EMERGY ANALYSIS OF SHRIMP MARICULTURE IN ECUADOR

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Prepared for

Coastal Resources Center
University of Rhode Island
Narragansett, R.I.

March, 1991

Citation:

Odum, H.T., Arding, J. (1991). Emergy Analysis of Shrimp Mariculture in Ecuador. Narragansett, RI: Coastal Resources Center, University of Rhode Island.

Preface

In 1988, H.T. Odum delivered a series of lectures at the University of Rhode Island. They were stimulating, at times baffling. They suggested a set of concepts that might link in a single framework the principals of ecology and economics as they apply to the processes that govern how living systems function and change. Such insights are central to the work of an organization like the Coastal Resources Center that is dedicated to formulation and testing of management strategies for coastal environments. The need for better understanding the linkages between ecological and economic processes is particularly urgent in developing tropical countries where the rate of change brought to coastal environments by man is accelerating and the long-term implications of such change to both ecosystems and the human economies they support are too often considered in a cursory manner, if at all. The lectures and a review of some of H.T. Odum's writings convinced me that the Coastal Resources Center needed to know more. One way to learn more was to apply EMERGY analysis to a specific resource management problem for which we had data on hand and that posed significant policy issues.

The Coastal Resources Center, through a Cooperative Agreement with the U.S. Agency for International Development (USAID), had just completed a synthesis of the available information on shrimp mariculture in Ecuador. The industry has, in a mere fifteen years, become Ecuador's second largest earner of foreign exchange. It has also brought greater changes to the country's coastal ecosystem than any other human activity. The industry has, with minor exceptions, transformed every estuary by the construction of ponds in former salt flats and mangrove wetlands, channelizing water flow and in some cases significantly altering water quality. Through the capture of seed shrimp and egg-bearing females, the industry has increased the pressures on all estuarine fisheries. It has also brought employment, and, to some, great wealth. This discussion paper is the result of applying EMERGY analysis to these issues.

H.T. Odum contends that human free choices, given enough time and sometimes after social turmoil and much wasteful destruction of natural resources, will through trial and error find the means for maximizing public wealth (which includes symbiotic designs of the economy with environmental systems). EMERGY evaluation, he suggests, by providing a means for predicting what actions will maximize public wealth and produce sustainable economies, provides policy makers with a means for short-circuiting the process and avoiding an otherwise slow and wasteful evolutionary process. Odum argues that the market value of products and services is of obvious importance to individuals and businesses but is largely irrelevant as a measure of the "true wealth" of a society or a geographic area.

> "A tank of gasoline drives a car the same distance regardless of what people are willing to pay for it. A day of summer sunlight generates so much corn growth regardless of whether a human thinks it's free or not. A nugget of copper concentrated by geological work will make so much electric wire regardless of its price."

and

"When resources are abundant, wealth is great, standard of living is high, and money buys more. But when resources are abundant, market values and prices are small. Prices are not a measure of resource contribution to wealth."

and

"When resources are scarce, prices are high not only because shortages affect demand, but because more human services are required to mine, transport, or concentrate scarce resources. By the time the resources have been collected and used, the net contributions of the resource have been diminished by the extra efforts to process the resources."

and

"In other words, prices are not only not a measure of the contribution of resources and commodities to an economy, they are inverse, being lowest when contributions are greatest. EMERGY provides another measure for evaluating contributions to public wealth."

(Quotes from Part Two of this volume.)

EMERGY analysis does not propose to replace the free market as the system for setting prices for human transactions. The price of lipstick, an art work, a piece of real estate or a commodity on the future's market should continue to be set by what society is willing and able to pay and what those who produce it are willing and able to make it for.

EMERGY analysis is offered as a tool for those charged with setting policy and attempting to balance between short-term gains and long-term stability for a society. This is, after all, one of the primary roles of government. If EMERGY analysis is based on sound perceptions of how ecosystems--including their human component--function and respond, then it can provide powerful insights when considering such questions as:

How much is a natural resource worth?

How great is the contribution of the unpaid environment to a commodity?

What is the wealth generating potential of the natural resources of a region or a country?

What substitutions can be made to the process of generating a product without changing the productivity of a system?

How can taxes be used to effectively reinforce those levels and types of consumption that benefit society without threatening the productivity of the economy?

How can we estimate quality of life and wealth in a non-monetary economy?

Questions such as these have long been the purview of economists. EMERGY analysis applies the principals of system ecology to such questions and brings to bear observations on how ecosystems function, and why, in competitive settings, certain systems prevail.

The conclusions offered by this analysis of shrimp mariculture and the recommendations regarding public policy, and particularly the recommendations as they relate to international trade, will be highly controversial. H.T. Odum has been a difficult target for critics. His concepts have been evolving rapidly and he freely admits that language and techniques he put forward in the past were incomplete and have had to be improved. Yet there can be no doubt that his is a giant intellect. He has played a central role in developing the science of systems ecology, performed much of the pioneering work in the ecology of reefs, rain forests and other systems, and co-authored the classic textbook on ecology with his brother. His 1971 book *Environment, Power and Society* has had a major impact. In 1987 he received, with his brother, the Crafoord Prize, the equivalent in the biological sciences of the Nobel Prize. For the past ten years he has devoted himself almost entirely to developing, testing and refining EMERGY analysis. Few of his students have kept pace with the evolution of his ideas. Some of the controversy it has triggered is summarized in a section of Part Two of this volume.

This volume is being distributed as a Working Paper because the usual review process is much complicated by the unfamiliarity and potentially far-reaching implications of this analysis. The next objective is to use this document as the basis for a series of structured discussions that will bring together economists, ecologists and those concerned with the policy of development to discuss not only the potential usefulness of EMERGY analysis but the other analytical techniques available to address the questions raised by this case study. Such discussion should address directly the limitations of neoclassical economics that were so widely discussed at a 1990 workshop sponsored by the World Bank entitled "The Ecological Economics of Sustainability: Making Local and Short-Term Goals Consistent With Global and Long-Term Goals." As a participant at that workshop, it appears to me that a conclusion was that neoclassical economics does not and cannot be relied upon to reasonably set values for natural resources and ecosystem processes. The impression created at that workshop was that no alternative analytical system as yet exists. These discussions should explore whether EMERGY analysis helps fill the gap.

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EMERGY Analysis of Shrimp Mariculture in Ecuador

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This work has been funded in part by a Cooperative Agreement between the United States Agency for International Development, Office of Forestry, Environment, Natural Resources, Bureau for Science and Technology and the University of Rhode Island Coastal Resources Center.

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INTRODUCTION

Marine Shrimp ponds (Figure 1) are being constructed in many developing tropical countries selling shrimp on the international market to meet a large demand from the developed countries. In Ecuador this new mariculture system is based on getting the young shrimp from the natural system, which also supports an established trawl shrimp fishery. The shrimp example highlights recurring problems with environmental development, international aid, and investment. Is the new development sustainable? Is its development at the expense of other values? Does it help the home country; does it help the consuming country? Is it likely to be economic in the long run? Is it a good model for developing countries to emulate?

In this study the EMERGY method for evaluating environmental contributions was used to evaluate the systems of shrimp production of Ecuador (Figure 2) and their relationship to the national and international economies. EMERGY, spelled with an "M", is a scientific-based measure of wealth, which puts raw materials, commodities, goods, and services on a common basis, the energy of one type required to generate that item. EMERGY measures the real basis for economic vitality in the long run. Sources of more explanation of EMERGY concepts and application are given under separate cover: "Principles of EMERGY analysis for Public Policy".

Theory of Maximum EMERGY Designs

According to the theory, the pattern that maximizes EMERGY contributes more wealth. Designs that draw more resources overcome more limitations, and displace alternatives. In general, economically developed resources prevail over the undeveloped ones because the environmental EMERGY contributions are augmented by additional resource inputs paid for from investments and sales. Figure 3 shows the evaluation plan used in this study, comparing EMERGY of a new project with EMERGY before development, with EMERGY of alternative investment, and with maximum potential EMERGY for those resources. Selection of project plans for maximum EMERGY can generate wealth according to an area's potential.

Systems of Shrimp Production and Sale

Understanding shrimp ponds, their estuarine basis and their relationship to the international economy requires systems thinking and wealth evaluations at several levels of size: the pond system, the regional economy, the national economy, international exchange and the world economy. Ideally, a new development should contribute to the wealth of all these, without one at the expense of another. Maximizing one does not maximize the whole system's wealth and performance. Nor are such developments sustainable.

