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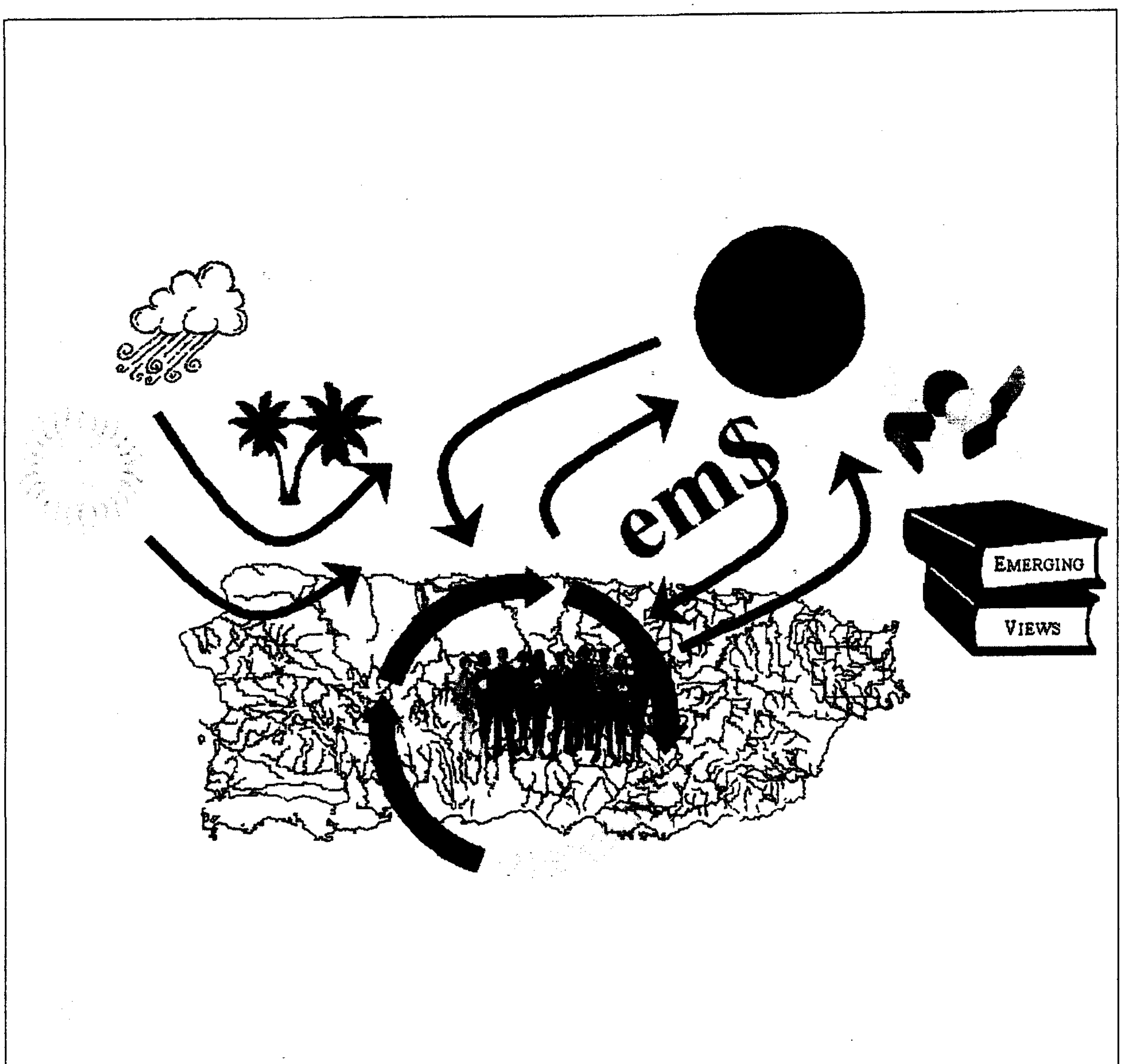
An EMERGY Evaluation of Puerto Rico and the Luquillo Experimental Forest

F.N. Scatena, S.J. Doherty, H.T. Odum, and P. Kharecha



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Abstract

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The many functions of Puerto Rico and the Luquillo Experimental Forest (the Forest) were evaluated in units of solar EMERGY, an energy-based measure of resource contribution and influence, defined as the energy of one type required to produce a flow or storage of another type. Rainfall and tectonic uplift are the largest environmental inputs into the Forest. The interaction of these inputs results in an erosional landscape where the EMERGY of biological processes is less than the EMERGY associated with the physical and chemical sculpturing of the landscape. The environmental work that built the natural capital of these forests is 9 to 50 times their current dollar market values. Of the investments evaluated in this study, the effects associated with water extraction are the largest.

Tectonic inputs and the hydrologic cycle also provide most of the environmental EMERGY flows in the island of Puerto Rico. The ratio of societal inputs to environmental inputs, however, is 45 for Puerto Rico and 3.5 for the Forest. Per capita EMERGY- use is typical of moderately developed economies, but the island has one of the most investment-intensive, least self-sufficient economies known and an EMERGY signature that resembles a city-state.

Keywords: Environmental economics, EMERGY, Luquillo Experimental Forest, Caribbean National Forest, Puerto Rico.

Contents

1 **Introduction**
2 Overview of Puerto Rico
6 Overview of the Luquillo Experimental Forest
6 **Methods**
6 Definitions
9 Solar EMERGY Analysis
12 Biophysical Evaluations
12 Economic Evaluations
14 **Results**
14 Ecological and Economic Evaluation of Puerto Rico
14 Environmental Support Base of Puerto Rico
15 Puerto Rican Imports and Exports
18 Comparisons of Puerto Rico with Other Regions
18 Ecological and Economic Evaluation of the Luquillo Experimental Forest
18 Forest Production and Storage
22 Effects of Hurricanes
22 Economic Support and Storages
22 Research and Graduate Education
25 Recreational Activities
25 Water Resources
26 Roads
26 **Synthesis**
26 Luquillo Experimental Forest
28 Puerto Rico
31 **Acknowledgments**
32 **References**
37 **Appendix 1:** Tables
70 **Appendix 2:** Import and Export Data for Puerto Rico in 1987
78 **Appendix 3:** Estimates of the Solar EMERGY use/GP Index for 1992

Introduction

We undertook a value analysis of the Luquillo Experimental Forest (the Forest)[1] in northeastern Puerto Rico to understand and quantify its many functions and their contributions to the local and global economy. A major objective of the study was to develop insights and policy recommendations for managing public forests. To accomplish these objectives, we analyzed the Forest as a system functioning within, and coupled to, the larger ecologic-economic system of Puerto Rico. Systems concepts and energy systems diagrams were used to help organize information on components, pathways of exchange, and resource flows that form the ecologic-economic systems of both Puerto Rico and the Luquillo Experimental Forest. Because resource management involves inputs, adverse environmental effects, and benefits quantified in different units (dollars, species diversity, gallons per day, and so on), systems were evaluated on the common basis of solar EMERGY. The term EMERGY represents an energy-based measure of the contribution and potential influence a given input has on a productive process and is defined as the energy of one type (in this case solar) required to produce a flow or storage of another type (Odum 1988, 1996). Using this system-based approach, EMERGY indices that relate environmental resource flows to monetary exchanges were calculated and analyzed to identify the support base, economic vitality, and contributions of Puerto Rico and the Forest.

Systems theory arose from the observation that common principles influence the design and outcome of diverse systems (table 1). A general hypothesis that emerges from this theory is that systems organize over time to develop designs and cooperative pathways that stimulate productive processes that capture and use effectively at least as much energy as they require. This hypothesis suggests the Maximum Empower Principle, which states that system designs prevailing in competition with others develop reinforcing actions that yield the most useful work from available sources (Lotka 1922, Odum 1988). Energy dissipation without "useful" contributions does not reinforce, and thus does not compete with, systems that use inflowing EMERGY in self-reinforcing ways. In this analysis, inflowing EMERGY sources of Puerto Rico and the Forest are quantified to identify choices that maximize EMERGY production, the whole economy, and public benefit. A conceptual diagram of the interdependency between economic and ecologic systems is illustrated in figure 1. The general thermodynamic principles of self-organization, hierarchical ordering, and energy transformation common to all systems are illustrated in figure 2. The symbols and definitions used in energy language diagramming are included in figure 3.

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[1] When "Forest" is capitalized in this report, it refers to the Luquillo Experimental Forest; "forest" refers to forests in general.

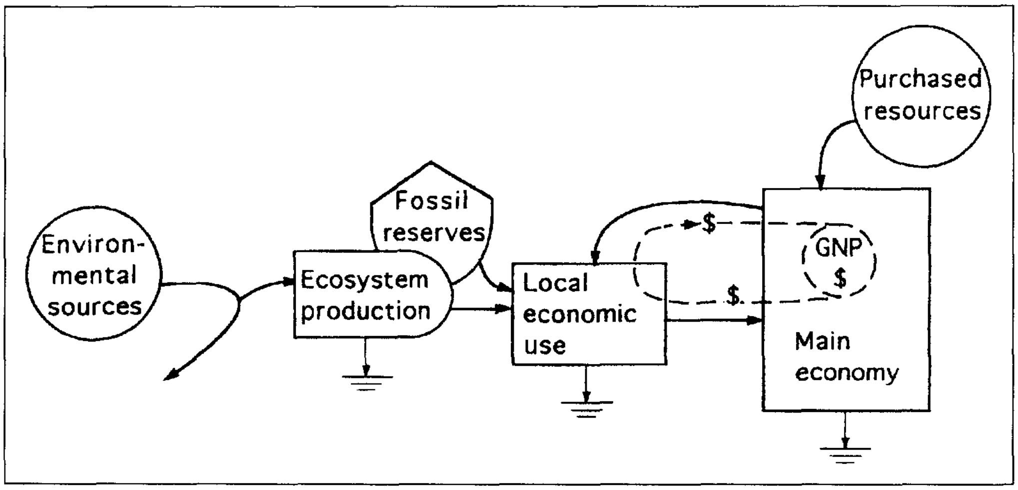


Figure 1—The interdependence between economic and ecological systems.

Overview of Puerto Rico

Puerto Rico is part of the Greater Antilles island chain of the northeastern Caribbean. The island and the major offshore islands of Culebra, Vieques, and Mona occupy 8900 km^2 (Pico 1974). The main island is mountainous and has a central cordillera and two smaller ranges in the eastern part of the island, the Luquillo and Cayey mountains. Elevations range from sea level to 1340 m; 45 percent of the land surface is above 150 m and 25 percent exceeds 300 m. Because it is surrounded by ocean and is in the path of easterly trade winds, the island has relatively minor fluctuations in daily and annual temperature. Average annual rainfall for the island is 1800 mm per year (Pico 1974). Rainfall and cloud cover, mostly orographic in origin, increase with elevation and from the southwest to the northeast corners of the island. Inversely, solar insolation decreases with elevation and from southwest to northeast.

About 30 percent of the main island is now forested (Birdsey and Weaver 1982, Franco et al. 1997). At the turn of the century when the island had an agrarian-based economy, less than 10 percent of the island was forested (Hill 1899).

Text continues on page 5.

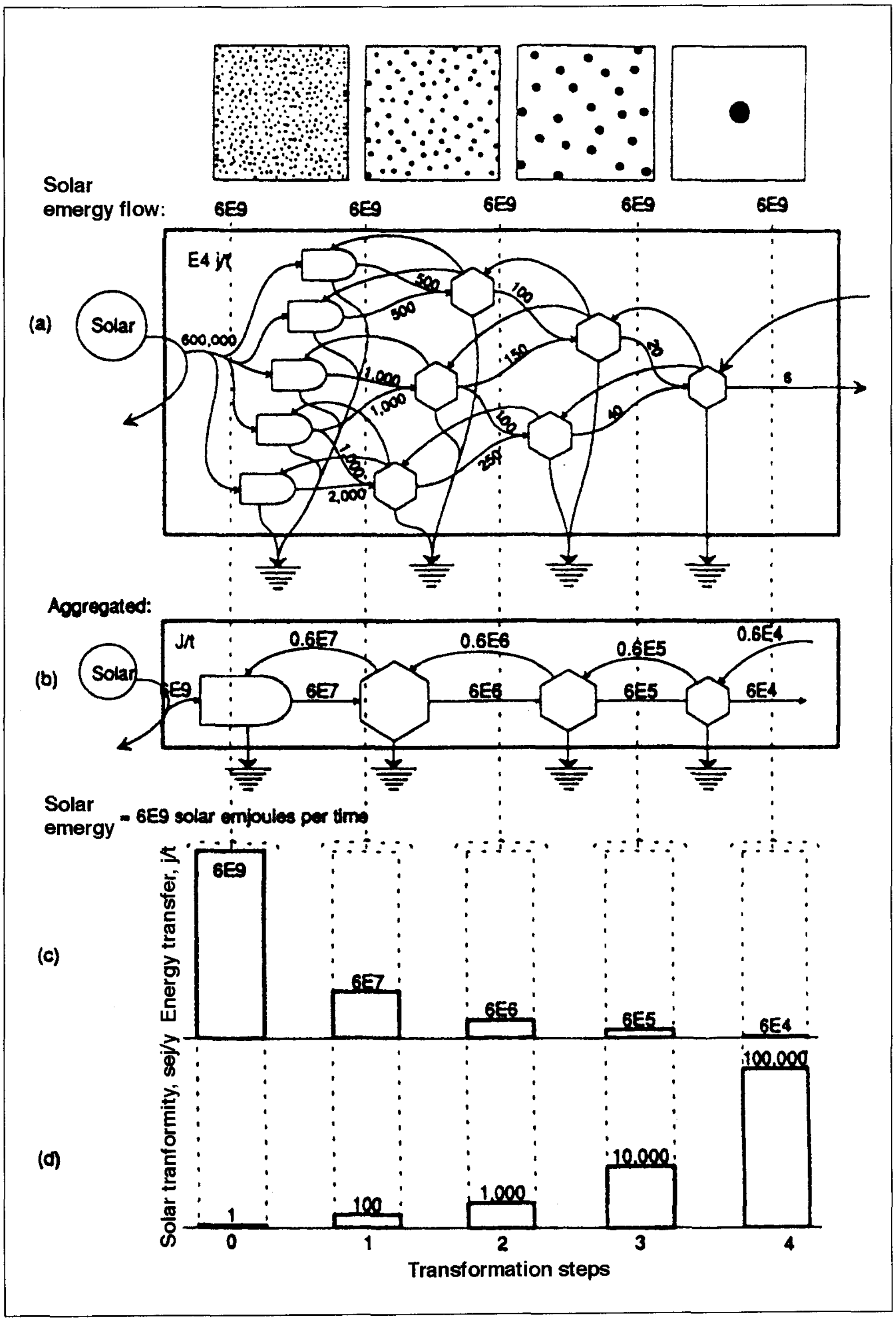
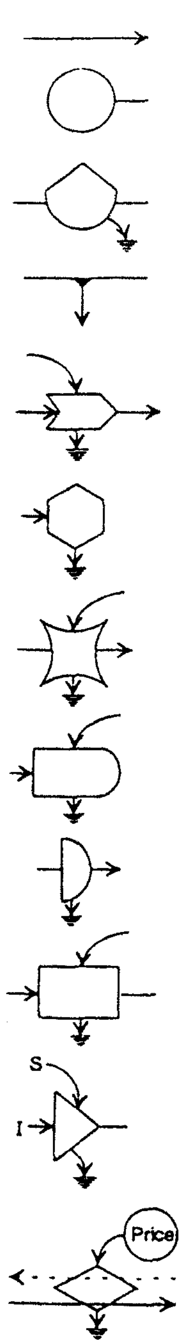


Figure 2—Energy transformations and hierarchical ordering of ecosystems illustrating the concept of solar EMERGY: (a) spatial pattern and system network, (b) network aggregation by hierarchical scales, (c) energy flows, and (d) solar transformities (from Odum 1996).



Energy circuit. A pathway whose flow is proportional to the quantity in the storage or source upstream.

Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.

Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.

Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

Switching action. A symbol that indicates one or more switching actions.

Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.

Self-limiting energy receiver. A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.

Box. Miscellaneous symbol to use for whatever unit or function is labeled.

Constant-gain amplifier. A unit that delivers an output in proportion to the input I but changed by a constant factor as long as the energy source S is sufficient.

Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 3—Symbols and definitions of the energy language diagramming used to represent systems (from Odum 1983, 1996).

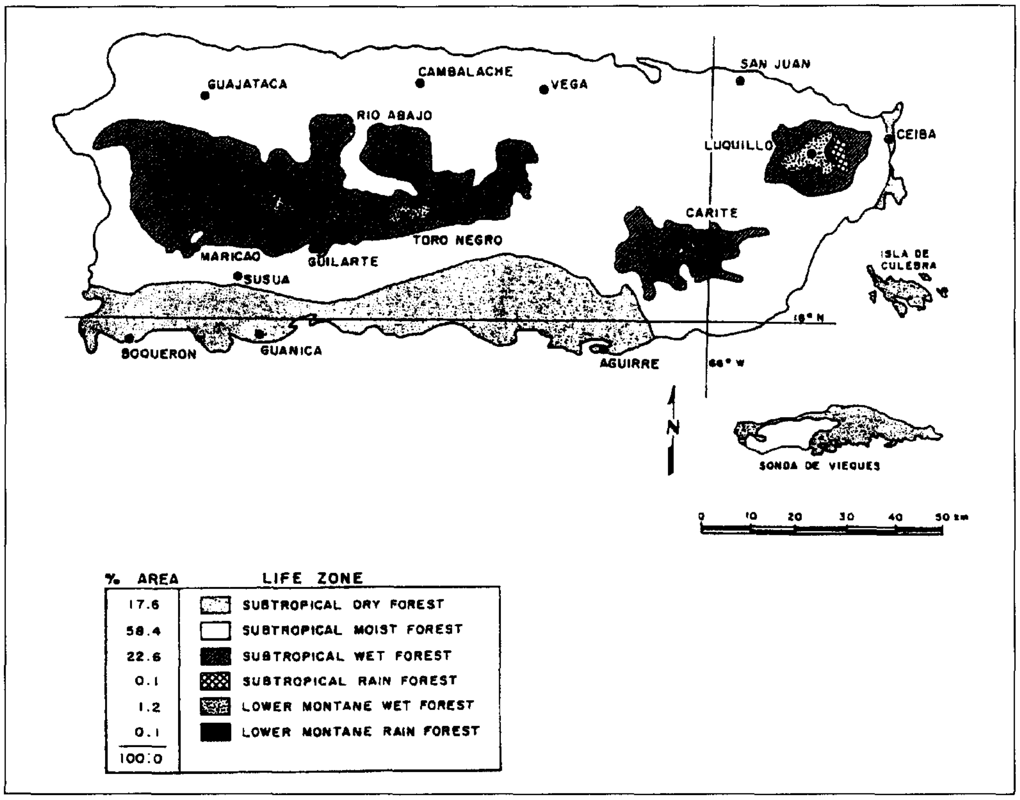


Figure 4—Puerto Rico and its ecological life zones (from Ewel and Whitmore 1973).

Ewel and Whitmore (1973) classified Puerto Rico into Holdridge-type life zones based on latitude, altitude, mean annual precipitation, and biotemperature (fig. 4). According to this scheme, almost 98 percent of the land area was lowland subtropical forest (60 percent moist forest, 24 percent wet forest, and 14 percent dry forest). Lower montane forests grow on isolated peaks and occupy 2 percent of the area. About 547 tree species are native to the island, and an additional 203 have naturalized (Little et al. 1974).

In 1996, Puerto Rico had a population of 3.7 million (416 people per km^2), a gross economic product of 30.3 billion US$, an average unemployment rate of 13.4 percent, and an average family income of $27,587 (GDB 1997). Since its discovery by Europeans in 1496, Puerto Rico has been under some form of colonial rule. From European discovery to 1898, the island was under Spanish rule. After the Spanish-American war, the island has been associated with the United States of America. During the present century, the island has shifted from a rural, agriculture-based economy to an industrialized economy based on manufacturing and services. Coincident with this shift has been the abandonment of agricultural lands, urban migration, and the importation of fuels and high-quality goods. Between the 1950s and the 1980s, forest cover on the island increased, as sugar cane, pasture, and other agricultural areas were abandoned and allowed to reforest naturally (Birdsey and Weaver 1982, Thomlinson et al. 1996). The rate of natural reforestation began to decrease in the 1970s, however, and the area of forest cover on the island remained fairly constant between 1980 and 1990 (Franco et al. 1997).

Overview of the Luquillo Experimental Forest

The Luquillo Experimental Forest, in the northeastern part of Puerto Rico, is an 11 268-ha forest managed by the USDA Forest Service under the auspices of the International Institute of Tropical Forestry and the Caribbean National Forest. The Forest is managed for multiple uses, including wood production, municipal water supply, recreation, telecommunications, education, and research (Brown et al. 1983, Lugo and Lowe 1995). It is also one of the most highly visited Forests per unit area in the entire National Forest System (Loudon 1989). The Caribbean National Forest is responsible for the Forest's land management activities. The institute is responsible for research activities and also for state, private, and international forestry activities outside the Forest boundaries. Both agencies participate in education and, in 1996, had a combined total of 224 full-time employees.

The forests of the Luquillo Mountains can be divided into four forest types or ecosystems (Lugo and Lowe 1995). The **elfin cloud forest**, also referred to as the dwarf forest, is the least extensive, found only on the uppermost peaks. It receives water from both rainfall and cloud interception. The **colorado forest**, dominated by *Cyrilla racemiflora* L., grows at mid-elevation (600 to 900 m) and areas underlain by granodioritic bedrock. The **palm forest**, dominated by the native mountain palm, *Prestoea montana* R. Grahm, typically grows on poorly drained windward sites throughout the Forest. The **tabonuco forest**, dominated by *Dacryodes excelsa* Vahl, grows in low-elevation sites (100 to 600 m) on about half of the Forest. Common natural disturbances include hurricanes and tropical storms, landslides, treefall gaps, and droughts (Scatena and Lugo 1995).

Methods

Definitions

Basic concepts and definitions used in this study are defined in table 1[2] and illustrated in figure 3. Additional information and examples of EMERGY analysis can be found elsewhere (Odum 1996).

Energy, a property of all things, can be turned into heat; it is measured in heat units (British thermal units, calories, or joules). **EMERGY** is the available energy of one kind, previously used—either directly or indirectly—to make a product or service; it is measured in emjoules (table 1).

Solar EMERGY, the solar energy required directly and indirectly to make a product or service, is measured in **solar emjoules** (sej). The flow of EMERGY per unit time is **empower**, usually expressed as sej/yr.

[2] To avoid frequent, long interruptions in the text, the tables are grouped in appendix 1, beginning on p. 36.

Transformity is the ratio of total EMERGY used in an energy transformation to the energy yielded by the process (table 1). **Solar transformity** is the ratio of solar EMERGY- use, divided by the energy yielded (sej/J), and it is the solar EMERGY required to make one joule of a service or product. Solar transformities reflect the EMERGY used per unit of available energy produced and are measures of position and influence in the energy hierarchy of a system (Odum 1996). Once the transformities are known, they can be used to convert energies of different types to solar EMERGY. A list of the solar transformities used to convert environmental flows, purchased fuels, and other commodities to solar EMERGY is given in table 2. These transformities are drawn from independent studies conducted by using the methods of this study (see footnotes to table 2 and Odum 1996).

The term **emdollars** (em$) refers to the total amount of dollar flow generated in the entire economy, supported by a given amount of solar EMERGY input. It is calculated by dividing the solar EMERGY of a product or process by the solar EMERGY/money index for the economy to which it contributes. This calculation provides a way of putting a monetary value on services and storages not traditionally accounted for in economics, such as transpired rainfall, photosynthetic production, forest biomass, and information. These emdollars are not market values; instead, they represent a value for public policy inferences and directives. To distinguish this measure from market dollar values (US$), we use em$ to indicate an EMERGY-based representation of part of the economy.

The **net EMERGY yield ratio** is the solar EMERGY of an output, divided by the solar EMERGY of those inputs to the process purchased and fed back from the economy (table 1). This ratio shows whether the process can compete in supplying a primary energy source for an economy. Since 1973, competitive fuel sources have had ratios between 4 and 12, but these favorable ratios are declining as extracting and processing costs increase.

The **EMERGY investment ratio** is the ratio of solar EMERGY derived from the economy to the solar EMERGY delivered from both renewable and nonrenewable environmental sources. The larger the investment ratio, the greater the amount of purchased EMERGY is required per unit of resident EMERGY. Activities with lower ratios receive less from the economy and more from the environment, and thus they suggest underused resources capable of stimulating more economic use.

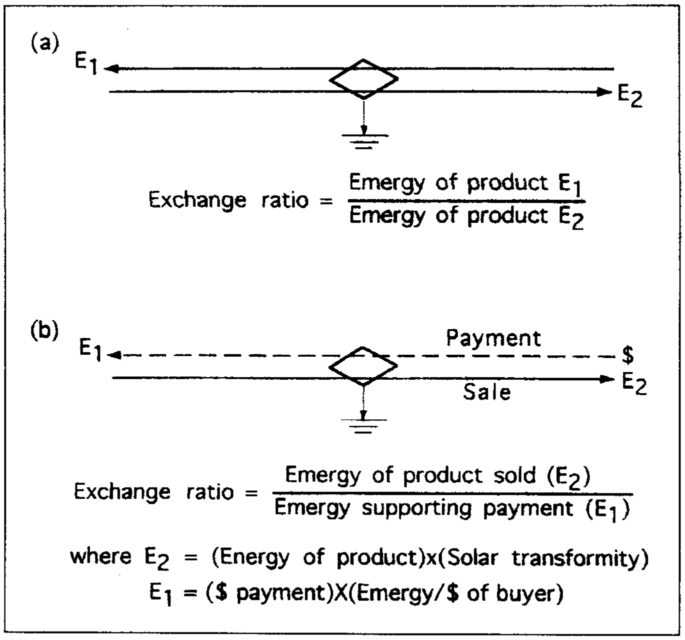


Figure 5—Solar EMERGY exchange of an economic transaction: (a) trade of two commodities, (b) sale of a commodity (from Doherty et al. 1994).

The **EMERGY exchange ratio** is the ratio of solar EMERGY received to solar EMERGY delivered in a trade or sales transaction. If the market transaction is trade—for example, a trade of grain for oil—the ratio can be expressed as the relation of solar EMERGY supporting each commodity (fig. 5). If the exchange is a sale of a commodity to generate revenue to purchase goods or services, the exchange ratio can be calculated as the solar EMERGY of the product sold divided by the solar EMERGY that could be purchased with the earned revenue. This ratio is estimated by using the solar EMERGY/dollar index for the buyer nation or region. The solar EMERGY exchange ratio was used in this study as a measure of the relative benefits or losses Puerto Rico received from external trade.

