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GLOBAL TRANSITION TO SUSTAINABLE DEVELOPMENT

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ABSTRACT

Global transition to sustainable development is possible but many obstacles lie in the way and it will require acts of political will on the part of both the developed and developing nations to become a reality. In this paper, sustainable development is defined as continuous progress toward higher states of human well-being given the constraints supplied by available resources at any particular time. This concept is examined from the perspective of Energy Systems Theory and the cycle of change that results from the slow accumulation and rapid consumption of energy and material resources. Human well-being depends on necessary inputs from the environment (clean air and water, living space), economy (fuels, materials, economic products) and society (information, *sensu lato*). Empower from these three sources minus detrimental effects (pollution, crime, etc.) expressed per person is proposed as the measure of human well-being. A theoretical argument is promulgated to show that sustainable development is possible. This argument was based on the trade-off between the intensity of energy use in economic production and environmental quality that makes it possible for human well-being to improve by decreasing fossil fuel consumption in developed nations and by increasing it in developing nations. Environmental accounting using emergy is proposed as a method for documenting environmental assets and liabilities to determine if any development alternative is sustainable, *i.e.*, assets must be sufficient to balance liabilities for an entity to be solvent. Several environmental assets and liabilities are evaluated for the countries of South and North America and then the two continents are compared. Three factors which could facilitate a global transition to sustainable development are: (1) the willingness of developed nations to decrease petroleum consumption, (2) the willingness to determine trade equity using emergy measures, and (3) the willingness to examine the distribution of wealth from the perspective of the emergy return to the whole system as a result of the emergy invested to support power and privilege.

1. INTRODUCTION

Sustainable development was proposed as a model to guide global economic development by the World Commission on Environment and Development, otherwise known as the Bruntdland Commission (WCED [1]). The Brundtland Commission defined sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. While this statement is laudable, it does not reflect the reality of limited global fossil energy reserves, which will result in a changing suite of energy resources to support society in the future. Nor does it recognize the imperative of evolutionary competition that drives societies to build organizational structures that maximize empower use now (Lotka's maximum power principle [2] as modified by Odum [3]). The strategies that maximize empower in a system will vary based on the energy that is available at any given time. Thus, development follows a cycle of change from rapid growth on abundant resources through climax and descent as resources peak and decline to a lower energy state in which resources are renewed (Odum [4], Holling [5], and Campbell [6]). In this cycle of change, human needs may be the same from one stage to the next, but the resources available to satisfy human needs at one stage of the cycle may be very different from those that will be present in the next. Different management actions, human attitudes, and patterns of interaction are required to maximize well-being in each stage of the cycle. For example, more efficient energy use and mutual cooperation appear to maximize empower under stable or declining energy resources. Under the intergenerational equity guidelines proposed by the Brundtland Commission, people in one stage have the obligation to plan for the welfare of their descendants who will be living in the next stage of the cycle. In this paper, sustainable development is defined differently. For our purposes, sustainable development simply means that a system, such as a state, a nation, or the world will become, continually, a better place for its inhabitants to live given the energy resource base that is available at any particular time. Thus in the present time, it must be possible for the well-being or quality of life experienced by people in both developed and underdeveloped countries to improve. This definition is better suited to answering the question, "Is it possible for the world to undergo a global transition to sustainable development?" Our definition is not materially different from that of the Brundtland Commission in its consequences for the nations and people of the world. Both definitions imply that satisfying the essential needs of the poor will be a priority consideration under sustainable development strategies as will the availability of resources, the application of technological "know-how" (*e.g.* in energy efficient technologies and designs), and the transfer of technology and information to the developing world, which will allow all of humanity to satisfy its needs. Enlightened self-interest that creates a sustainable world in the present may result in the best possible world for future generations.

2. THE ENERGY SYSTEMS APPROACH

Odum [4, 7] synthesized knowledge from general systems theory (von Bertalanffy [8, 9]), irreversible thermodynamics (Prigogine [10], DenBigh [11]), and ecology (Odum [12]) into a comprehensive approach (Energy Systems Theory) applicable to all natural phenomena. This methodology provides general explanatory principles (e.g., the maximum empower principle, the energy hierarchy law, and the pulsing paradigm) through which the phenomenological universe can be understood and interpreted. Odum realized that energy can be used as a general accounting tool if (1) the transformation of energy underlies all phenomena and (2) if the energy previously used up directly and indirectly to make any item can be accounted for as energy of one kind (e.g., solar emjoules). Odum's research led to the formulation of a powerful new concept, *emergy* (Odum [3]), which can be used to express all phenomena on a common basis so that the quantities of different things (e.g. iron, corn, oil, and human labor) are made directly comparable. *Emergy* is the available energy of one kind previously used up directly and indirectly to make a product or service. Its unit is the *emjoule*. Emergy can use any kind of energy as the common base, for example coal joules, solar joules, etc. However, in evaluating environmental systems, we commonly use solar energy as the base unit. *Solar emergy* is the available solar energy used up to make a product or service in an ecological or economic system. Its unit is the *solar emjoule* (abbreviated sej). *Available energy* is energy with the capacity to do work sometimes called *exergy* (Odum [3] p.264-267). *Empower* is the emergy flow per unit time and *empower density* is the emergy flux per unit area. Energy Systems Theory (Odum [4,7,13]) was used as a context for understanding and interpreting the idea of sustainable development and for defining what is meant by increased human well-being. Odum [3] proposed that human well-being was the result of a necessary interaction between the environment, fuel, minerals, and other economic resources and societal information and that well-being was diminished by energy drains that are detrimental to one or more of these factors, e.g., pollution, interrupted oil supplies, and crime. In this definition information includes all energy flows carrying information. Genes, books, computer programs, art music, television communications, human culture, political interactions and religious communications are all examples of information, in the broad sense. Characterization of the properties of national systems using this approach may help determine if transition to a state of global sustainable development is possible. The maximum power principle (Lotka [2]) provides a general criterion for identifying system designs that will succeed in evolutionary competition, i.e., this principle, as modified by Odum [3], states that designs that maximize system empower (emergy per unit time) will prevail in competition with others. As a working hypothesis, let us assume that an increase in human well-being can be measured by the increase in the product of environmental, social, and economic empower supporting an environmental system after total empower has been diminished by any detrimental impacts. One criterion for judging whether one system state is an improvement over another is that the emergy used per person in support of human welfare increases as a result of a given policy. To determine if a given state of development and the concomitant state of human welfare in a country is reasonable and appropriate relative to the state of development in other countries and in the world, the empower of the national system must be evaluated within the context of its resource base and the matching that the resource base can attract from the available emergy resources of the global system under the condition of equal emergy exchange in trade. Following emergy guidelines in trade will not make everyone in the world equally well-off, but the welfare of the people in each country will be as high as possible given the prevailing conditions.

