Emergy Measures of Carrying Capacity to Evaluate Economic Investments

Mark T. Brown
Univeristy of Florida, Gainesville

Sergio Ulgiati
University of Siena, Italy

This paper outlines a method for determining carrying capacity for economic investments based on an emergy evaluation of the environmental resources of a region. Using data from tourism development in Mexico and Papua New Guinea, the concept of carrying capacity is related to intensity of development, environmental support area, and the "fit" of economic development in local environments and economies.

Emergy, a unit of resource use and work potential, is used to quantitatively evaluate intensity of development. Emergy evaluation is briefly described and the evaluations of tourism used to further explain the methodology. The total annual resource use for the tourist resorts and the economies in which they are embedded (including inputs of renewable and nonrenewable resources and purchased goods and services) was calculated and converted to emergy units. The renewable resource base and an Environmental Loading Ratio (ELR), are proposed as a means for determining both long term and short term carrying capacity respectively. The concept of sustainable development is related to the net emergy benefits that result from development. Expressed as a ratio of the amount of emergy received by the local economy to the amount that is exported (embodied in tourists), sustainability is suggested to result from a positive emergy trade balance.

KEY WORDS: emergy; carrying capacity; economic development; sustainability; tourism.

Please send correspondence to Mark T. Brown, College of Engineering, Department of Environmental Engineering Sciences, University of Florida, A.P. Black Hall, P.O. Box 116450, Gainesville, FL 32611.

Population and Environment: A Journal of Interdisciplinary Studies
Volume 22, Number 5, May 2001

INTRODUCTION

With the increased emphasis placed on attracting economic investment by many governments around the world, some hard questions are beginning to emerge. What is the carrying capacity of local economies for economic development? What is the appropriate intensity of development for a given economy? How can sustainability be measured? Of major concern to many developing economies is the establishment of national parks and"bio-reserves," but from the perspective of the overall economy how much is enough?

The concept of carrying capacity relates resource use to environmental support. Reaching a carrying capacity for a population infers that there is a balance between the supply of resources and the impacts sustained as a result of that supply. The population size that can be sustained results from this balance . . . from the use of the environment for both a source of resources and a sink for wastes. It is true of all economic development that there is a carrying capacity, beyond which further development causes declines in resource availability and environmental integrity.

In recent years there has been some discussion concerning the carrying capacity of the earth for humans, and the ultimate limit to global carrying capacity for economic development. There are numerous papers that discuss qualitatively, the relationships of environment to carrying capacity (see for instance, Van Den Bergh, 1993; Sterrer, 1993; Carey, 1993; King and Slesser, 1995; Cohen, 1995; Arrow et al., 1995; Wetzel and Wetzel, 1995; Fearnside, 1997; Cohen, 1997), however there are few quantitative studies. Harris and Kennedy (1999) have suggested a logistic growth model for global agricultural yields and that projections for supply and demand in the 21st century based on a logistic model imply that the world is indeed close to carrying capacity in agriculture. Folke et al. (1997) calculated the area "appropriated" by cities in Baltic Europe and globally, estimating that the 29 largest cities of Baltic Europe appropriate for their resource consumption and waste assimilation an area of environment equal to at least 565–1130 times larger than the area of the cities themselves. Using a concept of "ecological footprint" Wakernagle and Rees (1995) have determined the amount of land required for various human processes and by summing the resource requirements for the various processes and economies they determined the amount of land required to support economies. McConnell (1995) estimated the carrying capacity of the Chesapeake Bay Watershed to be about 8 million people by relating past population in the watershed to the onset of major episodes of Bay degradation. Campbell (1998), in an emergy analysis of the State of Maine, USA, calculated carrying capacity for human populations.

This paper discusses the relationship of economic investment to environmental integrity, and to local economies, regional welfare, and international balance of payments. Then, using data from tourism development in Mexico and Papua New Guinea and techniques of emergy analysis, carrying capacity for economic investments within local, less developed regions is quantitatively explored. In addition, the benefits and costs of differing intensities of development are evaluated and proposals are made for a quantitative method for determining sustainability of developments.

Emergy is a record of the available energy previously used up. The units of emergy are emjoules (abbreviated ej). Most often, emergy is expressed as solar emergy (abbreviated as sej) which expresses emergy of a product or service in units of solar equivalent emergy. For a more complete explanation of emergy see Odum (1996).

Impacts of Economic Investments

A systems[1] overview of a region given in Figure 1 suggests that its ecological, economic, and cultural systems are closely intertwined. The larger rectangle surrounding the system components represents the regional boundary. All storages, processes, and flows within the boundary are considered internal to the region (referred to as "local storages, flows, or processes," in this paper). Anything outside the box is external to the region. External investments come from the world outside the region.

As a region's economic system develops, there are resulting changes in its ecological and cultural systems because the increased economic activity affects a wider and wider spatial area. Also economic development may cause cultural changes in values and ethics. The extent of change in each of these systems is more or less dependent on the extent of change in the other. Figure 1 illustrates the interconnections between environmental, cultural, and economic systems of regions. A balanced and well adapted subsistence economy might have the organization depicted in Figure 1a. Ecological resources are extracted by the economic system, converted to goods, and consumed by cultural components which, in turn, provide the necessary organizational structure and "manpower" for the economic system. Byproducts of the economic system are recycled back to the environment and information and "good stewardship" are fed back from culture. The driving forces are renewable energies shown coming from the left side of the diagram and the nonrenewable energy and material storages from

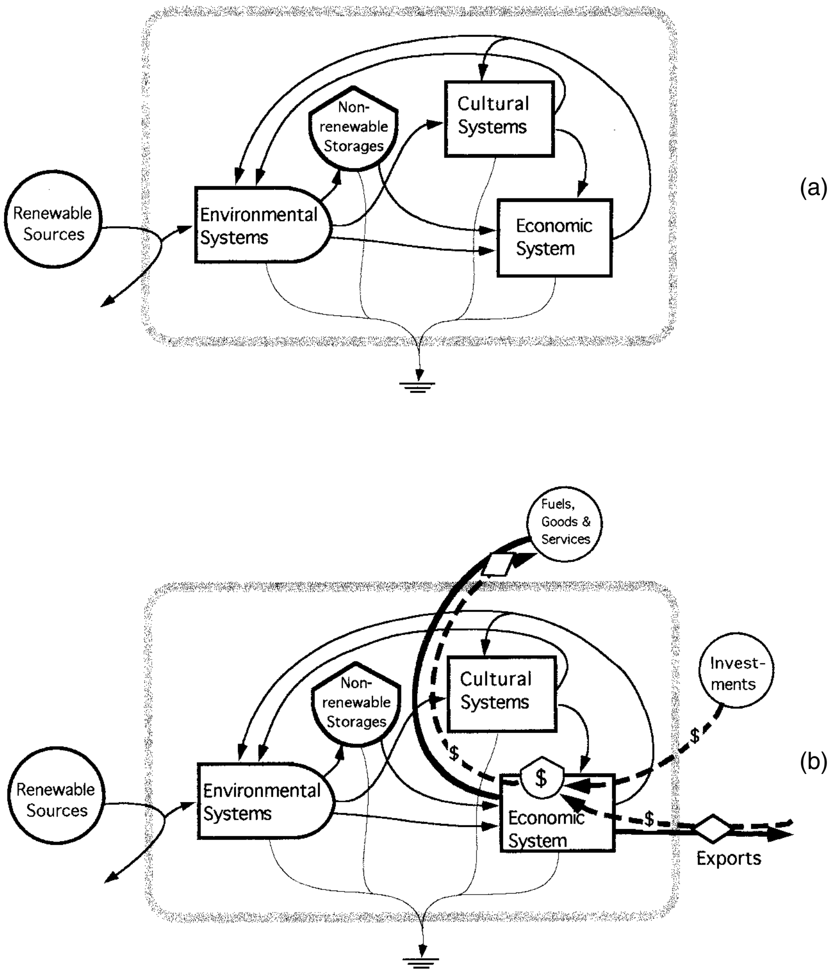


FIGURE 1. Systems diagrams of a regional economy (a) having no trade with external markets and an economy that has developed trade (b). Money is shown as dashed lines, and energy and information flows as solid lines. While invested money may circulate within the economic system, eventually, like income from exports, it is used to purchase goods and services from external economies.

within. The overall system that develops (i.e., the levels of ecological productivity, economic activity, and cultural organization) is, to a large degree, dependent on the magnitude of renewable emergy flow and the nonrenewable storages that are available.

A region with economic investment from outside is depicted in Figure 1b. Investment dollars are used to purchase fuels, goods, and services from outside the local economy. A second outside energy source now influences the system. As a result of the connections between components of the regional system, any change in one compartment affects the other two compartments. The bigger the influence from outside invested resources, that is, the bigger the magnitude of the flows coming from the top right (Figure 1b) compared to the renewable flows coming from the left, the greater the impact. The methodology described and illustrated in this paper quantitatively evaluates the relative size of both of these driving energy flows in a regional economy, and suggests that the appropriate intensity of a new economic investment is one that does not alter their relative proportion significantly.

