CHAPTER 25

Comparative Estimates of Sustainability

Economic, Resource Base, Ecological Footprint, and Emergy

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I. INTRODUCTION

Questions concerning sustainability, carrying capacity, and the welfare of developing nations tend to center on the role of natural resources, or what economists term "natural capital," in economies. In recent years, a number of economists have taken a hard look at resource depletion and its effect on GNP and net capital formation, suggesting that when taken into account, many otherwise growing economies may in fact be declining since declining levels of natural capital threaten long-term economic sustainability (e.g., Solorzano *et al.*, 1991). Carrying capacity and the welfare of growing populations in developing nations may be tied, ultimately, to natural resources much more tightly than industrial capital formation. This chapter summarizes several of the assessments of the resource base of Costa Rica given in other chapters and compares these to several relatively novel approaches to estimating the resource base of the economy of Costa Rica, the relation of that base to sustainability and carrying capacity, and the long-term implications of policies that favor exports of resources. We use several bio-

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physical economic analyses, a land area-based "footprint" analysis, and an energy-based "emergy" analysis. The question is, do the results differ when very different approaches are used to estimate sustainability?

II. SUMMARY FROM OTHER CHAPTERS OF THIS BOOK

Traditionally sustainability has been estimated using economic criteria. So we start our summary there. Chapters 2 and 4 show that the economy is growing, but little more than the population, so that per capita income is remaining about constant although it is being distributed increasingly to the wealthier component of society. These chapters, plus Chapter 23, also show that debt has become a very large and difficult issue, and has become nearly impossible to retire for a variety of reasons, including the need for imports to pay for the exports (e.g., Figure 23-7). Domestic food production is increasingly insufficient to feed Costa Ricans (Figures 5-5 and 23-2), and increasing yields have reached serious problems with diminishing agronomic returns to inputs of fertilizers or land area (Figure 12-4). Erosion continues to eat away at the productive potential of the nation's agriculture (Chapter 15). Since per hectare yields are stable or declining for most crops, it appears likely that the combined effects of declining returns on inputs and the cumulative losses due to erosion are compensating or more than compensating for any increases in agricultural technology. The number of people that can be fed without external resources appears to be no more than roughly 500,000, and with inputs of fertilizer and other technologies from the industrialized nations, perhaps about 4 million, if the inputs are paid for (Chapter 4, Figure 12-8). Natural forests continue to be destroyed (Chapter 16), although at a slower rate than in the recent past, lumber and paper are being imported (Chapter 18), and carbon emissions from deforestation are about as large as the quantity released from fossil fuel burning, and enormously greater than the carbon sequestered through reforestation (Chapter 17). Other tradeoffs are presented in Bouman *et al.* (1998) and Haines and Peterson (1998). None of these patterns represents sustainability, as is developed further in the final chapter.

There are some positive signs related to sustainability as well: tourism and ecotourism are increasingly important, population growth rates may (or may not) be declining, and the hydroelectric potential is large. The potential of the forests to supply energy also is large, but not in the forms needed. High-tech industries are beginning to locate in Costa Rica.

Generally both the positive and the negative trends are consuming increasing amounts of fossil fuel, which does not contribute to sustainability. It is very difficult to pay for the imports of fuels or the machines in which they are used (Figure 23-7). We conclude that Costa Rica left behind any possibility of sustainability at a modern standard of living using its own resources when the population passed about 1 to 2 million. Expressed differently, at the present standard of living Costa Rica is using 2 to 4 times the resources, many from external sources and much of that paid for with debt, that could be sustainably supported from the resource base that exists, which is mostly land, climate, and soils. Other Costa Rican scientists have reached more or less the same conclusions, although often expressed in very different ways (i.e., Hartshorn *et al.*, 1982; Monge, 1995). But there may be flaws in our (or their) analyses, and it is useful to compare our results with other techniques that attempt to measure sustainability from quite different perspectives. Thus we believe it useful to compare our results with those of others. There are two very clever techniques "out there" that attempt to measure sustainability in quite different ways. These analyses were made quite independently from the analyses presented in this book. What do they find?

III. CALCULATING THE ECOLOGICAL FOOTPRINT OF COSTA RICA: DOES COSTA RICA FIT INSIDE COSTA RICA?

A. Why Measure the Ecological Footprint of Costa Rica?

Sustainability means securing people's quality of life within the carrying capacity of nature. The preservation of nature is not only an ethical call in favor of other species' survival, but it is also the precondition for humane living conditions. People exist in, and are a part of, ecosystems. They depend on ecosystems for the steady supply of the basic requirements for life—food, water, energy, fibers, waste sinks, and life-support services. The "ecological footprint" concept enables us to quantify the human use of nature and compare it to nature's carrying capacity. It thereby summarizes society's "ecological impacts" and provides an indicator of ecological sustainability (Wackernagel *et al.*, 1999; Wackernagel and Rees, 1996).

B. The Calculation

People require land to grow their food, produce energy they use, grow the timber they consume, capture the water they drink and otherwise use and assimilate their wastes and those from their industrial activity. The ecological footprint keeps track of these uses based on two simple facts: first, we can monitor most of the resources we consume and many of the wastes we generate; second, most of these resource and waste flows can be converted to a corresponding biologically productive area. Thus, the *ecological footprint* of any defined population (from a single individual to a whole city or country) is the total area of ecologically productive land and water occupied exclusively to produce all the resources consumed and to assimilate all the wastes generated by that population, using prevailing technology. As people use resources from all over the world and affect far away places with their wastes, footprints sum up these ecological areas wherever that land and water may be located on the planet.