3. THE PULSING PARADIGM AND THE CYCLE OF CHANGE

According to the maximum empower principle, system designs that maximize empower prevail in competition; therefore, Nature's ubiquitous patterns may be considered to be the result of such designs. Pulsating systems are common on all scales of organization and may be an example of maximum power design (Odum [14]). W.E. Odum et al. [15] proposed the pulsing paradigm of system organization to replace the old concept of growth followed by steady state. Systems with coupled pairs of components can oscillate and such pairs are found on all hierarchical levels of organization (Figure 1).

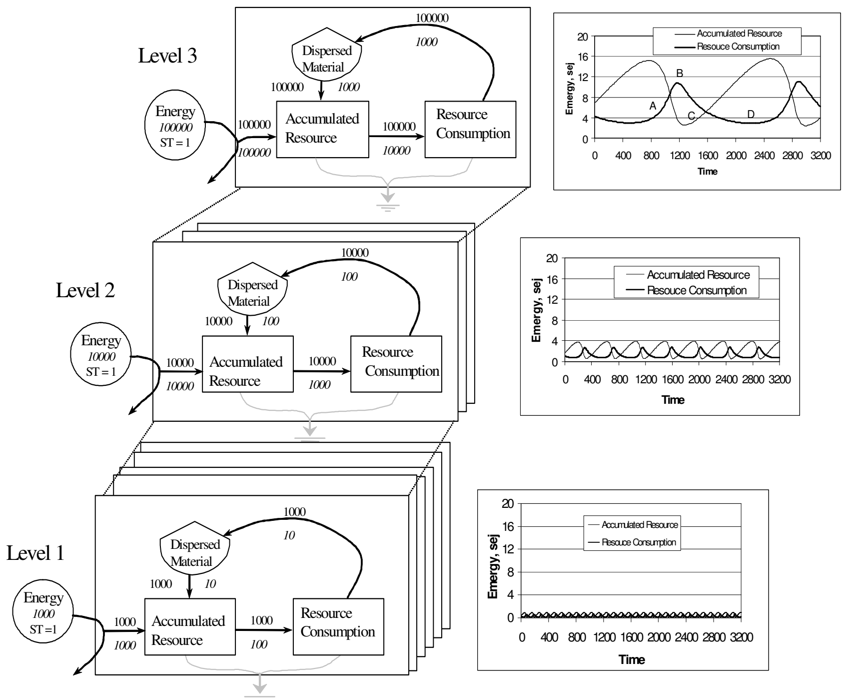

Figure 1. The hierarchical structure of pulsing pairs that produces cycles of change on many scales of space and time

Pulsing pairs contain one component, the accumulator, that slowly builds up resources and a second component, the frensor that rapidly consumes the accumulated resources once they pass a threshold. The pulsing paradigm for ecosystem development implies that a cycle of change is the fundamental characteristic of environmental systems rather than development through a series of stages to a climax condition that is sustainable. The cycle of change (Holling's figure 8) moves through four phases (1) exploitation, (2) climax or conservation, (3) creative destruction, and (4) renewal (Holling [5]). Figure 1 shows the cycle of change as a hierarchical wave function with the successive phases identified (Campbell [6], Odum [16]). The cycle of change supplies a time dimension for the efficacy of sustainable development strategies.

Sustainable development must be understood and analyzed within the context of a cycle of change for it to be a meaningful concept. Since the energy resource base supporting potential development in each phase of the cycle is changing, e.g., the rapid consumption and depletion of fossil fuels over the last 150 years, the designs that result in maximum human well-being as measured by empower per capita will also change in each stage. Also, substantial changes in the resource base within a stage may require changes in the sustainable development strategies used. We can expect human attitudes to change as a function of our position in the cycle of change and the energy resources available to support that stage in the cycle. The moral attitudes that we might expect to be accepted broadly by society based on the different system characteristics that are predicted to maximize system empower in each stage of the cycle of change are shown in Table 1.

Table 1. Stages in the cycle of change showing available energy sources for each stage, and the morality that may govern the stage

Stage in the Cycle	Available Energy Sources	Morality
(1) Exploiting resources (Rapid Growth)	Abundant primary nonrenewable sources.	Our children will have more material wealth than we do.
(2) Conserving resources (Climax)	Diverse primary and secondary sources both nonrenewable and renewable.	We will meet our needs without compromising the needs of our children.
(3) Creative destruction (Decline)	Declining nonrenewable sources diverse renewable sources.	We will do more with less, so our children may have less material wealth but life will be better.
(4) Replenishing resources (Renewal)	Primarily, renewable energy sources.	We plan for the 7th generation of our children.

A problem arises because broadly accepted moral attitudes tend to lag behind the exigencies of the times, thus transitions from one stage to the next may be difficult.

Finding the best system designs to maximize human well-being in the present stage in the cycle is one great challenge that scientists and managers must face. The second and more difficult challenge is to look ahead and plan sustainable development strategies for the next stage in the cycle (Odum and Odum [17]). This second task is often given little attention by policy makers because of the weight that past experience receives in making future predictions and because most people have difficulty understanding present events within the context of the next larger system. The larger system produces the trends that affect the system of concern, and therefore, an understanding of dynamics on this larger scale is a necessary prerequisite for accurate prediction of the future. This second task is particularly important because of the possibility of catastrophic change (a crash), when the energy resources of the present exceed those that will be available in the future.