Secondary impact of economic investments is also illustrated in Figure 1b. External economic investments from outside are made as a means of financing enterprises that either directly extract natural resources (wood, minerals, fuels, or fish, for instance) and sell them to outside markets, or to develop enterprises for the conversion of resources within the local economy (hydroelectric projects or tourist developments, for instance). In either case, the "attracted" investments carry with them a substantial debt that must be repaid and which is financed through the export and sale of resources. The net benefit to the local economy of investments from outside, then, becomes a matter of determining the balance between what is purchased with the investment, and the resources that are exported over the long term to repay that investment.

A Quantitative Approach to Determining Carrying Capacity of Local Environments and Economies

Carrying capacity can be determined based on the emergy requirements for a given population or the emergy intensity of a given economic development. The carrying capacity of an environment is determined by that environment's ability to supply the required emergy. A rich environment can support larger populations or more intense economic developments.

Ultimately, carrying capacity is related to the ability of a local environment to provide necessary resources for a population or economic endeavor on a renewable basis since non-renewables by their very definition cannot be depended on in the long term. In emergy terms, the long term carrying capacity of an area is limited by the flux of renewable emergy that is characteristic of that area. One might term this *renewable carrying capacity*, since it relies on an environment's ability to support economic development based solely on its renewable emergy sources. In many respects renewable carrying capacity is an unrealistic number, since all economic developments, by their very nature require non-renewable emergy which is matched with renewable emergy sources to extract a net yield. Be that as it may, the renewable carrying capacity provides a benchmark for a lower limit to the carrying capacity of a region.

Renewable carrying capacity can be calculated from the average renewable emergy inputs to a region by determining how much area is required to sequester sufficient inputs to provide the total emergy requirements of a population. Calculating a renewable carrying capacity assumes that all emergy requirements of a population will be derived from renewable sources. Since renewable emergy sources are aerial based, carrying capacity becomes area required for a population. The same technique can be applied to any economic development whether agricultural, industrial, or social. If the emergy requirements for the development are known, they can be expressed in equivalent renewable emergy and the required support area calculated. Carrying capacity calculated in this way may be a predictor of long term sustainability.

A second approach to carrying capacity is related to the "fitness" of development within a local economic and environmental system. This second approach is based on the intensity[2] of development, which has been termed *environmental loading*. The intensity of development in relation to existing conditions may be critical in predicting its effect and its short term sustainability (Brown et al., 1995; Ulgiati et al., 1996; Brown and Ulgiati, 1997). If a development's intensity is much greater than that which is characteristic of the surrounding region, on average, the development has greater capacity to alter existing social, economic, and ecologic patterns (Brown, 1980; Odum, 1980). If it is similar in intensity it is more easily integrated into existing patterns. This second method of evaluating carrying capacity uses a ratio of non-renewable emergy to renewable emergy, called an Environmental Loading Ratio (ELR) and provides an upper limit to carrying capacity.

Combined, the two approaches provide lower and upper bounds respectively, to carrying capacity of local environments for economic developments. In the first case, the renewable emergy carrying capacity assumes that all resources sustaining an economic endeavor must come from the local renewable resource base. In the second case, the average environmental loading ratio is used to determine how much of the local environment is matched with economic enterprises under current conditions and suggests new development should maintain a similar intensity so as not to alter current local cultural, economic, and environmental patterns.

METHODS IN EMERGY ACCOUNTING

The general methodology for emergy evaluations has been explained in numerous publications (Odum, 1996; Brown and Ulgiati, 1997) and thus only very brief methods are given here. The first step is to construct systems diagrams that are a means of organizing the analysis and elucidating relationships between components and pathways of exchange and resource flow. The second step is to construct emergy evaluation tables directly from the diagrams. The final step involves calculating several emergy indices that relate emergy flows of the economy with those of the environment, and allow the prediction of economic viability and carrying capacity. Additionally, using the results of the emergy evaluation tables, comparisons between the emergy costs and benefits of proposed developments as well as insights related to international flows of money and resources can be made. Definitions of terms and concepts used in this paper are given in the Appendix.

Calculating the Renewable Resource Base

Regions, economies, and economic processes are driven in part by the renewable resource base of the local environment. Renewable, by definition means a resource that is replaced at a rate that is faster than it is used. Renewable resources supporting a region can be things like fisheries or forests, if harvested on a sustainable basis where growth rates are greater than (or equal to) extraction rates. The environmental energy flows like sunlight, winds, rain, tides and ocean currents, among others, are renewable sources as well, driving economic processes and maintaining environmental integrity.

In the emergy evaluation method, the renewable resource base of a region or an economic activity, are the inputs of environmental energies that are used. In practice, the environmental energies including sunlight, rain, and tides are evaluated and multiplied by a solar transformity (see Appendix) to express them in solar emergy. Since they are all products of the same global sources of energy (sunlight, tidal momentum, and deep heat) once each of the sources are evaluated, only the largest is used as the resource base. In this way, double counting is avoided (Odum, 1996).

Evaluating Non-Renewable and Purchased Emergy Resource Base

Non-renewable inputs to a region or process are resources extracted from the local environment at rates greater than they are replenished. They include such things as minerals, soils, fossil fuels, wood, and fresh water aquifers . . . any resource that is an input obtained from the local environment and that is used faster than it is renewed. Generally the non-renewable inputs are determined through an inventory of the region or process Once they are known, the amount of each input is multiplied by a solar transformity to convert it to solar emergy.

Purchased inputs are materials, energies and services that are imported from outside the region (or process). In some cases the imports are evaluated in energy units, in some cases as mass, and sometimes as monetary expenditures. Energy inputs are multiplied by solar transformities, mass inputs are multiplied by emergy per mass conversions, and monetary expenditures are multiplied by average ratios of emergy per currency to convert all flows to solar emergy.

Emergy Indices of Carrying Capacity

Once the emergy analysis tables are completed, several indices using data from the tables are calculated, including: *Percent Renewable*, *Empower Density*, *Renewable Empower Density*, and *Environmental Loading Ratio* (see Appendix). The percent of emergy use that is renewable expresses the portion of a regional economy or an economic process that is supporterd by renewable inputs and is therefore sustainable in the long run. Many developing economies and regions have greater than 50% of their economies based on renewable inputs, while industrialized economies and intense economic activities have a much smaller percent renewable (Brown et. al., 1995). Empower density is a relative measure of the intensity of activity, expressed as the total emergy used per unit time per unit area. Rural areas have empower densities of 1 to 10 E11 sej m^{-2} yr^{-1}. Industrial agriculture and extractive industries have empower densities of from 10 to 1000 E11 sej m^{-2} yr^{-1}, while major urban centers are characterized by empower densities in excess of 1000 to 100,000 E11 sej m^{-2} yr^{-1}. Renewable empower density is the renewable emergy use per unit area per unit time. The average global renewable empower density is about 0.2 E11 sej m^{-2} yr^{-1}. On land, where geobiospheric processes converge, the renewable empower density is between 0.5 and 5 E11 sej m^{-2} yr^{-1}. Environmental loading is the relative strain, stress, or pressure exerted on the environment caused by non-renewable inputs. It is evalauted as a ratio of the total non-renewable inputs to a region or process divided by the renewable inputs. Typically undeveloped areas have ratios less than 1.0. developing regions have ratios of between 1/1 to 4/1, and developed economies have ratios greater than 5/1 (Brown et al., 1995). For individual processes or economic activities that require small area, environmental loading can be quite large. Industrial agriculture can have ELRs of 10–100 /1 while intense economic activities and highly urbanized areas can have ratios greater than 1000/1 (Odum, 1996).

Determining Renewable Carrying Capacity for Economic Investments

The carrying capacity indices are expressed as land area required to support an economic activity. We call this required area "support area." Renewable carrying capacity is derived by dividing the total emergy input to a process by the average renewable empower density of the region in which it is located as follows:

$$SA_{(r)} = (F + N) / Empd_{(r)} \tag{1}$$

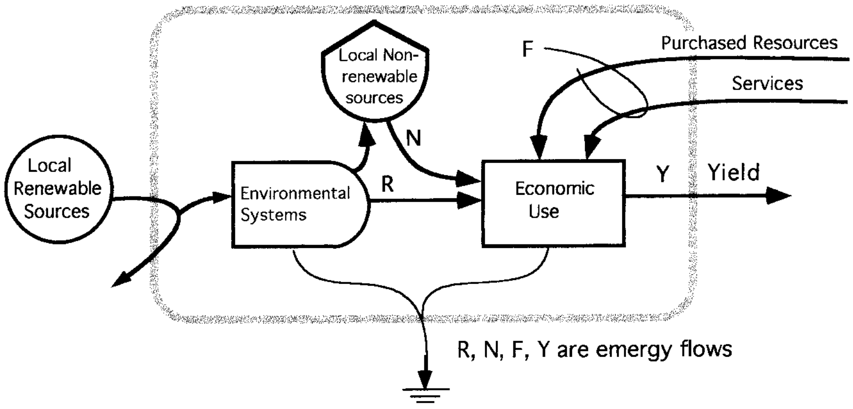
Where,

$SA_{(r)}$ = Renewable Support Area (m^2)
$Empd_{(r)}$ = renewable empower density (sej m^{-2} yr^{-1})
F = purchased inputs (sej yr^{-1})
N = non-renewable inputs (sej yr^{-1})

The result is the necessary area of the surrounding region that would be required if the economic activity were using solely renewable emergy inputs. It is a lower limit to environmental carrying capacity because it requires the largest support area, thereby placing the highest limits on development.