We prepared a comprehensive ecological footprint calculation for Costa Rica on a spreadsheet of 135 lines and 15 columns (Table 25-1). The calculation consists of a consumption analysis of 15 main resources (lines 8–46), a section where all uses of commercial energy are listed (lines 49–57), and an energy balance of traded goods (lines 61–114). All figures are taken from published UN statistics (Table 25-2). Consumption is translated into land areas using world average yield figures. To make these figures comparable with local ecological productivity, local areas are adjusted with yield factors. These factors indicate how much more (and less) productive Costa Rican areas are compared to world average areas. By standardizing the calculation with world average figures, ecological load and local ecological capacity can be compared among nations. Equivalence factors adjust the ecological categories for their productivity to make them mutually comparable.

The footprint and the available ecological capacity are composed of six types of ecologically productive areas: arable land, pasture, forest, sea space, built-up land, and energy land, all of which represent competing or potentially competing uses of nature. Fossil energy land is the land that we should be putting aside for CO_2 absorption. However, this is something that is not done in today's world.

The box on lines 117–130 summarizes the results using 1992 data. They show that Costa Rica uses 2.5 ha (25,000 m^2 or five football fields) of nature per person. However, there was only a little less than 2.5 ha of biotically productive space per person available within its perimeter in 1992, including sea space and assuming 12% is set aside for other species. On the land alone, Costa Ricans are using 0.1 ha more of biotically productive space than what is available. With increasing national consumption (because of larger population numbers and higher per capita consumption), the ecological deficit of Costa Rica will continue to grow. Assuming a growth rate of 3% for national consumption (of which 2.4% is used for demographic growth and 0.6% for per capita increase in consumption), it will take only 10 years to develop a 35% ecological deficit. In other words, the footprint would be one-third larger than the ecological capacity of Costa Rica.

1 **TABLE 25-1 Calculation of the Costa Rican's Average Ecological Footprint (1992 Data; Population of Costa Rica, 3,270,000)**

2

3	LAND AND SEA AREA ACCOUNTING												
4 5 6	CATEGORIES	Yield [kg/ha]^{a} (global average)	Ref.-yield^{b}	Production [t/yr]	Ref.-prod.	Import [1000 $]	Import [t/yr]	Ref.-imp.	Export [1000 $]	Export [t/yr]	Ref.-export	Apparent consumption [t/yr]	Footprint component [ha/cap]
7	FOODS					172,596		1:214#0	1,093,972		1:217#0		
8	meat. (yield for animal products from pasture; expressed in average units)	74	3:212#98, 3:228#105, 3:215#99, 3:3#1	152,000	3:209#97		430	4:27#12		23,550	4:27#12	128,880	
9	bovine, goat, mutton, and buffalo meat	33		82,000	3:197#92	200	100	4:30–34#13	56,000	23,048	4:30–34#13	59,382	0.5532 pasture
10	nonbovine, nongoat, nonmutton, nonbuffalo	457		70,000	calc. (equiv. in cereals)		330	calc.		502	calc.	69,828	−0.0001 arable land
11	dairy (milk equiv.)			470,000			6,300			6,150		470,150	0.2863 pasture
12	milk	502		470,000	3:215#99	5,520		4:60#27	5,350	5,350	4:60#27, 28 (est.)		
13	cheese	50				2,300	600	4:76#33	150	30	4:76#33		
14	butter	50				60	30	4:73#32	130	50	4:73#32		
15	marine fish	29										9^{d}	0.3140 sea
16	cereals	2,744	3:65#15	204,000	3:65#15	83,361	476,815	1:214#04 (est. of subcategories)	11,326	8,325	1:217#04 (est. 048)	672,490	0.0749 arable land
17	wheat					23,371	130,462	1:214#041					
18	rice					13,924	48,804	1:214#042					
19	maize					32,079	217,545	1:214#044					
20	veg. & fruit	18,000		2,573,000	3:123#49	18,967	39,126	1:214#05 (est.)	645,104	2,185,326	1:217#05 (est.)	426,800	0.0073 arable land
21	veg., etc.					2,934	5,010	1:214#054	33,941	87,868	1:217#054		
22	fresh fruit					4,100	9,500	4:123–150#58, #59	568,743	1,953,758	1:217#057		

(continues)

TABLE 25-1 (*Continued*)

LAND AND SEA AREA ACCOUNTING

	CATEGORIES	Yield [kg/ha][a] (global average)	Ref.-yield[b]	Production [t/yr]	Ref.-prod.	Import [1000 $]	Import [t/yr]	Ref.-imp.	Export [1000 $]	Export [t/yr]	Ref.-export	Apparent consumption [t/yr]	Footprint component [ha/cap]
23	roots and tubers	12,607	3:86#25	142,000	3:86#25	100	200	4:112#49	30	150	4:112#49	142,050	0.0034 arable land
24	pulses	852	3:97#31	33,000	3:97#31	1,500	2,500	4:115#50	480	1,200	4:115#50	34,300	0.0123 arable land
25	coffee & tea	566	3:171	74,000	3:171#78				215,304	157,980	1:217#07 (est. 071)	−83,980	−0.0454 arable land
26	cocoa	454	3:173#79									0[d]	0.0000 arable land
27	sugar	4,893	3:153–156#67, 68, 69	293,000	3:156#89				29,000	95,000	4:151#68	198,000	0.0124 arable land
28													
29	oil seed (incl. soya)	1,856	3:106, 111, 112, 114		3:106–121#38, #39, #40, #41, #42, #43, #44, #45, #46, #47	39,252	142,640	4:213–227#99, #100, #107	8	4	4:213–227#99	142,636	0.0235 arable land
30	TIMBER [in roundwood equivalent, m³]	1.99	FAO-calc.	2,794,474			259,976			14,250		3,040,200	0.4672 forest
31	roundwood [m³/ha,m³]		waste factors	4,315,000	5:03		5,000	5:05		0	5:10	4,320,000	
32	firewood	0.53		3,210,000	5:20							3,210,000	48% of consumption firewood
33	direct roundwood consumption [m³]	1 for RWE (roundwood equivalent in m³)									5:103	227,000	7.04% of consumption mines
34	sawed wood [m³]	1.50	for RWE	798,000	5:109		2,000	5:111#248		2,000	5:117	798,000	34% of consumption sawed wood