The index of annual solar EMERGY use to the gross economic product (GP), or the EMERGY/money ratio in units **sej/$**, is an estimate of the real wealth supporting each unit of currency circulating in an economy (Odum 1996). In this report, Puerto Rico's total EMERGY-use was related to its gross economic product in 1992 to estimate the EMERGY supporting human services used in production activities and exports. This index is also used to estimate solar EMERGY-supporting lifestyles of workers (that is, human services). The money paid for raw resources, machinery, fuels, and other goods necessary in a production sector pays for the human services required in refining, manufacturing, and delivering the commodity. Because money is paid to people only for their contributions and not for environmental work, a **sej/US$ index** was derived so that human services could be equivalently evaluated along with other inputs to production sectors. The sej/US$ index assigns a solar EMERGY value to human services in proportion to the money paid for the direct and indirect human

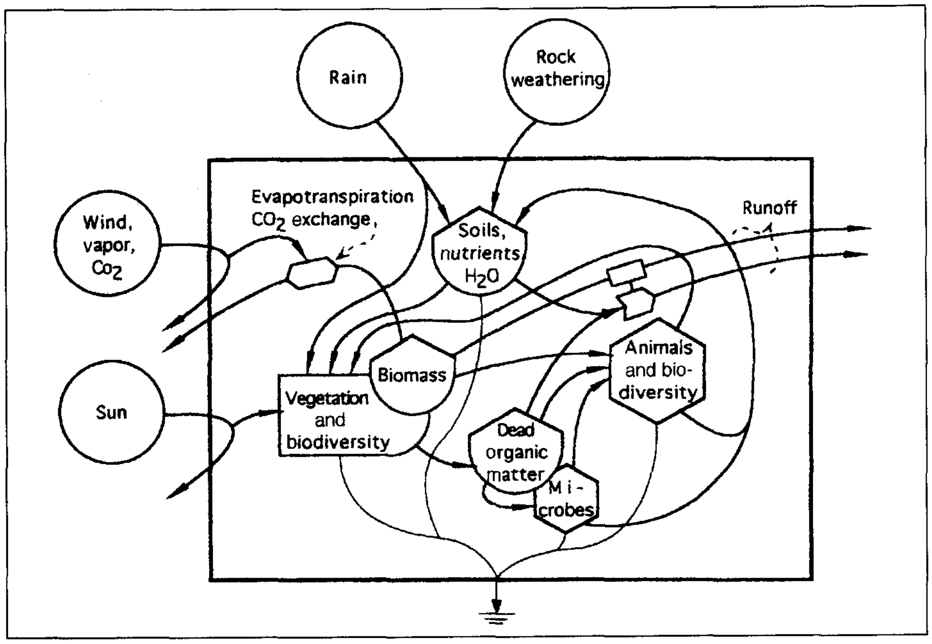


Figure 6—The aggregation of environmental source inputs.

labor requirements. In general, rural countries tend to have higher solar EMERGY/ dollar indices because more of their economy involves direct environmental resource inputs not directly paid for with money (Odum 1996).

Solar EMERGY Analysis

Each system and subsystem in this report was studied by using standard methods described briefly below and in detail elsewhere (Odum 1996). First, an energy systems diagram was drawn to provide an initial network overview of each system, combine information of participants, and organize data-gathering efforts for the entire island of Puerto Rico and the Luquillo Experimental Forest. All contributing sources for each system were identified, and basic data for each were collected from the literature or appropriate agencies and experts.

Then, EMERGY resource-evaluation tables were developed to facilitate calculations of main sources and contributions to each system studied. Resource inputs and yields are reported in each table as general accounting units (tons, joules, US$), and these values are converted to solar EMERGY units (solar emjoules) and emdollar values by using referenced transformities.

Indices of solar EMERGY use and source origin were then calculated to compare systems, relate solar EMERGY requirements to traditional economic measures, identify system efficiencies, and suggest alternatives. Energy systems diagrams and modeling are based on the following conventions of energy language diagramming (from Odum 1971, 1993, 1996).

Symbols—The symbols each have rigorous energetic and mathematical meanings (fig. 3). Examples are given of a system diagram illustrating aggregation of source inputs (fig. 6) and an overview systems diagram of Puerto Rico and its resource base (fig. 7).

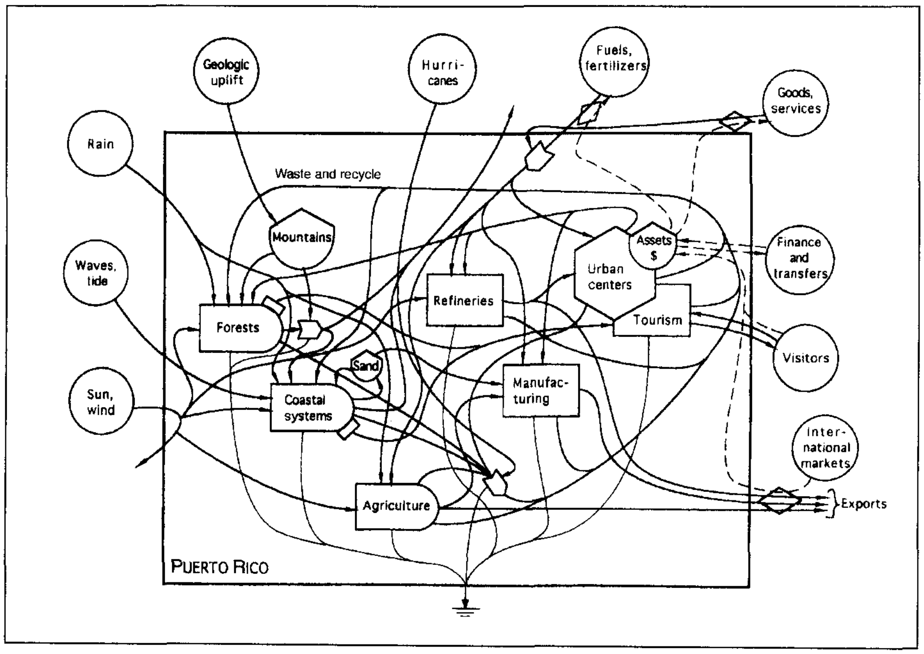


Figure 7—Overview of Puerto Rico and its resource base, major economic sectors, interactive flows, and circulation of money (from Doherty et al. 1994).

System frame—A rectangular box with rounded corners is drawn to represent the boundaries of the system selected for study.

Arrangement of sources—Any input that crosses a boundary is a source, including pure energy flows, materials, information, genes of living organisms, human services, and also destructive inputs. All these inputs are given a circular symbol. Sources are arranged around the outside border from left to right, in order of increasing solar transformity, starting with sunlight on the left and information and human services on the right.

Pathway line—Any flow is represented by a line including pure energy, materials, and information. Money is shown with dashed lines flowing in the opposite direction to energy flows. Lines with no barbs indicating direction may flow in either direction, depending on the difference between two forces.

Outflows—Any outflow that still has available potential energy, material more concentrated than the environment, or usable information is shown as a pathway from either of the three upper system borders, but not out of the bottom.

Degraded energy—Energy that has lost its ability to do work according to the second law of thermodynamics is represented as pathways converging to a heat sink at the bottom center of the diagram. Included are heat energy byproducts of processes and the dispersed energy from depreciation of storages.

Adding to pathways—Pathways add their flows when they join or when they go into the same storage tank. Every flow in or out of a tank must be the same type of flow and measured in the same units.

Interactions—Two or more different flows, but both required for a production process, are drawn to an interaction symbol. The flows to an interaction are connected from left to right in order of their solar transformity; the lower transformity flow connects to the notched left margin of the symbol.

Counterclockwise feedback—High-quality outputs from consumers—such as information, controls, and scarce materials—are fed back from right to left, counterclockwise in the diagram. Feedback from right to left represents a loss of concentration because the service is usually being spread out to a larger area.

Material and currency balances—Because all inflowing materials either accumulate in the system's storages or flow out, each inflowing material, such as water or money, needs to have outflows drawn.

Resource evaluation tables—Resource evaluation tables for each system being evaluated are set up with the headings in the following tabulations:

1	2	3	4	5	6
Footnote	Item	Basic data *(J, tons, $ cost)*	Solar EMERGY per unit *(sej/J, sej/g, sej/$)*	Solar EMERGY *(sej or sej/time)*	Emdollars value *(US em$)*

where:

Column one is for the line-item number, which is also the number of the footnote at the end of the table where the source of the raw data is cited and calculations shown.
Column two is for the name of the item being evaluated.
Column three is for the resource inputs to production, given in units reported by industry accounting or obtained from environmental and statistical abstracts. These inputs are reported as average annual flows (joules, grams, or US$) per unit volume or area and are derived from the sources identified in the footnotes.
Column four is for the solar transformity, measured in solar emjoules per joule (sej/J), per gram (sej/g), or per dollar (sej/$) and derived from separate studies.
Column five is for the solar EMERGY of the item. Storages are solar emjoules; solar EMERGY flows are reported in solar emjoules per year. These terms are the products of columns 3 and 4.
Column six is the emdollar value, reported in 1992 emdollars, obtained by dividing the solar EMERGY (column 5) by the relation of annual solar EMERGY use to the gross economic product of Puerto Rico in 1992. See definitions below for solar EMERGY per dollar index and macroeconomic value.

Biophysical Evaluations

The resource evaluations of Puerto Rico's indigenous environmental production, imports, and exports in 1987 are given in tables 3 through 6. In this island-wide analysis, the indigenous and incident energy sources evaluated were sunlight, rainfall, streamflow, geologic uplift, and the extraction of sand, gravel, and metal ores (fig. 7). The environmental functions evaluated in the Forest were net primary production (NPP), biomass storage, erosion, and surface-water runoff.

Tectonic inputs to the island were based on its average rate of Quaternary uplift, (Clark 1997, Taggart 1992). Island-wide environmental production was based on the average bioclimatic conditions of the island's life zones (Birdsey and Weaver 1982, Ewel and Whitmore 1973), and the Forest's analysis was based on the bioclimatic conditions of its four major forest ecosystems. Average annual volumes of water entering and passing through each life zone or forest type was considered to do environmental work through both chemical and geophysical processes. The chemical energy of rainfall, evapotranspiration, or stream runoff was calculated as the available Gibbs free energy of the water at average concentrations of dissolved solids (Odum 1996). Island-wide chemical and geopotential energies were based on average rainfall and evapotranspiration per life zone (Birdsey and Weaver 1982, Ewel and Whitmore 1973). The chemical potential energies for rainfall, runoff, and evapotranspiration were based on Forest-wide averages derived from long-term climatic and hydrological cycles (Garcia Martino et al. 1996). Solar transformities for the chemical potential energy in rainfall were based on global cycles (Odum 1996).

Geopotential energy of water flowing through the system includes the work done in erosion and landscape sculpturing, as evaluated by using the Bernoulli energy equation for open channel flow (Odum 1996). The geopotential energy of the island was calculated by dividing the island into three altitudinal regions: plains (75 m mean elevation), hills (225 m), and mountains (650 m). The gravitational energy for each region was calculated by using the average elevational gradient and runoff of each region. The available geopotential EMERGY for the Forest was based on the mean elevation and runoff of each forest type. The geopotential EMERGY of landscape sculpturing was estimated from the sediment yields of each forest type and the change in geopotential EMERGY across the elevational range of each forest type (Kharecha 1997, Romitelli 1997). The EMERGY of forest production and storage was calculated from published values of production and storage by forest type. The average ages of each forest type were calculated by dividing aboveground biomass by the rate of aboveground accumulation. In turn, the average accumulation rate of soil organic matter was estimated from the total storage of soil organic matter divided by the average age of the forest.

Economic Evaluations

External trade commodities, imported and exported fuels, human services, U.S. loans, and tourism were evaluated and used to calculate Puerto Rico's EMERGY/GP index for 1992. External trade was evaluated by using data from 1987, the most current year with tabulated statistics (Doherty et al. 1994, appendix 2). The human services supporting these imports were estimated by using the index of solar EMERGY/GNP for the United States. Fuel imports, trade costs, and revenues were evaluated from tabulated statistics for 1992 (Doherty et al. 1994, appendix 3). Environmental sources were considered unchanged from year to year.

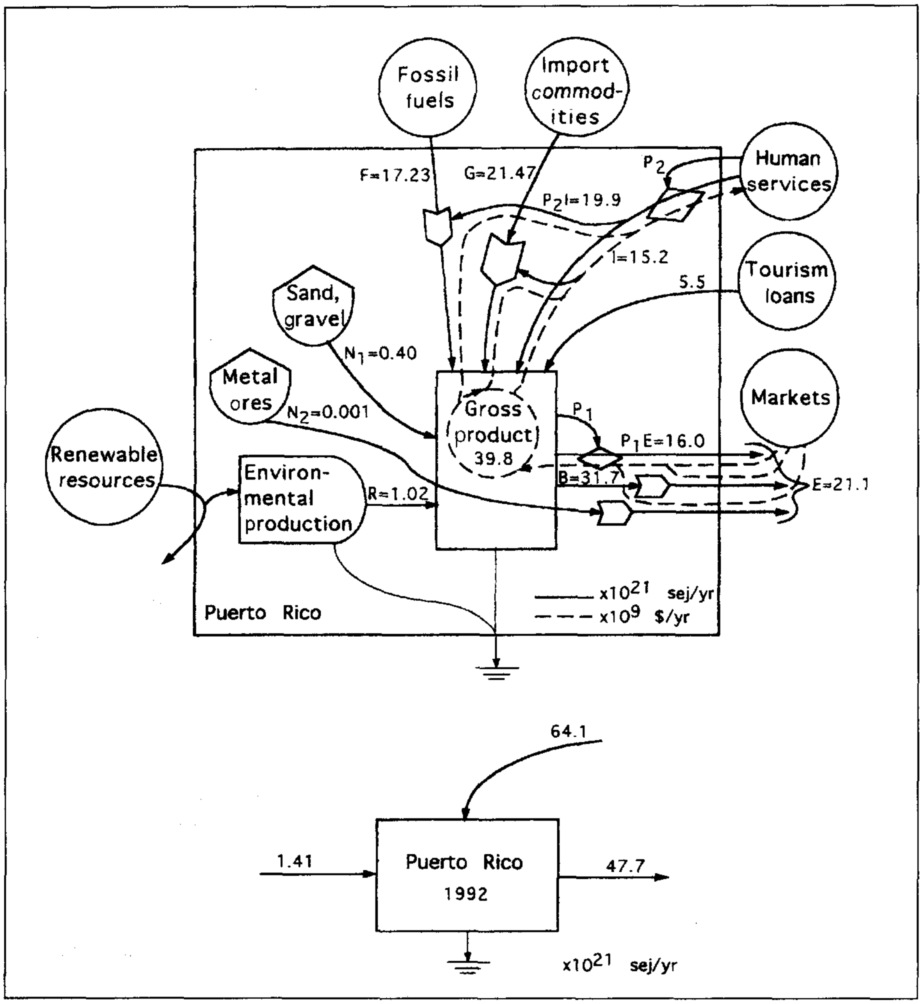


Figure 8—Aggregation of Puerto Rican EMERGY flows for environmental sources, imports, and exports in 1992 (from Doherty et al. 1994). See table 6.

The economic contributions to the Forest that were evaluated included fuels, annual dollar support for research and forest administration, and tourism (Doherty et al. 1994, Kharecha 1997). These values were based on annual administrative budgets and records obtained from the Caribbean National Forest and the International Institute of Tropical Forestry. The economic costs of roads and facilities in the Forest were estimated from the costs of roads and facilities recently built, as detailed in the table footnotes. The solar EMERGY supporting recreational and research activities were calculated in two parts: the monetary expense incurred by people visiting or studying the Forest, and the amount of EMERGY expended while they were there.

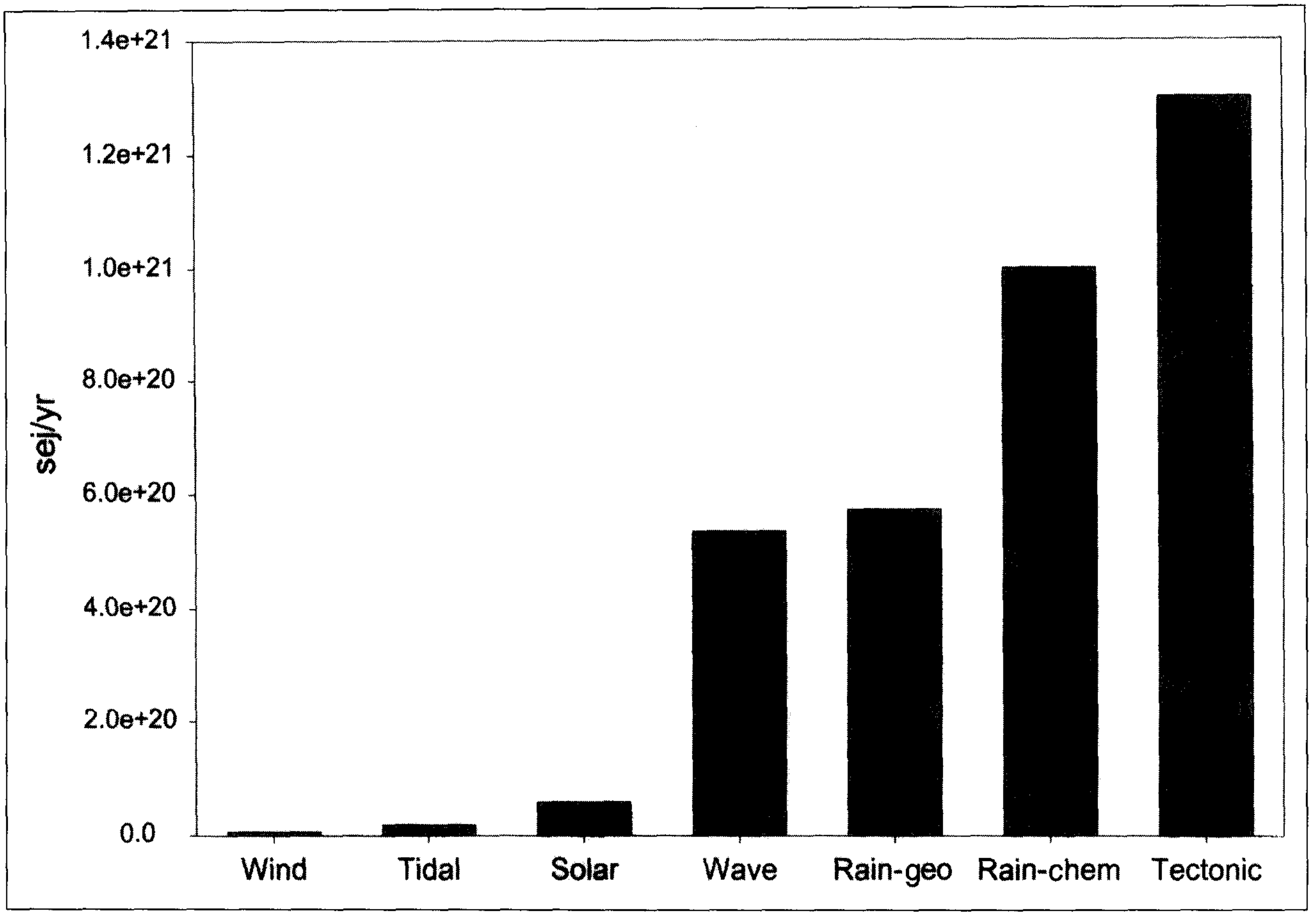


Figure 9—Annual solar EMERGY flows for environmental sources in Puerto Rico (see table 3).

Results

Ecological and Economic Evaluation of Puerto Rico

Environmental Support Base of Puerto Rico

An aggregate systems diagram of Puerto Rico's environmental sources, imports and exports, internal production, and storage is given in figure 8. Puerto Rico's largest EMERGY pool is what is stored in the island itself (table 3). Annual tectonic inputs account for the largest annual environmental contribution, and they are 1.3 times the second largest contributor, transpired rain (fig. 9). The island's total annual input of renewable solar EMERGY is 10.2E+20 sej/yr (that is, transpired rain + tidal; tables 3 and 6). The energy received from sunlight contributes the greatest amount of direct available energy, but it only accounts for 6 percent of the renewable contributions. The subtropical-moist-forest life zone accounts for 60 percent of the land mass and 62 percent of the island's renewable EMERGY flows. Island-wide, geo potential EMERGY (5.7E+20 sej/yr) is about half of the island's chemical potential EMERGY and less than the chemical potential EMERGY of the subtropical-moist-forest life zone. Waves and tides acting on the 540 km of coastline contribute 5.6 E+20 sej/yr to the island (table 3). This EMERGY contribution, similar in magnitude to the geopotential contribution of rain, supports a large part of the island's tourist industry.

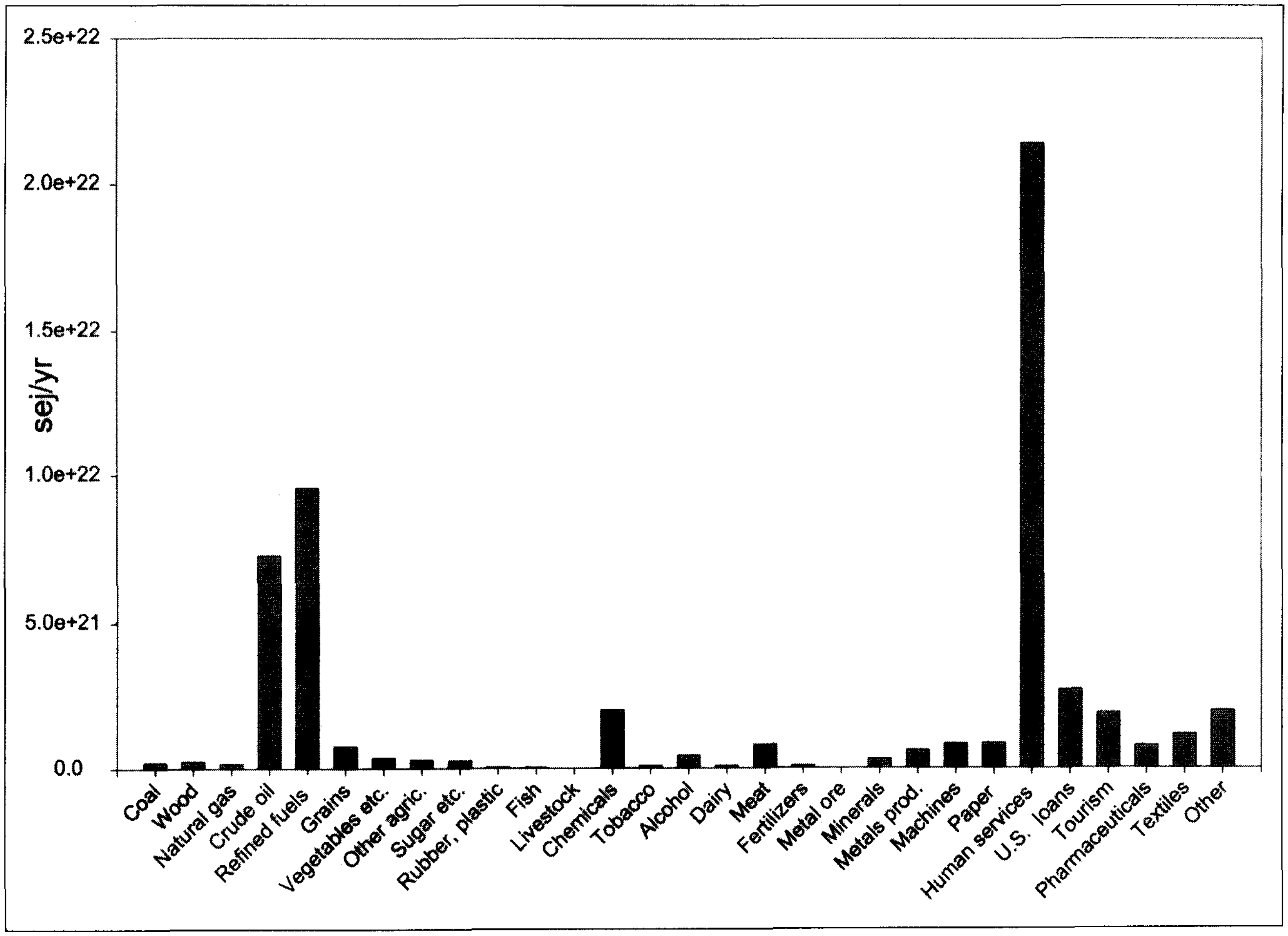


Figure 10—Solar EMERGY of imports for Puerto Rico in 1987, in order of increasing solar transformity from left to right (See table 4).

The mining of sand and gravel to produce cement and building materials contributes about 0.8 percent of the island's total EMERGY use but 28 percent of the total contribution of the nontectonic environmental EMERGY (tables 3 and 6). The extraction of other metal ores and minerals, as estimated from total export quantities, was considered insignificant.

Puerto Rican Imports and Exports

The human services embodied in imports carried 2.14 E+22 sej/yr, or about 33 percent of the island's annual EMERGY use (table 4, fig. 10). The island's largest EMERGY import commodity was fossil fuels. Moreover, fossil fuels comprised 57 percent of the total EMERGY imports and 33 percent of the island's annual EMERGY use. Other imported commodities with large EMERGY flows included meats and grains, paper products, textiles, and chemicals.

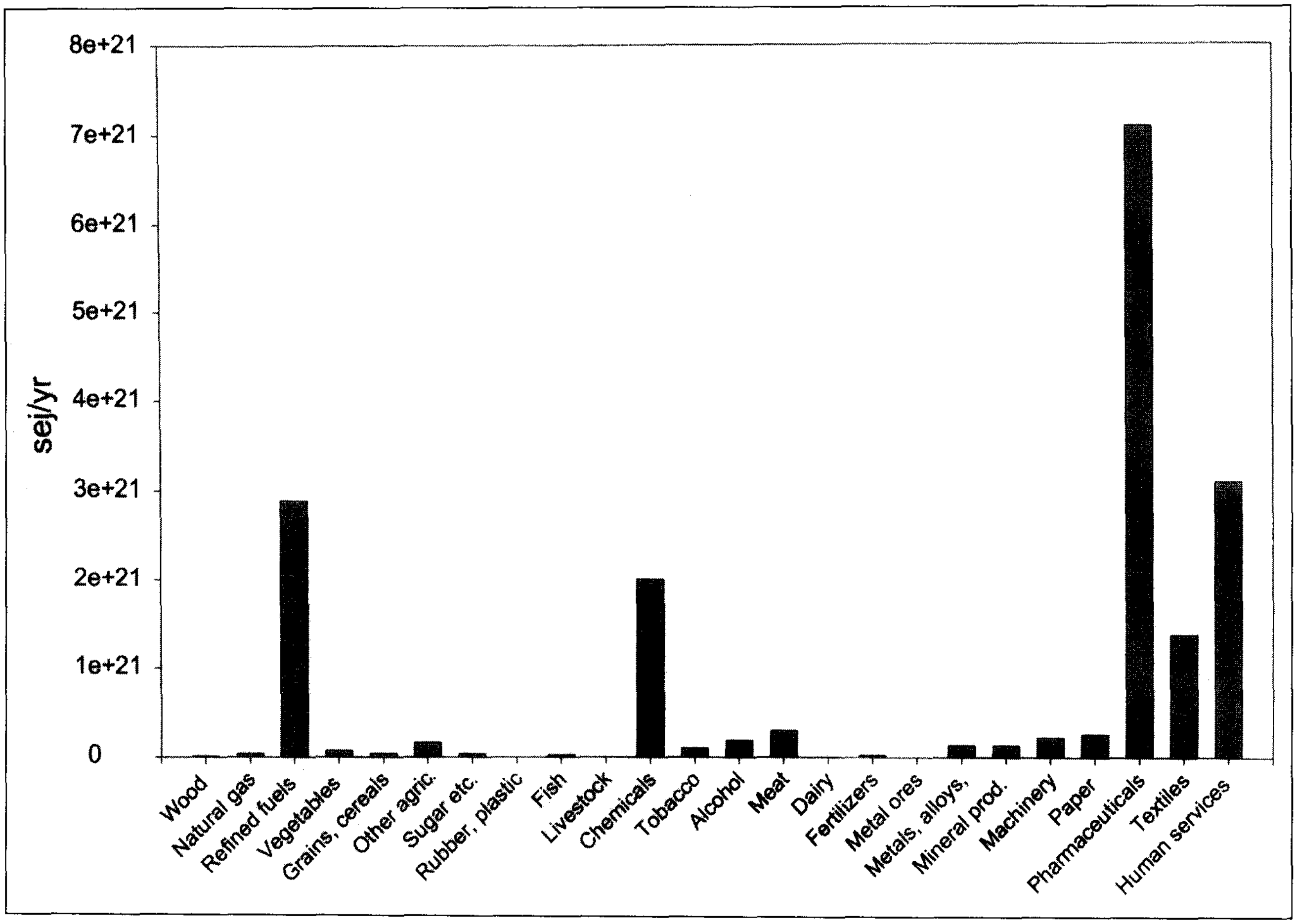


Figure 11—Solar EMERGY of exports for Puerto Rico in 1987, in order of increasing solar transformity from left to right (modified from Doherty et al. 1994) (see table 5).

