

Final Report to  
THE COUSTEAU SOCIETY

**EMERGY SYNTHESIS PERSPECTIVES,  
SUSTAINABLE DEVELOPMENT, AND  
PUBLIC POLICY OPTIONS FOR  
PAPUA NEW GUINEA**

Steven J. Doherty and Mark T. Brown

with

R.C. Murphy, H.T. Odum and G.A. Smith

CFWWR Publication # 93-06

Research studies conducted under contract  
to The Cousteau Society

**Center for Wetlands & Water Resources**  
University of Florida  
Phelps Lab, P.O. Box 116350  
Gainesville, Florida 32611-6350  
U.S.A.

1993

**The Center for  
WETLANDS**



**& WATER  
RESOURCES**  
An Education and Research  
Unit of the University of Florida

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## PREFACE

Among the most important problems humanity faces today are the management of natural resources and the integration of human and natural processes. There is a need to understand both human and natural domains, each in the context of the other, and it is important to develop sound management strategies which acknowledge and promote the vital interconnections between the two.

Traditionally, a reductionist approach to the study of humanity and nature has dominated. By comparison, much less attention has been given to studying the biosphere at the ecosystem level of organization. It is at the ecosystem level, however, where many of nature's most important processes occur, where human benefits are derived and where our impacts fall most severely.

Most regions of the planet have already felt the heavy hand of development. Often such activities undermine the natural resource base due to a focus on short-term benefits. Too often this approach sets in motion long-term processes that drastically affect culture and minimize alternatives for sustainability. There are, though, a few jewels, such as Papua New Guinea, where cultural and natural resources have not yet been eliminated. These regions are coming under greater external pressure to "develop" along the same destructive paths seen elsewhere. Consequently, there is an urgent need to protect and manage wisely the cultural and natural heritage of Papua New Guinea. For these reasons the Cousteaus committed the "Rediscovery of the World" expeditions to explore, study and document on film the richness of Papua New Guinea.

Part of this project has been an investigation of Papua New Guinea's wealth in the broadest sense and an analysis of major economic activities (forestry, fisheries and tourism). Supported by members of The Cousteau Society, a research team from the University of Florida, USA, working under the direction of Drs. H. T. Odum and Mark Brown, undertook a substantial research effort to understand the connections among the human and economic sectors and the natural system. Using energy as a common denominator, the study compares and analyzes alternative uses of Papua New Guinea's resources in a search for sustainable strategies.

The research effort has shown that Papua New Guinea is one of the richest countries in the world: its natural wealth provides people with a quality of life, independence and stability, which provide relative immunity from the unpredictable fluctuations of external economics and politics.

We hope the insights provided by this report will encourage leaders to implement long-term strategies to accomplish one of the objectives stated in Papua New Guinea's constitution, ". . . for Papua New Guinea's natural resources and environment to be conserved and used for collective benefit of us all, and be replenished for the benefit of future generations."

Richard C. Murphy  
Vice President for Science and Education  
Cousteau Society

## ACKNOWLEDGEMENTS

As part of our effort to evaluate resource management questions in Papua New Guinea, we traveled to Papua New Guinea in the spring of 1989. Responding to The Cousteau Society's strong interest in education, we offered a short course in techniques of resource evaluation and systems modeling at the University of Papua New Guinea. We would like to express our gratitude to Dr. Patty Osborne of the Biology Department, University of Papua New Guinea, for his hospitality and the excellent job he did in organizing our workshop. Without his help we could not have had such an outstanding short course. Participants in that workshop were a most interesting and enthusiastic blend of students and government officials and we would like to thank them and wish them well in their endeavors to manage the resources of their developing nation.

The participants in the short course were: David Coates, FAO, Papua New Guinea; Christopher Hershey, Melanesian Environment Foundation, Inc., Papua New Guinea; William Asigau, Department of Environment and Conservation, Papua New Guinea; Charles D. Tenakanai, Fisheries Research-DMFR, Papua New Guinea; Ana Marikawa, Finance and Planning, Papua New Guinea; Malcolm Leveti, Dept. of Geography, UPNG; Gavera Arua Rei, Melanesian Environment Foundation, Inc. Papua New Guinea; Phille P. Daur, Biology Department, UPNG; Monica T. Rau, Forest Research Institute, Papua New Guinea; Lester Seri, Department of Environment and Conservation, Papua New Guinea; Mary Walta, Biology Department, UPNG; Tatsio Matsuoka, Department of Biology, UPNG; Anne Bothwell, Department of Biology, UPNG; Ilaiah Bigilal, Natural History Museum, Papua New Guinea; Harold Ure, USAJD/Radio Science Project, Papua New Guinea; Mathias Ure, Division of Research and Planning, Papua New Guinea; Sir Ebia Olewale, Karawane Pty Ltd., Papua New Guinea; Alois Wafy, Department of Fisheries/Marine Resources, Papua New Guinea; Barbara Brett, Department of Education, Papua New Guinea; Carrie Turk, Department of Finance and Planning, Papua New Guinea; Pins Piskaut, Department of Biology, UPNG; Robert Vonole, Department of Education, Papua New Guinea.

We would also like to thank Max Benjamin, owner of the Walindi Plantation on the Island of New Britain, who provided a wonderful setting and data that allowed us to evaluate tourism. His dive resort was one of the most ecologically sensitive, low energy, and culturally friendly resorts we have experienced . . . not to mention the most incredible diving we have experienced anywhere in the world.

John Furby, company secretary for Burns Philp Limited, Port Moresby, provided travel assistance. Dr. David Scienceman of New South Wales, Australia, visiting scientist with the University of Florida's Center for Wetlands & Water Resources, helped with logistical support, initiated contacts and supplied preliminary data and literature sources. His interest and support are greatly appreciated.

An acknowledgement section would not be complete without recognizing the pivotal role The Cousteau Society, Captain Jacques-Yves Cousteau, and Jean-Michel Cousteau have played in supporting our research over the past eight years. Since beginning their series of expeditions titled "Rediscovery of the World" they have provided funds and logistical support for our research as we accompanied the Cousteau teams on numerous expeditions. As a result, we have gained much in our understanding of the relationships between humanity and nature and have been able to share our insights with governments and citizens around the world. We cannot thank the Cousteaus enough for the opportunity they have provided to both research the complex questions facing humanity and to educate leaders, and future leaders of our water planet in how we might begin to solve these important questions.



# TABLE OF CONTENTS

PREFACE . . . . .	i
ACKNOWLEDGEMENTS . . . . .	ii
LIST OF TABLES . . . . .	vi
LIST OF FIGURES. . . . .	viii
<b>1. INTRODUCTION . . . . .</b>	<b>1-2</b>
Ecological Economics . . . . .	1-2
Overview of Papua New Guinea. . . . .	1-3
Natural History and Ecological Support Base . . . . .	1-3
Economy . . . . .	1-5
Systems View of Papua New Guinea . . . . .	1-7
Study Plan . . . . .	1-10
<b>2. METHODS . . . . .</b>	<b>2-2</b>
Step 1: Detailed Energy Systems Diagrams . . . . .	2-2
Step 2: Aggregated Systems Diagrams . . . . .	2-4
Step 3: Solar Emergy Evaluation Tables . . . . .	2-5
Step 4: Solar Emergy Indices . . . . .	2-6
Step 5: Microcomputer Simulation Models. . . . .	2-16
Step 6: Public Policy Questions. . . . .	2-17
<b>3. RESULTS</b>	
Section A: Emergy Synthesis of Papua New Guinea's Resource Base . . . . .	A-1
National Overview . . . . .	A-1
Regional Analysis of the Highlands and Lowlands . . . . .	A-12
Emergy Evaluation of Indigenous Resource Reserves . . . . .	A-17
Section B: Subsystems Analyses of Major Rural Production Systems. . . . .	B-1
Forestry in New Britain. . . . .	B-1
Sago Palm Cultivation in the Gulf Province . . . . .	B-8
Sweet Potato Farming in a Typical Highland Village . . . . .	B-10
Section C: Rainforest-Land Rotation Model . . . . .	C-1
Introduction. . . . .	C-1
Model Description . . . . .	C-1
Model Simulation. . . . .	C-9
Discussion . . . . .	C-14



Section D: Emergy Basis for Determining the Carrying Capacity of Tourism. . . . .	D-1
Introduction. . . . .	D-1
Results . . . . .	D-8
Discussion . . . . .	D-21
Section E: Energy, Time and Economic Expectations in a Highland Village . . . . .	E-1
Introduction. . . . .	E-1
Results . . . . .	E-4
Discussion . . . . .	E-10
Section F: Perspectives on Emergy Support of Indigenous Culture . . . . .	F-1
Introduction. . . . .	F-1
Results and Discussion . . . . .	F-2
<b>4. RECOMMENDATIONS AND CONCLUSIONS</b>	
The Basis for Wealth in Ecologic-Economic Systems . . . . .	4-1
Resource Policy Perspectives for Papua New Guinea. . . . .	4-3
Solar Emergy Basis for Nation. . . . .	4-3
Comparisons with Other Countries . . . . .	4-5
International Trade and Balance of Payments . . . . .	4-10
Regulation and Investment Considerations in Forestry Sector. . . . .	4-15
Tourism Development, Environmental Impact, and the Local Economy . . . . .	4-17
A Definition for Ecotourism . . . . .	4-18

**LITERATURE CITED**

**APPENDIX:** Brochure of collaborative workshop titled: Into the Future: Ecology, Economic and Public Policy in Papua New Guinea. May 5-10, 1990. Co-Sponsored by The Cousteau Society, The Department of Environment and Conservation and The University of Papua New Guinea.

## LIST OF TABLES

<u>Table</u>	<u>Page No.</u>
3A-1. Solar energy basis for Papua New Guinea's indigenous resource base, imports and exports in 1987.	3A-2
3A-2. Summary of major solar energy and monetary flows for Papua New Guinea in 1987.	3A-7
3A-3. Overview indices of annual solar energy-use, origin, and economic and demographic relations for Papua New Guinea in 1987.	3A-11
3A-4. Indigenous renewable solar energy support for highlands and lowlands regions in Papua New Guinea.	3A-14
3A-5. Storage of solar energy in resource reserves within Papua New Guinea.	3A-19
3B-1. Resource flows supporting rainforest logging in New Britain, Papua New Guinea.	3B-4
3C-1. Calibration of variables and coefficients for Rainforest-Land Rotation Model (corresponding to systems diagram in Figure C-1).	3C-4
3C-2. BASIC computer program used in simulation of Rainforest-Land Rotation Model (Figure C-1).	3C-6
3D-1. Comparative national energy indices for Papua New Guinea , Mexico and the United States.	3D-12
3D-2. Energy evaluation of tourist resort on island of New Britain, Papua New Guinea.	3D-13
3D-3. Energy evaluation of four star tourist hotel in Puerto Vallarta, Mexico (from Brown et al 1992).	3D-15
3D-4. Comparative energy indices for tourist resorts in Papua New Guinea and Mexico.	3D-18
3E-1. Time budgets for nine-hour work days for highland villagers in Papua New Guinea in 1933 and 1953.	3E-6

<u>Table</u>	<u>Page No.</u>
3E-2. Summary of time budgets for a 168 hour-week for Papua New Guinea in 1933, 1953 and 1975 and for the USA in 1975.	3E-7
3E-3. A typical daily diet for an adult Papua New Guinea highland villager in 1953.	3E-9
3F-1. Estimate of solar energy basis of indigenous culture in Papua New Guinea based on resident renewable inputs from ecological support base.	3F-4
3F-2. Macro-economic value of shared and genetic information on Papua New Guinea culture.	3F-6
4-1. Summary of solar energy flows and indices for Papua New Guinea in 1987.	4-4
4-2. Solar energy self-sufficiency and trade balance for Papua New Guinea and other countries of the world for overview.	4-7
4-3. Environmental and economic components of annual solar energy-use for Papua New Guinea and other countries of the world for overview.	4-8
4-4. Population density and solar energy-use per unit area for Papua New Guinea and other countries of the world for overview.	4-11
4-5. Solar energy-use, population and per capita use for Papua New Guinea and other countries of the world for overview.	4-12
4-6. Solar energy-use, gross national products and solar energy/dollar indices for Papua New Guinea and other countries of the world for overview.	4-13
4-7. Summary of the solar energy evaluation of tourism in New Britain, Papua New Guinea.	4-17

## LIST OF FIGURES

<u>Figure</u>	<u>Page No.</u>
1-1. Map of Papua New Guinea showing its location in the Southwest Pacific Ocean, its major rivers, central mountain range, major cities, mining operations and ports.	1-4
1-2. Systems diagram of the combined ecologic-economic system of Papua New Guinea.	1-8
2-1. Symbols and definitions of the energy language diagramming used to represent systems.	2-3
2-2. Simplified diagrams illustrating calculation of (a) net energy yield ratio; (b) net energy exchange ratio; and (c) solar transformity.	2-7
2-3. Systems diagram illustrating a calculation of investment ratio, environmental loading ratio and net yield ratio for a regional economy.	2-10
2-4. Systems diagram illustrating calculation of investment ratio, environmental loading ratio and net yield ratio for a sector of an economy.	2-12
2-5. Overview diagram of a nation, its environmental resource base, economic component, imports and exports: (a) main flows of money and solar energy; (b) procedure for summing solar energy flows.	2-15
3A-1. National summary diagrams of annual solar energy flows of Papua New Guinea.	3A-9
3A-2. Map of Papua New Guinea showing its inland relief; lowlands coastal plains and highlands above 300m.	3A-13
3A-3. Systems diagram relating solar energy flows associated with highlands and lowlands regions of Papua New Guinea (data from Table A-4).	3A-18
3B-1. Map of Papua New Guinea showing its forests of known and possible development potential.	3B-3
3B-2. Systems diagram of biomass production and cutting in lowland rainforest of New Britain, Papua New Guinea (data from Table B-1).	3B-6

<u>Figure</u>	<u>Page No.</u>
3B-3. Aggregated systems diagram of sago palm cultivation in the Gulf Province of Papua New Guinea.	3B-9
3B-4. Aggregated systems diagram of sweet potato production in a typical highlands village.	3B-11
3C-1. Energy systems diagram of a computer simulation model of rainforest-land rotation.	3C-2
3C-2. Output of model simulation of rainforest growth and net primary production over 150 years.	3C-10
3C-3. Simulation of biomass yield, rainforest growth, and land rotations based on 57/30 harvest schedule over 300 years.	3C-12
3C-4. Simulation of total yield response over 300 years due to changes in minimum and maximum land rotations.	3C-13
3D-1. Systems diagram of (a) a regional economy having no trade with external markets and (b) an economy that has developed trade.	3D-6
3D-2. Systems diagram illustrating the interactions of tourism with the regional economy.	3D-9
3D-3. Detailed systems diagram of a tourist facility showing the main production function that provides goods and services from the tourists who are attracted by the resort's image.	3D-11
3D-4. Overview diagrams illustrating USA trade advantage when tourists spend money in (a) Papua New Guinea and (b) Mexico.	3D-20
3D-5. Schematic diagrams of a coastline showing alternate ways of grouping tourist resorts within their ecological support regions so as not to exceed economic carrying capacity.	3D-24
3E-1. Systems diagram of a pre-World War II village family unit in the highlands of Papua New Guinea, circa 1930 prior to industrialization.	3E-2
3E-2. Systems diagram of a modern family unit in the highlands of Papua New Guinea, circa 1980.	3E-3
3F-1. Systems diagram showing the resource basis of cultural and genetic information, and their role in the organization of the combined system of humanity and nature.	3F-3

Figure

Page No.

- 4-1. Summary diagrams of ecological contributions, imports and export exchanges with the world economy for Papua New Guinea and the United States (values are normalized relative to environmental source inputs).

4-9



# **Emergy Synthesis Perspectives, Sustainable Development, and Public Policy Options for Papua New Guinea**

S.J. Doherty and M.T. Brown, editors

## **INTRODUCTION**

Papua New Guinea is at a pivotal point in its history. Rich in both culture and resources, the country is poised between its isolated past and a complicated future. Papua New Guinea is increasingly being drawn into the greater world economy at the expense of these rich ecologic and cultural systems. As its population grows and its economy is further incorporated into the world economy, one based on imports and exports, Papua New Guinea is confronted with many of the policy questions regarding the exploitation of natural resources that all developing nations face.

This study was undertaken to address specific questions regarding resource utilization and proposed developments in order to identify public policy perspectives for Papua New Guinea and make recommendations for a sustainable future. Systems analyses of the national economy, its resource base of environmental flows, imports and its exports were conducted. Several subsystems within Papua New Guinea were also analyzed for investment requirements and net contribution to the combined national ecologic-economic system.

Forest operations, rural production systems and tourism were each analyzed using data obtained from industry experts and the current literature. Resource allocation between highland and lowland regions was investigated based on demographic, socioeconomic and environmental conditions unique to each region. A microcomputer simulation model of rainforest growth and harvesting was developed to investigate the relationships between land clearings and forest recovery. Energy and time in a highlands village was studied and the concept of ecological support was applied to indigenous cultures. The question of whether or not raw products should be directly shipped out of the country instead of using these resources internally was addressed. A proper balance of development and environment was investigated based on the extent of free indigenous sources which drive the economy. Alternative public policies were suggested which may aid Papua New Guinea in its effort to develop and still maintain its rich cultural and ecological systems.



## ECOLOGICAL ECONOMICS

Regional and national economies are increasingly becoming more global. Issues of resource development, trade and information exchange are likewise growing in proportion to expanding populations and related activities. Resources needed to support human potential today are placing great demands on our biosphere. The days of frontier economics are behind us. Uncontrolled exploitation of limited resources has proven disastrous in many regions of the globe. As economies and ecological support systems become more interdependent, new disciplines are needed to "bridge the gap" of understanding between societies and nature. It is now clear that neither ecology nor economics alone can address the problems of our global commons. New measures of wealth, of value, of contributions and production are needed that acknowledge the "natural capital" and "ecosystem services" provided from healthy environments.

A new interface is now being recognized called "ecological-economics." It is an ambitious and necessary attempt to understand the affairs of humanity and nature as a single, interdependent system. New tools are being investigated to measure wealth, services and production fairly and equitably. In this report we use systems analysis, a holistic approach to studying the combined ecological-economic system of Papua New Guinea. We use an alternative measure of value, based on real contributions to system performance, termed EMERGY, spelled with an "M." It is a concept which quantifies "energy memory" in products and processes. It is an accounting unit of total contributions, direct and indirect, used in the generation of a product or service. It is a concept derived from understanding whole systems, their interactions and interdependencies, and the resources driving and maintaining them.

While most analyses of energy investment have traditionally been used to investigate efficiency in industrial processes, a broader approach is undertaken here to investigate Papua New Guinea's resource utilization and exchange. Emergy analysis allows comparison and incorporation of environmental costs and benefits with variables of traditional economic costs and benefits to provide a more comprehensive perspective for public policy directives affecting the common good.

## **OVERVIEW OF PAPUA NEW GUINEA**

The country of Papua New Guinea (Figure 1-1) lies on the eastern half of the island of New Guinea just above Australia in the southwestern Pacific Ocean. Its only island neighbor is Irian Jaya, which occupies the island's western half. Together, they form the western end of Melanesia. It is one of the largest countries in the South Pacific with a total area of 460,000 km<sup>2</sup> including some 600 offshore islands.

### **Natural History and Ecological Support Base**

Situated between the stable land mass of Australia and the deep ocean basin of the Pacific, the island of New Guinea is considered one of the most mobile zones of the earth's crust (Loffler 1982). It is characterized by high seismic activity, widespread volcanism, with young faulted and folded mountain chains being the most conspicuous features of New Guinea. A great central spine of mountain ranges, extends for the length of the island, with few gaps below 2000 m for much of its length. Between 2 and 10 degrees south latitude, New Guinea lays claim to being the largest tropical island, the highest island, one of only three tropical areas with glaciers (Gressitt 1982), as well as a land of a great variety of vegetation types, and most kinds of environments except deserts (Johns 1982). Biologically, New Guinea is one of the most diverse habitats on earth, with characteristic groups of biota such as the famous birds of paradise, the tree kangaroos, and the specialized moss-forest weevils.

The indigenous populations of Papua New Guinea have historically been isolated from the world economy and have only recently been in contact with external markets and political forces (Matthiessen 1962, Howlett 1967, Rappaport 1968, Bulmer 1988). The country's independence only came in 1975 after a century of complicated political history and colonial rule. Owing to difficult terrain, plentiful resources as well as cultural mechanisms, the peoples of PNG remain a fragmented and diverse society with over 700 pidgin languages known to be spoken. The present day inhabitants of PNG exhibit a diversity that "undoubtedly reflects a lengthy and complex history of settlement from outside the area, internal migration and intermarriage" among the many villages (Chowning 1982).

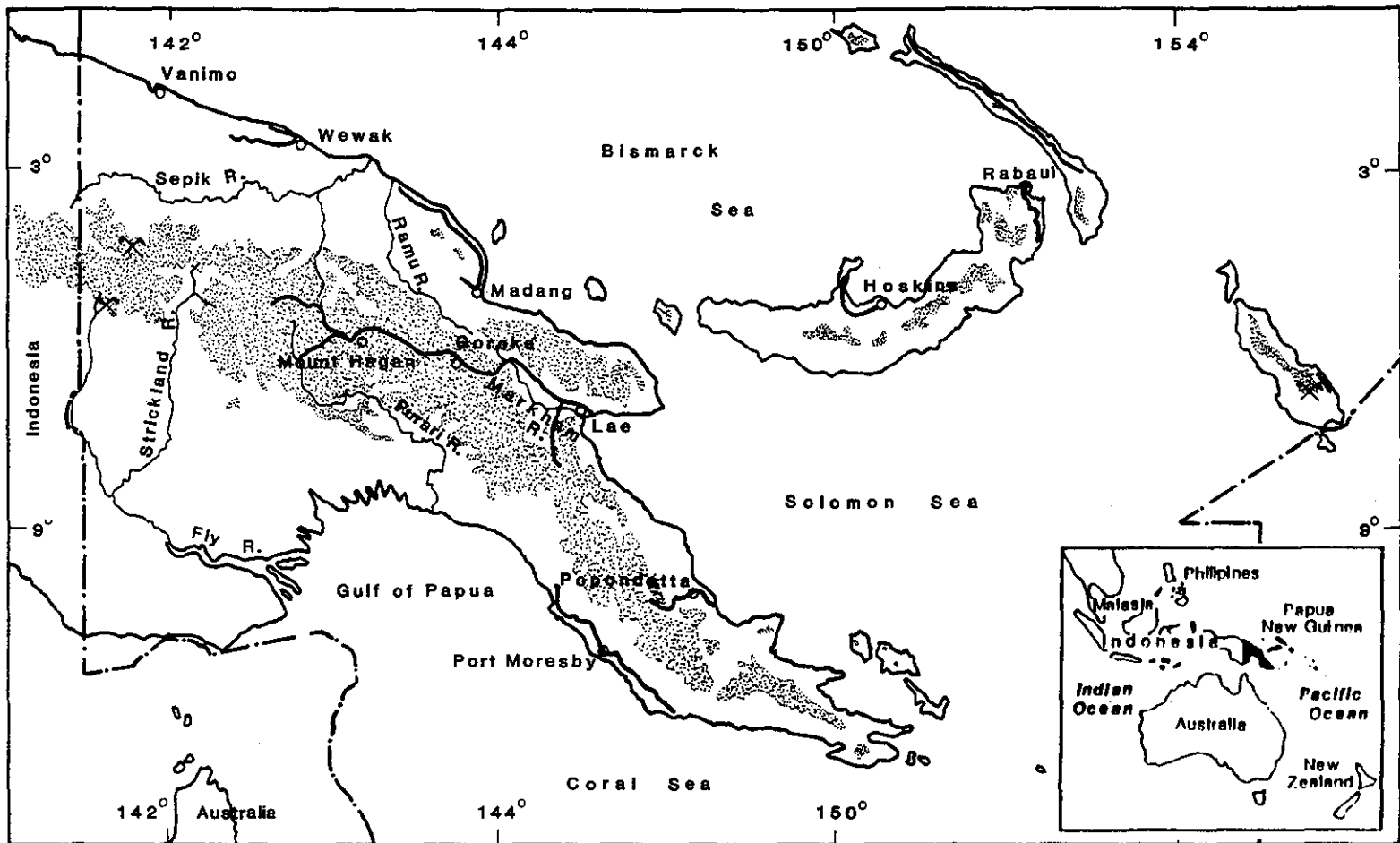


Figure 1-1. Map of Papua New Guinea showing its major rivers, central mountain range, major cities, mining operations and roads (from Baldwin et al 1978).

The country's population is about 3.5 million, but is growing at a rapid 2-3% per year (Qureshi et al 1988) due largely to immigration along its coastal port cities. Villages in the highlands, which has historically been the more populated region, however, have maintained an average population of about 200 over the past 30 years even though the country's population has doubled (Bell 1986). Most of the immigrant population is settling along coastal areas near ports where a monied economy has developed based mainly on exports of unprocessed minerals, timber, tuna, and cash crops.

### **Economy**

Traditionally, almost the entire indigenous population of Papua New Guinea was supported by a subsistence economy based on agriculture. A few groups were hunters and gatherers and those along the coast relied largely on fishing (Howlett 1967). Every village had pigs, though they were more a part of cultural and religious spheres rather than the economic sector (Rappaport 1968). The majority of inhabitants, however, were cultivators, practicing various forms of swidden agriculture. Trade has always been an important form of exchange which cannot be accounted for in traditional economic terms.

Even today, 80-85% of the population rely on some form of subsistence farming (Bell 1986, Qureshi et al 1988) and 97% of all land is still held within customary land tenure systems (Qureshi et al 1988). Contact with a monied economy has meant a shift from subsistence farming of indigenous crops to crops grown for sale outside the village for the purchase of materials and energy which are increasingly being incorporated into their culture. The economy is still in the early stages of development, dominated by agriculture and mining activities (PNG Information Booklet 1986). Since independence in 1975, the national economic policy has aimed at financial stability while "promoting sustained, broad based growth and raising the rural living standards" (Qureshi et al 1988). This is accomplished primarily by encouraging subsistence villagers to increasingly participate in the production of cash crops either for export or for domestic markets.

The mining sector now accounts for close to 15% of the gross domestic product (GDP) and 60% of the money received for exports (Qureshi et al 1988). Present mining of copper, gold, silver and the prospects for oil exploration indicate that this sector will continue to contribute significantly to the annual GDP (Coopers et al 1988). All minerals are extracted and exported directly; there is presently no internal processing of any

kind. Companies are foreign owned and Qureshi et al (1988) state that PNG receives only the money paid to its people for the work they contribute and through leasing of the land.

Agriculture, while supporting either directly or indirectly 85% of the population, accounts for only 35% of the GDP and about 43% of exports (Qureshi et al 1988) in monetary terms. Cash cropping systems constitute 55% of the total agricultural production, with the remaining 45% representing subsistence cultivation. Four tree crops--coffee, cocoa, oil palm and copra--provide about 90% of agricultural exports (PNG National Statistics Office 1986). Small holder farming tracts produce two-thirds of the output of these crops, with commercial plantations accounting for the rest. Presently timber extraction and fisheries together account for only 7% of the dollar income earned from exports, although both sectors are considered to have considerable potential for growth (Qureshi et al 1988). Exports, making up about 42% of the GDP, roughly balance imports in monetary terms.

GDP in 1987 was 2.535 billion US\$ with a debt service ratio (external loans/GDP) averaging 30% annually (Qureshi et al 1988). More than half of this foreign financing requirement is related to private industry, predominantly the mining sector. In addition foreign aid and an annual grant from the Australian Government amount for about 37% of budget revenue (PNG Information Booklet 1986). The growth of GDP during the seventies averaged 1.2% annually (Galenson et al 1982). With an annual population growth rate of 2.4%, the growth in GDP averaged less than half the rate of population increase. Growth of GDP has improved over the last few years, averaging 2.3% (Qureshi et al 1988), due mainly to increased mineral extractions and sales.

Because of the continued importance of subsistence agriculture, only about 12.5% of the labor force is considered formally employed (PNG National Stats. Office 1987a). The remainder of the labor force is part of the self-sustaining subsistence economy outside of the cash economy.

## SYSTEMS VIEW OF PAPUA NEW GUINEA

Papua New Guinea is an area of incredible variety of geomorphology, biota, peoples, languages, history, traditions and cultures. Diversity is its primary characteristic, whatever the subject of interest. These relationships of indigenous storage, environmental and economic inputs and outflows of Papua New Guinea are shown in the conceptual energy diagram in Figure 1-2. The system's boundaries include the continental shelf to a depth of 152 m below sea level (estimate made from map by Espenshade et al 1986) to insure the environmental contributions of marine resources to the overall economy.

At the left of the diagram, outside renewable sources of sunlight, rain and tides are illustrated as input flows driving the natural production systems. These major ecoregions are diagrammed as coastal/mangrove, grasslands, lowland rainforests and montane/alpine rainforests for overview. Mixed lowland rain forests are the predominant life zone, covering as much as 40% of the country (Davidson 1983). Geologic uplift is an important input to Papua New Guinea, creating the vast mountain ranges as a land form with great geopotential work stored. The top soils in the highlands valleys are fertile, often up to 1.5 m in depth (Grossman 1984), and the climate is tropical and monsoonal with a high average annual rainfall of 1.2 meters on the coasts to 3.8 m in the central highlands (PNG Information Booklet 1986). The heavy rainfall and steep slopes give rise to extensive rivers, considerable erosion, depositing large quantities of alluvial material into the highland valleys and flat coastal plains. These large river systems are shown being driven by the interaction of mountains and rainfall.

Large mineral deposits of copper, gold and silver exist and are being mined and potential hydrocarbon reserves are only beginning to be realized (Hapgood 1989). It is expected that these storage, although concentrated and exhaustible, will continue to be the major source of revenue from PNG's rich natural resources.

Subsistence farming is shown as a subsystem dependent on indigenous sources and energy production in natural systems, with only minimal ties to the main economy. Religion and rituals are still very important in rural villages shown in the diagram as information storage which feedback to the labor and land involved in gardens. Subsistence agriculture and smallholder cash cropping involve the

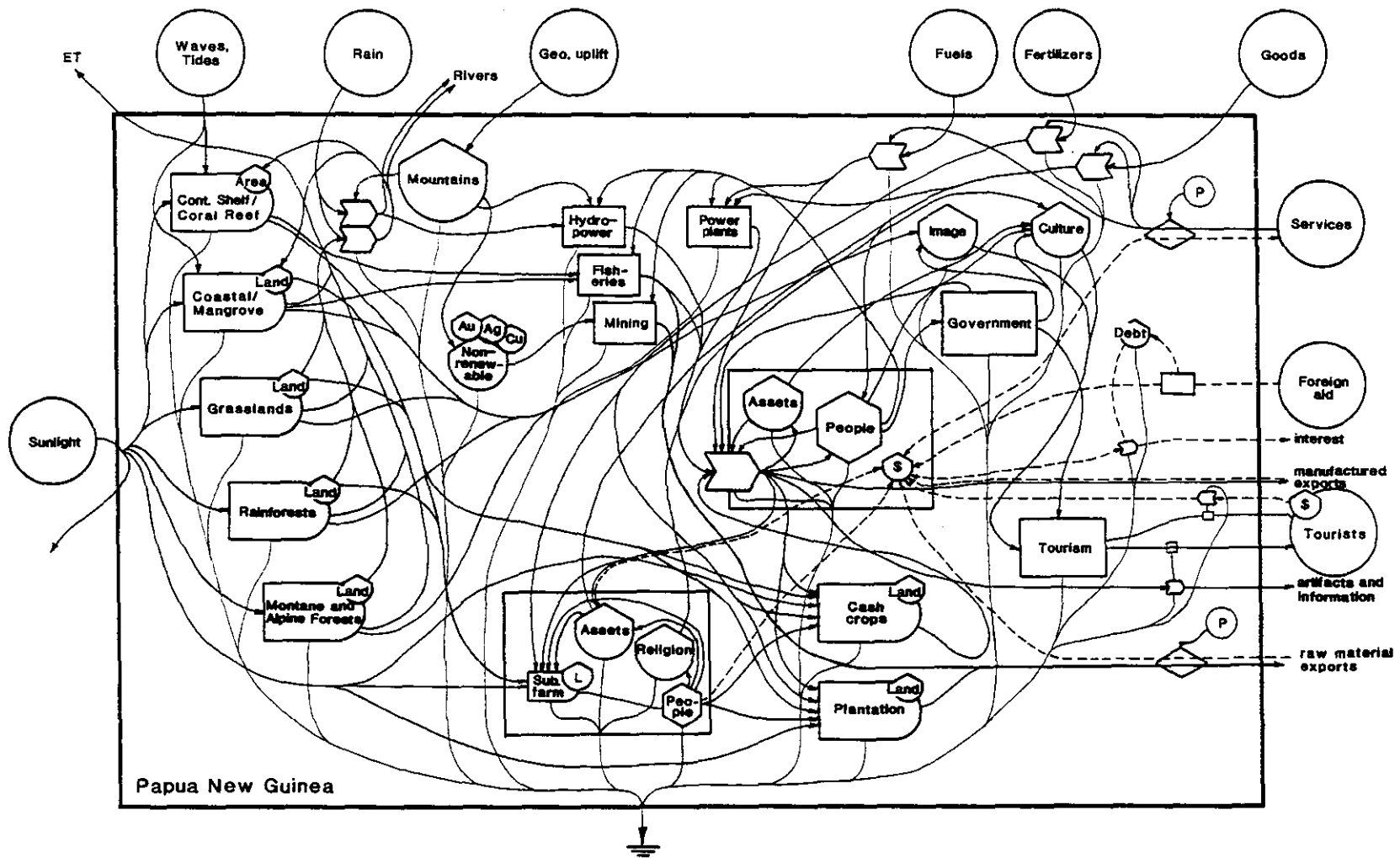


Figure 1-2. Systems diagram of the combined ecologic-economic system of Papua New Guinea for overview. Shown are indigenous source flows and imports (drawn outside the system frame); major ecological systems, resource reserves, industries, economic sectors, rural and urban communities, and culture (drawn as internal components); and exports and trade. P=Price.

most intensive and widespread use of Papua New Guinea's land resources. Bell (1986), however, notes that many parts of PNG, perhaps 80% of the total area, remain unused due to steep topographic relief and inhospitable climate. Most of Papua New Guinea's population is rural with 2/3 of the people involved in subsistence gardening or cash cropping in highlands valleys and coastal plains. Shifting cultivation with a rotation period of 10-15 years, has traditionally been the main basis of food production for villagers, growing sweet potato, taro, cassava, and sago. These gardens may be used for up to 5 years or more before a new site is selected (Bell 1986).

Increasingly, small landholders are converting land to produce cash crops such as coconuts, coffee, and cocoa. Cash crop farms and tree plantations are diagrammed as fuel subsidized production systems drawing from the environment. With human derived inputs of fossil fuels, fertilizers, goods and services the environmental resources are incorporated into the overall economy of PNG. Industries are shown as subsystems drawing from the storage of environmental and geologic production. Mining, fishing, and forest extraction are shown as subsectors within the overall system. As indicated by their outflow lines, most of their product is not incorporated or refined within the country and exported directly, contributing only to the economic (right hand) side of the system. Hydroelectric power is harnessed from the rivers and used internally, since it cannot be exported as a product like other fuels.

Money is shown on the right hand side of the diagram as dotted lines flowing in opposite direction of energy flow, acting as a counter current to real products. Notice that money is paying only for the services of human work and therefore not represented on the left hand, production side of the system diagram. Money is not represented as paying for the vast work of the environment. Further, as illustrated in the country diagram, major aspects of PNG's economy are operating without money pathways, and therefore not accompanied by dashed lines. Foreign aid is shown as an economic input with a multiplier action in the return flow of interest payments.



## STUDY PLAN

In the study that follows, the nation of Papua New Guinea is considered as a system with its large inventory of indigenous energy storages and flows as well as its interactions with the global economy. The report is organized in four sections: Introduction, Methods, Results and Discussion. Results and Discussion are presented as follows:

First, emergy analysis is used to develop perspectives on the country's resource-use and competitive position with other nations of the world. Relationships of solar emergy flows to the economy are developed to make policy recommendations based on resource requirements, use and exchange. All major components are identified, including environmental sources, flows of money, human roles, imported goods and fuels, and international exchanges. Highland and lowland regions are evaluated individually as well as analyses of all major, known resource reserves. Indices are then presented which enable comparisons of emergy measures with those of traditional economics.

Analyses of several sectors of Papua New Guinea's economy are then presented: evaluations of forest operations and tourism on the island of New Britain, sago palm cultivation in the Gulf Province, sweet potato production in a highland village. A microcomputer model of forest-land rotation is presented to investigate the exploitation rates, land clearings and ecosystem response in tropical rainforests. Activities studies are then used to evaluate changes in economic expectations and time spent in varying tasks in a typical highland village from 1930 to the present. Finally, a preliminary analysis of indigenous culture is presented.

New concepts such as *ecological support area*, *net yield on investment*, *environmental loading* and *buying power* are presented which may aid the reader in better understanding solar emergy measures of combined ecologic-economic systems. Conclusions are then drawn for each of these subsystems and an interpretation and discussion of the implications and meaning of the results are given. Finally, these results are used to evaluate management alternatives and make policy recommendations which account for the work of nature and humans in the capital production of Papua New Guinea.

Given next is a short list of definitions given for key words and concepts used throughout this report.

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

Emergy: An expression of all the energy used in the work processes that generate a product or service in units of one type of energy. **Solar emergy** of a product or service is the solar energy embodied, through successive transformations, required to create and maintain the product or service. Emergy can be thought of as **energy memory** -- that energy used up and transformed in a long chain of interactions, culminating in a product or process that is being evaluated. Emergy, unlike energy, is not directly measurable, but must be quantified using systems analysis.

Emjoule: The unit of measure of emergy is the "emergy joule," abbreviated emjoule. In this report, it is expressed in the units of solar energy previously used to generate a product or service, therefore expressed as a **solar emjoule (sej)**.

Empower: Power is defined as the ability to influence. **Empower** is the flow of emergy per unit time, a measure of potential influence.

Macro-economic value: This is a measure of the money that circulates in an economy as the result of some process. To obtain the macro-economic dollar value of an emergy flow or storage, the emergy was multiplied by the ratio of total emergy use by Papua New Guinea to its Gross National Product (**solar emjoules / kina or sej / US \$**).

Maximum empower principle: Systems that tend to prevail are those that take the most effective advantage of available **emergy**. Systems, economic or ecological, accomplish this by: reinforcing productive processes, drawing more resources, and overcoming more limitations through effective system organization. A theory investigated in this study is that patterns which maximize **emergy** contribute the most wealth.

Nonrenewable energy: Energy and material storages that are used at rates that far exceed the rates at which they are produced. Examples are fossil fuels and mineral ores. In each, geologic and environmental processes of heating, compression and concentration occur at a rate much slower than society's consumption. Soil can also be nonrenewable if it is depleted faster than its environmental support system can naturally replenish it. Nonrenewable resources generally have large energy values since they represent large amounts of biological and geologic work.

Renewable energy: Energy flows of the biosphere that are generally constant and reoccurring, and which ultimately drive the bio-chemical processes of the earth and contribute to geologic processes. Examples are sunlight, rainfall and wind. Each of these resources is ultimately limited by its flow rate -- systems cannot draw from these sources any faster than they are delivered.

Resident energy: These are renewable resources that are characteristic of a region.

Transformity: The ratio obtained by dividing the total energy used in a process by the energy yielded by the process. Solar transformity is measured as the **solar emjoules per joule (sej/J)** for a given product or service. Solar transformities are used to convert energies of different types to solar energy in order to compare different energies of resources, products and services.

## METHODS

This study was undertaken using a "top-down" systems approach. The first step is to construct systems diagrams that are a means of organizing large arrays of components, pathways of exchange and resource flows that combine to form the combined ecologic-economic systems under study. The second step was to evaluate all resources identified through discussion, literature review and diagramming which contribute to the combined ecologic-economic system under study. The third step involves calculating several indices that relate resource flows and monetary exchange in order to identify support base, economic vitality and carrying capacity. Finally, public policy options are recommended for proposed development and resource-use sectors.

In order to determine the relation between resource-use and the gross national product and to better understand and subsystem analyses and resource models in perspective of the national trends, the natural resource base and economy of Papua New Guinea was first synthesized. Subsystems analyses of the highlands and lowlands, forest operations, tourism and culture were then undertaken. Computer simulation models were constructed for forest rotations and offshore tuna and coastal shrimp fisheries operations.

Each system or subsystem was studied with a similar methodology (steps 1-6) as follows:

- (1) First a detailed energy systems diagram of each system studied was drawn as a way to gain an initial network overview, combine information of participants, and organize data-gathering efforts. This was done for the entire country of Papua New Guinea and each of the subsectors that were investigated.
- (2) Next, aggregated diagrams were generated from the detailed ones by grouping components into those believed important to system trends, those of particular interest to current public policy questions, and those to be evaluated as line items in resource evaluation tables.
- (3) Solar energy evaluation tables were set up 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, kina, US\$, etc.) and also evaluated in solar energy units (solar emjoules) and macro-economic terms to facilitate comparisons and public policy inferences.
- (4) Indices of solar energy-use and source origin were calculated to compare systems, predict trends, to suggest alternatives, identify system efficiencies, and which will be successful.
- (5) For some systems a microcomputer simulation program was written to study the temporal and/or spatial properties of an aggregated model. The program was used as a controlled experiment to

study the effects of varying one factor at a time. Data from literature, resource specialists in Papua New Guinea, and the solar energy analyses were used as calibration. Insights on sensitivities and trends were then suggested from computer graphs.

- (6) Models, evaluations and simulations were used to consider which alternatives generate more real contributions to the unified economy of humanity and nature in Papua New Guinea.

Each of these steps are described in detail below.

### **Step 1: Detailed Energy Systems Diagram**

For understanding, for evaluating, and for simulating, our procedures start with diagramming the system of interest, or a subsystem of particular interest. This initial diagramming is done in detail with anything put on paper that can be identified as a relative influence to the system of interest, even though it is thought to be minor. The first complex diagram is like an inventory. Since the diagram usually includes environmental and economic components, it might be considered an organized impact statement. The following are the steps in the initial diagramming of a system to be evaluated:

1. The boundary of the system is defined.
2. A list of important sources (external causes, external factors, forcing functions) is made.
3. A list of principal component parts believed important, considering the scale of the defined system, is made.
4. A list of processes (flows, relationships, interactions, production and consumption processes, etc.) is made. Included in these are flows and transactions of money believed to be important.
5. With these lists agreed on as the important aspects of the system and the question under consideration, the diagram is drawn using the following conventions of energy language diagramming (from Odum 1971, 1992):

Symbols: The symbols each have rigorous energetic and mathematical meanings (Figure 2-1). An example of a system diagram is given in Figure 3 as an overview of the combined environmental-economic system of Papua New Guinea.

System Frame: A rectangular box is drawn to represent the boundaries that are selected.