An Index of Environmental Loading: Environmental Loading Ratio

Nearly all productive processes of humanity involve the interaction of nonrenewable emergies with the renewable emergies of the environment and as a result the environment is "loaded." Figure 2 is a much aggregated



Yield (Y) = R+N+F
%Renew = R/(R+N+F)
Emergy Yield Ratio = Y/F
Environmental Loading Ratio = (F+N)/R

FIGURE 2. Diagram illustrating a regional economy that imports purchased inputs (F) and uses resident renewable (R) and nonrenewable (N) resources. Several ratios used for comparisons between systems are given below the diagram and explained in the text.

diagram of a region showing the concept of environmental loading. The economy uses local, nonrenewable storages (N) and renewable resources that come from the environment (R). Resources and services are imported (F) and used in the extraction and use of the local resources (R + N). Some of the yield is used internally (not shown) and some is exported. The environmental loading ratio (ELR) is the ratio of the sum of imports and nonrenewables to the renewable resource base. An index of environmental loading, the (ELR) is defined as follows:

$$ELR = (F + N)/ R \qquad (2)$$

Where:

ELR = Environmental Loading Ratio
F = Imported nonrenewable energy and resources (sej yr^{-1})
N = Local non-renewable energy resources (sej yr^{-1})
R = Local renewable energy and resources (sej yr^{-1})

The ELR reflects the potential environmental strain or stress of a development when compared to the same ratio for the region and can be used to calculate carrying capacity. Typically, new economic developments have ELR's that are higher than the regional average, due to the large convergence of nonrenewable and outside resources into a relatively small area. The use of environmental loading in determining carrying capacity is essentially the balancing of development intensities. It requires that the intensity of the regional economy, within which a new development is being placed, is known. Calculating the ELR for the region requires that data for non-renewable resource use and imports of goods and services can be determined with sufficient detail to allow an emergy analysis of the region to be performed (see Brown et al., 1995, or Odum, 1996, for methods of regional analysis).

A significant consideration in the regional analysis is the choice of regional boundaries. Specifically, what is the appropriate regional boundary for a given development (i.e., region that is affected by the development)? Choosing the region is important as it affects the analysis. In some cases the region might be a watershed, or market region. In other cases it might be a political region like a state or nation. The choice of regional area is important, but there are no fixed criteria for establishing one.

An emergy evaluation of the development is also performed yielding the total non-renewable and imported emergy required by the development. Then the area of land necessary to balance the development can be calculated using the average annual flux of renewable emergy per year per unit area of landscape. Renewable emergy/area is derived from the analysis of the regional economy. To determine the area of support necessary for a proposed development to remain competitive under current conditions, first the ELR for the region is calculated (as above) and then the following simple equivalent proportion is constructed:

$$ELR_{(r)} = ELR_{(d.)} \qquad (3)$$

where:

$ELR_{(r)}$ = environmental loading ratio of the region,
$ELR_{(d.)}$ = environmental loading ratio of the development
$= [F + N] / R^*$ (4)

and

F and N are as given in Equation 2

The $ELR_{(d)}$ is the loading ratio that is necessary to equal that of the region, thus the R* in Equation 3 is the required amount of renewable emergy necessary to lower the ELR of the development to that of the region. The equation is solved as follows:

$$R^* = [F + N] / ELR_{(r)} \tag{5}$$

Once the quantity, (R*), is known, the area of landscape required to balance the proposed development is calculated as follows:

$$S\ A_{(ELR)} = R^* / Empd_{(r)} \tag{6}$$

RESULTS: CALCULATING ENVIRONMENTAL SUPPORT AREA OF TOURISM DEVELOPMENT

To illustrate the method, the environmental support area was calculated for two very different tourist resorts. The first resort was a small diving resort in the province of East New Britain, on the Island of New Britain, in Papua New Guinea (PNG). The second resort was a large hotel resort complex in Mexico on the Bay of Bandaras in the city of Puerto Vallarta.

Emergy Evaluation of Tourist Resorts

A simplified systems diagram of the main driving energies and internal processes of a tourist resort facility is given in Figure 3. The diagram in Figure 3 is the diagram from which the emergy analysis of tourist resort in Papua New Guinea and Mexico was performed.

Table 1 gives the emergy evaluation of the tourist resort on the Island of New Britain, PNG, and Table 2 gives the evaluation of the "four-star" tourist hotel in Puerto Vallarta, Mexico. The facilities were as different as their total emergy flows indicate. The PNG resort was hand-built from local materials (wood and thatching), purchased fuel to generate its own electricity, burned coconut shells for hot water, and had 12 guest rooms serving an estimated 5,232 person-days per year. The Mexican hotel was built almost entirely of concrete and steel, purchased electricity, had 160 rooms and served a total of 37,584 person-days per year.

The main renewable inputs to each resort were evaluated and are given in Items 1–6 in Tables 1 and 2. Because of their coastal locations the largest renewable emergy input to both resorts was the wave energy absorbed along their coastal margins. In practice, the renewable emergy

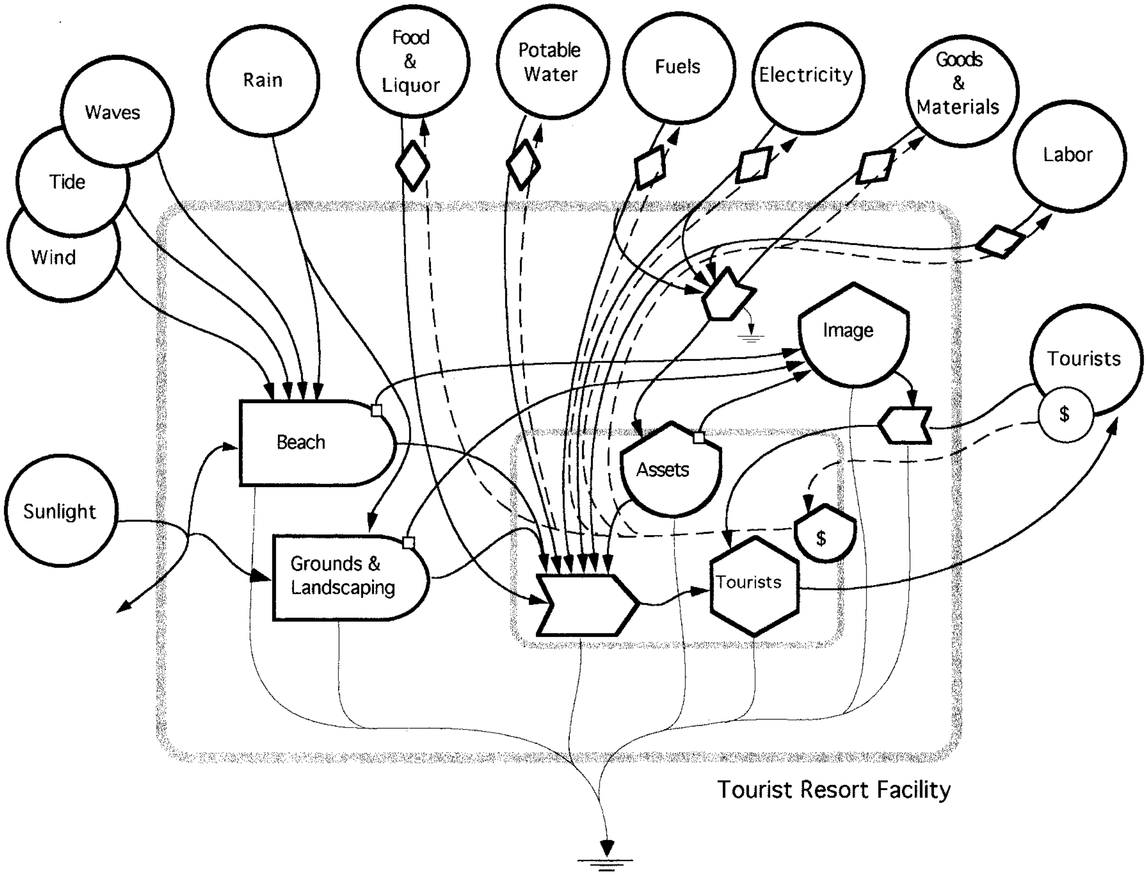


FIGURE 3. A summary diagram of a tourist resort facility showing the main production function that provides goods and services for the tourists who are attracted by the resort's image. Dashed lines are money and solid lines are energy flows. Annual flows of resources, goods and services are evaluated in Tables 2 and 3.