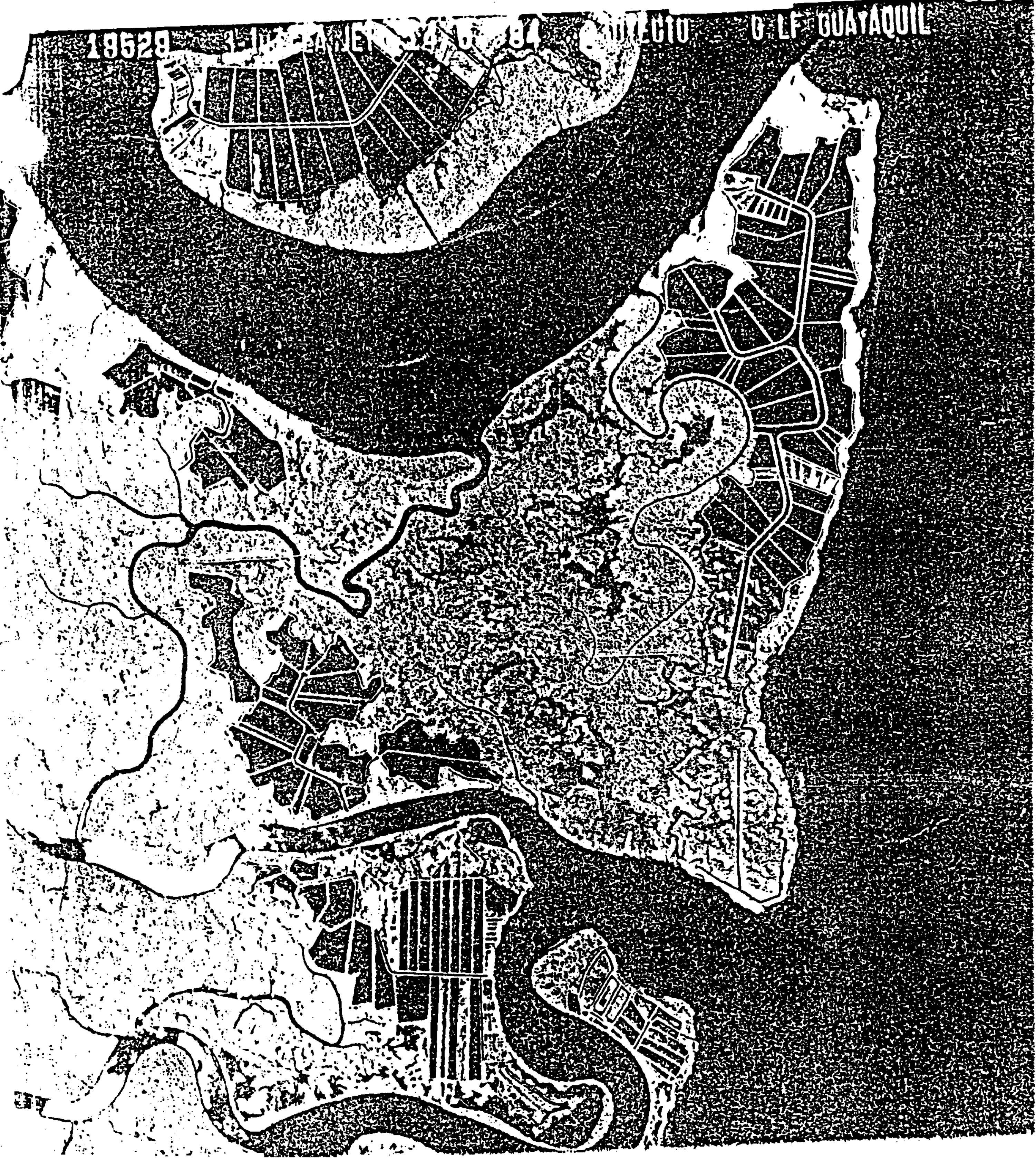


Figure 1. Aerial view of shrimp ponds in Ecuador.

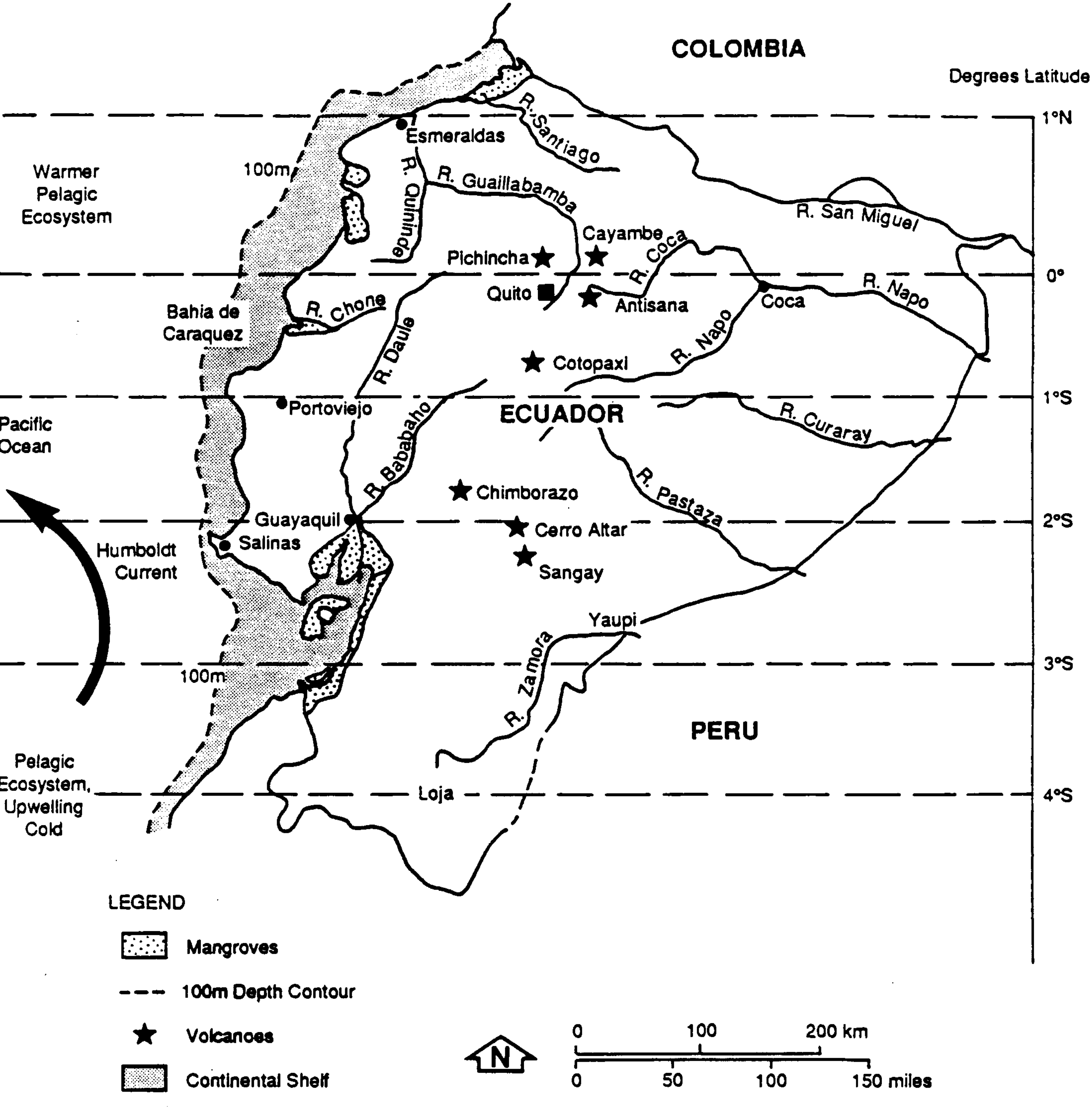


Figure 2. Map of Ecuador with Gulf of Guayaquil and offshore continental shelf that supports shrimp reproduction and larval growth.

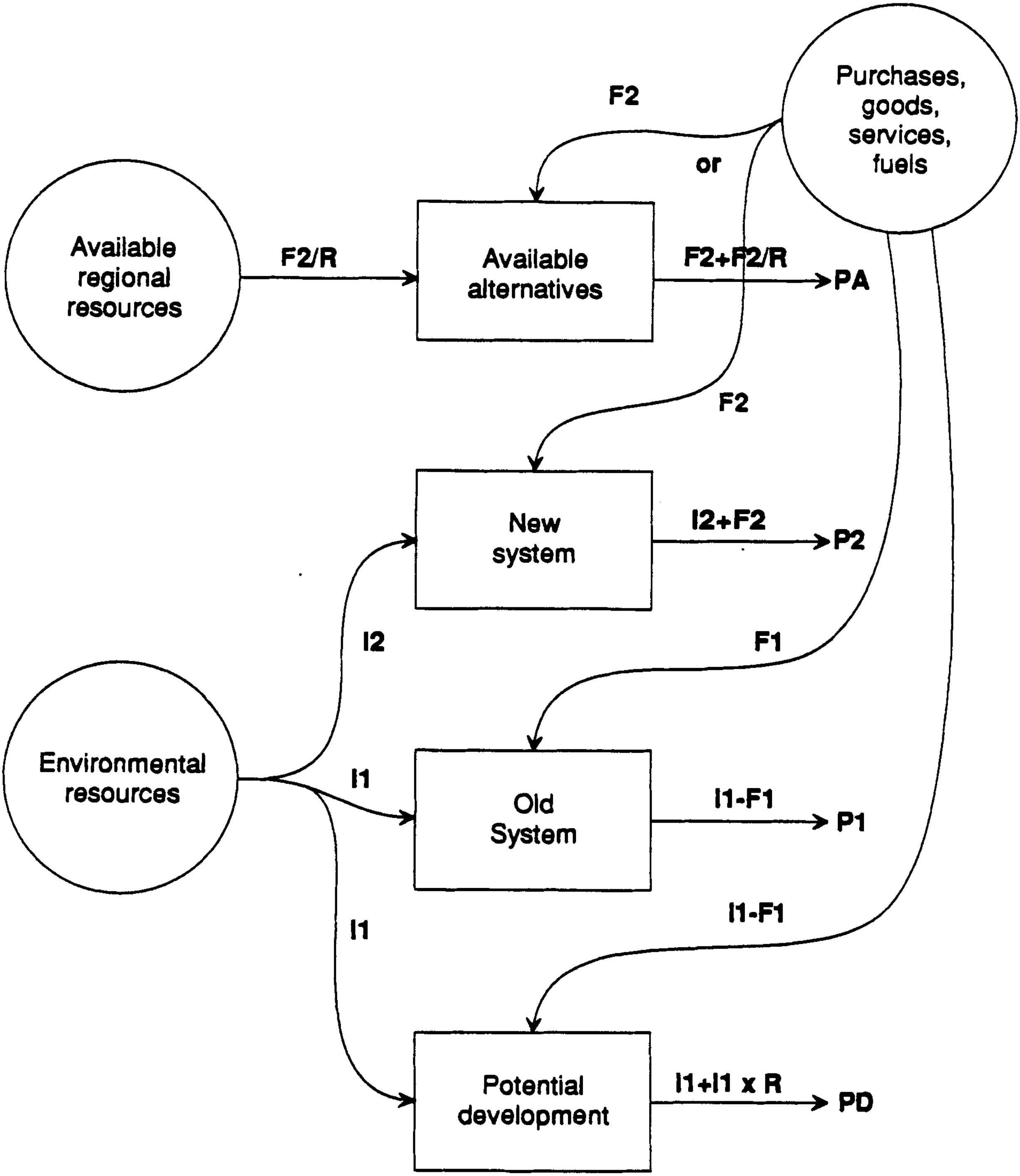


Figure 3. Diagram for comparing EMERGY benefit of a new environmental use (P2) with an old system (P1), with typical alternatives in the region (PA), and with maximum potential (PD) matching environmental EMERGY and economic inputs according to the regional investment ratio R.