35	wood-based panels [m³]	2.25	for RWE	74,000	5:146		5,000	5:148#634		5,000	5:154#634	74,000	5% of consumption panels
36	wood pulp [t]	1.98	for RWE	3,000	5:223		6,000	5:225			5:229#251	9,000	
37	paper and paper board [t]	0.94	for RWE	19,000	5:285		244,000	5:287#641			5:293#641	263,000	7% of consumption paper
38													
39													
40	OTHER CROPS												
41	tobacco	1,548	3:176#82	0	3:176#82	600	1,015	4:213#98	8	4	4:213#98	1,001	0.0002 arable land
42	cotton	1,000	IIED, p. 64				ref. of apparent cotton consumption; 2:247, 255					2,998	0.0009 arable land
43	jute	1,500	gov. of Vietnam				ref. of apparent jute consumption, 2:263, 267					0	0.0000 arable land
44	rubber	1,000	gov. of Vietnam				ref. of apparent rubber consumption, 2:231, 234					0	0.0000 arable land
45	wool	15	Wackernagel *et al.* (1993, 67)				ref. of apparent wool consumption, 2:280, 287					0	0.0000 pasture
46	hide	74	like bovine meat				ref. of apparent hide consumption, 2:227, 228					12,648	0.0523 pasture
47													

48										
49	ENERGY BALANCE:	Glob. ave.	Specific energy footprint[f]	Energy type	[GJ/yr/cap]		[GJ/yr/cap] for 1992	Ref.	Footprint component in [ha/cap]	
50		55	[GJ/ha/yr] coal	coal consumption	0	calc.	0	6#5:116	0.0000	fossil energy land for coal
51		71	[GJ/ha/yr] liquid fossil fuel	liquid fossil fuel consumption	15	calc.	5	6#14:172	0.2111	fossil energy land for liquid fuel
52		93	[GJ/ha/yr] fossil gas	fossil gas consumption	0	calc.	0	6#28:332	0.0000	fossil energy land for fossil gas
53				total fossil fuel consumption	15	calc. & WRI (1996, 287)	5	calc.		
54		71	[GJ/ha/yr] nuclear energy (thermal)	nuclear energy consumption (thermal)	0	WRI (1996, 285)			0.0000	fossil energy land for nuclear energy
55		71	[GJ/ha/yr] assumed to be fossil energy	energy embodied in net imported goods	12	calc.			0.1657	fossil energy land for embodied energy in net imp. goods
56		1,000	[GJ/ha/yr] hydroelectric energy	hydroelectricity consumption	4	WRI (1996, 285)			0.0043	built-up area for hydropower
57										
58										
59										
60										

(*continues*)

TABLE 25-1 (*Continued*)

61 62	CATEGORIES units if not specified	Energy intensity ([Gj/t] of embodied energy)	Import [1000 $]	Import [t/yr]	Ref-imp.	Export [1000 $]	Export [t/yr]	Ref.-export	Embodied energy in net import [PJ/yr]	
63	Beverages	10	10,881	6,102	1:214#1				0.06	
64	alcoholic beverages		7,996	4,484	1:214#112					
65	crude materials		71,158		1:241#2	91,091		1:217#2		
66	hides, skin	5				8,530	1,051	1:217#21 (est. 211)	−0.01	
67	textile fibers	5	8,355	7,996	1:214#26 (est. of Mexico)				0.04	
68	minerals	1.5	9,254	190,923	1:214#27 (est. of Brazil)				0.29	
69	Biological fat	39				9,391		1:217#4	0.00	
70	Chemicals		454,057		1:214#5	102,834		1:217#5		
71	chem. organics	40	54,246	87,212	1:214#51 (est.)[a] 512, 514, 515	11,472	30,042	1:217#51 (est. 512)	2.29	
72	alcohol, phenols		14,005	48,487	1:214#512	11,038	28,905	1:217#512		
73	nitrogen		7,330	2,345	1:214#514					
74	org.-inorg. compounds		11,235	1,531	1:214#515					
75	chem. inorganics	20	34,428	120,707	1:214#52 (est. 522, 523)				2.41	
76	oxides		19,763	78,465	1:214#522					
77	other inorganics		14,338	41,096	1:214#523					
78	dyes, tanning, color products		22,759	7,203	1:214#53 (est. 533)				0.00	
79	medicinal, pharm. products		80,579	3,100	1:214#541	39,577	2,521	1:217#541	0.00	
80	plastic materials	50	99,345	95,625	1:214#58 (est. 582, 583)	14,510	9,701	1:217#58 (est. 583)	4.30	
81	Basic manufactures		567,976		1:214#6	174,597		1:217#6		
82	rubber manufactures	35	28,632	8,563	1:214#62 (est. 625)	39,540	13,303	1:217#62 (est. 625)	−0.17	
83	paper, paperboard	35	159,071	234,976	1:214#64 (est. 641, 642)	28,232	18,739	1:217#64 (est. 642)	7.57	(included in line 42)
84	textile	20	102,133	23,470	1:215#65 (est. 651, 652)	25,244	7,494	1:218#65 (est. 651, 653)	0.32	0.0024 arable land)
85	iron and steel	30	117,146	276,024	1:215#67 (est. 672, 673, 674)	13,873	15,613	1:218#67 (est. 674)	7.81	
86	metal manufactures	60	77,803	29,187	1:215#69 (est. 691, 692, 699)	15,455	4,685	1:218#69 (est. 692)	1.47	
87	base metal manufactures		21,404	4,933	1:215#699					

