environmental Accounting Database (NEAD) provided an automated system that stores and supplies the necessary data, processes the data using standardized conversions, and computes the standard tables of line items, summary flows and indices. The NEAD data would be immensely helpful for creating emergy accounts of individual nations, as well as providing fast, efficient and standardized sets of accounts for comparative purposes (Sweeney et al., 2007). Here we cited the all NEAD nations data of 2000(Sweeney et al., 2007) and 2008 provided by Dr. S. Sweeney, University of Florida, Gainesville, personal communication (2011), and then compiled to Table 4, which lists the per capita emergy consumption categories, and the related ratio between 2000 and 2008. During the period from 2000 to 2008, accompanied with rapid growth of population and economy, and increased resources consumption, the per capita free emergy value in 2008 became 0.91 times the 2000 value, while the per capita natural emergy value was 1.36 times, the per capita economy emergy value was 1.43 times, per capita total emergy use value was 1.58 times, per capita total emergy consumption value was 1.39 times.

Energy consumption is loosely correlated with GDP and climate. The US consumes 25% of the world's energy with a share of global GDP at 22% and a share of the world population at 4.59% (United Nations, 2011). The most significant growth of energy consumption is currently taking place in China, which has been growing at 5.5% per year over the last 25 years. International Energy Outlook 2011 released by the U.S. Energy Information Administration presents updated projections for world energy markets through 2035. According to the report, worldwide energy consumption grows by 53 percentages between 2008 and 2035 in the Reference case, with much of the increase driven by strong economic growth in the developing countries especially China and India. China and India lead the growth in world demand for energy in the future. They continue to lead world economic growth and energy demand growth. In 2008, China and India combined accounted for 21 percentages of total world energy consumption.

4. Conclusions

Our results and those of previous studies confirm that environmental sustainability can be measured. We believe emergy analysis is a powerful tool, and select it to quantify nation's utilization of resources. By comparing the global resource carrying capacity with the resource consumption by 17 nations, we provided a clear image of each nation's sustainability condition. Our results provide insights that will guide local, national, and global efforts to close the sustainability gap. The emergy sustainability analysis we have described is an effective strategic planning tool that can lead nations to a more secure, equitable, and sustainable future.

Our analysis provides additional strong evidence that the world's store of nonrenewable resources is being used unsustainably, since most countries consume nonrenewable fossil fuels at a rate far greater than the world's ability to replenish these resources. Declining supplies means that the energy available for use by society will decline with increasing speed as the global population increases and as citizens of developing nations begin to demand a quality of life comparable to that in developed nations. In other words. it will take more energy to generate energy, and more emissions of pollutants and greater environmental destruction will result from production of the same amount of useful power. Although shifting towards greater use of renewable forms of energy is desirable, each of the renewable sources is far less concentrated than fossil fuels and therefore has lower energy quality; this means that it is not possible to meet current demand by shifting to these energy sources without large improvements in the underlying technologies (Brown et al., 2009).

Our data confirms previous suggestions that humanity exerts too much pressure on the Earth. Humanity's average per capita free emergy carrying capacity is 6.94×10^{15} sej. However, we consume 49.35×10^{15} sej per capita of natural emergy. This means that the average emergy consumption is 7.12 times the available renewable emergy. This imbalance indicates that humanity's consumption exceeds what nature can provide on a continuous basis, and indicates that we are following a dramatically unsustainable road. We found that all countries except India exceeded the sustainable level of emergy consumption at the strong sustainability level. China and Indonesia consumed less than the level at the weak sustainability line, which means that both countries use less emergy than the average global per capita natural emergy consumption.

Developing strategies to reduce resource consumption will be an important approach. Emergy consumption can be reduced by increasing the efficiency of resource use (e.g., energy-saving light bulbs, high-efficiency wood stoves, solar-heated warm water) and by reducing consumption (e.g., working less, spending less). The proportion of total resource use derived from renewable sources is calculated based on the total input from renewable sources divided by a country's area. The area cannot be increased, since it represents the total available input, thus to increase the proportion of renewable sources and thereby increase a nation's sustainability requires either confiscating land elsewhere or reducing the use of nonrenewable emergy.

Odum and Odum (2001) have outlined principles and policies to guide the transition from our current growth ethic, which assumes that we can grow our way out of any problem, to an ethic that is sustainable in the long run. They suggest that the

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only real solution will be a contraction of national economies, a decline in overall energy consumption and productivity, and reducing populations at the same rate as the decrease in available annual emergy—in short, to consume less emergy than is available. It will soon become necessary to accept a decreasing development style to increase the probability of long-term human survival.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2011.12.030.

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