TABLE 1

Emergy Evaluation of Tourist Resort on New Britain Island, Papua New Guinea

Note Item	Units	Units/Yr.	Transformity[a] (sej/unit)	Solar Emergy (E15 sej/yr)
Renewable Resources				
1 Sunlight	J	3.45E + 14	1.00E + 00	0.3
2 Wind	J	2.34E + 11	1.50E + 03	0.4
3 Rain	J	4.78E + 11	1.82E + 04	8.7
4 Tidal Energy	J	2.30E + 11	1.68E + 04	3.9
5 Wave Energy	J	1.96E + 12	3.06E + 04	60.0
Nonrenewable Storages				
6 Potable water	J	2.93E + 09	1.49E + 05	0.4
Sum of free inputs (wave energy + potable water)#				60.4
Purchased Inputs				
Construction inputs				
7 Wood	J	1.51E + 09	3.49E + 04	0.1
8 Concrete	g	1.70E + 06	9.26E + 07	0.2
9 Steel	g	5.10E + 04	1.80E + 09	0.1
10 Furnishings	J	3.16E + 09	4.00E + 06	12.7
11 Non-renewable services	$	7.50E + 03	6.50E + 12	48.8
Operational inputs				
12 Fuel	J	2.28E + 12	6.60E + 04	150.5
13 Electricity	J	0.00E + 00	2.00E + 05	0.0
14 Food	J	8.76E + 10	2.50E + 05	21.9
15 Liquor	J	1.10E + 10	7.00E + 05	7.7
16 Non-renewable services	$	1.04E + 05	6.50E + 12	676.0
Sum of purchased inputs				917.8
17 Tourists (number)		6.20E + 02	3.74E + 16	23,188.0

Solar emergy contribution from renewable sources is taken as the largest renewable input. Other renewable sources are not counted since they are coupled global inputs and their transformities result from the total global emergy flux.

[a] All transformities are from Odum, 1996.

Notes:

1 Sunlight—1.46 E5 cal/cm& circ;2/yr, Area = 40700 m^2 land; 40000 m^2 water; albedo = 30%
(1.46 E9 cal/m^2)(80.7 E3 m^2)(70%)(4.186 J/cal) = 3.45E + 14 J/yr
2 Wind—2.9 E6 J/m^2 (based on PNG average); Area = 80700m^2
(2.9 E6 J/m^2)(80.7E3 m^2) = 2.34E + 11 J/yr
3 Rain—1.2 m/yr; Area = 40700 m^2land, 40000 m^2 water
(1.2 m)(80.7 E3 m^2)(1000kg/m^3)(4.94 E3 J/kg) = 2.4 E11 J/yr 4.78E + 11 J/yr
4 Tidal—1.56 meter tidal range; shore length = 400 m; assume 100 m width
(4E4 m̂ 2)(0.5)(730 tides/yr)(1.56 m)(1.03E3kg/m̂ 3)(9.8m/ŝ 2) = 2.30E + 11 J/yr

TABLE 1 (*Continued*)

5 Waves = shore length = 400 m; wave height = 0.2m; velocity = 3.1m/sec
(400 m)(1/8)(1.025 E3 kg/m^3)(9.8 m/sec^2)(0.2m)^2(3.1 m/sec)(3.15 E7 sec/yr) = 1.96E + 12 J/yr
6 Potable water—113 1/capita/day = 593 m^3/yr
(593 m^3)(1000kg/m^3)(4.94 E3 J/kg) = 2.93E + 09 J/yr
7 Wood—544 m^3 ($12,500)
(544 m^3)(5.5 kg/m^3)(15.1 E6 J/kg) = 4.9 E10 J/30yr = 1.51E + 09 J/yr
8 Concrete—284m^3—181kg/m^3 = 5.1 E4 kg ($17,600)
(5.1 E4 kg)(1000g/kg) = 5.1 E7 g/30yrs = 1.70E + 06 J/yr
9 Steel—1.53 E3 kg (based on average steel/unit concrete) ($7,290)
(1.53 E3 kg)(1000 g/kg) = 1.53 E6 g/30yrs = 5.10E + 04 g/yr
10 Furnishings—240 kg/room, plus 500 kg misc furnishings (estimate) = 2420 kg ($16,000)
(2.4 E6 g)(90%drywt)(3500cal/g)(4.186 J/cal)/ 10years = 3.16E + 09 J/yr
11 Services—total costs of construction + furnishings = $US 200,000 (1988)
To avoid double counting, subtract money paid for wood, concrete, steel, and furnishings services = $2.0 E5–($12,500 + $17,600 + $7,290 + $16,000)
(1.5 E5 $) / 20 years = 7.50E + 03 $/yr
12 Fuel—55,609 liters per year of gasolines ($2.3 E4)
(5.56 E4 liters)(4.1 E + 7 J/l) = 2.28E + 12 J/yr
13 Electricity—elec is generated on site
(0 kwh)(3.6 E + 6 J/kwh) = 0 J/yr. 0.00E + 00 J/yr
14 Food—4 E3 kcal/capita*day-1 ($5.2 E4)
(4 E3 kcal/person*day-1)(5232 person days)(4186 J/kcal) = 8.76 E10J 8.76E + 10 J/yr
15 Liquor—1 liter/capita*day-1 ($2.1E4)
(1.01/capita*day-1)(5232 person days)(2.11 E7 J/l)(10% alcohol) = 1.1 E10 J 1.10E + 10 J/yr
16 Services. Total yearly income = $2.8 E5 (US dollar equivalent)
To avoid double counting, subtract money paid for fuel, food, and liquor as well as construction debt ($8E4/yr) services = $2.8 E5—($2.3 E4 + $5.2 E4 + $2.1 E4 + $ 8 E4) = 1.04E + 05 $/yr
17 Tourists—37.4 E15 sej/capita, assuming all visitors are American tourists

inputs are not summed as they are coupled to the global emergy inputs and their transformities result from the total global emergy flux. As a result, only the largest emergy input to a region or local area is counted.

Non-renewable emergy inputs for the two tourist systems reflect their differences in intensity. Emergy of potable water use in the Mexican resort was about 90 times that in the PNG resort. Potable water use at the PNG resort was quite small (about 113 liters capita^{-1} day^{-1}) as compared to the Mexican resort (1311 liters capita^{-1} day^{-1}).

Differences in purchased emergy inputs also revealed the differences in intensity of both resorts. Total emergy of structure was discounted over the estimated lifetime of the two resorts (see footnotes). In the PNG resort the total annual emergy input in structure was 60.4 E15 sej yr^{-1} (the sum of items 7–11), while in the Mexican resort it was 2880.2 E15 sej yr^{-1} (sum of items 7–10). In both cases, the largest construction inputs were the emergy in services (labor). The emergy of structure in the Mexican resort was about 48 times that of the PNG resort. The Mexican resort was a concrete struc-

TABLE 2

Emergy Evaluation of Four-Star Tourist Hotel in Puerto Vallarta, Mexico

Note Item	Units	Units/Yr.	Transformity (sej/unit)	Solar Emergy (E15 sej/yr)
Renewable Resources				
1 Sunlight	J	9.14E + 13	1.00E + 00	0.1
2 Wind	J	1.10E + 11	1.50E + 03	0.2
3 Rain	J	9.31E + 10	1.82E + 04	1.7
4 Tidal Energy	J	4.16E + 10	1.68E + 04	0.7
5 Wave Energy	J	3.48E + 12	3.06E + 04	106.4
Nonrenewable Storages				
6 Potable water	J	2.44E + 11	1.49E + 05	36.3
Sum of free inputs (wave energy + potable water)#				142.8
Purchased Inputs				
Construction inputs				
7 Concrete	g	1.15E + 08	9.26E + 07	10.6
8 Steel	g	2.71E + 07	1.80E + 09	48.8
9 Furnishings	J	5.72E + 10	4.00E + 06	228.9
10 Non-renewable services	$	9.97E + 05	2.60E + 12	2591.3
Operational inputs				
11 Fuel	J	3.91E + 12	6.60E + 04	257.8
12 Electricity	J	6.19E + 12	2.00E + 05	1238.4
13 Food	J	6.29E + 11	2.00E + 06	1258.6
14 Liquor	J	7.93E + 10	7.00E + 05	55.5
15 Non-renewable services	$	9.09E + 05	2.60E + 12	2364.4
Sum of purchased inputs				8054.5
16 Tourists (number)		5.37E + 03	8.50E + 15	45636.5

Solar emergy contribution from renewable sources is taken as the largest renewable input. Other renewable sources are not counted since they are coupled global inputs and their transformities result from the total global emergy flux.