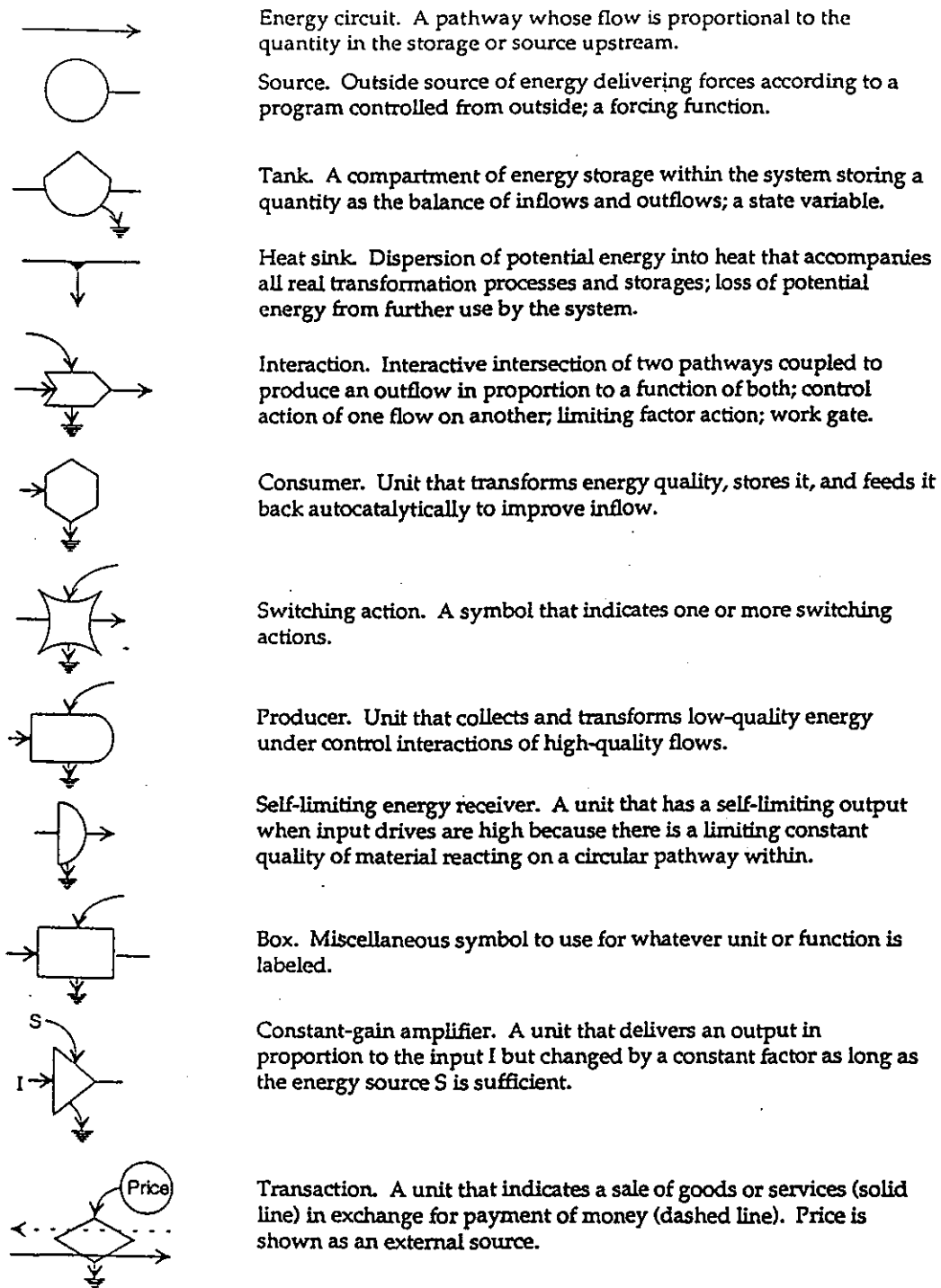


Figure 2-1. Symbols and definitions of the energy language diagramming used to represent systems (from Odum 1971, 1983).

**Arrangement of Sources:** Any input that crosses a boundary is a source, including pure energy flows, materials, information, the genes of living organisms, human services, as well as inputs that are destructive. All of these inputs are given a circular symbol. Sources are arranged around the outside border from left to right in order of their ability to influence the system (i.e., their solar transformities) 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 opposite direction of energy flows. Lines without barbs to indicate direction of flow, may flow in either direction dependent on the difference between two forces.

**Outflows:** Any outflow which 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 is heat energy as byproducts of processes and the dispersed energy from depreciation of storages.

**Adding Pathways:** Pathways add their flows when they join or when they go into the same the 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 flows that are different, but are both required for a 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 connecting to the notched left margin of the symbol (refer to Figure 2-1 for details).

**Counterclockwise Feedbacks:** High-quality outputs from consumers such as information, controls, and scarce materials are fed back from right to left in the diagram. Feedbacks from right to left represent a loss of concentration because of divergence, the service usually being spread out to a larger area.

**Material Balances:** Since all inflowing materials either accumulate in systems storages or flow out, each inflowing material such as water or money needs to have outflows drawn.

## **Step 2: Aggregated Systems Diagrams**

Aggregated diagrams were simplified from the detailed diagrams, not by leaving things out, but by combining them in aggregated categories. Simplified diagrams have: the source inputs (cross boundary flows) to be evaluated; environmental inflows (sun, wind, rain, rivers, and geological processes, etc.); the purchased resources (fuels, minerals, electricity, foods, fiber, wood); human labor and indirect services; money and

exchanges; and information flows. Export flows were also drawn. Initial evaluations were useful in deciding what was important enough to retain as a separate unit in the diagram.

Components inside the system boundary included: the main land use areas; large storages of fuel, water, and soil; the main economic interfaces with environmental resources; and final consumers. Interior circulation of money was not drawn, but all the major flows of money in and out of the systems were included.

### Step 3: Solar Energy Evaluation Tables

All systems studied, including the national overview analysis and subsystems evaluations of forest production, development and use are summarized using solar energy evaluation tables with calculations of inputs and summaries of solar energy indices given as footnotes. Each table is presented similarly, with 6 columns, each with the following headings:

1	2	3	4	5	6
Footnote	Item	Basic data (J, tons, \$ cost)	Solar transformity ( <i>sej/J</i> )	Solar energy ( <i>sej/quantity/time</i> )	Macro-economic value (US\$, 1988)

Column One is the line item number, which is also the number of the footnote in the table where the source of the raw data is cited and calculations shown.

Column Two is the name of the item being evaluated, which is also shown on the aggregated diagram.

Column Three is the resource inputs to production, given in units reported by industry accounting or obtained from environmental and statistical abstracts. These are reported as average annual flows (joules, grams or US \$) per unit volume or area, derived from various sources and identified as footnotes (column 1).

Column Four is the solar transformity or solar energy per unit for each input, measured in solar emjoules per joule, *sej/J* (or *sej/gram*; or *sej/dollar*, see definitions below). These are obtained from previous, independent studies (updated from Odum et al 1983; McClanahan and Brown 1991, Odum and Arding 1991, and Odum 1991).

Column Five is the solar energy of the resource input, measured in solar emjoules per year per production output. It is the product of columns 3 and 4.



Column Six is the macro-economic value, reported in macro-economic dollars, for 1988. This was obtained by dividing the solar energy (column 5) by the relation of annual solar energy-use to Papua New Guinea's GNP in 1988. See definitions below for solar energy per dollar index and macro-economic value.

Inputs and outputs for any evaluated sector is identified on each solar energy evaluation table and in the text and footnotes using a similar notation. Aggregations of environmental inputs are identified as (I<sub>i</sub>); each set of purchased inputs associated with a particular process step is summed as (F<sub>i</sub>); and product yields are identified as Y<sub>i</sub>. Any solar transformities calculated as a result of a subsystems analysis are indexed in the tables by lower case letters (*a, b, c...*) given as footnotes. This was done in order to separate solar transformities derived from other, referenced independent studies and those that were calculated as a result of this study.

#### **Step 4: Solar Energy Indices**

From the energy evaluation tables, comparative indices of solar energy origins, allocations, exchange, and relations to macro-economic valuation were calculated to draw inferences, gain perspectives, and aid in decisions regarding public policy and welfare.

#### **Net Yield Ratio**

The net solar energy yield ratio is the solar energy of an output divided by the solar energy of those inputs to the process that are purchased and fed back from the economy (Figure 2-2a). This ratio indicates whether the process can compete in supplying a primary energy source for an economy. Typical competitive fuel sources have been about 4 or 6 to 1, though these favorable ratios are declining as fossil reserves decline increasing extraction and processing costs. Processes yielding less than those available may not be currently economic as primary sources.

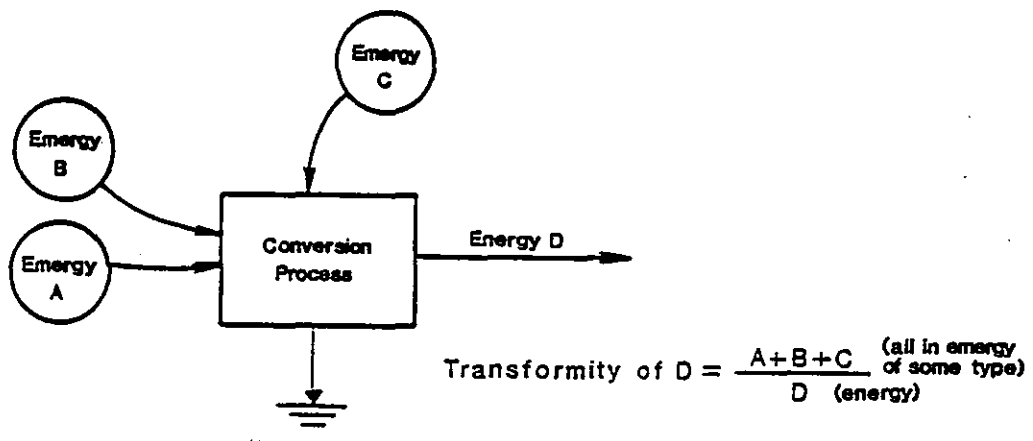
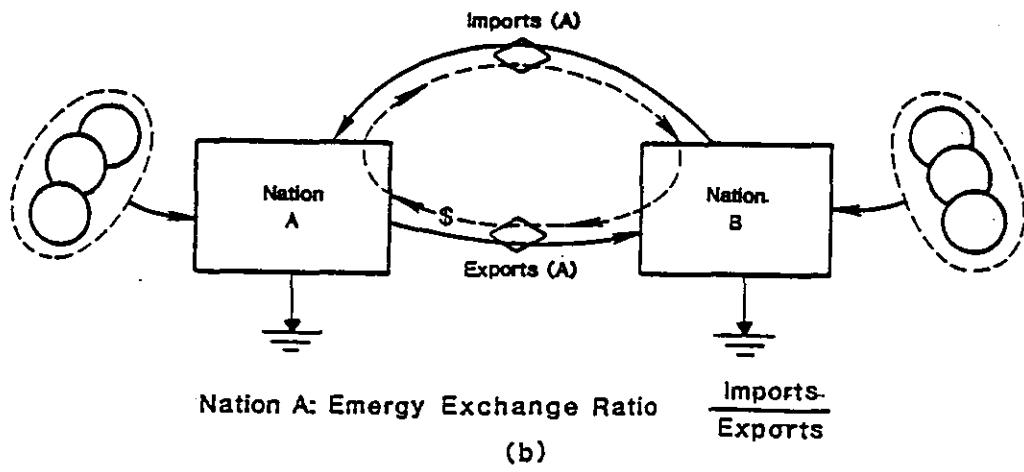
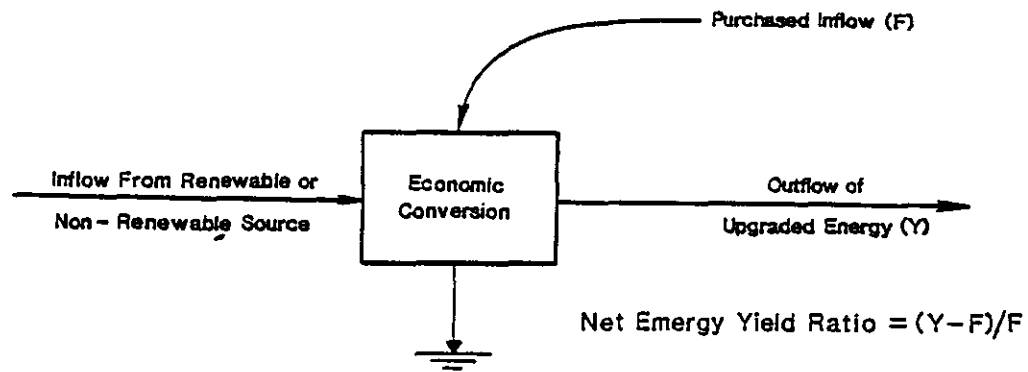


Figure 2-2. Simplified diagrams illustrating (a) the calculation of the net energy yield ratio (NYR) for an economic activity where purchased goods, fuels and services are used to upgrade a lower grade resource; (b) the calculation of the net energy exchange ratio (ER) for trade between two nations; and (c) the calculation of a solar transformity for the energy flow "D" that is a product of the process that requires the input of 3 different sources of solar energy.

## **Exchange Ratio**

The solar 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 (Figure 2-2b). If the exchange is a sale of a commodity in order to generate revenue to purchase necessary 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 is estimated using the solar emergy/dollar index for the buyer nation or region.

A central theorem investigated here is that the area receiving the more solar emergy due to the market transaction has its economy stimulated more. Previous studies have indicated that raw products such as minerals, rural products from agriculture, fisheries, and forestry generally tend to have high exchange ratios when sold at market price (Brown et al 1991, Brown and McClanahan 1991, Odum and Arding 1991). This is a result of money being paid for human services and not for the extensive work of nature that went into these products. The solar emergy exchange ratio is used in this study as a measure of the relative trade advantage of one trade partner over another.

## **Solar Transformity**

As previously defined, this is the relationship between "what it took" to make a product or service and its actual energy content. All independent contributing resources to a productive process, evaluated in solar emergy, are summed together as the numerator and divided by the observed or actual energy content in the denominator (Figure 2-2c). The units, therefore, are solar emjoules / joule (sej/J). Solar transformities used to convert natural resources, imports and exports in this study are drawn from independent studies [Odum and Odum 1983 (updated in Odum 1991), Odum et al 1986, Odum et al 1987, Odum and Arding 1991). From emergy evaluations conducted in this study, some solar transformities are calculated for products and services of Papua New Guinea and are listed separately (see emergy evaluation table heading descriptions above).

If systems are operating at maximum power, a solar transformity for a product or service is a measure of "potential value" to the receiving system. A related theorem investigated here, is that systems will self-

organize over time to develop components and pathways that stimulate productive processes which generate at least as much as they require.

### **Investment Ratio**

The solar energy investment ratio (IR) is the ratio of solar energy derived from the economy [F] to the solar energy delivered free from environmental sources (both renewable [I] and nonrenewable [N]) (Figure 2-3):

$$IR = F / ( I + N ) \quad (1)$$

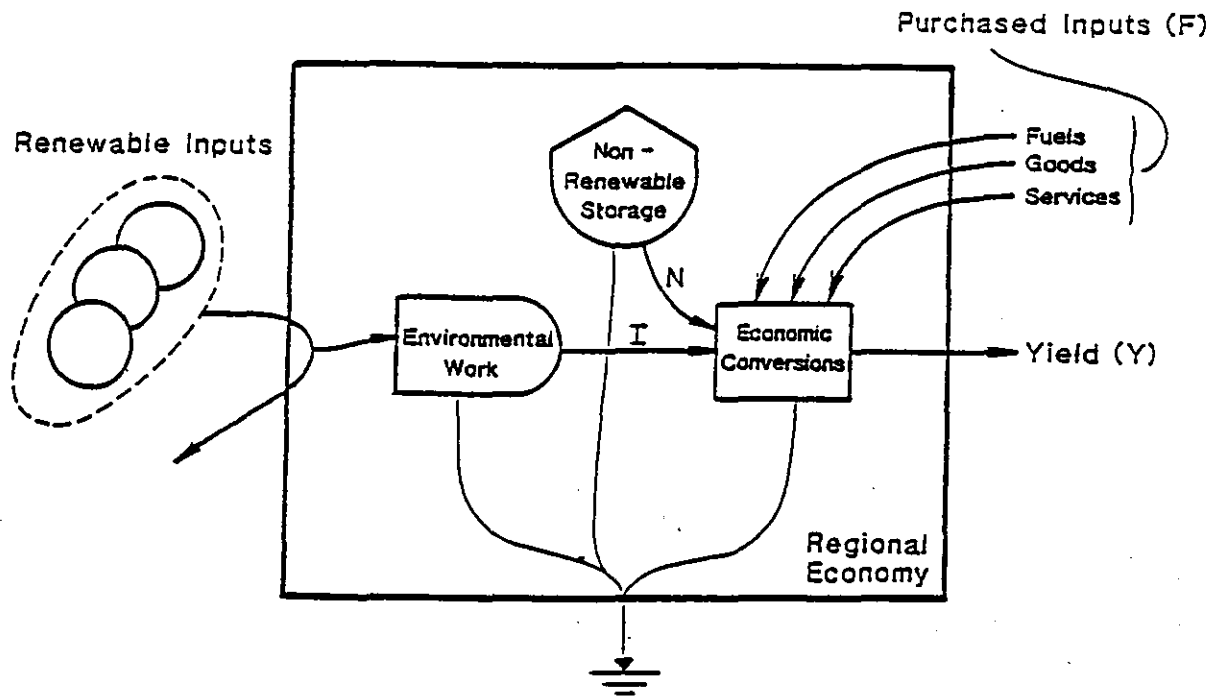
This ratio indicates if the process is economical as a utilizer of the economy's investments in comparison with alternatives. The larger the IR, the greater the amount of purchased energy is required per unit of resident energy. To be economical, the process should have a similar ratio to its competitors. If it receives less from the economy, the ratio is less and its prices are less so that it will tend to compete in the market place. Its prices are less when it is receiving a higher percentage of its useful work free from environmental inputs than its competitors.

However, operation at a low investment ratio uses less of the attracted investment than is possible. The tendency may be to increase the purchased inputs so as to process more output and generate more cash flow. The tendency is towards optimum resource use. This suggests that operations above or below the current regional investment ratio will tend to change towards the investment ratio common for that region.

### **Environmental Loading Ratio**

Environmental loading ratio (ELR) is a measure of potential impact or "loading" a particular development activity can have on its environment. It is the relationship of purchased energy [F] plus resident nonrenewable energy [N] to resident renewable energy [I] (Figure 2-3) as follows:

$$ELR = ( N + F ) / I \quad (2)$$



**Investment Ratio of Regional Economy:**

$$IR_{\text{region}} = F / ( I + N )$$

**Environmental Loading Ratio of Regional Economy:**

$$ELR_{\text{region}} = ( F + N ) / I$$

**Net Yield Ratio of Regional Economy:**

$$YR_{\text{region}} = Y / F$$

Figure 2-3. Systems diagram illustrating a regional economy that imports purchased inputs (F) and uses resident renewable inputs (I) and nonrenewable storages (N). Several ratios used for comparison between systems are below the diagram and are explained in the text. The letters on pathways refer to flows of solar energy per unit time. Thus, ratios of flows are dynamic and changing over time.

Nearly all productive processes of humanity involve the interaction of nonrenewable resources with renewable sources from the environment. Low ELRs indicate relatively small "loading" on the ecosystem support base, while high ELRs reflect greater potential impact. When compared with other ELRs of the region, an ELR as a measure of environmental stress due to a proposed action can be used to address carrying capacity.

### Evaluating Regional and Local IRs and ELRs

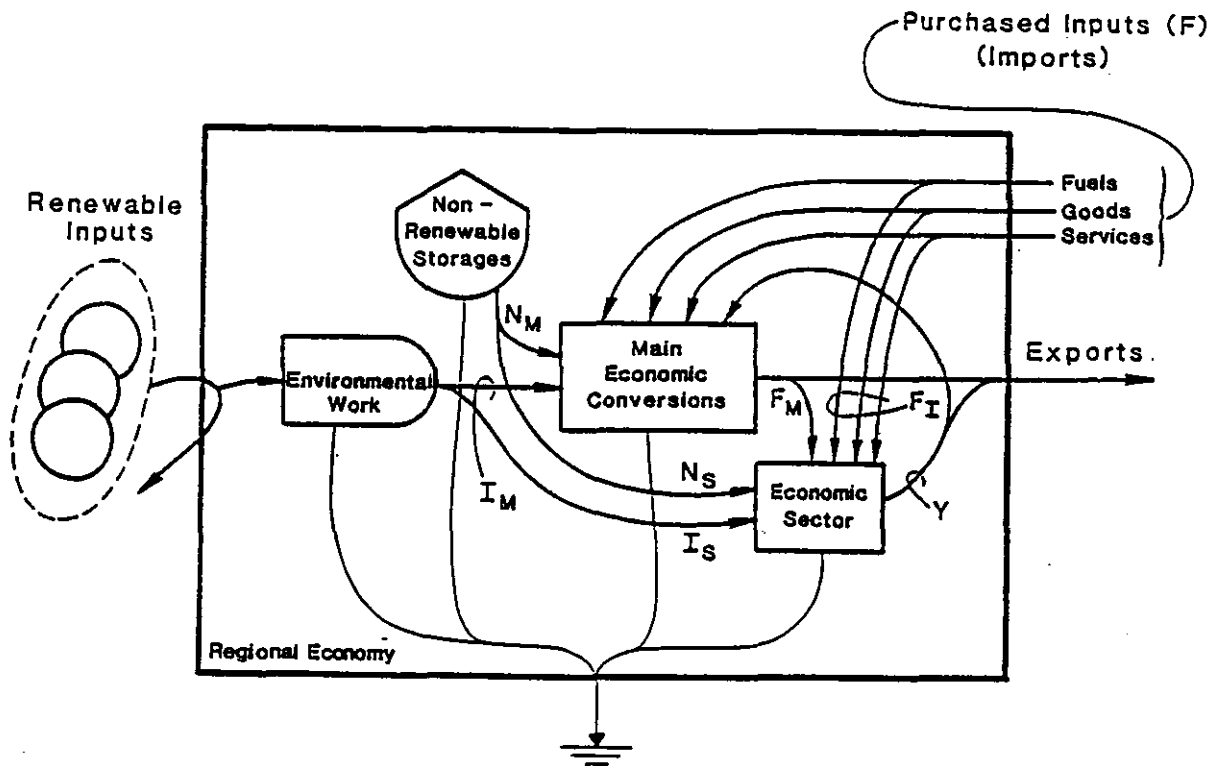
Figure 2-4 is a simplified diagram of a regional economy and a sector of the economy. The sector uses renewable resources ( $I_s$ ) and purchased goods and services from both the local economy ( $F_m$ ) and external markets ( $F_i$ ). The sector is actually part of the regional economy, but is shown separately to highlight the comparison between it and the region in which it is embedded. The investment ratio in the regional economy ( $IR_m$ ) is derived using the ratio of purchased resources ( $F$ ) to resident energy (renewable sources supporting the main economy [ $I_m$ ] plus nonrenewables [ $N_m$ ]) as follows:

$$IR_m = F / ( I_m + N_m ) \quad (3)$$

The investment ratio of the sector ( $IR_s$ ) is calculated in a similar manner, accounting for all sources of renewable and purchased resources as follows:

$$IR_s = (F_m + F_i) / ( I_s + N_s ) \quad (4)$$

The environmental loading for the region and sector within the regional economy are calculated somewhat differently from each other. The regional ELR is calculated as the ratio of nonrenewable ( $F+N_m$ ) to renewable energy ( $I_m$ ) as before. The ELR for the economic sector, however, has to take into account the portion of  $F_m$  that comes from  $I_m$ , since that area of environment is not adding to the "load" on the environment of the sector but, in effect is part of the environmental support for the sector. Thus the ELR for the sector is calculated by subtracting the portion of  $F_m$  that is from  $I_m$ . This done by first calculating the total solar energy of the main economy (Total solar energy  $\{U\} = F_m + F_i + N_m + N_s + I_m + I_s$ ), then dividing by  $I_m$  to determine the percent of the total that is derived from renewable sources supporting the main economy ( $I_m$ ).



**Investment Ratio for Economic Sector:**

$$IR_{\text{sector}} = (F_I + F_M) / (I_S + N_S)$$

**Environmental Loading Ratio for Economic Sector:**

$$ELR_{\text{sector}} = [F_I + (F_M - kF_M) + N_S] / (I_S + kF_M)$$

**Net Yield Ratio for Economic Sector:**

$$NYR_{\text{sector}} = Y / (F_M + F_I)$$

Figure 2-4. Systems diagram of a regional economy showing the flows of energy from external sources and from within the economy. The sector of the economy being investigated is shown separated from the main economy in the lower left. The sector receives resources from imports ( $F_I$ ), from the main economy ( $F_M$ ), from nonrenewable storages ( $N_S$ ), and from the environment ( $I_S$ ). The ratios given in the diagram are explained in the text.

The ELR for the sector is then determined as follows:

$$ELR_s = [ F_i + ( F_m - kF_m ) + N_s ] / ( I_s + kF_m ) \quad (5)$$

where:

$k$  = percent of total solar emery budget for main economy [U] that is derived from environmental sources [I]

### Determining Carrying Capacity for Economic Investments

Once the ELR for a region is known and the total annual nonrenewable emery use by a development is determined, the area of land necessary to balance the development can be calculated using the average annual flux of renewable solar emery per unit area of landscape. This is can be used as a measure of power density of renewable solar emery, and is derived from the analysis of the regional or national economy. The area of support necessary for a proposed development is here defined as its Carrying Capacity. To determine the carrying capacity of a proposed development, the ELR for the region is calculated (as above), and then the following equivalent proportion is determined:

$$ELR_{region} = ELR_{proposed\ development} \quad (6)$$

where:

$ELR_{region}$  = known

$ELR_{development} = [ F_i + ( F_m - kF_m ) + N_s ] / ( I_s + kF_m )$

and the equation is solved as follows:

$$( I_s + kF_m ) = [ F_i + ( F_m - kF_m ) + N_s ] / ELR_{region} \quad (7)$$

Once the quantity  $( I_s + kF_m )$  is known, the area of landscape required to balance the proposed development can be calculated as follows:

$$\text{Support area (i.e. Carrying Capacity)} = ( I_s + kF_m ) / I_{region} \quad (8)$$

where:

$I_{region}$  = known power density for renewable resources of the region (sej / m<sup>2</sup>)



### **Relation of Solar Emergy Support Base and Economic Product**

The relation of annual solar emergy-use to the gross national product of a country was considered an estimate of the solar emergy supporting each unit of currency circulating in the economy for a particular year (Figure 2-5). As the diagram shows, it includes renewable environmental sources such as sunlight, wind and rain, non-renewable resources used such as fossil and mineral reserves and soil, imported fuels, goods and services. In general, rural countries tend to have higher solar emergy/dollar indices because more of their economy involves direct environmental resource inputs that are not paid for (Odum et al 1983, Odum and Arding 1991, Brown et al 1991).

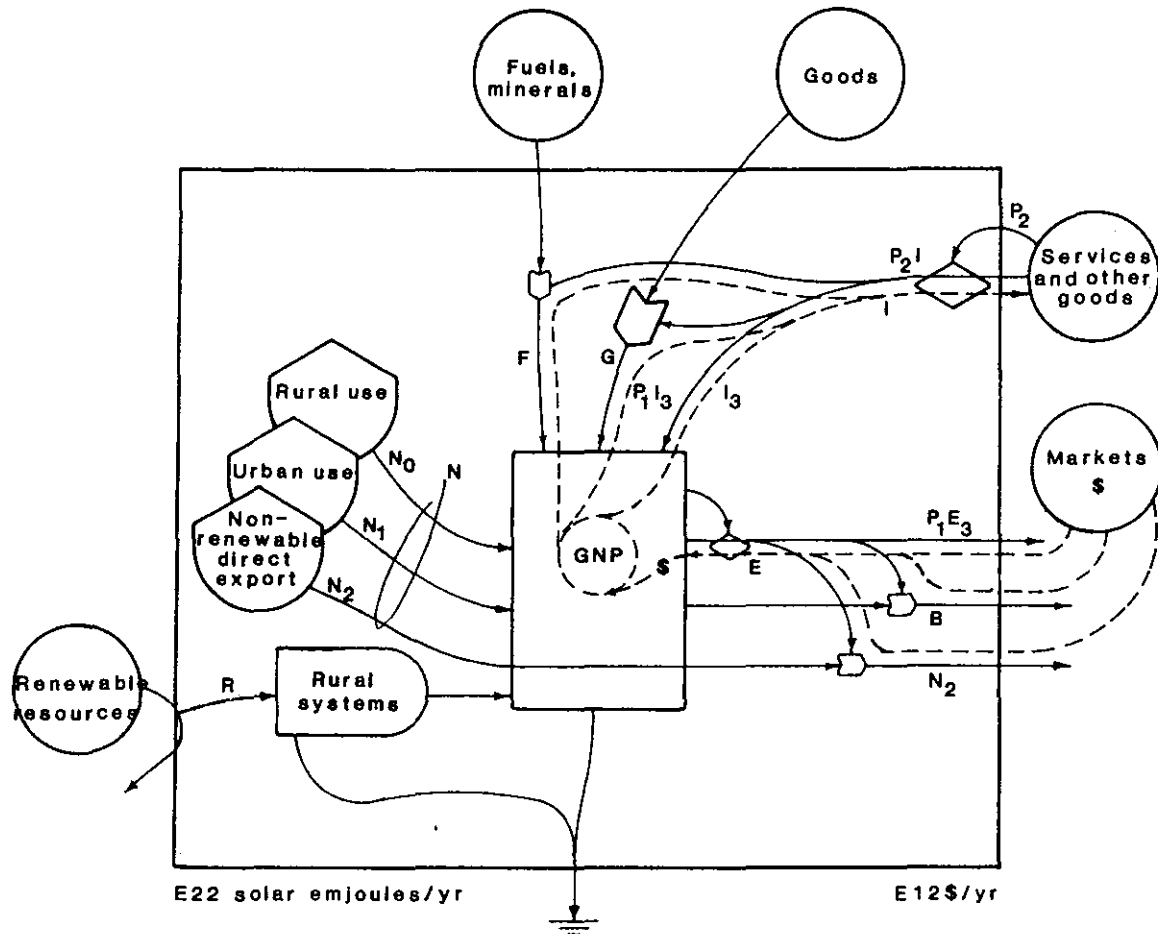
In this study, the solar emergy to dollar index calculated for Papua New Guinea in 1988 is used to estimate the amount of direct and indirect resources supporting each unit of currency. This is used to address all inputs and all costs to production sectors, including an estimate of solar emergy supporting life-styles of workers discussed below.

### Macro-economic Value

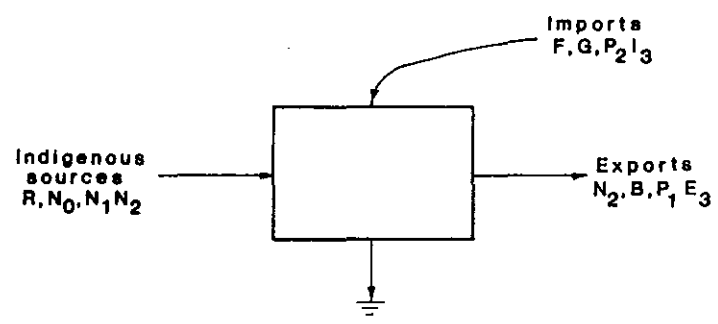
The term macro-economic value refers to the total amount of dollar flow generated in the entire economy supported by a given amount of solar emergy input. It is calculated by dividing the solar emergy of a product or process by the solar emergy/dollar index for the economy to which it contributes. This is a way of putting an monetary value on services and storages not traditionally accounted for in economics such as transpired rainfall, photosynthetic production, forest biomass, volunteer labor, parenting and information. This is not a market value, but instead a value for public policy inferences and directives.

### Estimate of the Solar Emergy Support Base of Human Services

The money paid for machinery, fuels and other goods necessary in a production sector pays for the human services involved in the refinement, manufacture and delivery of the commodity. By summing the total solar emergy input to Papua New Guinea in 1988, including environmental sources, fuels and foreign purchases, the amount of solar emergy supporting the gross national product was estimated, measured as solar emjoules per unit currency (sej/kina or sej/US\$) for that year. This relation was



(a)



(b)

Figure 2-5. Overview systems diagram of a nation, its environmental resource base, economic component, imports and exports (from Odum et al 1983): (a) main flows of money and solar energy; (b) procedure for summing solar energy inflows and outflows.

used to assign a solar energy value to human services in proportion to the money paid for the service, assuming that each kina paid for a product or service represents a proportional amount of solar energy supporting the direct and indirect human labor requirements. By multiplying the monetary cost of a commodity or labor hour by this index of annual solar energy flow to monetary flow, an estimate of solar energy supporting labor inputs and indirect human services was assigned.

Since money is only paid to people for their contributions and not for environmental work, this estimate was derived so that human services could be equivalently evaluated along with other inputs to the forest sector. An average solar energy base for wages earned is an estimate of the lifestyle support requirements of both direct forest laborers in Sweden as well as the associated human services that produce and deliver imported commodities. This method of assigning resources supporting labor in proportion to the money paid is used in other ecological economic accounting methods such as input-output matrix algebra (Costanza 1980, Hannon et al 1985) and is not without its limitations (Odum 1992). Other methods are possible. For example, the solar energy supporting labor can be estimated using an average solar transformity of human metabolism for a given socio-economic class. While the method used here is an approximation, some measure of total contributions to human work is necessary if the real requirements to system production is to be assessed.

### **Step 5: Microcomputer Simulation Models**

For simulation, the models in the systems diagrams were aggregated further, combining features that were unchanging, small, or belonging to a more general component or process. The source inputs, boundary flows of money, and the main features of production and consumption were retained. State variables were identified with descriptive names and mathematical expressions were written for interactions and processes between state variables. These equations follow criteria predetermined by the orientation of components and the relationships identified in the diagrams.

Numerical values for flows were written on the pathways and on the storage tanks for the state variables in the systems diagram. Steady states were estimated for expected carrying capacities within the system being modeled and coefficients were determined for each interactive pathway (i.e. mathematical expression identifying the relationship of two or more state variables over time). These equations, written into BASIC computer language, could then be simulated over time and with changes in inputs or state variables using the

constructed microcomputer program. By first identifying the baseline calibration at steady state, one variable at a time can be changed in the program to study the effects made by manipulating the system. Graphs were obtained from the computer simulations and included with the text in order to illustrate principles made clearer by the simulation models.

### **Step 6: Public Policy Questions**

Public policy alternatives that involve decisions regarding development and use of resources are guided by two criteria in this study: (1) the proposed or existing activity should increase the total flow of solar energy into the economy, and (2) the alternative should be sustainable in the long term. The tools for determining policy options have been outlined above. General thermodynamic principles of all systems are then used to evaluate these tools and develop criteria for alternative public policies.

Development alternatives that result in higher energy inputs to an economy increase its vitality and competitive position. A principle that is useful in understanding why this is so is the Maximum Energy Principle (which follows from the work of Lotka [1922a], who named it the "maximum power principle"). In essence, the Maximum Energy Principle states that the system (or development alternative, in this case) that will prevail in competition with others is the one that develops the most useful work with inflowing energy sources. Useful work is related to using inflowing energy in reinforcement actions that insure and, if possible, increase the inflowing energy. The principle is somewhat circular. That is, processes that are successful maximize useful work, and useful work is that work which increases inflowing energy.

It is important that the term "useful" is used here. Energy dissipation without useful contribution to increasing inflowing energy is not reinforcing, and thus cannot compete with systems that use inflowing energy in self-reinforcing ways. Thus, drilling oil wells and then burning off the oil may use oil faster (in the short run) than refining and using it to run machines, but it will not compete in the long run with a system that uses oil to develop and run machines that increase drilling capacity and, ultimately, the supply of oil.

Development alternatives that do not maximize energy may not compete in the long run and are "selected against." In the trial and error processes of open markets and individual human choices, the patterns that generate more energy will tend to be copied and will prevail. Recommendations for future plans and

policies that are likely to be successful are those that go in the natural direction toward maximum emergy production.

The second guiding criterion is that development alternatives be sustainable in the long run. To be sure, sustainability is an elusive concept. Ultimately, sustainable developments are activities that use no nonrenewable energy, for once supplies have dwindled, developments that depend on them must also dwindle. However, the criteria for maximum emergy would suggest that energy be used effectively in the competitive struggle for existence. Thus, when energy is available, its use in actions that reinforce overall performance is a prerequisite for sustainability. To do otherwise would suggest that the development would not be competitive, and in the short run would not be sustainable. This alternative (no use of nonrenewable energy) provides the lower bound for sustainability. The upper bound is determined by the Maximum Emergy Principle as well. Sustainable developments are those that operate at maximum power, neither too slow (efficient) nor too fast (inefficient). The question of defining sustainability becomes one of defining maximum power. In this analysis, we use the Investment Ratio and the Environmental Loading Ratio as the criteria for sustainability. By matching the ratios of a development with those of the economy in which it is imbedded, a proposed development is neither more nor less sustainable than the economy as a whole.

The systems analysis procedure is designed to evaluate the flows of energy and materials of systems in common units that enables one to compare environmental and economic aspects of systems. Usually questions of development policy and uses of resources involve environmental impacts that must be weighed against economic gains. Most often impacts and benefits are quantified in different units resulting in a paralysis of the decision-making process because there is not a common means of evaluating the trade-offs between environment and development. Emergy provides a common basis, the energy of one type that is required by all productive processes.

While "Ecological Economics" and methods of systems analyses of emergy support are comparatively new and still evolving, and often difficult to understand, we believe they offer an important step in developing a quantitative basis for public policy decision making.

# RESULTS

## Section A: Emergy Synthesis of Papua New Guinea's Resource Base

by S.J. Doherty

### NATIONAL OVERVIEW

Papua New Guinea is a resource rich country. Abundant rainfall, year round sun and deep soils provide a renewable supply of energy for forests and agriculture. Coastal resources are supported through waves and tidal action along extensive shorelines and the continuous inflow of rivers into estuarine systems. Reserves of minerals, metals and fossil fuels are currently being mined with increased prospects for the future based on explorations and new discoveries. An emergy analysis of indigenous sources, imports and exports identified major resource contributions to PNG's ecological and economic base (Table A-1). The table, as described in methods, identifies each source flow in energy units (J/yr) or mass (g/yr), in solar emergy units (sej/yr), as well as its macro-economic value. The resource flows are broken into three categories: 1) renewable inputs, 2) indigenous production, and 3) extraction of nonreplenishable storages.

Annual precipitation contributed the greatest emergy to terrestrial systems. A chemical potential energy in rainfall was calculated as the Gibbs free energy in transpired rain. It is a measure of energy derived (4940 J/kg) from a chemical gradient between soil water taken up by plants and pure water that is transpired at the leaf surface as part of photosynthesis and evaporative cooling. Geopotential energy in rainfall was calculated as a gravitational potential due to impact of the rainfall on the earth's contoured surface. Thus rain contributes to environmental work in two ways -- potential energies due to chemical composition and elevational position. The solar emergy was measured as  $600E+20$  sej/yr and  $730E+20$  sej/yr, respectively for each potential energy in annual rains (items 3 and 4, Table A-1).

Large numbers of islands, extensive coastlines and a wide continental shelf off the southern mainland result in large solar emergy contributions from waves received at shore and the tides. Together these

Table A-1. Solar energy support for Papua New Guinea's indigenous resource base, imports and exports. All flows are based on annual contributions, using 1987 data. Calculations for basic data are given as footnotes to this table (referenced in column 1).

Note	Item	Annual flows raw units/yr (J, g)	Solar transformity <sup>a)</sup> (sej/J)	Solar emergy (10 <sup>20</sup> sej/yr)	Macro-economic value <sup>b)</sup> (million US\$, 1987)
<b>RENEWABLE SOURCES:</b>					
1	Solar insolation	2.59E+21 J	1	25.89	53.97
2	Wind, kinetic	1.34E+18 J	1500	20.07	41.84
3	Rain, chemical	3.30E+18 J	18200	599.77	891.62
4	Rain, geopotential	8.57E+18 J	10500	729.70	1521.19
5	Waves received	6.15E+17 J	30550	187.85	391.60
6	Tidal energy	1.23E+18 J	16850	207.80	433.19
7	Earth cycle	1.85E+18 J	6100	112.65	234.84
<b>INDIGENOUS RENEWABLE PRODUCTION:</b>					
8	Hydroelectricity	1.08E+15 J	200000	2.16	4.50
	(total electric generation)	5.37E+15 J	200000	10.74	22.36
9	Agriculture production	3.97E+16 J	2.00E+05	79.30	165.32
10	Livestock	1.58E+15 J	2.00E+06	31.55	65.78
11	Fuelwood harvested	3.60E+16 J	40000	14.37	29.94
12	Fisheries	1.38E+14 J	2.00E+06	2.76	5.76
13	Forest extraction	2.00E+16 J	2.53E+05	50.60	105.42
14	Topsoil formation	1.43E+17 J	6.30E+04	90.14	187.91
<b>NONRENEWABLE RESOURCES, MINED:</b>					
15	Copper	1.75E+11 g	4.50E+10	78.80	164.26
16	Gold	1.45E+07 g	5.00E+10	0.01	0.02
17	Silver	3.68E+07 g	5.00E+10	0.02	0.04

a) Mineral and metal ore resources are evaluated using solar emergy per mass (sej/g).

b) Solar emergy value divided by annual solar emergy-use/GNP for PNG, 1987 ( $48 \times 10^{12}$  sej/\$).

Table A-1, continued.

Note	Item	Annual flows raw units/yr (J, g, \$, p-y)	Solar transformity <sup>a)</sup> (sej/J)	Solar emergy (10 <sup>20</sup> sej/yr)	Macro-economic value <sup>b)</sup> (million US\$, 1987)
<b>IMPORTS AND OUTSIDE SOURCES:</b>					
18	Oil	2.80E+16 J	66000	18.49	38.54
19	Phosphorus	1.49E+11 J	4.14E+07	0.06	0.13
20	Nitrogen	5.69E+11 J	1.69E+06	0.01	0.02
21	Potash	4.09E+10 J	2.62E+06	0.001	---
22	Miscellaneous goods	5.13E+08 \$	3.60E+12	18.48	38.53
23	Net human migration <sup>c)</sup>	9280 p-y	3.47E+16	3.22	6.72
24	Tourism	5.85E+06 \$	2.60E+12	0.15	0.32
25	Foreign aid	9.46E+08 \$	3.60E+12	34.06	71.00
26	Services in imports	9.63E+08 \$	3.60E+12	34.67	72.28
<b>EXPORTS:</b>					
27	Cash crops	5.52E+15 J	2.00E+05	11.04	23.02
28	Fisheries products	4.86E+13 J	2.00E+06	0.97	2.03
29	Forestry products	9.46E+15 J	2.53E+05	23.94	49.86
30	Copper	1.75E+11 g	4.50E+10	78.80	164.26
31	Gold	1.45E+07 g	5.00E+10	0.01	0.02
32	Silver	3.68E+07 g	5.00E+10	0.02	0.04
33	Services in exports	1.03E+09 \$	4.80E+13	495.47	1032.90

a) Mineral and metal ore resources are evaluated using solar emergy per mass (*sej/g*); human services, tourism and foreign aid are estimated using *sej/\$* for Papua New Guinea for 1987.

b) Solar emergy value divided by annual solar emergy-use/GNP for PNG, 1987 ( $P_1 = 48 \times 10^{12}$  *sej/\$*, Table A-2).

c) Net immigration of people to PNG is evaluated using an estimate for solar emergy supporting an immigrant for an average lifespan (*sej/people-year*).