88	Indust. products		710,123	1:215#7		60,325		1:218#7		
89	power generating		46,097	7,421	1:215#71 (est. 713, 716)					
90	internal combustion	140	13,043	1,712	1:215#713				0.24	
91	rotating electric plant	100	20,328	3,660	1:215#716				0.37	
92	machines for special industries	100	124,521	24,979	1:215#72 (est. with subcategories)				2.50	
93	tractors, nonroad		27,149	6,734	1:215#722					
94	civil engineering equip.		20,821	5,374	1:215#723					
95	textile, leather		20,235	3,787	1:215#724					
96	other machinery for special industries		20,909	1,981	1:215#728					
97	metalworking machinery	100	7,220	919	1:215#73 (est. 736)				0.09	
98	general industrial	100	111,386	11,236	1:215#74 (est. of subcategories)	9,106	2,363	1:218#74 (est. of subcategories)	0.89	
99	heating/cooling		21,133	3,361	1:215#741	5,600	1,453	1:218#741		
100	pumps for liquids		9,130	816	1:215#742					
101	pumps centrifuges		14,672	1,963	1:215#743					
102	nonelec. machinery		21,980	1,273	1:215#745					
103	nonelec. machinery parts		31,724	2,537	1:215#749					
104	office machines	140	48,298	1,044	1:215#75 (est. 752, 759)				0.15	
105	automatic data proc.		32,253	698	1:215#752					
106	office accessories		12,260	264	1:215#759					
107	telecom., sound	140	55,992	2,997	1:215#76 (est. 761, 762, 764)				0.42	
108	electric machinery	100	85,902	11,825	1:215#77 (est. 772, 773, 775)	42,486	7,781	1:218#77 (est. 772, 773, 778)	0.40	
109	road vehicles	140	225,475	52,088	1:216#78 (est. 781, 784)				7.29	
110	Misc. manufactured goods		241,717		1:216#8	137,582		1:218#8		
111	clothing and accessories	20	23,875		1:216#84	69,360	5,604	1:218#84 (est. 842, 843, 844)	−0.11	−0.0009 arable land
112	misc. manufactured	100	146,922	14,459	1:216#89 (est. 892, 893, 894)	38,136	15,922	1:218#89 (est. 892, 893)	−0.15	
113	Goods not classed by kind	50	313,883		1:216#9	148,912		1:218#9	0.00	
114	special transactions		309,725	58,690	1:216#931	138,930	44,777	1:218#931	0.00	
115					Energy embodied in net import per capita				11.76 [GJ/cap/yr]	
116										

(*continues*)

TABLE 25-1 *(Continued)*

117			SUMMARY							
118	DEMAND				SUPPLY					
119	FOOTPRINT (per capita)				EXISTING BIOCAPACITY WITHIN COUNTRY (per capita)					
120									OTHER INDICATORS	
121									(average land with world average productivity in [ha/capital])	
122	Category	Total [ha/cap]	Equivalence factor [−]	Equivalent total [ha/cap]	Category	Yield factor	National area [ha/cap]	Yield adjusted equiv. area [ha/cap]	2.4	footprint on the land
123	fossil energy	0.4	1.1	0.4	CO_2 absorption land		0.00	0.00	2.3	existing land-based capacity within Costa Rica
124	built-up area	0.0	2.8	0.0	built-up area	1.13	0.01	0.05		
125	arable land	0.1	2.8	0.3	arable land	1.13	0.16	0.52	0.0	Costa Rica's national ecological deficit
126	pasture	0.9	0.5	0.5	pasture	1.89	0.72	0.73	100%	Costa Rica's capacity as percentage of its footprint
127	forest (incl. deforestation)	1.1	1.1	1.2	forest	1.83	0.48	1.00	−0.4	Costa Rica's global deficit (for 1993)
128	sea	0.3	0.2	0.1	sea	1.00	2.60	0.57	121%	Costa Rica's per capita footprint compared to the global per capita biocapacity (for 1993)
129					TOTAL existing		4.0	2.9		
130	TOTAL used	2.8		2.5	TOTAL available (minus 12% for biodiversity)			2.5		
131										
132										
133										
134										
135										

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[a] Units if not specified.

[b] See Table 25-2 for references 1 to 6. For example, "3:212 #98" means book 3, page 212, category 98.

[c] Apparent consumption is calculated by adding imports to production and subtracting exports. All the production, import, and export data stem from United Nations' documents.

[d] Expressed in harvested fish in Kg/capita. From WRI (1996, 311).

[e] Reference of apparent cocoa consumption, 2:162, 169.

[f] The energy footprint for fossil fuel is expressed as area necessary for CO_2 absorption. Replacing the fossil fuel with biotically productive substitutes would occupy even larger areas.

[g] Est., derived from following sources.

TABLE 25-2 Source of Data Used to Calculate Ecological Footprint

(1) United Nations. 1995. *1993 International Trade Statistics Yearbook*, Vol. 1. Department for Economic and Social Information and Policy Analysis, Statistical Division, New York.