Notes:

1 Sunlight—1.64 E5 cal/cm^2/yr; Area = 19030 m^2 land, 11300 m2 water; albedo = 30%
(1.64 E9 cal/m^2)(30.33E3 m^2)(70%)(4.186 J/cal) = 1.46E + 14 J/yr
2 Wind—5.8 E6 J/m^2 (based on Mexico average)
(5.8 E6 J/m^2)(30.33E3 m^2) = 1.76E + 11 J/yr
3 Rain—0.99 m/yr; Area = 19030 m2
(0.99 m)(30.33 E3 m^2)(1000kg/m^3)(4.94 E3 J/kg) = 9.31 E10 J/yr 1.48E + 11 J/yr
4 Tidal—1.0 meter tidal range; shore length = 113.5 m; assume 100 m width
(11350 m^2)(0.5)(730 tides/yr)(1.0 m)(1.03E3kg/m^3)(9.8m/s^2) = 4.16E + 10 J/yr
5 Waves = shore length = 113.5 m; wave height = 0.5m; velocity = 3m/sec
(113.5 m)(1/8)(1.025 E3 $\mathrm{kg/m^3}$)(9.8 $\mathrm{m/sec^2}$)$(0.5\mathrm{m})^2$(3.1 m/sec) = 3.48E + 12 J/yr
6 Potable water—49,287 m^3/yr
(4.93E4m^3)*1000kg/m̂ 3)(4.94 E3 J/kg) = 2.44E + 11 J/yr

TABLE 1 (*Continued*)

7 Concrete—5736 tonns (based on average concrete/room) ($20.0 E6)
(5.736 E6 kg)(1000g/kg) = 5.736 E9 g/50yrs = 1.15E + 08 g/yr
8 Steel—1356 tonns (based on average steel/room) ($11.9 E6)
(1.356 E6 kg)(1000 g/kg) = 1.356 E9 g/50 yrs = 2.71E + 07 g/yr
9 Furnishings—240 kg/room, plus 5000 kg misc furnishings (estimate) ($8.8 E6)
total weight = 43,400kg
(43.4 E6 g)(90%drywt)(3500cal/g)(4.186 J/cal)/ 10years = 5.72 E10 J 5.72 + 10 J/yr
10 Services—total costs of construction + furnishings = 1.85 E9 pesos (1979)
(1.85 E9 pesos)/(26.24 pesos/$) = $70.5 E6 7.05E + 07 $/yr
To avoid double counting, subtract money paid for, concrete, steel, and furnishings services
= $70.5 E6—($20.0 E6 + $11.9 E6 + $8.7 E6) /30 yrs = 9.97E + 05 $/yr
11 Fuel—140,136 liters per year of liquified natural gas ($47.6 E3)
(1.4 E5 liters)(2.79 E + 7 J/l) = 3.91E + 12 J/yr
12 Electricity—1,719,929 kwh per year ($5.16 E5)
(1.72E + 6 kwh)(3.6 E + 6 J/kwh) = 6.2E + 12 J/yr. 6.19E + 12 J/yr
13 Food—4000 kcal/person*day-1 ($1.12 E5)
(4 E3 kcal/person*day-1)(37,584 people days)(4186 J/kcal) = 6.29E + 11 J/jr
14 Liquor—37.6 E3 liters—1 liter/person (est)*37,584 people ($1.5 E5)
(37.6 E3 l)(2.11 E7 J/l) (10% alcohol) = 7.93E + 10 J/yr
15 Services—4.848 E9 pesos (total yearly income, 1990)
(4.858 E9 pesos) / (2800 pesos/$) = $1.735 E6/yr
To avoid double counting, subtract money paid for fuel, electricity, food, and liquor services
= $1.735 E6—($47.6E3 + $5.16 E5 + $1.12 E5 + $1.5 E5) = 9.09E + 05
16 Tourists—5,369 tourists/yr.
Transformity = 8.5 E 15 sej/capita, assuming all visitors are Mexican tourists

ture having 8 floors, several large meeting rooms, a lobby, several dining rooms, and an extensive pool and patio. The PNG resort consisted of separate "huts" constructed of palm thatching and wood from nearby forests using local methods of construction and labor.

Since there was no purchased electricity in the PNG resort, the emergy of fuels and electricity were added together for comparison of the two resorts. Instead of purchasing electricity (there was no electric grid), the PNG resort had its own generator, which was turned on twice a day for about 4 hours, total. The Mexican resort uses more than 10 times the amount of fuels and electricity as the PNG resort, yet has only about 7 times the number of guests. Food and liquor consumption reflect the differences in the number of tourists served by the two resorts. Total purchased inputs (the sum of construction and operational inputs) in the Mexican resort were about 10 times as large as those in the PNG resort. The greatest emergy input to both resorts was the purchase of services from the local economy (amounting to about 75% of the total purchased emergy inputs). Overall the operational inputs of the Mexican resort were about 10 times those of the PNG resort. These differences in the inputs to the resorts underline the differences in their intensity and style. With small technological inputs, the

PNG resort required, proportionally, large amounts of human services to provide for the needs of the tourist guests, while in the Mexican resort, more of their needs were met by machines and technological tools.

Emergy Indices of the Tourist Resorts

Table 3 summarizes the emergy evaluations of the two resorts and the regions in which they are embedded. In the interest of space, the complete

TABLE 3

Comparative Emergy Indices for Tourist Resorts in Papua New Guinea and Mexico

	Papua New Guinea		Mexico	
Note Index	Region[a]	Resort	Region[b]	Resort
1 Total Emergy Use	4.8E + 21	9.8E + 17	9.4E + 21	8.2E + 18
Locally Renewable	4.2E + 21	6.0E + 16	2.3E + 21	1.1E + 17
Locally Nonrenewable	3.5E + 20	4.4E + 14	5.9E + 21	3.6E + 16
Imported	1.8E + 20	9.2E + 17	1.3E + 21	8.1E + 18
2 Percent Renewable	88.8%	6.1%	24.1%	1.30%
3 Empower density (E11 sej m-^{2} yr^{-1})	2.4	121.2	3.0	2702.7
4 Emergy per capita (E15 sej person^{-2}yr^{-1})	18.9	68.2	11.8	79.6
5 Environmental loading ratio	0.1	15.3	3.2	76.0
6 Renewable emergy/area (E11 sej m-^{2} yr^{-1})	2.1	7.4	0.7	35.1
7 Support Area required (m^{2})		3.4E + 07		3.5E + 07
8 Renewable support area (m^{2})		3.9E + 07		1.5E + 08

[a] Region is defined as the province of East New Britain, on the Island of New Britain, data are from Doherty and Brown, 1993.

[b] Region is defined as the State of Nayarit, Mexico, data are from Brown, et al. 1992

Notes:

1 Emergy use for resorts taken from Tables 1 and 2

2 Calculated as the ratio of locally renewable to total emergy use.

3 Calculated as the ratio of total emergy use to area (see Tables 1 and 2 for areas of resorts).

4 Calculated as total emergy divided by population (regions) and by average daily number of tourists (resorts).

5 Calculated as the ratio of nonrenewable + purchased inputs to locally renewable inputs.

6 Calculated as the locally renewable emergy divided by area.

7 Calculated according to equations 5 and 6 in text.

8 Sum of support area (Item 7) and the area required to supply non renewable and imported emergy from the environmental (renewable) resource base.

emergy evaluations of the regions are not included, only the summary data.[3] Item 1 in Table 3 lists the total emergy use and amounts of the total that come from renewable and local non-renewable sources, and purchased imports for the region and resort. For each of the two countries, the data and indices for the region are given first followed by the resort.

Items 2 through 6 in Table 3 are emergy indices that help to summarize the relative development intensities of the regions and resorts. The first column under each country heading is a summary of data for the regions. In general, the PNG region (the province of East New Britain, on the Island of New Britain) was less developed than the region in Mexico surrounding Puerto Vallarta. Renewable emergy inputs to the regional economy of New Britain were 88.8% of total inputs compared to only 24.1% in the Mexican state of Nayarit indicating that a relatively small proportion of the total economy of East New Britian was derived from non-renewable resources. The empower density in the Mexican region was about 25% higher than that of the PNG region. Interestingly, the emergy per capita was higher in the PNG region compared to the Mexican region, a result of much lower population densities on the island of New Britain and higher renewable emergy inputs. The environmental loading ratios for the regions reflect their differences in development intensity. The ELR in the Mexican region was almost 30 times the ELR in the PNG region (3.2 compared to 0.1). Item 6 is the renewable emergy input per unit area of the region. It was higher on the island of New Britain than in the Mexican region reflecting the higher rainfall characteristic of the island.