4. WHERE ARE WE NOW?

M. King Hubbert [18, 19] predicted that peak petroleum production in the U.S. would occur in 1970, which the history of U.S. petroleum production has verified (Campbell and Laherrere [20]). Using a similar model, Campbell and Laherrere [20] predicted that peak oil production for the world will occur around the present time. If they are right, we are already into the 2nd stage of the cycle where conserving global oil and other fossil fuel resources will become ascendant. This development cycle has been in a rapid growth phase supported by fossil fuel use (primarily liquid petroleum) for the past 150 years. At this time, if we follow the guidelines given above, we must develop strategies to maximize human well-being as global oil resources peak, while planning for the descent in global liquid petroleum production, which will inevitably come. The global energy picture is complicated because oil is only one of several fossil fuel and mineral resources; however, all are finite and in various stages of their production cycles. We can expect a similar cycle of production to play out for each of them, because a common model drives the exploitation of nonrenewable resources by society (Odum and Odum [21]). The mix of fossil fuel, other mineral (uranium), and renewable energy sources available at any given time will determine the system designs and strategies that lead toward a state of sustainable development for that particular phase in the conservation of resources stage. The criteria for judging the efficacy of alternatives was given above.

The characteristics of the energy resource base differ from one nation to another and individual nations find themselves in earlier or later phases of the cycle of change driven by resource use in both the national and global systems. Strategies promoting mutual cooperation and increased efficiency in the use of energy apparently bring about the highest levels of well-being (maximum empower) in all stages other than the initial phase of rapid exploitation (Odum [13]). Our present challenge in bringing about a transition to global sustainable development is how to balance the need for energy to support economic growth in the underdeveloped (poorer) nations with the over consumption of resources by the world's developed (richer) nations. One solution often proposed is for the developed nations to conserve resources (ostensibly for use by the poorer nations) through greater efficiency in the use of energy and mineral resources to support economic production. This strategy has proven to be largely ineffective because of Jevons paradox (Jevons [22]) where the conservation of resources through greater efficiencies in one economic use or sector leads to the expenditure of those resources in other desired activities and greater resource use by the whole system (Herring [23]). In a world with steady or declining petroleum resources, sustainable development as we have defined it will require that the developed nations of the world use less petroleum than they are using presently. Mechanisms for reducing the fossil fuel use of developed nations are already a subject of discussion for those concerned with the accumulation of greenhouse gases and global climate change (Aldy et al. [24]).

In addition, the world as a whole is strained by the ever expanding needs of its growing human population. There are many environmental, economic and social problems that limit the size of a sustainable world population. The environmental effects of human activities range from the local to global scale and include many difficult problems, such as, species extinction and other alterations of biodiversity, climate change, ground water depletion, soil loss, ecosystem change including the emergence of new pathways of interaction as illustrated by the zoonotic diseases, AIDS and SARS. In addition to the environmental and economic problems, rapidly growing human populations have unique social problems. Perhaps the most prevalent social problem affecting the transition to global sustainable development is the unequal distribution of the benefits of development among people and nations. Such disparities in human well-being and the perception that unfair interactions are in some way responsible for this condition give rise to deep seeded animosities that manifest as social protests, revolution, and in some cases anarchy and terrorism. Sustainable development requires that environmental, economic, and social problems, such as those mentioned above, be addressed in a systematic and comprehensive manner to identify design changes that will remove the causes of the initial problem.

5. ECONOMIC DEVELOPMENT AND ENVIRONMENTAL QUALITY

Environmental systems are networks of interacting components and processes that are defined by the overlapping interaction of organizing energies (forcing functions) on the landscape (Figure 2).

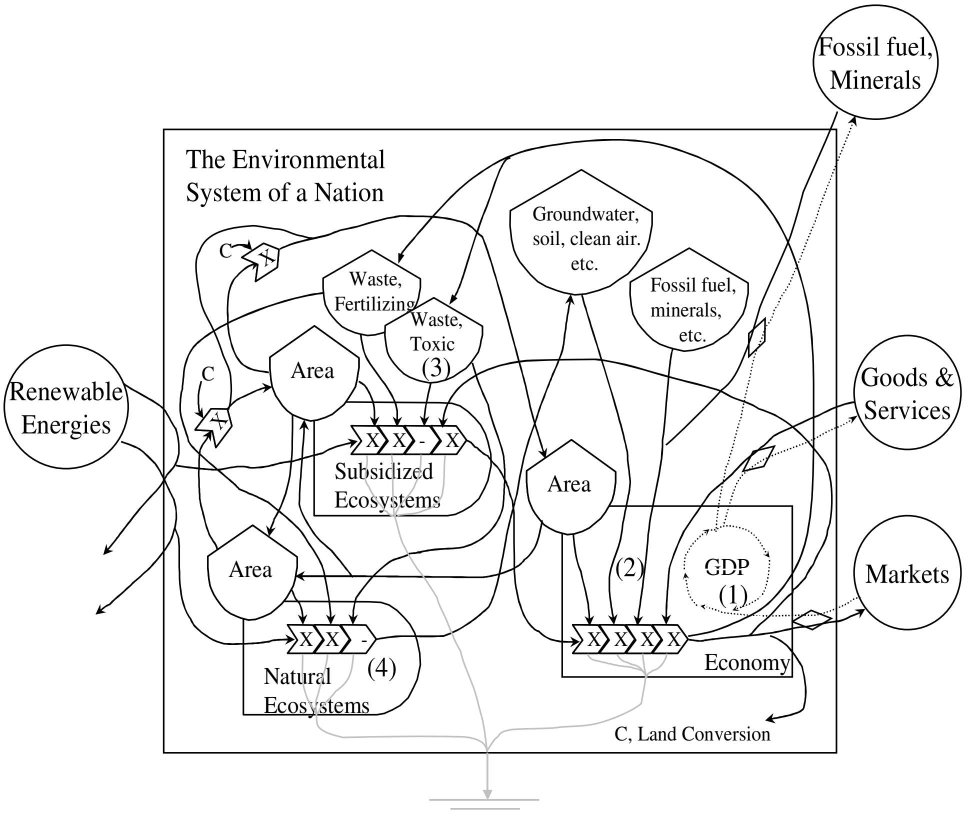

Figure 2. An energy systems diagram of the environmental system of a nation showing that renewable (groundwater, clean air, soil) and nonrenewable (fuels and minerals) resources are required for economic production, but that the production process (land conversion) and its by-products (fertilizing and toxic wastes) have negative effects on the environment