(2) United Nations Conference on Trade and Development (UNCTAD). 1994. *UNCTAD Commodity Yearbook 1994*. United Nations, New York/Geneva.

(3) Food and Agriculture Organization of the United Nations (FAO). 1995. *FAO Yearbook: Production 1994*, Vol. 48. FAO, Rome.

(4) Food and Agriculture Organization of the United Nations (FAO). 1994. *FAO Yearbook: Trade 1993*, Vol. 47, FAO, Rome.

(5) Food and Agriculture Organization of the United Nations (FAO). 1995. *FAO Yearbook: Forest Production 1993*. FAO, Rome.

(6) World Resources Institute. 1996. *World Resources 1996–1997*. World Resources Institute, UNEP, UNDP, The World Bank, Washington, DC.

C. INTERPRETING THE RESULTS

The numbers in Table 25-1 illustrate which consumption type occupies how much ecological space. In the end, the footprint assessment comes to the conclusion that Costa Rica's population is already consuming more than what the country can regenerate. This means that it has to import natural capital or deplete its own stocks, both of which it is doing. The current trend of a growing population and declining ecological capacity signals more severe conditions in the future. Because of its persistent international debt, Costa Rica may find it increasingly difficult to pay for its imports. In addition, if current worldwide tendencies of increasing resource consumption continue, the ecological capacity available "elsewhere" that is exported to countries with ecological deficits (such as Costa Rica) will diminish.

A similar, but less comprehensive, analysis of the Costa Rican footprint was completed by Ko *et al.* (1998). They found, as well, that the footprint was larger than the national area and increasing for the nation as a whole.

Costa Rica is not alone with its ecological deficit; similar calculations for Switzerland show that its average citizen occupies approximately 5 ha of ecologically productive space to provide for his or her current level of consumption. In comparison, the average American lives on a footprint twice the size of the Swiss one, or over 4 times that of the average Costa Rican. The United States is endowed with more biological capacity per capita than Costa Rica because of its relatively low population density and high biotic productivity. But, because of high levels of consumption, the U.S. national ecological deficit is 3.6 ha per capita, which is 45% larger than the average Costa Rican footprint.

As these calculations include basic ecological functions only, the results may fall short of what the actual ecological deficit is. Footprints underestimate the actual use of nature's ecological capacity because they assume that current yields are sustainable and do not include freshwater use and some human wastes. However, these assessments document the magnitude of humanity's impact on the earth. To improve these assessments, more resources and waste products will be included in later studies.

In conclusion, the ecological footprint is a simple resource accounting tool for measuring the ecological aspects of sustainability. As such, it indicates that the nation of Costa Rica, together with many others on the globe, is not sustainable by this criterion and is becoming less so.

Throughout history nations have enhanced their own ability to support their human population or its material affluence by bringing in resources from outside their borders through trade or conquest. How important is this today? To what degree can a nation be supported by its own resources?

IV. EMERGY, FOREIGN TRADE, AND CARRYING CAPACITY IN COSTA RICA

A. EMERGY, WEALTH, AND ECONOMIC VITALITY

A new unit of evaluation, called "emergy" (which is the energy required to make something), offers the potential to evaluate *all* resources in a national economy in the same units so that comparisons and judgments concerning sustainability can be made.

Emergy is a quantitative measure of all of the energy resources required to develop a product (whether those resources are mineral resources that result from biogeologic processes, renewable resources such as wood, a fuel source used directly, or an economic product that results from industrial processes). All these resources are expressed in units of one type of energy (usually solar energy). We suggest that evaluations using emergy may help to clarify policy options, because the use of emergy as a measure of value overcomes four important limitations of other methods for evaluating alternative fuels and technologies.

These limitations are as follows: (1) A truly comparative analysis cannot be undertaken by mixing units of measure such as weight, volume, heat capacity, or economic market price. (2) Evaluations that use only the heat value of (energy) resources (such as kcal or joules) for quantification assume that the only value of a resource is the heat derived from its combustion. In this way, for example, human services are evaluated as the calories expended doing work and, when compared to other inputs to a given process, are generally several orders of magnitude smaller than, for example, fossil fuel use. Thus human labor inputs are often considered irrelevant when in fact they are critical because of their quality. (3) Nonmonetary resources and processes (i.e., those outside the monetized economy) are often considered externalities and not quantified. Most processes, and all economies, are driven by a combination of renewable and nonrenewable energy. (4) An assumption that price determines value is often made. The price of a product or service reflects human preferences, often called "willingness-to-pay." It can also reflect the amount of human services "embodied" in a product. A valuing system based on human preference alone assigns either relatively arbitrary values, or no value at all, to necessary resources or environmental services. Emergy as a unit of evaluation avoids these problems.

Emergy is a quantitative measure of the ability to cause work that is independent of price (Odum, 1984; Odum, 1996). New energy sources often are evaluated based on dollar costs per unit of energy produced. Economic theory is based on the assumption that price is proportional to value, and suggests that if prices rise, a new source may become economical and thus competitive. However, price merely suggests what humans are willing to pay for something. The true value of something to society is determined by the ability of a resource to cause work, that is, the effect it has in stimulating an economy. For example, a gallon of gasoline will power a car the same distance no matter what its price. Its value to the driver is the number of miles (work) that can be driven, regardless of price. Its price reflects both the scarcity of gasoline and how important it is to do the work. Price is often inverse to a resource's contribution to an economy. When a resource is plentiful, its price is low, yet it contributes much to the economy. When a resource is scarce, its total contribution to the economy is small, yet its price is high. For example, 200 years ago salmon was very abundant in New England and contributed enormously to the welfare of society even though its price was very low. Today the converse is true.