The second column under each country lists the summary data and indices for each of the resorts. The percent renewable emergy input for each resort was small when compared to the larger regions (6.1% and 1.3% for the PNG and Mexico resorts respectively). This results from the fact that the only renewable emergy inputs counted in the analysis were those that "fall" on the property of the two resorts and the coastal waters immediately adjacent to the property. Because the resorts were intense developments compared to the regions as a whole, their empower densities were much higher than each of the regions. The resort on New Britain has an empower density of 121.2 E15 sej m^{-2} yr^{-1}, compared to 2.4 E15 sej m^{-2} yr^{-1} in the region. The differences were even more extreme between the Mexican resort and the state of Nayarit (2702.2 E11 sej m^{-2} yr^{-1} compared to 3.0 E11 sej m^{-2} yr^{-1}), reflecting the greater intensity of the larger hotel on a much smaller piece of land. The land area of the PNG resort was more than twice the land area of the Mexican resort. Emergy per capita was higher in the resorts compared to their surrounding regions (about 3.6 times higher in the PNG resort and almost 7 times higher in the Mexican resort.) In essence, emergy per capita measures the total emergy used in support of a population, so these numbers indicate that a tourist in the PNG resort receives nearly 3.6 times the emergy received by an average citizen of East New Britain. In the Mexican resort it requires nearly 7 times the emergy to support a tourist compared to the emergy required to support an average citizen of the state of Nayarit.

As might be expected, the environmental loading ratios (Item 5, Table 3) for the resorts were much higher than the regions in which they were embedded. This results from high purchased emergy inputs and very small renewable emergy inputs because the area of each resort was relatively small. The ELR of the PNG resort was 153 times larger than the ELR for the region, while the ELR for the Mexican resort was about 24 times that of the region.

Renewable emergy inputs per unit area of resort (Item 6) were higher than the surrounding regions. Since the resorts were both located on the coast and their land areas were relatively small, the effect of the wave energy striking their shorelines was to significantly increase the emergy per unit area of resort.

Required environmental support area (Items 7 and 8 in Table 3) for each of the resorts was based on the area required to supply renewable emergy inputs. Item 7 is the area of environment necessary to provide a sufficient renewable emergy base to reduce the ELR of the resorts to that of their respective regions (34 km^2 and 35 km^2 for the PNG resort and the Mexican resort respectively). As a ratio of area of environmental support to area of development, the PNG resort requires about 835 times the land area of the resort for environmental support while the Mexican resort requires about 1800 times the area. The renewable support area (Item 8) is the area that would be necessary if all the emergy required for the resorts came from the renewable environmental support base (39 km^2 for the PNG resort and 150 km^2 for the Mexican resort). This larger area represents a theoretical maximum area of region that would be necessary to provide the total emergy requirements of the tourist resort from renewable emergy inputs. The ratio of renewable support area to area of resort is about 958 times the land area of the PNG resort and about 7882 times the land area of the Mexican resort.

Carrying Capacity for Tourist Resorts

The support area calculated using the environmental loading ratio for an economic development reflects the area necessary to reduce its environmental loading to that which is characteristic of the regional economy.

Determination of support area establishes environmental carrying capacity using the ratio of support area to developed area. It is not a fixed land based ratio, but varies based on intensity of development and on the intensity of the regional economy. If the size and/or intensity of a development changes, the required support region will also change since its determination is based on the emergy intensity. In this way the determination of carrying capacity using the environmental loading ratio achieves a dynamic balance that is affected by the size and intensity of the development and the develoipment intensity of the region.

While the intensity of the PNG resort was less than the Mexican resort, the development intensity of the local PNG region was much less than that of the area surrounding the Mexican resort. These facts lead to the PNG resort requiring a support area that was nearly equal to the Mexican resort in order to match the development intensity of the local environment.

The general trend is that the less developed a region, the larger the support area required for new developments. So for a given development intensity, the support area would be larger in a less developed region as compared to a highly developed region.

The environmental support area includes land as well as marine systems. When coastal areas are evaluated, emergy inputs to the regional economy come from both land and coastal waters. The area of continental shelf and the renewable emergies associated with it (waves, tides, rainfall, and sunlight) are included in regional evaluations. So the support area includes this wider realm. The continental shelf areas of the PNG and Mexican regions amounted to about 24% and 18% of total area respectively. As a result the environmental support areas of the resorts were composed of the same portion of land to water.

This method of determining carrying capacity calculates the area of environmental support necessary for a given development. It can be used to evalaute proposed developments and if applied in this manner, limits development based on the ability of the region to provide environmental support, and limits intensity to that of the existing conditions. It provides a quantative rational for limiting development intensity and for setting aside support regions as non-developable environmental reserves.

Spatial Relationships of Resorts and Support Areas

There are numerous ways that resorts and support areas might be organized spatially. Figure 4 illustrates three different concepts for a group of resort complexes in a coastal zone. Since the environmental basis of coastal regions is a blend of both marine and terrestrial productivity, the support

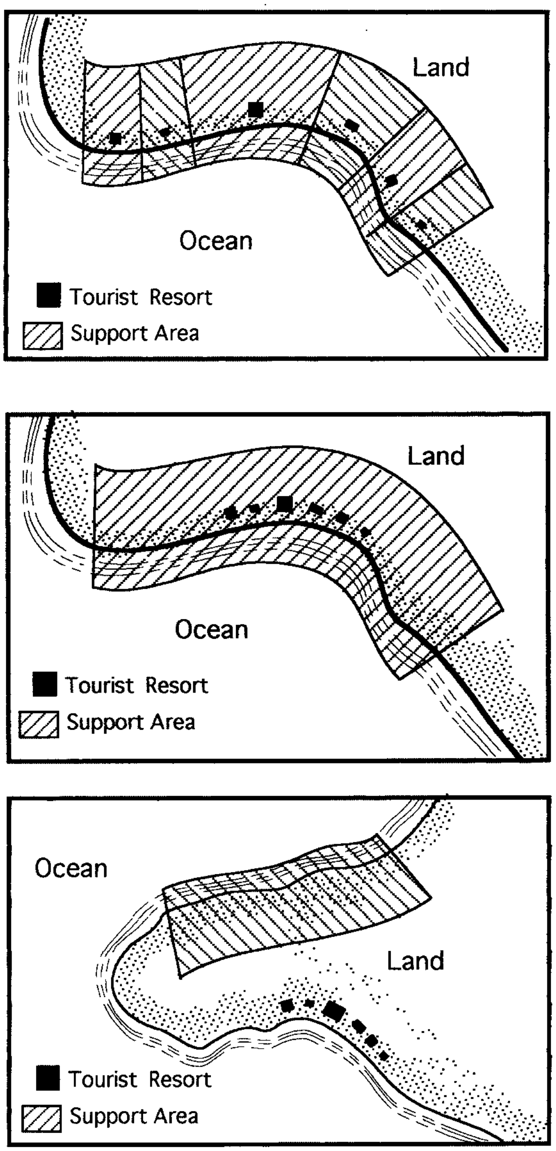


FIGURE 4. Schematic diagrams of a coastlines showing alternate ways of grouping tourist resorts within their support regions so as not to exceed environmental carrying capacity. In the top diagram resorts are spaced based on the size of the required support region, and in the bottom diagram, resorts are clustered leaving the remaining support region undeveloped.

regions (hatched areas) are composed of both of these environments. In the top illustration resort developments are spaced along the coast, each surrounded by their appropriate support region. In the middle illustration, the same number and size developments are clustered in one area and surrounded by a support region equal to the sum of the individual areas. To maintain a balanced ELR, further development within the support areas would be restricted. The bottom illustration shows a spatial arrangement where the support region does not surround the resorts, but is located elsewhere within the region. In many cases this arrangement may be more attractive as a means of setting aside ecological reserves or important wetland ecosystems, for example.

We have considered only the tourist resort in our analysis and in the above illustrations of spatial arrangements. In some developing regions, where the regional economy is already relatively intense, resort development also brings infrastructure development and urban expansion resulting from increased populations. We believe that this method for determining carrying capacity and support areas could apply in these circumstances as well, if the infrastructure and increased urban developments were factored into the calculations. Often feasibility studies for new developments determine infrastructure requirements and urban expansion that will result from the development. These data could provide the basis for an expanded evaluation of carrying capacity that included secondary development.

Sustainability Based on Emergy Trade Balance

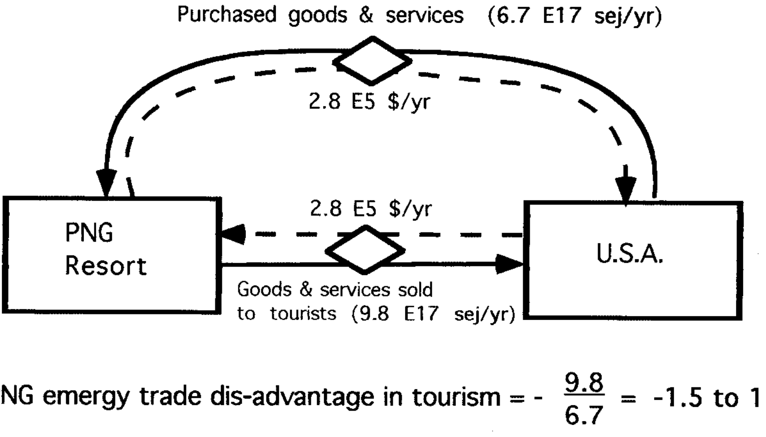
Emergy evaluations can provide quantitative insight into sustainability. While the forgoing analysis lends itself to regional sustainability, as it balances development within the regional economy, a wider perspective is also required. For a development to be sustainable it need contribute a net emergy benefit. Measured in emergy terms, a net emergy benefit means that the development causes more emergy to inflow to the economy than it uses from the economy.