Their boundaries are usually defined by a given area of the earth’s land and water ecosystems and include the human economic and social systems that may be found there. Environmental systems contain the interface between the environment and human activities. The diagram of a national system in Figure 2 shows this interface where economic production (1) requires renewable and nonrenewable resources (2) from the environment and produces toxic and fertilizing wastes (3) which in turn have negative effects (4) on both subsidized and natural ecosystems that then produce less of the natural products needed to support economic production. This diagram shows that economic production is not possible without the use and degradation of environmental resources and that there is a necessary trade-off between the two. For example, treatment of wastes can decrease environmental degradation but not without an additional energy cost. The central problem for sustainable development is how to balance the resource use and environmental impacts of economic production with the benefits of that production to society. As long as the production of nonrenewable resources is increasing, some of these resources can be used to mitigate the negative effects of resource use and wastes on the environment, thereby allowing economic growth to continue, while maintaining environmental functions at an acceptable level. However, once the production of a resource peaks, each year less resource is available to support the system and some formerly supported activities must be given-up. An understanding of the trade-off between economic production and environmental quality is essential to answer the question, “Is a global transition to sustainable development possible?”

6. IS SUSTAINABLE DEVELOPMENT POSSIBLE?

To answer the question, “Is sustainable development possible?” we must briefly return to the definition of human well-being given above. As you may recall, well-being requires emergy inputs from three sources, the environment, the economy, and society. If sustainable development is to proceed in all the countries of the world simultaneously, there must be an optimum nonrenewable (fossil fuel) emergy use for maximum human well-being. The trade-off between economic production and environmental quality discussed above gives a theoretical basis for the assumption that natural ecosystems decline as fossil fuel use increases. In addition, a society can suffer negative consequences at high empower densities, e.g., crime (U.S. Department of Justice [25]), drug use (Abraham [26]), and physical and mental stress increase in densely populated urban areas and in areas with rapid changes in empower density, e.g., increased drug use, crime and depression were observed in Prince William Sound, Alaska after the arrival of oil spill aid (Brown et al. [27]). Thus global environmental contributions to human well-being are expected to monotonically decline with increasing fossil fuel use; whereas, societal contributions to well-being apparently peak and then decline as the use of fossil fuel emergy increases. Social and cultural differences are large among countries and further investigation of the relationship between negative social consequences and increased empower density is needed. There are no apparent negative effects of fossil energy or emergy use on economic production as measured by GNP (Odum [28], Campbell [29], Ko and Hall [30]), and economic contributions to human well-being are expected to follow a curve of monotonic increase with diminishing slope as more fossil fuel is used. Figure 3 puts these three assumptions together to illustrate a mechanism that makes global sustainable development possible. In this figure using hypothetical data, the empower generated in the environment, economy, and society of an environmental system is shown on the ordinate and the emergy in the fossil fuel used is given on the abscissa. The pattern of environmental, economic, and social empower corrected for detrimental effects as a function of the fossil fuel emergy used is plotted in arbitrary units on the graph. If human well-being is a multiplicative function of these three, it takes a hump-backed form as shown by the dark solid line in Figure 3.

This figure illustrates that there is an optimum fossil fuel use for maximum human well-being under the assumptions stated above. Thus, it maybe possible for underdeveloped countries to improve well-being by using more nonrenewable emergy and for developed countries to increase well-being by using less, but improving design.

In natural systems, designs that maximize empower have evolved through successive cycles of pulsing. Hopefully, humanity can learn enough to do the same, even without the "benefit" of experiencing multiple pulsing fossil fuel cycles (Figure 1, Levels 1 thru 3). For us the challenge is managing the transition to a lower fossil fuel energy state, within the constraints of one major and long term fossil fuel accumulation phase and the timescale set by the related short resource consumption phase (Figure 1, Level 3 with the time line cut in half).