Emergy may be a measure of equivalence when one resource is substituted for another. Sunlight and fossil fuels are very different energies; yet when their heat values are used the difference is not elucidated. A joule of sunlight is not equivalent to a joule of fossil fuel in any system other than a laboratory heat engine. In the realm of the combined system of humanity and nature, sunlight and fuels are not equally substitutable joule for joule. However, when a given amount of fuel energy is expressed as the amount of solar energy required to make it (solar emergy), its equivalence to sunlight energy is defined. Since emergy is a measure of the work that goes into a product expressed in units of one type of energy (sunlight), it is also a measure of what the product should contribute in useful work in relation to sunlight.

B. EMERGY ANALYSIS

We used emergy analysis to evaluate the economy of Costa Rica, including its sustainability. It is a method of energy analysis that accounts for the direct and indirect use of energy in producing a commodity, resource fuel, or service, in energy of one type.

Consider a fine wooden chair. In Marxist terms the embodied labor in the chair is the hours of labor that went into the production of that chair. A comprehensive analysis should also include the hours of labor that went into cutting the tree and making the tools that the logger and the artisan used. Likewise there was energy used to make the chair. But that was not the only work processes required to make the chair. Solar energy grew the tree, evaporated water from the ocean to generate rain, generated the winds that blew the rain from the ocean to the land, and so on. Centuries of solar energy went into making the soil that the tree grew in, and thousands or millions of years to make the oil that powered the saws that cut the tree and produced the boards the artisan used. The sum of all of these energies represents the emergy input required to make the chair, and they all were necessary.

Thus the solar emergy in a resource, product, or service is the sum of the solar energies required to make it. Emergy includes both fossil fuel energies and environmental energies (like sunlight, rain, tides, etc.) that are necessary inputs of most processes of energy transformation. Cumulative emergy inputs of the past are found embodied in the soils, forests, petroleum, educated people, and other resources that constitute the resource base of a nation. Of particular importance here, the emergy resources of a region or a country largely define and limit the amount of economic work that can be done by that region or country, and that resource base divided by the number of people is the per capita resource base. The emergy base is related to the ecological footprint previously discussed in that the footprint is largely related to the energy-capturing potential of land, and is corrected at a national level for differing productivities. The emergy analysis is more comprehensive but more controversial (e.g., Brown and Herendeen, 1996).

Emergy can be conceptualized as energy memory (Scienceman, 1987, 1989), since it is a measure of all of the energy previously required to produce a given product or process. The term "emergy" differs somewhat from embodied energy as defined by other schools of thought. For example, environmental inputs and labor are omitted in the analyses of IFIAS (1974) and Slesser (1978), energies are added without using transformities (except for electricity) by Hall *et al.* (1986), and energies are assigned by input–output data (usually based on money flows) with different results by Hannon *et al.* (1976), Herendeen *et al.* (1975), and Costanza (1978).

We now provide some of our definitions:

- *Energy*. Sometimes referred to as the ability to do work, although this definition does not include the different qualities of different energies. Energy is a property of all things that 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 expressed in units of one type of energy. The solar emergy of a product is the emergy of the product expressed in the equivalent solar energy required to generate it. Sometimes it is convenient to think of emergy as energy memory.
- *Emjoule*. The unit of measure of emergy, or 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. Solar emjoule is abbreviated "sej."
- *Macroeconomic Dollar* (Emdollar or EM$). A measure of the money that circulates in an economy as the result of some energy-driven process. In practice, to obtain the macroeconomic dollar value of an emergy flow or storage, the emergy is divided by the ratio of total emergy to gross domestic product for the national economy.
- *Nonrenewable Energy*. Energy and material storages such as 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 Energy*. Energy flows of the biosphere that are more or less constant and reoccurring, which ultimately drive the biological and chemical processes of the earth and contribute to geologic processes.
- *Resident Energy*. Renewable energies that are characteristic of a region.
- *Transformity*. The ratio obtained by dividing the total emergy that was used in a process by the energy yielded in the process. 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 energies of different types to emergy of the same type.

A complete description of the methods employed to evaluate the economy of Costa Rica is beyond the scope of this short section but can be found in Odum (1978, 1984, 1995, and 1996). Data sources overlap with those in Table 25-2. The methodology evaluates the main flows of resources, energy, and human services within the economy for a given year and converts them into common units of emergy using transformities. Mark Brown calculated transformities for the most important resources, fuels, and human resources within the Costa Rican economy directly, but some others were calculated based on data for other areas, all based on the procedures in Odum (1996).

Our analysis was done for 1994, the latest year for which we had sufficient data. The flows of resources, energy, and services throughout, into, and out of the economy, evaluated in emergy terms, were compared and several ratios calculated to assess sustainability and carrying capacity of the economy as a whole. A more complete picture would emerge if data for several years were evaluated and compared, since long-term trends would be revealed.

V. RESULTS AND DISCUSSION OF EMERGY ANALYSIS

Per capita emergy use in Costa Rica was almost one-quarter that of the United States (Table 25-3; the U.S. per capita emergy consumption in 1987 was 29.2×10^{15} sej/yr). (An emergy analysis of Costa Rica is given in Table III-1 of Appendix III and summarized in Tables III-2 and III-3.) Emergy use per unit area (sej/m^2) was about one-half that of the United States (U.S. emergy use per unit area was 7.0×10^{11} sej/m^2/yr), reflecting the greater population density. Almost 90% of total emergy use is derived from within Costa Rica, compared to about 78% for the United States, showing that Costa Rica was still highly dependent on its own resources in 1987, although this appears to be changing rapidly. Costa Rica has a negative emergy balance of payments, exporting about twice as much emergy as it imports.