International development has become an important economic activity as accumulated currency in developed economies is invested in undeveloped economies to achieve high returns on investment. The resources and environment of any country, whether developed or not, represent its wealth. When money is invested in developing economies, the principal reason is to extract resources and sell them for more money than they cost to extract. Thus the activity results in the exportation of national wealth and the inflow of currency. Since currency cannot accumulate for long, but must be spent, it is used to purchase fuels, goods, and services from the developed world. Most often, the emergy of the goods purchased does not equal that which is exported (Brown et al., 1995). In other words, a developing economy that sells raw resources and imports finished goods from a developed economy supports the outside economy at the expense of its own.

The consequences of international tourism on trade balance are often seen as beneficial to developing economies since it seems to be a non-extractive source of much needed foreign currency. What is often overlooked is the environmental support required and resources consumed to provide the goods and services for an expanded population of visitors. In essence, the resources and environmental services that are consumed in support of a tourist population are "extracted" and exported with each tourist and therefore not available for consumption by the local population. In return, the local economy receives a currency income with which they purchase goods from the international market place. Evaluating tourism's economic impact by measuring only the currency input may miss this important consequence.

As an example of the use of emergy balance of trade, the emergy exchange of the PNG and Mexican resort developments with the economy of the USA are illustrated in Figure 5. An exchange of emergy is shown flowing countercurrent to the dollar exchange between the two economies. In the top diagram, the PNG resort received \$2.8 E5/yr as income, for which it provided 9.8 E17 sej/yr (Table 3, Item 1) in goods and services to the tourists (the emergy that was used by the resort in direct support of the tourists). The Mexican resort received \$3.15 E6/yr and provided 8.2 E18 sej/yr in goods and services. When the income from tourists was eventually spent for import purchases from the USA, the amount of emergy received from the USA (on average) was determined by multiplying the money spent for imports by the emergy/money ratio for the USA economy in that same year (2.4 E12 sej/\$ [Odum, 1996]). The calculated emergy values of imported goods and services were 6.7 E17 sej (PNG) and 7.6 E18 sej (Mexico) for the year of this evaluation. The net loss was derived by subtracting the emergy that was exported from the emergy that was imported. The emergy trade balance for the year in the PNG resort was negative (–3.1 E17 sej; or a trade imbalance of about –1.5 to 1) The balance in Mexico was also negative (–4.05 E18 sej.; or about –2 to 1).

We have made several simplifying assumptions with regard to the balance of international trade that may result from tourist development. We assumed that all the tourists were from the USA and that income from tourists was used to purchase goods and services from the USA economy. Further, the money spent by each tourist purchased local goods and resources



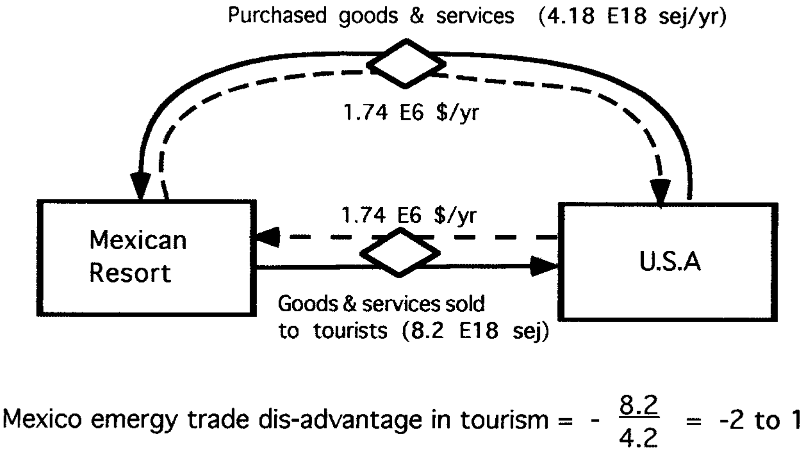


FIGURE 5. Diagrams illustrating the USA trade advantage when tourists spend money in Papua New Guinea (top) and Mexico (bottom). The trade advantage is calculated assuming that tourists are from the USA and all tourist currency is used to purchase goods and services from the USA economy.

and environmental support (for instance, a portion of the local estuary that cannot be used by the local population for sewage disposal or fish harvest because it is being used for waste disposal of the tourist facility). With these assumptions the emergy balance of trade was negative. In other words, more wealth was used and exported than was imported. While we have not analyzed tourism elsewhere in the third world, our analysis of other development projects (Brown et al., 1995; Brown et al., 1991; Odum et al., 1986; Brown and McClanahan, 1995) suggests that one of the main driving forces behind international trade and tourism is the fact that developed countries benefit greatly through the uneven emergy exchange.

SUMMARY: SUSTAINABILITY OF DEVELOPMENT PROJECTS

Global economic development seems to be increasing in rate and magnitude as developed countries seek higher returns on investment than are characteristic of their internal economies. The result is increased rates of change in environmental, cultural, and economic systems of the third world. With it an awareness has recently developed that sustainability is a key factor to consider when analyzing potential impacts of proposed projects. Yet sustainability remains an elusive concept. It can be argued that sustainable development, in the long run, is that which can be supported by the renewable flows of emergy of a region. Development that depends on purchased resources is ultimately not sustainable since purchased emergy is composed of nonrenewable flows and fluctuations in world prices. Yet, development that does not allow for the possibility of using purchased resources to amplify a region's environmental basis cannot give an economic return and becomes a moot point. Thus we have asserted that sustainability should reflect the current intensity of development of an economy and match it. In this way, it is no more dependent on limited supplies of nonrenewable emergies than the economy as a whole. As the economy's use of nonrenewable purchased energies may decline, new development under these circumstances does not draw more of these energies, on the average, than the rest. To put it another way, what is sustainable in the USA is much different from what is sustainable in Papua New Guinea.

Determinations of sustainability should take into account the relative mix of: (1) an economy's environmental basis (renewable emergy sources), (2) its use of nonrenewable storages from within, and (3) its purchased goods, resources, and services. These flows drive the economy and ultimately influence what is sustainable by defining an upper boundary to the present mix of purchased emergy, resources from within, and renewable emergy flows.

Where economic development results in extraction and sale of resources to foreign economies, sustainability may be related to the trade advantage or emergy exchange that results. If more emergy leaves the local economy than is received in exchange, the development is not sustainable. Balancing the exchange of emergy between that which is exported and that which is imported may lead to more sustainable developments in the long run. In the case of the tourist developments in PNG and Mexico, more wealth left both economies "embodied" in visitors, than was received when the income derived from tourists was used to purchase foreign goods and services.

In this paper we have demonstrated a quantitative method for evaluating regional carrying capacity and sustainability of economic development. In summary, regional carrying capacity for new economic development may be linked to preservation of environmental support area, and sustainable development depends on the wise use of indigenous resources and a positive, or at least equal, emergy balance of payments. Indeed, sustainability is an elusive concept, but by adding a quantitative methodology to the discussion of criteria and policy alternatives, we may move a step forward in achieving a more balanced approach to development and human use of environments.

ACKNOWLEDGMENTS

The authors wish to express their sincere gratitude to Captain Jacques Cousteau, who over the years provided much support and whose advocacy of good environmental stewardship will be much missed by our water planet. We also acknowledge Jean-Michael Cousteau and Dr. Richard Murphy of The Cousteau Society for their financial and logistical support of this work.

APPENDIX

Further discussion and definitions can be found in Odum, 1996; Brown and Ulgiati, 1997; Ulgiati et al., 1995.

Definitions

Energy. Sometimes referred to as the ability to do work. Energy is a property of all things which can be turned into heat and is measured in heat units (BTUs, calories, or joules).

Emergy. An expression of all the energy used in the work processes that generate a product or service in units of one type of energy. Solar emergy of a product is the emergy of the product expressed in equivalent solar energy required to generate it. Sometimes its convenient to think of emergy as energy memory.

Emjoule. The unit of measure of emergy, "emergy joule." It is expressed in the units of energy previously used to generate the product; for instance the solar emergy of wood is expressed as joules of solar energy that were required to produce the wood.

Non-Renewable Emergy. The emergy of energy and material storages like fossil fuels, mineral ores, and soils that are consumed at rates that far exceed the rates at which they are produced by geologic processes.