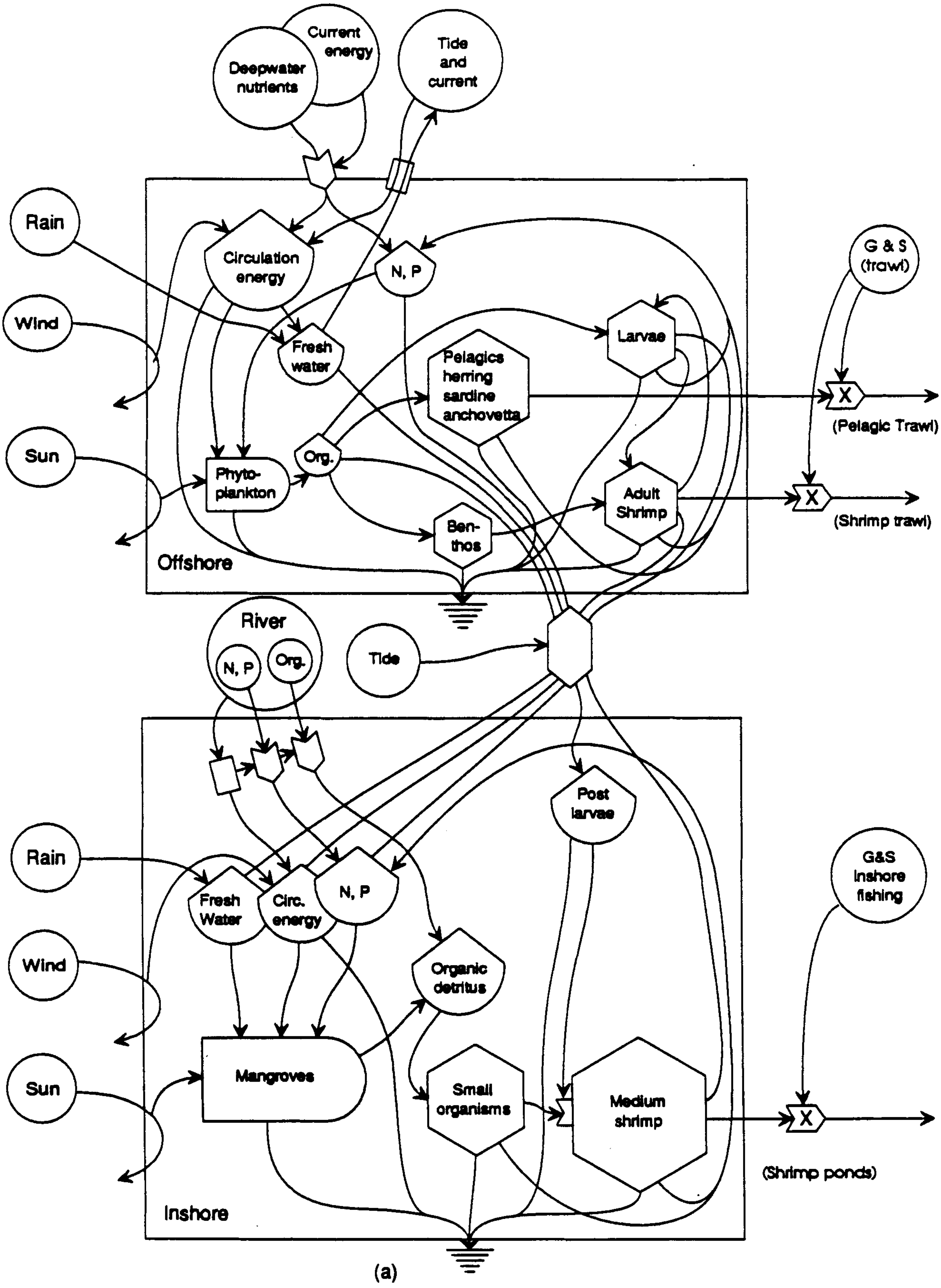
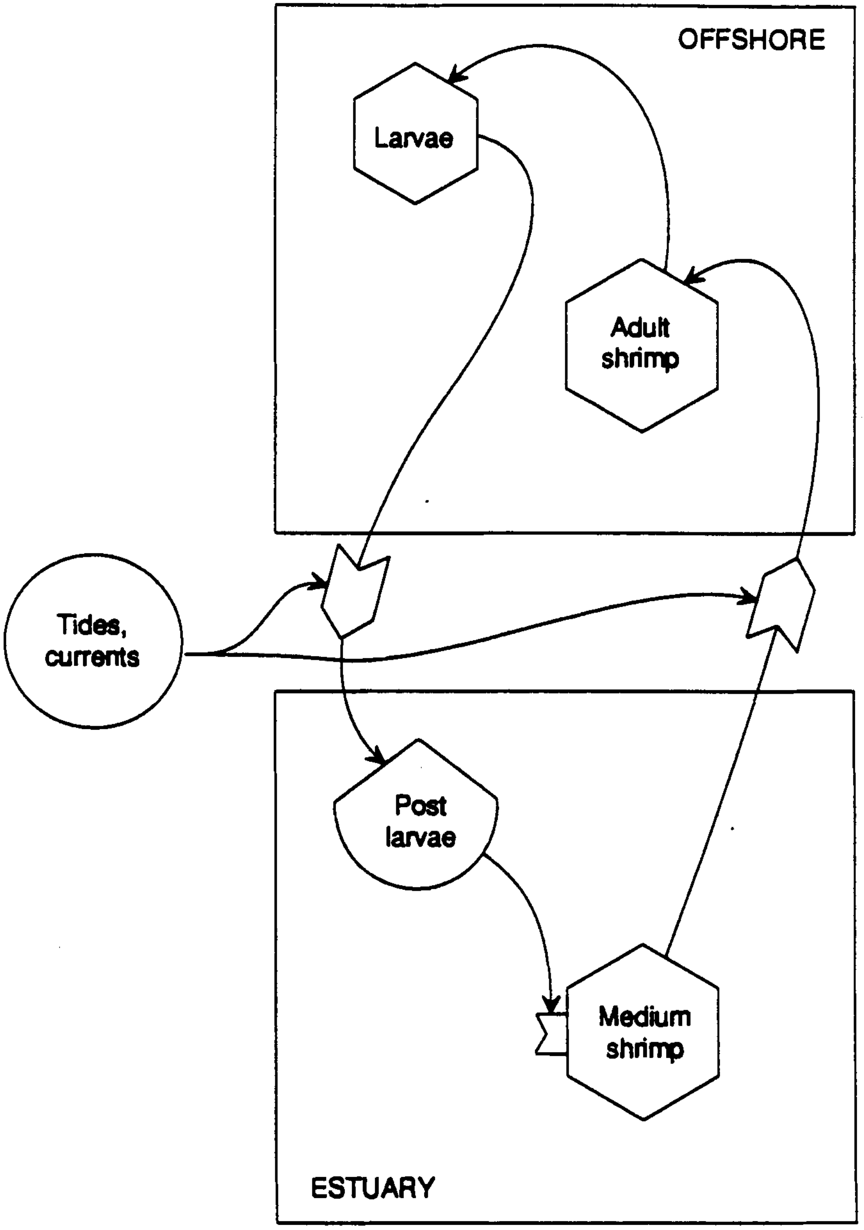


Figure 4. Energy systems diagram of the coastal system of Ecuador and the life cycle of shrimp between inshore mangroves (below) and offshore shelf ecosystems (above). (a) Whole systems; (b) life cycle of shrimp only.



(b)

Figure 4 (continued)

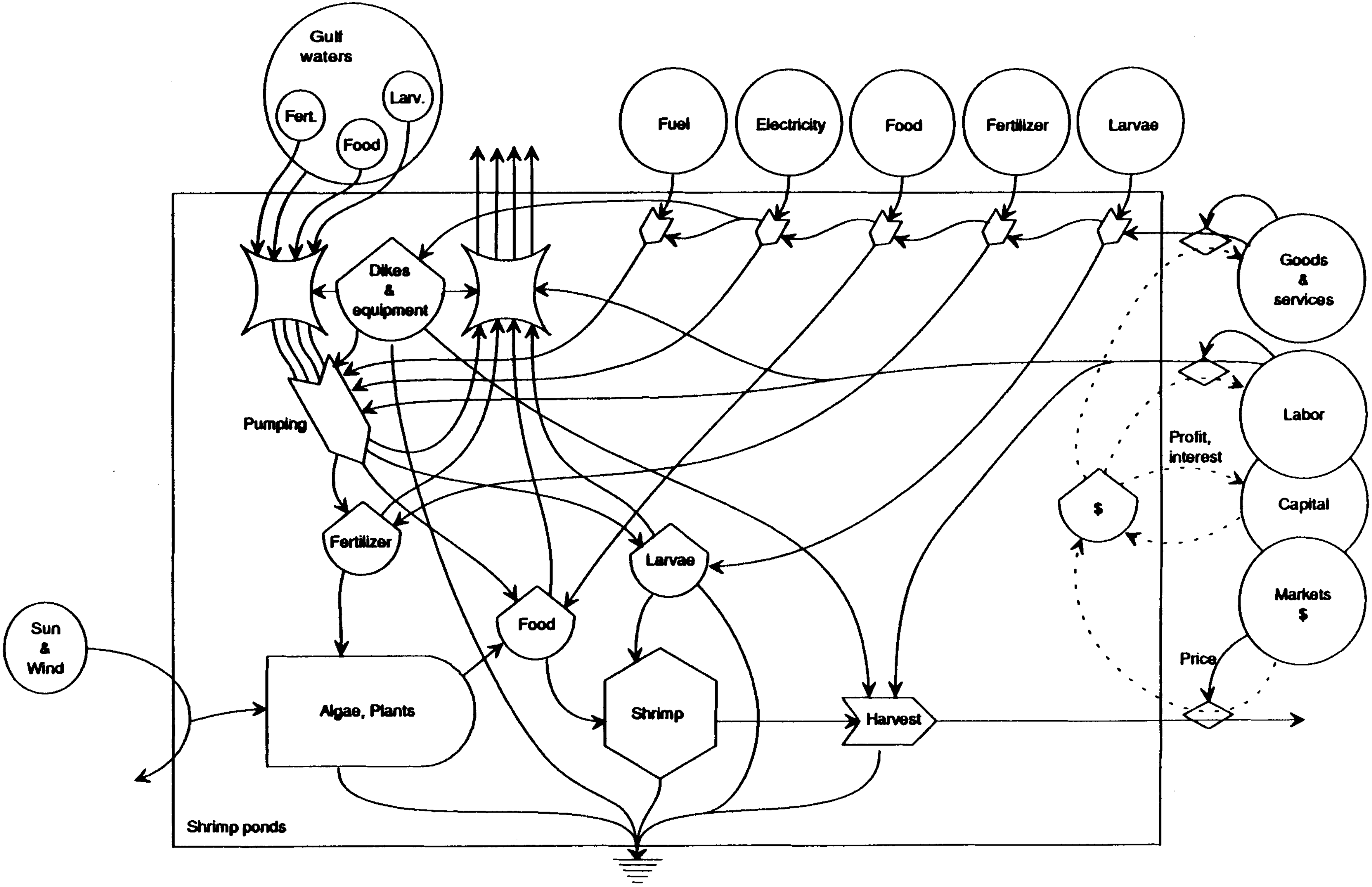


Figure 5. Overview system diagram of shrimp culture ponds and their inputs.