Major exports for Puerto Rico included pharmaceuticals, refined fuels, chemicals, synthetics, and textiles (table 5, fig. 11). The major exports are fuel-based derivatives from industries that employ island residents to upgrade imported low-transformity goods into products then exchanged in export markets (fig. 12). In 1987, human services accounted for 50 percent of the EMERGY embodied in these exports (table 5). The EMERGY of human services in these exports, however, appears to be decreasing (table 6). Traditional economic analysis also indicates that the wage and labor content of exports has decreased over the past 30 years (Montano 1997). Moreover, employment per million dollars of manufactured goods exported fell from 114 jobs in 1967 to 34 jobs in 1994. Wages and salaries per million dollars of manufactured goods exported also decreased from $215,000 to $115,239 over the same period.

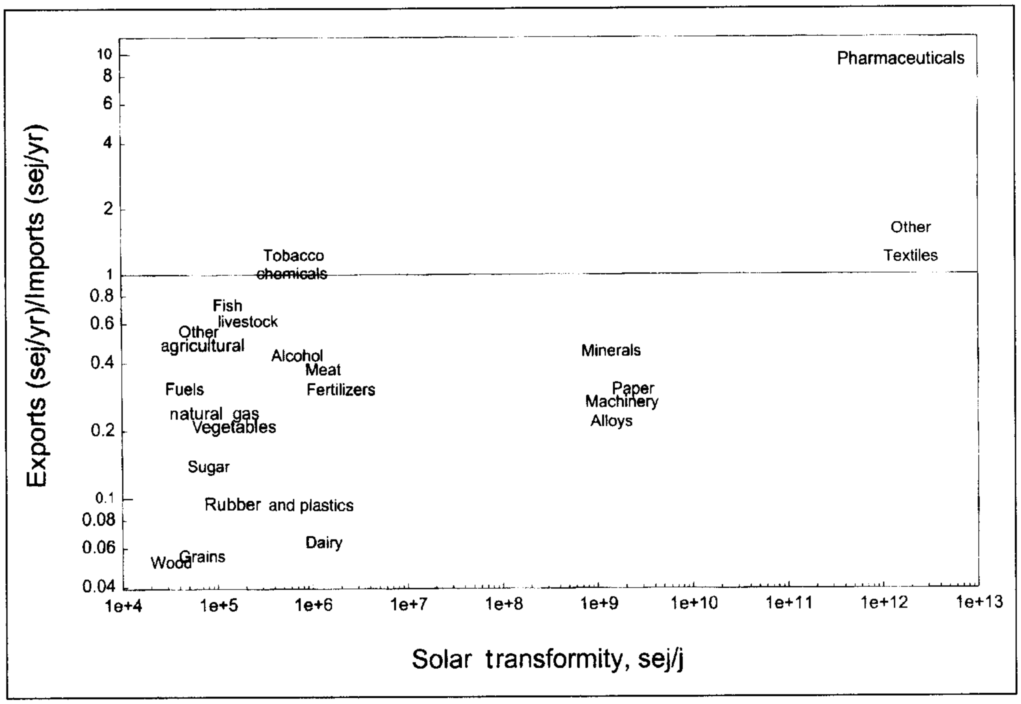


Figure 12—Solar transformities versus ratio of empower of imports to exports for Puerto Rico in 1987.

Comparison of the EMERGY embodied in imported and exported goods indicates that Puerto Rico receives more EMERGY per dollar of imports than it receives in per-dollar revenue of exports (tables 6 and 7). For both dollar and EMERGY measures, however, the net trade advantage per unit cost of imports decreased between 1987 and 1992. In 1987, the island imported 1.61 times the EMERGY it exported. In 1992, the island imported 1.22 times exports. Dollar revenues received from exports were 1.13 times dollar imports in 1987 and 1.39 times imports in 1992 (table 7). In 1987, the EMERGY import:export ratio was greater than the market dollar import: export ratio; in 1992, the ratio was less.

In addition to the EMERGY imported in goods, EMERGY can be purchased off-island from the net dollar revenues generated from trade. This additional EMERGY must be included to assess the EMERGY trade balance of the island accurately; it can be estimated by using the EMERGY/GNP ratio from an exporting country, such as the United States (see footnotes to table 7). Including this purchased EMERGY in the exchange ratio indicates that the actual net EMERGY trade benefit between 1987 and 1992 declined by 14 percent compared to a 24-percent decline when the purchased EMERGY is not included (table 7).

Comparisons of Puerto Rico with Other Regions

To place Puerto Rico's ecologic-economic system in a global context, its annual solar EMERGY-use, distribution, exchange, population, and gross economic product were compared with those of other areas (tables 8 to 12). Note that these indices are based on independent studies from various sources that used similar but not identical methods and data sources (table 8); therefore, the comparisons are restricted to broad trends and overviews. Because these other studies did not include tectonic contributions in their analysis, they are not included in the Puerto Rican indices in tables 8 to 12.

The 45:1 economic-to-environment EMERGY ratio of Puerto Rico is one of the highest for any evaluated area (table 8). Compared with the United States, with its 7:1 ratio or a developing country with a 0.1:1 ratio, Puerto Rico is investment intensive and highly dependent on external sources for its production and welfare. With only 2 percent of the island's annual EMERGY- use contributed from indigenous renewable EMERGY sources, Puerto Rico is also the least self-sufficient region known (table 9). Furthermore, the island has one of the highest EMERGY use per unit area (EMERGY power density) known (table 10). In these respects, the island resembles a city, but because of its high population density, Puerto Rico's EMERGY use per capita is moderate compared with other areas (table 11). In general, per capita EMERGY use is typically low for areas with poorly developed economies and low income per capita. When annual EMERGY use is compared to gross economic product (the EMERGY/GP index), Puerto Rico is characteristic of industrial economies like the United States (table 12). Thus, Puerto Rico benefits from an exchange with areas with higher EMERGY/GP indices because a dollar from Puerto Rico will purchase more EMERGY there than on the island.

Ecological and Economic Evaluation of the Luquillo Experimental Forest

Forest Production and Storage

The major environmental energies driving the Luquillo Forest's production include solar insolation, trade winds and hurricanes, tectonic uplift, rainfall, cloud condensation, and nutrient inputs from rock weathering and atmospheric sources (fig. 13). In general, cloud cover, cloud interception, annual precipitation, and runoff increase with elevation; solar insolation, evapotranspiration, and aboveground biomass decrease (table 13). Because of their large aerial extent, the tabonuco and colorado forest types dominate the storage and fluxes in the Luquillo Mountains. Nevertheless, each of the four forest types has a unique EMERGY signature, with a systematic shift from physically dominated to biologically dominated systems with decreasing elevation (table 14 and figs. 14, 15, 16).

The Elfin Forest has the largest amount of stored biomass when soil organic matter and aboveground biomass are considered together (table 13). It is also the only forest type where the geopotential EMERGY of rainfall is greater than its chemical potential EMERGY (table 14). These cloud forests also have the highest transformities for NPP and vegetation (table 15), the lowest biological EMERGY density, and the highest EMERGY in physical erosion, chemical streamflow, and physical streamflow (table 17). Based on EMERGY dollars, this forest type also has the highest value of streamflow (table 18) and supports the largest diversity per unit of EMERGY input (Doherty 1995). This EMERGY signature reflects the low transpiration of this forest type and the steep slopes and high rainfall of the sites it occupies.

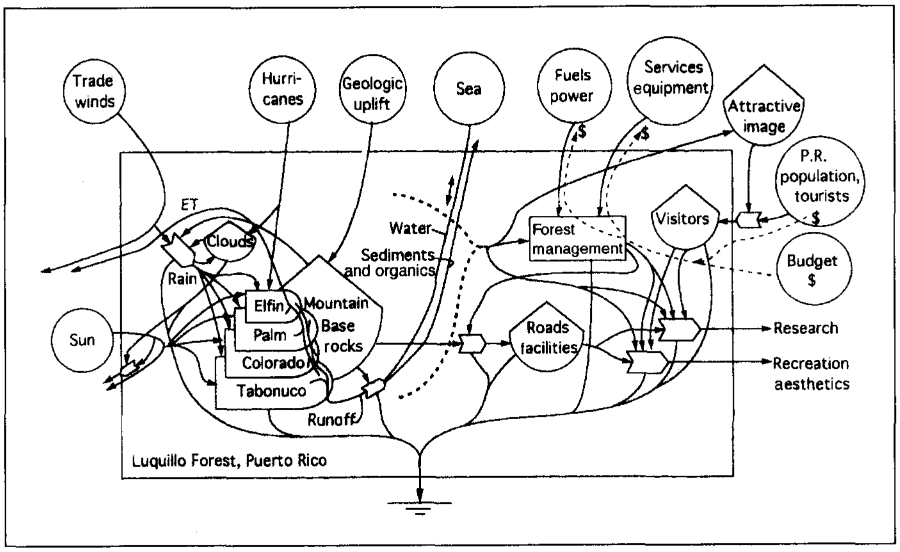


Figure 13—Systems diagram of the solar EMERGY basis of aboveground net primary production and biomass storage for the forest ecosystems in the Luquillo Experimental Forest (from Doherty et al. 1994).

The colorado forest has the lowest total organic matter (table 13), the oldest vegetation of any forest type in the Forest (table 15), and the largest total EMERGY-inputs (table 18). The EMERGY densities for runoff (table 16), biochemical processing (ET), and the chemical and physical sculpturing of the landscape (table 17) of the colorado forest are closer to the palm and elfin than to the tabonuco forest. Furthermore, the transformities for soil organic content and NPP of the colorado forest are most similar to the Luquillo's forest-wide values (table 15). These similarities reflect the central position colorado forest has in the Forest.

The Luquillo palm forests have the highest leaf biomass and total aboveground NPP of any forest type (table 13). They also have the lowest solar transformities for NPP, vegetation, and soil organic matter (table 15). The EMERGY stored in aboveground vegetation is also lowest for the palm forest (table 15). This EMERGY signature reflects the rapid growth of this light, woody monocot. The relatively low EMERGY embodied in palms also may explain why they are the most abundant species in the Forest and grow in all of its forest types.

By virtue of its aerial extent, the tabonuco forest dominates the fluxes and storages of the Luquillo Experimental Forest. On a per-area basis, this forest type also has the most aboveground biomass (table 13), the highest EMERGY densities of NPP (table 14), and the highest EMERGY/dollar value of vegetation of any forest type (table 18). This forest type also has the most solar EMERGY in vegetation and the highest transformity for soil organic matter (table 15, figs. 14 and 15). The tabonuco forest type also has the lowest chemical and geopotential EMERGY of runoff (table 16, fig. 16) and the highest biochemical EMERGY densities (table 17). This EMERGY signature reflects the low elevation, high transpiration, and high NPP of this forest type.

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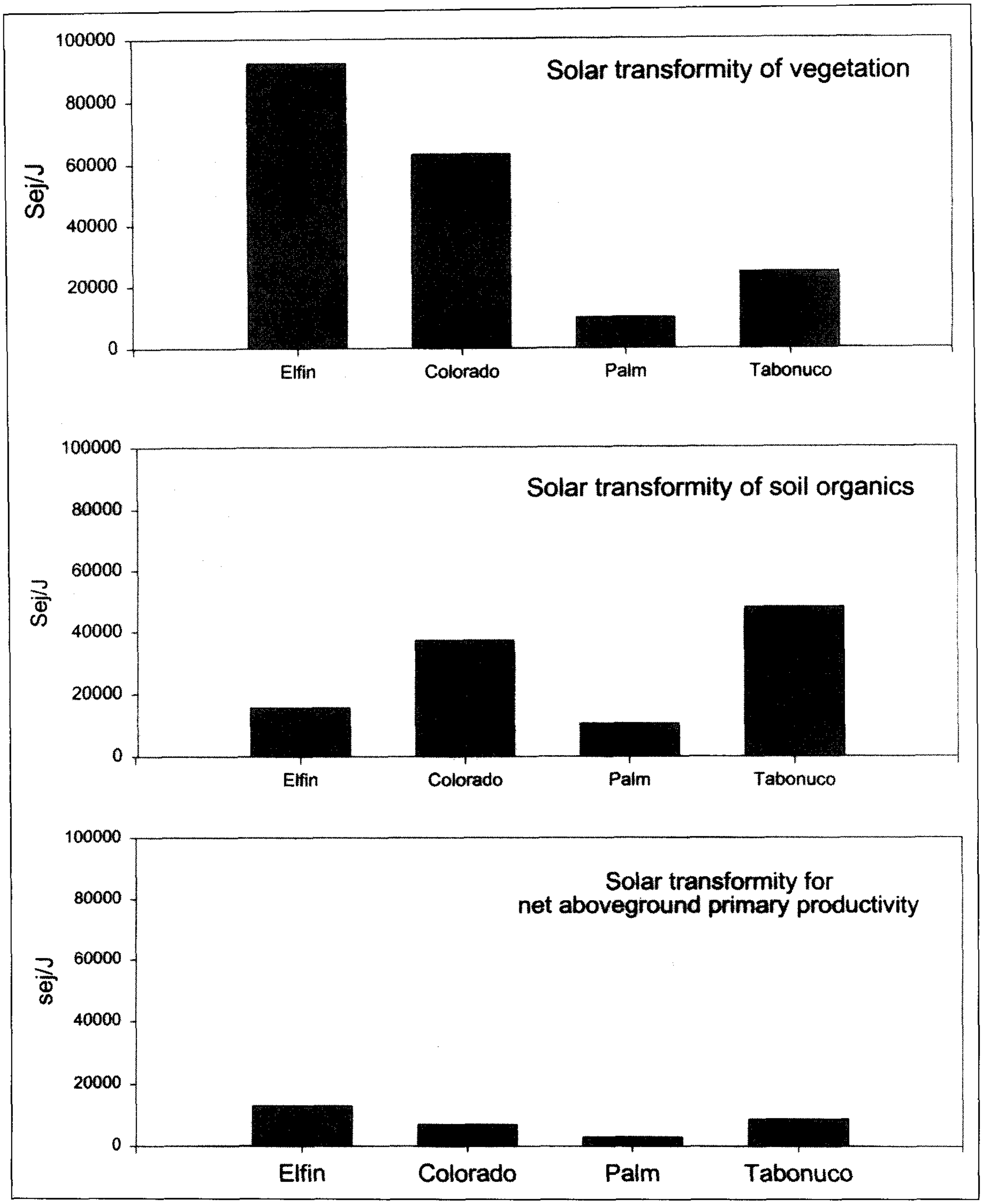

Figure 14—Solar transformities of aboveground vegetation, soil organic matter, and net aboveground primary production for the four different forest types of the Luquillo Experimental Forest, Puerto Rico.

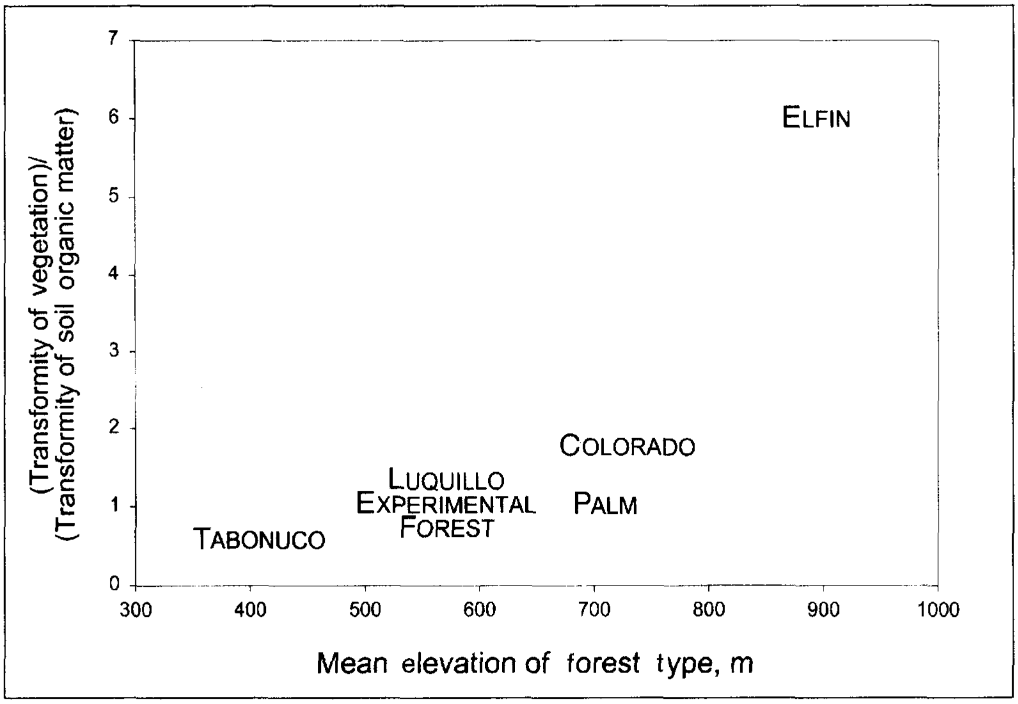

Figure 15—Ratio of the transformities of vegetation and soil organic matter versus elevation for forest types in the Luquillo Experimental Forest, Puerto Rico (see table 18).

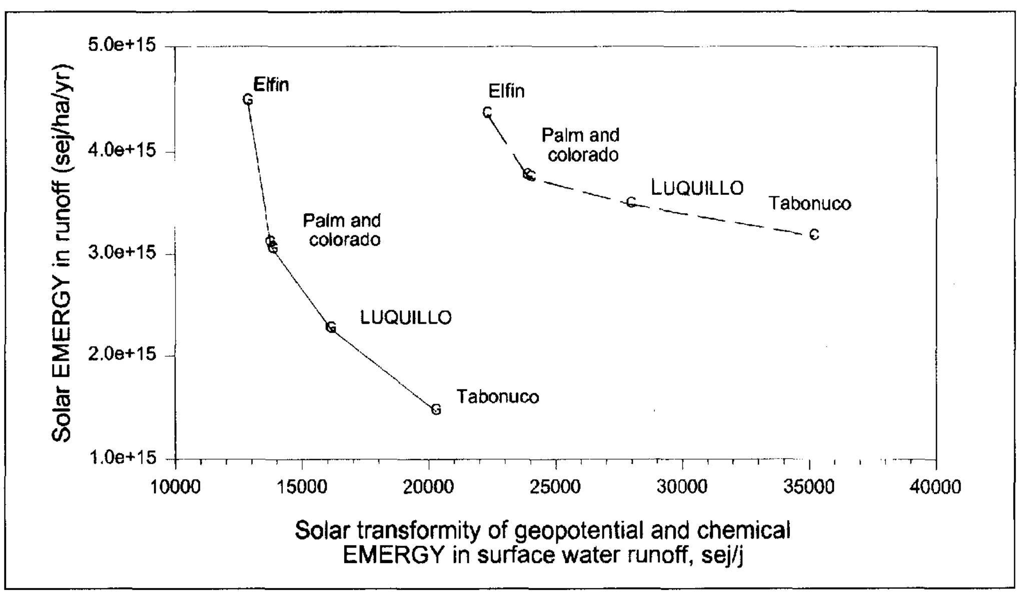

Figure 16—Solar transformity versus chemical and geopotential empower density in stream runoff for the different forest types of the Luquillo Experimental Forest, Puerto Rico.

Effects of Hurricanes

The biophysical evaluation of the Forest is based on long-term, average conditions. Nevertheless, pulses in atmospheric inputs, particularly from hurricanes and other large-scale organized atmospheric systems, are the norm rather than the exception. On average, a hurricane will pass close enough to the Forest to cause heavy rain once every 2 to 5 years (Scatena and Larsen 1991). Once every 20 years, a hurricane will extensively modify some part of the island. Once every 50 to 60 years, a hurricane will pass directly over the Forest and produce widespread defoliation and mortality.

The total EMERGY of the average hurricane that passes over Puerto Rico is estimated at 93.4E+20 sej/storm (table 19), or more than nine times the island's annual EMERGY contribution from renewable sources (table 6). The solar transformity of the hurricane-force winds acting on the Forest is similar to that of the gravitational potential of rain. When these hurricanes pass directly over the trees, the EMERGY contributed to the Forest from the kinetic energy of winds is about 2.96 E+20 sej/storm. This amount is roughly equivalent to 29 percent of Puerto Rico's annual EMERGY contributions from renewable sources and 9.8 times the annual environmental EMERGY inputs to the Forest (table 20). Because hurricanes of this magnitude pass over only once every 55 years, however, their annual contribution is 5.38E+18 sej/yr, or about 4 percent of the Forest's total annual EMERGY flow. Considering that hurricanes pass directly over some part of the island on the average of once every 20 years, the annual EMERGY contribution of hurricanes to Puerto Rico's combined ecologic-economic system is about 1.48E+19 sej/yr, roughly equal to 1 percent of the island's annual nontectonic environmental EMERGY and 0.5 percent of the total environmental contributions.

Economic Support and Storages

The societal source inputs into the Forest were divided into two groups: direct support inputs from the annual operating budgets, management activities, and consumption of fuel and electricity; and indirect inputs attracted by the Forest, including research activities and recreation (table 20).

The combined EMERGY flow in the Forest is 135E+18 sej/yr (table 20). The largest contribution is from human metabolism (59 percent), followed by environmental (22 percent), and economic (19 percent) inputs. In addition, 2.5 times the annual empower are stored in human-built structures in the Forest (table 21), including roads (58 percent of the total structures), communication facilities (25 percent), other buildings (13 percent), and water intakes (5 percent).

Research and Graduate Education

The Forest has been a major center of scientific research on tropical forests throughout this century (Wadsworth 1995). Like recreational activities, this activity is attracted to the area by the Forest's environmental production and the institutional stability and infrastructure provided by the USDA Forest Service. The Forest attracts about 2 million US$/yr in outside research and a similar amount in research sponsored by the Forest Service (table 20). The annual EMERGY flow of this activity is less than that of environmental inputs, support services, or tourism. The empower in the metabolism of researchers is also less than that of tourists or Forest Service support personnel, but it is similar to that of the entire Luquillo palm forest. The total emdollar value of this research and education is about 4.6 times the amount the institute spends on its administration.

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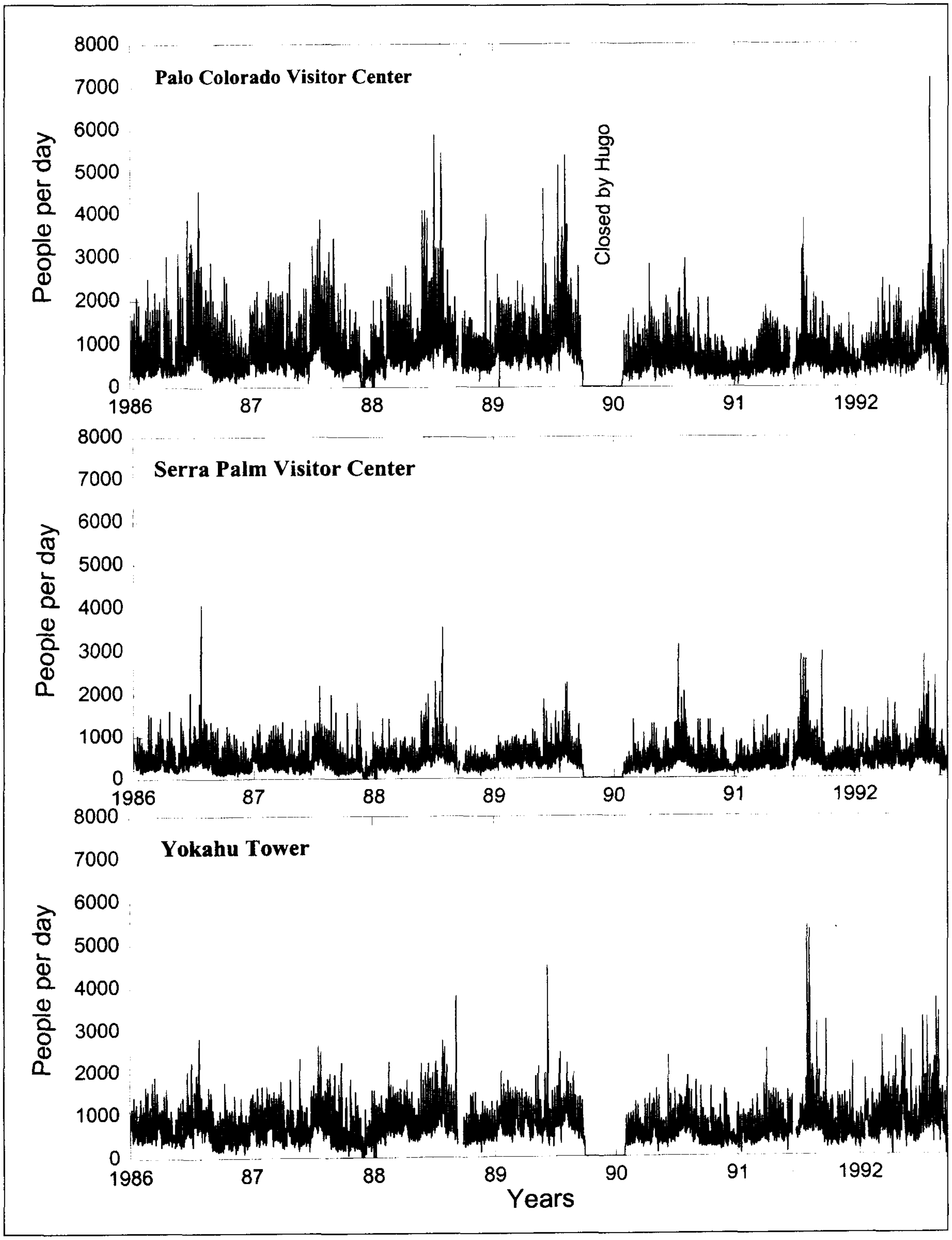

Figure 17—Daily visitor use at the major recreation areas of the Luquillo Experimental Forest, Puerto Rico, between 1986 and 1992.

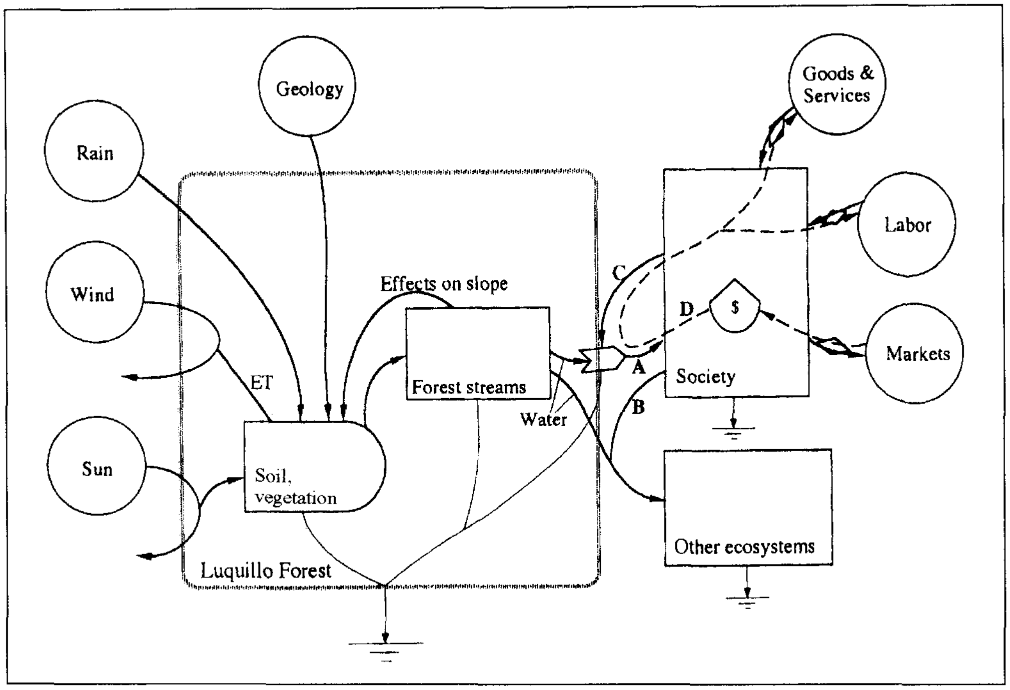

Figure 18—Water cycles and water extraction in the Luquillo Experimental Forest, Puerto Rico: (a) = extracted water, (b) = downstream effluent discharge, (c) = goods and services needed for water removal, and (d) = dollar costs (from Kharecha 1997).