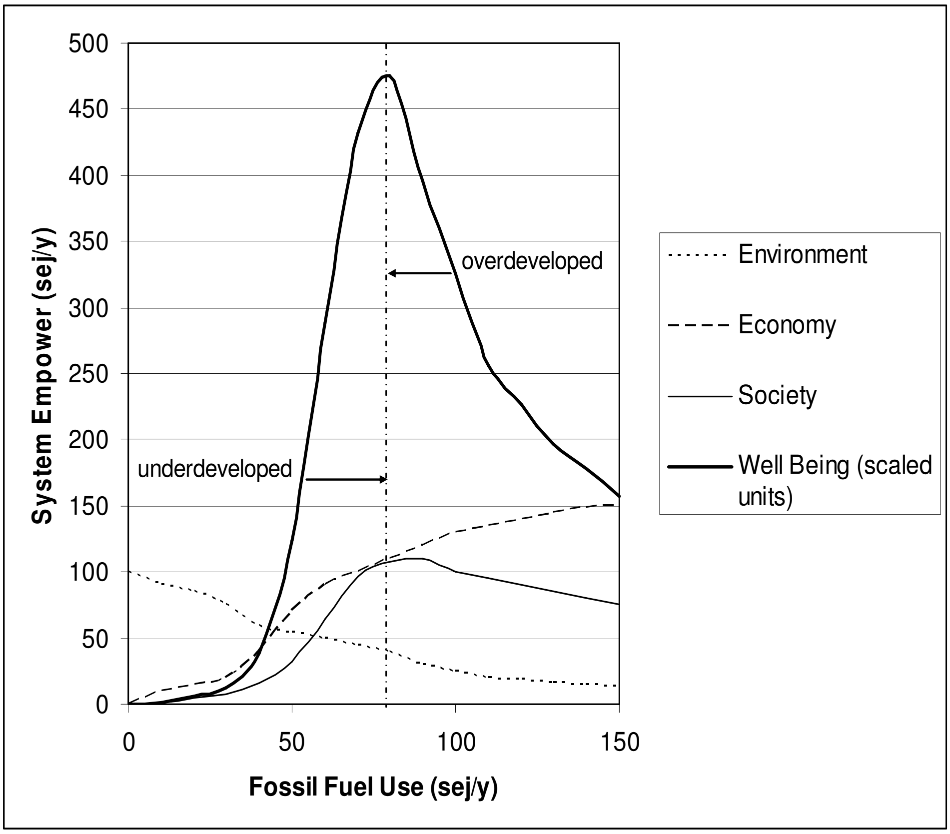

Figure 3. A graph constructed with hypothetical data based on hypothesized relationships between fossil fuel use and environmental condition, economic production, and social interaction and on a hypothesized relationship between these three factors and human well-being. If these assumptions are correct the figure illustrates how a global transition to sustainable development could come about

7. ENVIRONMENTAL ACCOUNTING

Since many alternative environmental system designs are possible, researchers in science and technology often seek options that produce win-win situations, promoting human well-being by balancing the trade-offs between economic productivity and environmental quality. Managers, in turn, will need scientific means to determine the integrated effects of these alternate designs and to evaluate how these actions affect sustainable development for nations and for the world. Evaluation of sustainable development strategies and alternatives will depend on the development of an adequate theory of human well-being and on the development of accounting methods to determine whether we are moving toward or away from this goal. Energy Systems Theory provides a criterion (maximum empower) for measuring human well-being and environmental accounting using emergy (Odum [3]) provides methods and measures needed to evaluate the environmental, economic, and social effects of management alternatives in common terms (as solar emjoules).

The concept of environment debt and how to measure it (Campbell [31]) can be used to illustrate the application of environmental accounting methods in evaluating sustainable development alternatives. Money is paid only to people for their work and does not compensate the environment for the work it contributes to economic production (Odum [4]). Thus, while the environment contributes real work to support economic production, it receives no payment for this work. Anything taken without payment is obtained on credit and becomes a liability on the financial balance sheet. Environmental debt is mostly external to the market system, thus it is not easily measured by money. However, the value of a thing can be measured by what was required to produce it as well as by what someone is willing to pay for it. The common denominator of the energy used up in making a product or service allows environmental liabilities to be evaluated and placed on the balance sheet. Environmental work can be measured by the emergy required for various environmental products and services. Emergy accounting makes it possible for accountants to create comprehensive balance sheets that include the debts owed to the environment along side the financial assets and liabilities of the firm.

Monetary and emergy accounts are reconciled on the balance sheet using a combined emergy-money measure, e.g., the emdollar in the United States. The emdollar value of an item is its emergy divided by the emergy-to-money ratio (GNP to total emergy used) for an economy in a given year. Emdollars are the result of distributing the dollar measure of total economic activity in proportion to the emergy flows within the environmental system. The emdollar uses a monetary unit ($) to show the real wealth (sej) behind each economic and environmental flow on the income statement or storage on the balance sheet.

The emergy balance sheet provides a method for directly determining what is sustainable. Sustainable systems must obtain a balance between the accumulation and the payment of environmental debt. Environmental accounting using emergy provides the means to document the debt that the economic system owes to the environment. The emergy balance sheet for a system shows its cumulative environmental debt and the assets available to pay it. This balance determines whether a system is “solvent” and therefore sustainable. The balance sheet like other energy systems methods requires that questions of solvency that cannot be resolved within the system be addressed through an analysis of interactions at the next larger scale of organization. Environmental liabilities must be documented and adequately serviced, if the nations and the world are to make the transition to sustainable development. Environmental accounting using emergy can also be used to evaluate development alternatives by determining their affect on what is sustainable. For example, the renewable emergy production of a sustainable system, at least must be equal to the use of renewable emergy to prolong the state of a system for a given level of fossil fuel use. Nations and other systems may choose to carry a certain amount of environmental debt but they must have the capacity to service the debt to remain viable entities and ultimately to pay it off to remain healthy in the long run.

8. EVALUATION OF ASSETS AND LIABILITIES

The evaluation of assets and liabilities on the emergy balance sheet is illustrated here by considering data from South American (SA) and North American (NA) countries. For each country, the emergy of fossil fuel reserves (coal, oil, and natural gas) and the emergy stored in endemic vascular plant species were evaluated as assets. The area no longer in forest and the number of extinct and threatened vascular plant species were evaluated in emergy terms as environmental liabilities. Table 2 shows the quantities of fossil fuel reserves remaining in the countries of North and South America in the mid-1990s. The countries of Central America are omitted from this analysis because only Guatemala has oil and gas reserves and these are small (≅ 1% of the total).

Table 2 The major fossil fuel reserves found in North and South America in the mid 1990s expressed as storages of energy and emergy

Country	Coal[1] Short tons	Natural Gas[1] cu.ft.	Petroleum[1] barrels	Energy[2] Joules	Emergy[3] sej
South America (SA)					
Argentina	4.74E+08	2.75E+13	2.90E+09	6.19E+19	4.65E+24
Bolivia	0.00E+00	5.49E+13	4.41E+08	6.06E+19	4.22E+24
Brazil	1.31E+10	8.10E+12	8.30E+09	4.78E+20	3.28E+25
Chile	1.30E+09	3.50E+12	1.50E+08	4.62E+19	3.06E+24
Colombia	7.30E+09	4.50E+12	1.84E+09	2.50E+20	1.67E+25
Ecuador	2.60E+07	3.45E+11	4.60E+09	2.93E+19	2.74E+24
French Guiana	0	0	0	0	0
Guyana	0	0	0	0	0
Paraguay	0	0	0	0	0
Peru	1.17E+09	8.70E+12	2.85E+08	4.84E+19	3.24E+24
Suriname	0	0	0	0	0
Uruguay	0	0	0	0	0
Venezuela	5.28E+08	1.48E+14	7.78E+10	6.48E+20	5.67E+25
SA Total	2.39E+10	2.56E+14	9.63E+10	1.62E+21	1.24E+26
North America (NA)					
Canada[4]	7.20E+09	5.91E+13	4.50E+09	3.20E+20	2.19E+25
Mexico	1.30E+09	1.50E+13	1.58E+10	1.54E+20	1.29E+25
United States	2.75E+11	1.83E+14	2.27E+10	9.13E+21	6.02E+26
NA Total	2.84E+11	2.57E+14	4.30E+10	9.61E+21	6.37E+26