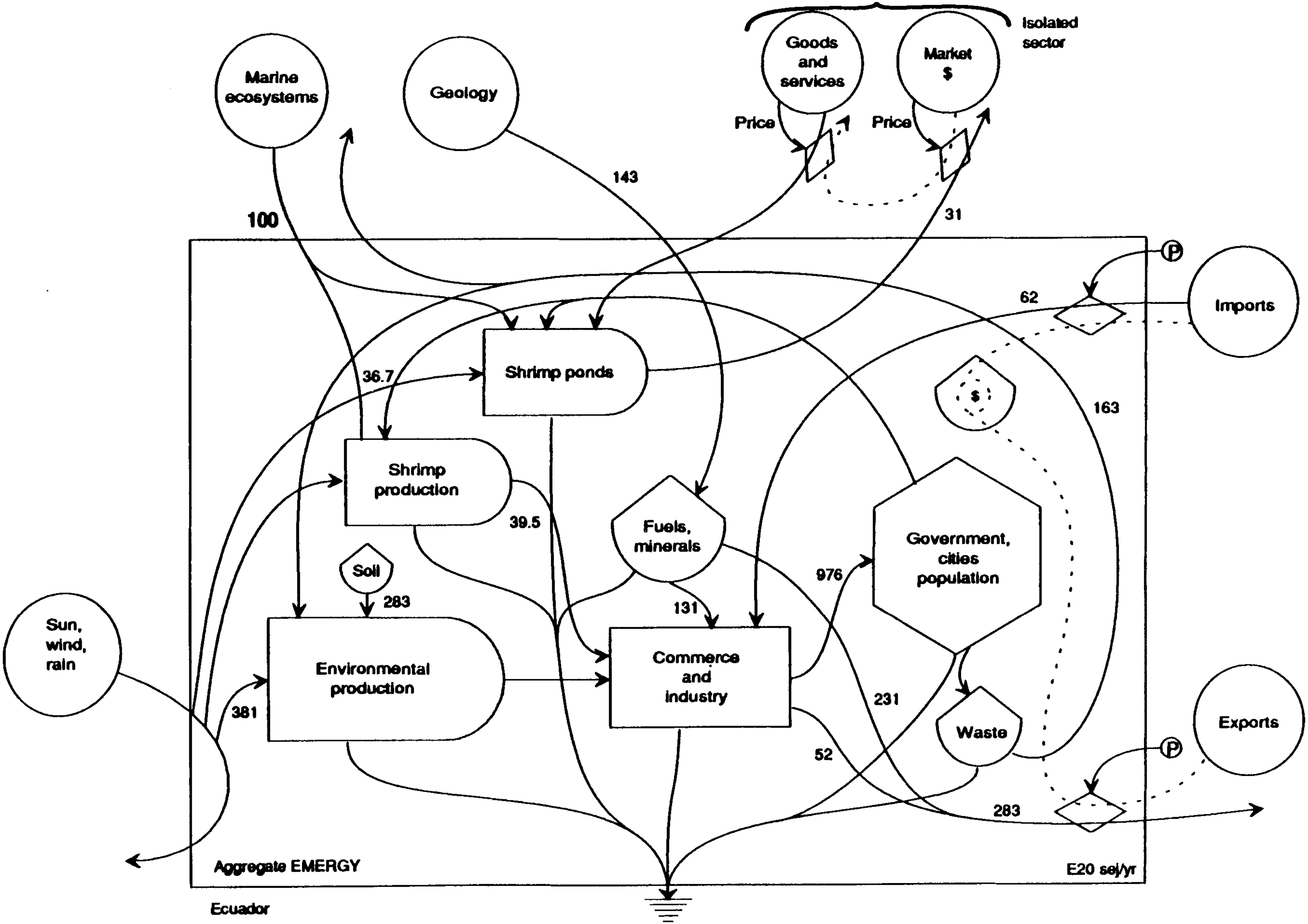


Figure 6. Overview systems diagram of Ecuador and its foreign trade.

Systems Diagrams and Their Hierarchical Organization

The parts and processes of shrimp systems are conveniently represented with diagrams in Figures 4-6, using the symbols in Figure 7. Diagrams drawn with energy systems language help visualize causal relationships, set up analysis tables and simulation programs. Circles outside the defined boundary frame are sources of external resources, goods, and services; tanks are stocks and storages; pointed blocks are interactions of more than one commodity or factor in a productive process. Diagrams of the larger system aggregate the the smaller systems, which are shown in more detail in the diagrams of the smaller scale subsystems.

The environment and the economy are hierarchical. Many small products, rapidly turning over are the basis for larger, longer-lasting products at a larger scale. Hierarchy within each diagram is represented with small to large in positions on the paper from left to right.

In some systems diagrams annual flows of solar EMERGY are written on the pathways to help the reader visualize which pathways are more important.

Figure 4 is the old system of shrimp production in the coastal area off Ecuador, including offshore waters at the top where shrimp reproduce and their tiny larvae start development. At the bottom of Figure 4 is the inshore, mangrove-lined estuary (Figure 1) where the post larvae achieve half of their growth. An inset (Figure 4b) shows the life cycle of the shrimp separated out from the main diagram.

Figure 5 is a systems diagram of the new shrimp pond mariculture system. Estuarine waters containing post larvae, shrimp food and fertilizer nutrients are pumped into the diked ponds. More organic food is generated by the pond algae and other plants. The pond managers add additional fertilizer, foods, post-larvae, utilizing goods and services, fuels, and electricity. Harvested shrimp are sold and the money obtained is used to buy purchased items, pay interest, repay loans, with the balance retained as profit.

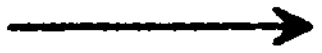
Figure 6 is an overview diagram of the shrimp production systems in their relationship to the economy of Ecuador and international markets for shrimp. The national economy is heavily based on the renewable resources, sun, wind, and rain on the left; the marine inputs of tide and species; the geologic inputs of mountain-building, petroleum generation above; and the purchased goods and services from abroad on the right. The shrimp production system is shown drawing on many aspects of the national system, and the product being sold on the international markets.

EMERGY Analysis Procedures

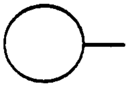
Application of the EMERGY method starts with overview diagrams of national economy and its international trade (Ecuador in Figure 6), the environmental systems on which shrimp trawl and pond production depends (Figure 4), and the shrimp pond system (Figure 5).

Then the main pathways of necessary inputs are evaluated in EMERGY units. Each inflow is expressed in solar emjoules per year. (A solar emjoule of a product is the solar energy previously required directly and indirectly to generate that product). EMERGY contributions are determined for nature's work, for purchased resources, and human services.

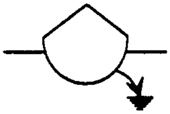
Old and new systems are compared to determine which contribute the most real value to the public economies as measured by EMERGY flux. After inputs are evaluated in EMERGY units,



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

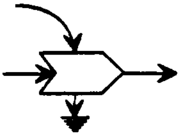


Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

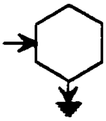


Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

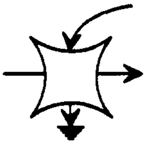
Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.



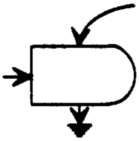
Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.



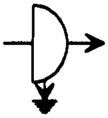
Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.



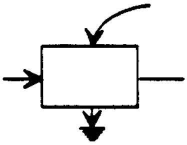
Switching action. A symbol that indicates one or more switching actions.



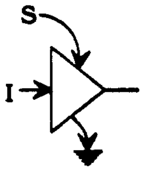
Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.



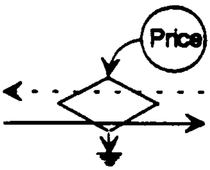
Self-limiting energy receiver. A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.



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



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



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

Figure 7. Symbols of the energy language used to represent systems (Odum, 1983).

different alternative investments and degrees of development are evaluated to find the optimum pattern for maximum EMERGY production and use. Details on the diagramming and EMERGY analysis procedure are given in the METHODS section below.

EMERGY Benefit of Alternatives

The concept of comparing EMERGY benefits of alternatives is shown in Figure 3. The diagram includes the old system of trawling shrimp from coastal ecosystems (third unit), the new system of shrimp pond mariculture (second unit), the typical alternative investments available in the region (third unit), and the potential maximum benefit (lower unit). Each of the alternatives is shown with environmental inputs (I) and purchased inputs feeding back from the economy (F). The solar EMERGY produced for the combined economy of humanity and nature (P) was calculated for each alternative as the sum of the solar EMERGY flows I and F.

Optimal Matching of Environmental and Economic Inputs

For any region there is an optimal matching of purchased inputs (F in Figure 8) with available environmental inputs (I in Figure 3) that is economic. If too few inputs are purchased, the output is less than competitors and others take the market. If too many inputs are purchased, costs are too high to be competitive and opportunities to use the investments to get greater environmental matching in other areas are lost. In any regional economy there is an average EMERGY investment ratio (R in Figure 8), which is the ratio of the flux of EMERGY purchased to the free EMERGY flux from the environment. An overly intensive economic investment has a higher investment ratio than the average for its region and loses economic position. However, it may be competitive as part of more intensively developed economies overseas that have higher ratios.

EMERGY Solutions to Other Questions

EMERGY indices derived from the evaluations help with other questions. For example, is there a net EMERGY contribution to the economy? What intensity of environmental use maximizes the economy where that environment is already providing contributions to the under-developed economy? If the market value does not represent a product's value to the public economy as a whole, what kind of microeconomic incentives would insure reinforcement to maintain resources and local economies? What is the most appropriate use of investment? What are the benefits of sales on the international market? Which benefits most from shrimp sales, buyer or seller? What is an appropriate interest rate for the investments?

Report Organization

In the text that follows, more procedural details are given next in METHODS. Then comes the EMERGY overview of Ecuador as a whole (Figure 2), and the EMERGY of foreign trade, which is necessary when putting the shrimp systems in perspective. Next, we consider the coastal system before shrimp ponds were developed and the various changes taking place with development. Then we consider shrimp pond development (Figure 3), and finally, the intensity of development that may maximize values.

Microcomputer Simulation

The time dimension is supplied by microcomputer simulation models with the same complexity as public policy thinking. These minimodel simulations are like controlled experiments, showing what would happen for the conditions given, with other factors held constant. A very simple model PRODSALE is given first to show how environmental work and economic sales are related.

The model MAXSHRIMP simulates the coastal system with trawl fishery and shrimp pond developments drawing on common resources and markets. Successive runs are made to find the degree of development which maximizes yields and values.

METHODS

In this study the environmental-economic system of Ecuador, the coastal system, and the shrimp mariculture system were studied with a similar methodology as follows:

(A) First a detailed energy systems diagram was drawn as a way to gain an initial network overview, combine information of participants, and organize data-gathering efforts.

(B) Next, an aggregated diagram was generated from the detailed one 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.