From these data we derived an index, called the Environmental Loading Ratio (ELR), defined as the ratio of nonrenewable emergy flow to renewable emergy flow in the economy. This ratio relates the use of nonrenewable sources of energy and materials to the ability of the environment to absorb the wastes and disorder that result from their use. In essence, the ELR reflects the intensity of use of nonrenewable energy as compared to that which is renewable. In Costa Rica the ELR was 0.51/1, meaning that nearly twice as much of the total emergy driving the economy comes from renewable sources as from nonrenewable ones. This also means that even though the economy of Costa Rica is industrializing rapidly, still some two-thirds of the emergy running it comes from solar-powered sources.

By way of comparison, in the United States the ELR ratio was about 7.2 : 1. One consequence of ratios this high is that the environment can no longer

TABLE 25-3 Summary of Emergy Indices of Costa Rica

Index	Value
Per capita emergy consumption	1.21×10^{6} sej/capita/yr
Emergy use per unit area	7.82×10^{11} sej/m^2
Emergy use from within Costa Rica	59%
Emergy use from renewable sources	53%
Environmental loading ratio	0.9 : 1
Ratio of exports to imports	1.39 : 1

assimilate wastes, and more and more nonrenewable resources must be expended to generate wealth and to process waste by-products, and a greater "load" is placed on the environment. Thus by this means of calculation, in the United States the load on the environment is nearly 14 times that in Costa Rica. When ELRs are relatively low, such as in Costa Rica, the environment assimilates wastes, processing and recycling them without enormous negative consequences. So, for example, many coffee wastes can be transported back to the fields to decompose there, and the potential for using "ecologically engineered" natural systems to process human sewage is great (although hardly developed).

The picture that emerges of Costa Rica's economy in 1987 is one that:

- Derives 59% of its resources and materials from within the country (about 41% of Costa Rica's total emergy use comes from imports)
- Could support only about one-quarter of its 1994 population at U.S. levels of consumption
- Could support about 78% of its 1987 population on its renewable resource base
- Was exporting about one and a half times the emergy it was importing, suggesting that continued negative emergy balance of payments may threaten long-term sustainability

This analysis is a relatively incomplete picture of the overall state of emergy balance of the economy of Costa Rica. Not accounted for in this overview are the many interior balances of emergy that could have serious impacts on long-term sustainability, such as agricultural sectors and their soil losses, deforestation, or overexploitation of coastal fisheries. For example, we have seen in other developing economies that the emergy lost in eroded soils from agricultural lands neutralizes gains that may be had from imports of resources obtained from the export of agricultural commodities grown on the soil (Doherty *et al.*, 1993). Thus even our present incomplete analysis suggests that the Costa Rican population is approaching or has arrived at the ability of the biophysical resources of Costa Rica to support them at a moderate standard of living, and that even this analysis neglects long-term erosion of national capital. More can be squeezed out of the economy by importing more oil, but the intrinsic resources must be squeezed even tighter to pay for that oil.

Policies that enhance external trade increase population and economic carrying capacity but work to decrease long-term sustainability by destroying soils, forests, and other basic emergy resources. These analyses provide some insights into the hard choices that face developing nations, probably the most important of which is the short-term vs the long-term perspective. To develop

TABLE 25-4 Summary of Different Analyses of the Number of People That Could Be Supported Sustainably in Costa Rica

Criteria	Method	No. of people	Source
BIOPHYSICAL: FOOD ONLY (does not account for other resources used)			
Agronomic	Indigenous resources only	400,000	Chapters 2, 12
Agronomic	Inputs bought with coffee	2,000,000	Chapters 2, 12
Agronomic	Land limitations, with inputs	4,000,000	Chapters 2, 12
BIOPHYSICAL: (present standard of living)			
Footprint	All resources used	2,400,000	This chapter (1987 population times 0.8)
Emergy	All resources used	1,750,000	This chapter (1987 population times 0.53)

their economies, developing nations tend to increase external trade for short-term gains in assets and carrying capacity, but by doing so they may be compromising long-term sustainability.

It is rather remarkable that each of these analyses, biophysical, economic, ecological footprint, and emergy, reaches approximately the same conclusion: that the resource base of Costa Rica has become in the past decade or two inadequate to support sustainably (that is, without using up environmental capital) the present population density at the present standard of living (Table 25-4). None of these analyses give very much hope for any future scheme that might generate a truly sustainable economy, although of course there is always the chance that some unforeseen technology or global market shift could make things much better (or much worse). Again these conclusions, done here in increasing detail, are hardly news to thoughtful Costa Ricans who have been warning of the dangers of continued population growth and high levels of resource exploitation for decades (i.e., Hartshorne *et al.*, 1982; Alvarado and Monge, 1997). And there is nothing special about Costa Rica. For example, the United States, while it has many resources and a low population density, is extremely and increasingly vulnerable to probable future oil shortages that may begin within a decade (Campbell and Laherrére, 1998; Kerr, 1998).

VI. SUMMARY AND CONCLUSIONS

Resource availability should be at the heart of questions concerning carrying capacity and sustainability. Developing nations are particularly susceptible to changes in resource availability since there is little luxury consumption and less "fat to trim." In addition population densities tend to be high and increase rapidly. Sustainability should be defined quantitatively to include depletions of resources, and it should include considerations of resource balance of payments at all scales within an economy. The use of monetary measures of resource use and trade does not value resources and energy adequately, and may give the false impression that economic activities are sustainable in the long run, when in fact they may be seriously degrading local environments and carrying capacity, and the ability to sustain local populations. In addition money can give false signals through inflation and speculation, which real resources do not. These lessons are hard to learn, as we saw with many Asian economies in 1998.