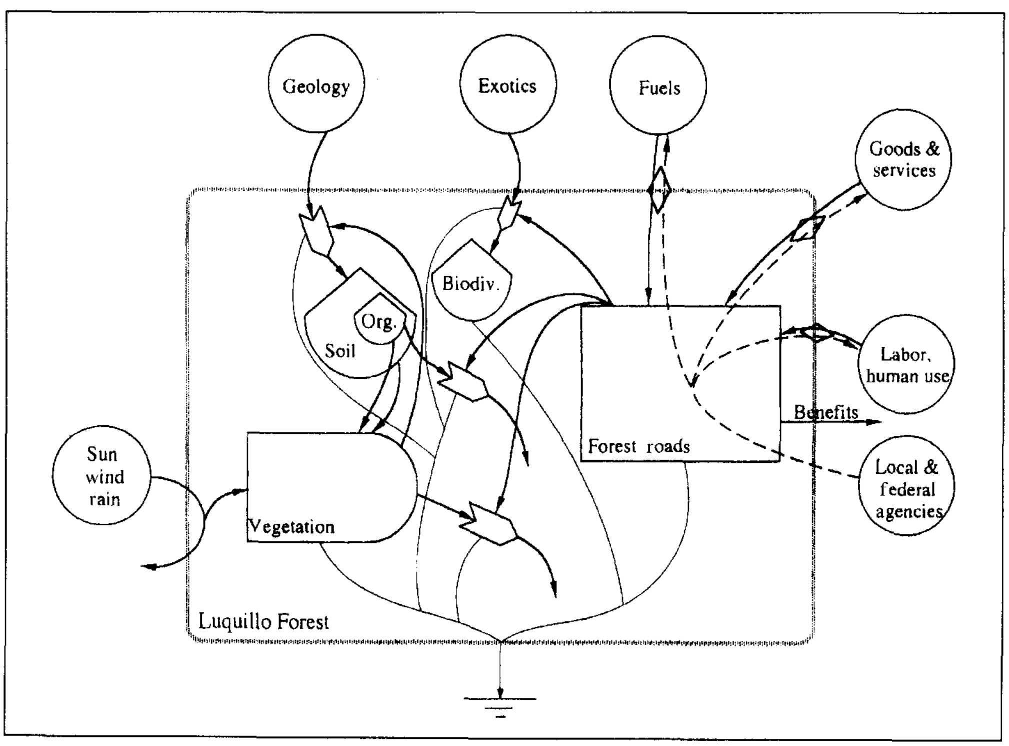

Figure 19—Forest roads in the Luquillo Experimental Forest, Puerto Rico; Org. = organic matter, Biodiv. = biodiversity (from Kharecha 1997).

Recreational Activities

About 500,000 people visit the Forest every year (fig. 17), making it one of the most highly visited per unit area in the entire National Forest system (Loudon 1989). About 600 ha of the Forest has roads, trails, or developed areas used to support recreational activities (CNF 1992). Therefore, nearly 19 ha of undeveloped areas support 1 ha of developed recreation. Of all the recreation facilities, the El Portal Visitor Center is the largest. This facility, opened in 1996, stores 1.7 more EMERGY than all of the other nonroad management or research facilities combined (table 21; Kharecha 1997).

The energy of metabolism spent while visitors are in the Forest is the largest EMERGY input associated with recreation (table 20). A benefit-to-cost ratio of recreation for visitors, calculated as the quotient of the EMERGY they expended while visiting the Forest related to the amount of EMERGY used in getting there, is 9.5 for Puerto Ricans and 3.8 for nonresidents. Likewise, the ratio of the total EMERGY flow of tourists is 1.6 times the EMERGY flows society provides to manage and understand the Forest. Both of these ratios indicate that tourism in the Forest is an attractive investment. Nevertheless, only 12 percent of the visitors are currently using the recently opened Visitor Center, and the total tourist dollar flow in the Forest is currently more than eight times the dollar flow of El Portal. This finding suggests that the recently opened center has ample opportunity to develop reinforcing actions and programs that attract visitors before it is limited by its size or existing resource base.

Water Resources

Rain that falls on the Forest travels through vegetation and soil and then leaves the area as evapotranspiration or surface runoff (fig. 19). The runoff sculptures the landscape as it moves down slope and eventually reaches downstream ecosystems or is removed for human use. About 24 percent of the streamflow from the Forest is extracted for municipal use before it reaches the coastal zone (Naumann 1994). The market value of this water, based on average U.S. consumer prices for domestic water of 0.13 cents/gal (Nieswiadomy 1992), is 24.2E+6 dollars per year. This consumer value only includes the direct costs of treatment and distribution and does not consider the environmental value of the water or the effects associated with extracting or using it.

At current costs, about 8.6E+6 US$ would be needed to build all the water-intake systems in the Forest and 220,500 US$/yr to operate them (table 22). Because these water systems are gravity-driven, their annual EMERGY inputs do not include fuel costs and are only 46.8E+16 sej/yr. Although they require low societal inputs to operate, they can generate considerable effects. The major effects of extracting water from the Forest are those associated with actually removing it from the streams and the downstream release of treated sewage effluent (Kharecha 1997). The EMERGY in the water removed (1190E+16 sej/yr, table 22) represents the annual EMERGY displaced from the stream ecosystems. Because water is the primary driving force in these systems, this EMERGY value encompasses the EMERGY in habitat and biotic losses and other indirect effects of water removal. Relative to the total EMERGY of chemical and physical streamflow of the Forest (table 17), the amount of water removed accounts for 30 percent of the chemical and 47 percent of the physical. The additional EMERGY impacts associated with the downstream release of treated sewage are almost nine times those associated with the effects of removal (table 22).

Because the gravity-driven intakes require relatively small inputs to operate annually, the EMERGY benefits of extraction are 25 times the EMERGY inputs when the effects are not considered (table 22). Thus, those who extract water from the Forest benefit greatly, but when the effects of extraction are also considered, the EMERGY effects are about 250 times the EMERGY of inputs. Furthermore, the effects of the EMERGY-to-dollar ratio for water extraction is the highest of any activity in the Forest. Most of this effect results from water pollution by treated sewage discharge, which imparts high stress to the naturally oligotrophic aquatic systems.

Roads

Both local and federal agencies provide financial support to build and maintain the roads in the Forest (table 23). These roads provide access for tourism, research, management, and communication. They also diminish slope stability and increase landslides, cause permanent loss of vegetation, and sometimes introduce exotic species. Because roads become part of the whole Forest structure, the effects of roads were calculated on both storage and annual bases (Kharecha 1997). The natural storage lost or displaced by roads includes the vegetation and soil organic matter removed during building and displaced by subsequent landslides. The EMERGY of road inputs includes both one-time building costs and yearly maintenance.

The 49 km of Forest roads occupy an area of about 49 ha (table 23). At current costs, building these roads would take more than 68 million dollars. The largest adverse effect associated with these roads is the loss of forest displaced by building them. The transformity of road effects (3.28 E5 sej/J) is 2.6 times that for water extractions (1.23E5 sej/J), but the effects of the EMERGY-to-money ratio is less. In addition, the annual inputs associated with roads is about eight times the annual inputs associated with water extraction, and the EMERGY of the annual effects of roads is nearly equal to the annual input EMERGY (table 24).

Synthesis

Luquillo Experimental Forest

About 22 percent of the total annual EMERGY flow in the Forest is environmental (table 20). Together, chemical potential EMERGY in annual rainfall (29 percent), tectonic inputs (12 percent), and hurricanes (4 percent) accounts for 47 percent of the total. When these rainfall inputs combine with the steep slopes developed from the tectonic inputs, the result is an erosional landscape where the EMERGY of biological processes is less than the EMERGY associated with the physical and chemical sculpturing of the landscape (table 17).

With decreasing elevation, this erosional landscape undergoes a systematic shift from physically to biologically dominated EMERGY flows. The upper elevation elfin and colorado forests are distinguished from the palm and tabonuco forests in that their transformities for soil organic matter are less than their transformities for vegetation (fig. 15). These differences indicate that the lower elevations are relatively efficient at accumulating biomass, and the upper forests are relatively efficient at

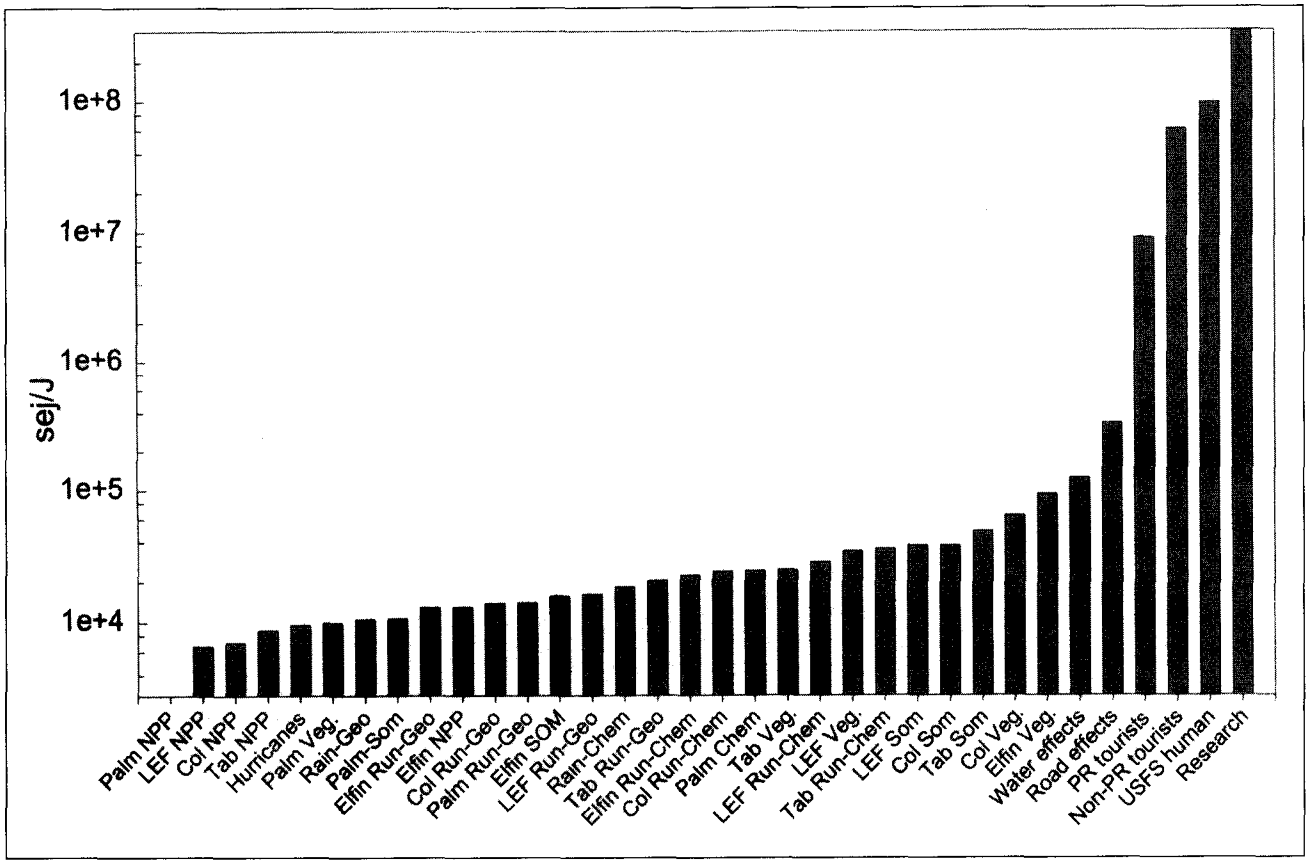

Figure 20—Solar transformities for the Luquillo Experimental Forest, Puerto Rico (for explanations of abbreviations, see tables 2, 14, and 15).

accumulating soil organic matter. Because the lower Forest is accumulating vegetation while the upper Forest is accumulating soil organic matter, the Forest-wide transformities of vegetation and soil organic matter are similar, and both components have similar positions in the Luquillo EMERGY hierarchy (fig. 20). Vegetation in the elfin and colorado forest types and soil organic matter in the tabonuco forest are among the highest quality indigenous components of the ecosystem. Therefore, removing these components should be minimized whenever possible.

About 59 percent of the total annual EMERGY flows in the Forest are from human metabolism. Forest Service employees account for 13 percent of the total, and the total EMERGY flows associated with tourism account for the largest annual EMERGY flow in the Forest (table 20). These relatively high positions of human activity in the Forest's EMERGY hierarchy reflect the high value society places on it. Nevertheless, current market values greatly underestimate the value of the Forest landscape to the local ecological-economic system. Recent property assessments of secondary, tabonuco-type forested land adjacent to the Forest indicate these areas have a market value between 2,255$/ha and 3,540$/ha (CNF 1993, unpublished data). At Puerto Rico's solar EMERGY-to-dollar ratio (1.64E+12 sej/$, table 6), this land has an average EMERGY value of 4.8E+15 sej/ha. In contrast, when the EMERGY of stored vegetation in the tabonuco forest is considered, these lands have a value 42E+15 sej/ha (table 15). When the total EMERGY inputs that have gone into a hectare of mature tabonuco forest are considered, these lands have an embodied value of 239E+15 sej/ha (table 18). Therefore, the previous environmental work that built the natural capital of these forests is 9 to 50 times their current market values.

The current price paid by consumers to use municipal water supplied by the Luquillo Mountains also underestimates the value of this water and the cost of its development to the local ecological-economic system. Recently, consumers paid about 24 million US$ per year for the water supplied by the Luquillo Mountains (Naumann 1994). The total EMERGY effect associated with this removed water is 73.1 emdollars per year (table 22). Thus, the effects of this water to the local ecological-economic system are about three times the direct cost to consumers. The value of the water is also underestimated when the public's willingness to pay to maintain the ecological integrity of Luquillo rivers for recreation is included. Moreover, a recent contingent-valuation, in-person survey of Puerto Rican households estimated that island residents were willing to pay 13 to 33 million dollars per year to maintain the ecological integrity of two of the principal rivers draining the Forest (Gonzalez-Caban and Loomis 1997). Combining these values with the amount consumers are already paying for water would raise the direct costs to consumers 37 to 57 million US$ per year. At these rates, the effects of current water use to the local ecological-economic system would be 2 to 1.3 times the direct cost to consumers.

Because these market values of land do not include contributions from environmental resources and the price of water to consumers does not include the costs of environmental effects, these values greatly underestimate the value of the Luquillo landscape to the ecological-economic system of Puerto Rico. These underestimated values and the large disparities between investment ratios for Puerto Rico and the Forest (table 24) will continue to attract societal pressures to invest in and around it. Of the investments evaluated in this study, the total and marginal effects of extracting water are the largest. Moreover, the EMERGY effect of extracting water per dollar input is almost 300 times that of building roads (table 24). These differences reflect the cumulative effects that water development can have and indicate the need to manage this resource wisely. Fortunately, using both natural and artificial wetlands for sewage treatment (Kent 1996, Kent et al. 2000) and reducing artificial channels and other structures that promote runoff at the expense of recycling can be used to maintain this resource.

Puerto Rico

Physically surrounding and highly integrated with the Forest is the industrial landscape of Puerto Rico. The hydrologic cycle and subtropical-moist-forest life-zones provide most of the island's renewable environmental EMERGY input. These life zones also supply most of the municipal water supplies and contain the largest reserve of renewable fossils fuels (that is, aboveground biomass). Given their importance, sustainably managing these areas is essential to the ecological-economic system of the island.

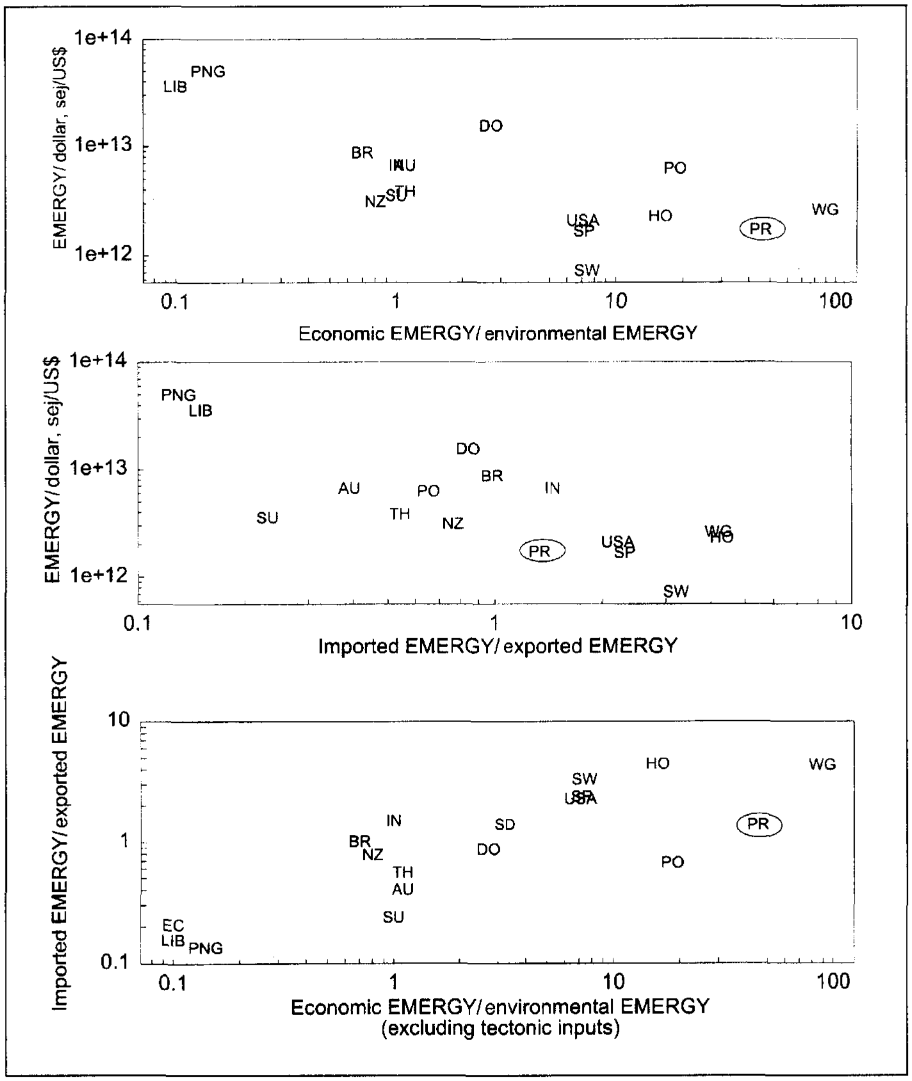

Figure 21—Relations between the ratios of imported and exported solar EMERGY and the solar EMERGY use: Dollar ratio and economic:environment ratio for various regions of the globe (from tables 8, 9, and 12); letters are initials of countries listed in the tables.

Human inputs into Puerto Rico's combined ecological-economic system are more than 460 times the environmental inputs (table 24). This human activity uses machinery and other goods with moderate transformities to change chemicals and other low-transformity commodities into high-transformity goods like pharmaceuticals for export (fig. 12). Because most economic and human production are supported by imported fuels and goods, the island has one of the least self-sufficient economies known (fig. 21, table 9). Recent trends suggest that the island is becoming less self-sufficient. Although total EMERGY use per capita and fuel use per capita have increased in the past decade, EMERGY use per gross economic product and environmental EMERGY use per gross economic product have decreased (table 6). Import-to-export ratios for both EMERGY and dollars also have decreased, and the EMERGY of human services embodied in exports has been decreasing as the island's manufacturing industries become less labor extensive and more capital and technology based.

Because of the island's dependence on imported EMERGY, the availability of imported commodities and the climate of international trade are important considerations for the future. Until recently, the most developed regions of the world, including the United States, had lower em-to-money ratios than Puerto Rico. Therefore, they benefited from trade with the island because their dollars could purchase more EMERGY in Puerto Rico than in their own regions. Puerto Rico now has one of the lowest em-to-dollar ratios known, and few regions of the globe benefit from trading with the island (table 12, fig. 22). Unfortunately, this position is unstable, and noncompetitive for an economy highly dependent on both imports and exports.

The island's competitiveness and economic stability can be improved by increasing its em-to-dollar ratio, thereby expanding the regions of the globe that benefit from purchasing Puerto Rican products. This improvement can be obtained by promoting activities that decrease the island's economic-to-environment ratio and the ratio of imported EMERGY to exported EMERGY. These changes can be achieved by reducing waste and inefficient energy use and by reducing the importation of products that can be produced locally. In addition, increasing the quality of exports by increasing the quality of human EMERGY embodied in those exports also will decrease the ratio of import EMERGY to export EMERGY and increase the island's competitiveness in global markets. In contrast, policies like tourism or other activities that increase the amount of dollars available for the same environmental EMERGY inputs should be avoided. Because these activities decrease the island's em-to-dollar ratio, they also decrease the island's competitiveness in global markets.

The island's lack of self-sufficiency, relatively high em-to-money ratio, and its moderate rank in per capita EMERGY use may reflect its historical development, temporary disequilibriums in the ecological-economic system created by the rapid industrialization in the past few decades, or both. Regardless of their origins, the trend to higher empower density, lower environmental share per person, less self-sufficiency, and lower em-to-money ratios is typical for areas becoming more and more urban. Like these areas, Puerto Rico is becoming a hierarchical center of a much larger area of environmental and economic support in the Caribbean and elsewhere. Like these other centers of population, commerce, and information, Puerto Rico's future well-being depends on the availability of inexpensive high-EMERGY fuel and on developing policies that allow reinforcing interactions to develop. We hope that this report, and the techniques it is based on, will be helpful in making those complex public policy decisions.

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Appendix 1: Tables

Table 1—Definitions and indices of system concepts used in this study[a]

Item	Definition	Units
EMERGY	Available energy of one type required directly and indirectly to produce a product or process	Emjoules
Solar EMERGY	Solar energy required directly and indirectly to produce a product or process	Solar emjoules (sej)
Transformity	EMERGY used per unit of available energy produced	Emjoule/joule
Solar transformity	Solar EMERGY used per unit of energy available	Sej/J
Em$; macroeconomic value	Proportion of the annual total EMERGY used in Puerto Rico multiplied by its gross economic product in 1992	Em$, 1992
Net yield ratio	EMERGY yield from a production sector (Y) divided by the emergy contributed from the economy (F)	Y/F (dimensionless)
Investment ratio	EMERGY purchased from the economy (F) divided by the EMERGY delivered from environmental sources (I)	F/I (dimensionless)
Attracted investment ratio	Resources (A) brought in (attracted) to a region as a result of a productive yield (Y) divided by investments from the economy (F)	A/F (dimensionless)
Exchange ratio	EMERGY received through transaction divided by the EMERGY measures as the buying power of the money paid	EMERGY sold/received (dimensionless)
EMERGY per unit money	Annual EMERGY use divided by the gross economic product for Puerto Rico in 1992	Sej/$, 1992

[a] Adapted from Odum (1996).

Table 2—Solar transformities, EMERGY per unit mass, and EMERGY per money measures used in this study to convert resources into common units of solar EMERGY (adapted from Odum 1996)

Solar EMERGY per unit of available energy:		
Insolation	1	sej/J[b]
Wind energy	1,500	sej/J[b]
Temperate forest NPP	4,530	sej/J[c]
Subtropical forest NPP	7,910	sej/J[d]
Rain, gravitational potential	10,500	sej/J[b]
Tidal energy	16,850	sej/J[b]
Rain, chemical potential	18,200	sej/J[b]
Stream, physical potential	27,800	sej/J[b]
Wave energy	29,000	sej/J[b]
Coal	30,550	sej/J[b,e(1)]
Wood products	32,400	sej/J[c]
Natural gas	34,800	sej/J[e(2)]
Crude petroleum	40,200	sej/J[e(3)]
Refined fuels	66,000	sej/J[e(4)]
Grains, cereals	68,000	sej/J[b]
Vegetables, fruits, coffee	72,000	sej/J[b,f]
Sugar, chocolate	85,000	sej/J[b,f]
Rubber, plastics	100,000	sej/J[g]
Paper products	120,325	sej/J[c]
Electricity	200,000	sej/J[e(5)]
Livestock, chickens	180,000	sej/J[b]
Synthetic chemicals	600,000	sej/J[h]
Cigarettes	650,000	sej/J[i]
Juices, alcohol	700,000	sej/J[j]
Meat, dairy products	1,300,000	sej/J[b,k]
Fertilizers	2,000,000	sej/J[l]
Human services, Puerto Rico	4,810,000	sej/J[m(1)]
Human services, United States	8,900,000	sej/J[m(2)]
Solar EMERGY per unit mass:		
Coal		
Granite rock	5.00E+8	sej/g[b]
Sand, gravel	8.00E+8	sej/g[b]
Metal ores	1.00E+9	sej/g[b]
Cement, glass	1.40E+9	sej/g[n]
Steel	1.40E+9	sej/g[b]
Paper products	2.50E+9	sej/g[c]
Rubber	4.30E+9	sej/g[b]
Machines, transport equipment	6.70E+9	sej/g[b]
Textiles	1.25E+10	sej/g[o]
Fertilizers	1.40E+10	sej/g[b]
Aluminum	1.60E+10	sej/g[b]
Copper alloy	2.00E+10	sej/g[b]
Pharmaceuticals	2.50E+10	sej/g[p]

Table 2—Solar transformities, EMERGY per unit mass, and EMERGY per money measures used in this study to convert resources into common units of solar EMERGY (adapted from Odum 1996) (continued)

Solar EMERGY in US$:		
Puerto Rico, 1992	1.64E+12	sej/US$[a]
United States, 1992	1.60E+12	sej/US$[r]

[a] Odum 1993.
[b] Doherty et al. 1993.
[c] Solar transformity for aboveground net primary production for the Forest, based on NPP and the area of the four forest types (see table 14).
[d] Fuel transformities based on calculations made by Odum (1993) as follows:
[d] (1)29,000 sej/J for sedimentary coal and 50,000 sej/J for coal relative to electric power (4:1).
[d] (2)Natural gas 20 percent more efficient in boilers than coal (Cook 1976); (1.2) (29,000 sej/J) = 34,800 sej/J.
[d] (3)19 percent crude petroleum used in refinement and transport (Cook 1976); (47,850 sej/J) / (1.19) =40,200 sej/J.
[d] (4)1.65 coal J/J refined fuels; (1.65)(29,000 sej/J) = 47,850 sej/J.
[d] (5)2.6 fuel J/J electricity (SPA 1981); (2.6)(47,850 sej/J) = 125,000 sej/J.
[e] Odum et al. 1987.
[f] (2.23E+8 lbs rubber, plastics imported, 1987)(454 g/lb)(4.3E+9 sej/g; Odum et al. 1987) = 4.4E+19 sej/yr; (4.4E+19 sej)/(4.2E+14 J; table 4, item 38) = 1E+5 sej/J.
[g] Estimated from import statistics (appendix 2) and EMERGY/GP index for Puerto Rico in 1992: (1.27E+9 $ imports)(1.6E+12 sej/US$)/(3.36E+15 J imported; table 4, item 35) = 605,000 sej/J.
[h] Estimate: (5.27E+7 $ import costs; appendix 2)(1.6 E+12 sej/US$)/(1.30E+14 J; table 4, item 30) = 648,000 sej/J.
[i] Estimate: (2.41E+8 $ import costs; appendix 2)(1.6E+12 sej/US$)/(5.47E+14 J; table 4, item 29) = 7E+5 sej/J.
[j] Estimate: (4.31E+8 $ import costs; appendix 2) (1.6E+12 sej/US$)/(6.22E+14 J; table 4, item 23) = 1.3E+6 sej/J.
[k] Estimate: based on EMERGY per unit mass of 1.4E+10 sej/g (8.94E+9 g/yr imported)/(3.7E+13 J/yr; table 4, item 37) = 3E+6 sej/J; we used 2/3 of the value to compare with other petroleum-based commodities.
[l] (l)Table 19, item 16.
[l] (2)Table 19, item 17.
[m] Brown and McClanahan 1992.
[n] Estimate: based on import statistics (appendix 2) and solar EMERGY flow calculated in table 4, item 34: (1.17E+21 sej/yr)/[(2.06E+8 lbs textiles imported,1987)(454 g/lb)] = 1.25E+10 sej/g.
[o] (7.74E+20 sej/yr; table 4 item 36)/[(6.92E+7 lbs pharmaceuticals imported, 1987)(454 g/lb)] = 2.47E+10 sej/g.
[p] Table 6, item 33.
[q] Odum 1996.