(C) An EMERGY analysis table was set up to facilitate calculations of main sources and contributions of the system. Raw data on flows and storage reserves were evaluated in EMERGY units and macroeconomic dollars to facilitate comparisons and public policy inferences.

(D) From the EMERGY analysis table EMERGY indices were calculated to compare systems, predict trends, to suggest which alternatives will deliver more EMERGY, which will be more efficient, and which will be successful.

(E) For some systems a microcomputer simulation program was written to study the temporal properties of an aggregated model. The program is used as a controlled experiment to study the effects of varying one factor at a time. Insights on sensitivities and trends are suggested from the computer graphs.

(F) Models, evaluations, and simulations were used to consider which alternatives generate more real contributions to the unified economy of humanity and nature. In particular, what are the relative contributions of shrimp mariculture and its optimal development obtained by evaluating Figure 3.

(A) DETAILED ENERGY SYSTEMS DIAGRAM

For understanding, for evaluating, and for simulating, our procedures start with diagramming the system of interest, or a subsystem in which a problem exists. This initial diagramming is done in detail with anything put on the paper that can be identified as a relevant influence, even though it is thought to be minor. The first complex diagram is like an inventory. Since the diagram usually includes environment and the economy, it is 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 problem under consideration, the diagram is drawn on the blackboard and on large sheets of paper.

   Symbols: The symbols each have rigorous energetic and mathematical meanings (Figure 7) that are given elsewhere (Odum, 1983). Examples of a system diagram involving both nature and the human economy are given in Figures 5 and 6.

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

   Arrangement of Sources: Any input that crosses the boundary is an energy source, including pure energy flows, materials, information, the genes of living organisms, 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 energy quality 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. Lines without barbs flow in proportion to the difference between two forces; they may flow in either direction.

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

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

   Intersection: Two or more flows that are different, but are both required for a process are drawn to an intersection symbol. The flows to an intersection are connected from left to right in order of their transformity, the lowest quality one connecting to the notched left margin.

   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 system storages or flow out, each inflowing material such as water or money needs to have outflows drawn.

(B) AGGREGATED DIAGRAMS

Aggregated diagrams were simplified from the detailed diagrams, not by leaving things out, but by combining them in aggregated categories. See example in Figure 6 for Ecuador.

Simplified diagrams show the source inputs (cross boundary flows) to be evaluated: environmental inflows (sun, wind, rain, rivers, and geological processes); the purchased resources (fuels, minerals, electricity, foods, fiber, wood); human labor and services; money exchanges; and information flows. Exports are also drawn. Initial evaluations may help in deciding what is important enough to retain as a separate unit in the diagram.

Inside components include the main land use areas; large storages of fuel, water, or soil; the main economic interfaces with environmental resources, and final consumers. Interior circulation of money is not drawn, but all the major flows of money in and out of the systems are shown.

(C) EMERGY ANALYSIS TABLE

An EMERGY analysis table is prepared with 6 columns with the following headings:

1 Note	2 Item	3 Raw Data	4 Transformity	5 Solar EMERGY	6 Macro-economic $

If the table is for flows, it represents flows per unit time (usually per year). If the table is for reserve storages, it includes those storages with a turnover time longer than a year.

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

Column number two is the name of the item, which is also shown on the aggregated diagram.

Column number three is the raw data in joules, grams, or dollars derived from various sources.

Column number four is the transformity in solar emjoules per unit (sej/joule; sej/gram; or sej/dollar, see definition below.) These are obtained from previous studies.

Column number five is the solar EMERGY. It is the product of columns three and four.

Column number six is the macroeconomic value in macroeconomic dollars for a selected year. This is obtained by dividing the EMERGY in column number five by the EMERGY/dollar ratio for the selected year. The EMERGY/dollar ratio is obtained by dividing the gross national product by the total contributing EMERGY use by the combined economy of man and nature in that country that year.

(D) EMERGY INDICES

The following are EMERGY indices used to draw inferences from EMERGY analyses.

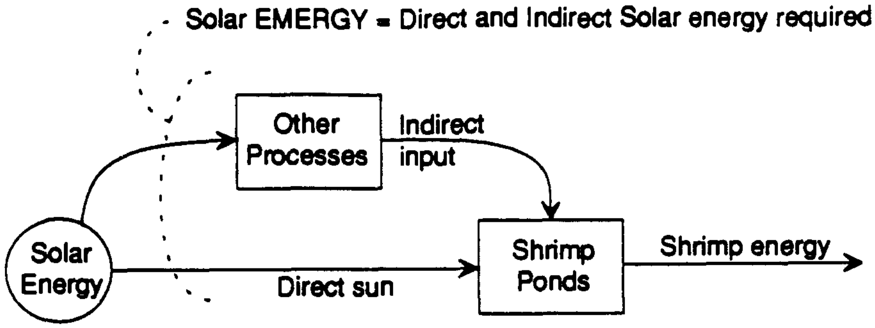
The solar transformity of an object or resource is the equivalent solar energy that would be required to generate (create) a unit of that object or resource efficiently and rapidly. Figure 8a shows the solar transformity defined as the solar EMERGY required for one joule of another form of energy, which is shrimp energy in the example.

The net EMERGY yield ratio is the EMERGY of an output divided by the EMERGY of those inputs to the process that are fed back from the economy (see Figure 8b). This ratio indicates whether the process can compete in supplying a primary energy source for an economy. Recently the ratio for typical competitive sources of fuels has been about 6 to 1. Processes yielding less than this are not economic as primary EMERGY sources.

The EMERGY investment ratio is the ratio of the EMERGY fed back from the economy to the EMERGY inputs from the free environment (see Figure 8b). This ratio indicates if the process is economical as utilizer of the economy's investments in comparison to alternatives. 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. Its prices are less when it is receiving a higher percentage of its useful work free from the environment than its competitors.

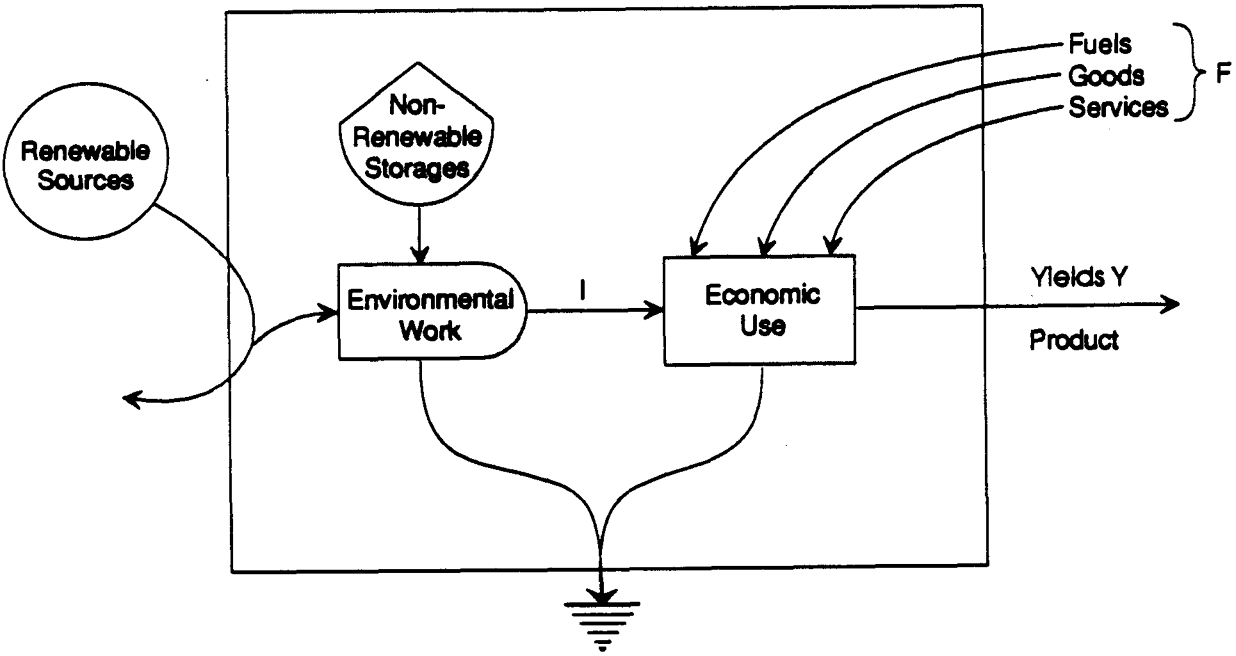
However, operation at a low investment ratio matches attracted investment at a level below what is possible. In other words, there is an unused potential available in the natural resources that can be usefully applied when they are combined with more economic inputs. The tendency will be to increase the purchased inputs so as to process more output and more money. The tendency is towards optimum matching.

Thus, operations above or below the regional investment ratio will tend to change towards the investment ratio. The ratio for an area is set by the state of development of the economy using non-renewable resources.



$$\text{Solar Transformity of shrimp in sej/J} = \frac{\text{Solar EMERGY required}}{\text{Shrimp energy}} = \frac{\text{18.6 E6 solar emjoules}}{\text{1 Joule}}$$

Figure 8a. Definition of solar Transformity applied to shrimp (Table 15).

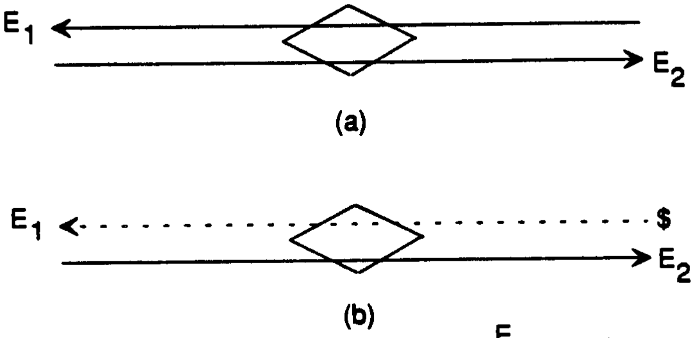


$$\text{EMERGY Investment Ratio} = \frac{F}{I} = R$$

$$\text{Net EMERGY yield ratio} = \frac{Y}{F}$$

Figure 8b. Net EMERGY yield ratio for evaluating primary sources and EMERGY investment ratio for evaluating whether matching of investments with environmental contributions is competitive. I and F should both be in solar EMERGY units (Odum and Odum, 1983).