[1] Data on coal, natural gas and petroleum reserves were obtained from the Energy Information Administration, U.S. Department of Energy, Country Analysis Briefs website (EIA [32]).
[2] The following conversions were used to obtain energy in joules: 6.1 E9 J/42 gal. barrel, 1.06 E6 J/cu ft., and 3.2 E 10 J/short ton.
[3] Emergy was determined using the following transformities: petroleum, 94,700 sej/J; natural gas, 68,400 sej/J; and coal, 65,400 sej/J. All transformities are relative to the 15.83 E24 sej/y baseline (Odum et al. [33]). Revised transformities for oil and gas are from Bastianoni et al. [34] and coal is from Odum [3].
[4] Tar sands were not included in this estimate.

Table 3 shows the area no longer in forest in South and North America determined as the difference between present forest area and the area that could potentially support forest 8000 years ago (based on climatic factors). The emergy no longer stored as forest ecosystems was taken as a measure of the environmental debt incurred in each country as a consequence of converting forest lands to agricultural and urban uses. The debt accumulated as a result of the annual diminishment of forest productivity since the time of first settlement was not evaluated. The three North American countries in Table 3 include more than 90% of the forest area converted to other uses. Table 3 gives the magnitudes of two annual emergy flows, total emergy use and the emergy of fossil fuels used for comparison with the estimates of environmental assets and liabilities given in Tables 2-4.

The number of endemic vascular plant species, the number threatened, and the number that have become extinct in each country of North and South America were used, respectively, as indicators of the unique assets stored in biodiversity in each country, the likely future debt to biodiversity and the existing permanent debt that has been incurred (Table 4). The emergy needed to evolve a rainforest tree species from Odum [3] was multiplied by the number of vascular plants in each category to estimate the emergy assets in biodiversity and the debt incurred as a result of species extinction.
No data were available on endemic species from Brazil which is probably the largest reservoir of such species in South America.

Table 3. Emergy debt to forest ecosystems incurred in North and South America as a result of land conversion since original colonization compared to the annual emergy used in each country during the mid-1990s

Country	Forest Area Converted[1] m^2	Emergy Debt[2] sej	Emergy Use[3] sej/y	Fossil Fuel Use[4] sej/y
South America (SA)				
Argentina	2.36E+11	8.31E+24	4.52E+23	2.58E+23
Bolivia	1.57E+11	5.52E+24	1.94E+22	1.00E+21
Brazil	2.75E+12	9.70E+25	1.79E+24	8.83E+23
Chile	2.27E+11	8.00E+24	2.80E+23	1.58E+23
Colombia	4.31E+11	1.52E+25	5.72E+23	1.68E+23
Ecuador	5.34E+10	1.88E+24	1.62E+23	5.40E+22
French Guinea	0	0	no data	3.48E+21
Guyana	4.51E+9	1.59E+23	2.70E+22	5.00E+21
Paraguay	2.91E+11	1.03E+25	4.84E+22	1.00E+22
Peru	1.01E+11	3.55E+24	no data	1.23E+23
Suriname	6.50E+9	2.29E+23	no data	5.97E+21
Uruguay	0	0	3.10E+22	1.10E+22
Venezuela	9.71E+10	3.42E+24	no data	5.03E+23
SA Total	1.04E+11	1.53E+26	≅3.38E+24	2.18E+24
North America (NA)				
Canada	2.36E+11	8.31E+24	2.34E+24	1.56E+24
Mexico	3.19E+11	1.12E+25	6.14E+23	5.19E+23
United States	1.49E+12	5.26E+25	9.00E+24	8.16E+24
NA Total	2.05E+12	7.21E+25	1.19E+25	1.02E+25

[1] Data on forests were taken from the World Resources Institute website, Earth Trends (WRI [35]). Current forest area (Bryant et al. [36]) and current area as a percent of the original forest was used to estimate the original forest area from which the current forest area was subtracted to get the forest area converted to other uses. WRI estimated the original forest area based on a World Conservation

Monitoring Centre (WCMC) map, but that information was not given. Plantations and secondary growth were included as current forest and thus the estimate of emergy debt is conservative.

[2] Emergy debt to forest ecosystems was estimated by multiplying the hectares of forest area converted to other uses by the transformity for a hectare of 300 year old Puerto Rican tropical rain forest (Odum [3]).

[3] Annual emergy use in the mid-1990s was taken from Brown [37] except for Ecuador which was taken from Odum and Arding [38].

[4] Annual fossil fuel (nonrenewable use) in the mid-1990s was taken from Brown [37] supplemented by data on coal, oil, and natural gas consumption from the Energy Information Administration, U.S. Department of Energy, Country Analysis Briefs website (EIA [32]).