#### Footnotes to Table A-1.

Derivation of annual energy flows of environmental contributions and principle production systems in Papua New Guinea, circa 1987. 1 joule = 10<sup>7</sup> ergs = 1 kg\*m<sup>2</sup>/sec<sup>2</sup>.

#### Renewable resources:

##### 1. Direct solar insolation received over inland areas and continental shelf:

Shelf area based on measurement within the 153 m below sea level contour [est. from Espenshade (1986)].

$$= [\text{land area} + \text{shelf area}] * (\text{avg. insolation}) * (1 - \text{albedo}) = (4.62\text{E}+11 \text{ m}^2 + 1.43\text{E}+11 \text{ m}^2) (85 \text{ kcal/cm}^2/\text{yr}) (E+4 \text{ cm}^2/\text{m}^2) * (1-0.3) (4186 \text{ J/kcal}) = 2.59\text{E}+21 \text{ J/yr}$$



Table A-1 footnotes, continued.

2. Wind, kinetic energy (within 90 m of surface) =  $(3.717E+11 \text{ kWh/yr})(3.6E+6 \text{ J/kWh}) = 1.34E+18 \text{ J/yr}$  (Gabel et al 1987)
3. Chemical potential energy in rainfall is estimated as the sum of highlands, lowlands and coastal systems contributions (see subsystems analysis): highlands,  $1.31E+18 \text{ J/yr}$  + lowlands,  $0.87E+18 \text{ J/yr}$  + continental shelf,  $0.17E+18 \text{ J/yr}$  =  $2.35E+18 \text{ J/yr}$
4. Gravitational potential energy in rainfall is estimated as the sum of highlands and lowlands contributing energies (see subsystems analysis): highlands,  $6.58E+18 \text{ J/yr}$  + lowlands,  $0.10E+18 \text{ J/yr}$  =  $6.95E+18 \text{ J/yr}$
5. Wave energy received at shoreline;  $(1.708E+11 \text{ kWh/yr}; \text{ Gabel et al 1987}) (3.6E+6 \text{ J/kWh}) = 6.15E+17 \text{ J/yr}$
6. Tidal energy = (continental shelf area) (0.5) (no. tides/yr)<sup>2</sup> (density of seawater) (gravitational force) =  $(1.43E+11 \text{ m}^2; \text{ Espenshade et al 1986})$  (mean tidal range, 1.56 m; US Dept. Commerce 1987)  $(1030 \text{ kg/m}^3; \text{ Odum et al 1983})$   $(706 \text{ tides/yr}) (9.8\text{m/s}^2) = 1.23E+18 \text{ J/yr}$
7. Earth cycle =  $(4.62E+11 \text{ m}^2)$  (estimate heat flow/area,  $4E+6 \text{ J/m}^2/\text{yr}; \text{ Odum et al 1983}) = 1.85E+18 \text{ J/yr}$
8. a) Hydroelectricity;  $(300E+6 \text{ kWh/yr}; \text{ Gabel et al 1987}) (3.6E+6 \text{ J/kWh}) = 1.08E+15 \text{ J/yr}$   
 b) Total electricity generation,  $1.49E+9 \text{ kWh, 1984 (UN 1986); (1.49E+9 kWh/yr) (3.6E+6 J/kWh)}$   
 =  $5.37E+15 \text{ J/yr}$
9. Agricultural production,  $2.71E+6$  tonne crop yield, 1982; United Nations 1984a);  $(2.706E+6 \text{ t}) (E+6 \text{ g/t}) (3.5 \text{ kcal/g})$   $(4186 \text{ J/kcal}) = 3.97E+16 \text{ J/yr}$
10. Livestock production,  $4.28E+5 \text{ t, 1982 (UN 1984a); (4.28E+5 t) (E+6 g/t) (4 kcal/g) (4186 J/kcal) (22\% protein) = 1.58E+15 J/yr}$
11. Fuelwood production,  $1.796E+6 \text{ t, 1983 (UN 1985); (1.796E+6 t) (1E+6 g/t) (2E+4 J/t) = 3.60E+16 J/yr}$   
 Solar transformity  $(40,000 \text{ sej/J})$  from subsystems analysis of rainforest biomass (Table B-1)
12. Fisheries (tuna, crayfish and prawn),  $3.75E+4 \text{ t, 1982 (UN 1984a); (3.75E+4 t) (E+6 g/t) (4 kcal/g) (4186 J/kcal) (22\% protein) = 1.38E+14 J/yr}$
13. Forestry,  $1.25E+6 \text{ m}^3$  avg. annual harvest (PNG Information Booklet 1986);  $(1.25E+6 \text{ m}^3) (8E+5 \text{ g/m}^3) (2E+4 \text{ J/g}) = 2.00E+16 \text{ J/yr}$ . Solar transformity  $(253,000 \text{ sej/J})$  from subsystems analysis of forest products (Table B-1).
14. Net topsoil formation;
  - a) Soil formation assumed occurring on half of forest area =  $(1/2)(3.39E+11 \text{ m}^2 \text{ rainforest}; \text{ McIntosh 1974}) (1260 \text{ g soil build up/m}^2/\text{yr}) = 2.14E+14 \text{ g/yr};$
  - b) Soil loss on agricultural areas estimated as  $(3.78E+9 \text{ m}^2 \text{ agricultural land}; \text{ UN 1984b}) (850 \text{ g soil loss/m}^2/\text{yr}; \text{ est. Odum et al 1987}) = 3.2E+12 \text{ g/yr};$ $(\text{soil formation}) - (\text{soil eroded}) = (2.14E+14 \text{ g/m}^2/\text{yr}) - (3.2E+12 \text{ g/m}^2/\text{yr}) = 2.11E+14 \text{ g/yr}$   
  
 Energy in organic matter of soil estimated as  $(2.11E+14 \text{ g/yr}) (3\% \text{ OM content}) (5.4 \text{ kcal/g}) (4186 \text{ J/kcal}) = 1.43E+17 \text{ J/yr}$
15. Copper,  $1.75E+5 \text{ t/yr}$  mined (UN 1984a);  $(1.75E+5 \text{ t/yr}) (1.0E+6\text{g/t}) = 1.75E+11 \text{ g/yr}$
16. Gold,  $1.45E+4 \text{ kg/yr}$  mined (UN 1984a);  $(14500 \text{ kg}) * (1000\text{g/kg}) = 1.45E+7 \text{ g/yr}$

Table A-1 footnotes, continued.

17. Silver, 36800 kg/yr (UN 1984);  $(36800 \text{ kg}) \cdot (1000 \text{ g/kg}) = 3.68\text{E}+7 \text{ g/yr}$
  18. Oil, foreign imports =  $2.80\text{E}+16 \text{ J/yr}$  (Johnston 1984)
  19. Phosphorus imports, 1300 t/yr (UN 1984); % P by atomic wgt,  $\text{PO}_4 = .33$ ; est.  $[\text{PO}_4]$  as 10% of bulk fertilizer;  $(1300 \text{ t}) \cdot (.33) \cdot (.1) \text{ (E+6g/t)} \cdot (348 \text{ J/g}) = 1.49\text{E}+11 \text{ J/yr}$
  20. Nitrogen imports, 3200 t/yr (UN 1984); % N by atomic wgt,  $\text{NH}_3 = .82$ ; est.  $[\text{NH}_3]$  as 10% of bulk fertilizer;  $(3200 \text{ t}) \cdot (.82) \cdot (.1) \text{ (E+6g/t)} \cdot (2.17\text{E}+3 \text{ J/g}) = 5.69\text{E}+11 \text{ J/yr}$
  21. Potash imports, 1100 t/yr (UN 1984); est. K as 53% of bulk fert;  $(1100 \text{ t}) \cdot (.53) \text{ (E+6g/t)} \cdot (702 \text{ J/g}) = 4.09\text{E}+10 \text{ J/yr}$
  22. Goods (Yearbook of International Trade Statistics 1981): (food/live animals,  $9.227\text{E}+7 \text{ US\$}$  + beverages/tobacco,  $7.334\text{E}+6 \text{ US\$}$  + crude materials excluding fuels,  $2.028\text{E}+6 \text{ US\$}$  + machines/transport equipment,  $1.378\text{E}+8 \text{ US\$}$  + basic manufactures,  $6.066\text{E}+7 \text{ US\$}$ , misc. manufactured goods,  $3.471\text{E}+7 \text{ US\$}$  + other goods not classified,  $1.785\text{E}+8 \text{ US\$}$  =  $5.13\text{E}+8 \text{ US\$}$
  23. Net human immigration, 371 immigrations (PNG Natl. Stats. Office 1987b);  $(371 \text{ persons/yr}) \cdot (25 \text{ yrs old, avg.}) = 9280 \text{ people-years}$
  24. Tourism, visitor arrivals (1986) = 8363 people (PNG Natl. Stats. Office 1987b);  $(8363) \cdot (\$100/\text{day average expenditures}) \cdot (7 \text{ day stay}) = 5.85\text{E}+6 \text{ US\$}$
  25. Foreign Aid, K 880 million (Coopers and Lybrand 1988);  $(8.8\text{E}+8) \cdot (\text{US\$ } 1.075/\text{K}) = 9.46\text{E}+8 \text{ US\$}$
  26. Human services in import products;  $(\text{K } 8.73\text{E}+8 \text{ import expenditures; Qureshi et al 1988}) / (\text{K } 0.9302/\text{US\$}) = 9.63\text{E}+8 \text{ US\$}$ . Solar energy determined from energy/GNP index calculated from this study (Table A-2).
  27. Cash crop exports (PNG National Stats. Off. 1986); (cocoa beans,  $3.09\text{E}+4$  + coffee,  $5.31\text{E}+4$  + copra,  $1.13\text{E}+5$  + copra oil,  $4.11\text{E}+4$  + palm oil,  $1.29\text{E}+5$  + rubber, 4940 + tea, 5320)tonnes =  $3.77\text{E}+5 \text{ t}$ ;  $(3.77\text{E}+5 \text{ t}) \cdot (\text{E+6 g/t}) \cdot (3.5 \text{ kcal/g}) = (4186 \text{ J/kcal}) = 5.52\text{E}+15 \text{ J/yr}$
  28. Fisheries 1985 exports,  $1.32\text{E}+4 \text{ t}$  (PNG Info. Booklet 1987);  $(1.32\text{E}+4 \text{ t}) \cdot (\text{E+6 g/t}) \cdot (4 \text{ kcal/g}) \cdot (4186 \text{ J/kcal}) \cdot (22\% \text{ protein}) = 4.86\text{E}+13 \text{ J/yr}$
  29. Forest products 1986 exports (PNG Info. Booklet 1987); logs,  $4.5\text{E}+5 \text{ m}^3$  + lumber,  $4.0\text{E}+4 \text{ m}^3$  =  $4.9\text{E}+5 \text{ m}^3$ ;  $(4.95 \text{ E+5 m}^3) \cdot (8\text{E}+5 \text{ g/m}^3) \cdot (2\text{E}+5 \text{ J/g}) = 7.84\text{E}+15 \text{ J/yr}$ .  
woodchips,  $8.10\text{E}+4 \text{ t}$  (PNG Natl. Stats. Office 1987a);  $(8.1\text{E}+4 \text{ t}) \cdot (\text{E+6 g/t}) \cdot (2\text{E}+4 \text{ J/g}) = 1.62\text{E}+15$   
total energy in forest exports =  $9.46\text{E}+15 \text{ J/yr}$ .  
Solar transformity (253,000 sej/J) from analysis of forest products (Table B-1).
- All mineral, metal ores are exported without refinement:
30. Copper exports,  $1.75\text{E}+11 \text{ g/yr}$
  31. Gold exports,  $1.45\text{E}+7 \text{ g/yr}$
  32. Silver exports,  $3.68\text{E}+7 \text{ g/yr}$
  33. Human services in export products, 1987 =  $1.03\text{E}+09 \text{ US\$}$  (Qureshi et al 1988)
-

independent sources supply almost  $400E+20$  sej/yr to PNG, about 20% of total free contributions from indigenous environmental resources. Productive estuaries and extensive coral reefs are supported by these energies along with extensive inland runoff resulting in large volumes of freshwater to deltas supplied from numerous rivers. An estimate of earth cycling due to subsurface heat flow was calculated as about 10% of indigenous renewable contributions. This estimate is considered low, as evidenced by the high degree of orographic and volcanic activity in this geologically young land mass (Dow 1977, Loffler 1982).

Many environmental inputs (ie. rain, wind, waves and earth heat flow) are byproducts of the same coupled solar, atmospheric and geologic processes. Global solar insolation drives physical processes and biological processes, which in turn are coupled. Wind patterns and surface waves, convection currents, evaporation over oceans and land surfaces, and weather systems, among other processes are all driven either directly or indirectly from the sun's energy. The solar transformities used to determine the solar emergy of each of these inputs were calculated using the annual global flux of solar insolation and deep earth heat released. The solar transformities are therefore coupled, and in order not to "double count" resource inputs that are not independent, only the largest contributor of solar emergy is counted, representing all coupled environmental sources. A total renewable solar emergy flow for Papua New Guinea (R) was estimated as the sum of rain, tides and earth cycle -- a contribution of  $1050E+20$  sej/yr, over 80% of annual solar emergy-use in the country. Table A-2 summarizes all resource flows for Papua New Guinea in 1987.

Productive sectors of the economy include agriculture, livestock, forest, and fisheries (items 8-13, Table A-1). Hydroelectricity generation is a fledgling industry with potential for growth as evidenced by current production and the emergy supplied from runoff collected in rivers moving across elevated gradients (i.e. gravitational potential energy of rain runoff). These indigenous production systems are supported by the independent sources described above. Almost 2 million tons of fuelwood is harvested each year for domestic cooking and heating, representing a rural resource formed from past environmental work. This resource supplies  $14E+20$  sej/yr on average to the country's indigenous resource base. Extraction of forest materials was calculated using a solar transformity of  $2.53E+5$  sej/J derived from a subsystems analysis of forest development in Section B of this report. Forest products contributed  $50E+20$  sej in 1987 and over half was exported as logs and woodchips (items 13 and 29). An estimate of topsoil loss and formation showed a net build up contributing about 8% of the

Table A-2. Summary of major solar energy flows and market economic monetary flows for Papua New Guinea, 1987. Complete analyses are given in Table A-1.

Variable	Item	Solar energy ( $10^{20}$ sej/yr)	Market value ( $10^9$ US\$, 1987)	sej/\$
R	Renewable sources <sup>1)</sup>	1050.1		
N	Nonrenewable sources within Papua New Guinea	190.3		
	N <sub>0</sub> Dispersed rural sources <sup>2)</sup>	104.5		
	N <sub>1</sub> Concentrated use <sup>3)</sup>	2.6		
	N <sub>2</sub> Export of unprocessed raw materials <sup>4)</sup>	78.8		
F	Imported fuels and fertilizers	18.6	0.246	
G	Imported goods	18.5	0.717	
I	Dollars paid for imports <sup>5)</sup>		0.963	
P <sub>2</sub> I	Solar energy value of service in imports <sup>6)</sup>	17.1		
E	Dollars received for exports <sup>5)</sup>		1.033	
P <sub>1</sub> E	Solar energy value of service in exports <sup>7)</sup>	290.5		
B	Exports transformed, upgraded within country <sup>8)</sup>	36.0		
x	Gross National Product, 1987 (0.93 kina/US\$)		2.535	
P <sub>2</sub>	World solar energy/\$ index <sup>9)</sup>			$3.6 \times 10^{12}$
P <sub>1</sub>	Papua New Guinea's solar energy/\$ index			$48.0 \times 10^{12}$

Footnotes to Table A-2.

- 1) solar energy contributions from rainfall, tidal energy and earth cycle. Other renewable sources are accounted in this summation -- since they are coupled, global flows, their solar transformities share global solar energy flux.
- 2) fuelwood production and net top soil formation (items 11 and 14, table 1)
- 3) hydroelectricity generation (item 8, table 1)
- 4) all mined minerals (Cu, Ag, Au) are currently exported directly without value-added processing.
- 5) data for import expenditures and export revenues from Qureshi et al (1988).
- 6) imported services (P<sub>2</sub>I) are corrected by subtracting the cost of goods (item 22, table 1) whose solar transformity includes human services from import expenditures:  $(0.9631 - 0.513)E+9$  US\$ =  $0.450 E+9$  US\$; solar energy value is estimated by multiplying the \$ received for imported services by  $3.6E+12$  sej/\$ (average sej/\$ index for world economy):  $(0.450E+09 \$) (3.8E+12 \text{sej}/\$) = 17.12 E+20 \text{sej}/\text{yr}$
- 7) exported services (P<sub>1</sub>E) are corrected by subtracting revenues for agricultural, forestry, and fishery products (items 27-29, table 1) whose solar transformities include human labor involved in their production and retrieval:  $(1.033 - 0.342 - 0.077 - 0.008)E+9$  US\$ =  $0.6056 E+9$  US\$; solar energy value is estimated using sej/\$ index for Papua New Guinea ( $48.0E+12$  sej/\$):  $(0.6056E+9 \$) (48.0E+12 \text{sej}/\$) = 290.69 E+20 \text{sej}/\text{yr}$
- 8) agriculture, fisheries and forestry products (items 27-29, table 1)
- 9) from Odum and Odum (1983), updated in Odum 1991.

solar energy base of Papua New Guinea. Large reserves of solar energy are mined each year in the form of copper, gold and silver (items 15-17), totaling about  $80E+20$  sej/yr. All excavated material is currently exported, thus not contributing directly to production sectors in the country's economy, except for what the revenues from overseas sales can purchase in terms of needed goods, fuels and services not yet available within its borders.

Goods (G), fuels (F) and services ( $P_2I$ ) purchased outside the country contributed  $54E+20$  sej in 1987, about 5% of annual solar energy-use (Table A-2). Imported fuels represented the largest single import commodity in 1987 (item 18, Table A-1); over 30% of imports, though less than 2% of the total solar energy used. The solar energy buying power in foreign aid (950 million US \$ in 1987) represented an inflow of  $35E+20$  sej, representing 60% of imports, yet only 3% of the country's annual energy base. Over seven times as much solar energy was exported than received through imports in 1987. Direct export of unrefined metal ores ( $N_2$ : Cu, Ag, Au) accounted over 20% of exports. Cash crops such as coffee, cocoa, sorghum, and rubber, accounted for roughly 3% of exports. A majority of forest products are still used within the country as indicated by the larger amount of wood harvested for domestic use than for export pulp and logs.

Copper ores and forest products represented the two greatest exports of solar energy. The solar energy supporting Papua New Guineans employed in services related to the extraction, production and delivery of export commodities was estimated at  $290E+20$  sej in 1988 ( $P_1E$ ). As described in methods, this value is a measure of resources and purchased goods that are consumed directly and indirectly in order to support the people who produce services or commodities for sale to outside markets. This value suggests that the majority (75%) of solar energy exported from Papua New Guinea was the support base of the people, largely the environment. In other words, low cost raw materials and upgraded goods are subsidized by an abundant and still healthy ecosystem life support base.

Figure A-1(a) summarizes resource flows for Papua New Guinea in 1987. Environmental sources are identified at the left; mineral, soils and forest wood are shown as internal storages; market goods, services and money are shown toward the right. Numbers and variables on the pathways correspond to evaluations in Table A-1 and summarized in Table A-2. A three-arm diagram [Figure A-1(b)] further aggregates contributing flows as three pathways: 1) free indigenous, environmental sources

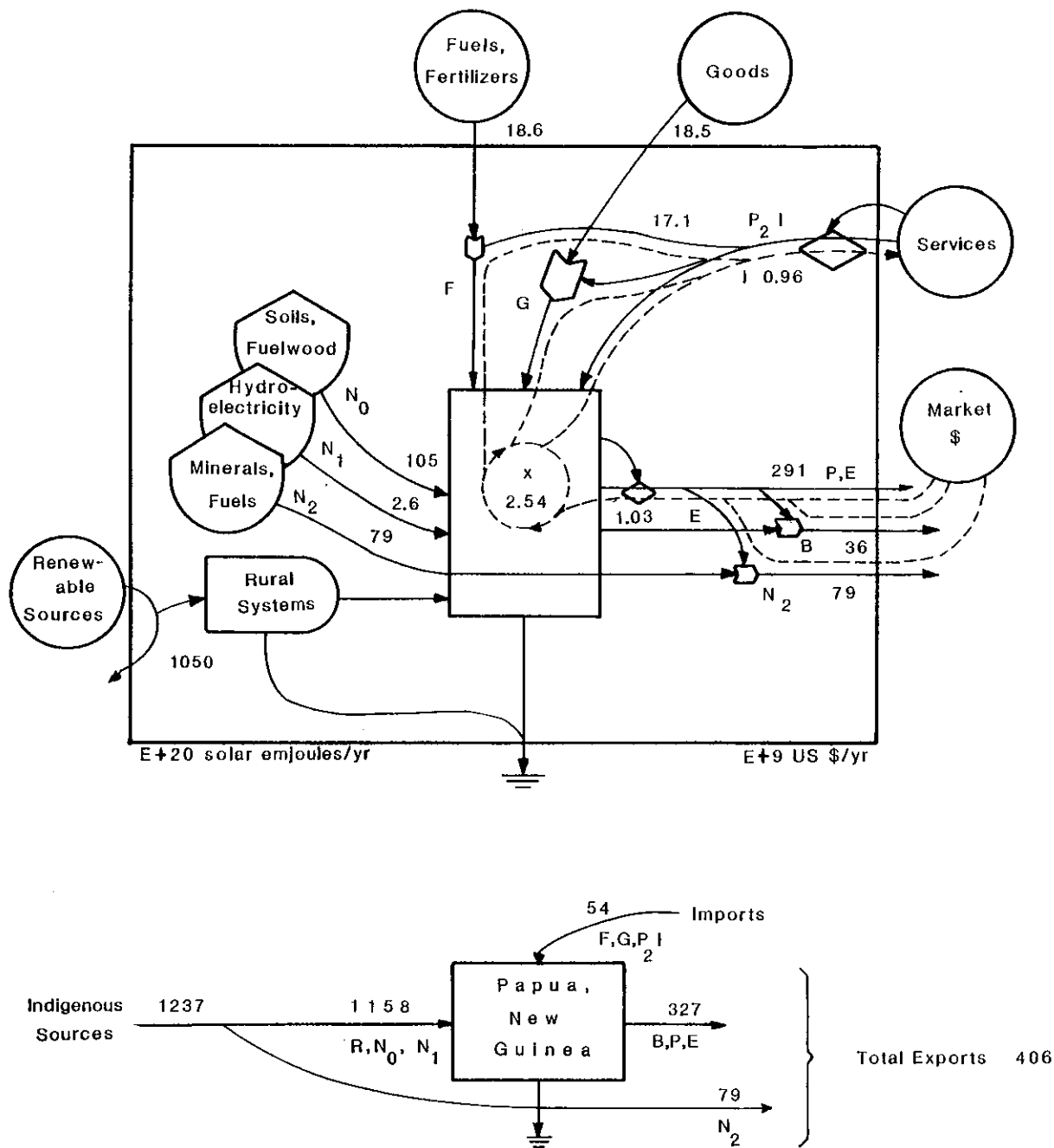


Figure A-1. National summary diagrams of annual solar energy flows of Papua New Guinea. (a) Aggregated diagram of major resource flows and monetary exchange. Values on pathway correspond to Table A-2. (b) Three-arm diagram further summarizing contributions as indigenous sources, imports and exports.

[ $R + (N_0 + N_1)$ ]; 2) purchased imports ( $F + G + P_2I$ ); and 3) exports to other countries ( $B + P_1E$  and  $N_2$ ).

These diagrams assist the reader in synthesizing the energy evaluations by combining similar flows from the tables and aggregating the systems diagram of the country presented in the introduction.

A number of indices relating resources, people and the economy of Papua New Guinea have been prepared in order to draw perspectives on the relative importance of contributing energy sources (Table A-3). The first seven entries are simple aggregations of supporting energy flows evaluated in Tables A-1 and A-2. The other listings are ratios and indices derived from these summations. Over 85% of PNG's total support base is delivered from renewable environmental sources -- much higher than most other countries of the world. Including nonrenewable sources, about 95% of PNG's energy basis is derived from within the country (item 14). In other words, the environment contributes more than 6 times the solar energy than is received through economic transactions. Currently, electricity and fossil fuel consumption account for less than 5% of the country's annual energy-use.

On the other hand, Papua New Guinea exports more than 7 times as much solar energy as it can purchase with revenues from overseas sales (item 11, Table A-3). This translates into a net energy deficit due to trade of about  $350E+20$  sej/yr -- about 25% of the country's annual energy-use. Relating annual energy-use to the country's GNP, 52 trillion solar energy joules are used annually for each kina circulating in the economy (exchange rate 0.93 kina/US \$, 1988 ;  $48E+12$  sej / international \$ US). This index is an order of magnitude higher than more developed countries. For instance, in 1987 the USA energy/money index was about  $2E+12$  sej/\$ US (Odum 1988). This suggests that much more solar energy supports each unit of currency in PNG. When products are sold at market value to overseas buyers, PNG delivers 20 times more solar energy to the foreign market than they could purchase with the revenues from the sale. This solar energy represents environmental resources supporting the people of PNG, including both monied and unmonied lifestyles. By not recognizing the services and products provided from PNG's ecological support base, resources sold to foreign buyers are subsidized resulting in low prices that do not accurately reflect the ability of a resource to stimulate real work in the receiver's economy.

An estimate of a carrying capacity based on renewable resource use for the people of Papua New Guinea was estimated using current energy-use and the percentage of that annual consumption that

Table A-3. Overview indices of annual solar energy-use, origin, and economic and demographic relations for Papua New Guinea, 1987.

	Name of Index	Derivation	Quantity
1	Renewable solar energy flow (rain, tides, earth heat flow)	R	1050.1 x 10 <sup>20</sup> sej/yr
2	Solar energy flow from indigenous nonrenewable reserves	N	190.3 x 10 <sup>20</sup> sej/yr
3	Flow of imported solar energy	F+G+P <sub>2</sub> I	54.1 x 10 <sup>20</sup> sej/yr
4	Total solar energy inflows	R+N+F+G+P <sub>2</sub> I	1294.6 x 10 <sup>20</sup> sej/yr
5	Total solar energy used, U	N <sub>1</sub> +R+F+G+P <sub>2</sub> I	1215.8 x 10 <sup>20</sup> sej/yr
6	Economic component	U-R	165.6 x 10 <sup>20</sup> sej/yr
7	Total exported solar energy	N <sub>2</sub> +B+P <sub>1</sub> E	405.3 x 10 <sup>20</sup> sej/yr
8	% Locally renewable (free)	R / U	86.4 %
9	Economic/environment ratio	(U-R) / R	0.14
10	Ratio of imports to exports	(F+G+P <sub>2</sub> I) / (N <sub>2</sub> +B+P <sub>1</sub> E)	0.13
11	Export to imports	(N <sub>2</sub> +B+P <sub>1</sub> E) / (F+G+P <sub>2</sub> I)	7.49
12	Net solar energy deficit due to trade (imports minus exports)	(F+G+P <sub>2</sub> I) - (N <sub>2</sub> +B+P <sub>1</sub> E)	- 351.2 x 10 <sup>20</sup> sej/yr
13	% of solar energy-use purchased	(F+G+P <sub>2</sub> I) / U	4.5 %
14	% of solar energy-use derived from home sources	(N <sub>1</sub> +R) / U	95.5 %
15	Solar energy-use per unit area (0.462 million km <sup>2</sup> )	U / area	0.26 x 10 <sup>12</sup> sej/m <sup>2</sup>
16	Solar energy-use per person (3.5 million people)	U / population	34.7 x 10 <sup>15</sup> sej/person
17	Renewable carrying capacity at present living standard	(R/U)*(population)	3.02 x 10 <sup>6</sup> people
18	Developed carrying capacity at same living standard	8*(R/U)*(population)	24.2 x 10 <sup>6</sup> people
19	Index of solar energy-use to GNP	P <sub>1</sub> = U / GNP <sub>1987</sub>	48.0 x 10 <sup>12</sup> sej/\$
20	% Electric (1.5 TWh)	(electricity use) / U	1.8 %
21	% Fossil fuels	(fuel use) / U	1.5 %
22	Fuel-use per person	fuel-use / population	0.53 x 10 <sup>15</sup> sej/person



was renewable (R/U). Just over 3 million people can presumably be supported on a sustainable basis using only resident renewable resources (about 87% of current population). With increasing ties to world economies, developing to global standards, Papua New Guinea could presumably support almost 7 times the current population. This assumes greater trade with outside markets, greater use of indigenous resources, and an increase in the country's regional investment ratio (IR) to a world average of 8 to 1 (purchased imports to environmental source contributions). Such an increase would be accompanied by further integration into a monied economy and a lowering of per capita energy consumption resulting in a lower standard of living. A few other indices relating population and area to solar energy-use are presented in Table A-3. These indices and the others discussed here will be revisited in the Recommendations and Conclusion Section of this report comparing Papua New Guinea's energy and economic indices to other countries of the world.

It is evident here that Papua New Guinea is still a rural country with most of its real wealth derived from free indigenous sources. There is a 20:1 ratio of environmental energy to purchased imports, revealing a low dependence on foreign exchange. At the same time, a large amount of solar energy is exported without any refinement in the country. Raw materials provide society with a net contribution of solar energy due to past unmonied environmental work, supporting value-added industries and peoples. Currently, as evidenced by low solar energy contributions from imports relative to exported resources, Papua New Guinea is operating at a net trade deficit. This is possible due primarily to a large ecological support system -- one that will increasingly be threatened with further developments that don't consider these free contributions.

## **REGIONAL ANALYSIS OF THE HIGHLANDS AND LOWLANDS**

An energy evaluation of the highland and lowland regions of Papua New Guinea was undertaken to better understand the role of ecological and physiographic conditions considered unique to each region and their effects on resource production and allocation. The country's relief is shown in Figure A-2 and Table A-4 summarizes physiographic and climatological differences between the regions.

The highlands represent those lands greater than 300 meters in elevation, comprising 56% of PNG's land base. Based on data from Davidson (1983), the mean elevation of the highlands above the upper limit of the lowlands (300 meters) is 1000 meters. This elevation was used to calculate the

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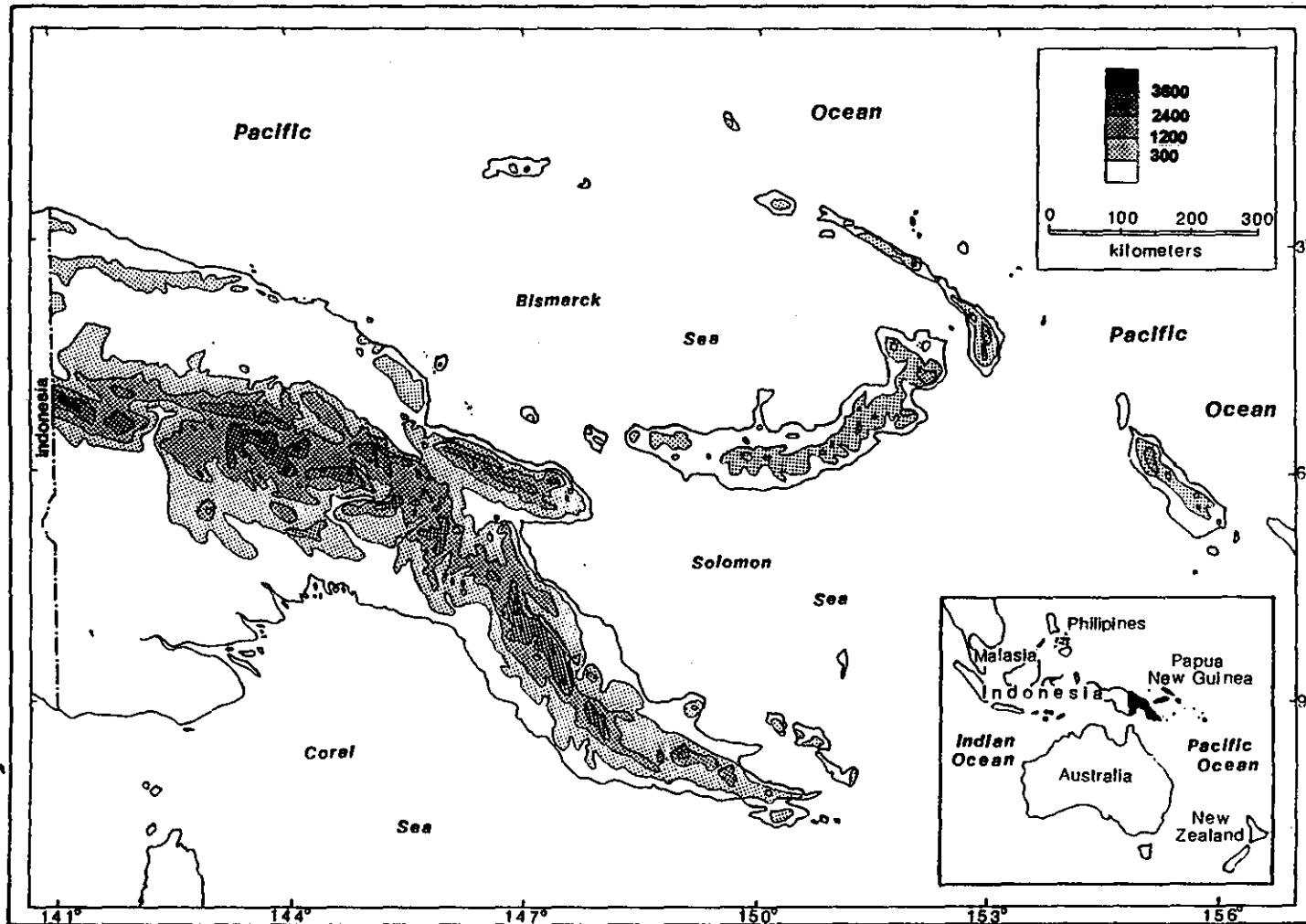


Figure A-2. Map of Papua New Guinea, showing its inland relief; lowlands coastal plains, highlands above 300m, and the central cordillera above 2400m.

Table A-4. Indigenous, renewable solar energy support for highlands and lowlands regions in Papua New Guinea. Calculations are given as footnotes to this table.

	Highlands <sup>1)</sup>	Lowlands <sup>2)</sup>	Country total
% Total area	56	44	100 %
Avg. elevation	1000	150	794 m
Annual rainfall	3.73	1.20	2.62 m/yr
Runoff			
volume	699	68	767 x 10 <sup>9</sup> m <sup>3</sup> /yr
percent of incident rainfall	72	28	53 %
Evapotranspiration	28	72	47 %
Chemical potential emergy in rainfall <sup>a</sup>	238	189	427 x 10 <sup>20</sup> sej/yr
Geopotential energy in rainfall <sup>b</sup>	719	11	730 x 10 <sup>20</sup> sej/yr
Chemical stream emergy <sup>3)</sup>	----	----	1708 x 10 <sup>20</sup> sej/yr
Physical stream emergy <sup>4)</sup>	----	----	314 x 10 <sup>20</sup> sej/yr

Footnotes to Table A-4.

1. Highlands region

- a. chemical potential: (highlands area) (rainfall) (% ET) (density of rain water) (Gibbs free energy) = (56%)(4.62E+11 m<sup>2</sup>) (3.73 m rain) (0.28) (1000 kg/m<sup>3</sup>) (4940 J/kg) = 1.31E+18 J/yr;  
solar emergy = (1.31E+18 J/yr)(18200 sej/J) = 2.38E+22 sej/yr
- b. geopotential energy: (highlands area) (avg. elevation) (rainfall) (% runoff) (density of rain water) (gravitational force) = (56%)(4.62E+11 m<sup>2</sup>) (1000 m) (3.73 m rain) (0.72) (1000 kg/m<sup>3</sup>) (9.8 m/s<sup>2</sup>) = 6.85E+18 J/yr;  
solar emergy = (6.85E+18 J/yr) (10500 sej/J) = 7.19E+22 sej/yr

2. Lowlands region

- a. chemical energy, rain over land: (lowlands area) (rainfall) (% ET) (density of rain water) (Gibbs free energy) = (44%)(4.62E+11 m<sup>2</sup>) (1.20 m rain) (0.72) (1000 kg/m<sup>3</sup>) (4940 J/kg) = 0.87E+18 J/yr;  
solar emergy = (0.87E+18 J/yr) (18200 sej/J) = 1.58E+22 sej/yr
- chemical energy, rain over coastal system: (continental shelf) (rainfall) (density of rain water) (Gibbs free energy for seawater/rainwater differential) = (1.43E+11 m<sup>2</sup>) (1.20 m rain) (1000 kg/m<sup>3</sup>) (1000 J/kg) = 0.17E+18 J/yr;  
solar emergy = (0.17E+18 J/yr, over sea) (18200 sej/J) = 3.09E+21 sej/yr
- total chemical emergy in rainfall = (1.58 + 0.31)E+22 sej/yr = 1.89E+22 sej/yr

Table A-4 footnotes, continued.

2. b. physical energy, rain over land: (lowlands area) (avg. elevation) (rainfall) (% runoff) (density of rain water) (gravitational force) = (44%)(4.62E+11 m<sup>2</sup>) (150 m) (1.20 m rain) (.28) (1000 kg/m<sup>3</sup>) (9.8 m/s<sup>2</sup>) = 0.10E+18 J/yr;  
solar energy = (0.10E+18 J/yr) (10500 sej/J) = 1.05E+21 sej/yr

3. Chemical stream energy estimated as contributions from 2 sources: 1) volume flow from highlands runoff into lowlands and 2) runoff from lowlands into coastal systems:

1) highlands runoff into lowlands = (% runoff from highlands) (highlands rain) (highlands area) = 6.99E+11 m<sup>3</sup>/yr;  
(6.99E+11 m<sup>3</sup>/yr) (1000kg/m<sup>3</sup>) (4940 J/kg) = 3.45E+18 J/yr;

2) lowlands runoff into coastal systems = (lowlands runoff) (lowlands rain) (lowlands area) = 6.83E+10 m<sup>3</sup>/yr;  
(6.83E+10 m<sup>3</sup>/yr) (1000kg/m<sup>3</sup>) (1000 J/kg) = 0.068E+18 J/yr;

Solar energy = (3.45E+18 J/yr + 0.68E+18 J/yr) (48500 sej/J) = 1.71E+23 sej/yr

4. Physical stream energy estimated as the sum of 1) surface water runoff from highlands into lowlands and 2) direct precipitation on lowlands not evapotranspired:

Solar energy = (highlands + lowlands runoff) (avg. elev. drop of lowlands drainage area) (gravitational force) (density of water) = [6.99E+11 m<sup>3</sup> + 0.68 m<sup>3</sup>] (150 m elevational change) (9.8 m/s<sup>2</sup>) (1000 kg/m<sup>3</sup>) = 1.13E+18 J/yr;  
(1.13E+18 J/yr) (27900 sej/J) = 3.14E+22 sej/yr

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geopotential energy due to rain runoff for the highlands. Average annual rainfall for this region is 3.73 m (van der Leeden 1985). Evapotranspiration rates (ET) were estimated to be around 30% of incident rain; runoff was considered to be that which is not evaporated or transpired ( $100 - \%ET = 72\%$ ).

The lowlands represent the remaining 44% of the land area with an average elevation of 150 m (the mean height between sea level and 300 m), including the coastal waters out to the edge of the continental shelf. Lowlands have lower cloud coverage, greater solar insolation, lower rainfall, more winds and less steep slopes yielding greater evapotranspiration rates and lower runoff rates. An average of 1.20 m of precipitation falls annually on the lowlands and surrounding coastal waters (PNG Info. Booklet 1986). Evapotranspiration and runoff rates were considered inverse of those in the highlands.

From these regional analyses, it is clear that a vast majority of the energy delivered from annual rains is due to climatic conditions, ecological cover and physiographic relief unique to the highlands. Nearly all of the gravitational potential in rainwater across the country's topography is due to highland conditions. About 98% of the  $730E+20$  sej/yr is contributed from actions of highlands rains (Table A-4). In contrast, much of rain's chemical potential energy is derived from lowland vegetative cover, higher temperatures and winds which drive photosynthesis and transpiration (almost 60% of the  $427E+20$  sej/yr in transpired rain is delivered from lowland and coastal areas).

The chemical and physical energies in rivers were also estimated based on volume of runoff from the two regions: 1) the volume of surface water runoff leaving the highlands which is concentrated in river channels and flows into the lowlands, and 2) the volume of runoff into coastal systems due to the direct rainfall on the lowlands which is not evapotranspired. The chemical potential energy in river flow was estimated  $1708E+20$  sej/yr; the physical stream energy was estimated at  $314E+20$  sej/yr. This regional analysis brings into perspective the large energy contributions due to prevailing conditions of the environment in these two regions of the mainland. Further, it is apparent that although the highlands receive greater rainfall, most is runoff and collected in stream channels entering the lowlands, so that much of its potential is directed downstream toward the receiving systems below.

In an attempt to investigate issues of resource allocation, demographic and socioeconomic conditions were attributed to each region. Two-thirds of the country's population was considered rural highlands (Bell 1986) or roughly 2.3 million people, with 1.2 million inhabitants in the lowlands and along the coast. It was

assumed that a quarter of the imported goods and services reached the highlands; the lowlands being the more urban area with its large port cities. Solar energy flows for both regions are summarized in Figure A-3. The total solar energy base for the highlands was estimated at just over  $1000E+20$  sej/yr. Lowlands solar energy base totalled  $2500E+20$  sej/yr, over twice that of the highlands. Using this scenario, per capita energy-use in the lowlands was over 4 times as great as per capita-use in the highlands. This regional analysis identifies the importance of highlands rain, forest cover and stream network to the country's renewable resource base.

### ENERGY EVALUATION OF INDIGENOUS RESOURCE RESERVES

Papua New Guinea has large resource reserves, including forest biomass, organic matter in soil, metal ores and fossil hydro-carbon reserves. Estimates of solar energy were made for all known major reserves (Table A-5). Solar energy of rainforest reserves were calculated using a solar transformity for standing forest biomass derived in the subsystems analysis of forest operations in New Britain (see Table B-1). Coastal plain swamps were evaluated using a solar transformity derived from subsystems analysis of sago palm (see footnotes to Figure B-2). Other solar transformities are drawn from independent studies and cited as footnotes. All storages are expressed in billion macro-economic dollars, by dividing the solar energy stored in a resource reserve by  $2E+12$  sej/\$ US, the energy/dollar index for the United States in 1987 (Odum 1988). This was done in order to relate real value based on past environmental production of existing reserves. As defined in the methods section, macro-economic value refers to the total amount of dollar flow that could be generated by use of a resource. By expressing solar energy in macro-economic dollars, potential contributions to Papua New Guinea's total, combined economy are made relative to international markets.