The EMERGY exchange ratio is the ratio of EMERGY received for EMERGY delivered in a trade or sales transaction (see Figure 9). For example, a trade of grain for oil can be expressed in EMERGY units. The area receiving the larger EMERGY receives the larger value and has its economy stimulated more. Raw products such as minerals, rural products from agriculture, fisheries, and forestry, all tend to have high EMERGY exchange ratios when sold at market price. This is a result of money being paid for human services and not for the extensive work of nature that went into these products.



$$\text{EMERGY exchange ratio} = \frac{E_2}{E_1}$$

Figure 9. EMERGY exchange ratio of a transaction. (a) Trade of two commodities; (b) sale of a commodity.

The EMERGY/dollar ratio for a country and a particular year is the ratio of the total EMERGY used by the country from all sources divided by the gross national product for that year (see Figure 10). As the diagram shows, it includes EMERGY used in renewable environmental resources such as rain, non- renewable resources used such as fuel reserves and soil, imported resources, and imported goods and services. Rural countries have a higher EMERGY/dollar ratio because more of their economy involves direct environmental resource inputs not paid for.

The term macroeconomic value refers to the total amount of dollar flow generated in the entire economy by a given amount of EMERGY input. It is calculated by dividing the EMERGY input by the EMERGY/dollar ratio.

The EMERGY amplifier ratio is the EMERGY increase produced in some process compared to an EMERGY increase applied. In Figure 11, an increase in EMERGY input (dF) causes increase in consumer service EMERGY (dY). The ratio is a measure of efficiency of the applied action. For example, increasing health services for the working population to some optimum point will maximize productive work hours.

The alternative benefit ratios are used to make decisions between investment options (Figure 3.). Selecting different options for a given investment creates different systems within which each can be evaluated. This ratio should be used in a two-step comparison. First compare the

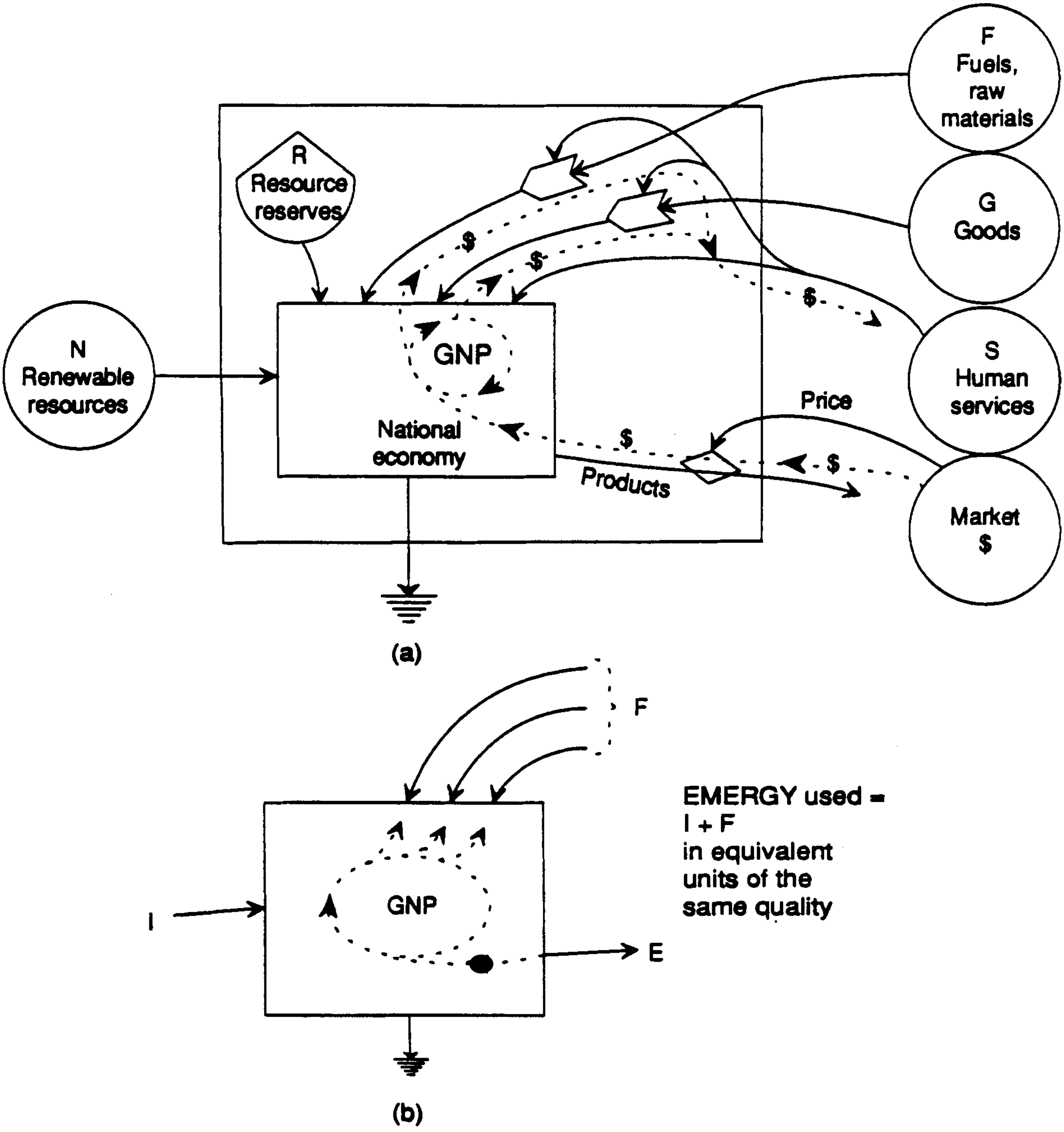
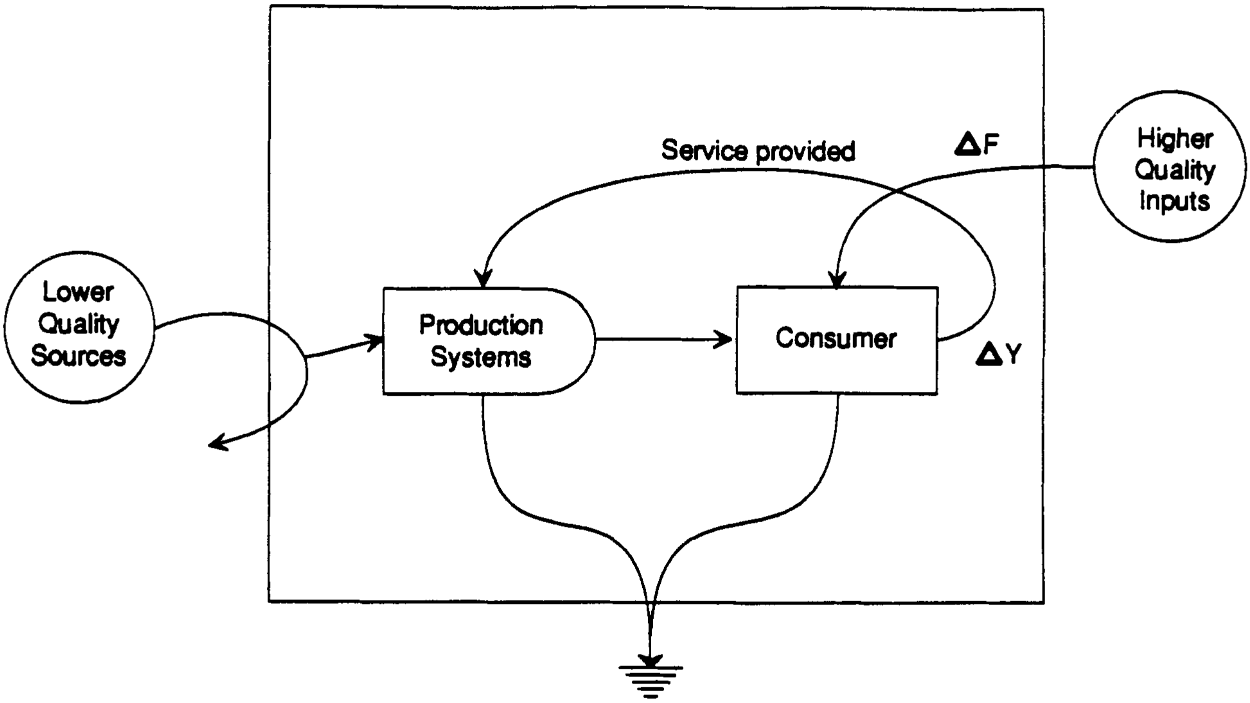


Figure 10. overview diagram of a national economy. main flows of dollars and energy; (b) summary of procedure for summing solar EMERGY inflows.



$$\text{EMERGY amplifier ratio} \quad \frac{\Delta Y}{\Delta F} = \frac{\text{Service Increase}}{\text{Investment increase}}$$

Figure 11. EMERGY amplifier ratio.

EMERGY contributions of the alternatives. In Figure 3, P is the sum of the free environmental EMERGY, I, and the attracted investment EMERGY from the economy, F. In the diagram, P2 is predicted to out compete, or prevail over P1 if its EMERGY is higher. PA is EMERGY from alternative investments typical of the region in regard to investment ratio R. PD is the highest benefit possible obtained by retaining all environmental inputs plus investment inputs.

A second comparison must then be made to assure that the investment that appears to be the best alternative among a set of options considered is also reasonably attractive compared with the average regional competitive investment ratio. In the United States the competitive investment ratio for purchased goods and services (not source inputs) is about 7 to 1 (the ratio of F to I in Figure 8b). This represents the fact that, in highly industrialized society, it requires about 7 units of paid goods and services for every unit of environmentally contributed input to generate products in that economy. The alternative which has the highest EMERGY contribution must also have an EMERGY investment ratio comparable with that for the region in order to survive or succeed. Otherwise, resources will gravitate to more productive options.

Ratios of EMERGY outputs (P's) are EMERGY benefit ratios.

Various EMERGY indices of an economy are useful for comparing states and nations. These include:

EMERGY flow per person is a measure of the standard of living that includes free environmental inputs, which may be large in areas of low population.

EMERGY flow per area is a measure of spatial concentration of an economy.

EMERGY carrying capacity is the sum of the renewable environmental EMERGY flow plus an attracted EMERGY flow from the economy equal to the competitive investment ratio times the environmental flow, and is a measure of the total macroeconomic activity that can be supported by the resources available to a region.

Fraction of total EMERGY that is indigenous is an index of self sufficiency.

(E) MICROCOMPUTER SIMULATION

For simulation, the models in the energy systems diagrams were aggregated further, combining features that were unchanging, small, or belonging to a more general category. The main source inputs, boundary flows of money, and the main features of production and consumption were retained. A new simpler diagram resulted. Equations automatically implied by the diagramming were written and placed in a BASIC simulation program.

Numerical values for flows and storages were written on the pathways and "tanks" of a copy of the diagram and adjusted for steady states expected at carrying capacity. Coefficients were evaluated with a spread-sheet template and entered in the simulation program. Graphs were obtained from simulation runs for the base calibration. Then one variable was changed at a time to study effects as a controlled experiment and for study of various changes.