Table 4. Total, threatened, and extinct vascular plant species and estimates of the assets stored as vascular plant biodiversity along with the debt incurred to planetary biodiversity as a result of extinctions and the debt that may be incurred in the near future based on the number of species that are presently threatened

Country	Number Vascular Plants[1]			Emergy Evaluation[2]		
	Endemic	Threatened	Extinct	Endemic	Threatened	Extinct
				sej	sej	sej
South America (SA)						
Argentina	1100	42	1	1.66E+24	6.34E+22	1.51E+21
Bolivia	4000	70	0	6.04E+24	1.06E+23	0
Brazil	no data	381	15	no data	5.75E+23	2.26E+22
Chile	2698	40	7	4.07E+24	6.04E+22	1.06E+22
Colombia	1500	213	4	2.26E+24	3.21E+23	6.04E+21
Ecuador	4000	197	3	6.04E+24	2.97E+23	4.53E+21
French Guiana	144	no data	1	2.17E+23	no data	1.51E+21
Guyana	no data	23	1	no data	3.47E+22	1.51E+21
Paraguay	no data	10	0	no data	1.51E+22	0
Peru	5356	269	7	8.08E+24	4.06E+23	1.06E+22
Suriname	no data	27	0	no data	4.07E+22	0
Uruguay	40	1	0	6.04E+22	1.51E+21	0
Venezuela	8000	67	0	1.21E+25	1.01E+23	0
SA Total	no estimate	no estimate	no estimate	4.05E+25	2.02E+24	5.89E+22
North America (NA)						
Belize	150	28	0	2.26E+23	4.23E+22	0
Canada	147	1	1	2.22E+23	1.51E+21	1.51E+21
Costa Rica	950	110	4	1.43E+24	1.66E+23	6.04E+21
El Salvador	17	23	0	2.57E+22	3.47E+22	0
Guatemala	1171	77	3	1.77E+24	1.16E+23	4.53E+21
Honduras	148	27	3	2.23E+23	4.07E+22	4.53E+21
Mexico	12500	221	12	1.89E+25	3.34E+23	1.81E+22
Nicaragua	40	39	2	6.04E+22	5.89E+22	3.02E+21
Panama	1222	192	0	1.84E+24	2.90E+23	0
United States	4036	169	163	6.09E+24	2.55E+23	2.46E+23
NA Total	no estimate	no estimate	no estimate	3.08E+25	1.34E+24	2.84E+23

[1] World Resources Institute website, Earth Trends (WRI [35]). Data posted on total species and endemic species are from the World Conservation Monitoring Centre (WCMC) of the United Nations Environment Programme (UNEP-WCMC), 2002. Extinct and extinct in the wild species data are from WCMC and World Conservation Union (IUCN).

[2] Data on vascular plant species were multiplied by 1.51 E+21 sej/species (Odum [3]), the emergy required to evolve one species in the El Verde rain forest of Puerto Rico assuming 10,000 years are required for speciation.

Based on the ratio of Mexico's endemic species to total vascular plant species and knowing the total vascular plant species found in Brazil, I estimated that if the number of endemic species in Brazil was known it would double the total emergy attributed to endemic species in South America. The data did not allow estimates of endemic, threatened or extinct species for North and South America as a whole. However, emergy estimates for the two continents were provided by summing the emergy for each country in the respective categories. These sums are a minimum estimate of the actual value of the asset or liability in each category.

The information in Tables 2-4 gives us a glimpse of some of the relationships between assets and liabilities on the emergy balance sheets for the countries of North and South America. The emergy evaluation indicates that South American assets in endemic vascular plant diversity are about 33% of the emergy of fossil fuel reserves. However, if the endemic species of Brazil and three other countries had been counted I estimate that the two numbers would be close to the same value (1.0E+26 sej). Threatened plant species embody stored wealth as great as the emergy in annual fossil fuel use; however, only about 5% of SA's vascular plant species are threatened and 0.15% have become extinct. The emergy debt to forest ecosystems in SA is 1.23 times the emergy of its assets in fossil fuel reserves and over 70 times the emergy of annual fossil fuel use. At the present rate of use fossil fuel reserves in S.A. can supply the continental economies for approximately 57 years given that all fossil fuel needs are supplied from these reserves. In North America, the emergy assets of endemic plant biodiversity are only 4.8% of the assets in fossil fuel reserves and the emergy debt to forest ecosystems is 12.4% of these reserves (using 7.89 E+25 sej as the debt, which includes the Central American countries). The environmental debt from vascular plant extinction is a small fraction (0.9%) of the emergy in endemic plant biodiversity. The potential environmental debt that may be incurred soon as a result of the loss of threatened species is 4.4 % of the emergy stored in NA's endemic vascular plants. At the present rate of use fossil fuel reserves in NA can supply the continental economies for about 62 years given that all fossil fuel needs for Canada, the United States and Mexico are supplied from these reserves.

Table 5 shows a comparison of environmental assets and liabilities between North and South America. The stored emergy of fossil fuel reserves in oil, coal, and natural gas is 5 times greater in NA than in SA. This difference is reflected in the use of fossil fuels where 4.7 times more emergy of fossil fuels is being used in NA and also in plant extinctions, which are 4.8 times greater in NA. In contrast, the existing wealth in vascular plant biodiversity as estimated using emergy is 1.25 to 4 times greater in SA than in NA. The ratio of debt to forest ecosystems is 0.47 which implies that forest conversion has been about 16% more intense in SA than expected based on a ratio of 0.56 for the original forest areas. The threat of extinction of vascular plants is 17% more intense in NA than in SA based on the assumption that threat should be proportional to forest area. However, if threat is proportional to fossil fuel consumption then SA has 10 times more risk of plant extinction than would be expected based on the ratio of fossil fuel use. The emergy estimates of biological assets and liabilities reported here are very coarse; nevertheless, they provide a rough idea of how biological emergy values compare to the emergy in fossil fuel reserves and in the annual flow of fossil fuel consumed. Work on the development of complete balance sheets for entities at various scales is underway at USEPA's National Health and Environmental Effect Research Laboratory, Atlantic Ecology Division.

Table 5. A comparison assets and liabilities on the balance sheets for North and South America represented as the sum of assets and liabilities of the individual nations

Item	Ratio (NA/SA)
Assets	
Emergy in fossil fuel reserves	5.13
Emergy in endemic vascular plants	0.76 – 0.25
Liabilities	
Debt to forest ecosystems[1]	0.47
Permanent debt in plant extinction	4.82
Potential debt in threatened plants	0.66
Consumption	
Emergy of annual fossil fuel use	4.68

[1] Ratio of initial forest areas (NA/SA) was 0.56.