Based on energy content and wood density values for rainforest biomass derived from Brown and Lugo (1984) and standing crop estimates of PNG's different forest types (Davidson 1983), estimates of stored solar energy were made. Lowland rainforests, the largest area of forest cover type (about 20 million ha), had the largest biomass storage of solar energy (item 1, Table A-5), about  $6.5E+24$  sej.

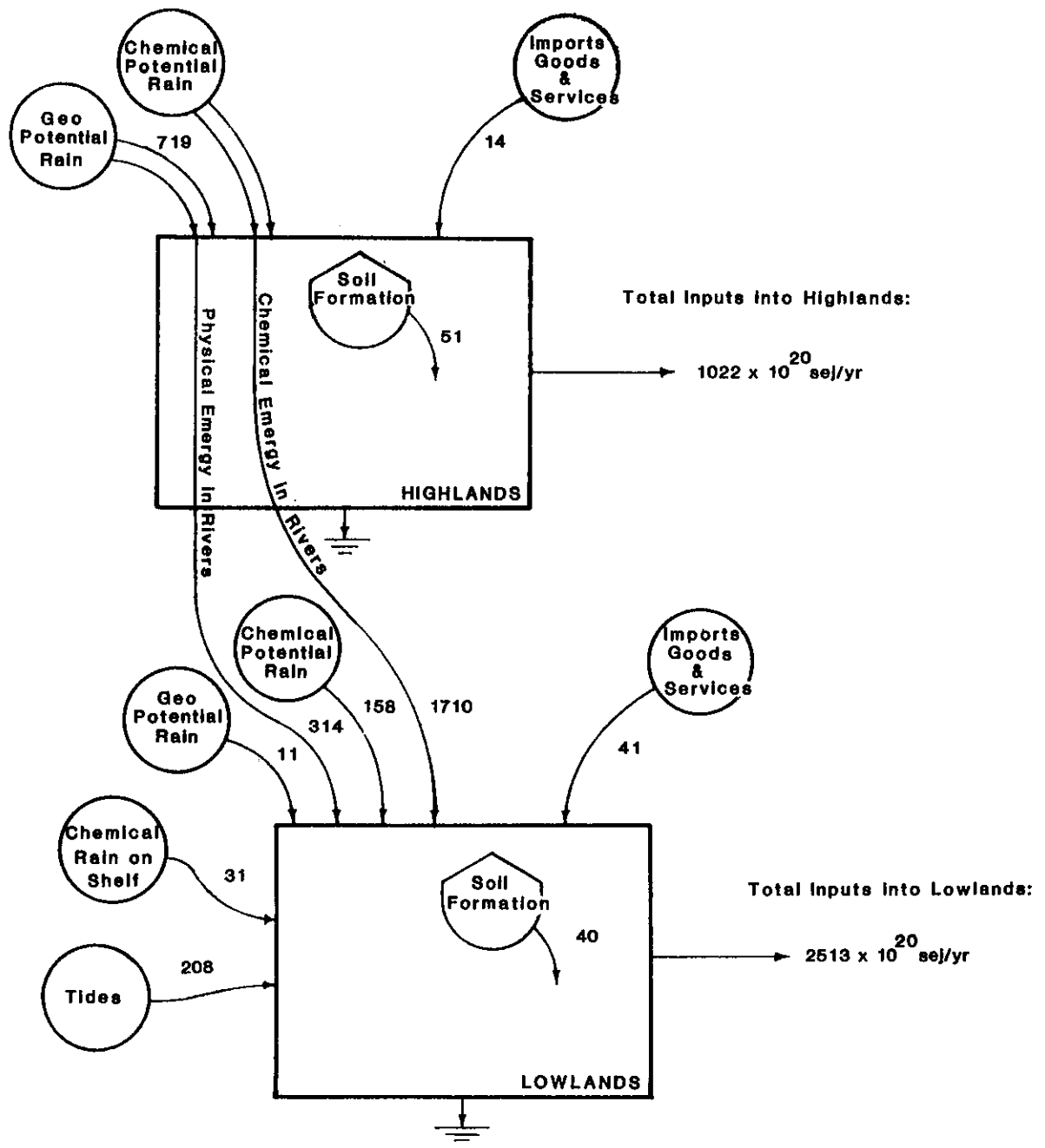


Figure A-3. Systems diagram relating solar energy flows associated with highlands and lowlands regions of Papua New Guinea. Calculations for pathway values are given as footnotes to Table A-4.

Table A-5. Storage of solar emergy in resource reserves within Papua New Guinea.  
Calculations for basic data given as footnotes to this table.

Note	Indigenous reserves	Storage quantity (J, g)	Solar emergy <sup>a)</sup> (sej)	Macro-economic value <sup>b)</sup> (billion US \$, 1988)
1	Lowland rainforest	1.62E+20 J	6.46E+24	3228
2	Lower montane forest	1.04E+20 J	4.17E+24	2085
3	Alpine/montane forest	9.48E+18 J	3.80E+23	190
4	Coastal plains swamps	5.88E+17 J	7.44E+22	39
5	Mangroves	7.10E+18 J	1.04E+18	52
6	Regrowth and gardens	2.95E+18 J	5.60E+22	28
7	Soil organic matter	6.65E+18 J	4.15E+23	208
8	Copper ore	6.24E+12 g	2.81E+23	140
9	Gold	9.72E+09 g	4.86E+20	< 1
10	Oil	2.95E+18 J	1.56E+23	78
11	Natural gas	1.10E+19 J	5.29E+23	265

total macro-economic value of resource reserves: 6.3 trillion US \$, 1988.

a) Solar emergy derived using solar transformities given below.

b) Solar emergy divided by solar emergy/\$ index for U.S. in 1988 ( $2 \times 10^{12}$  sej/\$) to give perspective of value on international markets.



Footnotes to Table A-5.

- 1 Lowland tropical rainforest; area of forest cover =  $19.9 \times 10^6$  ha (McIntosh 1974), biomass = 405.4 ton/ha (Brown and Lugo 1984); energy content = 4.78 kcal/g (E.P. Odum 1971); solar transformity = 40,000 sej/J (for derivation see Table B-1); ( $19.9 \times 10^6$  ha) (405.4 t/ha) ( $1 \times 10^6$  g/ton) (4.78 kcal/g) (4186 J/kcal) =  $1.62 \times 10^{20}$  J; ( $1.62 \times 10^{20}$  J) (40000 sej/J) =  $6.46 \times 10^{24}$  sej
  - 2 Lower montane forest;  $9.1 \times 10^6$  ha (McIntosh 1974), 572.6 t/ha (Brown and Lugo 1984); ( $9.1 \times 10^6$  ha) (572.6 t/ha) ( $1 \times 10^6$  g/t) (4.78 kcal/g) (4186 J/kcal) =  $1.04 \times 10^{20}$  J; ( $1.04 \times 10^{20}$  J) (40000 sej/J) =  $4.17 \times 10^{24}$  sej
  - 3 Montane and alpine forest;  $1.2 \times 10^6$  ha (McIntosh 1974), 394.9 t/ha (Brown and Lugo 1984); ( $1.2 \times 10^6$  ha) (394.9 t/ha) ( $1 \times 10^6$  g/t) (4.78 kcal/g) (4186 J/kcal) =  $9.48 \times 10^{18}$  J; ( $9.48 \times 10^{18}$  J) (40000 sej/J) =  $3.80 \times 10^{23}$  sej
  - 4 Sago palm and woodland swamps;  $3.5 \times 10^6$  ha (McIntosh 1974), 4.012 kcal/ha (Ulijaszek and Poraituk 1983); solar transformity = 131600 sej/J (for derivation see footnotes to Figure B-2); ( $3.5 \times 10^6$  ha) (135 trunks/ha) (74.3 kg/trunks) (400 kcal/0.1 kg) (4186 J/kcal) =  $5.88 \times 10^{17}$  J; ( $5.88 \times 10^{17}$  J) (131600 sej/J) =  $7.74 \times 10^{22}$  sej
  - 5 Mangroves;  $4.5 \times 10^6$  ha (McIntosh 1974);  $1 \times 10^4$  g/m<sup>2</sup> (Snedaker 1986); energy content 3.77 kcal/g; ( $4.5 \times 10^6$  ha) (10000 m<sup>2</sup>/ha) ( $1 \times 10^4$  g/m<sup>2</sup>) (3.77 kcal/g) (4186 J/kcal) =  $7.10 \times 10^{18}$  J; ( $7.10 \times 10^{18}$  J) (14700 sej/J) =  $1.04 \times 10^{23}$  sej
  - 6 Regrowth and gardens;  $2.4 \times 10^6$  ha (McIntosh 1974), 4.2 kcal/g (Odum et al 1983); ( $2.4 \times 10^6$  ha) (10000 m<sup>2</sup>/ha) (7000 g/m<sup>2</sup>) (4.2 kcal/g) (4186 J/kcal) =  $2.95 \times 10^{18}$  J; ( $2.95 \times 10^{18}$  J) (19000 sej/J) =  $5.60 \times 10^{22}$  sej
  - 7 Organic matter in soil; est. 7000 g/m<sup>2</sup>, 10% organic matter content: ( $4.2 \times 10^7$  ha) (10000 m<sup>2</sup>/ha) (7000 g/m<sup>2</sup>) (0.1) (5.4 kcal/g) (4186 J/kcal) =  $6.65 \times 10^{18}$  J; ( $6.65 \times 10^{18}$  J) (62500 sej/J) =  $4.15 \times 10^{23}$  sej
  - 8 Copper ore; estimates 950 million tons (Panguna Mine, 0.4% Cu content) + 350 million tons (Ok Tedi Mine, 0.7%) (PNG Info. Bk. 1984) =  $6.25 \times 10^6$  tons: ( $6.25 \times 10^6$  t) ( $1 \times 10^6$  g/t) =  $6.25 \times 10^{12}$  g; ( $6.25 \times 10^{12}$  g) ( $4.5 \times 10^{10}$  sej/g) =  $2.81 \times 10^{23}$  sej
  - 9 Gold; estimate  $34 \times 10^6$  tons, (Ok Tedi Mine, 286g/t purity) (PNG Info. Bk. 1984): ( $3.4 \times 10^7$  t) (286 g/t) =  $9.72 \times 10^9$  g; ( $9.72 \times 10^9$  g) ( $5 \times 10^{10}$  sej/J) =  $4.86 \times 10^{20}$  sej
  - 10 Oil reserves = 345 mbbbl oil + 137 mbbbl condensate (Qureshi et al 1988): ( $482 \times 10^6$  bbl) ( $5.8 \times 10^6$  Btu/bbl) ( $1055$  J/Btu) =  $2.95 \times 10^{18}$  J; ( $2.95 \times 10^{18}$  J) (53000 sej/J) =  $1.56 \times 10^{23}$  sej
  - 11 Natural gas; estimate 10 trillion cu ft (Qureshi et al 1988): ( $10 \times 10^{12}$  cu ft) ( $2.832 \times 10^{-2}$  m<sup>3</sup>/cu ft) ( $3.89 \times 10^7$  J/m<sup>3</sup>) =  $1.102 \times 10^{19}$  J; ( $1.102 \times 10^{19}$  J) (48000 sej/J) =  $5.29 \times 10^{23}$  sej
-

Referring back to Table A-1, only about  $0.04E+24$  sej of forest products including fuelwood was harvested in 1988. This lowland rainforest emergy expressed as macro-economic contributions, was estimated to be worth 3.2 trillion dollars, roughly half of all solar emergy stored in major reserves in PNG. Lower montane forests are the next largest emergy storage with over 9 million ha and over  $2E+12$  sej stored in standing biomass (Table A-5, item 2). Coastal plain swamps and mangroves together represent about  $90E+9$  US\$ in storages.

Other biotic reserves of include regrowth and gardens and organic matter stored in forest soils, together worth almost 250 billion macro-economic dollars (items 6 and 7). The two largest mining companies in Papua New Guinea, Panguna and Ok Tedi, have an estimated 140 billion macro-dollars in copper reserves (item 8). Known gold reserves represent insignificant contributions of solar emergy. Known, potential and possible hydrocarbon reserves, while relatively small (oil and natural gas store 340 billion US\$), may be significantly larger if future explorations meet current discoveries (Dow 1977 and Hapgood 1989).

Together, all major reserves store over 6 trillion US\$ in macro-economic value within Papua New Guinea. The macro-economic value of these resource reserves is almost 2500 times greater than the current national product of 2.54 billion US\$. Further, 90% of all reserves are forest biomass, based on renewable energy sources of sunlight and rainfall. These resource reserves will play important and expanding roles in the country's future economy. In chapter 3-F of this report, we make a preliminary estimate of the solar emergy of stored genetic and cultural information in PNG nationals, representing the convergence of past environmental work into high quality information storages. The large solar emergy stored in these resource and information reserves illustrates the abundant wealth not only in annual production but in savings as well. By recognizing real value of all contributing sources, not simply those with market value, a new perspective is gained which identifies Papua New Guinea as a resource wealthy country with great amounts of solar emergy delivered mostly free from home sources and stored in indigenous reserves. These values will be compared with those of other countries as concluding remarks to this report in order to draw perspectives relative to other rural and developed nations.



## **Section B: Subsystems Analyses of Major Rural Production Systems**

by S.J. Doherty

In this section, three indigenous production systems are evaluated for net yield and return on investments using measures of solar energy. These systems are: 1) a lowland rainforest logging operation on the island of New Britain; 2) sago palm cultivation in the Gulf Province; and 3) sweet potato production in a typical highlands village. Each one will be introduced briefly, accompanied by a systems diagram with calculations footnoted. Sources from both the environment and any purchased resources derived outside the system were evaluated. Ratios of net yield and investment as described in the methods section of this report are calculated for each production sector. Solar transformities calculated for each product was then used in the national overview analysis (Section A) in order to estimate as accurately as possible the contributions due to major production sectors. Finally an estimate of environmental support area is given for each sector which demonstrates the role of Papua New Guinea's rich renewable resource base in supporting its people and their activities.

### **SUBSYSTEMS ANALYSIS OF FORESTRY IN NEW BRITAIN**

#### **Overview of Forest Resources**

For many thousands of years the forests of Papua New Guinea have been the primary renewable resource for its people, providing building materials, fuels, food, medicine and gardening plots. The commercial exploitation of forests began after World War II. Eighty-five percent of the country's land area is tree-covered, and one-third is considered accessible commercial forest (King et al 1982). Other valuations are lower; Galenson et al (1982) estimated that one million hectares (2 percent of the land area) were under allocation for exploitation and another 6 million hectares are of known and possible potential. The discrepancy in figures is largely due to the debate over accessibility of forest products and variable assessments of timber grade. Davidson (1984) reports that although PNG has the highest forest/land area ratio of all the Indo-Pacific nations, it has a low percentage of operable forest area due to difficulty of the terrain.

The forests of Papua New Guinea are broken into major ecotypes Table A-5, along with emergy valuations of standing reserves based on solar transformities determined from these subsystem analyses. The major forestry operations have been in lowland rainforests which cover the greatest land area. Much of the country is difficult to access owing to extensive swamps and steep slopes. What is accessible is of a mixed variety hardwood type with generally low economic returns on investment (McIntosh 1974, Tickell per. comm. 1990). Some 200 timber species have economic potential (Komtagarea 1979), but presently only a few account for the bulk of merchantable timber. The island of New Britain is the major forest industry area of PNG (Perry 1985), but the largest individual clear felling project has been the Gogol/JANT project in the valleys south of Madang Province.

The Office of Forests (1977) developed an inventory of known, possible and potential forest development areas based on difficulty of access, suitability of terrain to clear felling operations and risk assessment. Important ecological variables such as biomass productivity, stability, evapotranspiration rates and water quality have not been included in the inventory. These known and possible areas of forestry potential along with the major timber operations existing in 1977 are given in Figure B-1. Most of the marketable timber comes from a few select species such as Pometia spp., Eucalyptis spp., Agathis spp., and Araucaria spp. in the higher elevations. Because of the high diversity of low-grade timber, the steep slopes, high rainfall (average 2500-3500 mm annually), the remoteness of much of the resource, and the division of land tenure, the rainforests of much of Papua New Guinea's landscape are afforded, at least temporarily, some protection--if by nothing more than aggravation.

### **Emergy Analysis of Forestry in New Britain**

Data for forestry operating expenses (fuel, machinery, road materials, labor) and estimates of forest biomass (total organic matter, stemwood biomass, annual production) were derived from the literature and synthesized with known values supplied by industry (Tickell per. comm. 1990). The evaluation was made for a 20,000 ha operation in lowland rainforests of New Britain. Table B-1 lists all resource flows in raw input units per ton wood product and as solar emergy (sej/ton). All calculations are given as footnotes to the table. An overview diagram is given in Figure B-2 summarizing all solar emergy flows for forest production.

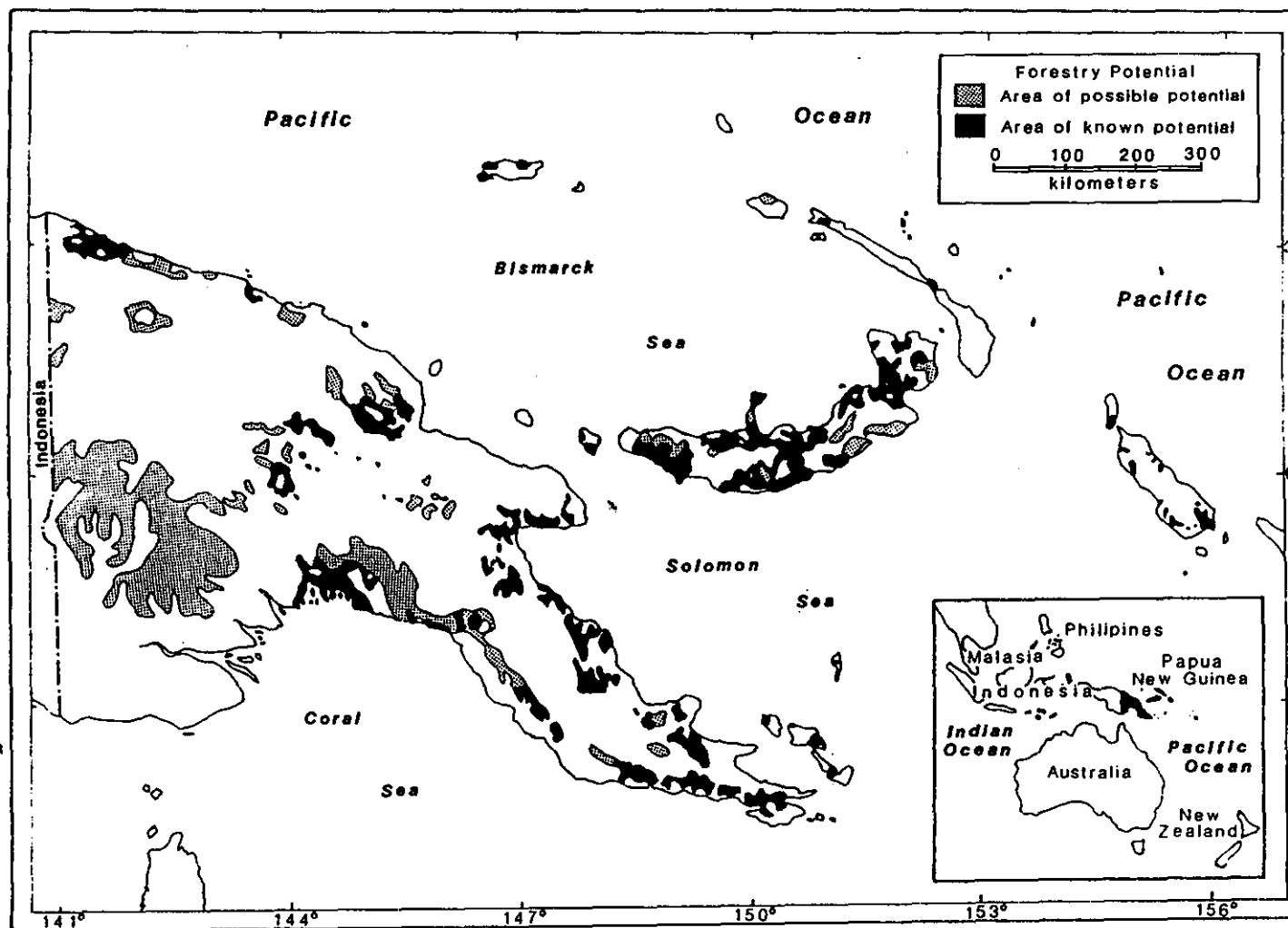


Figure B-1. Map of Papua New Guinea showing its forests of known and possible development potential (redrawn from Baldwin et al 1978). Areas of forest types (lowland, montane, alpine, coastal plains and mangroves) are reported in Table A-5 with the emergy calculations of forest biomass reserves. Note the high development potential on the island of New Britain.

Table B-1. Resource flows supporting rainforest logging in New Britain, Papua New Guinea. All values are given per ton of harvestable wood.

Note	Item	Resource inputs (J, g, \$/ton)	Solar transformity (sej/J)	Solar energy (sej/ton)
1	environmental energy	4.40E+10 J	1.82E+04	8.00E+14
2	fuels	2.70E+08 J	5.30E+04	1.43E+13
3	oil	6.77E+07 J	6.80E+04	4.61E+12
4	machinery	11.20 \$	2.00E+12	2.24E+13
5	other equipment	1.28 \$	2.00E+12	2.55E+12
6	road construction	3.20E+06 g	1.50E+06	4.80E+12
7	labor	4.57 \$	4.80E+13	2.19E+14
8	miscellaneous costs	12.10 \$	2.00E+12	2.42E+13
	Standing crop biomass	2.00E+10 J	(a)	8.00E+14
	Harvested yield	4.32E+09 J	(b)	1.09E+15

(a) Solar transformity of standing biomass:	40000 sej/J
(b) Solar transformity of harvested wood:	253000 sej/J
Net yield ratio of harvested wood:	4.19
Investment ratio of harvested wood:	0.33

Footnotes to Table B-1.

Energy content of rainforest wood: 4.78 kcal/g (4186 J/kcal) = 2.00E+4 J/g

Wood density: 8.00E+5 g/m<sup>3</sup>

Estimate of standing crop of lowland rainforest biomass (Tickell per. comm. 1990):

min 120 m<sup>3</sup>/ha, max 250 m<sup>3</sup>/ha; 185 m<sup>3</sup>/ha avg.

extractable, usable volume = 40 m<sup>3</sup>/ha = 22 % of avg volume

(40m<sup>3</sup>/ha) (0.8E+6 g/m<sup>3</sup>) = 148 tons/ha (2E+4 J/g) = 2.96E+12 J/ha

total standing crop on 20,000 ha: (185 m<sup>3</sup>/ha) (0.8 t/m<sup>3</sup>) (20000 ha) = 2.96E+06 tons

total energy: (2.96E+6 t) (2E+4 J/g) = 5.92E+16 J

Annual yield

premium quality: (1500 m<sup>3</sup>/mo) (0.8E+5 t/m<sup>3</sup>) (12 mo/yr) = 14400 tons/yr (2E+4 J/g) = 2.88E+14 J/yr

construction quality: (3500 m<sup>3</sup>/mo) (0.8E+6 g/m<sup>3</sup>) (12 mo/yr) = 33600 tons/yr (2E+4 J/g) = 6.72E+14 J/yr

total volume harvested: 48000 tons/yr

total energy in harvest: 9.60E+14 J/yr

Table B-1 footnotes, continued.

Percent of total harvested annually: (annual harvest, 48000 tons/yr) / (total standing crop, 2.96E+6 tons) = 2 %

Average area cleared annually: 324 ha/yr

Lifetime of project: 62 yrs

1. Transpired rain, chemical potential: land area = 10000 m<sup>2</sup>/ha; annual rainfall = 80 in; runoff = 28%; evapotranspiration = 72; (72%) (80 in) (.0254 m/in) (10000 m<sup>2</sup>) (1000 kg/m<sup>3</sup>) (4940 J/kg) = 7.23E+10 J/ha/yr; (7.23E+10 J/ha/yr) (18200 sej/J) = 1.32E+15 sej/ha/yr

Total rainfall supporting total standing crop: estimated time to grow forest (200t/ha, max voume) = 90 yrs (based on simulation of forest land rotation model, section C); (90 yrs) (1.32E+15 sej/ha/yr) = 1.19E+17 sej;

sej per ton standing crop: (1.19E+17 sej) (148 t/ha, average) (20,000 ha, total project area) = 8.00E+14 sej/ton

sej per ton harvested: (8.00E+14 sej/ton) (22% extractable) = 3.70E+15 sej/ton

2. Fuel used: 30000 liters/mo; (30000 liters/mo) (energy content 3.60E+07 J/l) (12 mo/yr) = 1.30E+13 J/mo (53000 sej/J) = 6.87E+17 sej/yr;

sej per ton: (6.87E+17 sej/yr) / (48000 tons/yr harvested) = 1.43E+13 sej/ton

3. Oil, lubricants, etc. (3500 kina/month) / (0.93 k/\$) / (0.50 \$/liter) = (7527 l/mo) (energy content, 3.60E+07 J/l) (12 mo/yr) = 3.25E+12 J/mo (68000 sej/J) = 2.21E+17 sej/yr;

sej per ton: (2.21E+17 sej/yr) / (48000 tons/yr harvested) = 4.61E+12 sej/ton

4. Machinery: (capital outlay, 2.00E+06 kina) (estimated lifetime, 4 yrs) / (0.93 k/\$) = 5.38E+5 \$/yr (U.S. sej/\$ index, 2.00E+12 sej/\$) = 1.08E+18 sej/yr;

sej per ton: (1.08E+18 sej/yr) / (48000 tons/yr harvested) = 2.24E+13 sej/ton

5. Other equipment: (5.70E+05 kina) (est. lifetime, 10 yrs) / (0.93 k/\$) = 6.13E+04 \$/yr (2.00E+12 sej/US \$) = 1.23E+17 sej/yr;

sej per ton: (1.23E+17 sej/yr) / (48000 tons/yr harvested) = 2.55E+12 sej/ton

6. Road construction: (length, 4 km) (width, 6 m) = 22000 m<sup>2</sup> surface area:  
gravel: (800 m<sup>3</sup>/mo) (est. rock density 2.00E+06 g/m<sup>3</sup>) (12 mo/yr) = 1.54E+11 g/yr (est. solar transformity using concrete, 1.50E+06 sej/g) = 2.30E+17 sej/yr;

sej per ton: (2.30E+17 sej/yr) / (48000 tons/yr harvested) = 4.80E+12 sej/ton

7. Labor:

nationals, 8000 kina/mo / (0.93 k/\$) (12 mo/yr) = 1.03E+05 \$/yr;

expatriates, 9000 kina/mo / (0.93 k/\$) (12 mo/yr) = 1.16E+05 \$/yr

total labor costs = 2.19E+05 \$/yr (4.80E+13 sej/\$, P<sub>1</sub>, table A-2) = 1.05E+19 sej/yr;

sej per ton: (1.05E+19 sej/yr) / (48000 tons/yr harvested) = 2.19E+14 sej/ton

8. Miscellaneous costs = 45000 kina/mo / (0.93 k/\$) (12 mo/yr) = 5.81E+05 \$/yr (2.00E+12 sej/ US \$) = 1.16E+18 sej/yr;

sej per ton: (1.16E+18 sej/yr) / (48000 tons/yr harvested) = 2.42E+13 sej/ton



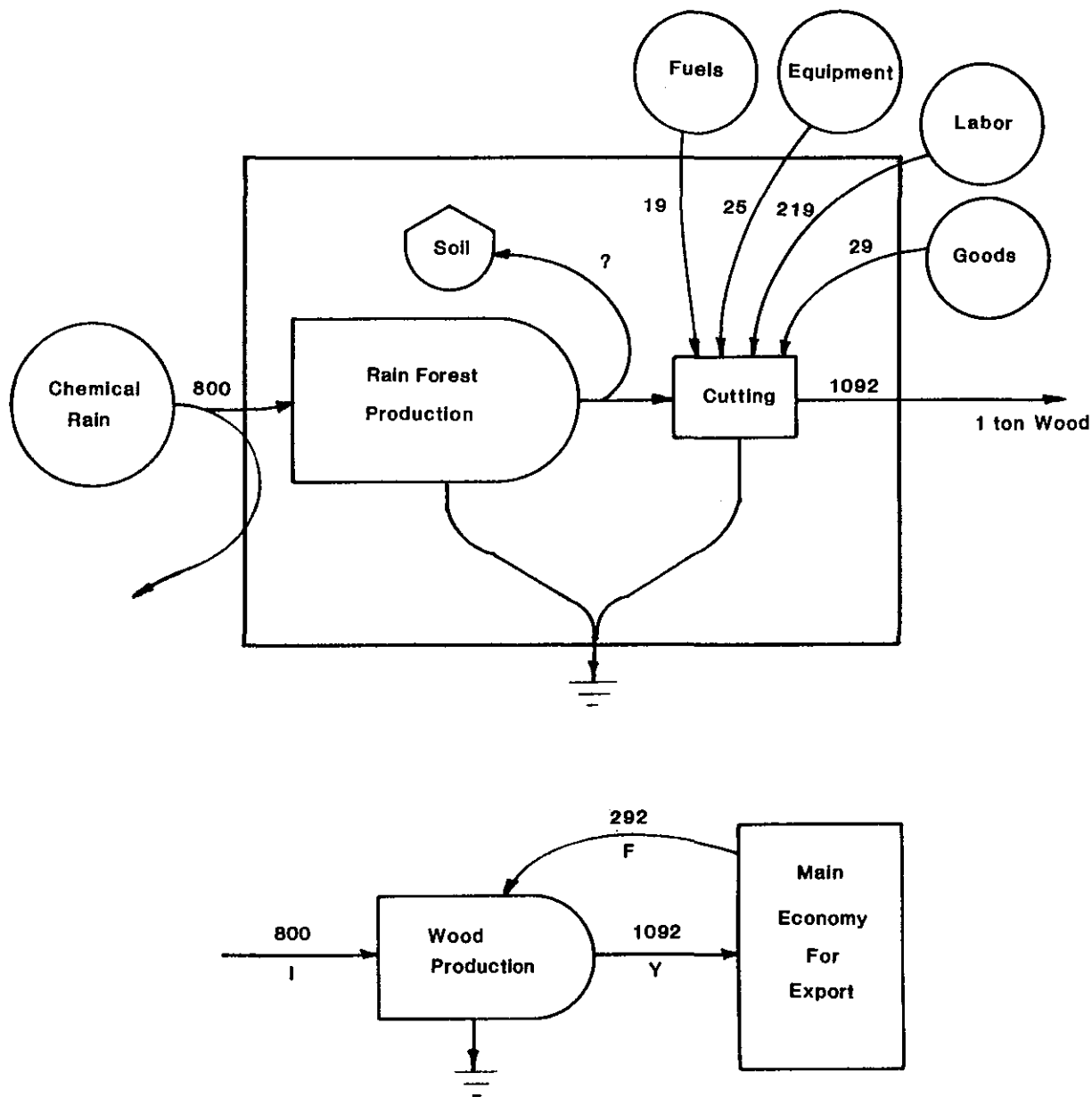


Figure B-2. Systems diagram of biomass production and cutting in lowland rainforests in New Britain. All pathway values are  $10^{12}$  sej/ton. Values correspond to those in Table B-1 with accompanying footnotes and citations.

Transpired rainfall was used to estimate environmental energy supporting forest growth and maintenance. Rainfall in New Britain averages 80 inches (2000 mm) annually. Using the forest land rotation model (Section 3-C of this report), it was estimated that about 90 years would be required to reach a mature steady state forest, averaging 148 tons of stemwood biomass per hectare. Using a wood density estimate for tropical woods of 0.8 tons/m<sup>3</sup>, this represents 185 m<sup>3</sup>/ha. As described in the previous paragraphs, although there is a high volume of forest biomass (range 120 m<sup>3</sup> to 250 m<sup>3</sup> per hectare, mean 185 m<sup>3</sup>/ha), the exportable volume of lumber and construction quality stemwood was estimated to be 40 m<sup>3</sup>/ha (32 tons), or about 22% of total volume.

Using this information, a solar transformity for total biomass standing in forest was calculated as 40,000 sej/J [Table B-1, item (a)]. This is the same order of magnitude as other tropical wood (Odum et al 1986, Keitt 1991) though this transformity does not include societal goods and services required to extract and process it. Once the wood has been harvested, the solar transformity increases to 253,000 sej/J (item b). Solar transformities for temperate wood products are generally much lower. For instance, harvested spruce and pine in Sweden had solar transformities of about 10,000 sej/J (Doherty et al 1991). The higher values for tropical woods are due in part to two factors: 1) high environmental energy per unit product and 2) a greater diversity of structure in complex rainforests. This greater complexity yields much of material that is not targeted for exploitation and structure that is wasted in the process of extracting marketable timber. This is certainly the case in Papua New Guinea where, because of the difficult terrain and diverse mix of forest species, much of the standing forest biomass is wasted when forests are clearcut.

A net yield ratio of just over 4 to 1 suggests that forest products deliver a net benefit to Papua New Guinea's combined economy, though the net yields are not as high as previous studies of other tropical regions have reported. An investment ratio of 0.3 similarly demonstrates that nature is contributing 3 times as much solar energy as that invested from the main economy for forest development projects. Using 40,000 sej/J for standing forest biomass, the rainforests of Papua New Guinea were estimated to store as much as 14E+24 sej with a macro-economic value of 5.5 trillion dollars (refer to Table A-5, items 1, 2 and 3 summing lowland rainforests, montane and alpine forests). Of course, this value is an estimate for all forest biomass, not just export quality stemwood. The question of whether these forest products should be used by PNG nationals or sold overseas for needed revenues will be discussed in the concluding sections of this report.

## SUBSYSTEMS ANALYSIS OF SAGO PALM CULTIVATION

Sago palm woodlands along the coastal plains of Southern Papua New Guinea cover an estimated 3.5 million hectares (Davidson 1983). Traditionally sago palm has been either harvested through progressive clearings from natural woodlands or cultivated under limited management by local villagers for building materials and other resources. Although some plantations exist, sago palm is still considered a local resource and is not targeted for export (Pernetta and Hill 1984). Coastal plains woodlands are vast wetlands receiving large amounts of environmental resources in the form of surface water runoff from the highlands. Direct rainfall is typically lower than in the highlands and solar insolation is greater than average due to lower cloud coverage.

A subsystems analysis for sago palm cultivation was conducted using data drawn from a comprehensive study in Papua New Guinea's Gulf Province by Ulijaszek and Poraituk (1983). Values for productivity ranged from 7 mature trunks/ha per annum for subsistence gathering of uncultivated woodlands to 330 trunks/ha/yr from plantations under intensive management. A mean production of 135 trunks/ha taken annually under village management was considered a sustainable harvest. This value was used in the following analysis. Palm trunk weight (74 kg/trunk) and energy content (4000 kcal/kg) and estimates of village labor (133 hrs/10<sup>6</sup> kcal dry sago palm) were drawn from Ulijaszek and Poraituk (1983). Rainfall was estimated as the average for the country (2.62 m).

The solar energy supporting labor was calculated two ways: 1) using a transformity for human metabolism calculated in Section F (Table F-1, item 2) and 2) using a measure of solar energy per capita calculated from the national analysis (Section A, Table A-3, item 16). The average of these two calculations was used to estimate solar energy supporting labor. The ecological support area for labor was estimated following methods for calculating carrying capacity for economic investments described in the Methods Section of this report. Simply, the percent of the country's total energy budget that was locally renewable ([R/U = 86%]; Table A-3, item 8) was used as to determine how much village labor was supported by the local environment.

Solar energy values are shown in Figure B-3 with corresponding calculations given as footnotes to the summary diagram. A solar transformity for harvested sago palm was determined at 131,600 sej/J.

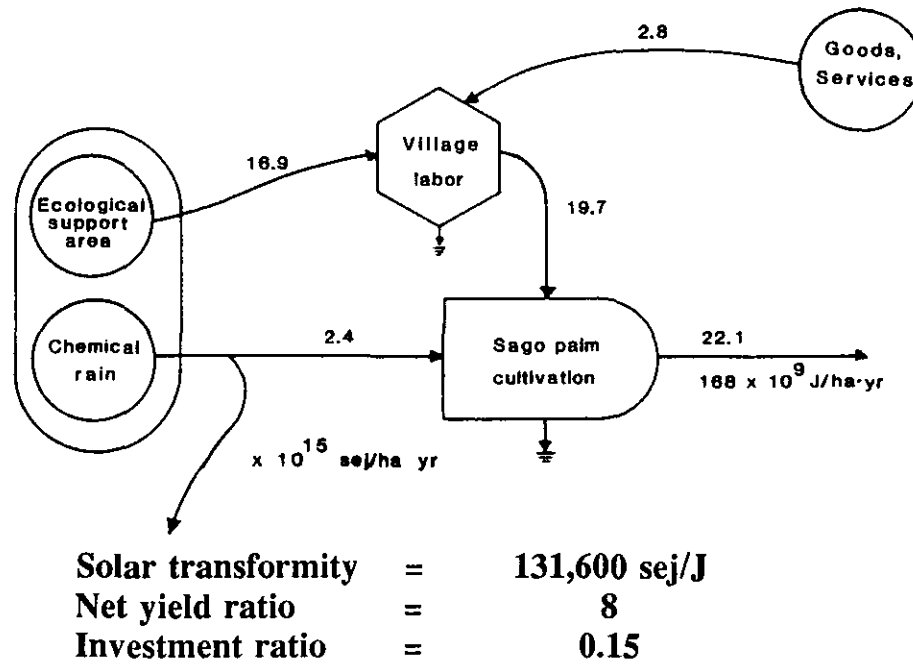


Figure B-3. Aggregated systems diagram of sago palm cultivation in the Gulf Province of Papua New Guinea. All pathway values are  $10^{15}$  sej/ha/yr for sustainable production.

footnotes to Figure B-3

Sago palm yield = (135 trunks/ha/yr) (74.3 kg/trunk) (400 kcal/0.1 kg) (4186 J/kcal) =  $1.68E+11$  J/ha/yr

Chemical rain = (2.62 m/yr) (10000 m<sup>2</sup>/ha) (1000 kg/m<sup>3</sup>) (4940 J/kg) =  $1.29E+11$  J/ha/yr; ( $1.29E+11$  J/ha/yr) (18200 sej/J) =  $2.36E+15$  sej/ha/yr

Labor estimated using average of two calculations:

(133 hrs labor/1E+6 kcal dry sago palm) (4.0122E+7 kcal SP/ha/yr production) (2927 kcal/day food intake) / (24 hrs/day)

(4186 J/kcal) =  $2.724E+9$  J/ha/yr; ( $2.724E+9$  J/ha/yr)( $6.7E+6$  sej/J; Table F-1, item 2) =  $18.25E+15$  sej/ha/yr

(133 hrs labor/1E+6 kcal dry sago palm) (4.0122E+7 kcal SP/ha/yr production) = 5336 hrs/yr; (5336 hrs/yr) / (8736

hrs/yr) = 61% of annual activity; U/person =  $34.7E+15$  sej/per (Table A-3, item 16); (0.61) ( $34.7E+15$  sej/per) =

$21.2E+15$  sej/ha/yr

average = [( $18.25 + 21.2$ )/2]  $E+15$  sej/ha/yr =  $19.7E+15$  sej/ha/yr

Environmental support for labor,  $I_{(labor)} = R/U = 86\%$  (Table A-3, item 8); (0.86) ( $19.7E+15$  sej/ha/yr) =  $16.9E+15$  sej/ha/yr

Outside village support for labor,  $F_{(labor)} = 1 - R/U = 14\%$ ; (0.14) ( $19.7E+15$  sej/ha/yr) =  $2.8E+15$  sej/ha/yr

$I$  = total ecosystem energy = rain +  $I_{(labor)} = (2.36 + 16.9) E+15$  sej/ha/yr =  $19.3E+15$  sej/ha/yr

$F$  = total support outside village =  $F_{(labor)} = 2.8E+15$  sej/ha/yr

$Y$  = total solar energy input =  $I + F = 22.1E+15$  sej/ha/yr

Net yield ratio =  $Y/F = 8:1$

Investment ratio =  $F/I = 0.15$

Solar transformity = ( $22.1E+15$  sej/ha/yr) / ( $1.68E+11$  J/ha/yr) = 131600 sej / J

Renewable energy density for country  $[R/ha] = [R - (\text{waves, tides})] / (\text{area of PNG}) = (712E+20 \text{ sej/yr}) / (46.2E+6 \text{ ha}) = 1.54E+15$  sej/ha

Ecological support area =  $I_{(labor)} / (R/ha) = (16.9 E+15 \text{ sej/ha/yr}) / (1.54E+15 \text{ sej/ha/yr}) = 11$

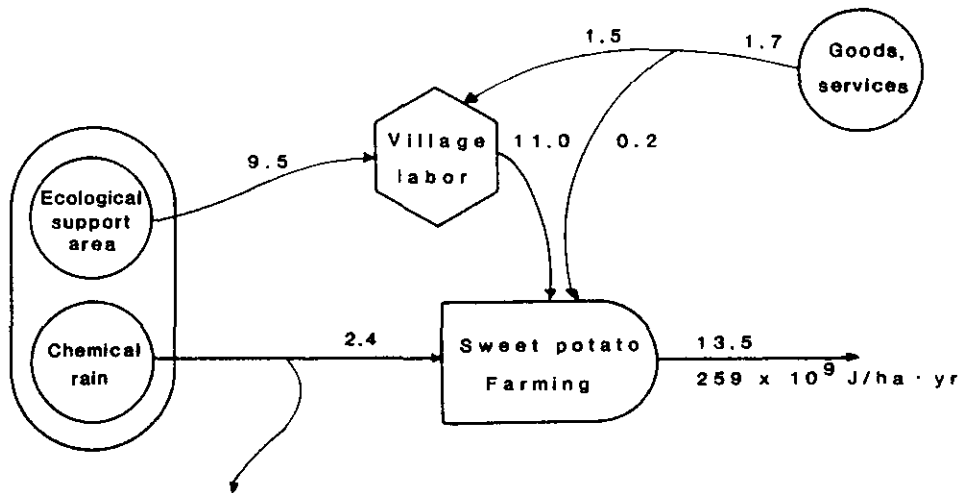
This value is of similar magnitude of other agricultural crops in tropical regions ( $2E+5$  sej/J). A net emergy yield ratio of 8:1 and an investment ratio of 0.15 suggest the importance of environmental sources in sago palm cultivation. Most other agro-forest operations yield much lower returns on investment [compare for example harvested lowland rainforest wood at 4:1 (Table B-1)]. An ecological support area of 11 ha for each hectare of sago palm further demonstrates the role of the environment in rural production of indigenous crops.

### **SUBSYSTEMS ANALYSIS OF SWEET POTATO PRODUCTION**

Although not native to Papua New Guinea, the sweet potato or yam (*Ipomea batatas*) has quantitatively been the most important food crop in subsistence agriculture (Kimber 1972). As of 1985, sweet potato production was worth an estimated K200 million per year (0.22 trillion US \$) (Bourke 1985). No other single crop, including exports crops, contributes as much to the national economy. Over 100,000 ha of sweet potato are planted throughout the country. As well as being a major subsistence crop, sweet potato is now an important cash crop with over 450,000 tons produced per annum. The role of the sweet potato in village life has been widely reported through ethnographic and agronomic studies (Rappaport 1968; Malynicz 1971; Kimber 1972; Bourke 1977; Grossman 1984 among many others). The principle products are cooked tubers for human consumption and raw tubers, vines and leaves used as pig feed.