(F) PUBLIC POLICY QUESTIONS

Various policy questions were examined by comparing EMERGY contributions of alternatives. The alternatives with higher EMERGY flows represent solutions that will tend to prevail because their contribution to the economy is richer. The presumption is that through trial and error as well as through rational argument, alternatives are tried so that their utility can be observed by the public decision process. Ultimately, people will come to accept the high EMERGY alternatives because these succeed and survive. By doing the EMERGY analysis in advance, one is able to predict what will eventually be the accepted policy.

EMERGY Benefit of Alternatives

To evaluate a new development using Figure 3, EMERGY analysis tables are evaluated for the original system and the new system including the environmental inputs and the purchased inputs. The new development is also compared with the typical alternative investment for that region. The flux of environmental EMERGY typically matching purchased EMERGY is the regional investment ratio defined in Figure 8. This ratio is 7 in the United States and less than one in many under-developed regions. The EMERGY of a new development can be compared with typical developments that are economic in that region by adding the purchased EMERGY (F) to the environmental matching (F/R),

$$\text{Environmental Matching} = I = \frac{\text{(Purchased EMERGY)}}{\text{(EMERGY investment ratio)}} = \frac{F}{R}\ \text{sej/yr}$$

A new development, to be a net EMERGY benefit, should have a higher annual solar EMERGY yield than the previous system and/or be higher than typical alternative investments.

EMERGY Change Analysis

On comparing a development with the system it displaces, it may not be necessary to evaluate all the resource inputs. An EMERGY change table can be evaluated, including in the table only those items that have changed. Because a change table is smaller and simpler, it is easier for readers to study.

Uses of the EMERGY Investment ratio

Often in the development of environmental resources, early success is followed by over-development which puts too much purchased EMERGY for the matching environmental input. This wastes economic potential and overloads the environmental resource. The EMERGY investment ratio (Figure 8) is the index for determining the development intensity and the environmental loading. The ratio should not exceed the regional investment ratio if the development is to be part of that economy.

Sustainability

Sustainability of a development is possible when its EMERGY yield is higher than alternatives AND when EMERGY feedback from the economy goes to the environmental work processes (not to humans) so as to reinforce their ability to compete with alternative ecosystems that tend to displace the ones under environmental loading. Many fisheries of the world get little or no feedback reinforcement and have crashed one after another, being displaced by other environmental species and patterns not under economic use. Partly this was a result of failed policy based on optimum catch calculations for only one species, ignoring the whole ecosystem. The tendency for an environmental use system to be displaced is accentuated by supply and demand that causes rising prices to sustain demand at the critical stage when an environmental system is overloaded. Public policy should be designed to encourage sustainability with incentives or regulations for feedback EMERGY reinforcement. Policy should consider EMERGY ratios.

Significance of the EMERGY Exchange Ratio

When products are exchanged or sold, the relative benefit is determined from the exchange ratio (Figure 9). A local economy is hurt when the new development takes more EMERGY than it returns in buying power. Keeping the product for home use raises the standard of those living at home.

NATIONAL SYSTEM OF ECUADOR

An EMERGY analysis overview was made of Ecuador including diagrams, annual EMERGY analysis table, and indices of the national economy.

Energy Systems Diagrams

The aggregated diagram of the national system of Ecuador in Figure 6 is shown in more detail in Figure 12, including the features prominent in the summarizing map (Figure 2). Major sectors are the tropical rain forests of the Amazon Basin, the high Andes with their populations and agriculture, and the coastal systems and fisheries. Oil from the Amazon is pumped up over the mountains and down to a shipping terminal on the Pacific ocean for export. For the national analysis the coastal boundary was taken as the edge of the continental shelf defined by the 100 meter depth contour (Figure 2). The overview diagrams were used to identify the main resources contributing EMERGY from within and from outside imports.

EMERGY Analysis of Annual Flows

Annual flows of EMERGY evaluated in Table 1 include renewable sources, indigenous non-renewable resources, and economic imports utilized in 1986. Economic exports are in Table 2. Some of the line items in these tables include others, and some are byproducts of common processes and thus were not added in deriving total EMERGY use. Total EMERGY use of Ecuador is summarized in Table 3 and Figure 13. EMERGY indices of the national economy are given in Table 4.

Summation of EMERGY inputs to a nation is made so as to avoid double counting two inputs that come from the same process and same EMERGY originally. Items in Table 1 and 2, identified by their line numbers, were summarized for Figure 13 and for a summary Table 3 as follows:

Summation of EMERGY inputs to Ecuador

		Annual EMERGY sej/yr
Renewable flows (Table 1):		
8	Tide absorbed inshore	67.0 E20
7	Offshore area (Humboldt current)	33.0 E20
5	Rain over land (Chemical potential)	381.0 E20
	Total renewable	481.0 E20
Nonrenewable uses (Table 1):		
14	Wood from mature forests	5.7 E20
21	Soil loss	283.0 E20
19	Home oil used	121.0 E20
18	Natural gas	11.0 E20
	Total non-renewable	420.7 E20
Total Annual EMERGY Use		**901.7 E20**
Exports (Table 2)		
Without transformation & use		
1	Oil	231.0 E20
With transformation		
2	Shrimp	31.2 E20
3,4,6,7	Agricultural products	10.7 E20
6	Fish	2.6 E20
	Total transformed	44.5 E20
Exported services (not included in those above)		
9	Goods and services	38.7 E20

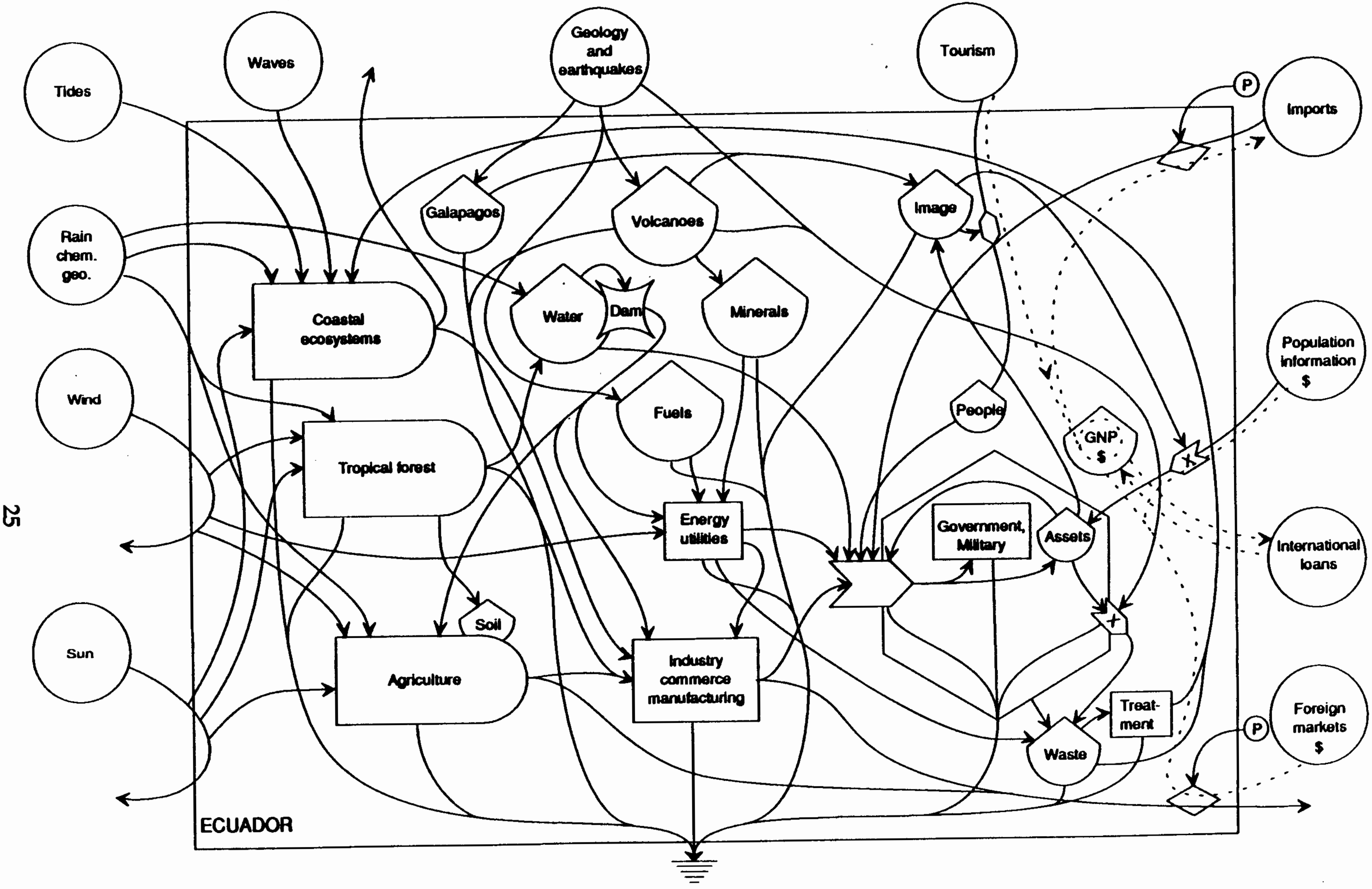


Figure 12. Main sectors of society and nature in Ecuador. See also Figure 6.