9. TRANSITION TOWARD SUSTAINABLE DEVELOPMENT

A global transition to sustainable development appears to be possible based on the arguments given above; however, many obstacles stand in the way, the greatest of which is the influence that our past technological success has on determining our present actions and our vision of the future. The idea of "coming down", i.e., using less energy and resources and doing things in a smarter way has not been embraced by many in the developed world, yet it is the key idea needed to guide the world toward sustainable development. Many people are willing to think about smarter designs, but not about less resource use. As I have mentioned above, simply improving efficiency and conserving resources for one purpose does not necessarily lead to a decrease in resource use on the whole. It is this latter condition that must prevail in the developed countries for there to be enough energy and material resources to allow the underdeveloped and developing countries to improve their condition simultaneously and for the world as a whole to move toward more sustainable system designs. Decreasing fossil fuel use in the developed countries will require setting priorities for fuel consumption by dedicating liquid fuel to the uses for which it is best suited as determined by emergy indices and other comprehensive indicators, while eliminating inefficient uses, waste, and luxury consumption. To avoid the continued exacerbation of global, regional and local environmental problems that affect human well-being, resource use by the developed countries should not be decreased without some controls (e.g., best management practices) on how the released resources will be used by developing nations. Comprehensive scientific methods like environmental accounting using emergy should be used to create balance sheets on which environmental liabilities and assets are shown along side those of the economy and society. Careful monitoring of the accumulation and repayment of environmental debt will help ensure that renewable energy and material resources are used in a sustainable manner and that environmental damage is constrained within a country's capacity to service and repay environmental debt wherever growth occurs in the world.

Because of the differing resource base, states of development, and human needs of the nations, sustainable development will mean different things to different countries and to the world as a whole. For some countries, sustainable development will mean additional growth and nonrenewable energy use, but for others it will mean a decline and/or a shift in energy use and improvements in conservation and design. In all cases, sustainable development under different scenarios of energy use implies that the nations will become better places to live overall as measured by empower per person after accounting for detrimental effects. Different development alternatives can be evaluated using emergy analysis and other methods to determine which choice maximizes well-being. All countries, regardless of their state of development, need to keep track of their environmental debt to determine a reasonable debt load and repayment schedule that maximizes human well-being in their particular situation and for the world at large. The amount of debt that a national system can carry will depend on the resources available to each individual nation and the effects of the debt load on the annual emergy income statement (Campbell [31]). Balance sheets using emergy-based monetary units provide the means to determine directly the solvency of our national and global economic systems, including the ability to pay debts owed to the environment for its unpaid contributions to economic production and human welfare. The emergy balance sheet provides a mechanism to directly determine a balance between satisfying human needs and the global environmental impacts of economic development.

A second important factor in promoting a transition to global sustainable development is the equity of exchange among nations. If international exchanges are not fair, the probability of discontent and discord increases within the community of nations. Real or perceived economic injustice often leads to rebellion, civil war and other forms of violence. Emergy accounting provides a method to determine whether trade is equitable. Often the money exchanged will balance but the real wealth exchanged as measured by emergy is unbalanced. Brown [37] examined the effects of world trade on the sustainability of 41 world economies using emergy analysis. If world trade is evaluated in this manner, checking the emergy balance of payments, governments will be better able to determine if their relations with other nations are equitable.

Finally, the distribution of wealth among people and nations is another factor, determining social stability in a nation and in the world. Social stability is a necessary condition for sustainable development. Appropriate distributions of wealth will vary from one country to another; however, general systems principles can be used to guide a society toward wealth distributions that maximize overall well-being within a nation and for the world. One such principle is that with wealth comes the responsibility to provide feedbacks to the larger system that at least balance the emergy used in producing the position of privilege. According to the maximum empower principle, the lack of such feedbacks will cause a given wealth structure to be replaced in time by a structure better adapted to use the available resources. Alternative income structures might be evaluated and their effects on the national emergy income statement determined. Taxes, incentives, and other economic tools can be used to adjust individual income structures to increase the real wealth of the nation as a whole.

For there to be a global transition to sustainable development, developed countries must find the political will to implement policies that will move toward the environmental, economic, and social designs (described above). Developed countries must rely more on renewable energy sources and material recycle as the underdeveloped countries "catch up" to the developed standard of human well-being through increasing their fossil fuel and material use. Developing nations must also make a political decision to grow their economies using the best available technology along with appropriate checks on environmental impacts, which were not available or were not utilized by the developed nations during their rapid growth phase. The growth phase for developing countries on liquid petroleum resources will proceed very rapidly and be of limited duration, because world petroleum production is approaching its peak and the technology to allow the efficient use of petroleum is already widely available. Current projections of world energy use by the International Energy Agency (IEA [39]) call for increased energy consumption by both developed and developing nations through 2030. They believe that current energy reserves are sufficient to meet the increased demand and that world petroleum production will not peak before this time. While recognizing that the status quo will lead to their predicted increase in fossil fuel energy use by both developed and developing nations, the IEA [39] calls for policy changes that would begin to address the environmental impacts of continued fossil fuel energy use. With the Kyoto agreement coming into force and more free-market greenhouse gas emissions trading schemes being proposed (Aldy et al. [24]), we may be witnessing the emergence of mechanisms that can smooth the transition from Stage 2 to Stage 3 in the cycle of change.

Because of the diversity of energy resources and the uncertainty of their ultimate supply, the timing of peak production for a single resource and for all resources together is uncertain. The only certainty is that all fossil energy supplies are limited, and because of this reality, all must peak and decline eventually. Therefore, the cycle of change will play out in one way or another, either in the form of an orderly gradual transition to a lower energy world or in catastrophic changes that lead to that state. To achieve states of sustainable development and to ensure the well-being of future generations, it behooves us to plan for the transition to a Stage 3 world now (Odum and Odum [11]) and to begin moving toward environmental system designs that rely more on renewable and lower quality nonrenewable energy resources, checking the proposed alternatives using emergy accounting methods to ensure that they are sustainable.

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