In this overview analysis, 22.4 tons/ha of sweet potato produced annually was used as an average production (from Grossman 1984 and Bourke 1985). Purchased inputs included fertilizers as well as goods and services supporting village labor. About 30% of a villager's time was estimated spent tending sweet potato gardens (2770 hrs/yr). This value was determined as the average of two activities studies in Papua New Guinea villages (Lea 1970 and Grossman 1984). Solar emergy basis for labor and its ecological support area were determined using the methods given in the subsystems analysis of sago palm.

Solar emergy flows are summarized in Figure B-4 with accompanying calculations given as footnotes. A solar transformity of 52,100 sej/J was calculated for sweet potato. A net emergy yield ratio of 12:1



**Solar transformity = 52,100 sej/J**  
**Net yield ratio = 12**  
**Investment ratio = 0.14**

Figure B-4. Aggregated systems diagram of sweet potato production in a typical highland village. All pathway values are  $10^{15}$  sej/ha/yr for average production.

Footnotes to Figure B-4.

Sweet potato yield = (22.4 tons/ha/yr) ( $1E+6$  g/t) (2.77 kcal/g) (4186 J/kcal) =  $2.59E+11$  J/ha/yr

Chemical rain = (2.62 m/yr) (10000 m<sup>2</sup>/ha) (1000 kg/m<sup>3</sup>) (4940 J/kg) =  $1.29E+11$  J/ha/yr; ( $1.29E+11$  J/ha/yr) (18200 sej/J) =  $2.36E+15$  sej/ha/yr

Nitrogen fertilizer = (100 kg/ha/yr) (1000 g/kg) (0.82) (0.1) (2170 J/g) =  $1.78E+7$  J/ha/yr; ( $1.78E+7$  J/ha/yr) (1.69E+6 sej/J) =  $3.01E+13$  sej/ha/yr;

Potash = (100 kg/ha/yr) (1000 g/kg) (0.53) (702 J/g) =  $3.72E+7$  J/ha/yr; ( $3.72E+7$  J/ha/yr) (2.62E+6 sej/J) =  $9.75E+13$  sej/ha/yr;

Phosphorus = (50 kg/ha/yr) (1000 g/kg) (0.33) (0.1) (348 J/g) =  $5.74E+5$  J/ha/yr; ( $5.74E+5$  J/ha/yr) (4.14 E+7 sej/J) =  $2.38E+13$  sej/ha/yr;

total fertilizer input =  $0.15E+15$  sej/ha/yr

Village labor = 2768 hrs/ha/yr (Lea 1970 and Grossman 1984); (2768 hrs/ha/yr)/(8736 hrs/yr) = 32% of annual activity;

(U/person) =  $34.7E+15$  sej/person (Table A-3, item 16); (0.32) ( $34.7E+15$  sej/per) =  $11.0E+15$  sej/ha/yr

Environmental support for labor, [I(labor)] = R/U = 86% (Table A-3, item 8); (0.86) ( $11.0E+15$  sej/yr) =  $9.45E+15$  sej/ha/yr

Outside village support for labor, [F(labor)] = 1 - R/U = 1 - 0.86 = 0.14; (0.14) ( $11.0E+15$  sej/yr) =  $1.54E+15$  sej/ha/yr

I = total ecosystem emergy = chemical rain + I(labor) = (2.36 + 9.45)  $E+15$  sej/ha/yr =  $11.81E+15$  sej/ha/yr

F = total support outside village = fertilizers + F(labor) = (0.15 + 1.54)  $E+15$  sej/ha/yr =  $1.69E+15$  sej/ha/yr

Y = total solar emergy input = I + F = (11.81 + 1.69)  $E+15$  sej/ha/yr =  $13.5E+15$  sej/ha/yr

Net yield ratio = Y/F = 12:1

Investment ratio = F/I = 0.14

Solar transformity = ( $13.5E+15$  sej/ha/yr) / ( $2.59E+11$  J/ha/yr) = 52100 sej/J

Ecological support area = I(labor) / (R/ha) = ( $9.45E+15$  sej/ha/yr) / ( $1.54E+15$  sej/ha/yr) = 6.1

suggests a greater return on labor and investment than either rainforest wood or sago palm production. More than seven times as much solar emergy is contributed from environmental sources than from outside goods and services delivered outside the village as illustrated by an investment ratio of 0.14. An ecological support area of 6 ha means that six hectares of surrounding environment is required or "used" by villagers indirectly in support of one hectare of sweet potato gardens.

In each of these studies, as well as the analysis of tourism (Section D), it is clear that resources from surrounding areas are needed to support not only production or proposed development, but the people themselves. In fact, it is this "ecological support area" that determines the large net yields for rural production systems. It is therefore unreasonable to assume that much of the country could be opened for development since a large portion of it is required for support of rural production systems, the people and their lifestyles. Further, cash crops and tourist activities generally draw emergy away from local production systems because, as shown in Section A, the revenues cannot purchase an equivalent amount of solar emergy as was sold to overseas buyers. These issues will be further explored in the Recommendations and Conclusions Section of this report.

## **Section C: Rainforest-Land Rotation Model**

by S.J. Doherty

### **INTRODUCTION**

Large scale clear-fell logging operations in the tropical lowland rainforests of Papua New Guinea began in 1973 with the Gogol/JANT timber project. This operation has since cleared all of its 68,140 hectares at an annual cutting rate of 3-4000 hectare per annum (Seddon 1984). Eighty-seven percent of the cleared areas have naturally reverted to secondary regrowth and grasslands, while only 4800 hectares (13%) have been actively reforested (Qureshi et al 1988). A study of the site indicates that primary and secondary trees account for only 15 and 1 percent, respectively, of the abandoned clear-fell area (Saulei 1984). Further, most of the regrowth was achieved by coppicing from old tree stumps and germination of the stored seed bank in the soil. There is little indication of seed dispersal from adjacent forests (Saulei 1984).

At the time of this research, forestry staff indicated that the government had put a halt on all forestry projects until a thorough assessment of the costs (including land, forest products, and money lost overseas) incurred from the Gogol Valley project is complete. Due to problems of slope, heavy rains, and increased runoff with land clearings, forestry projects are met with limited success in most parts of Papua New Guinea. A better understanding of the role of forest seed reserves left in place to aid secondary succession through recolonization of forest species and the multiplicative effects from clearcuts of increasing size are sought to alleviate some of the problems of the past. As an initial inquiry into the problems with forestry in lowland rainforest areas of difficult terrain, a computer simulation model was developed to explore the relationships between forest production, harvest rates and the rotation of lands between forested and unforested states.

### **MODEL DESCRIPTION**

A theoretical model of timber extraction and the resulting patterns of landscape disturbance is presented which addresses some of the problems caused by large scale clear-cutting and raw resource extraction in lowland rainforests. The model, shown in Figure C-1, rotates land area between three



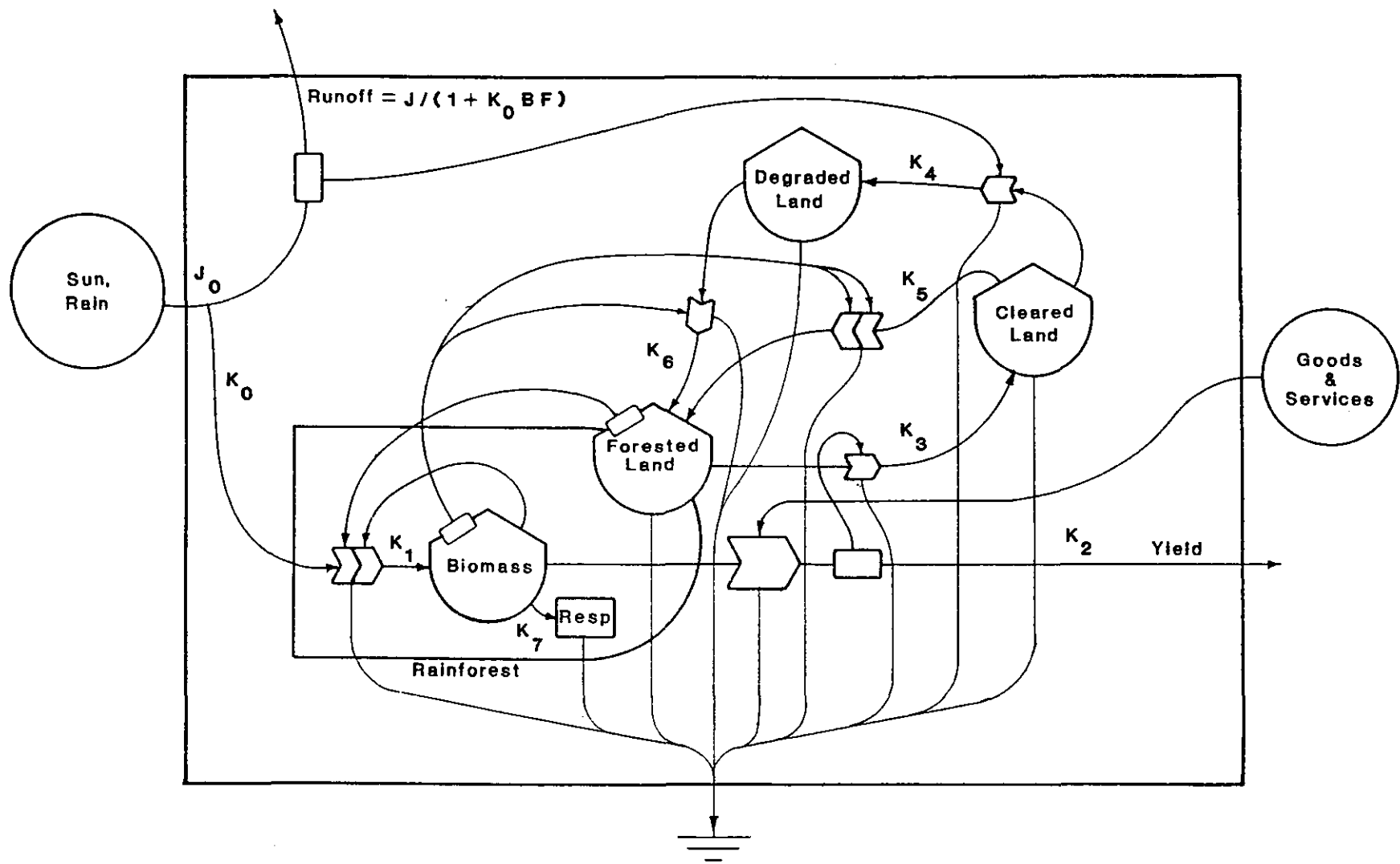


Figure C-1. Energy systems diagram of the rainforest-land rotation model. Variables ( $k_i$ ) are pathway coefficients; their mathematical expressions are given in Table C-1 and explained in the text.

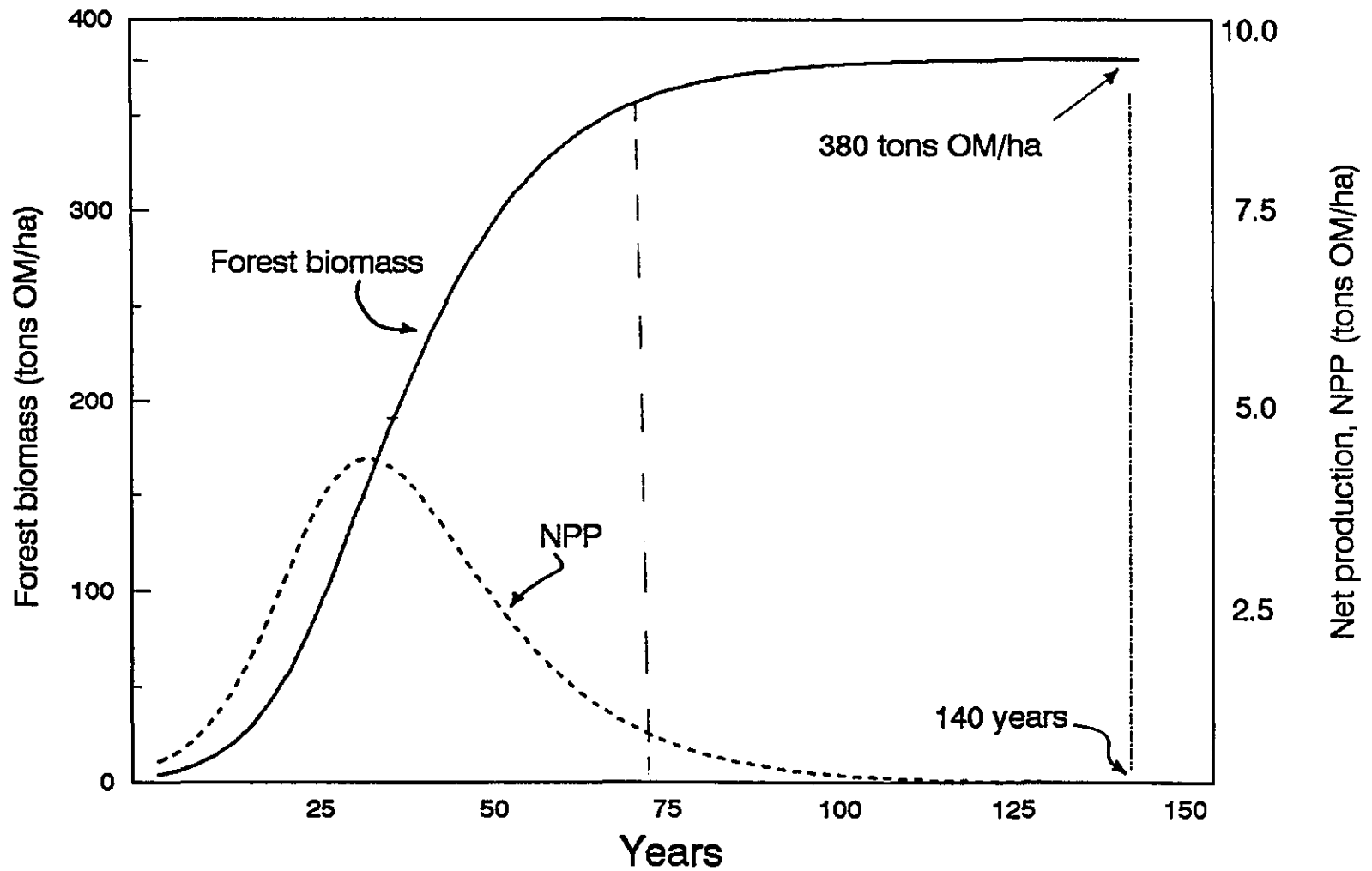


Figure C-2. Output of model simulation of rainforest growth and net primary production over 150 years. A mature steady state forest (NPP= 0) takes 143 years.

conditions: 1) native forest [F] (though mostly second growth); 2) cleared land [C] immediately following harvest; and 3) degraded land [D] which results from both the scale of clearcuts as well as erosion of exposed top soil from the run off of heavy rains. The percentage of land that is forested [F] is directly proportional to amount of forest biomass [B] present. Forest biomass changes as a function of its own mass, respiration, and the environmental inputs which drive production as well as the rate of land returning to forest.

The systems diagram is a visual expression of the mathematics which determine the flows and storages within the model. A set of calibrated values for initial storages and flows were determined for steady state forest production (Table C-1). Data were synthesized from Saulei (1984), Brown and Lugo (1984), Odum (1971) and Vitousek et al (1971). A mature tropical lowland rainforest was estimated to have a standing crop of 380 tons/ha (item 2, Table C-1) and an average annual gross production of 42 tons/ha/yr [20,000 kcal/m<sup>2</sup>/yr] (item 6). These values were calibrated to determine transfer coefficients ( $k_i$ ) for each pathway and rates of change for state variables when the model is simulated (items 5-12). A computer program written in BASIC is listed in Table C-2. In this program are the mathematical expressions that represent pathways and rate equations that represent changes in state variables.

The environmental energy driving forest production was considered the amount of incident rain that is transpired. This is a flow-limited source; only a given amount of rain is available during any given time period (3.73 m/year). Thus forest production is limited if all incident rain is transpired [initial capture was estimated as 60% of incoming rainfall for a mature forest; see Table C-1 (1)]. The more biomass that is present the greater the percentage of incoming rain that is transpired, and less is runoff. Notice that some pathways are connected to state variables by a small rectangular box. This symbol, called a sensor, indicates that the state variable changes in proportion to the flow or storage where the symbol is located, but does not directly draw from that flow or storage. In the example of degraded land [D], cleared land [C] becomes degraded as a function of the amount of runoff [R] -- the greater the amount of rain that is unused and runoffs, the greater the rate at which recently cleared land becomes degraded.

Table C-1. Calibration of variables and coefficients for Rainforest-Land Rotation Model (RF\_ver\_2.BAS) corresponding to systems diagram in Figure C-1.

---

**Sources:**

1	Total incident energy inflows (J0):	184.3	E+9J/ha/yr
	a. Energy used by system ( $k_0 \cdot R \cdot B$ ):	110.6	E+9 J/ha/yr
	b. Available energy, unused (R):	73.7	E+9 J/ha/yr

**State variables:**

2	B = Forest biomass (380 tons/ha):	7.603	E+12 J/ha
3	Land quality types:		
	a. F = Forested land =	1	ha
	b. C = Recently cleared land =	1	ha
	c. D = Degraded land =	1	ha
4	Mangement switch: H = Harvest	1 = begin cutting	
		0 = stop cutting	

**Flow equations (E+12 J/ha/year):**

5	Available incident energy	$R = J_0 / (1 + k_0 \cdot B \cdot F) =$	0.0737;	$k_0 =$	0.197291
6	Average annual production	$k_1 \cdot R \cdot B \cdot F =$	0.8372;	$k_1 =$	1.494009
7	Annual harvest	$k_2 \cdot B \cdot H =$	0.4186;	$k_2 =$	0.055057
8	Forested land that is cleared	$k_3 \cdot F \cdot (k_2 \cdot B \cdot H) =$	0.0551;	$k_3 =$	0.131527
9	Cleared land that is degraded	$k_4 \cdot C \cdot R =$	0.0275;	$k_4 =$	0.373502
10	Cleared land returning to forest	$k_5 \cdot C \cdot B^2 =$	0.0275;	$k_5 =$	0.000476
11	Degraded land returning to forest	$k_6 \cdot D \cdot B =$	0.0275;	$k_6 =$	0.003621
12	Forest metabolism	$k_7 \cdot B =$	0.8372;	$k_7 =$	0.110114

---

Footnotes to Table C-1

- 1 Chemical potential energy in transpired rainfall:  
 annual rainfall = 3.73 m/yr; evapotranspiration = 60 %; runoff (100 - %ET) = 40 %
- Total energy coming in (J0): (3.73 m) (10,000 m<sup>2</sup>) (1000 kg/m<sup>3</sup>) (4940 J/kg) = 1.8426E+11
- b. Incident energy used by forest system = evapotranspired rain ( $k_0 \cdot R \cdot B$ ) = (% ET) (J0) = 1.1056E+11 J/ha/yr  
 c. Available energy, unshed = runoff [remainder (R)] = J0 / (1 +  $k_0 \cdot B$ ) = (% runoff) (J0) = 7.3704E+10 J/ha/yr
- 2 Energy in forest biomass [B] after 143 years of growth; (36 yrs to reach 50% of steady state storage):
- Organic matter in stemwood biomass = 380 tons/ha (Brown and Lugo 1984);
- Caloric content per unit mass = 4.78 kcal/g (E.P. Odum 1971)  
 (380 tons OM/ha) (1E+6 g/ton) (4.78 kcal/g) (4186 J/kcal) = 7.603E+12 J/ha

Footnotes to Table C-1, continued.

- 3 Rotational lands: At steady state calibration, each land cover type occupied 1 ha (1/3 total area).
- 4 Harvest (H) is a management switch that is turned on (1) or off (0) to initiate or stop forest cutting based on extent of forested land available.
- 5 Available incident energy = unused chemical energy from rainfall (i.e., runoff); see 1b.
- 6 Annual production ( $GPP = k_1 * R * B$ ) = 20,000 kcal/m<sup>2</sup>/yr, Vitousek 1971):  
 $(2.0E+4 \text{ kcal/m}^2/\text{yr}) (10,000 \text{ m}^2/\text{ha}) (4186 \text{ J/kcal}) = 8.372E+11 \text{ J/ha/yr} = 41.84 \text{ tons OM/ha/yr}$
- 7 Annual harvest ( $k_2 * B * H$ ): considered 50% of annual production at steady state:  
 $(0.837E+12 \text{ J/ha/yr}) (50\%) = 0.4185E+12 \text{ J/ha/yr cut (21 tons/ha/yr)}$   
then,  $(0.4185E+12 \text{ J/ha/yr}) / (7.603E+12 \text{ J/ha mature forest biomass}) = 5.51\%$
- 8 Forested land cleared [ $k_3 * F * (k_2 * B * H)$ ] = constant percent of harvested biomass: 5.51% (F) = 0.055 ha/yr
- 9 Cleared land that is degraded ( $k_4 * C * R$ ) = 50%;
- 10 Cleared land returned to forested land ( $k_5 * C * B^2$ ) = 50%;  $(0.0551 \text{ ha}) (50\%) = 0.0275 \text{ ha/yr}$
- 11 Degraded lands returning to forested lands ( $k_6 * D * B$ ) = 50%
- 12 Annual forest metabolism (Respiration + Death =  $k_7 * B$ ):  
NPP = GPP - Respiration; at steady state NPP = 0, therefore GPP = Respiration:  
 $k_1 * R * B * F = k_7 * B$
- Forest turnover time: (forest biomass) / (annual production) =  
 $(7.603E+12 \text{ J/ha}) / (0.837E+12 \text{ J/ha/yr}) = 9.08 \text{ years} = 11.0 \% \text{ annual replacement}$
-

Table C-2. BASIC computer program used in simulation of Rainforest-Land Rotation Model.

---

```

1  REM filename: RF_ver_2.BAS
5  REM PNG Rainforest - Land Rotation Simulation Model
10 CLS 'Clears monitor for new simulation
20 REM Opens output file to store data for graphic analysis:
21   'OPEN "B:\RF-OUT.PRN" FOR OUTPUT AS #1
30 REM Sets coordinates of graph for monitor display:
31   SCREEN 1, 1: COLOR 0, 1
32   REM Colors are defined at end of LINE and PSET statements as:
33   REM   1 = blue; 2 = purple; 3 = white
34   LINE (0, 0)-(300, 180), 3, B
35   LINE (0, 100)-(300, 100), 3, B
36   LINE (0, 45)-(300, 45), 3, B
40 REM Initial values:
41   I = 1
42   T = 1
50 REM Management switches:
51   CUT = 2.9
52   GROW = 1
53   H = 1
60 REM Scaling factors:
61   F0 = 25
62   C0 = 25
63   D0 = 25
64   B0 = .25
65   Y0 = 60
66   T0 = 1
70 REM Inputs (chemical potential energy driving gross production):
71   J0 = .18426
80 REM Initial Storages:
81   B = .76
82   F = 1; C = 1; D = 1
90 REM Transfer coefficients:
91   k0 = .197291
92   k1 = 1.494009
93   k2 = .055057
94   k3 = .131527
95   k4 = .373502
96   k5 = .000476
97   k6 = .003621
98   k7 = .110114
100 REM Sets X,Y coordinates for monitor display:
101  PSET (T / T0, 45 - Y * Y0), 1 ' Yield (Y) is displayed in top graph
102  PSET (T / T0, 100 - B / B0), 2 ' Biomass is graphed second from top
103  PSET (T / T0, 170 - C * C0), 3 ' Cleared land is displayed in lower graph
104  PSET (T / T0, 160 - D * D0), 1 ' Degraded land is displayed in lower graph

```

Table C-2, continued.

---

```

110 REM Management alternatives:
111 IF F > CUT THEN H = 1 ' Begin harvesting
112 IF F < GROW THEN H = 0 ' Stop harvesting, allow forest recovery
120 REM Mathematical model:
121 R = J0 / (1 + k0 * B * F)
122 Y = k2 * B * H
123 Ytot = Ytot + Y
130 REM Difference equations:
131 DB = (k1 * R * B * F) - (k2 * B * H) - (k7 * B)
132 DF = (k5 * C * B ^ 2) + (k6 * D * B) - (k3 * F * k2 * B * H)
133 DC = (k3 * F * k2 * B * H) - (k4 * C * R) - (k5 * C * B ^ 2)
134 DD = (k4 * C * R) - (k6 * D * B)
140 REM Rate equations:
141 B = B + DB
142 F = F + DF
143 C = C + DC
144 D = D + DD
145 T = T + I
150 REM Prints data to output file identified in line 20 of program:
151 PRINT #1, T, Y, B, C, D
200 REM Subroutine 1: Loop counter to simulate model for 300 years:
210 'LOCATE 15, 1
211 'PRINT "NPP="; 'PRINT USING "####.###"; ((k1 * R * B * F) - (k7 * B))
220 IF T / T0 < 300 GOTO 100
221 GOTO 400
300 REM Subroutine 2: Loop counter to determine which management alternative
301 REM results in maximum total yield (Ytot) over 300 year rotation:
302 REM Note: must disable lines 200-221 for subroutine 2 to work.
310 REM Sets X,Y coordinates for monitor display
311 REM (Total biomass harvested as a function of forest rotation):
312 PSET (GROW * GROW0, 180 - Ytot / Ytot0), 1
320 REM Simulate total yield under different harvest and fallow requirements:
322 IF GROW < 3 THEN GROW = GROW + 0.05
323 IF GROW >= 3 THEN GOTO 400
330 REM Reset initiation values:
331 T = 1
332 Ytot = 0
340 GOTO 60
400 END

```

---

The amount of forested land available for reseeded acts as a control over the rate of biomass production. Here, biomass [B] is increased proportionally to the change in forested land [F] as indicated by the pathway expression  $k_1RBF$ . This is a measure of gross primary production (GPP). For initial calibration, the model was set at steady state for a mature rainforest. At steady state, there is no net primary production (NPP), and forest respiration (R, defined as forest metabolism and death) was calculated to equal gross primary production [ $(k_7B) = (k_1RBF)$ ].

As an approximation of the effects of spatial scale of land clearings on seed dispersal from forest biomass, a sensor was put on the biomass variable which controls the rate at which cleared and degraded lands return to forest. If there is too little land left as seed refugia, the successional ability of forest clearings is slowed by lack of seed reserves. Cleared land, however, can be cycled back to forest as a square function of the biomass because of its limited scale ( $k_5CB^2$ ). As more of the forest is cut, more land becomes cleared and consequently more land becomes degraded. The rate at which cleared land becomes degraded [D] is a function of the amount of cleared land [C] and amount of runoff [R] due to low forest cover--thus the pathway expression  $k_4CR$ . The gravity model suggests that communication (in this case genetic dispersal by seeds) is a phenomenon of the squared distance between two objects (Forman and Godron 1987). Once land has become degraded it is more difficult for secondary succession to regenerate forest. Therefore degraded land only cycles back to forest as a simple multiplier interaction with biomass as a control ( $k_6CB$ ). Finally, cutting of forest biomass is activated with a switch [H], representing goods and services, that is either on (1) or off (0). Thus a certain percentage of forest biomass is harvested as a function of the transfer coefficient  $k_2$ .

In the initial calibration, forests were cut at a rate equal to 50% of average annual production or about 5% of mature forest biomass at steady state [Table C-1 (7)]. This value was chosen as it closely approximates the harvest schedule of Gogol/JANT. Each of three land conditions were given equal area (1 ha each, totalling 3 ha) for model calibration. Since the model tracks biomass on a per hectare basis, the results of the model can be interpreted per hectare. Thus, each land type can be considered to represent a percentage of the total (i.e., 1 = 33% of land total). Management switches, therefore, rotate forest land between values of 0 and 3 (0% and 100%). Next, a few outcomes of model simulation are given to illustrate trends and forecast predictions, followed by some simple management recommendations based on insights gained from the model.



## MODEL SIMULATION

First, only the forest production and metabolism components of the model were run in order to determine forest maturation and turnover times. Based on 3.73 meters of incident rainfall driving an average gross primary production (GPP) of 42 tons/ha/yr, about 140 years is required for the system to develop a mature forest of 380 tons OM/ha (Figure C-2). Maximum net primary production (NPP) was measured at 34 years (9.4 tons OM/ha/yr). At a mature steady state gross production is balanced with forest respiration and net production equals zero. These calibrations suggest that this forest system has an annual replacement rate of about 10% (Table C-1).

State variables and production processes are calibrated in energy units (J/ha for biomass storage and J/ha/yr for production and harvest yields). Therefore in order to express model outputs on a volume basis, the values must be converted using an energy content of 4.78 kcal/g (20000 J/g) and the estimate for biomass volume (380 tons OM/ha). These conversions are given in Table C-1 and discussed in the text.

The next step was to simulate the model using all state variables, i.e. incorporating the rotation of land storages with forest production and harvesting schedules. Forest harvesting is started and stopped with a switch (H) in the program, based on management alternatives which are input by the user. Two variables determine the harvesting schedule: CUT and GROW (lines 110-112). The forest is allowed to grow until its land area reaches a value set by the variable CUT, at which time harvesting begins until the forested area is below a value set by variable GROW (lines 50-53). Input values range between 0 and 3 (0% and 100% of land area as explained in the methods).

A management period of 300 years was chosen in order to simulate long-term trends based on forest growth, harvest schedules and land rotations. Thus, annual changes in forest production, harvest volumes and land cover are re-calculated each time the program loop is executed for 300 iterations (subroutine 1). This simulation period allows a natural forest to complete two full successional cycles of growth (143 years to maturation) and the biomass to turn over more than 20 times, as well as adequate time to observe trends from harvest schedules and land rotations.

In the example in Figure C-3, the rainforest was allowed to grow until it reached 57% ( $CUT = 1.7$ ) of the total land area. Harvesting then began until the amount of forested land was reduced to 30% ( $GROW = 0.9$ ), at which time cutting is stopped and the cleared and degraded lands begin to recover to forest. This management schedule resulted in a rotation of about 60 years. Forest biomass (middle graph) recovers quickly as secondary growth is most rapid in early stages of succession. Before net production begins to decline as the forest matures toward steady state, the forested land is again harvested when it has recovered 57% of the land in rotation. Lands rotate between forested, cleared and degraded states (lower graph-- forested land is not shown as it changes in direct proportion to forest biomass). Harvest yields (upper graph) are greatest at initial cutting when biomass is highest, and declines in volume as the return per unit harvesting effort increases. In this example, yields range between 5 and 7 tons/ha/year, on average with a total yield of 870 tons/ha over 300 years.

In a series of computer runs, the minimum amount of forest land required before harvesting was discontinued was held constant (i.e.,  $GROW = 0.9$ ; 30%) while the extent of recovered forest land required before harvesting could begin again (i.e.,  $CUT$ ) was changed by increments of 0.05 (approximately 2% change in total land cover). The harvest schedule described above (and shown in Figure C-3), rotating forested land between 30 and 57%, was determined to yield the greatest volume output over the 300 year simulation period, without degrading forest lands to an unrecoverable extent.

Figure C-4 shows the results of this simulation, changing both the harvest times and recovery times (given as subroutine 2 in program). Here the total yield over 300 years is calculated based on extent of forest land necessary before harvesting can begin as well as the minimum extent at which time harvesting is stopped. Forest yields are reduced as a function of the extent of forest land required by management for a particular rotation schedule. It appears that maintaining forest land extent between about 60% (before cutting begins) and 30% (when cutting stops) yields the greatest volume of biomass while still allowing the land enough time and resources to recover to forest.

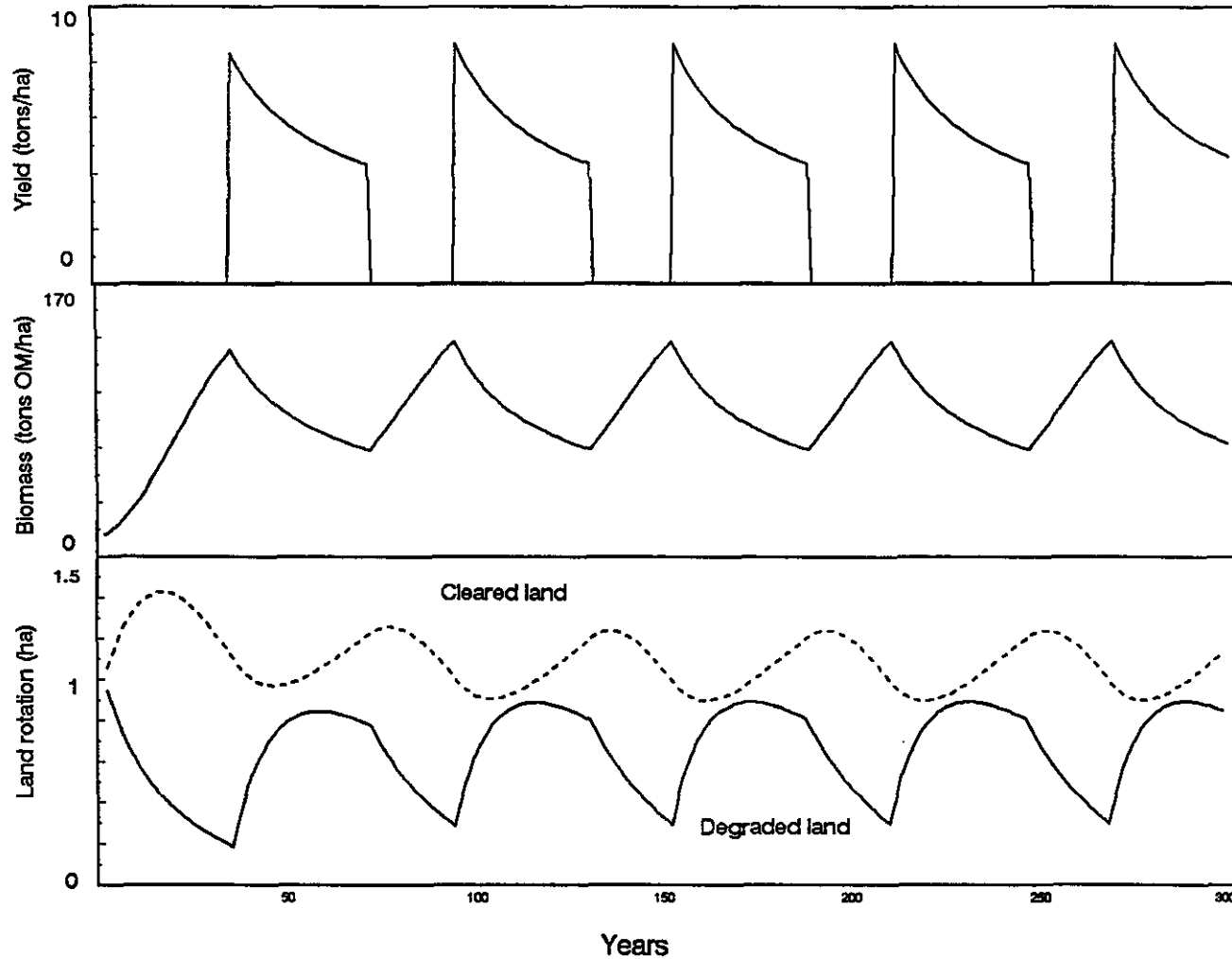


Figure C-3. Simulation of biomass yield (upper graph), rainforest growth (middle), and land rotations (lower) based on 57/30 harvest schedule over 300 year management scenario (start cutting when forest land reaches 57% of total land area; Stop cutting when forest land reaches 30%).

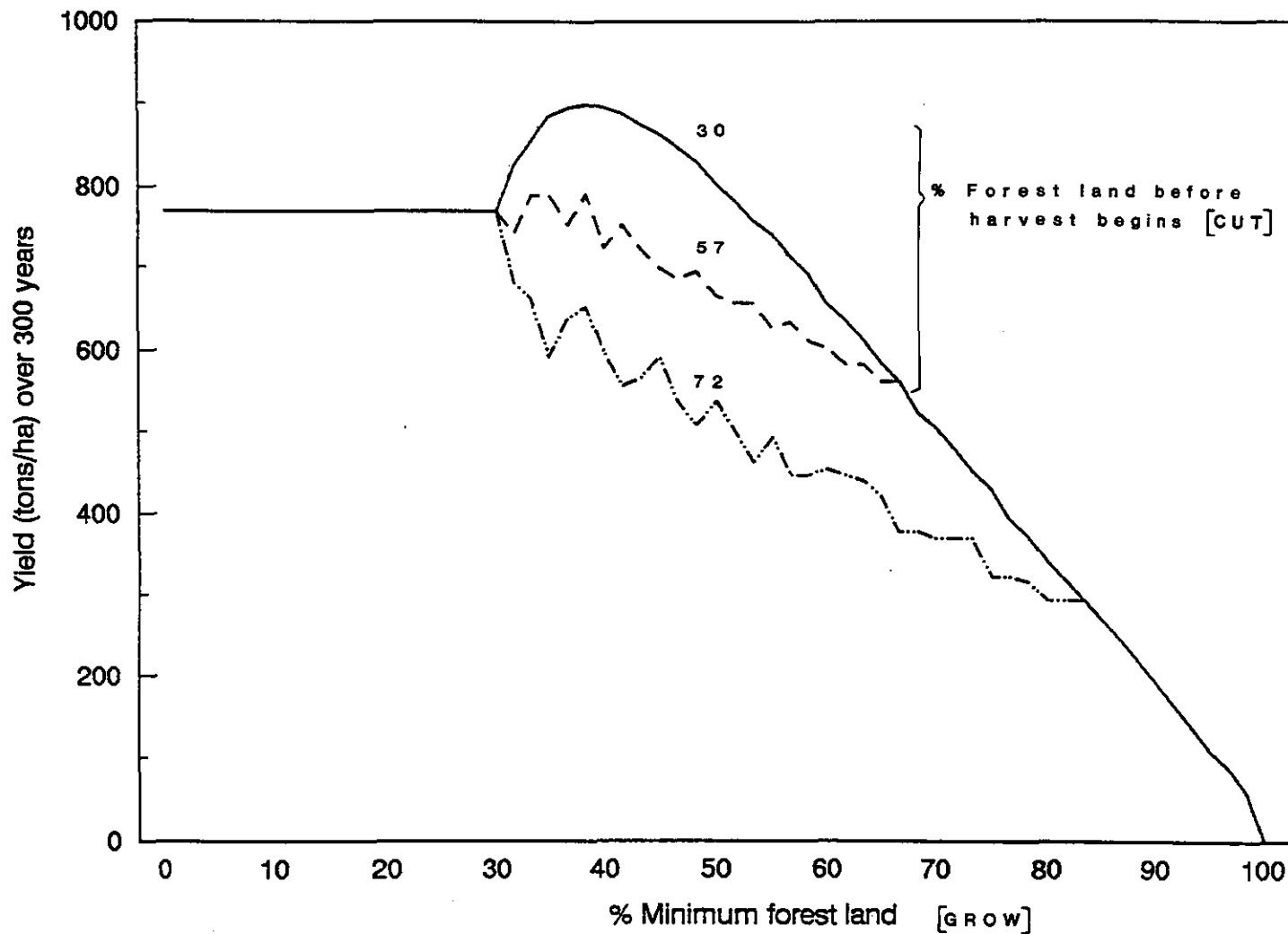


Figure C-4. Simulation of total harvest yields over 300 years (Y-axis) due to changes in minimum and maximum allowable land rotations. X-axis is the minimum amount of forest land allowed before cutting is stopped [GROW]. Graphed are results based on forest land requirements of 30%, 57%, and 72% necessary before cutting is again started [CUT].

## DISCUSSION

The rainforest-land rotation model presented here simulates forest production and recovery based on harvest schedules and rotation of land between forested and two states of post-clearcut lands. It makes an attempt at accounting for conditions of increased runoff from forest cover removal compounded by high rainfall and mountainous terrain. Forest operations in Papua New Guinea have faced these adverse conditions with limited success in the past (Saulei 1984 and Seddon 1984). It is shown that previously forested lands can quickly degrade and that degraded land is slow to recover. Further, the ability of cleared lands to reforest is not a simple linear function of available forest seed reserves; harvest schedules, recovery times, proximate forest reserves, and spatial extent of clearcuts, among others, all contribute to successful and sustainable forest management practices. The model illustrates some of these principles. If for example, harvesting began before the forest had recovered, cleared lands became degraded and land could no longer recover. Also if the forest is not cut before the forest begins to mature and net production declines, total yield also declines.

A question not addressed with this model is "what is the optimum harvesting schedule not only for maximizing yield but minimizing investment" -- i.e., optimizing effort. Forest plantations are generally managed on rotations that cut the forest when it is at its maximum net production (the inflection point in Figure C-2; 34 years). In fact the rotation schedules determined by this model to maximize yields include this interval. Further, forest trees could be harvested in small quantities but at very rapid intervals so that the effect is an almost continual thinning program. This combination, however, would not reduce investment inputs but rather increase them, diminishing the *net* return on investment.

An evaluation of solar energy supporting forest production as well as the solar energy in required economic investments may provide the information needed to determine net yield and investment ratios for forest schedules. The subsystems analysis of forest operations in New Britain (Section B) found that 3 times as much solar energy is contributed from environmental sources than from the main economy in rainforest harvests, providing a net yield on investments of about 4 to 1 (Table B-1). In New Britain, annual harvests were estimated to be about 2% of standing crop--a rate slower than reported by Gogo/JANT and slower than the 5% cutting rate used in this model.

These questions of net return and investment should be addressed as a next step of model development, using solar energy as a baseline unit of measure. As in the past, rainforests, their services and products, will continue to play important roles in the quality of life of nationals and the sustainable development of their resource base. This was demonstrated in calculation of macro-economic values for forest reserves (Table A-5) and in the 4:1 net yield ratio determined for forest operations in New Britain. The few general recommendations that are given here are based on energetic, temporal and spatial considerations. This model of forest-land rotation is presented as an exercise to investigate some of the problems forest operations are faced within diverse rainforest systems on difficult terrain and to begin considering harvesting schedules that are appropriate for a given set of site conditions. Management goals ultimately should pertain to more than just resource output yields and begin to ensure the full range of ecologic values and functions remain intact.



## **Section D: Emergy Basis for Determining the Carrying Capacity of Tourism**

by Mark T. Brown and Richard C. Murphy

### **INTRODUCTION**

With the recently increased emphasis placed on tourism and on attracting economic investment for tourism development by many governments around the world, some hard questions are beginning to emerge. Is tourist development the environmentally benign industry it is touted to be? Is tourist development beneficial to local cultures and economies? Is tourist development a form of sustainable development that should be encouraged in developing economies of the world?

This portion of the study investigates the relationship of outside investment, in general, and tourism development, in particular, to cultural and environmental integrity, and to local economies, regional welfare, and international balance of payments. Using data from tourism development in New Britain, Papua New Guinea and a related study in Nayarit, Mexico, and techniques of emergy analysis, several questions related to economic development are addressed: (1) What is the carrying capacity for outside economic investment within local, undeveloped regions that is environmentally and culturally benign and economically beneficial? (2) What are the benefits and costs of differing intensities of development? (3) What intensity of economic development is most beneficial to the economy and welfare of populations?