Table 3—Evaluation of environmental sources, use of indigenous reserves, and local production sectors in Puerto Rico, 1987

	Annual		Solar transformity	Solar EMERGY E18 (sej/yr)	Emdollars E6 (em$)
Environmental contributions:					
Insolation[a]	5.89E+19	J	1	58.9	28.08
Wind, kinetic energy[b]	4.18E+15	J	1,500	6.26	2.99
Rain, geopotential[c]	5.46E+16	J	10,500	574	273.67
Rain, chemical potential[d]	5.50E+16	J	18,200	1000	477.26
Subtropical dry forest	5.80E+15	J	18,200	106	50.38
Subtropical moist forest	3.48E+16	J	18,200	634	302.23
Subtropical wet forest	1.34E+16	J	18,200	243	116.10
Subtropical rain forest	8.21E+13	J	18,200	1.49	0.71
Lower montane wet forest	6.14E+14	J	18,200	11.2	5.33
Lower montane rain forest	5.67E+13	J	18,200	1.03	0.49
Coastal shelf	2.30E+14	J	18,200	4.19	2.00
Wave energy[e]	3.18E+16	J	16,850	536	255.77
Tidal energy[f]	6.16E+14	J	30,550		18.8
Tectonic[g]	1.30E+12	g	1.0E+09	1300	620
Mining of nonrenewable storages:					
Sand, gravel[h]	4.07E+11	g	1.00E+09	407	194.08
Metal ores[i]	3.00E+8	g	1.00E+09	0.30	0.14
Major production sectors:					
Agriculture[j]	4.57E+15	J	68,000	311	148.28
Livestock, dairy[k]	9.92E+14	J	2.00E+6	1980	946.46
Forestry[l]	3.79E+14	J	3.24E+4	12.3	5.86
Fisheries[m]	6.31E+12	J	3.50E+6	22.1	10.53
Cement[n]	1.30E+12	g	8.40E+8	1100	522.80
Textiles[o]	6.55E+8	$	2.10E+12	1370	655.34
Pharmaceuticals[p]	3.38E+9	$	2.10E+12	7090	3381.53
Electricity production[q]	3.97E+16	J	1.25E+5	4960	2368.05

Note: The area of Puerto Rico is 8897 km^2; mainland + islands + lagoons (Pico 1974); the gross domestic product (JdP 1989, 1992) was 2.52E+10 US$ in 1987, 3.98E+10 US$ in1992; and the population (GDB 1997) was 3.29E+6 persons in 1987, 3.56E+6 persons in 1992, and 3.7E+6 persons in 1997.

Table 3—Evaluation of environmental sources, use of indigenous reserves, and local production sectors in Puerto Rico, 1987 (continued)

Environmental contributions:

[a] Daily solar insolation. 18.1 MJ/m^2 per day (Lopez and Soderstrom 1983):

Over land (18.1 E+6 J/m^2 per day)(1-0.20 albedo)(365 d/yr)(8897 km^2)(1E+6 m^2/km = 4.70E+19 J/yr.

Over the continental shelf (18.1E+6 J/m^2 per day)(365 d/yr)(1.792 E+9 m^2) = 1.18E+19 J/yr

Total solar insolation = 5.89E+19 J/yr.

[b] Kinetic wind energy. 2.9E+9 kWh/yr (Gabel et al. 1979)(3.6E+6 J/kWh)(0.4) = 4.18E+15 J/yr, assuming that 40 percent of surface wind energy is used by land systems.

[c] Gravitational potential energy of rainfall (Pico 1974).

Mountains (40 percent land area), (3.56E+9 m^2)(3 m/yr, avg. rain)(650 m, avg. elevation) (70 percent runoff)(1000 kg/m^3 H_2O)(9.8 m/s^2 gravity) = 4.76E+16 J/yr.

Hills (35 percent), (3.11E+9 m^2)(1.8 m/yr)(225 m, avg. elev.)(50 percent runoff)(1000 kg/m3)(9.8 m/s^2) = 6.18E+15 J/yr.

Plains (25 percent), (2.22E+9 m^2)(1.3 m/yr)(75 m, avg. elev.)(40 percent runoff)(1000 kg/m^3)(9.8 m/s^2) = 8.50E+14 J/yr.

Total geopotential energy in rainfall = 5.46E+16 J/yr.

[d] Chemical potential energy in rainfall (Ewel and Whitmore 1973).

Subtropical dry forest (901 mm/yr rain): 1398.3 km^2)(840 mm/yr ET)(1000 kg/m^3 H_2O)(4940 J/kg, Gibbs free energy) = 5.80E+15 J/yr.

Subtropical moist forest (1550 mm/yr rain): (5370.9 km^2)(1312 mm/yr ET)(1000 kg/m^3)(4940 J/kg) = 3.48E+16 J/yr.

Subtropical wet forest (2460 mm/yr rain): (2124.8 km^2)(1274 mm/yr ET)(1000 kg/m^3) 4940 J/kg) = 1.34E+16 J/yr.

Subtropical rain forest (4660 mm/yr rain): (13.2 km^2)(1259 mm/yr ET)(1000 kg/m^3)(4940 J/kg) = 8.21E+13 J/yr.

Subtropical lower montane wet forest (2863 mm/yr rain): (109.1 km^2)(1140 mm/yr ET) = 6.14E+14 J/yr.

Subtropical lower montane rain forest (4533 mm/yr rain): (12.3 km^2)(933 mm/yr ET)(1000 kg/m^3)(4940 J/kg) = 5.67E+13 J/yr.

Chemical potential energy over continental shelf: (60 in/yr, average)(0.0254 m/in)(1792km^2)(1025 kg/m^3, salt-water density)(4940 J/kg) = 2.31E+14 J/yr.

Total chemical potential energy from evapotranspired rain = 5.50E+16 J/yr.

[e] Wave energy received at shore: (5.39E+5 m shoreline)(0.6 m, avg. wave height)(1025 kg/m^3)(0.125; fraction of energy received at shore)(1.75 m, mean shoaling depth) (4.14 m/s, wave velocity)(3.15E+7 s/yr) = 3.18E+16 J/yr.

[f] Tidal energy: (0.3 m, mean amplitude; NOAA)(1790 km^2, shelf area)(760 tides/yr)(1025 kg/m^3)0.5; fraction received) = 6.16E+14 J/yr.

[g] Tectonic inputs: Average Quaternary uplift of island 0.055 mm/yr (Taggart 1992)(area of island, 8892 km^2)(density of rock, 2.65 g/cm^3) = g/yr of new land added by tectonic processes.

[h] Sand and rock mining: (30,598,000 bags of cement produced annually)(94 lbs/bag)(30 percent sand mix) = 8.63E+8 lbs + 3.40E+7 lbs. gravel, lime, granite, other exported minerals = 8.97E+8 lbs/yr (453.6 g/lb) = 4.07E+11 g/yr.

[i] Metal ores mined: (661,782 lbs exported, 1987)(453.6 g/lb) = 3.0E+8 g/yr.

[j] Agricultural production: (2.73E+5 tons; Caribbean. Stats, EIU 1984)(1E+6g/t)(4 kcal/g)(4186 J/kcal) = 4.57E+15 J/yr.

[k] Livestock, dairy production: (3.59E+8 kg; JdP 1989)(1000 g/kg)(12560 J/g)(22 percent protein) = 9.92E+14 J/yr.

[l] Forestry: considered volume of all exported wood volume for 1987 (see appendix 2 and item 59, table 5); 40.7E+6 lbs (453.60 g/lb)(20520 J/g) = 3.79E+14 J/yr.

[m] Fisheries: (1256 tons; JdP 1989)(1E+6 g/t)(5020 J/g) = 6.31E+12 J/yr.

[n] Cement production: (30,598,000 bags)(94 lbs/bag)(453.6 g/lb) = 1.30E+12 g/yr.

[o] Textiles estimated by using income earnings; 6.55E+8 US$, 1987.

[p] Pharmaceuticals estimated by using income earnings; 3.38E+9 US$, 1987.

[q] Electric energy: (1.10E+10 kWh, 1987) (3.60E+6 J/kWh) = 3.97E+16 J/yr.

Table 4—Evaluation of imports by commodity groups and by related human services, loans, and tourism for Puerto Rico, 1987

Imports	Annual contributions (J, g,$)	Solar transformity (sej/J)	Solar EMERGY E18(sej/yr)	Emdollar value (millionem$)
Crude petroleum[a]	1.81E+17 J	40,200	7280	3473.49
Refined fuels, oils[b]	2.00E+17 J	47,900	9570	4567.52
Natural gas, propane[c]	4.71E+15 J	34,800	164	78.21
Coal[d]	7.36E+15 J	29,000	214	101.86
Livestock, chickens[e]	1.83E+13 J	2.00E+5	3.66	1.75
Meat[f]	6.22E+14 J	1.30E+6	809	386.01
Fish[g]	2.53E+14 J	1.30E+5	32.9	15.69
Dairy[h]	6.06E+13 J	1.30E+6	78.8	37.61
Grain, cereals[i]	1.14E+16 J	68,000	776	370.22
Vegetables, fruits, coffee[j]	5.36E+15 J	68,000	365	173.93
Sugar, chocolate, derivatives[k]	3.14E+15 J	85,000	267	127.52
Juices, alcohol, soda[l]	6.35E+14 J	7.00E+5	444	211.97
Tobacco, cigarettes[m]	1.30E+14 J	6.50E+5	84.6	40.37
Other agriculture[n]	4.33E+15 J	68,000	294	140.36
Wood products[o]	7.46E+15 J	32,400	242	115.27
Paper products[p]	3.46E+11 g	2.50E+9	866	413.07
Textiles[q]	5.87E+8 $	2.00E+12	1170	560.26
Chemicals, synthetics[r]	3.36E+15 J	6.00E+5	2020	962.13
Pharmaceuticals[s]	3.87E+8 $	2.00E+12	774	369.40
Fertilizers, industrial chemicals[t]	3.74E+13 J	2.00E+6	74.8	35.70
Rubber, plastic products[u]	4.24E+14 J	9.08E+4	38.5	18.36
Mineral prod. (cement, glass)[v]	2.19E+11 g	1.40E+9	306	146.15
Metal ores[w]	5.54E+6 g	1.00E+9	0.006	0.0026
Metals, alloys, products[x]	4.42E+11 g	1.40E+9	619	295.13
Machines, electronics, transport[y]	4.64E+11 g	1.80E+9	836	398.84
Other, nonspecific goods[z]	9.87E+8 $	2.00E+12	1970	941.6
Human services in imports[aa]	1.07E+10 $	2.00E+12	21400	10231.57
U.S. loans[bb]	1.35E+9 $	2.00E+12	2700	1288.03
Tourism[cc]	9.55E+8 $	2.00E+12	1910	911.16

Table 4—Evaluation of imports by commodity groups and by related human services, loans, and tourism for Puerto Rico, 1987 (continued)

Imports (JdP 1989): See additional footnotes in appendix 2.

[a] Crude petroleum: (2.96E+7 bbl/yr)(5.80E+6 Btu/bbl)(1,055 J/Btu) = 1.81E+17 J/yr.
[b] Refined petroleum products:
Gasoline: (5,702,752 bbl unleaded gas + 64,810 bbl motor fuel + 14,761,000 bbl naphtha) = 2.05E+7 bbl/yr (5.25E+6 Btu/bbl)(1,055 J/Btu) = 1.138E+17 J/yr.
Diesel, jet fuel (kerosene): 1,433,638 bbl jet fuel + 91,354 bbl diesel = 1.52E+6 bbl/yr (5.36E+6 Btu/bbl)(1,055 J/Btu) = 8.62E+15 J/yr.
Oils: (1.31E+7 bbl/yr)(5.59E+6 Btu/bbl)(1,055 J/Btu) = 7.75E+16 J/yr.
Total refined petroleum: 2.00E+17 J/yr.
[c] Ethane, propane, butane: (1.15E+6 bbl/yr)(3.84E+6 Btu/bbl)(1,055 J/Btu) = 4.67E+15 J/yr.
Natural gas: (42,131 mcf/yr)(1035000 Btu/mcf)(1,055 J/Btu) = 4.6E+13 J/yr.
[d] Coal, peat: (266,496 tons)(6.60E+6 kcal/t)(4,186 J/kcal) = 7.36E+15 J/yr.
[e] Livestock, chickens: (3.22E+6 lbs/yr)(453.60 g/lb)(12,560 J/g) = 1.83E+13 J/yr.
[f] Meats: (4.85E+8 lbs/yr)(453.60 g/lb)(12,560 J/g)(22-percent protein content) = 6.08E+14 J/yr.
Hides: (2.57E+6 lbs/yr)(453.60 g/lb)(12,560 J/g) = 1.46E+13 J/yr.
Total meat, hides = 6.22E+14 J/yr.
[g] Fish: (5.05E+8 lbs/yr)(453.60 g/lb)(5,020 J/g)(0.22) = 2.53E+14 J/yr.
[h] Dairy: (2.36E+8 lbs/yr)(453.60 g/lb)(2,570 J/g)(0.22) = 6.06E+13 J/yr.
[i] Grains, cereals: (1.15E+9 lbs/yr)(453.60 g/lb)(20,520 J/g) = 1.07E+16 J/yr + 2.23E+6 bu/yr (3.52E-2 m^3/bu)(8.72E+9 J/m^3) = 6.84E+14 J/yr.
Total grains = 1.14E+16 J/yr.
[j] Vegetables: (5.97E+8 lbs vegetables + 1.31E+8 lbs fruits, nuts + 4.31E+6 lbs coffee, tea, spices + 7.99E+5 lbs live plants = 7.33E+8 lbs/yr)(453.60 g/lb)(16,120 J/g) = 5.36E+15 J/yr.
[k] Sugar, chocolate, syrups: (5.02E+8 lbs/yr)(0.4536 kg/lb)(3,300 kcal/kg)(4,186 J/kcal) = 3.14E+15 J/yr.
[l] Juices and alcoholic beverages: (1.32E+7 gal/yr)(8.34 lbs/gal) = 1.10E+8 lbs/yr + 5.50E+8 lbs/yr = 6.60E+8 lbs/yr (453.60 g/lb)(2,120 J/g) = 6.35E+14 J/yr.
[m] Tobacco, cigarettes: (1.78E+7 lbs/yr)(453.60 g/lb)(16,120 J/g) = 1.30E+14 J/yr.
[n] Other animal and vegetable products: (1.94E+8 lbs animal, vegetable oils + 5.66E+8 lbs other) = 7.59E+8 lbs/yr (453.60 g/lb)(12,560 J/g) = 4.33E+15 J/yr.
[o] Wood products: (5.07E+8 lbs wood products + 2.44E+6 lbs cork, bamboo, rattan + 2.92E+8 lbs/yr veneer, bldg boards) = 8.01E+8 lbs/yr (453.60 g/lb)(20,520 J/g) = 7.46E+15 J/yr.
[p] Paper products: (7.33E+8 lbs paper, cardboard + 3.10E+7 lbs books, printed material) = 7.64E+8 lbs/yr (453.60 g/lb) = 3.46E+11 g/yr.
[q] Textiles: 5.87E+8 $/yr; (2.06E+8 lbs/yr)(453.60 g/lb)(16,740 J/g) = 1.56E+15 J/yr.
[r] Chemicals, synthetics: (8.30E+8 lbs benzene, cyclic org. chem. + 4.86E+8 lbs org., inorg. chemicals + 1.47E+8 lbs synthetic resins, rubber + 2.76E+8 lbs gels, preps, soaps, dyes + 3.09E+7 lbs misc. chem., acids) = 1.77E+9 lbs/yr (453.60 g/lb)(4,187 J/g; energy content of oil) = 3.36E+15 J/yr.
[s] Pharmaceuticals: 3.87E+8 $/yr; 6.92E+7 lbs/yr.
[t] Fertilizers, photo. chem: (1.97E+7 lbs/yr)(453.60 g/lb)(4,187 J/g) = 3.74E+13 J/yr.
[u] Rubber, plastic products: (2.23E+8 lbs/yr)(453.60 g/lb)(4,187 J/g) = 4.24E+14 J/yr.
[v] Nonmetal minerals, products (cement, glass, etc.): (4.82E+8 lbs/yr)(453.60 g/lb) = 2.19E+11 g/yr.
[w] Metal ores: (2,502 lbs nonspecific + 1,674 lbs zinc ore + 3,832 lbs bauxite + 4,216 lbs iron ore) = 12,224 lbs/yr (453.60 g/lb) = 5.54E+6 g/yr.
[x] Metals, alloys, products: (7.17E+8 lbs metals, alloys + 2.57E+8 lbs metal products) = 9.74E+8 lbs/yr (453.60 g/lb) = 4.42E+11 g/yr.
[y] Machinery: (1.85E+8 lbs mechanical + 2.03E+8 lbs electrical + 6.35E+8 lbs transport) = 1.02E+9 lbs/yr (453.60 g/lb) = 4.64E+11 g/yr.
[z] Other import commodities: 9.87E+8 US$, 1987.
[aa] Total human services in imports: 1.07E+10 US$, total expenditures, 1987.
[bb] Loans, U.S. aid: 1.35E+9 US$, 1987 = 1.83E+9 US$, 1992.
[cc] Tourism: 2.62E+6 visitors, 1987; 9.55E+8 US$ spent, 1987.

Table 5—Evaluation of exports by commodity groups and related human services for Puerto Rico, 1987

Exports	Annual contributions (J, g,$)	Solar transformity (sej/J)	Solar EMERGY E18(sej/yr)	Emdollar value (E+6))
Refined fuels, oils[a]	6.03E+16 J	47,900	2,890	1,378.14
Natural gas, propane[b]	1.09E+15 J	34,800	38	18.11
Livestock, chickens[c]	1.11E+13 J	2.00E+5	2	1.06
Meat[d]	2.29E+14 J	1.30E+6	297	141.89
Fish[e]	1.81E+14 J	1.30E+5	23.5	11.23
Dairy[f]	3.77E+12 J	1.30E+6	4.9	2.34
Grains, cereals[g]	6.18E+14 J	68,000	42	20.04
Vegetables, fruits, coffee[h]	1.09E+15 J	68,000	74	35.3
Sugar, chocolate, derivatives[i]	4.30E+14 J	85,000	36.5	17.43
Juices, alcohol, soda[j]	2.69E+14 J	7.00E+5	188	89.9
Tobacco, cigarettes[k]	1.56E+14 J	6.50E+5	102	48.52
Other agriculture[l]	2.35E+15 J	68,000	160	76.1
Wood products[m]	3.79E+14 J	32,400	12.3	5.85
Paper products[n]	1.04E+11 g	2.50E+9	259	123.77
Textiles[o]	6.55E+8 $	2.10E+12	1370	655.34
Chemicals, synthetics[p]	3.35E+15 J	6.00E+5	2010	958.91
Pharmaceuticals[q]	3.38E+9 $	2.10E+12	7,090	3,381.53
Fertilizers, industrial chemicals[r]	1.12E+13 J	2.00E+6	22.4	10.7
Rubber, plastic products[s]	3.90E+13 J	9.08E+4	3.5	1.69
Mineral products (cement, glass)[t]	9.63E+10 g	1.40E+9	135	64.34
Metal ores[u]	3.03E+8 g	1.00E+9	0.3	0.14
Metals, alloys, products[v]	9.47E+10 g	1.40E+9	133	63.26
Machinery[w]	1.22E+11 g	1.80E+9	219	104.35
Other, nonspecific goods[x]	1.48E+9 $	2.10E+12	3,100	1,479.53
Human services in exports[y]	1.21E+10 $	2.10E+12	25,300	12,068.22

Exports (JdP 1989): see additional footnotes in appendix 2.

[a] Refined fuels: (1,726,271 bbl unleaded gas + 847,644 bbl motor fuel + 787,656 bbl naphtha = 3.36E+6 bbl/yr (5.25E+6 Btu/bbl)(1,055 J/Btu) = 1.863E+16 J/yr

Diesel, jet fuel (kerosene): 112,281 bbl/yr (5.36E+6 Btu/bbl)(1,055 J/Btu) = 6.343E+14/yr.

Oils: (3.13E+6 bbl fuel oils + 3.83E+6 bbl other oils = 6.96E+6 bbl/yr (5.59E+6 Btu/bbl)(1,055 J/Btu) = 4.11E+16 J/yr.

Ethane, propane, butane: (2.54E+5 bbl/yr)(3.84E+6 Btu/bbl)(1,055 J/Btu) = 1.03E+15 J/yr.

[b] Natural gas: (5,6917 mcf/yr)(1,035,000 Btu/mcf)(1,055 J/Btu) = 6.22E+13 J/yr.

[c] Livestock, chickens: (1.94E+6 lbs/yr)(453.60 g/lb)(12,560 J/g) = 1.11E+13 J/yr.

[d] Meats: (5.16E+7 lbs/yr)(453.60 g/lb)(12,560 J/g)(0.22) = 6.47E+13 J/yr

Hides: (2.88E+7 lbs/yr)(453.60 g/lb)(12,560 J/g) = 1.64E+14 J/yr

Total meat, hides = 2.29E+14 J/yr.

[e] Fish: (3.61E+8 lbs/yr)(453.60 g/lb)(5,020 J/g)(0.22) = 1.81E+14 J/yr.

[f] Dairy: (1.47E+7 lbs/yr)(453.60 g/lb)(2,570 J/g)(0.22) = 3.77E+12 J/yr.

Table 5—Evaluation of exports by commodity groups and related human services for Puerto Rico, 1987 (continued)

[g] Grains, cereals: 6.20E+7 lbs/yr (453.60 g/lb)(20,520 J/g) = 5.77E+14 J/yr 1.33E+5 bu/yr (3.52E-02 m^3/bu)(8.72E+9 J/m^3) = 4.09E+13 J/yr

Total grains = 6.18E+14 J/yr.

[h] Vegetables: (91,606,102 lbs vegetables + 47,162,818 lbs fruits, nuts + 7,013,484 lbs coffee, tea, spices + 3.02E+6 lbs live plants) = 1.49E+8 lbs/yr (453.60 g/lb)(16,120 J/g) = 1.09E+15 J/yr.

[i] Sugar, chocolate, syrups: 6.86E+7 lbs/yr (0.4536 kg/lb)(3,300 kcal/kg)(4,186 J/kcal) = 4.30E+14 J/yr.

[j] Juices, alcoholic beverages: 3.36E+7 gal/yr (8.34 lbs/gal) = 2.80E+8 lbs/yr (453.60 g/lb)(2,120 J/g) = 2.69E+14 J/yr.

[k] Tobacco, cigarettes: 2.14E+7 lbs/yr (453.60 g/lb)(16,120 J/g) = 1.56E+14 J/yr.

[l] Other animal and vegetable products: (5.58E+6 lbs animal, veg. oils + 4.06E+8 lbs other) = 4.12E+8 lbs/yr (453.60 g/lb)(12,560 J/g) = 2.35E+15 J/yr.

[m] Wood products: (3.21E+7 lbs wood products + 3.29E+5 lbs cork, bamboo, rattan + 8.29E+6 lbs veneer, boards) = 4.07E+7 lbs/yr (453.60 g/lb)(20,520 J/g) = 3.79E+14 J/yr.

[n] Paper products: (2.27E+8 lbs paper, cardboard + 2.20E+6 lbs books, printed material) = 2.29E+8 lbs/yr (453.60 g/lb) = 1.04E+11 g/yr.

[o] Textiles: 6.55E+8 $/yr; 7.85E+7 lbs/yr (453.60 g/lb)(16,740 J/g) = 5.96E+14 J/yr.

[p] Chemicals, synthetics: (1.51E+9 lbs benzene, cyclic org. chemicals + 5.84E+7 lbs org., inorg. chemicals + 3.26E+7 lbs synthetic resins, rubber + 1.48E+8 lbs gels, preps, soaps, dyes + 1.72E+7 lbs misc. chem., acids) = 1.76E+9 lbs/yr (453.60 g/lb)(4,187 J/g; energy content of oil) = 3.35E+15 J/yr.

[q] Pharmaceuticals: 3.38E+9 $, 1987; 1.75E+8 lbs/yr.

[r] Fertilizers, photo. chem: 5.90E+6 lbs/yr (453.60 g/lb)(4,187 J/g) = 1.12E+13 J/yr.

[s] Rubber, plastic products: 2.06E+7 lbs/yr (453.60 g/lb) (4,187 J/g) = 3.90E+13 J/yr.

[t] Nonmetal minerals, products (cement, glass): 2.12E+8 lbs/yr (453.60 g/lb) = 9.63E+10 g/yr.

[u] Metal ores: 668,399 lbs/yr nonspecific (453.60 g/lb) = 3.03E+8 g/yr.

[v] Metals, alloys, products: (1.68E+8 lbs metals, alloys + 4.11E+7 lbs metal products) = 2.09E+8 lbs/yr (453.60 g/lb) = 9.47E+10 g/yr.

[w] Machinery: (7.64E+7 lbs mechanical + 1.10E+8 lbs electrical + 8.17E+7 lbs transport) = 2.68E+8 lbs/yr (453.60 g/lb) = 1.22E+11 g/yr.

[x] Other export commodities: 1.48E+9 US$, 1987.

[y] Total human services in exports: 1.21E+10 US$, total export revenues, 1987.

Table 6—summary statistics and indices for Puerto Rico, 1987 and 1992

Item, index	1987	1992	Units	Change (%)
Environmental contribution (nontectonic)[a]	1.43E+21	1.41E+21	sej/yr	-1
Environmental contribution (with tectonics)	2.73E+21	2.71E+21	sej/yr	-1
Renewable sources[b]	1.02E+21	1.02E+21	sej/yr	0
Mineral and metals[c]	4.07E+20	3.95E+20	sej/yr	-3
Economic contribution:[d]	5.14E+22	6.41E+22	sej/yr	25
Imported goods and fuels[e]	2.93E+22	3.87E+22	sej/yr	32
Services supporting imports[f]	1.75E+22	1.99E+22	sej/yr	13
U.S. loans[g]	2.70E+21	2.93E+21	sej/yr	8
Tourism[h]	1.91E+21	2.56E+21	sej/yr	34
Exports[i]	1.82E+22	3.17E+22	sej/yr	74
Services supporting exports[j]	1.38E+22	1.60E+22	sej/yr	16
U = total solar EMERGY use[k]	5.29E+22	6.55E+22	sej/yr	24
Environmental, renewable (%)[l]	1.9	1.6	%	-19
Local, nonrenewable (%)[m]	0.8	0.6	%	-22
External, economic (%)[n]	97	98	%	1
Imported goods (%)[o]	23	26	%	14
Imported fossil fuels (%)[p]	3.6	33	%	1
Import services (%)[q]	33	30	%	-8
U.S. loans (%)[r]	5.1	4.5	%	-12
Tourism (%)[s]	3.6	3.9	%	8
Electricity (%)[t]	9	9	%	0
Economic/environment ratio[u]	36.1	45.3		26
Import/export ratio[v]	1.61	1.22		-14
Net benefit/loss from trade[w]	1.11E+22	7.00E+21	sej/yr	-37
Trade surplus/deficit as percent of total used[x]	21	11	%	-49
Import services/export services (%)[y]	85	70	%	-17
Imported EMERGY/unit cost[z]	4.37E+12	3.85E+12	sej/$	-12
Exported EMERGY/unit revenue[aa]	2.65E+12	2.27E+12	sej/$	-14
Solar EMERGY use/area[bb]	5.94E+12	7.36E12	sej/m²/yr	24
Population[cc]	3.29E+6	3.56E+6	people	9
Gross product[dd]	2.52E+10	3.98E+10	$US	58
Solar EMERGY use/capita[ee]	1.61E+16	1.84E+16	sej/p/yr	14
Fuel use/capita[ff]	5.25E+15	6.07E+15	sej/p/yr	16

Table 6—Summary statistics and indices for Puerto Rico, 1987 and 1992 (continued)

Item, index	1987	1992	Units	Change (%)
Solar EMERGY use/GP[gg]	2.10E+12	1.64E+12	sej/yr	-22
Environmental EMERGY use GP[hh]	5.66E+10	3.55E+10	sej/yr	-37

[a] Environment contribution = renewable + nonrenewable.
[b] R = chemical potential energy of transpired rainfall (item 4) plus tidal energy (6).
[c] N = sand, gravel, + ores = items 8-9.
[d] Total economic input = import commodities (items 18-43) + loans (45) + tourism (46).
[e] G = import commodities = items 18-43.
[f] P2I = human services in imports = item 44; estimated from total import costs ($) x sej/$ index for the United States, 1987 and 1992. Imported commodities were evaluated by using dollar expenditures (items 34, 36, and 43 are subtracted to reduce double counting).
[g] Item 45.
[h] Item 46.
[i] Items 47-70.
[j] Item 71; estimated from total export revenues ($) x sej/$ index for Puerto Rico, 1987 and 1992. Imported commodities were evaluated by using dollar expenditures (items 34, 36, and 43 are subtracted to reduce double counting).
[k] U = environment + imports + loans + tourism.
[l] R/U.
[m] N/U.
[n] (Imports + loans + tourism)/U.
[o] Imports/U.
[p] (Items 18-21)/U.
[q] (Item 44)/U; corrected for double counting by subtracting commodities evaluated by using $ costs (textiles, pharmaceuticals, nonspecific goods).
[r] (Item 45)/U.
[s] (Item 46)/U.
[t] (Item 17)/U.
[u] (Imported goods + services + loans + tourism)/(R + N).
[v] (Items 18-44)/(items 47-71).
[w] Imports - exports = (18-43) - (47-70).
[x] (Imports - exports)/U.
[y] Item 44/item 71.
[aa] (Items 47-70)/export revenues, $.
[bb] U/area of Puerto Rico.
[cc] Resident population.
[dd] GP includes revenues received overseas for on-island production (Section 936 generates most of this revenue) plus net balance from external trade not accounted for in the gross domestic product; Corrected GP = GDP + trade balance.
[ee] U/population.
[ff] (Items 18-21)/population.
[gg] U/gross economic product.
[hh] R/gross economic product.