Renewable Emergy. The emergy of energy flows of the biosphere that are more or less constant and reoccurring, and that ultimately drive the biological and chemical processes of the earth and contribute to geologic processes.

Resident Emergy (or local emergy). The renewable emergy flows that are characteristic of a region such as sunlight, winds, rain, and tidal flux.

Indices

Emergy/GDP ratio. The ratio of total emergy flow in the economy of a region or nation to the GDP of the region or nation. The emergy/GDP ratio is a relative measure of purchasing power when the ratios of two or more nations or regions are compared.

Empower density. The ratio of total emergy use in the economy of a region or nation to the total area of the region or nation. Renewable and nonrenewable emergy density are also calculated separately by dividing the total renewable emergy by area and the total nonrenewable emergy by area, respectively.

Emergy exchange ratio. The ratio of emergy exchanged in a trade or purchase (what is received to what is given). The ratio is always expressed relative to one or the other trading partners and is a measure of the relative trade advantage of one partner over the other.

Emergy investment ratio. The ratio of emergy fed back from outside a system to the indigenous emergy inputs (both renewable and non-renewable). It evaluates if a process is a good user of the emergy that is invested, in comparison with alternatives.

Environmental loading ratio. The ratio of nonrenewable and imported emergy use to renewable emergy use.

Emergy per capita. The ratio of total emergy use in the economy of a region or nation to the total population. Emergy per capita can be used as a measure of potential, average standard of living of the population.

Emergy Sustainability Index. The ratio of the Emergy Yield Ratio to the Environmental Loading Ratio. It measures the contribution of a resource or process to the economy per unit of environmental loading.

Emergy yield ratio. The ratio of the emergy yield from a process to the emergy costs. The ratio is a measure of how much a process will contribute to the economy.

Percent renewable emergy (%Ren). The ratio of renewable emergy to total emergy use. In the long run, only processes with high %Ren are sustainable.

Renewable carrying capacity. The environment's ability to support economic development based solely on its renewable emergy sources. Calculated by dividing the sum of non-renewable and purchased emergy inputs to a region or economic process by the average renewable emergy flows per unit area of the region. The result is the area required to "sequester" the equivalent emergy required for the population or process from renewable sources.

Solar transformity. The ratio of the solar emergy that is required to generate a product or service to the actual energy in that product of service. Transformities have the dimensions of emergy/energy (sej/J). A transformity for a product is calculated by summing all the emergy inflows to the process and dividing by the energy of the product. Transformities are used to convert resources of different types to emergy of the same type. The transformity is a measure of the "value" with the assumption that systems operating under the constraints of the maximum emergy principle generate products that stimulate productive process at least as much as they cost (Odum, 1996).

ENDNOTES

1. Systems symbols and definitions can be found in Odum (1996). Like any simplification of the "real world" a systems diagram is only a representation, in this case an aggregation of the complexities of the larger reality.
2. Intensity may be measured using any quantity (energy, materials, money, or information) per unit time per unit area. If one uses emergy per unit time (or empower), expressed over a unit area, the intensity is empower density. In this paper, intensity is measured using units of empower (sej year^{-1} area $^{-1}$).
3. Regional analyses are not included here, but can be found in Doherty and Brown (1993) and Brown et al. (1992).

REFERENCES

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C. S., Jansson, B. O., Levin, S., Maeler, K. G., Perrings, C., & Dimentel, D. (1995). Economic growth, carrying capacity, and the environment. *Science 268 (5210),* 520–521.

Brown, M. T. (1980). Energy Basis for Hierarchies in Urban and Regional Landscapes. PhD Dissertation. Gainesville: University of Florida.

Brown, M. T., Gonzales, A., Green, P., & Venegas, J. (1992). *Energy Analysis Perspectives, Public Policy Options, and Development Guidelines for the Coastal Zone of Nayarit, Mexico.* Final Report to the Cousteau Society. Gainesville: Center for Wetlands, University of Florida.

Brown, M. T., & McClanahan, T. (1996). Emergy Analysis Perspectives for Thailand and Mekong River Dam Proposals. *Ecological Modeling 91,*105–130.

Brown, M. T., Odum, H. T., Murphy, R. C., Christianson, R. A., Doherty, S. J., McClanahan, T. R., & Tennenbaum, S. E. (1995). Rediscovery of the World: Developing an Interface of Ecology and Economics. In C.A.S. Hall (Ed.), *Maximum Power: The Ideas and Applications of H. T. Odum*, pp. 216–250. Boulder: University of Colorado Press.

Brown, M. T., Tennenbaum, S., & Odum, H. T. (1990). *Emergy Analysis and Public Policy Perspectives of the Sea of Cortez, Mexico.* Final Report to The Cousteau Society. Gainesville: Center for Wetlands, University of Florida.

Brown, M. T., & Ulgiati, S. (1997). Emergy Based Indices and Ratios to Evaluate Sustainability: Monitoring technology and economies toward environmentally sound innovation. *Ecological Engineering 9,* 51–69.

Campbell, D. E. (1998). Emergy analysis of human carrying capacity and regional sustainability: An example using the State of Maine. *Environmental Monitoring and Assessment 51,* 531–569.

Carey, D. I. (1993). Development based on carrying capacity: A strategy for environmental protection. *Global Environmental Change 3(2),* 140–148.

Cohen, J. E. (1995). Population growth and Earth's human carrying capacity. *Science 26(5222),* 341–346.

Cohen, J. E. (1997). Population, economics, environment and culture: An introduction to human carrying capacity. *Journal of Applied Ecology 34(6),* 1325–1333.

Doherty, S. J., & Brown, M. T. (1993). *Emergy Analysis Perspectives, Sustainable Development, and Public Policy Options for Papua New Guinea.* Final Report to Cousteau Society. Gainesville: Center for Wetlands, University of Florida.

Fearnside, P. M. (1997). Human carrying capacity estimation in Brazilian Amazonia as a basis for sustainable development. *Environmental Conservation 24(3),* 271–282.

Folke, C., Jansson, A., Larsson, J., & Costanza, R. (1997). *Ambio 26(3),* 167–172.

Harris, J. M., & Kennedy, S. (1999). Carrying capacity in agriculture: Global and regional issues. *Ecological Economics 29,* 443–461.

King, J., & Slesser, M. (1995). Prospects for sustainable development: The significance of population growth. *Population and Environment 16(6),* 487–505.

McConnell, R. L. (1995). The human population carrying capacity of the Chesapeake Bay Watershed: A preliminary analysis. *Population and Environment 16(4),* 339–352.

Odum, H. T. (1980). Principle of Environmental Energy Matching for Estimating Potential Economic Value: A Rebuttal. *Coastal Zone Management 5(3),* 239–243.

Odum, H. T. (1983). *Systems Ecology: An Introduction.* New York: John Wiley.

Odum, H. T. (1984). Embodied Energy, Foreign Trade, and Welfare of Nations. In A. M. Jansson (Ed.), *Integration of Economy and Ecology: An Outlook for the Eighties,* pp. 185–199. Proceedings of the Wallenberg Symposium. Stockholm, Sweden: Asko Laboratory.

Odum, H. T. (1988). Self-Organization, Transformity, and Information. *Science 242,* 1132–1139.

Odum, H. T. (1996). *Environmental Accounting*: *Emergy and Environmental Decision Making*. New York: John Wiley.

Odum, H. T., Brown, M. T., & Christianson, R. A. (1986a). *Energy Systems Overview of the Amazon Basin*. Report to the Cousteau Society. Gainesville: Center for Wetlands, University of Forida.

Sterrer, W. (1993). Human economics: A non-human perspective. *Ecological Economics 7(3),* 183–202.

Ulgiati, S., & Brown, M. T. (1998). Monitoring patterns of sustainability in natural and man-made ecosystems. *Ecological Modeling 108(1–3),* 1 May 1998.

Ulgiati, S., Brown, M. T., Bastianoni, S., & Marchettini, N. (1996). Emergy Based Indices and Ratios to Evaluate Sustainable Use of Resources. *Ecological Engineering 5,* 497–517.

Ulgiati, S., Odum, H. T., & Bastianoni, S. (1994). Emergy Use, Environmental Loading and Sustainability. An Emergy Analysis of Italy. *Ecological Modeling 73,* 215–268.

Van Den Bergh, J. C. J. M. (1993). A framework for modeling economy-environment-development relationships based on dynamic carrying capacity and sustainable development feedback. *Environmental Resources and Economics 3(4),* 395–412.

Wakernagle, M., & Rees W. E. (1995). *Our Ecological Footprint: Reducing Human Impact on Earth*. Gabriola Island, BC and Philadelphia, PA: New Society Publishers.

Wang, F., Odum, H. T., & Kangas, P. (1980). Energy Analysis for Environmental Impact Assessment. *Journal of Water Resources, Planning and Management Division*, July, 451–466.

Wetzel, K. R., & Wetzel, J. F. (1995). Sizing the earth: Recognition of economic carrying capacity. *Ecological Economics 12(1),* 13–21.