#### **Ecotourism and Intensity of Economic Investment**

Recently, ecotourism (Laarman and Durst 1987, Boo 1989) has been coined to mean a variety of things, but primarily to mean tourism that has an ecological imperative. Ecotourism should not only seek to expose tourists to the environment of a region, but should also be balanced with the local environment and not cause cultural degradation or serious economic shifts. There is much in the literature documenting the consequences of large development projects on the culture, environment, and economy of relatively "underdeveloped" regions (e.g., Archer and Sadler 1976; Archer 1985; Burn 1975; Caribbean Tourism Research Center 1976, 1977 a, b; Cohen 1978; Edelman 1975 a, b; Jenkins 1982; Oliver-Smith et al. 1989; Rodenburg 1980). Some of the documented impacts are as follows:



- Cross-cultural contacts result in changes in traditional dress, habits, values, ethics, and social organization.
- Local economies become more externalized as wages are paid to populations who never used money before and who have to import goods and resources to purchase.
- Additional strain is placed on the environment to provide food, building materials, and other services like waste recycling, which result in loss of environmental value and capacity for support of the population.
- Local control of resources like land and water is lost as the result of their sale to foreign investors.

In all, the larger the development and its intensity, the greater the potential for negative impacts on culture, environment, and economy (Jenkins 1982, Rodenburg 1980). Thus, ecotourism that seeks to expose the traveler to a natural environment without regard to the effect a visitor's presence has on that environment may not be sustainable in the long run. To be truly an ecotourist development, it should neither exceed the carrying capacity of the local environment and culture, nor cause secondary or tertiary environmental degradation.

### **Tourism as an Extractive Industry**

Economic investments in undeveloped regions of the world are, for the most part, investments in extractive enterprises. The investments are used to assemble the technology and pay the human labor necessary to extract resources and sell them for more than the costs of extraction. In a way, tourist development is an extractive enterprise. The resources are more varied: sun, wind, waves, and scenic vistas, as well as an unspoiled environment and a dissimilar culture. Unlike other extractive industry, the tourist industry does not cut, dig, or catch its resource and thereby exhaust the reserve. Yet with over-exploitation, the tourist resource is "used up" (Mathieson and Wall 1982). Too many tourists translates into loss of environmental quality and shifting of the local culture away from traditional elements that were of interest, toward the values, customs, and fads of the outside culture.

The question regarding outside investment and its sustainability is: how much is too much? At certain levels of investment and for certain resources, the extracted resource may last indefinitely because it is renewed at a rate that is equivalent to or less than the rate at which it is extracted. Under these circumstances the development is often described as sustainable. As in other types of extractive investments, tourism

development has an appropriate intensity of investment at which it will not exceed the ability of the local environment and culture to absorb it (Edelman 1975a,b; Gunn and Jafari 1980). Determining the appropriate intensity of development that does not cause negative cultural, economic, or ecologic impacts is what is meant by determining the economic carrying capacity of an external investment.

### **The Benefits and Costs of Economic Investments**

For many years, economic investments in undeveloped and developing regions have been considered beneficial to the local economy. The increased number of jobs and higher wages were cited as proof of the positive benefits of investment. For the most part, it has long been believed that the bigger the project, the greater the benefit to the local economy, since bigger always translated into more jobs and greater payrolls. In fact, the opposite in many cases was true. Large projects often displaced local populations, disordered the environment, and disrupted the local economic system. Smaller projects, scaled to the local economy and social organization, were better integrated into the economy and caused less social and environmental disruption (Jenkins 1982, Lichty and Steinnes 1982, Rodenburg 1980).

It appears that an economic investment from outside can either act to amplify existing social and ecologic order and stimulate the local economy, or it can act as a disruptive force, much like a disaster. In fact, "economic earthquake" might be a fitting way of describing what happens to local, small-scale economies and social organization when large-scale investments occur. The greater the differences in intensity between existing systems and imposed developments, the more disaster-like they become.

### **The Disappearing Benefits of Economic Investments**

Experience has shown that some economic investments have not yielded the benefits to local economies that were anticipated (Oliver-Smith et al. 1989). This results from several different but complementary factors: First, investments from outside must be repaid. Considering current interest rates and the energy trade advantage enjoyed by most developed nations over undeveloped nations, investing nations receive far more from their investments than just repayment of principle and interest (Odum 1984, Odum et al. 1986, Odum and Arding 1991). The undeveloped nation finds that more national wealth flows out of their economy than flows in as the result of an unfavorable energy exchange ratio. Second, if the investment is from sources outside the region, little of the currency generated by it remains within the local economy (Oliver-Smith et al.

1989). Other than a local payroll and some user taxes, if a development project uses funds from elsewhere and is foreign owned, most of the currency generated is "drawn" back outside the region as profit and debt service. Third, the currency that is added to the local economy causes local inflation (Oliver-Smith et al. 1989). When more money "chases" the same amount of resources, prices rise.

### **Unaccountable Costs of Economic Investments**

Impact analyses aimed at determining costs and benefits often fail to properly account for costs, especially social and environmental costs (Archer 1985, Burn 1975, Cohen 1983, Pigram 1980, Wang et al. 1980). When economic benefit/cost accounting is used, the benefits are easily quantified using a monetary system of value, but social and environmental costs, since they are outside the monied economy, are often not included because they are not easily or reliably quantified in monetary units. The resulting picture of economic benefits is one-sided, showing increased numbers of people employed and money flowing through the economy, but not including increased costs of social disorder, or loss of environmental systems or services.

### **Impacts of Economic Investments**

Energy analysis may offer a more complete perspective of the impacts of economic investments on the ecological and cultural resources of regions. A systems perspective of a region suggests that its ecological, economic, and cultural systems are closely inter-twined. As a region's economic system changes, for example, there are resulting changes in its ecological and cultural systems, as the increased economic activity affects a wider and wider spatial area and may cause changes in values and ethics. The extent of change in each of these systems is more or less dependent on the extent of change in the other. Figure D-1 illustrates the interconnections between environmental, cultural, and economic systems of regions. A balanced and well-adapted subsistence economy might have the organization depicted in Figure D-1a. Ecological resources are extracted by the economic system, converted to goods, and consumed by cultural components which, in turn, provide the necessary organizational structure and "manpower" for the economic system. By-products of the economic system are recycled back to the environment, and information and "good stewardship" are fed back from culture. The driving forces are renewable emergies shown coming from the left side of the diagram and the nonrenewable energy storages from within. The overall system that develops (i.e., the levels of ecological productivity, economic activity, and cultural organization) is, to a large degree, dependent on the magnitude of renewable energy flow and the nonrenewable storages that are available.

Economic investment from outside can be depicted like that in the bottom diagram (Figure D-1b). Investment dollars are used to purchase fuels, goods, and services from outside the local economy. A second outside energy source now influences the system. As a result of the connections between components of the regional system, any increase in one compartment affects the other two compartments (whether they increase or decrease depends on the nature of the interconnections and is not necessarily important at this point). The bigger the influence of outside investment (that is, the bigger the magnitude of the flows coming from the top right compared to the flows coming from the left), the greater the impact. The emergy analysis technique utilized in this study quantitatively evaluates the relative size of both of these driving energy flows in a regional economy, and suggests that the appropriate intensity of a new economic investment is one that does not alter their relative proportion significantly (Odum 1980).

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

One of the basic principles of the emergy systems perspective is that true wealth comes from resources, not from money (Odum and Arding 1991). Money can be used to purchase resources, but the money in itself is not representative of wealth. Evaluating international trade and net benefit from investments using only the inflows and outflows of currency often shows a monetary balance of payments, but does not take into account the inflows and outflows of wealth. Often, the investing economy receives double benefit--the resources extracted directly, and the resources that must be extracted and sold by the developing economy in order to pay interest on outside loans. Most developing economies seek money from outside sources instead of seeking resources (the true basis of wealth), and thus often sell their wealth cheaply to purchase economic goods that have less effect in stimulating their economy and that do not lead to a sustainable future.

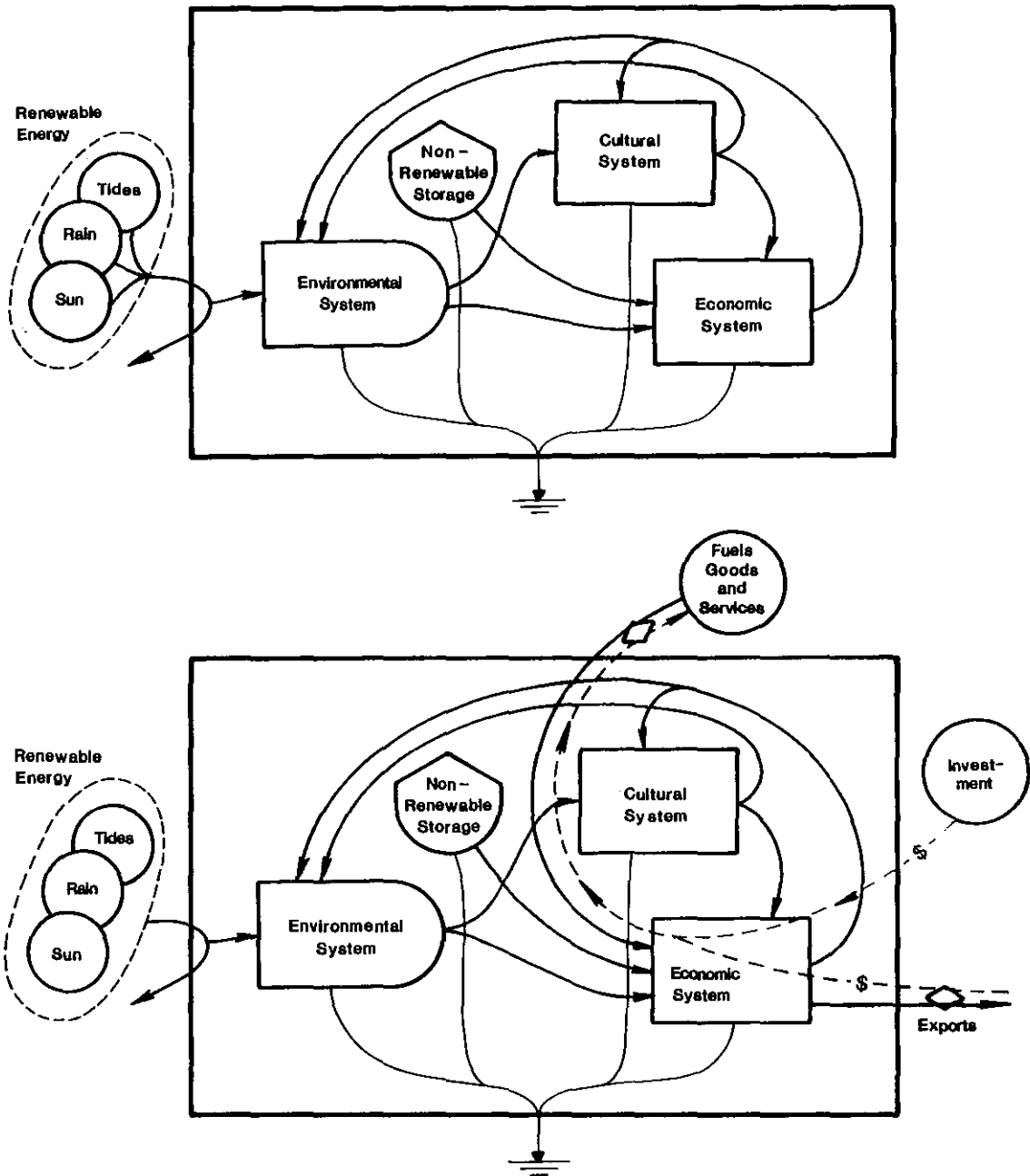


Figure D-1. Systems diagram of a regional economy having no trade with external markets (top) and an economy that has developed trade (bottom). Money is shown as dashed lines, and energy and information flows as solid lines. While invested money may circulate within the economic system, eventually, like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

## **A Theoretical Approach to Determining Carrying Capacity of Local Environments**

One theory for determining carrying capacity is that the scale or intensity of development<sup>1</sup> in relation to existing conditions may be critical in predicting its effect and ultimately its sustainability (Odum 1980, Odum and Arding 1991). If a development's intensity is much greater than that which is characteristic of the surrounding landscape, the development has greater capacity to disrupt existing social, economic, and ecologic patterns (Brown 1980, Odum 1980). If it is similar in intensity it is more easily integrated into existing patterns. For example, because of the differences between a heavily urbanized area and an undeveloped wilderness area, the appropriate intensity of development in each environment is much different.

Large-scale developments and those with greater intensity than the surroundings can be integrated into the local economy and environment if there is sufficient regional area to balance their effects. Much like the ecological concept of carrying capacity, where differing environments require different aerial extent of photosynthetic production for support of a given biomass of animals, environmental carrying capacity for economic investments depends on the area of "support" over which a development can be integrated. As the intensity of development increases (and therefore its consumption of resources, requirement for laborers, and environmental impacts increase), the area of natural, undeveloped environment required for its support must increase. All other things being equal, the more intense a development, the greater the area of environment necessary to balance it. Thus, the spacing between developments should increase as their intensity increases.

The methodology described in this report uses emergy analysis to measure intensity of two tourist resorts and the local environment, and then uses a ratio of purchased emergy to resident renewable emergy as a means of determining carrying capacity. The theoretical construct and primary assumption is that this ratio is, in itself, a measure of the intensity of the local economy, based on how the environmental and cultural systems are adapted to the level of economic activity present. This is complicated when the local economy is in a state of flux, to which neither the ecological nor cultural systems have adapted or reached a balanced steady-state. Our rationale for using the current regional intensity of economic activity (the Environmental Loading Ratio) is that, if a new development is significantly greater in intensity than the surroundings, even if a balance has

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<sup>1</sup>Intensity may be measured using any quantity (energy, materials, money, or information) per unit time per unit area. If one uses energy per unit time, or power, expressed over a unit area, the intensity is power density (Brown 1980).

not been reached, it may further exacerbate the existing problems of cultural and ecological integration of change.

## RESULTS

### Systems Diagrams

Figure D-2 is a systems diagram of a region that includes, among other activities, tourism. Tourism is shown drawing on resources of the local economy and importing resources from outside. The region is shown as being driven by two main sources of outside energy: (1) free, renewable energies, and (2) purchased energies (sometimes referred to as nonrenewable since they are based on resources that are nonrenewable). Inflowing renewable energies combine and interact to drive the productive processes in ecological systems. Purchased inputs from outside develop systems of extraction and consumption internally, which interact with indigenous environmental resources to provide resources, energies and products for use and export. Money derived from exported resources and from visiting tourists is used to purchase goods and fuels from other regions.

As with any tourist facility or tourist region, there is an image maintained by the combined interaction of the environment, urban structure, culture, and the development itself. Image is the information that "draws" people from outside to visit the development. The greater the image, the greater the draw. Image is negatively affected by increased wastes in the environment (pollution), overcrowding, and loss of resources, including culture, that form the image of a region or development.

Resources are extracted or harvested from marine and terrestrial systems and sold to the local economy or to the tourist facility. Money paid by tourists for imported goods, fuels, services, and locally derived resources enters the local economy before exiting the region in quantities equal to the inflows. Increased spending by tourists drives inflation up if inflows of local and imported resources and fuels are not increased.

A simplified systems diagram of the main driving energies and internal processes of a tourist resort facility is given in Figure D-3. As in the regional diagram (Figure D-2), image plays a central role in "attracting" tourists. The regional image is augmented by the attributes of the resort facility including beach, grounds and landscaping, and assets (or hotel structure and furnishings). The main production function of the hotel

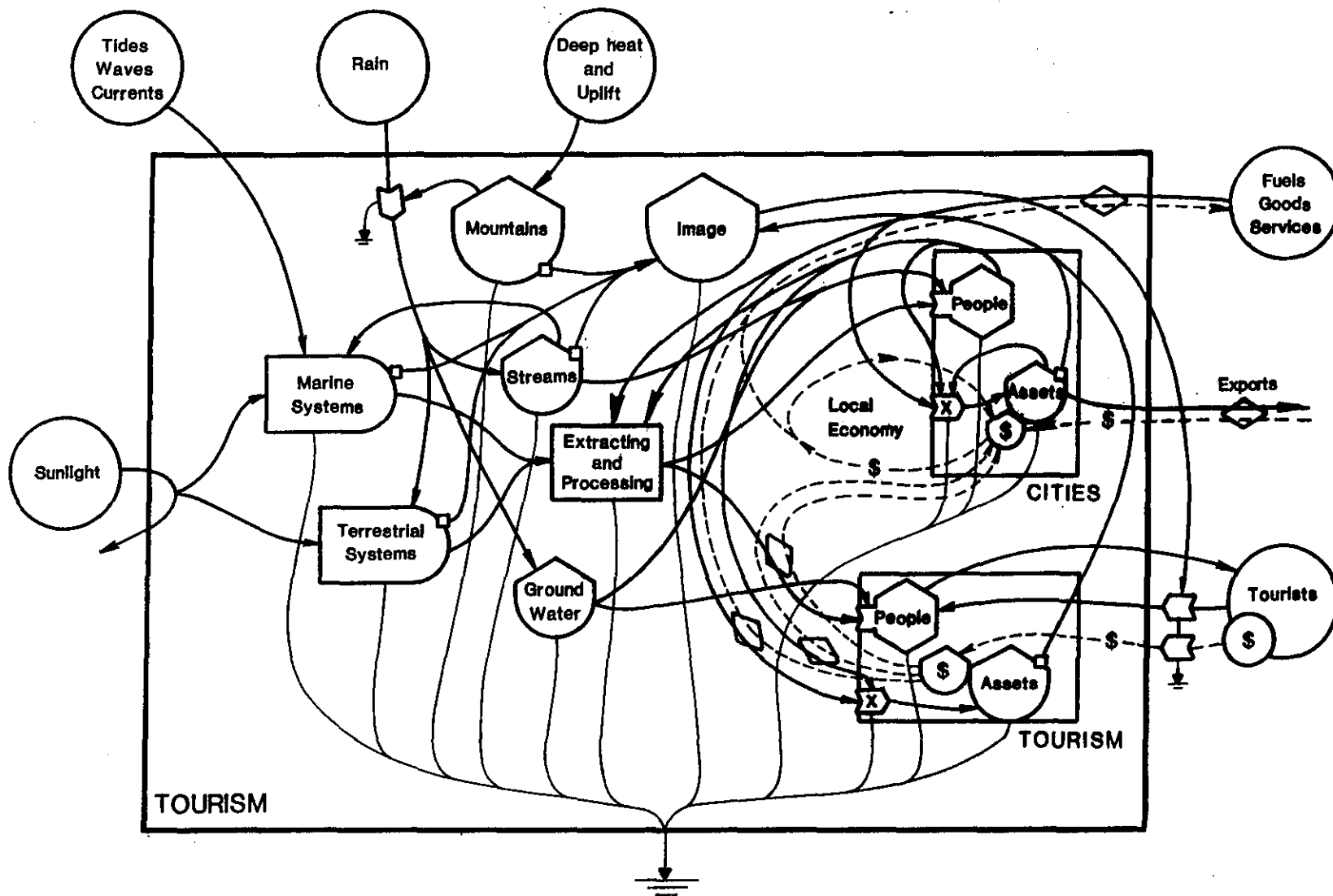


Figure D-2. Energy systems diagram of a region showing the relationship of tourism with the local economy. Often tourism is a competitive system, competing with the local economy for goods and resources. Dashed lines are money and solid lines are energy flows.



provides goods and services for tourists by combining potable water, food and liquor, fuels, electricity, goods and materials, and labor. The assets and tourists are also part of the production function. Money income from tourists is used to pay for all of the above goods and services, shown as the dashed lines accompanying each purchased flow of energy. The diagram in Figure D-3 is the diagram from which the emergy analysis of tourism in Papua New Guinea and Mexico (Brown et al. 1992) were performed.

### **Emergy Analysis of National Economies**

Summary statistics and indices of Papua New Guinea, Mexico and the USA are given in Table D-1. Total emergy-use ( $U$ ) varies from a low of  $1213 \text{ E}+20 \text{ sej/yr}$  (PNG) to a high of  $87,570 \text{ E}+20 \text{ sej/yr}$  (USA). Gross national product (GNP) varies by 3 orders of magnitude, with PNG having a GNP of only 0.005% of the USA. Probably the most telling relationships are the various ratios (E-I). The relation between emergy and money ( $\text{sej} / \$$ ), a measure of relative buying power, shows that the USA has the lowest ratio. Thus when US dollars are used to purchase goods and services from PNG or Mexico, the benefit to the US economy is 18.5 to 1 and about 1.5 to 1, respectively. The USA has the highest emergy density --3.6 times that of PNG and about 2.7 times that of Mexico. Emergy per capita in the USA and PNG are similar, but result from different supporting resources. The main emergies driving the PNG economy are inflows of renewable resources (about 85%) of the economy while nonrenewable resources are the dominant sources of emergy of the US economy (about 75%).

Total emergy-use per capita in the USA and PNG is nearly equal. The world emergy exchange ratio, which is a relative measure of world buying power (or trading advantage), shows that the USA has the highest trade advantage; it receives, on the average, 1.5 units of emergy for each unit of emergy exported. Mexico's ratio suggests it receives roughly equal emergy imported for each unit exported; PNG has, on the average, a net loss receiving only 0.08 units of emergy for each unit exported (an average trade deficit of 13 to 1). The highest environmental loading is in the USA; it is 30 times that characteristic of the PNG economy.

### **Emergy Analysis of Tourism**

Tables D-2 and D-3 give the results of the emergy analysis of a small, high quality tourist resort on the island of New Britain, PNG, and a "four-star" tourist hotel in Puerto Vallarta, Mexico. The facilities are as different

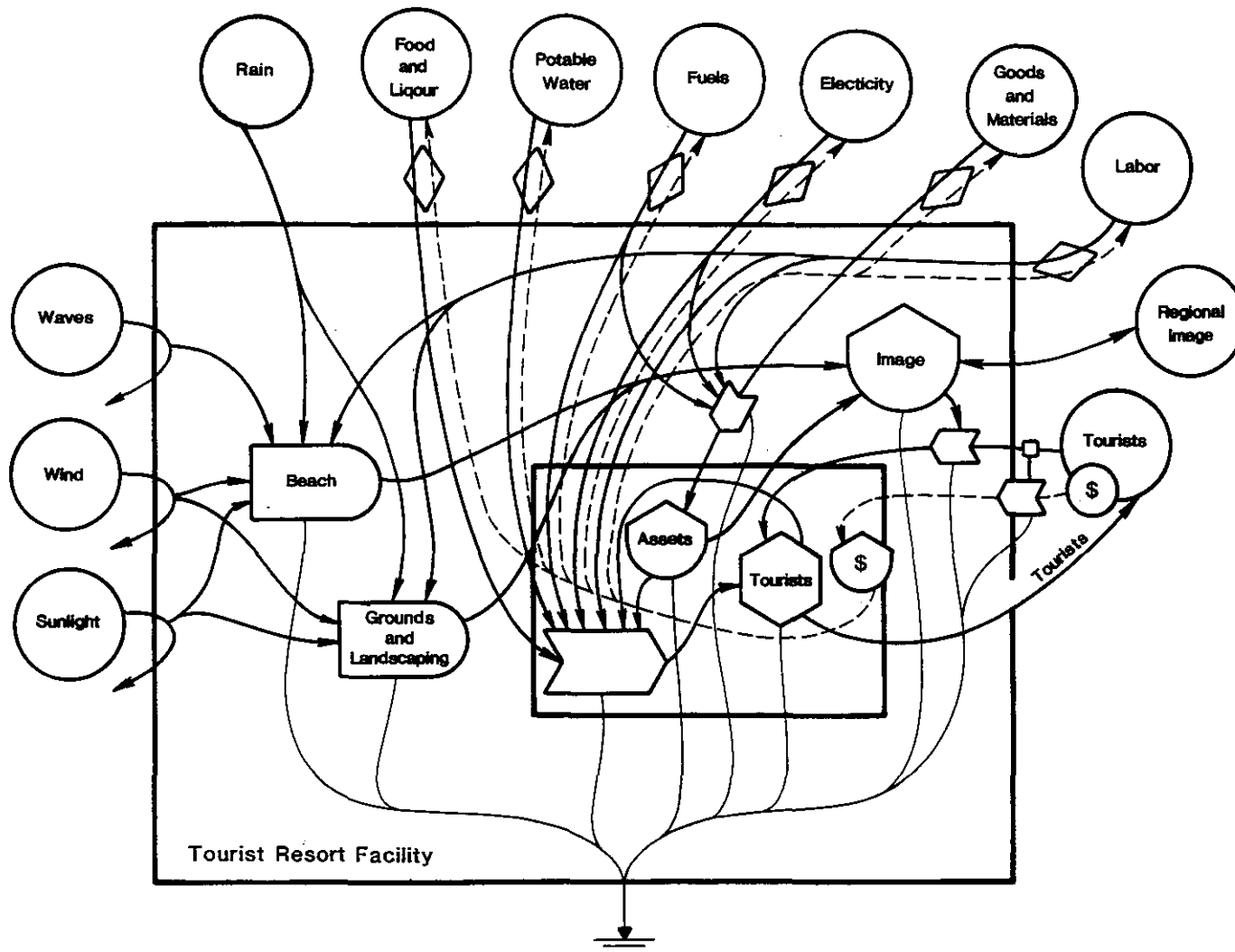


Figure D-3. A detailed systems diagram of a tourist facility showing the main production function that provides goods and services from the tourists who are attracted by the resort's image. Dashed lines are money and solid lines are resource flows.

Table D-1. Comparative national Emergy indices for Papua New Guinea, Mexico,  
and the United States

Row	Index	PNG (1) '(1987)	Mexico (2) '(1987)	USA (3) '(1983)
A	Total Emergy Use (E20 sej/yr)	1213	6955	87570
	Renewable Emergy Use (E20 sej/yr)	1050	1386	12355
	Nonrenewable Emergy Use (E20 sej/yr)	163	5569	75215
B	GNP (E9 US \$/yr)	2.5	185	3305
C	Area (E10 M <sup>2</sup> )	46.2	196	940
D	Population (E6 people)	3.5	81.1	234
E	Emergy/money ratio (E12 sej/\$)	48	3.8	2.6
F	Empower density (E11 sej/m <sup>2</sup> *yr)	2.6	3.5	9.3
G	Emergy per capita (E15 sej/person*yr)	34.7	8.5	37.4
H	World Emergy exchange ratio@	0.08	1.0	1.5
I	Environmental loading ratio	0.2	4.0	6.1

(1) from Doherty (1991)

(2) from Brown et al. (1992)

(3) from Brown and Arding (1991)

@ Emergy trade advantage of country based on ratio of world  
EMergy/money ratio (3.8 E12 sej/\$) to the EMergy/money  
ratio for the country.

Table D-2. Emery evaluation of tourist resort on New Britain Island, Papua New Guinea

Note	Item	Units	Units/Yr.	Transformity (sej/unit)	Solar Emery (E15 sej/yr)	Macroeconomic value (1988 US\$)
<b>RENEWABLE RESOURCES</b>						
1	Sunlight	J	1.74E+14	1.00E+00	0.17	3.63
2	Wind	J	1.18E+11	1.50E+03	0.18	3.68
3	Rain	J	2.41E+11	1.82E+04	4.39	91.43
4	Tidal Energy	J	2.21E+11	1.68E+04	3.72	77.56
5	Wave Energy	J	1.53E+11	3.06E+04	4.66	97.10
<b>NONRENEWABLE STORAGES</b>						
6	Potable water	J	2.93E+09	6.66E+05	1.95	40.64
	Sum of free inputs (sun,wind,waves omitted)				10.06	209.63
<b>PURCHASED INPUTS</b>						
<b>Construction inputs</b>						
7	Wood	J	1.64E+09	3.49E+04	0.06	1.19
8	Concrete	g	1.70E+06	9.26E+07	0.16	3.28
9	Steel	g	5.10E+04	1.80E+09	0.09	1.91
10	Furnishings	J	3.16E+09	4.00E+06	12.66	263.72
11	Services	\$	2.40E+04	4.80E+13	1,152.00	24,000.00
<b>Operational inputs</b>						
12	Fuel	J	2.28E+12	6.60E+04	150.45	3,134.45
13	Electricity	J	0.00E+00	2.00E+05	0.00	0.00
14	Food	J	1.25E+13	2.50E+05	3,113.75	64,869.79
15	Liquor	J	1.28E+10	6.00E+04	0.77	16.00
16	Services (PNG)	\$	1.40E+05	4.80E+13	6,720.00	140,000.00
17	Services (World)	\$	1.40E+05	3.60E+12	504.00	10,500.00
	Sum of purchased inputs				11,149.94	232,290.34
18	Tourists (number)		6.20E+02	3.74E+16	23,188.00	483,083.33

Footnotes:

1 Sunlight - 1.46 E5 cal/cm<sup>2</sup>/yr

$$(1.46 \text{ E9 cal/m}^2)(40.7 \text{ E3 m}^2)(70\%)(4.186 \text{ J/cal}) = 1.741 \text{ E14 J/yr}$$

2 Wind - 2.9 E6 J/m<sup>2</sup> (based on PNG average)

$$(2.9 \text{ E6 J/m}^2)(40.7 \text{ E3 m}^2) = 1.2 \text{ E11 J/yr}$$

3 Rain - 1.2 m/yr

$$(1.2 \text{ m})(40.7 \text{ E3 m}^2)(1000 \text{ kg/m}^3)(4.94 \text{ E3 J/kg}) = 2.4 \text{ E11 J/yr}$$

4 Tidal - 1.2 meter tidal range; shore length = 500 m; assume 100 m width

$$(5 \text{ E4 m}^2)(0.5)(730 \text{ tides/yr})(1.2 \text{ m})(1.03 \text{ E3 kg/m}^3)(9.8 \text{ m/s}^2) = 2.2 \text{ E11 J/yr}$$

5 Waves - shoaling area = 50000 m<sup>2</sup>; wave energy = 7.29 E6 cal/m<sup>2</sup>/yr

$$(50000 \text{ m}^2)(7.29 \text{ E6 cal/m}^2/\text{yr})(4.186 \text{ J/cal}) = 1.5 \text{ E11 J/yr}$$

Notes to Table D-2 continued

- 6 Potable water - 593 m<sup>3</sup>/yr  
 $(593 \text{ m}^3)(1000\text{g/m}^3)(4.94 \text{ E3 J/g}) = 2.93 \text{ E9 J/yr}$
- 7 Wood - 544 m<sup>3</sup>  
 $(593 \text{ m}^3)(5.5 \text{ kg/m}^3)(15.1 \text{ E6 J/kg}) = 4.9 \text{ E10 J/30yr} = 1.6 \text{ E9 J/yr}$
- 8 Concrete - 284m<sup>3</sup> - 181kg/m<sup>3</sup> = 5.1 E4 kg  
 $(5.1 \text{ E4 kg})(1000\text{g/kg}) = 5.1 \text{ E7 g/30yrs} = 1.7 \text{ E6 g/yr}$
- 9 Steel - 1.53 E3 kg (based on average steel/unit concrete)  
 $1.53 \text{ E3 kg}(1000 \text{ g/kg}) = 1.53 \text{ E6 g/30 yrs} = 5.1 \text{ E4 g/yr}$
- 10 Furnishings - 240 kg/room, plus 500 kg misc furnishings ( estimate) = 2420 kg  
 $(2.4 \text{ E6 g})(90\% \text{ drywt})(3500\text{cal/g})(4.186 \text{ J/cal}) / 10\text{years} = 3.16 \text{ E9 J}$
- 11 Services - total costs of construction + furnishings = \$ US 200,000 (1988)  
 $(2.0 \text{ E5 } \$) / 10 \text{ years} = \$2.0 \text{ E4 /yr}$
- 12 Fuel- 55,609 liters per year of gasoline  
 $(5.56 \text{ E4 liters})(4.1 \text{ E+7 J/l}) = 2.28\text{E+12 J/yr}$
- 13 Electricity - elec is generated on site  
 $(0 \text{ kwh})(3.6 \text{ E+6 J/kwh}) = 0 \text{ J/yr.}$
- 14 Food - 2.645 E6 kg/yr  
 $(2.6 \text{ E9g})(25\% \text{ dry weight})(4500\text{cal/g})(4.186 \text{ J/cal}) = 1.2 \text{ E13 J}$
- 15 Liquor - 1.435 E9 liters  
 $(1.435 \text{ E9 l})(2.11 \text{ E7 J/l}) (10\% \text{ alcohol}) = 3.02 \text{ E15 J}$
- 16 Services - PNG = \$1.4 E5 purchased from PNG @ 4.8 E13 sej/\$  
 PNG = \$1.4 E5 purchased from PNG @ 4.8 E13 sej/\$
- 17 Services - World = \$1.4 E5 purchased from world @ 3.8 E12 sej/\$
- 18 Tourists - 620 people/yr. (5232 person days) - 37.4 E15 sej/capita  
 Transformity = 37.4 E15 sej/capita, assuming all visitors  
 are American tourists

Table D-3. Energy evaluation of four star tourist hotel in Puerto Vallarta, Mexico

Note	Item	Units	Units/Yr.	Transformity (sej/unit)	Solar Energy (E15 sej/yr)	Macroeconomic Value (1988 US\$)
<b>RENEWABLE RESOURCES</b>						
	1 Sunlight	J	9.14E+13	1.00E+00	0.09	24
	2 Wind	J	1.10E+11	1.50E+03	0.16	43
	3 Rain	J	9.31E+10	1.82E+04	1.69	446
	4 Tidal Energy	J	4.18E+09	1.68E+04	0.07	19
	5 Wave Energy	J	1.60E+10	3.06E+04	0.49	129
<b>NONRENEWABLE STORAGEES</b>						
	6 Potable water	J	2.44E+11	6.66E+05	162.43	42746
	Sum of free inputs (sun,wind,waves omitted)				164.20	43210
<b>PURCHASED INPUTS</b>						
<b>Construction inputs</b>						
	7 Concrete	g	1.15E+08	9.26E+07	10.65	2802
	8 Steel	g	2.70E+07	1.80E+09	48.60	12789
	9 Furnishings	J	5.72E+10	4.00E+06	228.80	60211
	10 Services	\$	1.41E+06	3.80E+12	5,358.00	1410000
<b>Operational inputs</b>						
	11 Fuel	J	3.90E+12	6.60E+04	257.40	67737
	12 Electricity	J	6.20E+13	2.00E+05	12,400.00	3263158
	13 Food	J	8.46E+11	2.00E+06	1,692.14	445300
	14 Liquor	J	7.93E+10	6.00E+04	4.76	1253
	15 Services	\$	1.74E+06	3.80E+12	6,593.00	1735000
	Sum of purchased inputs				26,593.35	6998250
	16 Tourists (number)		5.37E+03	8.50E+15	45,636.50	12009605

Footnotes:

1 Sunlight - 1.64 E5 cal/cm<sup>2</sup>/yr

$$(1.64 \text{ E}9 \text{ cal/m}^2)(19.03\text{E}3 \text{ m}^2)(70\%)(4.186 \text{ J/cal}) = 9.14 \text{ E}13 \text{ J/yr}$$

2 Wind - 5.8 E6 J/m<sup>2</sup> (based on Mexico average)

$$(5.8 \text{ E}6 \text{ J/m}^2)(19.03\text{E}3 \text{ m}^2) = 1.1 \text{ E}11 \text{ J/yr}$$

3 Rain - 0.99 m/yr

$$(0.99 \text{ m})(19.03 \text{ E}3 \text{ m}^2)(1000\text{kg/m}^3)(4.94 \text{ E}3 \text{ J/kg}) = 9.31 \text{ E}10 \text{ J/yr}$$

4 Tidal - 1.0 meter tidal range; shore length = 113.5 m; assume 100 m width

$$(1135 \text{ m}^2)(0.5)(730 \text{ tides/yr})(1.0 \text{ m})(1.03\text{E}3\text{kg/m}^3)(9.8\text{m/s}^2) = 4.18 \text{ E}9 \text{ J/yr}$$

5 Waves - shore length = 113.5 m; wave energy = 3.36 E7 cal/m/yr

$$(113.5\text{m})(3.36\text{E}7 \text{ cal/m/yr})(4.186 \text{ J/cal}) = 1.6 \text{ E}10 \text{ J/yr}$$

6 Potable water - 49,287 m<sup>3</sup>/yr

$$(4.93\text{E}4\text{m}^3)(1000\text{g/m}^3)(4.94 \text{ E}3 \text{ J/g}) = 2.44 \text{ E}11 \text{ J/yr}$$

Notes to Table D-3 continued

- 7 Concrete - 5736 tons (based on average concrete/room)  
 $(5.736 \text{ E}6 \text{ kg})(1000\text{g/kg}) = 5.736 \text{ E}9 \text{ g}/50\text{yrs} = 1.15 \text{ E}8 \text{ g/yr}$
- 8 Steel - 1356 tons (based on average steel/room)  
 $1.356 \text{ E}6 \text{ kg}(1000 \text{ g/kg}) = 1.356 \text{ E}9 \text{ g}/50 \text{ yrs} = 2.7 \text{ E}7 \text{ g}$
- 9 Furnishings - 240 kg/room, plus 5000 kg misc furnishings ( estimate) = 43400 kg  
 $(43.4 \text{ E}6 \text{ g})(90\%\text{drywt})(3500\text{cal/g})(4.186 \text{ J/cal})/ 10\text{years} = 5.72 \text{ E}10 \text{ J}$
- 10 Services - total costs of construction + furnishings = 1.85 E9 pesos (1979)  
 $(1.85 \text{ E}9 \text{ pesos}) / (26.24 \text{ pesos/\$}) = \$70.5 \text{ E}6 / 50 \text{ years} = \$1.41 \text{ E}6 \text{ /yr}$
- 11 Fuel- 140,136 liters per year of liquified natural gas  
 $(1.4 \text{ E}5 \text{ liters})(2.79 \text{ E}+7 \text{ J/l}) = 3.9\text{E}+12 \text{ J/yr}$
- 12 Electricity - 17,199,287 kwh per year  
 $(17.2\text{E}+6 \text{ kwh})(3.6 \text{ E}+6 \text{ J/kwh}) = 6.2\text{E}+13 \text{ J/yr.}$
- 13 Food - 75168 kg - 2kg/person (est.) \* 37,584 people  
 $(75.2 \text{ E}6\text{g})(25\% \text{ dry weight})(4500\text{cal/g})(4.186 \text{ J/cal}) = 8.46 \text{ E}11 \text{ J/yr}$
- 14 Liquor - 37.6 E3 liters -1 liter/person (est) \* 37,584 people  
 $(37.6 \text{ E}3 \text{ l})(2.11 \text{ E}7 \text{ J/l}) (10\% \text{ alcohol}) = 7.9 \text{ E}10 \text{ J/yr}$
- 15 Services - 4.858 E9 pesos (total yearly income, 1990)  
 $(4.858 \text{ E}9 \text{ pesos}) / (2800 \text{ pesos/\$}) = \$1.735 \text{ E}6\text{/yr}$
- 16 Tourists - 5,369 tourists/yr.  
 Transformity =  $8.5 \text{ E} 15 \text{ sej/capita}$ , assuming all visitors are Mexican tourists

as their total energy flows indicate. The PNG resort is hand-built from local materials (wood and thatching), purchases fuel to generate its own electricity, burns coconut shells for hot water, and has 12 guest rooms serving a total of about 3924 person-days per year. The Mexican hotel is built almost entirely of concrete and steel, purchases electricity, has 160 rooms, and serves a total of 37,584 person days per year.

Renewable and nonrenewable energy inputs for the two tourist systems reflect the differences in intensity. By far the most significant non-purchased energy flow in the Mexican resort is potable water use (nearly 99% of the total), while the largest flows in the PNG resort are from rain and tides. Potable water use at the PNG resort is quite small (about 228 liters/person/day) as compared to the Mexican resort (1311 l/person/day).

Since there is no purchased electricity in the PNG resort, the energy of fuels and electricity are added together for comparison between the PNG and Mexican resorts. Probably the most telling, with respect to intensity of development, is that the Mexican resort uses more than 110 times the amount of fuels and electricity as the PNG resort, yet has less than 10 times the number of guests. Food and liquor consumption reflect the differences in the number of tourists served by the two resorts.

Total purchased inputs are similar for each of the resorts, considering the differences in size. While the total is similar, the source of the largest inputs is quite different. The greatest energy input in the Mexican resort is electricity (over 50% of the total), while the greatest in the PNG resort is the purchase of services from the local and world economies (added together they amount to over 50% of the total purchased energy).

### **Energy Indices of The Tourist Resorts**

Table D-4 contains summary statistics of the two resorts, and the economies of Papua New Guinea and Mexico, for comparison. Since the spatial area of each resort is relatively small, the percent of total energy flows from renewable and nonrenewable energy (rows 2 and 3 in Table D-4) are small in comparison with the national economies. When only the land area occupied by the resort is used, the intensity of development of both resorts is 3 to 4 orders of magnitude greater than the average for their respective economies. Per capita energy flows are from 6 (PNG resort) to 22 times (Mexican resort) that which is characteristic of the national economies.



**Table D-4. Comparative Emergy indices for tourist resorts in Papua New Guinea and Mexico**

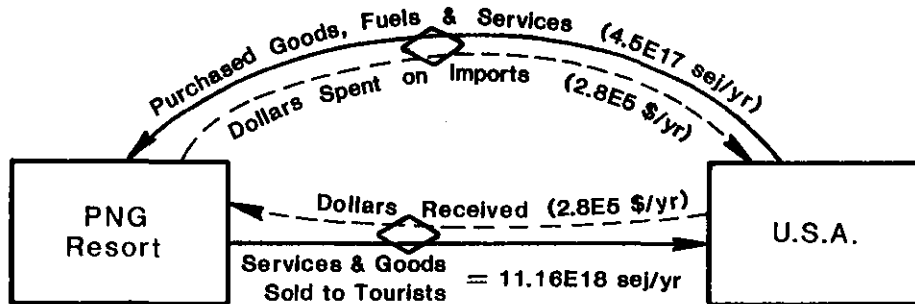
Index	PNG		Mexico	
	Country	Resort	Country	Resort
Total Emergy Use (E18 sej/yr)	121600	11.2	695500	26.8
Percent Renewable	86.4%	0.1%	19.9%	0.0%
% renewable + nonrenewable storage	95.5%	0.1%	52.6%	0.6%
Empower density (E11 sej/m <sup>2</sup> *yr)	2.6	2741.8	3.5	14056.8
Emergy per capita (E15 sej/person*yr)	34.7	778.5	8.5	259.8
Environmental loading ratio	0.16	194.1	8.9	12189.5
Support Area required (m <sup>2</sup> )	--	5.66E+07	--	4.17E+07

Using the actual area occupied by each resort, the Environmental Loading Ratios (ELR) vary from 8 times (Mexican resort) to 4 times (PNG resort) the environmental loading characteristic of the national economy. Using the ELRs, the support areas were calculated as 156 km<sup>2</sup> and 117 km<sup>2</sup> for the PNG and Mexican resorts, respectively. In other words, to balance and reduce the ELR of each resort to that of the national economy, 156 km<sup>2</sup> are required for the PNG resort and 111 km<sup>2</sup> for the Mexican resort. Once the support area is known, the Investment Ratio (IR) is determined. The IRs show higher investments per unit of resident energy flow than is characteristic of the national economies (10 times the national average for the PNG resort and 9 times the national average for the Mexican resort).