Table 7—Comparison of traditional economic and EMERGY accounts of external trade in Puerto Rico between 1987 and 1992

Market dollars (billion US$/year):	Export costs	Import costs	Net trade advantage	Export: import ratio
1987	12.1	10.7	1.4	1.13
1992	21.1	15.2	5.9	1.39

Solar EMERGY (10^{21}sej/ year):	Imported EMERGY	Exported EMERGY	Net trade advantage	Import: export Ratio
1987	29.3	18.2	11.1	1.61
1992	38.7	31.7	7.0	1.22

Percentage of change in trade ratio from 1987-92:	
Market $	+ 23%
Solar EMERGY without revenue purchases	- 24%
Solar EMERGY with revenue purchases	- 14%

[a] The additional resources that can be purchased with the net trade revenues must be included in calculating the percentage change in trade ratio, as follows: additional resources potentially purchased with net revenues received in external trade (market dollar value of net trade advantage):

U.S. EMERGY/ $, 1987; (1.4E+9 US$)(2.0E+12 sej/$) = 2.8 x 10^{21} sej.
U.S. EMERGY/ $, 1992; (5.9E+9 US$)(1.6E+12 sej/$) = 9.4 x 10^{21} sej.
Adjusted incoming EMERGY = (import EMERGY)+(additional resources purchased with net market revenues):
1987; 29.3E+21 sej + 2.8E+21 sej = 32.1.
1992; 38.7E+21 sej + 9.4E+21 sej = 48.1.
Adjusted import:export ratio = (adjusted incoming EMERGY)/(exported EMERGY):
1987; 32.1/18.2 = 1.76.
1992; 48.1/31.7 = 1.52.
Adjusted net trade advantage, including resources purchased with net revenues:
(EMERGY value of net trade advantage)+(additional resources obtained with net market revenues):
1987; 11.1E+21 sej + 2.8E+21 sej = 13.9 x 10^{21} sej.
1992; 7.0E+21 sej + 9.4E+21 sej = 16.4 x 10^{21} sej.
Adjusted percentage change in exchange ratio from 1987 to 1992:
(1992 ratio - 1987 ratio)/(1987 ratio)*100% = -14 percent.

Table 8—Environmental and economic components of annual solar EMERGY use for Puerto Rico and other countries; tectonic contributions are not included[a]

Nation	Environmental component (renewable solar EMERGY) (x 10^{20} sej/yr)	Economic component of solar EMERGY (x 10^{20} sej/yr)	Environmental ratio
West Germany	193	17,300	89.6
Puerto Rico	**10.2**	**641**	**45.3**
Poland	159	2,946	18.5
Holland	219	3,483	15.9
Switzerland	87	646	7.4
U.S.A.	8,240	58,160	7.1
Spain	255	1,835	7.2
Sweden	630	1,923	3.1
Dominica	2	5	2.7
Australia	4,590	3,960	1.1
Thailand	779	811	1.1
India	3,340	3,410	1.0
Soviet Union	9,110	9,110	1.0
World (3)	94,400	90,000	0.96
New Zealand	438	353	0.8
Brazil	10,100	7,600	0.7
Papua New Guinea	1,050	166	0.14
Ecuador	891	483	0.1
Liberia	427	38	0.1

[a] Based on Odum 1996; values for Puerto Rico for 1992 are based on our study.

Table 9—Solar EMERGY self-sufficiency and trade balance for Puerto Rico and other countries; tectonic contributions are not included in country totals[a]

Nation	Solar EMERGY (%) from within	Solar EMERGY imported / Solar EMERGY exported
Netherlands	3	4.3
West Germany	10	4.2
Switzerland	19	3.2
Spain	24	2.3
U.S.A.	77	2.2
India	88	1.45
Sweden	34	1.35
Puerto Rico	**2**	**1.34**
Taiwan	28	1.19
Brazil	91	0.98
Dominica	69	0.84
New Zealand	60	0.76
Poland	66	0.65
Thailand	70	0.54
Australia	92	0.39
Soviet Union	97	0.23
Ecuador	94	0.20
Liberia	92	0.15
Papua New Guinea	96	0.13

[a] Based on Odum 1996; values for Puerto Rico for 1992 are based on our study.

Table 10—Population density and solar EMERGY use per unit area for Puerto Rico and other countries: tectonic contributions are not included in totals[a]

Nation	Area ($\times 10^{10}$ m^2)	Population density (people/km^2)	Annual solar empower density ($\times 10^{10}$sej/m^2)
Netherlands	3.7	378	100.0
Taiwan	3.6	494	94.6
Puerto Rico	**0.9**	**400**	**73.6**
West Germany	24.9	247	70.4
Sweden	41.1	20.7	62.1
Switzerland	4.1	154	17.7
Poland	31.2	111	10.6
Dominica	0.1	107	8.8
U.S.A.	940	24.2	7.0
Liberia	11.1	16.1	4.1
Ecuador	28.0	34	3.4
Spain	50.5	68.5	3.12
New Zealand	26.9	11.5	2.94
Papua New Guinea	46.2	7.6	2.63
Thailand	74.0	67.6	2.15
Brazil	918	13.2	2.08
India	329	192	2.05
Soviet Union	2,240	11.6	1.71
Australia	768	1.9	1.42

[a] Based on Odum 1996; values for Puerto Rico for 1992 are based on our study.

Table 11—Solar EMERGY use, population, and per capita solar EMERGY use for Puerto Rico and other countries; tectonic contributions are not included in country totals[a]

Nation	Solar EMERGY- use d (x 10^{20} sej/yr)	Population (x 10^6)	Annual EMERGY use per person (x 10^{15}sej/person)
Australia	8,850	15	59
Papua New Guinea	1,216	3.5	35
Sweden	2,552	8.5	30
U.S.A.	66,400	227	29
West Germany	17,500	62	28
Netherlands	3,702	14	26
New Zealand	791	3.1	26
Liberia	465	1.3	26
Puerto Rico	**655**	**3.6**	**18.4**
Soviet Union	43,150	260	16
Brazil	17,820	121	15
Dominica	7	.08	13
Poland	3,305	34.5	10
Switzerland	733	6.37	12
Ecuador	964	9.6	10
Taiwan	1,340	17.8	8
Spain	2,090	134	6
Thailand	1,590	50.0	3.2
India	6,750	630	1

[a] Based on Odum 1996; values for Puerto Rico for 1992 are based on our study.

Table 12—Solar EMERGY- use , gross national products and solar EMERGY: money indices for Puerto Rico and other countries in the early 1990s; tectonic contributions are not included in country totals[a]

Nation	Solar EMERGY- use d (x 10^{20} sej/yr)	GNP (x 10^{9} US$/yr)	Solar EMERGY- use /dollar (x 10^{12} sej/US$)
Papua New Guinea	1,216	2.6	48.0
Liberia	465	1.34	34.5
Dominica	7	.08	14.9
Brazil	17,820	214	8.4
India	6,750	106	6.4
Australia	8,850	139	6.4
Poland	3,305	55	6.0
Thailand	1,509	43.1	3.7
Soviet Union	43,150	1300	3.4
New Zealand	791	26	3.0
West Germany	17,500	715	2.5
U.S.A.	66,400	2600	2.0
Netherlands	3,702	16.6	2.2
Taiwan	1,861	99.3	1.9
Sweden	2,553	155	1.7
Puerto Rico	**665**	**39.8**	**1.64**
Spain	2,090	139	1.6
Switzerland	733	102	.7

[a] Based on Odum 1996 and our study.

Table 13—Physical parameters, energy inputs, and production characteristics of the four major forest ecosystems in the Luquillo Experimental Forest, Puerto Rico[a]

	Elfin	Colorado	Palm	Tabonuco	Total
Physical parameters:					
Area, ha	412	3,285	1,914	5,657	11,268
Mean elevation (m)	897	720	711	402	565
Elevation change (m)	150	300	300	400	800
Environmental sources:					
Daily insolation (kcal/m^2)	3,210	3,520	3,520	3,820	3,659
Annual wind J/ha	7.9E+9	3.95E+9	3.95E+9	3.60E+9	3.92E+9
Cloud condensation (m/yr)	.45	0	0	0	.02
Precipitation (m/yr)	4.85	4.19	4.17	3.54	3.88
Evapotranspiration (m/yr)	.89	.99	1.00	1.71	1.35
Runoff (m/yr)	3.96	3.20	3.16	1.83	2.53
Annual sediment erosion (t/km^2)	360	289	286	162	227
Annual organic budget, t/ha:					
Total AG growth, woody	.45	.57	3.3	2.5	2.0
Total AG NPP	3.7	7.6	19.5	10.5	10.9
Litter fall	3.1	6.8	8.8	8.61	7.9
Leaf	2.45	5.05	6.26	4.94	5.1
Wood	.28	1.22	.86	1.38	1.2
Flower			.18	.17	.1
Fruit		.23	1.14	.34	.4
Miscellaneous	.37	.3	.36	1.78	1.1
Stored biomass, t/ha:	637	473	521	624	562.7
Loose litter	4.34	8.76	5.4	6	6.7
AG woody biomass	80	130	174	190	165.8
Leaf biomass	2.9	5.8	25.1	7.9	10.0
Soil organic matter	550	328	316	420	380.3

AG = aboveground; NPP = net primary production.

[a] Data from Odum 1970, Brown et al. 1983, Weaver and Murphy 1990, Garcia Martino et al. 1996, Kharecha 1997.

Table 14—Evaluation of annual resource inputs supporting net primary production in the forest ecosystems of the Luquillo Experimental Forest, Puerto Rico (* = g/ha, ** = sej/g)

	Annual energy flows (J/ha)	Solar transformity (sej/J)	Annual solar EMERGY (sej/ha)
Luquillo Forest:[a]			
Solar insolation	5.59E+13	1	0.059E+15
Wind energy	3.92E+9	1500	
0.00588E+15			
Tectonic uplift	1.46E+6*	1.0E+9**	1.46E+15
Geopotential in rainfall	2.15E+11	10,500	2.26E+15
Chemical potential in rainfall	1.92E+11	18,200	3.49E+15
Chemical potential in evapotranspiration	6.68E+10	18,200	1.22E+15
Net primary production	1.83E+11	6,643	1.22E+15
Sediment erosion	2.27E+6*	1.0E+9**	2.27E+15
Elfin cloud forest:[b]			
Solar insolation	4.90E+13	1	0.049E+15
Wind energy	7.90E+9	1,500	0.012E+15
Geopotential in rainfall	4.26E+11	10,500	4.48E+15
Chemical potential in cloud condensation	2.22E+10	18,200	0.404E+15
Chemical potential in rainfall	2.4E+11	18,200	4.36E+15
Chemical potential in evapotranspiration	4.4E+10	18,200	0.80E+15
Net primary production	6.20E+10	12,919	0.80E+15
Sediment erosion	3.60E+6*	1.0E+9**	3.6E+15
Colorado forest:[c]			
Solar insolation	5.38E+13	1	0.054E+15
Wind energy	3.95E+9	1,500	0.0059E+15
Geopotential in rainfall	2.91E+11	10,500	3.06E+15
Chemical potential in rainfall	2.07E+11	18,200	3.77E+15
Chemical potential in evapotranspiration	4.91E+10	18,200	0.895E+15
Net primary production	1.27E+11	7047	0.895E+15
Sediment erosion	2.89E+6*	1.0E+9**	2.89E+15
Palm forest:[d]			
Solar insolation	5.38E+13	1	0.054E+15
Wind energy	3.95E+09	1,500	0.0059E+15
Geopotential in rainfall	2.96E+11	10,500	3.11E+15
Chemical potential in rainfall	2.07E+11	18,200	3.77E+15
Chemical potential in evapotranspiration	4.98E+10	18,200	0.91E+15
Net primary production	3.27E+11	2,780	0.91E+15
Sediment erosion	2.86E+6*	1.0E+9**	2.86E+15

Table 14—Evaluation of annual resource inputs supporting net primary production in the forest ecosystems of the Luquillo Experimental Forest, Puerto Rico (* = g/ha, ** = sej/g) (continued)

	Annual energy flows (J/ha)	Solar transformity (sej/J)	Annual solar EMERGY (sej/ha)
Tabonuco forest[e]			
Solar insolation	5.84E+13	1	0.058E+15
Wind energy	3.60E+9	1,500	0.0054E+15
Geopotential in rainfall	1.39E+11	10,500	1.46E+15
Chemical potential in rainfall	1.75E+11	18,200	3.18E+15
Chemical potential in evapotranspiration	8.43E+10	18,200	1.53E+15
Net primary production	1.76E+11	8,693	1.53E+15
Sediment erosion	1.62E+6*	1.0E+9**	1.62E+15

[a] Luquillo Experimental Forest; area-weighted value:

Annual solar insolation: (3,659 kcal/m^2 per day)(10,000 m^2/ha)(4,186 J/kcal)(365 days) = 5.59E+13 J/ha.

Annual wind, kinetic energy: area-weighted estimate, 3.92E+9 J/ha.

Annual tectonic uplift (0.055 mm/yr)(10,000 m^2/ha)(2.65 g/cm^3) = 1.46E+6 g/ha of new land.

Annual geophysical potential energy from falling rain: [3.88 m rain, Garcia et al. 1996](565 m, mean elevation)(10,000 m^2/ha)(10,000 kg/m^3)(9.8 m/s^2) = 2.15E+11 J/ha.

Annual chemical potential energy of rain: (3.88 m rain, Garcia Martino et al. 1996)(10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 1.92E+11 J/ha.

Annual chemical potential of evapotranspiration: (1.35 m, Garcia Martino et al. 1996)(10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 6.68E+10 J/ha.

Annual NPP_{AG}: (10.9 tons/ha)(1E+06 g/ton)(4 kcal/g)(4,186 J/kcal) = 1.83E+11 J/ha.

Annual sediment erosion (see table 17).

[b] Elfin cloud forest:

Annual solar insolation: (3,210 kcal/m^2 per day)(10,000 m^2/ha)(4,186 J/kcal) (365 days) = 4.9E+13 J/ha.

Annual El Yunque wind speeds = 7.90E+09 J/ha (wind driven at 45-degree angle).

Annual geophysical potential energy from falling rain: [4.85 m/yr rain, Garcia Martino et al. 1996](897 m, mean elevation)(10,000 m^2/ha)(1,000 kg/m^3)(9.8 m/s^2) = 4.26E+11 J/ha.

Annual cloud condensation: [0.45 m; Weaver 1972](10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 2.22E+10 J/ha.

Annual chemical potential energy of rain: [4.85 m rain, Garcia Martino et al. 1996 (10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 2.4E+11 J/ha.

Annual chemical potential energy of evapotranspiration (0.891 m/yr, Garcia Martino et al. 1996)(10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 4.4E+10 J/ha.

Annual aboveground net primary production (NPP_{AG}): (Weaver and Murphy 1990): (3.7 tons/ha)(1E+6 g/ton)(4 kcal/g; Odum 1970)(4,186 J/kcal) = 6.2E+10 J/ha.

Annual sediment erosion (see table 17).

Table 14—Evaluation of annual resource inputs supporting net primary production in the forest ecosystems of the Luquillo Experimental Forest, Puerto Rico (* = g/ha, ** = sej/g) (continued)

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[c] Colorado forest:

Annual solar insolation: (3,520 kcal/m^2 per day)(10,000 m^2/ha)(4,186 J/kcal)(365 days) = 5.38E+13 J/ha.

Annual wind, kinetic energy: estimate, mean of El Yunque and Catina records = 3.95E+9 J/ha.

Annual geophysical potential energy from falling rain: (4.19 m/yr rain, Garcia Martino et al. 1996)(720 mean elevation)(10,000 m^2/ha)(1,000 kg/m^3)(9.8 m/s^2) = 2.96E+11 J/ha.

Annual chemical potential energy of rain: (4.19 m/yr, Garcia Martino et al. 1996)(10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 2.07E+11 J/ha.

Annual chemical potential of evapotranspiration: (0.99 m/yr, Garcia Martino et al. 1996)(10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 4.91E+10 J/ha.

Annual NPP_{AG}: (7.6 tons/ha)(1E+6 g/ton)(4 kcal/g)(4,186 J/kcal) = 1.27E+11 J/ha.

Annual sediment erosion (see table 17).

[d] Palm forest:

Annual solar insolation: (3,520 kcal/m^2 per day)(10,000 m^2/ha)(4,186 J/kcal)(365 days) = 5.38E+13 J/ha.

Annual wind kinetic energy: estimate, mean of El Yunque and Catalina records = 3.95E+9 J/ha.

Annual geophysical potential energy from falling rain: (4.17 m/yr rain, Garcia Martino et al. 1996)(711 m mean elevation)(10,000 m^2/ha)(1,000 kg/m^3)(9.8 m/s^2) = 2.91E+11 J/ha.

Annual chemical potential energy of rain: (4.17 m/yr, Garcia Martino et al. 1996)(10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 2.07E+11 J/ha.

Annual chemical potential of evapotranspiration: (1.01 m/yr, Garcia Martino et al. 1996) (10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 4.98E+10 J/ha.

Annual NPP_{AG}: (19.5 tons/ha)(1E+06 g/ton)(4 kcal/g)(4,186 J/kcal) = 3.27E+11 J/ha.

Annual sediment erosion (see table 17).

[e] Tabonuco forest:

Annual solar insolation: (3,820 kcal/m^2 per day) (10,000 m^2/ha)(4,186 J/kcal) (365 days) = 5.84E+13 J/ha.

Annual wind kinetic energy: estimate, 3.60E+9 J/ha.

Annual geophysical potential energy from falling rain: (3.54 m/yr rain, Garcia Martino et al. 1996) (402 m, mean elevation)(10,000 m^2/ha)(1,000 kg/m^3)(9.8 m/s^2) = 1.39E+11 J/ha.

Annual chemical potential energy of rain: (3.54 m/yr rain, Garcia Martino et al. 1996)(10,000 m^2/ha)(1,000 kg/m^3)(4,940 J/kg) = 1.75E+11 J/ha.

Annual chemical potential of evapotranspiration: (1.71 m/yr, Garcia Martino et al. 1996)(10,000 m^2/ha)(1,000 kg/m^3) (4,940 J/kg) = 8.43E+10 J/ha.

Annual aboveground NPP: (10.5 tons/ha)(1E+06 g/ton)(4 kcal/g)(4,186 J/kcal) = 1.76E+11 J/ha.

Annual sediment erosion (see table 17).

Table 15—Average age, solar transformities, and solar EMERGY of aboveground organic matter storage per hectare calculated for the Luquillo Experimental Forest and its four forest types[a]

Forest type	Average age of forest[b] (yrs)	Transformity of vegetation[c] (sej/j)	Transformity of soil organics[d] (sej/j)	Transformity of NPP[e] (sej/j)	Stored solar EMERGY in vegetation[f] (E+15 sej/ha)
Luquillo:	120	33,917	37,304	6,643	28
Elfin	178	92,300	15,600	12,919	21
Colorado	228	63,200	37,200	7,074	23
Palm	53	9,931	10,600	2,780	14
Tabonuco	76	24,600	47,900	8,693	42

[a] Calculations based on data from tables 13 and 14.

[b] Average age of mature forest = woody biomass storage/woody biomass growth:
- Elfin: (80 t/ha)/(0.45 t/ha) = 178 yr;
- Colorado: (130 t/ha)/(0.57 t/ha) = 228 yr;
- Palm: (174 t/ha)/(3.3 t/ha) = 53 yr;
- Tabonuco: (190 t/ha)/(2.5 t/ha) = 76 yr; and
- Luquillo Forest: area weighted average = (78*412/11,268) + (228*3,285/11,268) + (53*1,914/11,268) + (76*5,657/11,268) = 120 yrs.

[c] Annual transformity of vegetation = (annual NPP EMERGY*age)/(J veg., roots, and litter):
- Elfin: (8.01E+14 sej/ha)(178 yr)/(93 t/ha*1.67E+10 J/t) = 92,300 sej/j;
- Colorado: (8.95E+14 sej/ha)(228 yr)/(193.6 t/ha*1.67E+10 J/t) = 63,200 sej/j;
- Palm: (9.09E+14 sej/ha)(53 yr)/(291 t/ha*1.67E+10 J/t) = 9,931 sej/j;
- Tabonuco: (1.53E+15 sej/ha)(76 yr)/(284.9 t/ha*1.67E+10 J/t) = 24,600 sej/j;
- Luquillo Forest: (1.22E+15 sej/ha)(120 yr)/(252 t/ha*1.67E+10 J/t) = 33,917 sej/j;

[d] Annual transformity of soil organics = (Annual NPP EMERGY*age)/(J in soil organics):
- Elfin: (8.01E+14 sej/ha/yr)(178 yr)/(550 t/ha*1.67E+10 J/t) = 15,600 sej/j;
- Colorado: (8.95E+14 sej/ha/yr)(228 yr)/(328 t/ha*1.67E+10 J/t) = 37,200 sej/j;
- Palm: (9.09E+14 sej/ha/yr)(53 yr)/(272 t/ha*1.67E+10 J/t) = 10,600 sej/j;
- Tabonuco: (1.53E+15 sej/ha/yr)(76 yr)/(146 t/ha*1.67E+10 J/t) = 47,900 sej/j;
- Luquillo Forest: (1.22E+15 sej/ha/yr)(120 yr)/(235 t/ha*1.67E+10 J/t) = 37,304 sej/j.

[e] Solar transformity of NPP, from table 14.

[f] Stored aboveground solar EMERGY = (energy in biomass above and below the ground)(transformity of NPP):
- Elfin: (93 t/ha)(1 E+6 g/t)(4 kcal/g)(4,186 J/kcal)(12,919 sej/J) = 2.10 E+16 sej/ha;
- Colorado: (194 t/ha)(1 E+6 g/t)(4 kcal/g)(4,186 J/kcal)(7,047 sej/J) = 2.28 E+16 sej/ha;
- Palm: (291 t/ha)(1 E+6 g/t)(4 kcal/g)(4,186 J/kcal)(2,780 sej/J) = 1.35 E+15 sej/ha;
- Tabonuco: (285 t/ha)(1 E+6 g/t)(4 kcal/g)(4,186 J/kcal)(8,693 sej/J) = 4.15 E+16 sej/ha;
- Luquillo Forest: (252 t/ha)(1E+6 g/t)(4 kcal/g)(4,186 J/kcal)(6,643 sej/J) = 2.8 E+16 sej/ha.

Table 16—Annual volume runoff, energy, and solar EMERGY flux for surface water in the Luquillo Experimental Forest

	Water (E+6 m^3/yr)	Energy (J/yr)	Solar transformity (sej/J)	Empower (sej/yr)	Annual empower density (E+15 sej/ha)
Geopotential EMERGY of runoff:[a]					
Luquillo--	285	1.58E+15	16,124	2.54E+19	2.26
Elfin	16	1.43E+14	12,864	1.84E+18	4.48
Colorado	105	7.41E+14	13,765	1.02E+19	3.11
Palm	60	4.21E+14	13,855	5.84E+18	3.05
Tabonuco	104	4.08E+14	20,294	8.28E+18	1.46
Chemical Potential EMERGY of runoff:[b]					
Luquillo--	285	1.41E+15	27,948[c]	3.93E+19	3.49
Elfin	16	8.06E+13	22,297	1.80E+18	4.36
Colorado	105	5.19E+14	23,859	1.24E+19	3.77
Palm	61	2.99E+14	24,015	7.17E+18	3.75
Tabonuco	102	5.11E+14	35,177	1.80E+19	3.18

[a] Geopotential EMERGY of runoff:
Geopotential-potential energy = (vol. runoff)(mean elevation)(H_2O density)(gravity):
Luquillo total= (284.6E+6 m^3/yr)(565 m)(1,000 kg/m^3)(9.8 m/s^2) = 1.58E+15 J/yr;
Elfin = (16.3E+6 m^3/yr)(897 m)(1,000 kg/m^3)(9.8 m/s^2) = 1.43E+14 J/yr;
Colorado = (105E+6 m^3/yr)(720 m)(1,000 kg/m^3)(9.8 m/s^2) = 7.41E+14 J/yr;
Palm = (60.4E+6 m^3/yr)(711 m)(1,000 kg/m^3)(9.8 m/s^2) = 4.21E+14 J/yr;
Tabonuco = (103.5E+6 m^3/yr)(400 m)(1,000 kg/m^3)(9.8 m/s^2) = 4.08E+14 J/yr.
Transformities for geopotential-potential EMERGY = geopotential EMERGY of rain/geopotential energy of runoff = ((rain volume)(density)(g)(mean elevation)(global transformity of geopotential EMERGY of rain)/((runoff volume)(density)(g)(mean elevation)) = (rain volume)(global transformity of geopotential EMERGY)/(runoff volume), where global transformity of geopotential EMERGY = 10500 sej/j.
Luquillo total = (3.879 m)(10,500)/(2.526) = 16124 sej/j;
Elfin = (4.849 m)(10,500)/(3.958) = 12,864 sej/j;
Colorado = (4.191)(10,500)/(3.197) = 13,765 sej/j;
Palm = (4.167)(10,500)/(3.158) = 13,855 sej/j;
Tabonuco = (3.537)(10,500)/(1.83) = 20,294 sej/j.