The seemingly hard choice for developing nations is to temper consumption, resource use, and exports now, and instead use domestic resources at home to foster long-term sustainability. This is a conclusion contrary to the increasing worldwide emphasis on free trade, the net effect of which is to strip less developed countries of their basic resources, such as forests and soils, and to encourage the unsustainable consumption of industrially-derived products through market penetration and advertising. The net result is debt and a destruction of the productive capacity of environments and hence the ability to ever pay back that debt, not to mention providing increasing populations with basic goods and services.

REFERENCES

Bouman, B. A. M., R. A. Schipper, A. Nieuwenhuyse, H. Hengsdijk, and H. G. P. Janson. 1998. Quantifying, economic and biophysical sustainability trade-offs in land-use exploitation: a case study for the Northern Atlantic Zone of Costa Rica. *Ecological Modelling* 114:95–109.

Brown, M. T. and R. A. Herendeen. 1996. Embodied Energy Analysis and Emergy Analysis: A comparative view. *Ecological Economics* 19:219–235.

Campbell, C. 1997. Depletion patterns show change due for production of conventional oil. Oil and Gas Journal (Special Publication. December 29:33–37.

Campbell, C. and J. H. Laherrére. 1998. The end of cheap oil. *Scientific American:* 78–83.

Costanza, R. 1978. Energy Costs of Goods and Services in 1967 Including Solar Energy Inputs and Labor and Government Service Feedbacks. Urbana, IL: Center for Advanced Computation, University of Illinois at Urbana-Champaign. 46 pp.

Doherty, S. J., M. T. Brown, R. C. Murphy, H. T. Odum, and G. A. Smith. 1993. *Emergy Synthesis Perspectives, Sustainable Development, and Public Policy Options for Papua New Guinea. Final Report to the Cousteau Society.* Center for Wetlands and Water Resources, University of Florida, Gainesville, FL. 182 pp. {CFWWR-93-06}

Haines, B. and C. Peterson. 1998. El desarrollo sustentable en montañas des de la perspectiva de un ecologo: el caso del "proyecto charral" en Costa Rica. Geografia aplicado 'y desarrollo. III Simposio Internacional, Quito, Ecuador.

Hall, C. A. S., C. J. Cleveland, and R. K. Kaufmann. 1986. *Energy and Resource Quality: The Ecology of the Economic Process.* Wiley–Interscience, New York. Reprinted 1992, University Press of Colorado, Boulder, CO.

Hannon, B. M., C. Harrington, R. W. Howell, and K. Kirkpatrick. 1976. *The Dollar, Energy, and Employment Costs of Protein Consumption.* Center for Advanced Computation, University of Illinois at Urbana-Champaign, Urbana, IL. 81 pp.

Hartshorn, G. S., L. Hartshorn, A. Atmella, L. D. Gomez, A. Mata, R. Morales, R. Ocampo, D. Pool, C. Quesada, C. Solera, R. Solarzano, G. Stiles, J. Tosi, A. Umaña, C. Villalobos, and R. Wells. 1982. *Costa Rica: Country Environmental Profile: A Field Study.* Tropical Science Center, San Jose, Costa Rica.

Herendeen, R. A., B. Z. Segal, and D. L. Amado. 1975. *Energy and Labor Impact of Final Demand Expenditures, 1963 and 1967.* Center for Advanced Computation, University of Illinois at Urbana-Champaign, Urbana, IL. 17 pp.

IFIAS. 1974. Energy Analysis. International Federation of Institutes of Advanced Study, Report 6. Ulriksdal Slott, Solna, Sweden.

Ko, J-Y, C. A. S. Hall, and L. G. López Lemus. 1998. Resource use rates and efficiencies as indicators of regional sustainability: An examination of five countries. *Environmental Monitoring and Assessment* 51:571–593.

Monge, C. 1995. Costa Rica se ahoga en deudas. *La Prensa Libre,* Martes, 11 de julio.

Odum, H. T. 1978. Energy analysis, energy quality and environment. In M. W. Gilliland (Ed.), *Energy Analysis: A New Public Policy Tool,* pp. 55–87. Selected Symposia of American Association for Advancement of Science. Westview Press, Boulder, CO.

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. Asko Laboratory, Stockholm, Sweden.

Odum, H. T. 1986. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley and Sons. New York. 370 p.

Odum, H. T. 1995. Self organization and maximum empower. In C. Hall (Ed.), *Maximum Power. The Ideas and Applications of H. T. Odum,* pp. 311–329. University Press of Colorado, Niwot, CO.

Scienceman, D. 1987. Energy and emergy. In G. Pillet and T. Murota (Eds.), *Environmental Economics—The Analysis of a Major Interface,* pp. 257–276. Leimgruber, Geneva, Switzerland.

Scienceman, D. M. 1989. The emergence of emonomics. In *Proceedings of the International Society for Social Systems Science, 33rd Meeting, 1989, Edinburgh, Scotland,* Vol. 3, pp. 62–68.

Slesser, M. 1978. *Energy in the Economy.* Macmillan, London.

Wackernagel, M., and W. Rees. 1996. Our ecological footprint. New Society Publishers, Gabriolie Island, B.C.

Wackernagel, M., L. Onisto, P. Bello, A. C. Linares, I. S. L. Falfán, J. M. García, A. S. Guerrero, and M. G. S. Guerrero, "National Natural Capital Accounting with the Ecological Footprint Concept." *Ecological Economics* (June 1999 Vol. 29:375–390).