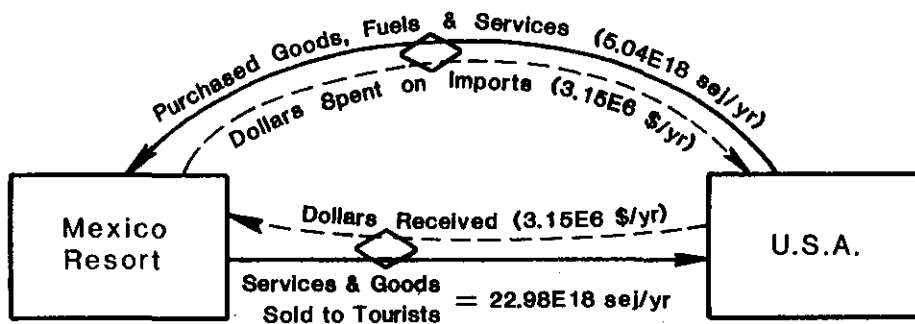
### **Emergy Exchange of Tourism**

The emergy exchange of the PNG and Mexican resort developments are illustrated in Figure D-4. An exchange of emergy is shown flowing countercurrent to the dollar exchange between the two economies. In both examples, the tourists are assumed to be 100% from the USA; while this is not necessarily accurate, it serves to make our point. In the top diagram, the PNG resort receives \$2.8 E+5/yr as income, for which it provides 11.2 E+18 sej/yr in goods and services to the tourists (this is the emergy that is consumed by the resort in direct support of the tourists). The Mexican resort receives \$3.2 E+6/yr and provides 23.0 E+18 sej/yr in goods and services.

When the income from tourists is eventually spent for import purchases from the USA, the amount of emergy received (on average) is determined by multiplying the money spent by the emergy/money index for the USA economy. The calculated emergy values of imported goods and services is 4.5 E+17 sej/yr (PNG) and 5.0 E+18 sej/yr (Mexico). The trade advantage for the USA in both these examples is calculated by dividing what is received by the USA by what is exported. The USA trade advantage over PNG is 16 to 1, and over Mexico it is 1.4 to 1. In other words, for every unit of emergy that is sold to PNG and Mexico using money these countries received from USA tourists, the USA economy receives, on the average, 16 units and 1.4 units of value, respectively, from PNG and Mexico. All international transactions are subject to these relative values (Emergy/\$). As we have shown, this ratio exists for all transactions irrespective of whether they are tourism, forestry or fisheries.



U.S.A. Trade Advantage = 25/1



U.S.A. Trade Advantage = 4.6/1

Figure D-4. Overview diagrams illustrating the USA trade advantage when tourists spend money in Papua New Guinea (top) and Mexico (bottom). The trade advantage is calculated assuming that all tourist currency is used to purchase goods and services from the USA economy.

Another way of looking at value received is that an American tourist receives about 16 times the energy for each dollar spent in PNG at this tourist resort than if it were spent in the USA economy. The advantage in Mexico is smaller, receiving only 1.4 times the energy.

## DISCUSSION

### Carrying Capacity for Tourist Resorts

The support area calculated using the ELR for each of the tourist developments in this study reflects the area necessary to reduce their environmental loading to that which is characteristic of the national economy. In essence, the support area provides the carrying capacity of the environment to absorb the resort itself, and possibly more developments of a similar type (i.e., of similar size and energy intensity). If the size and/or intensity of a development changes, the support region will also change since its determination is based on these factors. In this way the determination of carrying capacity using the ELR achieves a dynamic balance that is affected not only by the environment's ability to absorb the development, but by the size and intensity of the development itself.

To illustrate this point, suppose the PNG resort was built in Mexico, and the Mexican resort built in PNG. Much different support area requirements result because of the differences in each economy and the intensity of each development. If the PNG resort were constructed in Mexico, its support area would need to be only 33 km<sup>2</sup> as compared to the 117 km<sup>2</sup> required by the Mexican resort. And if the Mexican resort were constructed in PNG, it would require a support area of 547 km<sup>2</sup>.

Comparison between the two resorts and their required support areas can be expressed relative to their physical size and the average number of tourists served per day. These may be more familiar ways of expressing carrying capacity. Assuming that energy use per tourist and per resort room does not change appreciably as the size of the facility is varied, these measures could be used to determine, relatively quickly, the support area required for a given resort size. The PNG resort had 12 rooms and served 3924 person days per year (or an average of about 11 tourists per day), while the Mexican resort had 160 rooms and served 37,584 person days per year (103 tourists per day). Using the support area for each resort (156 km<sup>2</sup> in PNG and 117 km<sup>2</sup> in Mexico) the number of rooms and average density of tourists can be determined. In PNG the

support area per room was 13 km<sup>2</sup>/room, and the average daily number of tourists per square kilometer of support area was 0.07 tourists/km<sup>2</sup>. The support area per room in Mexico was 0.73 km<sup>2</sup>/room and the average daily number of tourists per unit support area was about 0.9 tourists/km<sup>2</sup>.

### **International Trade and Tourist Resorts**

Emergy as a measure of value, offers interesting perspectives on issues of national wealth and economic well being. International development has become an important economic activity as accumulated currency in developed economies is invested in undeveloped economies to achieve high returns on investment. The resources and environment of any country, whether developed or not, represent its wealth (Odum 1984). When money is invested in developing economies, the principle reason is to extract resources (i.e., wealth) and sell them for more money than they cost to extract. Thus, the activity results in the exportation of national wealth and the inflow of currency. Since currency cannot accumulate for long, but must be spent, it is used to purchase fuels, goods, and services from the developed world. Most often the goods purchased do not equal in units of wealth (emergy) that which is exported. In other words, a developing economy that sells raw resources and imports finished goods from a developed economy supports the outside economy at the expense of its own. In a recent analysis of the shrimp fishery in the Sea of Cortez, Mexico (Brown et al. 1990), it was found that the consequences of an expanded mechanized fishing fleet and international sales were to raise the price of shrimp beyond local purchasing power (thus eliminating their consumption by local populations) and exportation of 1.4 times more emergy than was purchased with the currency from the sale.

The consequences of international tourism on trade balance is often seen only as beneficial to undeveloped economies since it seems to be a non-extractive source of much needed foreign currency. What is often overlooked is the environmental support required and resources consumed to provide the goods and services for an expanded population of visitors. In essence, the resources that are consumed in support of a tourist population are "extracted" and exported with each tourist and therefore not available for consumption by the local population. In return, the local economy receives a currency income with which they purchase goods from the international market place. Evaluating tourism's economic impact by measuring only the currency input misses this important consequence. The money spent by each tourist purchases local goods and resources and environmental support (for instance, a portion of the local estuary that cannot be used by the local population for sewage disposal or fish harvest because it is being used for waste disposal of the tourist facility). When these are expressed in their emergy equivalent and compared with the emergy that is

imported, as was done in this study, more wealth is used and exported than is imported, based on the assumption that 100% of tourists are from the U.S. In PNG, the ratio of energy exported to that received was 18 to 1 and in Mexico it was 1.4 to 1. This assumes that all tourists originated in the USA. In reality, tourists come from many different countries, each having a different energy currency ratio. Thus the aggregate ratio of energy exported to that received could be significantly different. For instance, at the PNG resort, about 40% of the visitors originated from within the country, and the balance came from many different countries. To determine the aggregate energy balance of payments would require calculating currency ratios for each of the home countries. While this was beyond the scope of our analysis, we can say that the aggregate ratio for the PNG resort, instead of being 18/1, would be somewhat lower, on the strength that 40% of the tourists visiting the resort were from PNG.

While we have not analyzed tourism in other developing nations, our analyses of other development projects (Odum and Arding 1991, Odum et al. 1986) suggests that one of the main driving forces behind all international trade and tourism is the fact that developed countries benefit greatly through an uneven energy exchange. In spite of the fact that tourism does have extractive aspects, ecotourism in particular is certainly less harmful than most other activities in which resources are exploited for international exchange. The tourist facility analyzed in PNG was a unique facility that strove to be environmentally benign, economically integrated into the local economy, and socially acceptable. To be sure, the facility was well designed and thought out. Local materials and renewable energies were used wherever possible (for instance water was heated using coconut shells from a nearby coconut plantation), local sources of foods and labor were favored over importing, and in general it was one of the most ecologically sensitive tourist developments we have seen. Our analysis in no way should suggest that this development was insensitive to the ecology, economy or culture of PNG. It was very well done. Our analysis, especially as it relates to international trade, does point out, however, that no matter how sensitive a development, tourism is an extractive industry albeit far less destructive of environmental and cultural resources than the extraction of minerals or forestry products for instance.

### **Spatial Relationships of Resorts and Support Areas**

There are numerous ways that resorts and support areas might be organized spatially and yet maintain a balanced Environmental Loading Ratio. In coastal regions, much of the new tourist development is within the coastal zone to take advantage of the interface of marine and terrestrial environments and the diversity

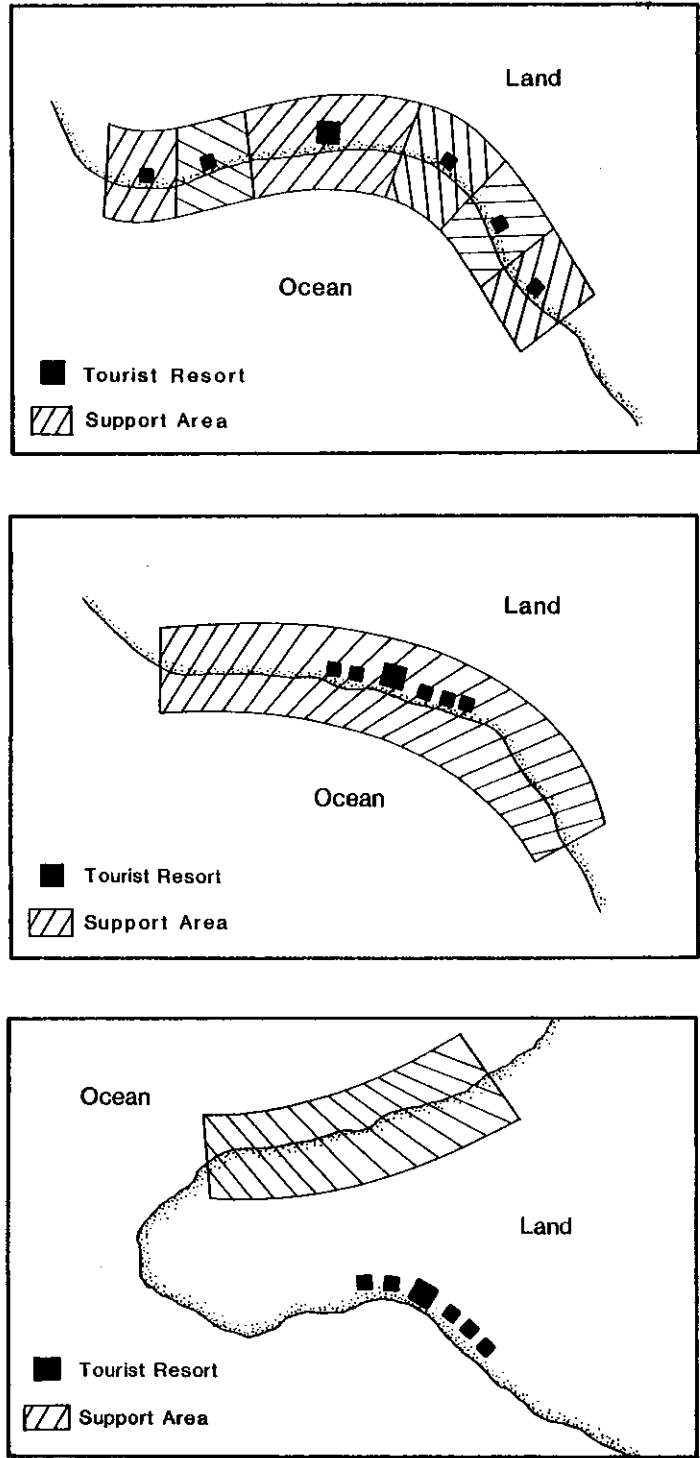


Figure D-5. Schematic diagrams of a coastline showing alternate ways of grouping tourist resorts within their support regions so as not to exceed economic carrying capacity. In the top diagram, resorts are spaced based on the size of the required support region; and in the bottom diagram, resorts are clustered leaving the remaining support region undeveloped.

that results. Figure D-5 illustrates three different concepts for a group of resort complexes in a coastal zone. Since the environmental basis of coastal regions is a blend of both marine and terrestrial productivity, the support regions (hatched areas) are composed of both of these environments. In the top illustration resort developments are spaced along the coast, each surrounded by their appropriate support region. In the middle illustration, the same number and size developments are clustered in one area and surrounded by a support region equal to the sum of the individual areas. To maintain a balanced ELR, further development within the support areas would be restricted. The bottom illustration shows a spatial arrangement where the support region does not surround the resorts, but is located elsewhere within the region. In many cases, this arrangement may be more attractive as a means of setting aside ecological reserves or important wetland ecosystems. We have considered only the tourist resort in our analysis and in the above illustrations of spatial arrangements. In some developing regions, where the regional economy is already relatively intense, resort development also brings infrastructure development and urban expansion resulting from increased populations. We believe that this method for determining carrying capacity and support areas could apply in these circumstances as well, if the infrastructure and increased urban developments were factored into the calculations. Often feasibility studies for new developments determine infrastructure requirements and urban expansion that will result from the development. These data could provide the basis for an expanded evaluation of carrying capacity that included secondary development.

### **Sustainability of Development Projects**

Economic development in the developing nations seems to be increasing in rate and magnitude as developed countries seek higher returns on investment than are characteristic of their internal economies. The result is increased rates of change in environmental, cultural, and economic system. With it, an awareness has recently developed that sustainability is a key factor to consider when analyzing potential impacts of proposed projects. Yet sustainability remains an elusive concept. It can be argued that sustainable development, in the long run (100 years or more?), is that which can be supported by the renewable flows of energy of a region.

Development that depends on purchased resources is ultimately not sustainable, since purchased energy is composed of nonrenewable flows and fluctuations in world prices. Yet, development that does not allow for the possibility of using purchased resources to amplify a region's environmental basis cannot give an



economic return and becomes a moot point. Thus, sustainability should reflect the current intensity of development of an economy and match it. In this way, it is no more dependent on limited supplies of nonrenewable energies than is the economy as a whole. As the economy's use of nonrenewable purchased energies may decline, new development under these circumstances does not draw more of these energies on the average than the rest. To put it another way, what is sustainable in the USA is much different from what is sustainable in Papua New Guinea.

Determinations of sustainability should take into account: (1) the relative mix of an economy's environmental basis (renewable energy sources), (2) its use of nonrenewable storages from within, and (3) its purchased goods, resources, and services. These flows drive the economy and ultimately influence what is sustainable, by defining an upper boundary to the present mix of purchased energy, resources from within, and renewable energy flows. The Investment Ratio described in this report is a ratio of purchased energy to resident energy and, when the ratios of development proposals are compared to the ratio for the economy in which they are imbedded, may provide one means of defining sustainability.

Development proposals that have IRs that are higher than the economy require more purchased energy per unit of resident energy, and therefore are more vulnerable, on the average, to changes in availability of purchased energy. Developments with lower IRs than the local economy are less vulnerable, but also yield less, on average. If these support areas could remain undeveloped, each of the resorts can potentially use more resident energy and, as a consequence, be less vulnerable to outside economic fluctuations.

Where economic development results in extraction and sale of resources to foreign economies, sustainability may be related to the trade advantage or energy exchange that results. If more wealth leaves the local economy than is received in exchange, the development is probably not sustainable. Balancing the exchange of wealth between that which is exported and that which is imported may lead to more sustainable developments. In the case of the tourist developments in PNG and Mexico that were analyzed, more wealth left both economies "embodied" in visitors than was received when the income derived from them was used to purchase foreign goods and services. In other words, tourists and the nation from which they came gained more energy than the nation they visited. In the case of PNG, the advantage for the USA resulting from one tourist's visit was 25 to 1, while in the Mexican resort the advantage to the USA

economy was 4.6 to 1; more total wealth left each of the economies embodied in tourists than was purchased from foreign economies with the tourist-derived income.

The use of energy flows as a means of evaluating costs and benefits of economic investments and the carrying capacity of regional economies may lend insight into the complex questions surrounding the increased integration of national economies on a global scale and whether such developments are beneficial and sustainable in the long run. The proposed methods of quantitative evaluation are tendered more as a means of helping guide public policy decisions than as the means to answer, once and for all, the questions surrounding soundness of economic policy that fosters economic investments in developing nations.



## Section E: Energy, Time and Economic Expectations in a Highlands Village

by G.A. Smith, S.J. Doherty and M.T. Brown

### INTRODUCTION

Energy, time and economic expectations are basic concepts which are interrelated. Individuals and communities have a given amount of resources and a fixed amount of time with which they can use to meet their economic expectations. These expectations here are broadly defined as 'needed and/or hoped-for commodities and services.' Generally, the available forms of incident energy including sun, rain and land resources have to be transformed by plants, animals or technology before they are directly useful to humans. This process of energy transformation includes land clearing, crop cultivation, harvesting and food preparation, as well as building construction and development of other commodities. Both rural and industrial societies require basic transformations, although in differing degrees. This manipulation of primary resources into upgraded goods and services is called production and consumes greater amounts of concentrated forms of energy as societies become industrialized.

A common observation in modern times is that past generations of people seemed to have more time to visit and relax -- more free time -- than people today. Modern middle class Americans, for example, live in the midst of more time-saving devices than their ancestors or people in other parts of the world, yet their lives do not necessarily seem to be any less hurried as a result. One would think that with all these labor and time saving technologies now available, technology would reduce the amount of time spent working and humans would be afforded greater leisure. If anything, the opposite seems to be true (this is described by Staffan Linder in *The Harried Leisure Class*). Or as John Stuart Mills once noted, there was never a labor-saving device invented that saved anybody a minute's labor.

In order to address these observations, this section will focus on time budgets and economic expectations of a typical highlands village in Papua New Guinea as it moved from a subsistence level to a more industrialized setting. Systems diagrams illustrate the differences between a typical family unit in a highlands village prior to World War II (Figure E-1) and a modern, industrialized family unit (Figure E-2). Village life in 1930 was subsistence-based, generally sustainable and self-sufficient.

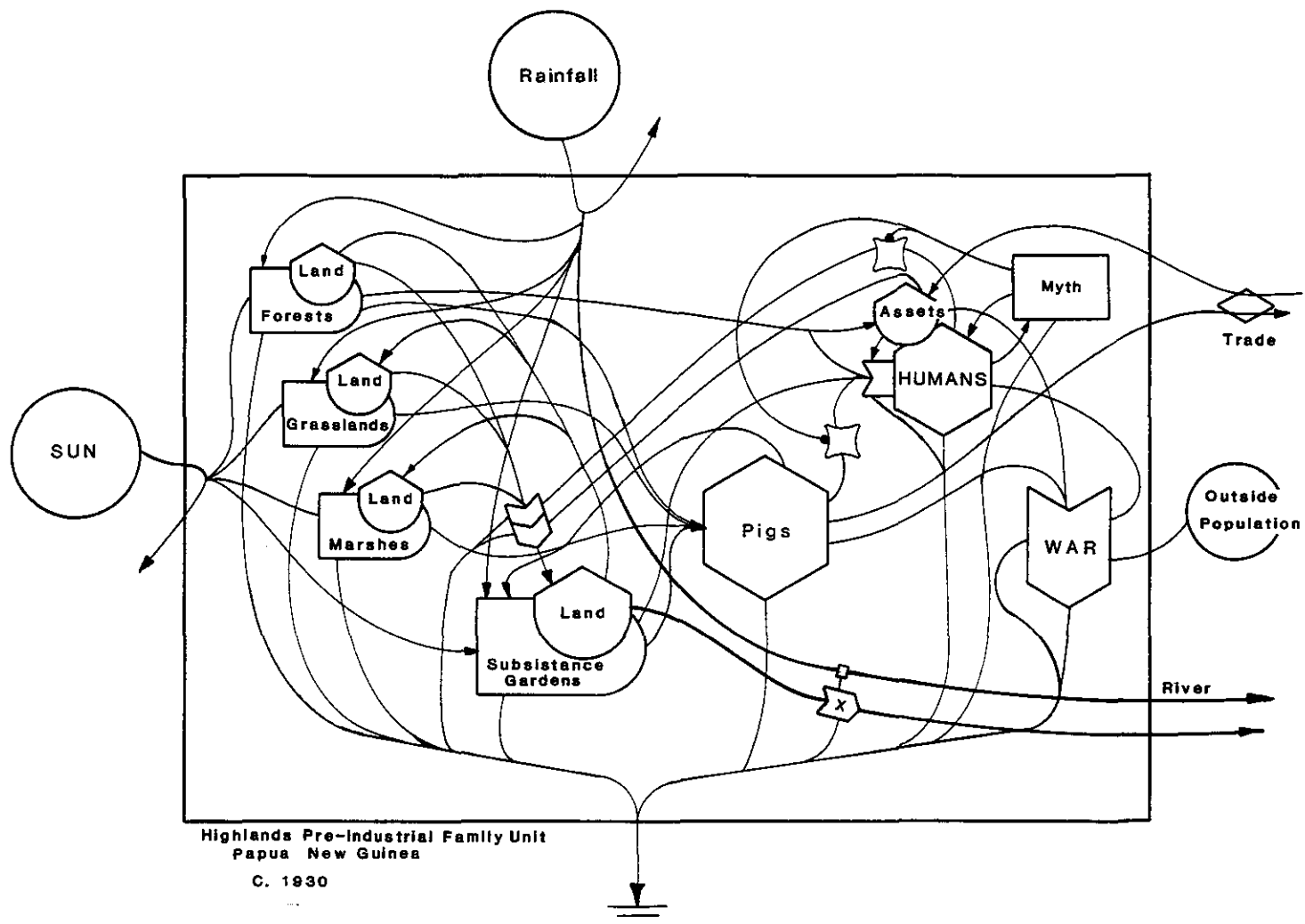


Figure E-1. Systems diagram of a village family unit in the highlands of Papua New Guinea, circa 1930 prior to industrialization.

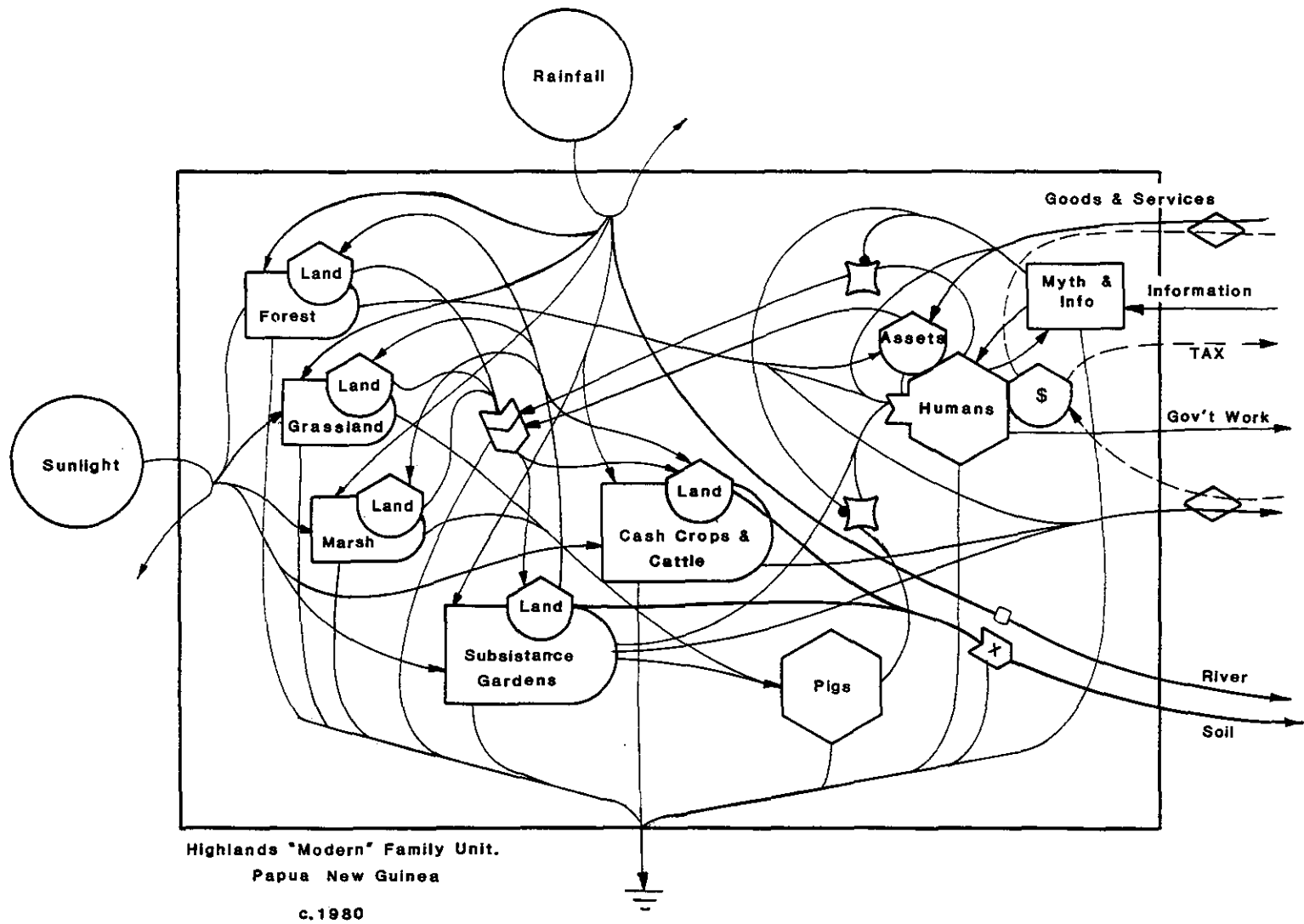


Figure E-2. Systems diagram of a modern family unit in the highlands of Papua New Guinea, circa 1980.

There was little contact with other populations since most of the resources needed to support lifestyles were came directly from the environment. Gardens were rotated in fallow systems, resources were drawn directly from secondary growth forests and grasslands. Pigs supplied essential proteins and recycled unused garden wastes. Trade was generally for ceremonial purposes. In modern villages, an increasing portion of environmental support energy is consumed by cash crops. Forests and minerals are extracted without use and sold as raw materials to foreign markets. There is an increase in exports, imports, financial aid and government work. With greater ties to outside markets, there is less emphasis on subsistence farming and more basic resources such as food and building materials are purchased from external markets.

Time budgets are generated for three different years: 1933, 1953 and 1976. A time budget for an average worker in the U.S.A. circa 1975 is also constructed for comparison. In the short course of a person's lifetime, Papua New Guinea nationals have seen their lifestyles change from subsistence-based communities with little connection to external markets to more "modern" lifestyles, greatly affected by industrialization and global markets. Here, "modern" is not used to elicit connotations of betterment or wealth, but instead is simply a reference to current conditions of modern society. Real wealth, as measured by solar energy available to do useful work for the combined ecologic-economic system, is discussed in the national overview (Section A) and again as the support basis for agro-forest production sectors (Section B), tourism (Section D) and indigenous culture (Section F) in this report. The questions of whether or not these momentous changes during the past century have affected a villager's allocation of time spent in work and leisure or their economic expectations are addressed.

## RESULTS

### Daily Activities

Time spent in varying activities were monitored by Salisbury (1962) in a highland village during 1953. In addition, the author assembled time schedules for villagers before contact with western civilization in 1933 by questioning the village elders. From this data, time budgets for nine working hours during the day were constructed for 1933 and 1953. Data from a 1975 study of daily schedules for highland villagers (Grossman 1984) was used to construct time budgets for typical adult workers living in more modern times. Finally, a study by (Hill 1985) was used to assemble activity schedules of a typical American worker in order to draw

comparisons with an industrialized economy. Lea (1970) cautions that many activities are seasonal so that studies over many years are required to produce meaningful data. With this in mind, we draw some general conclusions regarding how activity schedules have changed from 1930's to the mid 70's with the introduction of technologies, fossil fuels, and western influence and information.

In 1933, a little over 7 hours per day were spent at the work site (Table E-1), though all of those hours were not spent directly working any more than Americans work the entire time they are at a work place. By 1953, the amount of time spent working for village men was reduced by 40% (32 hrs/wk compared with 50 hrs/wk in 1933). At least partial explanation is that by the mid 50's much of the traditional work of village men -- clearing forests for gardens, building fences and housing -- had been eased due to the introduction of steel axes, replacing traditional stone tools. The steel axes did not, however, seem to reduce the women's work load. This introduction of steel axes occurred rapidly but was unaccompanied by other technologies, ideas or values due to World War II which kept the industrialized nations, particularly Japan and Australia, occupied with other concerns than the exploration and colonization of the highlands of Papua New Guinea.

However, the 1950's, 60's and 70's were a time when at least the ideas of modern civilization advanced rapidly in the highlands through road construction, truck transportation and the transistor radio. By 1975, previously subsistence-based communities and family units began to devote a portion of their labor, time and land resources to producing items for sale to outside markets -- generally coffee and cattle. Table E-2 compares life in Papua New Guinea during this period of technological change and western influence to past years of subsistence and relative isolation. Activities for a 24 hour-day (168 hours/week) were divided into 5 categories: 1) work -- which includes all work for income as well as any activity which is done to provide one's self, family or community with food, shelter or other useful commodities; 2) childcare; 3) personal care -- this includes sleeping and eating as well as grooming and washing; 4) ceremonies, religious or educational activities; and 5) leisure or 'free' time.



Table E-1. Time budgets for nine-hour work days (63 hr work-wk) for highlands villagers in Papua New Guinea in 1933 and 1953 (data compiled from Salisbury 1962).

Activity	Mean time allocation (hours/person/week)					
	in 1933			in 1953		
	men	women	average	men	women	average
<b>General:</b>						
a at home sick	6.3	6.3	6.3	6.3	6.3	6.3
b leisure, visiting	1.9	3.2	2.5	3.8	3.2	3.5
c total	--	--	--	--	--	--
<b>Ceremonial:</b>						
c religious	4.4	1.9		8.8	1.9	
d courts	0	0		2.5	0	
total	4.4	1.9	3.2	11.3	1.9	6.6
<b>Subsistence work:</b>						
e clan work	34.7	--		13.9	--	
f lineage work	15.1	--		10.1	--	
g home crafts	0.6	--		7.6	--	
total (for men)	50.4			31.5		
h traveling to gardens and tending pigs	--	12.9		--	12.9	
i garden work	--	12.9		--	12.9	
j harvesting crops	--	12.9		--	12.9	
k cooking and crafts	--	12.9		--	12.9	
total (for women)		51.7	51.4		51.7	41.6
<b>Introduced activities:</b>						
l government work	0	0		6.3	0	
m missionary work	0	0		1.9	0	
n football	0	0		2.5	0	
total:	0	0		10.7	0	5.4

Table E-2. Summary of time budgets for a 168 hour-week<sup>1)</sup> for Papua New Guinea in 1933, 1953, 1975 and for the U.S.A. in 1975.

Activity	Papua New Guinea			U.S.A.
	1933	1953	1975	1975
Work	51.2	45.0	44.8	46.0
Childcare	3.5	3.5	3.5	2.6
Personal care	67.0	67.0	67.6	76.9
Ceremonies, education	3.2	7.5	7.5	4.5
Leisure	43.1	45.0	44.6	38.0

1) PNG data compiled from Salisbury (1962) and Grossman (1984). Data for U.S. from Hill (1985).

Although the data set is small and synthesized from unrelated studies, a conclusion drawn here would be that there is great similarity between daily activities for both cultures (PNG and USA), and that allocation of time and responsibilities has not been greatly affected by changes in technology and information over the course of almost half a century. Though there are some differences in time spent in different activities, the differences are not major and may be artifacts of surveying techniques and differing interpretations of personal care and leisure.

Some differences are noteworthy. It appears that the amount of time villagers spent working had been reduced by about 13% from 51hrs/wk in 1933 to around 45 hrs/wk in modern times (Table E-2). This savings of almost 6 hrs/wk had been reallocated into ceremonies and education which has increased from around 3 hrs/wk in 1933 to over 7 hrs/wk in 1975. Leisure time also appears to have increased possibly an hour or two per week for PNG nationals. In the U.S. in 1975, about the same amount of time was spent working as in Papua New Guinea, yet more time was spent in personal care, less in education and ceremonies, and there was generally less time for leisure activities (38 hrs/wk for U.S. workers compared with 45 hrs/wk for PNG workers). In a very rough sense however, in either cultures, past or present, people spend about a third of their time working, a little more than a third in personal care, and a little less than a third of their time in other activities such as cultural and religious ceremonies, education, child care and leisure.

## **Economic Expectations**

Wealth has been variously defined as an abundance of material possessions or resources, but more generally understood as a measure of well-being. In this report, wealth is measured as available and useful resources, all expressed in common units of solar energy so they may be "added up" expressing contributions relative from one source to another. As expressed by Sahlins (1972, p. 37) in his book *Stone Age Economics*; "the world's most [primitive] people have few possessions, but they are not poor. Poverty is not a certain small amount of goods, nor is it just a relation between means and ends; above all it is a relation between people." For villagers in pre-World War II Papua New Guinea, although personal possessions were small, total resources available for the common good were large. Villages were relatively small [80-200 people (Bell 1984)], un-moned and self-sufficient, and therefore with little exchange with other villages. Land and resources were held in commons and decisions as to which land to take out of fallow and put into garden cultivation were discussed by the married men of the community. After consensus was reached, men would take responsibility for land clearing. The communal garden would be subdivided into smaller plots for individual women who were responsible for planting, tending the garden, harvesting and food preparation. The food was then shared by all villagers. There appeared to be little incentive to acquire individual wealth.

Estimates for food consumption for typical village adults in 1953 is given in Table E-3. This diet of almost 3000 kcal/day was at least sufficient to meet daily nutritional needs, and as reported in several ethnographic studies, the problem of food production and distribution was largely solved in Papua New Guinea at the time (although essential proteins were not always obtained). Thus, there was no need or possibility of individual acquisition of land resources or food items.

Table E-3. A typical daily diet for an adult Papua New Guinea highland villager circa 1953 (from Salisbury 1962).

Food item	Bulk weight (lbs/adult/day)	Energy content (kcal/adult/day)
sweet potato	4.20	1890
maize	0.25	105
taro	0.33	135
green vegetables	0.87	90
cucumber	0.66	31
sugar cane	2.20	305
pork	0.17	317
		total: 2927 kcal/person/day

Non-subsistence items were few and could be divided into 2 categories: ceremonial items and luxuries. Ceremonial items were symbolically traded at public events and between villages. Pigs were the main ceremonial goods; others included necklaces, cowry shells and plume feathers from the bird-of-paradise. These items were not usually gained by labor but rather exchanged in a ritual manner at events such as weddings, funerals and initiations into adulthood. Respect was earned not through owning these possessions but rather giving them to others.

Luxury items in 1933-53 generally consisted of the following: tobacco, palm oil for washing, pandanus nuts, drums, sharpening stones, and palm wood for spears. Again, however, there was not much differentiation in amounts owned of these items. Such luxuries were useful to the extent that an individual could use them. Quality of life was in no way enhanced by possession of large numbers of these goods, so that villagers saw no advantages in owning anything more than could be immediately and directly used.

In conclusion, economic expectations were few and constrained and generally were met for indigenous people of Papua New Guinea prior to World War II. As the country was increasingly drawn into modern times, personal ownership became more important. Money and goods were in such demand that "cargo cults" started in which members would try to emulate their understanding of western "production." Money was created by mysterious machines and money could buy anything. Possessions became valuable regardless of utility. Cult leaders would tell curious villagers how, by mimicking the white man's ways, they too could

become rich in material goods or wealth (Kirk 1973). Government officials discouraged activities of cargo cultists since cult members often abandoned normal occupations in their mystic strivings after cargo. Although cargo cults are no longer common, there is still concern within government that an increasing number of youths are abandoning rural lifestyles and skills for a chance at a "richer life" in port cities and urban centers.

## DISCUSSION

Villagers of the 1930's and 1950's did not have the machines and tools available to them as modern people have today, yet their working hours were only slightly higher (51 hrs/wk in 1933 compared with about 45 hrs/wk in 1975 for both PNG and USA). Although the reasons for this are complex, a few observations help explain the discrepancy between technological advancement and corresponding reductions of worker-related activities. First, although modern machines are productive, many hours and resources are required for invention, testing, construction, transportation and maintenance of the technologies. Education is also time and resource consumptive and is required with modern industrialization. Secondly, in modern times, people have a greater amount of commodities available to them, each requiring time and resources that could otherwise be used in other activities. An example is in the U.S., where so much time is spent watching television, and where an essential part of television is commercial advertizing, the objective of which is to promote desires for things.

Thirdly, and perhaps most importantly, an increasing number of hours in modern times are devoted to work which the environment does free of charge in the highlands of Papua New Guinea. For example, in the important area of gardening, the fallow method has historically been used to re-build soil fertility. In this method garden plots are left abandoned for about 15 years, allowing for regrowth from the surrounding matrix of forested areas in order to re-nourish topsoil depleted of organic matter, humus and essential nutrients. No human effort is spent through fertilizers or pest control. Instead, these tasks are performed by the ecological support base that such a fallow system requires. Another example is waste control. Due both to a lack of synthetic and inorganic products foreign to the environment and because of the size of the environment in relation to the population, waste disposal is a simple matter. As Salisbury (1962, p. 83) noted, "the bush is large and requires fertilizing."

Although today cargo cults are uncommon, economic expectations have grown. There are numerous stories of individuals and communities trading land, timber and mineral rights for material possessions such as trucks and televisions even though there was little use for such commodities and perhaps no fuels available to even use them. With the expansion of local economies, there is a growing influence from foreign markets. Increasingly the ecological support base of village enterprises is being sold or traded for promises of material wealth, schools, road construction and other infrastructure. While most of these agreements with foreign owned and operated companies have been met, there is generally no provisions made for maintenance and operating costs of the facilities set in place. Saulei (per. comm. 1990) reiterated this point with regard to the Forest Research Institute in Lae -- a facility donated by Japanese forestry operations but with no additional support to operate the station or hire adequate research staff.

These observations are substantiated through the analyses of solar energy support for production sectors in Papua New Guinea in other sections of this report. As stated earlier, the solar energy per capita is very large for Papua New Guinea nationals compared with other countries of the world, especially more industrialized nations (Table A-3, item 16). Further, as evidenced in Section B, the large net yields delivered from production systems such as forestry, sago palm cultivation and sweet potato farming, are due to the large ecological support base delivering constant, renewable sources of solar energy as the basis for production. This is also demonstrated with tourism (Section D).

One consequence of industrialization appears to be an increasing externalization of local economies, with increasing dependence on purchased, upgraded fuels. Technology and fossil fuels support increased production, however often at the expense of local resources that are unaccounted for in market decisions. And because there is greater reliance on purchased goods and services, economies experience lower net yields for production sectors. Papua New Guinea's self-sufficiency may be a cost of economic expansion, especially if environmental contributions continue to go unrecognized.



## Section F: Perspectives on Emergy Support of Indigenous Culture

by H.T. Odum and S.J. Doherty

Because Papua New Guinea remained in relative isolation until the last century from development activities occurring in most other countries of the world, it presents itself as a case history of cultural evolution based almost entirely on resident sources of renewable, environmental energies. As a preliminary effort to investigate the emergy basis of genetic and cultural information, we used the renewable emergy flows determined from this study as the annual contribution supporting indigenous populations during their isolated past. Demographic data was drawn from the literature and estimates of delivery time requirements for genetic evolution and cultural information were made. Together, this data was used to investigate the solar emergy basis for information storages in indigenous cultures of Papua New Guinea.

### INTRODUCTION

Inheritance of genetic information is the primary mechanism that ecosystems and species can store and copy information. When an ecosystem has developed a functioning set of species through self-organization of available seeds, genetic stocks and immigrants, this integrated set of reproductives constitutes a package of information that can restore itself after disturbances much more rapidly than occurred the first time. A premise we explore here is that the emergy requirements for maintenance of genetic stocks and ordered systems are appreciably less than the emergy of origination or evolution.

In addition to the inherited genetic information, humans as well as other social organisms have the capacity to develop and use learned information individually and in social organization with its group. We define the learned information of society as *culture*. The ability to learn and to be socially organized (among other reasons) causes humans to become dominant mechanisms of ecosystem transformations. This emerging economy of nature and society now in progress re-organizes system resources, accelerates emergy transformations and develops new processes and storages that would not exist without learned and shared cultural information. Through education and roles in social hierarchies, human beings can utilize a wide range of resident solar emergy sources from their local environment as well as outside resources obtained through exchange with other social groups and nations. Another thesis investigated here is that human



society, as information processors, is at the top of the hierarchy of the ecological life support system. Hence, the energy of a system such as Papua New Guinea converges in support of the culture.

Human information was considered here to have evolved and been stored in two forms: 1) shared, cultural information and 2) genetic information. These information fluxes are shown in Figure F-1, supported by the landscape. Shown is genetic inheritance, the shared information of culture through customs and objects, and the important interchange of information with the ecosystem. Exchange of goods and services with outside systems is also represented. This includes immigration and emigration of people.

In this preliminary study, we investigated the solar energy supporting: 1) cultural and 2) genetic information of PNG nationals. For each of these information forms, 2 categories of solar energy were investigated: 1) the energy necessary to maintain the information and 2) the energy required to generate the information in the first place. The solar energy supporting annual information fluxes and long term steady state storages was considered to be the annual renewable resource base [R] for Papua New Guinea of  $1050E+20$  sej/yr (Table A-2), assuming this representative of past years. Data on daily human metabolism, life expectancies, reproductive age of females, generation turnover time, and village hours spent on cultural and social activities were derived from the literature. From this information perspectives on energy support for information creation and maintenance of indigenous people of Papua New Guinea are drawn for overview.