[b] Chemical potential EMERGY of runoff:
Chemical potential energy = (volume runoff) (Gibbs free energy of dissolved solids, 150 ppm; 4,940 J/kg) (H_2O density):
Luquillo total = (284.6E+6 m^3/yr)(1,000 kg/m^3)(4,940 J/kg) = 5.11E+14 J/yr;
Elfin = (16.3E+6 m^3/yr)(1,000 kg/m^3)(4,940 J/kg) = 8.06E+15 J/yr;
Colorado = (105E+6 m^3/yr)(1,000 kg/m^3)(4,940 J/kg) = 5.19E+14 J/yr;
Palm = (60.4E+6 m^3/yr)(1,000 kg/m^3)(4,940 J/kg) = 2.99E+14 J/yr; and
Tabonuco = (284.6E+6 m^3/yr)(1,000 kg/m^3)(4,940 J/kg) = 1.41E+15 J/yr.
Transformities for chemical-potential EMERGY = chemical-potential EMERGY of rain/geopotential energy of runoff = ((rain volume)(Gibbs free energy of dissolved solids)(H_2O density)(global transformity of chemical potential EMERGY of rain)/((runoff volume)(Gibbs free energy of dissolved solids)(H_2O density) = (rain volume global transformity of chemical EMERGY in rainfall)/(runoff volume), where global transformity of geopotential EMERGY = 18,200 sej/j:
Luquillo total = (3.879 m)(18,200)/(2.526) = 27,948 sej/j;
Elfin = (4.849 m)(18,200)/(3.958) = 22,297 sej/j;
Colorado = (4.191)(18,200)/(3.197) = 23,859 sej/j;
Palm = (4.167)(18,200)/(3.158) = 24,015 sej/j; and
Tabonuco = (3.537)(18,200)/(1.83) = 35,177 sej/j.

Table 17—Summary of annual solar EMERGY supporting biological processes and geomorphic sculpturing of the Luquillo Experimental Forest; values are solar empower densities

	Processes			
	Biological	Physical	Chemical	Physical
Forest type	(ET)[a] E+15 (sej/ha)	Erosion[b] E+15 (sej/ha)	Streamflow[c] E+15 (sej/ha)	Streamflow[d] E+15 (sej/ha)
Luquillo:	1.22	2.3	3.5	2.3
Elfin, cloud	.80	3.6	4.4	4.5
Colorado	.89	2.9	3.8	3.1
Palm	.90	2.9	3.8	3.1
Tabonuco	1.53	1.6	3.2	1.5

[a] Biological EMERGY = chemical potential of ET from table 14.

[b] Erosion and weathering are based on annual sediment yield at Río Mameyes at Puente Roto of 227 t/km^2 (Larsen 1997). Sediment yields for each forest type were estimated based on the average elevation of each one (Kharecha 1997):

Elfin = (227 t/km^2/yr)(897 m/565 m)(1 km^2/100 ha)(1E6 g/t)(1.0E9 sej/g)
= (3.6E+15 sej/ha);

Colorado = (227 t/km^2/yr)(720 m/565 m)(1 km^2/100 ha)(1E+6 g/t)(1.0E+9 sej/g)
= (2.89E+15 sej/ha);

Palm = (227 t/km^2/yr)(711 m/565 m)(1 km^2/100 ha)(1E+6 g/t)(1.0E+9 sej/g)
= (2.86E+15 sej/ha);

Tabonuco = 227 t/km^2/yr(402 m/565 m)(1 km^2/100 ha)(1E+6 g/t)(1.0E+9 sej/g)
= (1.62E+15 sej/ha);

Luquillo = 227 t/km^2/yr(1 km^2/100 ha)(1E+6 g/t)(1.0E+9 sej/g)
= (2.27E+15 sej/ha).

[c] Chemical sculpturing of the landscape = chemical potential of runoff = (volume of runoff)(Gibbs free energy at typical dissolved solids)(H_20 density)(transformity, sej/j), from table 16.

[d] Physical EMERGY of stream sculpturing = (geopotential at mid elevation)(m/yr runoff)(mean elevation)(H_20 density)(acceleration to gravity)(transformity, sej/j), from table 16.

Table 18—Emdollar values by hectare and forest type for the Luquillo Experimental Forest, Puerto Rico

Forest type	All inputs (em$/ha)[a]	Storage in vegetation and soil (em$/ha)[b]	Annual aboveground net primary productivity (em$/ha/yr)[c]	Annual streamflow (em$/ha/yr)[d]
Luquillo:	255,366	17,073	744	2,128
Elfin, cloud	517,068	12,805	488	2,659
Colorado	524,122	13,902	540	2,299
Palm	121,835	8,232	554	2,287
Tabonuco	147,366	25,305	945	1,939

[a] Emdollars value of total EMERGY inputs = (annual chemical-potential input from rainfall, table 14) (age of forest, table 15)/(sej/$, 1992):

Luquillo	(3.49E+15 sej/ha)(120 years)/1.64E+12 sej/$)	= 255,366;
Elfin	(4.04E+14 + 4.36E+15 sej/ha)*(178 years)/1.64E+12 sej/$)	= 517,068;
Colorado	(3.77E+15 sej/ha/yr)*(228 years)/1.64E+12 sej/$)	= 524,122;
Palm	(3.77E+15 sej/ha)*(53 years)/1.64E+12 sej/$)	= 121,835;
Tabonuco	(3.18E+15 sej/ha)*(76 years)/1.64E+12 sej/$)	= 147,366.

[b] Emdollar value of organic matter above and below ground = (stored EMERGY in vegetation, table 15)/(sej/$, 1992):

Luquillo	(28E+15 sej/ha)/(1.64E+12 sej/$)	= 17,073 emdollars/ha;
Elfin	(21E+15 sej/ha)/(1.64E+12 sej/$)	= 12,805 emdollars/ha;
Colorado	(22.8E+15 sej/ha)/(1.64E+12 sej/$)	= 13,902 emdollars/ha;
Palm	(13.5E+15 sej/ha)/(1.64E+12 sej/$)	= 8,232 emdollars/ha;
Tabonuco	(41.5E+15 sej/ha)/(1.64E+12 sej/$)	= 25,305 emdollars/ha.

[c] Emdollar value of annual aboveground net primary productivity (NPP); (EMERGY supporting NPP, table 14)/(EMERGY use/$, 1992):

Luquillo	(1.22E+15 sej/ha)/(1.64E+12 sej/$)	= 744 emdollars/ha;
Elfin	(8.01E+14 sej/ha)/(1.64E+12 sej/$)	= 488 emdollars/ha;
Colorado	(8.95E+14 sej/ha)/(1.64E+12 sej/$)	= 540 emdollars/ha;
Palm	(9.09E+14 sej/ha)/(1.64E+12 sej/$)	= 554 emdollars/ha;
Tabonuco	(1.55E+15 sej/ha)/(1.64E+12 sej/$)	= 945 emdollars/ha.

[d] Emdollars value of annual streamflow emdollars/ha = (chemical potential EMERGY in streamflow, table 16)/ (sej/$,1992):

Luquillo	(3.49E+15 sej/ha)/(1.64E+12 sej/$)	= 2,128;
Elfin	(4.36E+15 sej/ha)/(1.64E+12 sej/$)	= 2,659;
Colorado	(3.77E+15 sej/ha)/(1.64E+12 sej/$)	= 2,299;
Palm	(3.75E+15 sej/ha)/(1.64E+12 sej/$)	= 2,287;
Tabonuco	(3.18E+15 sej/ha)/(1.64E+12 sej/$)	= 1,939.

Table 19—The EMERGY and solar transformities of Puerto Rican hurricanes

	Solar Energy flow (j/storm)	Solar transformity (sej/j)	empower (E+20 sej/storm)
Hurricane EMERGY flow[a]	—	—	93.4
Available kinetic energy of wind[b]	9.75E+17	9,579	—
Hurricane wind energy, Luquillo[c]	3.09E+16	9,579	2.96

[a] Solar energy over the area covered by the average Atlantic hurricane on its track to Puerto Rico multiplied by the days between hurricanes where the ocean and air masses are collecting energy. Daily solar insolation from Cabo Rojo, 1.81E+11 j/ha. Area of storm track inputs (3,000-km width, Riehl 1979; 5,000-km track to Puerto Rico) = 1.2E+9 ha. Days per storm = 43; 36 days between storms (8.4 tropical storms or hurricanes/yr, 10-month hurricane season)+duration of storm (7.5 days per storm, Neumann et al. 1988); (1.2E+9 ha)(43-day/storm)(1.81E+11 j/ha per day) = 93.4E+20 sej/storm.

[b] Kinetic energy of wind, 1.3E+18 j/day for average hurricane (Riehl 1979), 7.5 days/storm (Neumann et al. 1988), 10% of kinetic energy available for work at ground. (1.3E+18 j/day)(7.5 day/storm)(0.1) = 9.75E+17 j/storm.

[c] Wind energy used at the Luquillo Forest, available kinetic energy of wind 9.75E+17 j/storm; average time storm is over the island is 0.24 days/storm (Scatena and Larsen 1991); total duration of storm, 7.5 days (9.75E+19 j/storm)(0.24 days over the Luquillo (7.5 total storm days) = 3.09 E+16 j/storm.

Table 20—Evaluation of annual EMERGY flows in the Luquillo Experimental Forest, Puerto Rico

	Resource flows (J, $/yr)	Solar transformity (sej/J, sej/$)	Solar EMERGY (sej/yr)	Emdollars 1992 (1,000 em$/yr)
Environmental source inputs (including tectonic):				
Luquillo[a]			3.0 E+19	18,293
Elfin, cloud			9.3 E+17	567
Colorado			7.8 E+18	4,756
Palm			4.5 E+18	2,744
Tabonuco			1.7 E+19	10,366
Societal source inputs:				
Forest Service support services:				
Caribbean NF budget[b]	2.86E+6 $	1.64E+12	4.69E+18	2,860
El Portal only	7.49E+5 $	1.64E+12	1.23E+18	750
Institute administration[c]	1.69E+6 $	1.64E+12	2.77E+18	1,685
Electricity[d]	2.48E+12 J	1.74E+5	4.32E+17	263
Fuel[e]	1.83E+13 J	6.60E+4	1.21E+18	738
Human metabolism[f]	1.88E+11 J	9.55E+7	1.80E+19	10,976
Subtotal		2.71E+19	16,524	
Research and education:				
IITF research[g]	2.5E+6 $	1.64E+12	4.15E+18	2,530
International forestry[h]	6.4E+5 $	1.64E+12	1.06E+18	646
Other research[i]	2.0E+6 $	1.64E+12	3.33E+18	2,030
Human metabolism[j]	1.2E+10 J	3.43E+8	4.12E+18	2,512
Subtotal			1.27E+19	7,718
Tourism:				
Island residents (386,000 visitors/year)				
Costs to get to Luquillo[k]	2.70E+6 $	1.64E+12	4.44E+18	2,707
Human metabolism[l]	8.42E+11 J	5.00E+7	4.21E+19	25,671
Nonisland residents (114,000 visitors/year)				
Costs to get to Luquillo[m]	2.49E+6 $	1.60E+12	3.98E+18	2,427
Human metabolism[n]	2.49E+11 J	6.00E+7	1.49E+19	9,085
Subtotal			6.54E+19	38,890
Summary of solar EMERGY inputs and attracted resources:				
Environmental input[o]		30.2E+18 sej/yr		
Economic support[p]		9.1E+18 sej/yr		
Human support metabolism[q]		18.0E+18 sej/yr		
Total support resources and services[r]		57.3E+18 sej/yr		
Total attracted resources[s]		78.0E+18 sej/yr		
Total annual EMERGY flow:[t]		135.0E+18 sej/yr		
Human metabolism		59%		
Environmental		22%		
Economic		19%		

Table 20—Evaluation of annual EMERGY flows in the Luquillo Experimental Forest, Puerto Rico (continued)

[a] Environmental source inputs from evapotranspiration plus tectonics (table 14).
[b] Caribbean NF budget, 1992 = 2.865E+6 US$.
[c] Institute administration in 1992 = (1.362E+6 US$, salary + 3.23E+5 US$, fixed costs) = 1.685E+6 US$.
[d] Electricity consumption from Forest Service records (Doherty et al. 1994).
[e] Fuel consumption from Forest Service records (Doherty et al. 1994).
[f] Annual human energy expenditure, 121 Caribbean NF employees, 104 in Institute (225 employees) (100 kcal/person per hr)(40 hr/wk)(50 wk/yr)(4,186 J/kcal) = 1.88E+11 J/yr. Transformity from Odum (1996), Kharecha (1997).
[g] Institute research = (1.368E+6 US$, salary + 5.29E+5 US$, fixed costs + 6.30E+5 US$, outside funds) = 2.527E+6 US$.
[h] International cooperation = (4.05E+5 US$, salary + 1.58E+5 US$, fixed costs + 8.0E+4 US$ outside funds) = 6.43E+5 US$.
[i] Other research (Univ. of Puerto Rico, National Science Foundation) = 2.025E+6 US$ total.
[j] Annual human energy expenditure by researchers (60 researchers)(100 kcal/person/h)(40 h/wk)(12 wk/yr)(4,186 J/kcal) = 1.21E+10 J/yr. Transformity of individuals with post-college education (Odum 1996).
Island residents:
[k] Money spent: (386,000 visitors in 1992)($7/person) = 2.7E+6 $.
[l] Energy expended during visit = (386,000 p/y)(5 h/visit)(2,500 kcal/d)/(24 hr/d)(4,186 J/kcal) = 8.42E+11 J/yr. Transformity from Odum (1996).
Nonisland residents visiting the Luquillo:
[m] Money spent: (114,000 foreigners visited the Caribbean NF in 1992)/(3,703,200 foreigners visited Puerto Rico in 1992) = 3.1%; $408 spent + $300 est. airfare = $708/foreigner per visit; ($708)(0.031) = $21.80/foreigner (114,000 foreigners) ($21.80/visit) = 2.49E+6 US$.
[n] Energy spent by nonisland residents during visits = (114,000 p/y)(5 hr/visit)(2,500 kcal/d)/(24-hr/d) (4186 J/kcal) = 2.49E+11 J/y. Transformity from Kharecha (1997).
Summary of solar EMERGY inputs and attracted resources:
[o] Item 1.
[p] Sum of items 2 to 5.
[q] Item 6.
[r] Sum of items 13 to 15.
[s] Sum of items 7 to 12.
[t] Sum of items 16 and 17:
18a: Sum of items 6, 10, 11b, and 12b/item 18;
18b: Item1/item 18, and 18c: and
18c: Sum of items 2, 3, 4, 5, 7, 8, 9 , 11a, and 12a/item 18.

Table 21—Comparison of EMERGY storages in forest structure and human-built structures in the Luquillo Experimental Forest, Puerto Rico

	Solar EMERGY storage (E18 sej)
Forest structure[a]	4,720
Total human-built structures	334
Roads[b]	193
Communications facilities[c]	82
El Portal visitors center[d]	27
Water intakes[e]	17
Other Forest Service facilities[f]	9
University of Puerto Rico facilities[g]	6

[a] EMERGY stored in the Luquillo was assessed based on total rainfall:
annual rainfall EMERGY = 3.49E+15 sej/ha for the whole forest (table 14); area = 11268 ha;
age = 117 yr; (3.49E+15 sej/ha per year)(11,268 ha)(117 yr) = 4.60E+21 sej.

Human-built structures (roads and facilities) in the Luquillo:

[b] EMERGY stored in roads is based on total inputs for roads:
total costs for all Forest roads = 1.18E+8 $; EMERGY/$ ratio = 1.64E+12 sej/$; see table 23,
(1.18E+8 $)(1.64E+12 sej/$) = 1.93E+20 sej.

[c] Estimated monetary value of all communications facilities = 50E+6 $ (Scatena 1995);
(5.00E+7 $)(1.64E+12 sej/$) = 8.20E+19 sej.

[d] Costs of El Portal facility = 16.365E+6 $ (USDA Forest Service 1991b); (1.6365E+7 $)
(1.64E+12 sej/$) = 2.68E+19 sej.

[e] Water intakes = (annual cost for building and maintenance)(design life) = (192,000$/yr + 37,500 $/yr)
(45 years) = 1.03E+7 $, see table 22 (1.03E+7 $)(1.64E+12 sej/$) = 1.69E+19 sej.

[f] Total costs for USDA Forest Service facilities within the Luquillo, excluding El Portal = 5.694E+6 $
(USDA Forest Service 1991b);(5.694E+6 $)(1.64E+12 sej/$) = 9.34E+18 sej.

[g] Costs of University of Puerto Rico's Luquillo facilities = 3.421E+6 $ (USDA Forest Service 1991b);
(3.421E+6 $) (1.64E+12 sej/$) = 5.61E+18 sej.

Table 22—EMERGY evaluation of the effects of extracting water from the Luquillo Experimental Forest, Puerto Rico (modified from Kharecha 1997)

Item	Annual data	Solar EMERGY/ unit data (sej/unit)	Solar EMERGY (E16 sej/yr)
Inputs:			
Building[a]	1.92E+5 $/yr	1.64E+12 sej/$	31.50
Other services[b]			
Maintenance	3.75E+4 $/yr	1.64E+12 sej/$	6.15
Energy spent	1.26E+9 J/yr	7.30E+7 sej/J	9.20
Total inputs			46.90
Effects:			
Water removed[c]	7.38E+14 J/yr	1.61E+4 sej/J	1190
Off-site pollution[d]	2.11E+14 J/yr	5.00E+5 sej/J	10,500
Total effect[e]	9.49E+14 J/yr	1.23E+5 sej/J	11,700

[a] Building costs of 10E+6 gal/d intake system = 1.7E+6 $; amount of water extracted from Luquillo = 50.9E+6 gal/d; average useful life of intake system = 45 yr; EMERGY/$ ratio = 1.64E+12 sej/$ (based on data provided by Forest Service staff): Average costs of all intake systems: [(1.7E+6 $)(10E+6 gal/d)](50.9E+6 gal/d)/(45 yr) = 192,000 $/yr.

[b] Costs to maintain intake systems (based on data provided by Forest Service staff):
Technicians require 2 hr/wk for each intake; salary = 25,000$/yr for 40 hr/wk; number of intakes = 30 (Naumann 1994);
Total time spent in maintaining each intake = (2 hr)(30 intakes) = 60 hr/wk; technician transformity taken as 7.3E+7 sej/J (Odum 1996); Total maintenance costs = (25,000 $/yr)(60/40) = 37,500 $/yr; Total energy expenditure = (100 kcal/h, metabolism)(60h/wk)(50wk/yr worked)(4186 J/kcal) = 1.26E+9 J/yr.

[c] Energy in 50.9E+6 gal/d of extracted water:
Transformity = 16,124 sej/J (geopotential EMERGY of runoff, table 16); [(1.58E+15 J;geopotential + 1.41E+15 J chemical)/(285E+6 m3)](1 m^3/264 gal) = 39,700 J/gal; Total energy extracted = (50.9E+6 gal/d)(365 d (39,700 J/gal) = 7.38E+14 J/yr.

[d] Downstream pollution: 60 percent of extracted water in Puerto Rico returns as treated effluent (Dopazo and Molina-Rivera 1995); assumed free energy of effluent = 5 J/g; transformity of treated discharge = 5.0E+5 sej/J (Green 1992); pollution energy = (0.60)(50.9E+6 gal/d)(365 d)(3.785 L/gal)(1000 g/L, density)(5 J/g) = 2.11E+14 J/yr.

[e] Total energy of effects = sum of above energy = 6.01E+14 J/yr; transformity of effects calculated by taking sum of EMERGY of items 1-4 and dividing by total energy of effects: (1.17E+20 sej/yr) / (9.49E+14 J/yr) = 123,000 sej/J.

Table 23—EMERGY evaluation of the effects of roads on the Luquillo Experimental Forest, Puerto Rico (modified from Kharecha 1997)

Item	Data	Solar EMERGY/ unit data (sej/unit)	Solar EMERGY (E16 sej/yr)
Inputs:			
Costs[a]	1.18E+8 $	1.64E+12 sej/$	19300
Effects:			
Storages			
Vegetation[b]	2.06E+14 J	33,917 sej/J	699
Landslides[c]—			
Soil organics	8.04E+13 J	37,200 sej/J	299
Vegetation	8.63E+13 J	33,917 sej/J	293
Total effects[d]	3.73E+14 J	5.52E+5 sej/J	20591
Annual:			
Production[e]	8.97E+12 J/yr	6,643 sej/J	5.96/yr
Landslides[f]—			
Soil organics	6.70E+11 J/yr	37,200 sej/J	2.49/yr
Vegetation	3.75E+12 J/yr	6,643 sej/J	2.49/yr
Total effects[g]	1.34E+13 J/yr	3.28E+5 sej/J	440/yr

[a] Costs: total length of roads in the Luquillo Forest = 49 km (based on Institute GIS data); recent cost of building of 1 km = 1,403,669 US$ (CNF 1997); maintenance costs = 22,323 $/km (CNF 1991); estimated age of roads = 45 yr;
total costs of roads = (1,403,669 $/km)(49 km) + (22,323 $/km/yr)(45 yr)(49 km) = 118,001,996 $.

[b] Forested area lost from road building: average width of roads = 10 m; 49,000 m of roads = (49,000 m) (10 m)(1 ha/10,000 m^2) = 49 ha; vegetation storage of Luquillo = 4.21E+12 J/ha (table 15, item 5); solar transformity of vegetation = 33,917 sej/J (table 15); energy impact = (4.21E+12 J/ha)(49 ha) = 2.06E+14 J.

[c] Landslide effects: total area of road-associated landslides in the Luquillo = 20.5 ha (estimate based on Guariguata and Larsen 1990); soil organic storage in Luquillo = 3.92E+12 J/ha; transformity of soil organics = 37,200 sej/J (table 15); energy effect on soil organic matter = (3.92E+12 J/ha)(20.5 ha) = 8.04E+13 J; energy effect on vegetation = (4.21E+12 J/ha)(20.5 ha) = 8.63E+13 J.

[d] Total stored energy effect of roads = sum of two and three = 2.06E+14 J + 8.04E+13 J + 8.63E+13 J = 3.73E+14 J. Solar transformity calculated by adding EMERGY of items 1, 2, 3, and dividing by total energy: [(19,300 + 699 + 299 + 293) E+16 sej]/(3.73E+14 J) = 552,038 sej/J.

[e] Production loss from presence of roads: aboveground net primary productivity of the Luquillo = 1.83E+11 J/ha/yr; transformity = 6643 (table 14); annual energy effect = (1.83E+11 J/ha)(49 ha) = 8.97E+12 J/yr.

[f] Landslide annual effects: energy of soil organic matter accumulation rate in the Luquillo, taken as energy of soil organic storage/age of the vegetation = (3.92E+12 J/ha)/(120 yr, table 15) = 3.27E+10 J/ha per yr; annual energy of soil organic matter affected by landslides = (3.27E+10 J/ha)(20.5 ha) = 6.70E+11 J/yr; annual energy of aboveground net primary production affected by landslides = (1.83E+11 J/ha)(20.5 ha) = 3.75E+12 J/yr.

[g] Total annual energy effect of roads = sum of energy described above = 8.97E+12 J/yr + 6.70E+11 J/yr + 3.75E+12 J/yr = 1.34E+13 J/yr; solar transformity for road effects was calculated by adding annual EMERGY of items 1, 5, and 6 and dividing by total annual energy: [(19,300/45 + 5.96 + 2.49 + 2.49) E+16 sej/yr]/(1.34E+13 J/yr) = 328,000 sej/J.

Table 24—EMERGY evaluation indices for Puerto Rico and the Luquillo Experimental Forest; environmental flows do not contain tectonic contributions, unless noted

Indices of investment and contribution for the Luquillo Experimental Forest and Puerto Rico:	
Total societal flows/environmental flows:	
Puerto Rico—	45
Societal flows/environmental flows including tectonics[a]	24
Human metabolism/environmental flows[b]	462
Luquillo—	
Total societal flows/environmental flows[c]	3.5
Tourism societal flows/environmental flows[d]	2.2
Forest Service societal flows/environmental flows[e]	.9
Research and education societal flows/environmental flows[f]	.4
Human metabolism/environmental flows[g]	3
Tourism metabolism/environmental flows[h]	2
Research and education metabolism/environmental flows[i]	.1
Indices of human influence on the Luquillo Experimental Forest:	
Roads[j]—	
Annual impact EMERGY/annual input EMERGY	1.0
Annual impact EMERGY/annual $ costs	1.7E+12 sej/$
Water[k]—	
Annual impact EMERGY/annual input EMERGY	250
Water EMERGY/input EMERGY	25
Annual impact EMERGY/annual $ costs	5.1E+14 sej/$
Management, research, tourism[l]—	
Annual impact EMERGY/annual input EMERGY	.30
Attracted EMERGY/Luquillo support EMERGY	2.73
Annual impact EMERGY/annual $ costs	7.6E+10 sej/$

[a] Total economic inputs/environmental inputs = (6.41E+22 sej/yr)/(1.41E+21 sej/yr) = 45. With tectonic contribution = (6.41E+22 sej/yr)/(2.71E+21 sej/yr) = 24.

[b] Puerto Rico human services/environmental inputs. Puerto Rico human services = (3.56E+6 persons in 1992)(100 kcal/for each person)(8760 hr/yr)(4186 j/kcal) = 1.31E+16 j/yr. Solar transformity for Puerto Rico = 5.0E+7 (table 20, Odum 1996) = 6.53E+23. (6.63E+23 sej/yr)/(1.41E+21 sej/yr) = 462. See table 6.

[c] Total economic inputs/environmental inputs = (10.5E+19 sej./yr)/(3.0E+19 sej/yr) = 3.5. See table 20.

[d] Tourism/environment = (6.54E+19 sej/yr)/(3.0E+19 sej/yr). See table 20.

[e] (Forest Service)/environment = (2.71E+19)/(3.0E+19 sej/yr). See table 20.

[f] Research and education/environment = (1.27E+19)/(3.0E+19 sej/yr). See table 20.

[g] Human/environmental = (7.91E+19)/(3.0E+19) = 2.64. See table 20.

[h] Tourism metabolism/environmental = (5.7E+19)/(3.0E+19) = 1.9. See table 20.

[i] Research and development/environment = (4.12E+18)/(3.0E+19) = 0.14. See table 20.

[j] Roads:
Annual effect EMERGY/annual input EMERGY; (440E+16 sej/yr)/(430E+16 sej/yr) = 1.03. See table 23.
Annual effect EMERGY/annual $ costs; (440E+16 sej/yr)/(1.18E+8 / 45 yrs) = E+12 sej/$.

[k] Water indices:
Annual effect EMERGY/annual input EMERGY. Inputs = 4.69E+17 sej/yr, effects = 11,700E+16 sej/yr. See table 22.
Water EMERGY/input EMERGY. EMERGY of water removed = 1190E+16 sej/yr.
Input EMERGY = 46.9E+16 sej/yr. See table 22.
Annual effect EMERGY/annual costs. Effect EMERGY = 11,700E+16 sej/yr; annual costs = 229,500 $. See table 22.

Table 24—EMERGY evaluation indices for Puerto Rico and the Luquillo Experimental Forest; environmental flows do not contain tectonic contributions, unless noted (continued)

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[l] Management, research, and tourism:

Annual effect EMERGY/annual input EMERGY; effects = lost production in 600 ha of developed areas in the Forest = (600 ha)(1.22E+15 sej/ha)/(8.15E+18 sej/ha) = 0.30.

Attracted EMERGY/Luquillo support EMERGY; (73.9E+18 sej/yr)/(2.71E+19 sej/yr) = 2.72. See table 20.

Annual-impact EMERGY/annual costs. Annual costs of the Caribbean NF and IITF = (600 ha)(1.22E+15 sej/ha)/(2.86E+6 + 1.69E+6 + 2.5E+6 + 6.4E+5 + 2.0E+6) = 7.6E+10.

Appendix 2: Import and Export Data for Puerto Rico in 1987

Appendix 2: Import and export data for Puerto Rico in 1987 used in resource evaluation tables 3-6

Imports: 1987		USA		Foreign Countries		Virgin Islands		Total imports	
		$	Quantity	$	Quantity	$	Quantity	$	Quantity
Crude petroleum	bbl	56,133,000		439,370,000	29,601,030[a]			495,503,000	29,600,311 bbl
Fuel oils	bbl	4,714,000	272,380[a]	173,995,000	12,622,781[a]	1,354,723	64,510[a]	180,063,723	12,959,671 bbl
Gasoline	bbl	28,172,000	1,206,029[a]	96,455,000	4,220,651[a]	6,823,803	276,072[a]	131,450,803	5,702,752 bbl
Motor fuel	bbl			1,344,000	64,810[a]			1,344,000	64,810 bbl
Kerosene, jet fuel	bbl	27,000	1,203[a]	28,763,000	1,297,534[a]	2,948,239	134,901[a]	31,738,239	1,433,638 bbl
Naphthas	bbl	232,000	2,334[a]	265,021,000	14,758,666[a]			265,253,000	14,761,000 bbl
Oils	bbl	9,734,000	115,638[a]	2,089,000	52,711[a]			11,823,000	168,349 bbl
Diesel	bbl	8,509,000	91,354[a]					8,509,000	91,354 bbl
Other oils	bbl	1,340,000	18,404[a]					1,340,000	18,404 bbl
Ethane, propane, butane	bbl	392,747	33,109[a]	13,272,767	1,117,468[a]			13,665,514	1,150,577 bbl
Natural gas	mcf	87,733	42,131[a]					87,733	42,131 mcf
						Total petrol import costs:		1,140,778,012	
Live animals	lbs	3,073,472	3,213,362[a]	1,928	2,016[c]			3,075,400	3,215,378 lbs
Meat	lbs	330,692,749	391,534,827[a]	103,560,033	93,401,373[a]			434,252,782	484,936,200 lbs
Fish	lbs	22,702,418	15,712,752[a]	254,574,911	489,410,438[a]			277,277,329	505,123,190 lbs
Dairy	lbs	167,474,949	224,423,189[b]	7,237,499	12,045,309[a]			174,712,448	236,468,498 lbs
Hides	lbs	13,326,991	2,496,703[b]	371,253	69,551[c]			13,698,244	2,566,254 lbs
Live plants	lbs	585,536	605,756[b]	186,777	193,227[c]			772,313	798,983 lbs
Grains, cereals	lbs	101,403,826	1,141,436,409[b]	2,286,979	11,197,526[a]	4,030	27,616[a]	103,694,835	1,152,661,551 lbs
Grains, cereals	bu			5,632,592	2,225,270[a]			5,632,592	2,225,270 bu
Vegetables	lbs	166,859,365	483,444,210[a]	24,881,390	113,470,000[a]			191,740,755	596,914,210 lbs
Fruits, nuts	lbs	43,264,814	100,343,492[a]	8,353,099	30,920,291[a]			51,617,913	131,263,783 lbs
Sugar, choc., syrup	lbs	108,271,906	217,043,426[b]	35,157,905	284,850,000[a]			143,429,811	501,893,426 lbs

Appendix 2: Import and export data for Puerto Rico in 1987 used in resource evaluation tables 3-6 (continued)

Imports: 1987		USA		Foreign Countries		Virgin Islands		Total imports	
		$	Quantity	$	Quantity	$	Quantity	$	Quantity
Coffee, tea, spices	lbs	4,165,271	2,217,195[a]	3,617,192	2,094,642[a]			7,782,463	4,311,837 lbs
Juice, alcohol	lbs	183,667,140	550,007,191[b]					183,667,140	550,007,191 lbs
Juice, alcohol	gal			56,939,575	13,192,563[a]	4,660	6,000[a]	56,944,235	13,198,563 gal
Tobacco, cigarettes	lbs	44,590,739	15,081,355[b]	8,058,972	2,725,683[c]			52,649,711	17,807,038 lbs
Animal, vegetation oils	lbs	51,037,495	165,914,527[b]	4,492,823	27,997,893[a]			55,530,318	193,912,420 lbs
Other animal and vegetable	lbs	245,461,658	492,519,445[b]	36,392,991	73,022,630[c]			281,854,649	565,542,074 lbs
Wood product	lbs	36,968,451	235,765,601[b]	30,520,748	268,833,828[e]	2,000	2,000,000[a]	67,491,199	506,599,429 lbs
Cork, bamboo, rattan	lbs	251,584	159,490[b]	2,600,881	2,277,252[e]			2,852,465	2,436,742 lbs
Veneer, building boards	lbs	32,834,237	150,561,339[b]	22,368,459	141,664,869[e]			55,202,696	292,226,208 lbs
Paper, cardboard	lbs	301,667,992	569,804,151[b]	62,405,339	162,801,229[e]			364,073,331	732,605,380 lbs
Books	lbs	41,149,268	18,248,799[b]	20,747,227	12,707,842[e]			61,896,495	30,956,641 lbs
Textiles	lbs	523,080,893	176,221,926[b]	64,132,876	29,840,862[e]			587,213,769	206,062,788 lbs
Organic chemicals	lbs	14,078,997	41,679,155[b]	266,429,986	788,733,514[c]			280,508,983	830,412,669 lbs
Inorganic chemicals	lbs	218,124,634	394,065,028[b]	50,914,429	91,982,256[c]			269,039,063	486,047,283 lbs
Pharmaceuticals	lbs	330,388,442	56,882,356[b]	51,479,139	12,241,188[e]	5,300,459	42,132[a]	387,168,040	69,165,676 lbs
Synthetic resins, rubber	lbs	81,933,489	136,728,996[b]	5,370,476	10,199,155[a]			87,303,965	146,928,151 lbs
Gels, preps, soaps, dyes	lbs	582,005,664	261,986,610[b]	21,869,937	13,596,871[e]			603,875,601	275,583,481 lbs
Fertilizer, pesticides, photo chem.	lbs	29,486,499	19,554,352[a]	4,130,826	146,973[a]			33,617,325	19,701,325 lbs
Misc, chemicals, acids	lbs	21,709,186	21,991,261[b]	6,376,787	8,921,709[e]			28,085,973	30,912,970 lbs
Nonmetal minerals and prods.	lbs	93,321,667	265,036,698[b]	76,551,383	217,408,523[c]			169,873,050	482,445,221 lbs

Appendix 2: Import and export data for Puerto Rico in 1987 used in resource evaluation tables 3-6 (continued)

Imports: 1987		USA		Foreign Countries		Virgin Islands		Total imports	
		$	Quantity	$	Quantity	$	Quantity	$	Quantity
Metal ores, non-specific	lbs	34,339	2,502[a]					34,339	2,502 lbs
Zinc ore	lbs	6,144	1,674[a]					6,144	1,674 lbs
Bauxite	lbs			146,492	3,832[a]			146,492	3,832 lbs
Iron ore	lbs			96,172	4,216[a]			96,172	4,216 lbs
Metals, alloys	lbs	175,434,517	254,188,601[b]	140,284,884	462,900,000[a]	19,620	220,413[a]	315,739,021	717,309,014 lbs
Metal products	lbs	212,126,246	174,346,702[b]	63,894,093	82,541,868[d]	1,155	750[a]	276,021,494	256,889,320 lbs
Mechanical machinery	lbs	455,033,348	127,780,750[b]	130,434,395	57,571,638[d]			585,467,743	185,352,389 lbs
Electrical machinery	lbs	413,252,983	121,247,671[b]	177,728,799	81,961,419[d]	2,484	16[a]	590,984,266	203,209,106 lbs
Transport equip, vehicles	lbs	574,871,706	231,546,617[b]	637,863,742	403,821,720[d]	144,688	56,000[a]	1,212,880,136	635,424,337 lbs
Rubber, plastic products	lbs	238,397,254	166,023,212[b]	59,491,265	57,221,643[e]			297,888,519	223,244,855 lbs
Other, non-specific	lbs	752,133,056	269,232,403[b]	231,681,522	114,541,695[e]	3,097,091	179,009[a]	986,911,669	383,953,107 lbs
Total revenues:		6,724,210,405		3,699,575,543		19,702,952		11,584,266,912	

Exports: 1987		USA		Foreign Countries		Virgin Islands		Total imports	
		$	Quantity	$	Quantity	$	Quantity	$	Quantity
Crude petroleum	bbl					12,080	719[a]	12,080	719 bbl
Fuel oils	bbl	24,829,715	1,494,072[a]	25,606,975	1,552,385[a]	1,872,232	86,448[a]	52,308,922	3,132,905 bbl
Gasoline	bbl	7,122,556	278,033[a]	20,426,493	1,133,531[a]	8,059,555	314,707[a]	35,608,604	1,726,271 bbl
Motor fuel	bbl	3,376,061	165,548[a]	12,111,861	677,811[a]	75,705	4,285[a]	15,563,627	847,644 bbl
Kerosene, jet fuel	bbl	702,419	40,796[a]	1,346,148	59,909[a]	251,320	11,576[a]	2,299,887	112,281 bbl
Naphthas	bbl	4,551,227	302,096[a]	8,564,204	478,279[a]	272,062	7,281[a]	13,387,493	787,656 bbl
Oils	bbl								
Diesel	bbl								
Other oils	bbl	104,977,485	3,115,073[a]	33,781,715	627,922[a]	3,503,060	86,669[a]	142,262,260	3,829,664 bbl
Ethane, propane, butane	bbl			2,018,357	253,668[a]			2,018,357	253,668 bbl

Appendix 2: Import and export data for Puerto Rico in 1987 used in resource evaluation tables 3-6 (continued)

Exports: 1987		USA $	USA Quantity	Foreign Countries $	Foreign Countries Quantity	Virgin Islands $	Virgin Islands Quantity	Total imports $	Total imports Quantity
Natural gas	mcf			26,000	14,445[a]	76,450	42,472[a]	102,450	56,917 mcf
					Total petrol export revenues:			263,563,680	
Live animals	lbs	46,200	108,393[b]	495,855	1,163,357[c]	465,375	670,595[b]	1,007,430	1,942,345 lbs
Meat	lbs	2,683,274	1,860,192[a]	17,136,314	34,602,530[a]	8,892,494	15,180,954[a]	28,712,082	51,643,676 lbs
Fish	lbs	534,577,555	357,553,507[a]	4,565,823	3,306,018[a]	812,161	595,743[a]	539,955,539	361,455,268 lbs
Dairy	lbs	5,213,428	6,249,604[b]	5,000,835	5,994,757[c]	1,819,489	2,469,709[b]	12,033,752	14,714,070 lbs
Hides	lbs	2,546,208	3,203,825[b]	20,341,160	25,594,738[c]			22,887,368	28,798,563 lbs
Live plants	lbs	3,448,261	2,110,108[b]	454,576	278,171[c]	231,051	635,197[a]	4,133,888	3,023,476 lbs
Grains, cereals	lbs	563,001	2,750,298[a]	6,839,610	44,518,360[a]	3,509,126	14,689,984[b]	10,911,737	61,958,642 lbs
Grains, cereals	bu	162,408	53,866[a]	373,259	79,253[a]			535,667	133,119 bu
Vegetables	lbs	29,309,396	60,058,411[a]	7,316,634	20,106,130[a]	6,236,588	11,441,561[a]	42,862,618	91,606,102 lbs
Fruits, nuts	lbs	19,617,489	27,922,642[a]	8,929,549	17,435,461[a]	776,386	1,804,715[a]	29,323,424	47,162,818 lbs
Sugar, choc., syrup	lbs	48,848,658	52,049,684[a]	4,566,853	14,933,691[a]	964,630	1,630,100[a]	54,380,141	68,613,475 lbs
Coffee, tea, spices	lbs	8,687,621	4,931,322[a]	404,820	294,728[a]	1,539,192	1,787,434[a]	10,631,633	7,013,484 lbs
Juice, alcohol	lbs								
Juice, alcohol	gal	115,089,525	26,278,005[a]	7,855,776	2,416,842[a]	10,956,250	4,872,076[a]	133,901,551	33,566,923 gal
Tobacco, cigarettes	lbs	65,368,835	13,825,305[b]	35,432,366	7,493,835[a]	360,693	82,333[b]	101,161,894	21,401,474 lbs
Animal, vegetable oils	lbs	65,593	150,671[a]	1,895,154	4,810,276[a]	241,053	623,990[b]	2,201,800	5,584,937 lbs
Other animal and vegetable	lbs	1,052,394,999	273,210,124[b]	53,255,851	105,460,000[a]	16,310,254	27,524,447[b]	1,121,961,104	406,194,571 lbs
Wood product	lbs	3,616,049	5,582,433[b]	3,698,577	5,709,840[c]	4,605,909	20,781,470[b]	11,920,535	32,073,742 lbs
Cork, bamboo, rattan	lbs	35,780	22,136[a]	496,174	306,968[c]			531,954	329,104 lbs
Veneer, building boards	lbs	3,927,321	4,924,768[b]	1,628,432	2,042,015[c]	1,057,592	1,326,195[c]	6,613,345	8,292,978 lbs
Paper, cardboard	lbs	14,034,599	13,201,794[b]	25,109,950	206,210,000[a]	3,360,778	7,179,247[b]	42,505,327	226,591,041 lbs
Books	lbs	7,771,689	1,403,316[b]	3,168,515	664,434[f]	267,911	128,027[b]	11,208,115	2,195,777 lbs
Textiles	lbs	557,518,675	64,669,874[b]	95,549,757	12,871,470[f]	2,273,660	925,736[b]	655,342,092	78,467,079 lbs

Appendix 2: Import and export data for Puerto Rico in 1987 used in resource evaluation tables 3-6 (continued)

Exports: 1987		USA		Foreign Countries		Virgin Islands		Total imports	
		$	Quantity	$	Quantity	$	Quantity	$	Quantity
Organic chemicals	lbs	162,580,832	831,932,835[a]	83,010,876	675,130,000[a]	516,159	677,029[b]	246,107,867	1,507,739,864 lbs
Inorganic chemicals	lbs	144,724,880	47,113,137[a]	12,186,324	3,967,085[c]	7,111,296	7,295,868[b]	164,022,500	58,376,090 lbs
Pharmaceuticals	lbs	3,014,475,919	153,137,845[b]	364,672,206	21,514,404[f]	2,381,238	395,733[b]	3,381,529,363	175,047,982 lbs
Synthetic resins, rubber	lbs	8,452,349	8,346,188[a]	10,937,331	23,384,525[a]	726,345	887,540[b]	20,116,025	32,618,253 lbs
Gels, preps, soaps, dyes	lbs	549,513,442	132,187,685[a]	26,400,360	8,568,124[a]	10,245,985	7,218,249[a]	586,159,787	147,974,058 lbs
Fertilizer, pesticides, photo chem.	lbs	53,560,468	4,639,842[a]	2,877,165	1,183,347[a]	134,041	81,325[a]	56,571,674	5,904,514 lbs
Misc, chemicals, acids	lbs	87,915,587	15,430,163[b]	8,084,752	1,647,887[f]	180,923	161,944[b]	96,181,262	17,239,994 lbs
Nonmetal minerals and prods.	lbs	179,112,490	103,933,026[b]	10,572,465	6,134,850[c]	5,304,834	102,317,497[b]	194,989,789	212,385,373 lbs
Metal ores, non-specific	lbs	772,485	150,562[a]	8,786	1,712[c]	32,798	516,125[a]	814,069	668,399 lbs
Zinc ore	lbs								
Bauxite	lbs								
Iron ore	lbs								
Metals, alloys	lbs	26,826,417	44,340,209[b]	18,332,222	117,140,000[a]	2,630,081	6,268,446[b]	47,788,720	167,748,654 lbs
Metal products	lbs	71,509,135	21,933,006[b]	16,210,934	11,629,597[d]	6,841,331	7,508,667[b]	94,561,400	41,071,270 lbs
Mechanical machinery	lbs	1,212,523,621	52,839,872[b]	157,506,050	16,054,204[d]	12,043,902	7,466,160[b]	1,382,073,573	76,360,237 lbs
Electrical machinery	bs	766,852,528	92,844,150[b]	55,385,862	15,684,172[d]	4,925,466	1,318,076[b]	827,163,856	109,846,398 lbs
Transport equip, vehicles	lbs	175,385,203	49,772,242[b]	28,861,036	19,156,941[d]	36,279,308	12,781,122[b]	240,525,547	81,710,304 lbs
Rubber, plastic products	lbs	33,032,026	10,800,574[b]	21,728,013	7,104,469[c]	2,936,666	2,645,244[b]	57,696,705	20,550,287 lbs
Other, non-specific	lbs	1,347,937,658	119,520,570[b]	88,981,691	7,889,936[c]	42,608,903	33,632,151[b]	1,479,528,252	161,042,657 lbs
Total revenues:		10,456,261,067		1,314,153,666		213,702,332		12,247,680,745	

Source: 1987 External trade statistics, Junta de Planificacion, 1989.

Appendix 2: Net balance of imports and exports

Exports-imports: 1987		$	Quantity
Crude petroleum	bbl	-495,490,920	-29,599,592
Fuel oils	bbl	-127,754,801	-9,826,766
Gasoline	bbl	-95,842,199	-3,976,481
Motor fuel	bbl	14,219,627	782,834
Kerosene, jet fuel	bbl	-29,438,352	-1,321,357
Naphthas	bbl	-251,865,507	-13,973,344
Oils	bbl	-11,823,000	-168,349
Diesel	bbl	-8,509,000	-91,354
Other oils	bbl	140,922,260	3,811,260
Ethane, propane, butane	bbl	-11,647,157	-896,909
Natural gas	mcf	14,717	14,786
Total petrol:		-877,214,332	
Live animals	lbs	-2,067,970	-1,273,033
Meat	lbs	-405,540,700	-433,292,524
Fish	lbs	262,678,210	-143,667,922
Dairy	lbs	-162,678,696	-221,754,428
Hides	lbs	9,189,124	26,232,309
Live plants	lbs	3,361,575	2,224,492
Grains, cereals	lbs	-92,783,098	-1,090,702,909
Grains, cereals	bu	-5,096,925	-2,092,151
Vegetables	lbs	-148,878,137	-505,308,108
Fruits, nuts	lbs	-22,294,489	-84,100,965
Sugar, choc., syrup	lbs	-89,049,670	-433,279,951
Coffee, tea, spices	lbs	2,849,170	2,701,647
Juice, alcohol	lbs	-183,667,140	-550,007,191
Juice, alcohol	gal	76,957,316	20,368,360
Tobacco, cigarettes	lbs	48,512,183	3,594,435
Animal, vegetable oils	lbs	-53,328,518	-188,327,483
Other animal, vegetable	lbs	840,106,455	-159,347,503
Wood products	lbs	-55,570,664	-474,525,687
Cork, bamboo, rattan	lbs	-2,320,511	-2,107,638
Veneer, building boards	lbs	-48,589,351	-283,933,230
Paper, cardboard	lbs	-321,568,004	-506,014,339
Books	lbs	-50,688,380	-28,760,864
Textiles	lbs	68,128,323	-127,595,708
Organic chemicals	lbs	-34,401,116	677,327,194
Inorganic chemicals	lbs	-105,016,563	-427,671,193
Pharmaceuticals	lbs	2,994,361,323	105,882,306
Synthetic resins, rubber	lbs	-67,187,940	-114,309,897
Gels, preps, soaps, dyes	lbs	-17,715,814	-127,609,423

Appendix 2: Net balance of imports and exports (continued)

Exports-imports: 1987		**$**	**Q**
Fertilizer, pesticides, photo chem	lbs	22,954,349	-13,796,811
Other chemicals, acids	lbs	68,095,289	-13,672,976
Nonmetal minerals and prod.	lbs	25,116,739	-270,059,848
Metal ores, non-specific	lbs	779,730	665,897
Zinc ore	lbs	-6,144	-1,674
Bauxite	lbs	-146,492	-3,832
Iron ore	lbs	-96,172	-4,216
Metals, alloys	lbs	-267,950,301	-549,560,360
Metal products	lbs	-181,460,094	-215,818,050
Mechanical machinery	lbs	796,605,830	-108,992,152
Electrical machinery	lbs	236,179,590	-93,362,709
Transport equip, vehicles	lbs	-972,354,589	-553,714,033
Rubber, plastic products	lbs	-240,191,814	-202,694,567
Other, non-specific	lbs	492,616,583	-222,910,450
Net trade (exports - imports):		663,413,833	

Product weights for some commodity groups were not given or only given as shipping weights and had to be estimated as follows:

[a] = quantity is considered actual shipping weight of product.

[b] = product wt. is estimated as a percent of shipping wt.(drawn from subsample of 10 items from each commodity group with known product wts.):

- bottled goods = 1.15
- nonspecific goods = 1.12
- agricultural products = 1.1
- wood products = 1.02
- metals, machinery = 1.01

[c] = FC-imp-$ * US-imp-wgt / US-imp-$; relative price determined 1:1 based on subsample of 10 items from each commodity group.

[d] = ratio of metals, alloys (US-imp-wgt) / other metal category (US-imp-wgt) * metals, alloys (FC-imp-wgt)

	imports: US price ratios	imports: est. FC price ratios	exports: US price ratios	exports: est. FC Price ratios
met alloys	0.690(actual price)	0.303(actual price)	0.605(actual)	0.156
m prod	1.763x m-alloy	0.774	5.389x m-alloy	1.394
mech	5.160x m-alloy	2.266	37.928x m-alloy	9.811
electr	4.938x m-alloy	2.168	13.652x m-alloy	3.531
trans	3.597x m-alloy	1.580	5.824x m-alloy	1.507

[e] = est of average price difference between US imports and FC imports, based on 17 commodities with known unit prices (then FC-imp-wt = US price *FC/US price ratio)

	US $/lb, bbl	FC $/lb, bbl	US/FC price ratio:
Fuel oils	17.31	13.78	1.26
Gasoline	23.36	22.85	1.02
Kerosene	22.44	22.17	1.01
Naphthas	99.40	17.96	5.53
Oils	84.18	39.63	2.12
Ethane, propane	11.86	11.88	1.00

Appendix 2: Net balance of imports and exports (continued)

	US $/lb, bbl	FC $/lb, bbl	US/FC price ratio:
sMeats	0.84	1.11	0.76
Fish	1.44	0.52	2.78
Dairy	0.68	0.60	1.13
Grains	0.08	0.20	0.40
Vegetables	0.35	0.22	1.57
Fruits, nuts	0.43	0.27	1.60
Sugar, choc., syrups	0.43	0.12	3.51
Coffee, tea, spices	1.88	1.73	1.09
Animal, veg oils	0.27	0.16	1.71
Syn resins, rubber	0.54	0.53	1.02
Metals, alloys	0.68	0.30	2.25
Metal products	1.20	0.53	2.25
Mech machinery	3.53	1.56	2.25
Electr mach.	3.37	1.50	2.25
Transport equip, vehicles	2.46	1.09	2.25

US mean price is 1.75 times higher than FC prices (1.38 times higher w/o naphthas, sugar)

^{f} = est. of average unit cost difference between exports to US and FC markets,based on 36 commodities with known unit costs (then FC-exp-wt = US-price* FC/US price ratio)

	US $/lb, bbl	FC $/lb, bbl	US/FC price ratio:
Fuel oils	16.62	16.50	1.01
Gasoline	25.62	18.02	1.42
Motor fuel	20.39	17.87	1.14
Keroene, jet fuel	17.22	22.47	0.77
Naphthas	15.07	17.91	0.84
Other oils	33.70	53.80	0.63
Live animals	0.43	0.43	1.00
Meat	1.44	0.50	2.91
Fish	1.50	1.38	1.08
Dairy	0.83	0.83	1.00
Hides	0.79	0.79	1.00
Live Plants	1.63	1.63	1.00
Grains, cereals	0.20	0.15	1.33
Grains, cereals	3.02	4.71	0.64
Vegetables	0.49	0.36	1.34
Fruits, nuts	0.70	0.51	1.37
Sugar, choc., syrup	0.94	0.31	3.07
Coffee, tea, spices	1.76	1.37	1.28
Juice, alcohol	4.38	3.25	1.35
Tobacco, cig	4.73	4.73	1.00
Animal, veg oils	0.44	0.39	1.10
Wood prod.	0.65	0.65	1.00
Cork, bamboo, rattan	1.62	1.62	1.00
Veneer, bldg boards	0.80	0.80	1.00
Books	5.54	5.54	1.00
Textiles	8.62	8.62	1.00
Organic chemicals	0.20	0.12	1.59
Inorg chemicals	3.07	3.07	1.00
Pharmaceuticals	19.68	19.68	1.00
Syn. resins, rubber	1.01	0.47	2.17
Gels, preps, soaps, dyes	4.16	3.08	1.35
Fertilizer, pesticides, photo chem.	11.54	2.43	4.75
Misc. chem., acids	5.70	5.70	1.00
Nonmetal minerals, prods.	1.72	1.72	1.00
Metal ores, non-specific	5.18	5.18	1.00
Metals, alloys	0.61	0.16	3.87

US mean cost is 1.39 times higher than FC costs (1.16 times w/o sugar, fertilizers, metals)

Appendix 3: Estimates of the Solar EMERGY use/GP Index for 1992

Appendix 3: Estimates of solar EMERGY use/GP index for 1992

	1987	1992	Notes
Crude oil	7.28E+21	8.11E+21 sej	Actual
Refined fuels, oils	9.61E+21	1.30E+22 sej	Actual
Natural gas	1.64E+20	2.05E+20 sej	Actual
Coal	2.14E+20	2.68E+20 sej	Actual
Total petrol import	1.73E+22	2.16E+22 sej	Actual
Total petrol cost	1.14E+09	1.47E+09 $	Actual
All other imports	1.20E+22	1.71E+22 sej	Estimate
Import costs	1.07E+10	1.52E+10 $	Actual
Import services	1.75E+22	1.99E+22 sej	Estimate
Tourism	9.55E+08	1.60E+09 $	Actual
	1.91E+21	2.56E+21 sej	Actual
Loans	1.35E+09	1.83E+09 $	Actual
	2.70E+21	2.93E+21 sej	Actual
Environment	1.02E+21	1.02E+21 sej	Actual
Non-renew extraction	4.07E+20	3.95E+20 sej	Estimate
Total solar EMERGY	5.29E+22	6.55E+22 sej	
GDP	2.52E+10	3.98E+10 $	Actual
sej / $	2.10E+12	1.64E+12 sej/$	Actual
$ Export revenues	1.21E+10	2.11E+10 $	Actual
Export services	1.38E+22	1.60E+22 sej	
Export EMERGY	1.82E+22	3.17E+22 sej	

Appendix 3: Solar EMERGY from fuel imports and exports

	Total Imports 1987		Total Imports, 1992	
	$	Quantity	$	Quantity
Crude petroleum	495,503,000	29,600,311 bbl	558,792,000	32,951,390 bbl
Fuel oils	180,063,723	12,959,671 bbl	223,751,000	19,213,470 bbl
Gasoline	131,450,803	5,702,752 bbl	101,464,000	4,115,601 bbl
Motor fuel	1,344,000	64,810 bbl	50,238,000	2,053,060 bbl
Kerosene, jet fuel	31,738,239	1,433,638 bbl	123,000	5,501 bbl
Naphthas	265,253,000	14,761,000 bbl	438,145,000	18,904,710 bbl
Oils	11,823,000	168,349 bbl	6,420,000	83,597 bbl
Diesel	8,509,000	91,354 bbl	89,044,000	3,384,153 bbl
Other oils	1,340,000	18,404 bbl	2,648,000	49,349 bbl
Ethane, propane, butane	13,665,514	1,150,577 bbl		bbl
Natural gas	87,733	42,131 mcf		mcf
Total petrol cost:	1,140,778,012		1,470,625,000	$

	Total Imports 1987		Total Imports, 1992	
	$	Quantity	$	Quantity
Crude petroleum	12,080	719 bbl	540,000	bbl
Fuel oils	52,308,922	3,132,905 bbl	28,987,000	1,651,358 bbl
Gasoline	35,608,604	1,726,271 bbl	83,637,000	2,676,613 bbl
Motor fuel	15,563,627	847,644 bbl	39,265,000	1,624,930 bbl
Kerosene, jet fuel	2,299,887	112,281 bbl	138,000	6,183 bbl
Naphthas	13,387,493	787,656 bbl	18,869,000	1,078,155 bbl
Oils		bbl	5,519,000	53,872 bbl
Diesel		bbl	156,858,000	2,957,479 bbl
Other oils	142,262,260	3,829,664 bbl	140,000	1,127 bbl
Ethane, propane, butane	2,018,357	253,668 bbl		bbl
Natural gas	102,450	56,917 mcf		mcf
Total petrol revenues:	263,563,680		333,953,000	

Source: Junta de Planificacion 1987, 1992. Estimates were made using weighted average: ((Imports $, 92)/ (Imports $,87))* (Imported EMERGY, 1987)

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