## RESULTS

A number of solar transformities are given in Table F-1 in order to draw comparisons between genetic and learned information fluxes and storages. A typical diet supporting villagers in a study by Salisbury (1969) was 2900 kcal/person/day, with just over 35% of a typical day spent on activities of social interaction and learning (Salisbury 1962, Grossman 1984). Annual genetic information flux was estimated using a generation time of 33 years [49 year average life expectancy (Gabel et al 1987) - 16 year average reproductive age] and an estimate for the energy content of DNA (footnote 7). Relating

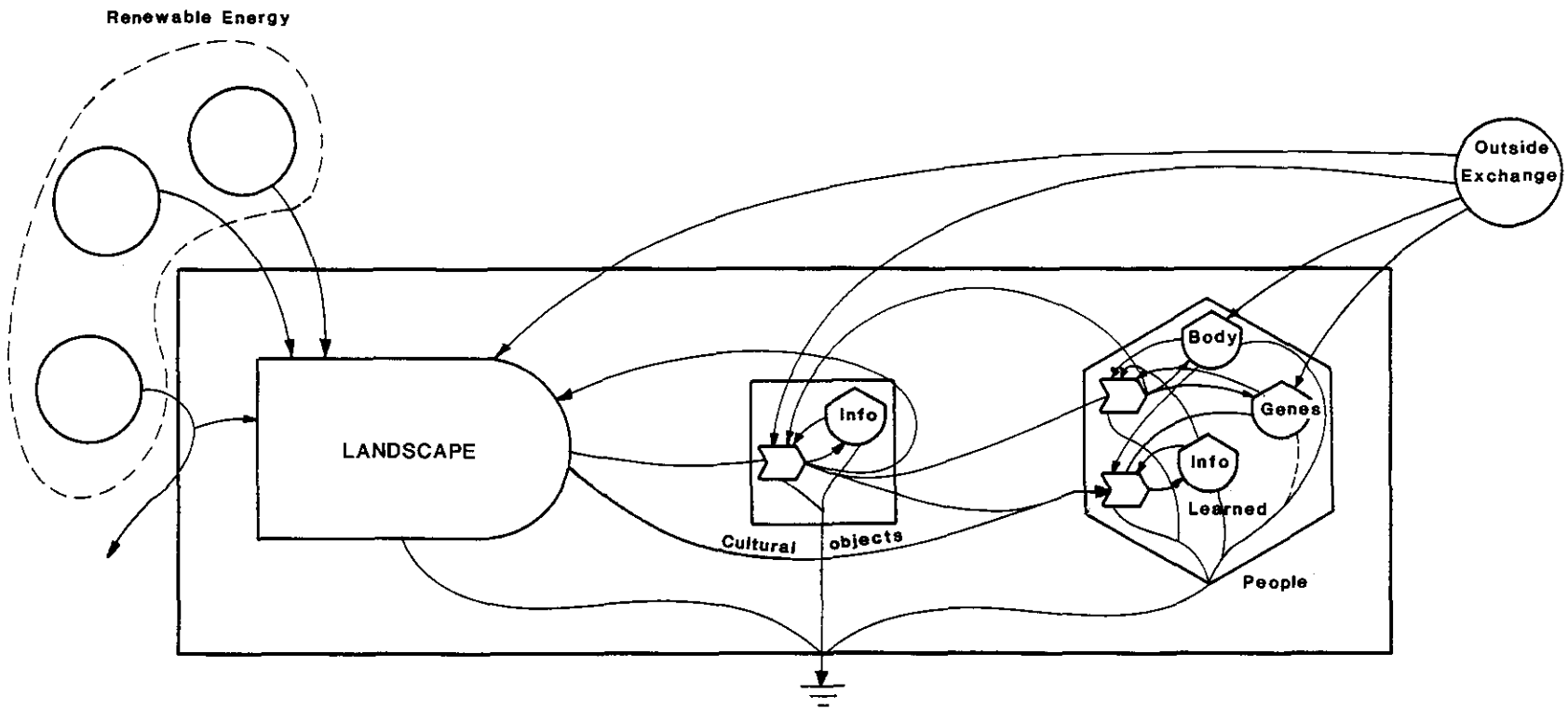


Figure F-1. Systems diagram showing the resource basis of cultural and genetic information, and their role in the organization of the combined system of humanity and nature. (Inf = information).

Table F-1. Estimate of solar energy basis of indigenous culture in Papua New Guinea based on resident renewable inputs from ecological support base.

Annual Flux:	Solar energy flux (sej/yr)	Energy flux (J/yr)	Solar transformity (sej/J)
1 Renewable sources	1050 E+20		
2 Human metabolism	1050 E+20	1.6 E+16	6.7 E+6
3 Information flux	1050 E+20	5.7 E+15	1.8 E+6
4 Genetic flux	1050 E+20	6.3 E+10	1.7 E+12
Steady state storage:	(sej)	(J)	(sej / J)
5 Human population (3.5 million people)	3.5 E+24	1.0 E+15	3.5 E+9
6 Cultural information	3.5 E+25	1.0 E+14	3.5 E+11
7 Human DNA (genetic information)	3.2 E+26	2.1 E+12	1.5 E+14

Footnotes to Table F-1.

- 1) Annual renewable resource base (R) for Papua New Guinea (from tables A-1 and A-2).
- 2) Annual metabolism of human population: Average daily caloric intake per person = 2927 kcal/day (Table E-3); (3.5 E+6 people) (2927 kcal/person/day) (4186 J/kcal) (365 days/yr) = 1.57 E+16 J/yr
- 3) Annual information flux for village population: 61.3 hours/week spent on activities of social interaction and learned information (Salisbury 1962, Grossman 1984); 61.3 hrs/168 hrs/week = 36.5% of metabolism allocated for shared information; (37%)(1.57 E+16 J/yr) = 5.73 E+15 J/yr
- 4) Annual genetic information flow: 49 year life expectancy (Gabel et al 1987); average reproductive age = 16 years; generation time of village population estimated as 49 yrs - 16 years = 33 years; turnover time = 1/33 yrs = 0.03; (0.03) (2.1 E+12 J/DNA, see item 7 below) = 6.3 E+10 J/yr
- 5) Energy storage in village population: (3.5 E+6 people) (150 lbs, average weight) (20% dry matter) (454 g/lb) (5 kcal/g) (4186 J/kcal) = 9.98 E+14 J;  
Solar energy storage estimated as total resident, renewable resource base (R) over generation time of population (33 yrs, see item 4 above); (1050 E+20 sej/yr) (33 yrs) = 3.47 E+24 solar emjoules
- 6) Storage of learned, shared information (i.e. culture) based on estimate of 10 generations with social information exchange with information carriers assumed to store information as 10% of biomass (J) in item 5; (1050 E+20 sej/yr) (10 generations) (33 yrs/generation) = 3.47 E+25 sej
- 7) Storage of human DNA (information carrier): (2.1 mg DNA/g dry) (9.98 E+14 J energy storage in population, item 5 above) (0.001 g/mg) (5 kcal/g) = 2.1 E+12 J human DNA in population;  
Genetic differences from precursor stocks generated in 100,000 years (estimate): (1050 E+20 sej/yr) (3 generations/100 yrs) (100,000 years) = 3.15 E+26 sej

this information to its annual solar energy support (R), solar transformities were calculated for annual information fluxes (items 2, 3, and 4). Notice that solar energy supporting one unit of genetic energy flux is on the order of one million times greater than the solar energy supporting cultural information flows (approximately  $2E+12$  sej/J compared with  $2E+6$  sej/J).

The solar energy supporting a population is less per unit energy (i.e. the smaller transformities) than that of the information stored in the minds and genetic material of the population. Further, the solar energy of steady state, information storages are much higher than annual fluxes representing a history of resources that both directly and indirectly support the origination of information (Table F-1, items 5, 6, and 7). With an approximation for turnover of social information of 10 generations, a solar transformity for shared cultural information was calculated at  $3.5E+11$  sej/J (item 6). By comparison, a transformity for genetic information stored as human DNA was estimated at  $1.5E+14$  sej/J (item 7; using a gross approximation for genetic differences in precursor stocks of 100,000 years).

Two trends are evidenced from these overview calculations. First, the solar energy of learned information of culture is much less than that in the genetic information of human species, since learned information is readily changed to make people more adapted to their environment. Second, once information has been either coded (genetic) or shared (cultural), the solar energy required to transfer or share that information is much less than codifying or learning the information in the first place. This observation supports the common postulate that high quality information such as electronic bits uses less energy per unit processed, although as demonstrated here, the solar energy is greater.

In order to relate cultural and genetic information with national energy contributions, macro-economic values were calculated for the energy supporting PNG nationals, their culture and their genetic stocks (Table F-2). It should be noted that these values are very preliminary and intended only to illustrate the importance of recognizing these information services and maintaining both cultural and genetic stocks.

Table F-2. Macro-economic value<sup>a)</sup> of shared and genetic information of Papua New Guinea culture.

item	Solar energy (sej)	Macro-economic value (US\$)
1 Support base for one human	1.0 E+18	0.5 E+6
2 Support base of indigenous population	1.05 E+23	52.5 E+9
3 Support base for shared, cultural information	3.5 E+25	17 E+12
4 Support base for genetic information	3.2 E+26	158 E+12

a) Macro-economic value estimated by dividing solar energy base by the energy to dollar index for U.S.A. in 1990 (2 E+12 sej / US \$; Odum 1991).

Footnotes to Table F-2.

- 1) Considered single copy of genetic information, with 33 year generation; solar energy stored in population (item 5, Table F-1) divided by population;  $(3.5 \text{ E}+24 \text{ sej}) / (3.5 \text{ E}+6 \text{ people}) = 9.9 \text{ E}+17 \text{ sej}$
- 2) Renewable solar energy (table A-1) supporting 3.5 million indigenous people.
- 3) item 6, table F-1; based on estimated of 10 generation culture.
- 4) item 7, table F-1; estimate based on 100,000 years to generate precursor genetic stocks; 3 generations/100 yrs; renewable solar energy supporting populations.

The gross national product in 1987 was 2.5 billion US\$. By comparison, the solar emergy support base for the country's population of three and a half million people was estimated at over 50 billion US\$ (item 2). The macro-economic value of culture was estimated to be 7000 times greater than the national product (item 3) while the support base for genetic information in the people of PNG when expressed as macro-economic dollars was almost 70,000 times greater (item 4). These calculations illustrate the real value inherent in indigenous peoples and their diverse cultures.

Activities which threaten the quality of life and resource support base of PNG nationals threaten these information stocks as well. Further, these high quality forms of information control large areas of resource development and exchange with only small amounts of energy relative to the investments of solar emergy in their origination over previous generations. Thus educational roles and information sharing influences larger areas with less energy. Similarly, genetic stocks transfer from one generation to the next with relatively small amounts of solar emergy, even though their territories of control are large. As evidenced by solar transformities calculated here, copies of genetic material or shared cultural information are thousands of orders of magnitude less to undertake than developing that same information from scratch. By understanding the hierarchical position of shared and stored information in a system, and by recognizing the diverse roles, the influence, and the flexibility of this information, we can now begin to address policy choices that affect the resource base of people and thus their lifestyles, which together maintain high quality services at relatively low amounts of solar emergy.



# SUMMARY AND DISCUSSION

by M.T. Brown and S.J. Doherty

In this section, a summary of the results from this study is given. First, the concept of wealth is again visited from a solar energy perspective. Then national trends are reviewed and Papua New Guinea's solar energy basis is compared with other nations for overview. Issues of international trade and balance of payments are addressed relating indices of solar energy-use to traditional economic indicators. Resource policy perspectives are given for indigenous production systems of agriculture and forestry. Tourism and human resources are then reconsidered based on sustainable development and an understanding of ecological support.

## THE BASIS FOR WEALTH IN ECOLOGIC-ECONOMIC SYSTEMS

The wealth of nations is not the amount of money that is held or controlled, but the basic resources that are available to drive machinery and transportation, to supply the raw materials for agricultural and industrial production, and to support the quality of life of its people. The wealth of a region includes its storage of mineral and metal ores, fossil carbons, soils and forests, the productive processes of its ecosystems, and its climate that includes renewable sources of sun and rainfall. In the case of Papua New Guinea, it also stems from tidal action, waves and ocean currents driving bay, estuarine and coral reef ecosystems and related fisheries. An economy is not a circulation of currency, but the circulation and *use* of resources. Currency circulation is a measure of an economy, much like degrees of temperature are a measure of the potential energy in a heat source. The *potential energy* in resources that drive an economy is the actual basis for its production, and the circulation of currency is but one measure of this driving force.

An economy is the sum total of productive processes that make available goods and services. The processes are extraction, collection, concentration, transformation and exchange. In each of these processes, some resources are used up and others are transformed or upgraded. The circulation of currency is one measure of



the work or productivity of an economy. When the performance of a national economy is expressed using currency circulation, the measure is the relative dollar value of all exchanges of resources, goods and services. Called the Gross National Product (GNP), it measures the currency circulation within, and into and out of a national economy. When corrected for inflation and differing exchange ratios between currencies, yearly changes in GNP and the differences between nations can be compared. The changes and differences are enlightening, but do not reflect in any real sense the actual productivity that occurs.

Increasingly, over the last several decades, an economy's production has been made synonymous with its GNP. A large circulation of currency meant the economy was productive. With this over-emphasis on the circulation of currency as a measure of economic performance has come an increased use of money as the means of determining value and wealth. This may seem appropriate, on the surface, since money can be converted to resources in almost any marketplace throughout the world. Yet, inherent in the use of money to establish value and measure wealth is a serious omission. Money cannot be used to measure the value of things for which there is no market. In other words, *price* cannot measure the value of resources relative to their contribution to productive processes outside the monied economy.

Traditional economic theory is based on the premises of scarcity and the belief that the wants of humans are virtually unlimited. From these two premises comes the concept of willingness-to-pay. Essentially, the value of a commodity, service, or resource is determined by its scarcity and how badly an individual wants it (often called supply and demand). Traditional economic value is determined by the user; what a consumer is willing to pay. In this context, economic value is equivalent to price. However, price says nothing about the contribution a commodity, service, or resource can make to an economy; it is only an account of scarcity and the amount of money an individual is willing to pay to obtain it. Its value to the productive processes of an economy is unchanged regardless of price. As an example, consider gasoline: While its price fluctuates based on supply and demand, the number of miles that can be driven using a gallon of gasoline remains unchanged. The actual work that can be accomplished with the gallon of gas is unchanged, yet with fluctuations in the "value of a dollar", the amount of gasoline that can be purchased with a single dollar changes.

Further, the price of a commodity or resource is generally inverse to the material's potential to contribute to productive processes. Consider a basic resource like water: When its abundant, it can support large amounts of agricultural production, yet its relatively inexpensive. When water is scarce, on the other hand, few crops

can be grown, there is little contributed to the regional economy, yet its price can be quite high. Economics--the science of scarcity--does not adequately measure real contributions. GNP, while accounting for capital stocks of human industries, says nothing about stocks of natural capital such as forests or the productive capacity of its land. Repetto (1989) points out that a country's natural resource base, upon which its economy is based, can be depleted to an unrecoverable extent, yet the country's leading economic indicators can still show productive growth and development. It is because of concerns such as these, that an alternative measure of real contributions is needed to better assess the wealth of combined ecologic-economic systems.

**EMERGY** evaluates the potential contribution of all resources to the economy, including those that are independent of market price. As a result, resources that are necessary inputs to an economy, but that do not carry a monetary price, can be evaluated and their contribution to productive processes of the combined and *interdependent* ecologic-economic system can be estimated. Using solar emergy, all resources as well as flows of renewable energy can be included and their relative contributions evaluated. In this way, public policy decisions regarding resource-use, protection, or conservation can be better facilitated, since a more comprehensive picture of their contribution to the economy emerges when evaluated using solar emergy.

The units of measure we used in this study, solar emjoules (sej), are unfamiliar to most people. This is a serious limitation and we recognize the difficulty this presents. In this discussion, we will try to present the results of our analysis in units of solar emergy as well as in macro-economic value, a public policy measure of relative contribution. Results will also be compared with other studies and with those of other countries in percentage terms and using the indices discussed in the methods section. This should help to overcome the inherent difficulties of using unfamiliar units of measure.

## **RESOURCE POLICY PERSPECTIVES FOR PAPUA NEW GUINEA**

### **Solar Emergy Basis for Nation**

Papua New Guinea is a country rich in resources; its ecologic and cultural diversities are recognized the world over. Yet traditional economic analyses indicate that Papua New Guinea has a small amount of money circulating in its economy and thus a relatively poor standard of living. This study, however, by synthesizing all contributing resources based on solar emergy, indicates a country with great quantities of largely

renewable resources supporting diverse ecosystems, its people and its economy. The following table summarizes some of the most important features of Papua New Guinea's combined ecologic-economic system:

Table 4-1. Summary of solar emergy flows and indices of Papua New Guinea in 1987.

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Renewable solar emergy-use	1050	E+20 sej/yr
Non-renewable solar emergy-use	190	E+20 sej/yr
Total solar emergy-use	1216	E+20 sej/yr
Exported solar emergy	405	E+20 sej/yr
Imported solar emergy	54	E+20 sej/yr
Solar emergy/money	48	E+12 sej/US\$
Solar emergy/person	35	E+15 sej/person
Dollars received from exports	1033	E+6 \$/yr
Dollars paid for imports	963	E+6 \$/yr

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Papua New Guinea has a low economic to environment ratio of 14% indicating the important role of ecological support systems to the nation's vitality. In fact, over 85% of all solar emergy used each year is supplied through locally renewable sources without direct payment from the economy. As illustrated by the investment ratio, less than 5% of the resources used within the country are purchased from foreign markets. This can be considered an index of the degree of industrial development. Used as a measure of self-sufficiency, Papua New Guinea correspondingly receives more than 95% of its total resource base from largely renewable resources within its border (mining of metal ores and fossil carbons contribute 10%).

A subsystems analysis of Papua New Guinea's highlands and lowlands indicates that the majority of the country's renewable inputs are a result of trade winds condensing moisture over the forested central cordillera. These tropical, premontane, montane and alpine rainforest systems act as headwaters for large watersheds converging in lowlands and supporting coastal communities, port cities and the island's fisheries. Lowland

and lower montane rainforests represent the largest storage of solar energy among the country's reserves (84%), reflecting past contributions of environmental transformations. The country's reserves of fossil carbons as well as the fledgling industry of hydro-electric power generation may fill much of the country's fuel needs if those resources are developed within the country for internal consumption.

Since the net yield of fossil fuels currently remains high compared with other primary sources available in the world markets (Odum 1991), Papua New Guinea will benefit in an energy exchange for oil with other trading nations. Continued exploration, extraction and refinement efforts for the country's fossil carbon reserves should be directed, as much as possible, to home-use. As the net yields of fossil fuel derivatives decrease with increasing expenditures required for extraction and refinement, alternative fuels and practices will become more competitive. It may be prudent then, for Papua New Guinea to use that primary source to develop lower energy, sustainable technologies and avenues for commerce which will not find themselves dependent on those fuels should they become limiting in the future.

In the probable event that a lower energy world is forthcoming as declining reserves of fossil fuels are used up world wide, Papua New Guinea will find itself in a secure position to face that future because of its large ecological support base. Papua New Guinea is unique among other nations in that it still has a largely renewable, self-supporting resource base with which it can draw upon for sustainable development of a steady-state economy.

### **Comparisons with Other Countries**

Indices of solar energy-use, origin and exchange for Papua New Guinea are compared with results of studies of other countries in order to draw general conclusions and identify trends using relative numbers for easier understanding. Papua New Guinea has the lowest ratio of imports to exports, when accounted for in solar energy, of any country of the world thus far studied (Table 4-2). Comparing countries' economically derived resources with environmental sources, Papua New Guinea is currently among the most self-sufficient nations of the world. It is characteristic of rural, developing nations to derive most of their support base from local, largely renewable sources. Industrialized nations, those tied to external markets and with infrastructure in place to utilize refined fuels, generally show the opposite trend. Compare for example, PNG with the USA (0.14 compared with 7.1, respectively, Table 4-3).

Given in Figure 4-1 are conceptual diagrams of PNG and the USA showing their relationships of ecological support and exchanges with the world economy. Here, solar energy values are normalized so that imports, exports and nonrenewable reserves are expressed relative to renewable sources, set at "100" for each country. Differences between the 2 countries stand out. The United States imports 3 times more solar energy than Papua New Guinea, each relative to its ecological contributions. It also exports more resources relative to its ecological inputs than PNG. The US economy is more tied to external markets and more dependent upon stored reserves than Papua New Guinea.

Yet a measure of surplus energy available for growth and progress shows similar values. Papua New Guinea has a *net per capita surplus* of  $25 \times 10^{15}$  sej/person/yr, while the United States is of similar magnitude ( $28 \times 10^{15}$  sej/person/yr). The difference lies in the origins of the inputs and their magnitude relative to exports. Here we see that while the USA operates at a net trade benefit of over 400 billion macro-economic dollars per annum, Papua New Guinea has a trade deficit of almost \$1 billion/yr ( $0.73\text{E}+9$  \$US, 1987). Our studies indicate that countries with positive trade imbalances (generally industrialized) derive their surpluses from countries operating trade deficits (generally developing countries). An intuitive conclusion, the consequences of which are discussed in the following section.

Papua New Guinea currently has a low population density (8 people/km<sup>2</sup>) compared with other nations (Table 4-4). And although the country's annual energy-use is relatively low compared with other larger, more industrialized countries, on a per capita basis it has among the highest energy-use of any nation (Table 4-5). While many of the nations with high per capita resource consumption rates are industrialized and dependent upon foreign markets and nonrenewable fuels, PNG is exceptional in that it derives the vast majority of its solar energy from home sources.

Finally, relating annual solar energy-use with gross national product (sej/\$), Papua New Guinea is shown to have a high index of solar energy to money (Table 4-6). Again, rural countries tend to have more resources supporting each unit of currency than developed countries which have comparatively small amounts of real resources contributing to relatively large circulations of currency (i.e., GNP). Papua New Guinea has as much as 20 times the resources per GNP as some industrialized nations. This is due to a largely rural population which derives its basic resources from the surrounding ecological support base. Much of the

Table 4-2. Solar emergy self-sufficiency and trade balance for Papua New Guinea and other countries of the world for overview.

Nation	% solar emergy from within <sup>1)</sup>	<u>solar emergy imported</u> <sup>2)</sup> solar emergy exported
Netherlands	23	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
Taiwan	28	1.19
Brazil	91	0.98
Dominica	69	0.84
New Zealand	60	0.76
Thailand	70	0.54
Australia	92	0.39
Soviet Union	97	0.23
Ecuador	94	0.20
Liberia	92	0.15
<b>Papua New Guinea</b>	<b>96</b>	<b>0.13</b>

Solar emergy valuations for countries compared in Tables 4-1 - 4-5 are based on revised national analyses from Odum et al (1983) except Thailand (McClanahan et al 1990), Taiwan (Huang and Odum 1991), Ecuador (Odum and Arding 1991) and Sweden (Doherty et al 1991). Values for Papua New Guinea based on national analysis documented in Section 3-A of this study.

1)  $(N_1+R) / U$ ; item 14, Table A-3.

2)  $(F+G+P_2I) / (N_2+B+P_1E)$ ; item 10, Table A-3.

Table 4-3. Environmental and economic components of annual solar emergy-use for Papua New Guinea and other countries of the world for overview.

Nation	Environmental component <sup>1)</sup> (renewable solar emergy) (x 10 <sup>20</sup> sej/yr)	Economic component of solar emergy <sup>2)</sup> (x 10 <sup>20</sup> sej/yr)	Economic/ environment ratio
West Germany	193	17300	9.0
Switzerland	87	646	7.4
U.S.A.	8240	58160	7.1
Spain	255	1835	7.2
Sweden	630	1923	3.1
Dominica	2	5	2.7
Australia	4590	3960	1.1
Thailand	779	811	1.1
India	3340	3410	1.0
Soviet Union	9110	9110	1.0
World <sup>3)</sup>	94400	90000	0.96
New Zealand	438	353	0.8
Brazil	10100	7600	0.7
<b>Papua New Guinea</b>	<b>1050</b>	<b>166</b>	<b>0.14</b>
Ecuador	891	483	0.1
Liberia	427	38	0.1

1) R = independent, renewable environmental sources; Table A-2.

2) Total solar emergy-use minus renewable environmental contribution = U - R, item 6, Table A-3.

3) Annual global solar emergy flux divided by annual world fossil fuel consumption (updated from Odum and Odum 1983).

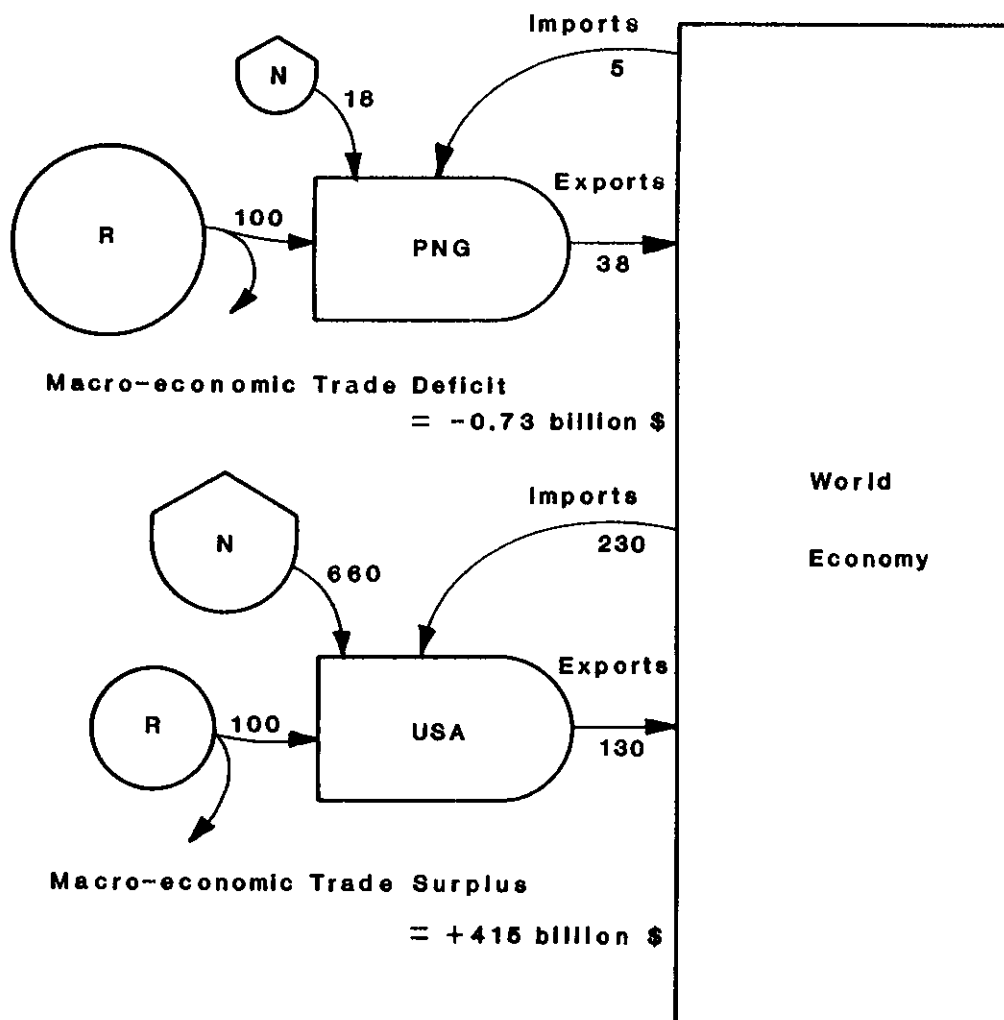


Figure 4-1. Summary diagrams of ecological contributions (R, N), imports and export exchanges with the world economy for Papua New Guinea and the United States. Annual emergy flows are normalized, calculated relative to renewable sources (set at 100).

Footnotes to Figure 4-1.

Papua New Guinea data from this study (Table A-3); USA data from Odum et al 1987.

Net per capita surplus emergy = Annual emergy contributions [U; R+N+(F+G+P<sub>2</sub>J)] - exports (N<sub>2</sub>+B+P<sub>1</sub>E) / population:

$$\text{PNG} = ([1050+190+54-406]E+20 \text{ sej/yr}) / (3.5E+6 \text{ people}) = 25E+15 \text{ sej/person}$$

$$\text{USA} = ([82+543+190-107]E+20 \text{ sej/yr}) / (227E+6 \text{ people}) = 28E+15 \text{ sej/person}$$

Trade benefit (or deficit) = (Imports - Exports) / (sej/\$) = (macro-economic value):

$$\text{PNG} = ([54-406]E+20 \text{ sej/yr}) / (48E+12 \text{ sej/$}) = -0.73E+9 \$$$

$$\text{USA} = 9[190-107]E+20 \text{ sej/yr}) / (2E+12 \text{ sej/yr}) = +415E+9 \$$$



activities which generate revenue, which yield products for export, are supported by the country's natural resource base, outside of market valuation. While a high solar energy to dollar index is one measure of wealth, buying power actually rests with those economies with low sej/\$ indices. This is because countries with large GNPs generally invest less actual resources per unit currency yet can turn around and purchase commodities from exporting countries which invest more total resources in their services and commodities made available for purchase. These concepts are explored further in the following section.

### **International Trade and Balance of Payments**

Papua New Guinea currently has a 7:1 ratio of exports to imports [see Table A-3(11)]. This indicates that although there exists a balance of trade in monetary terms for imports and exports (Table 4-1), more than seven times as much solar energy leaves PNG as is purchased. This represents an imbalance between the products sold and the buying power of the money received. By exporting raw materials such as copper ores, unrefined fossil carbons or unprocessed rainforest logs, a trade deficit is realized. Because of the great amount of environmental resources supporting the country's currency, Papua New Guinea gives to its buyers on the international market more than it can purchase with the revenues received from exports.

A couple of examples help to demonstrate this issue. In 1988 while 1.033 billion dollars were paid for exported goods and services,  $405E+20$  sej were exported. By dividing the revenues received by the solar energy obtained by foreign markets, an index of solar energy received per dollar spent of  $39E+12$  sej/\$ is obtained. In contrast, Papua New Guinea paid  $0.963E+9$  US\$ for  $54E+20$  sej of imported fuels, goods and services; a index  $5.6E+9$  sej/\$. The difference is striking. Papua New Guinea operates under a net trade deficit, supplying purchasing nations with basic resources at a low costs, subsidized by its ecological support systems and geologic reserves. In 1988, PNG had a net solar energy deficit due to trade of  $350E+20$  sej [Table A-3(12)]. This is represents 0.73 billion dollars in macro-economic value lost due to trade practices-- 29% of the gross national product.

To illustrate this concept in another way, the solar energy exported can be related to the amount of solar energy that Papua New Guinea can purchase in return for the revenues received. The billion dollars received in revenues for the country's exports is used to to purchase necessary fuels, goods and services not currently

Table 4-4. Population density and solar emergy-use per unit area for Papua New Guinea and other countries of the world for overview.

Nation	Area (x 10 <sup>10</sup> m <sup>2</sup> )	Population density <sup>1)</sup> people/km <sup>2</sup>	Solar empower density <sup>2)</sup> (x 10 <sup>11</sup> sej/m <sup>2</sup> /yr)
Netherlands	3.7	378	100.0
Taiwan	3.6	494	94.6
West Germany	24.9	247	70.4
Sweden	41.1	20.7	62.1
Switzerland	4.1	154	17.7
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
<b>Papua New Guinea</b>	<b>46.2</b>	<b>7.6</b>	<b>2.63</b>
Thailand	74.0	67.6	2.15
Brazil	918	13.2	2.08
India	329	192	2.05
Soviet Union	2240	11.6	1.71
Australia	768	1.9	1.42

1) Population divided by national area.

2) Rate of solar emergy-use, U (item 5, Table A-3) divided by national area.

Table 4-5. Solar emergy-use, population and per capita solar emergy-use for Papua New Guinea and other countries of the world for overview.

Nation	Solar emergy used <sup>1)</sup> (x 10 <sup>20</sup> sej/yr)	Population x 10 <sup>6</sup>	Solar emergy-use per person <sup>2)</sup> (x 10 <sup>15</sup> sej/person/yr)
Australia	8850	15	59
<b>Papua New Guinea</b>	<b>1216</b>	<b>3.5</b>	<b>35</b>
Sweden	2552	8.5	30
U.S.A.	66400	227	29
West Germany	17500	62	28
Netherlands	3702	14	26
New Zealand	791	3.1	26
Liberia	465	1.3	26
Soviet Union	43150	260	16
Brazil	17820	121	15
Dominica	7	0.08	13
Switzerland	733	6.37	12
Ecuador	964	9.6	10
Taiwan	1340	17.8	8
Spain	2090	134	6
Thailand	1590	50.0	3.2
India	6750	630	1

1)  $U = N_1 + R + F + G + P_2 I$ ; item 5, Table A-3.

2) Papua New Guinea's population (1987) = 3.5 million; item 16, Table A-3.

Table 4-6. Solar emergy-use, gross national products and solar emergy/dollar indices for Papua New Guinea and other countries of the world for overview.

Nation	Solar emergy used <sup>1)</sup> (x 10 <sup>20</sup> sej/yr)	GNP <sup>2)</sup> (x 10 <sup>9</sup> US\$/yr)	Solar emergy-use/dollar <sup>3)</sup> (x 10 <sup>12</sup> sej/US\$)
<b>Papua New Guinea</b>	<b>1216</b>	<b>2.6</b>	<b>48.0</b>
Liberia	465	1.34	34.5
Dominica	7	0.08	14.9
Brazil	17820	214.	8.4
India	6750	106.	6.4
Australia	8850	139.	6.4
Thailand	1509	43.1	3.7
Soviet Union	43150	1300.	3.4
New Zealand	791	26.	3.0
West Germany	17500	715.	2.5
U.S.A.	66400	2600.	2.0
Netherlands	3702	16.6	2.2
Taiwan	1861	99.3	1.9
Sweden	2553	155.	1.7
Spain	2090	139.	1.6
Switzerland	733	102.	0.7

1)  $U = N_1 + R + F + G + P_2 I$ ; item 5, Table A-3.

2) Gross national product for 1987; Table A-2.

3) Solar emergy supporting a unit of currency, expressed in international US\$, 1987; P<sub>1</sub>, Table A-2.

available within Papua New Guinea. Again a net trade deficit is realized because trading nations generally have lower sej/\$ indices. If the trade partner were the U.S.A. for example, with its  $2E+12$  sej/\$ (Odum 1987), it would receive 24 times as much solar emergy as Papua New Guinea could purchase with the earned revenues of its export sales. These issues of trade advantages are addressed with specific examples in Section D on tourism and later in this concluding section.

Currently, international free trade agreements such as GATT only acknowledge market values of trade commodities and services. As discussed previously, monetary prices are subject to fluctuations based on market temperment and do not account for the indirect but necessary contributions of ecological support systems. In light of this and the large trade imbalances documented in this analysis, an obvious conclusion for Papua New Guinea is to develop local industries to process indigenous resources before they are exported. In this way, net losses of solar emergy through trade are minimized while jobs and resources are kept at home. By processing and using indigenous resources at home, value is added each time high quality services or fuels transform the materials into upgraded products. This provides a greater contribution to the economy than the money received in sales. A traditional economic argument is that by keeping raw products at home instead of exporting them for income earnings, the local prices are forced down and the country will not receive a maximum economic return on its investment. Another way to look at this is that falling prices can attract internal investments--necessary income for building the industries and providing jobs to use the resources at home. Product transformations take place at home and employment is internalized. The local economy is benefited, rather than that of urban industrialized nations overseas.

Borrowing and debt servicing, as demonstrated from a systems perspective, is also detrimental to the economic health of rural countries. Papua New Guinea, for example, borrows international currency from developed nations at an average of  $2-4E+12$  sej/\$, yet pays back the principle and its interest with it's own currency at  $48E+12$  sej/\$. For every dollar PNG borrows, it pays back between 12-24 times that amount in real buying power. When an international dollar is converted to kina, it can purchase greater amounts of resources than it can at home. This is, at least in part, why industrialized economies invest in less developed countries; their investments derive greater net benefits as they receive basic resources at low costs which fuel their home industries and provide jobs and resources with high net yields.

## Regulation and Investment Considerations in Forestry Sector

It is encouraging to read the country's preamble and constitution which purports self-sufficiency and recognizes the costs of foreign owned and operated industries. Major timber projects, along with mineral and hydrocarbon exploration, offshore fishing and agriculture are listed as priority activities, in which the government of Papua New Guinea is actively seeking new foreign investment (Baldwin et al 1977). The National Investment and Development Authority, however, has recognized the losses associated with over participation by foreign companies and the direct export of the raw timber products as indicated in the following passage:

"The utilization of our forest resources must be carefully planned. We will not allow systematic logging or clear felling of our forest areas purely for the export of the unprocessed wood. The export of logs as a revenue earner is no longer appropriate and will be eliminated. Existing operations will be encouraged to increase the degree of processing and vertical integration within Papua New Guinea. In any forestry development, reforestation must be undertaken as a means of renewing the resource and sustaining the industry" (Baldwin et al. 1977).

Yet because of national pressure for economic development, decisions were made to proceed with offering timber concessions for development of a major export industry (FAO 1976, Davidson 1983). Although further research and baseline data collection was commissioned and is continuing (Davidson 1983), there has been little effort to refine and analyze the data for use in a comprehensive forestry development policy (Seddon 1984).

Reforestation efforts to date have been minimal. Presently, only about 12% of the cleared areas of the major forestry projects have been developed for reforestation (Seddon 1984) and agricultural development on these areas is met with only limited success. Qureshi et al (1988) report that log exports are a major export item and continued growth in export volumes is expected over the medium term. They further suggest that a resource management strategy is urgently needed so that these resources can be developed on a sustainable basis.

A Tropical Forestry Action Plan for Papua New Guinea (see World Bank 1990) has been issued which outlines a course of action the government should take to promote sustainable development of its forest resources. The TFAP is not without its criticisms. The World Resources Institute reported that the TFAP in

general is not achieving many of the plan's original objectives (Winterbottom 1990). The Papua New Guinea Law Reform Commission published a critique stating that the TFAP is "flawed by its failure to confront the fundamental contradiction between a money-based profit-oriented economic system and its values on the one hand, and wider national, global, ecological, customary, political and social needs on the other" (Brunton 1990). The critique argues that the role of the forests must not rest solely in development for market exchange but also and perhaps more importantly their "use value" should be acknowledged, i.e., those ecosystem services without market value.

Our analyses of forest reserves demonstrate that the tropical forests of Papua New Guinea are its greatest assets. The subsystems analysis of forest operations in New Britain indicates that although the lowland forests deliver as much as 4 to 1 net returns on investments, because of their diversity and their great mix of unmarketable timber species, large-scale clearfell forest practices may not be sustainable nor competitive in the long-term. Presently "wokabot" sawmills are being distributed to communities through government loan programs. These are small-scale, transportable sawmills that can process about 0.5-1 km board feet of timber daily and cost 7-10,000 kina for the equipment and training. This technology is intended to bring a level of internal-use of forest resources and perhaps a level of self-sufficiency for villagers. It is recommended that appropriate technologies that support local peoples be given increased consideration in forest policy.

The rainforest-land rotation model suggests that better monitoring of baseline data is essential for proper management and sustainable use of these resources. Lowland and montane rainforest ecosystems in Papua New Guinea embody a great history of environmental work, transforming resident energy flows of sun and rain into vast stores of biomass in complex and functioning ecosystems. But because of the risk of land degradation due to high rains and increased runoff on mountainous terrain, if exploited these forests may prove to be non-substitutable ecosystems. Further, many of the services provided by these systems are in fact without market value. The indigenous people of Papua New Guinea have developed integrated yield systems with their environment throughout their history. Our analyses of forests and the ecological support basis of developments and indigenous culture have demonstrated real wealth contributed by these systems, values most of which are outside the market place.

## TOURISM, DEVELOPMENT, ENVIRONMENTAL IMPACT AND THE LOCAL ECONOMY

Tourist developments in undeveloped regions often compete with local populations for resources from land and marine systems, for potable water and for available land. Emergy evaluation of tourism in Papua New Guinea evaluated the intensity of a small scale tourist development, and then determined a carrying capacity or support region that is necessary to insure that development does not have negative environmental, economic, and cultural impacts. Determination of carrying capacity was based on the premise that for development to fit within a region its intensity should nearly match the intensity of development of the region on the average. The following table summarizes several important indices for a typical tourist development in Papua New Guinea.

Table 4-7. Summary of the solar emergy evaluation of tourism in New Britain, PNG.

	<u>Tourist Resort</u>	<u>PNG</u>
Renewable solar emergy (E+15 sej/yr)	8.11	---
Non-renewable solar emergy (E+15 sej/yr)	1.95	---
Percent renewable	0.1 %	86 %
Solar emergy density ( $10^{11}$ sej/m <sup>2</sup> /yr)	2742	2.6
Solar emergy per capita (sej/person/yr)	779	35
Ratio of solar emergy: exports/imports	16:1	7:1

Several interesting facts are apparent in the table: (1) the percent of supporting emergy in tourist resorts that is from renewable sources is very small (less than 0.1%), (2) the energy intensity of tourist resorts is nearly 1000 times the average intensity in PNG, and (3) the per capita energy-use by tourists is over 20 times that of the average PNG national. The ratio of emergy exports to imports shows a net export for both tourism and the national economy as a whole, although tourism appears to be as much as 3 times greater.



## **A Definition for Ecotourism**

The term 'ecotourism' has recently become much in vogue. While it means many things to many people, its basis lies in the desire of tourists and the world tourist industry to seek out an unspoiled environment to observe "nature". Most often this means observing wildlife of some form in its natural environment. Natural environments are decreasing as population increases and development spreads, so the few that remain are deserving of special attention to ensure that the very environment upon which the wildlife depends is not degraded by tourists who seek to enjoy it. To ensure that there is an unspoiled environment for future generations, ecotourism should strive to fit within a region's carrying capacity and achieve a sustainable level of development that does not draw more from the regional resource base than it can provide. The following are several general principles that we feel are important guidelines for an ecologically based tourism industry in undeveloped regions of the globe:

**Ecotourism should be environmentally benign.** Environmental pollution of any sort should be cause for disqualification. An ecotourism resort should fit within the local environment's ability to handle and process wastes. Use of resources should be minimized and waste byproducts like sewage and solid wastes should be recycled. Developments should be favored that, because of their size or for cultural reasons, (1) do not require imports of foods and materials, (2) do not overload the local environment's ability to provide these commodities, and (3) do not produce waste byproducts that overload the environment's ability to process them.

**Ecotourism should be sustainable.** All ecological systems have a sustainable yield that is a function of their productivity and the positive feedback actions of those harvesting the resources. For instance, forests have a sustainable yield that is based on the production of wood on the one hand, and management actions of foresters that increase production on the other. When the sustainable yield is exceeded, declines in both the quantity and quality of the harvest results. With continued overload, the environmental system can degenerate to such a point that no yield is possible. Local fisheries, ecological and agricultural systems, and the local pool of labor have a sustainable yield that, if not exceeded, can provide the resources necessary for a tourist development that is sustainable in the long run; however, if exceeded, it not only jeopardizes the development, but the local population as well.

**Ecotourism should be scaled to the local economy.** Large developments often exceed the local economy's ability to provide start-up capital and needed infrastructure. As a result, external financing is required. Tourist developments and needed infrastructure like airports, roads, and waste treatment plants that are externally financed often result in secondary environmental degradation as resources from other sectors of the environment are extracted and sold to earn the necessary currency to pay back principle and interest on tourism related infrastructure. On the other hand, small-scale, locally financed operations are more apt to fit within current infrastructure and not require external financing.

**Ecotourism development should not increase the rate of change in economic or cultural systems.** The rate at which development occurs often can exceed the ability of the local culture and economy to absorb it, and while its ultimate size may not be a problem, if developed too quickly it may cause disruption. The rate of change also applies to the ability of the local environment's sustainable rates of production of resources.



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