Table 1

EMERGY Evaluation of Annual Environmental Flows for Ecuador in 1986

Note	Item	Raw Units J,g,or $	Transformity Sej/unit	Solar Emergy E20 sej/yr	Macroeconomic* E6 1989 US $
RENEWABLE SOURCES:					
1	Sunlight	1.09E+21	1	10.90	545.000
2	Wind	2.72E+18	623	16.95	847.280
3	Mangroves	2.87E+16	14684	4.21	210.715
4	Rain, geopotential	3.28E+18	8888	291.53	14576.320
5	Rain, chemical	2.47E+18	15444	381.47	19073.340
6	Rain, kinetic	1.31E+13	15444	0.00	0.101
7	Humboldt current	4.17E+14	8000000	33.36	1668.000
8	Tide	2.85E+17	23564	67.16	3357.870
9	Waves	7.76E+16	25889	20.09	1004.493
10	Volcanic activity ??	–	–	??	??
11	Geological uplift ??	4.93E+17	29000	143.0	7148.500
12	Hydroelectricity	6.30E+15	159000	10.02	500.850
13	Earthquake activity	5.29E+13	3.73E+07	19.73	986.585
14	Wood consumption	1.64E+16	34900	5.72	286.180
15	Fishing yields	4.01E+15	1.31E+05	5.25	262.655
16	Shrimp trawl yields	2.08E+13	4.00E+06	0.83	41.600
17	Shrimp pond yields	1.68E+14	18.6E+06	31.25	1562.000
INDIGENOUS NON-RENEWABLE SOURCES:					
18	Natural gas	2.27E+16	48000	10.90	544.800
19	Oil use	2.42E+17	53000	128.37	6418.500
20	Electricity	1.59E+16	159000	25.28	1264.050
21	Soil loss	4.53E+17	62500	283.13	14156.250
22	Gold (g)	3.13E+04	2.51E+12	<0.01	<0.01
23	Silver (g)	6.26E+04	2.51E+10	<0.01	<0.01
24	Copper (g)	8.00E+06	9.60E+07	<0.01	<0.01
25	Zinc (g)	1.48E+07	3.64E+07	<0.01	<0.01
26	Crude steel (g)	1.70E+10	1.78E+09	0.30	15.130
SERVICES IN IMPORTS (US $1986)					
27	Fuels	8.20E+07	2.40E+12	1.97	98.400
28	Raw Material (Ag&Ind.)	6.77E+08	2.40E+12	16.26	812.880
29	Cap. goods (Ag&Ind)	4.00E+08	2.40E+12	9.59	479.400
30	Transport equipment	2.03E+08	2.40E+12	4.87	243.600
31	Construction materials	4.98E+07	2.40E+12	1.20	59.760
32	Consumer goods	2.19E+08	2.40E+12	5.26	262.800
33	Imported Services (US$)	9.54E+08	2.40E+12	22.90	1144.800

* Solar EMERGY divided by 2.0 E12 sej/$

Footnotes for Table 1

1. Sunlight: Country area 283,561 E6 m2 (T. E. Weil et al., 1973); 18500 E6 m2 shelf, 6330 E6 m2 estuary; total 308361 E6 m2. Av. solar radiation 127 kcal/cm2/yr (assume .7 absorbed).
   (308361 E6 m2)(.7)(127 E4 kcal/m2/yr)(4186 J/kcal) = 1.09 E21 J/yr.
2. Wind: 7.552 E11 kWh/yr potential (World Bank, 1981).
   (7.552 E11 kWh/yr)(3414 Btu/kWh)(1054.35 J/Btu) = 2.72 E18 J/yr.
3. Mangroves : area 18.2 E8 m2 (1984); 1E4 g/m2 density observed (Snedaker, 1986).
   (1E4 g/m2)(18.2E8 m2)(3764 cal/g)(4.186 J/cal)(0.10/yr) = 2.87 E16 J/yr.
4. Rain, geopotential: mean elevation 741 m. (Area Handbook for Ecuador, 1973); average rainfall 1603 mm, 80% runoff.
   (741m)(1.603 m)(.8)(1E3 kg/m3)(9.8 m/s2)(281561 E6 m2) = 2.62 E18 J/yr.
5. Rain, chemical: Gibbs free energy of rainwater relative to seawater, 4.94 J/g.
   (283561 E6 m2)(1.603 m)(1 E6g/m3)(4.94 J/g) = 2.47 E16 J/yr.
   Rain on offshore area
   (18500 E6 m2)(1.6 m/yr)(1 E6 g/m3)(4.94 J/g)= 1.46 E17 J/yr
6. Rain, kinetic: (av.rainfall/yr)(1/2)(density)(av.velocity)^2).
   (160.3 cm/yr)(1 E4 cm2/m2)(6.91 E-6 Cal/m3)(4.186 J/cal)(281561 E6m2) = 1.32 E13 J/yr.
7. Humboldt current - physical energy (see Table 14) 1.68 E4 J/m2/yr. Coastal system area (Table 12) 24830 E6 m2.
   (1.68 E4 J/m2)(24830 E6 m2) = 4.17 E14 J.
8. Tidal energy (assume 50% absorbed): coastal area 24830 E6 m2, av.height, 1.8 m.
   (24.83 E9 m2)(0.5)(706/yr)(1.8 m)(1.8 m)(9.8 m/s2)(1.025 E3 kg/m3)
   = 2.85 E17 J.
9. Waves: straight shore line 560 E3 m (av. h 1 m).
   (560 E3 m)(.125)(1.025 E3 kg/m3)(9.8 m/s2)(1 m2)^2 (9.8 m/s2 x 1.25 m)
   (.5) (3.154 E7 s/yr) = 7.76 E16 J.
10. Volcanic activity as hierarchical top of energy chain for which the base is some fraction ? of the world annual EMERGY flow, 8 E24 solar emjoules/yr manifest in solar and earth's deep heat (Odum, 1988), 30 of world's 800 active in Ecuador.
    (8 E24 sej/yr)(30/800)(? fraction of earth process)= <<3000 E20 sej/yr
11. Geologic continental cycle: Stable area. 1 E6 J/m2/yr for 0.739 land area; active 5.26 J/m2/yr for 0.261 land area in active mountains.
    (.261)(283561 E6 m2)(5.26E6 J/m2/yr) + (.739)(283561 E6 m2)(1E6 J/m2/yr)
    = 3.89 E17 + 1.04 E17 = 4.93 E17 J/yr.
12. Hydroelectricity: 1750 E6 kWh 1984. (Stat. Abstracts of Latin America).
    (1750 E6kWh)(3414 Btu/kWh)(1054.35 J/Btu)(3.606 E6 J/kWh) = 6.30 E15 J/yr.
13. Earthquake activity: E = Ke x a^2 x f (cal/m2/y), where Ke = 4168 (constant), a = .2 % one g acceleration, f = frequency/100 years; Ecuador earthquake activity assumed similar to northern California).
    (4168)(0.2)^2(110/100)(4186 J/cal)(6.89 E10 m2) = 5.29 E13 J/yr.
14. Wood consumption (1985): 5879 E3 m3 (Europa Year Book, 1988 EYB).
    (5879 E3 m3)(.7 E6 g/m3)(.25 DM)(3.8 kcal/g)(4186 J/g) = 1.64 E16 J/yr.
15. Fishing yield (1985) herring, sardine, anchovie, mackerel: 826.1 E3 mt (EYB).
    (826.1 E9 g)(0.2 DM)(5800 cal/g)(4.186 J/cal) = 4.01 E15 J/yr.
    Transformity from Table 14, footnote 9.

16. Shrimp trawl yield (McPadden, 1986) 3710 mt.
    (3710 E6 g)(.2 DM)(6.7 kcal/g)(4186 J/kcal) = 2.08 E13 J/yr.
    Transformity: lower value from Table 15.
17. Shrimp yield (1986): 30,000 mt (Estadisticas de Importacion y Exportacion in Acuacultura del Ecuador, July 1988).
    (30 E9 g)(.2 DM)(6700 cal/g)(4.186 J/cal) = 1.68 E14 J/yr.
18. Natural gas consumption (1985)(South America Economist, 1987 - SAE) 21495 E6 ft3.
    (21495 E6 ft3)(E3 Btu/ft3)(1054.35 J/Btu) = 2.27 E16 J/yr.
19. Oil used 106E6 barrels/day
    (106 E3 bbl/day)(6.28 E9 J/bbl)(365 d/yr) = 2.42 E17 J/yr.
20. Electricity: (SAE) 4400 E6 kWh.
    (4400 E6 kwh)(3.606 E6 J/kwh) = 1.59 E16 J/yr.
21. Soil loss: Data by L.A. Medina and E.Erraez C. for Guayas River basin, (mean of 79 stream areas).
    (283,561 E6 m2)(7080 g/m2)(.01 organic)(5.4 Kcal/g)(4186 J/Kcal)
    = 4.53 E17 J/yr
22. Gold (1984) (Statistical Abstract of Latin America, 1987): 1000
    T.oz. (= 31300 g).
23. Silver (1984) (Statistical Abstract of Latin America, 1987):
    2000 T.oz. (62600 g).
24. Copper (1983) (EYB): 7,960 kg.
25. Zinc (1983) (EYB): 14,820 kg.
26. Crude steel (1984) (SAE): 17000 mt.
27. Fuels & lubricants imports (EYB): 82 E6 US $.
28. Raw material (Ag and industry) (EYB): 677.4 E6 US $.
29. Capital goods (Ag and inustry) (EYB): 399.5 E6 US $.
30. Transport equipment (EYB): 203 E6 US $.
31. Construction materials (EYB): 49.8 E6 US $.
32. Consumer goods (EYB): 219 E6 US $.
33. Imported Services (EYB): 954 E6 US $.

TABLE 2

EMERGY Evaluation of Annual Export Flows for Ecuador in 1986

Note	Item	Raw Units J,g,$	Transformity Sej/unit	Solar Emergy E20	Macroeconomic US $E6*
1	Petroleum - energy	4.35E+17	5.3E+04	230.55	11527.50
2	Shrimp				
	Efficient equivalent	1.68E+14	4.0E+06	6.72	336.00
	Resource used	1.68E+14	1.82E+07	31.25	1562.00
3	Bananas	1.20E+15	3.2E+05	3.84	192.00
4	Coffee (1985)(g)	9.60E+10	9.3E+05	31.25	0.04
5	Cocoa (1985)(g)	1.28E+11	9.3E+05	0.00	0.06
6	Fish products	2.00E+15	1.30E+05	2.60	130.00
7	Cocoa products (US $)	7.71E+07	8.70E+12	6.71	335.39
8	Petroleum deriv. (US $)	7.01E+07	8.70E+12	6.10	304.94
9	Services (US $)	4.40E+08	8.70E+12	38.28	1914.00

Footnotes for Table 2

* dividing Solar Emergy values by 2.0 E12 sej/U.S. 1989 $.
U.S.Dollar values from Europa Yearbook(1988) are included in footnotes.

1. Petroleum exports (1986): 190 E3 b/d. (South America Economist, 1987).
   (190 E3 b/d)(365 d)(6.28 E9 J/b) = 4.35 E17 J. ($ 912 E6).
2. Shrimp exports: 100% production 1986 (30,000 mt).
   (30 E9 g)(.2 DM)(6700 cal/g)(4.186 J/cal) = 1.68 E14 J. Dollar value $315 E6 (EYB, 1988).
   The first value is the EMERGY minimum to make shrimp anywhere; The second value is the resource used in shrimp pond exports. See Table 15.
3. Bananas: 2.3 E6 mt (Europa Year Book, 1988 - EYB).
   (2.3 E12 g)(.25 DM)(5 kcal/g)(4186 J/kcal) = 1.20 E15 J. ($263.4 E6).
4. Coffee (EYB): 96 E3 mt.
   ($ 298.9 E6).
5. Cocoa (EYB): 128 E3 mt.
   ($ 71 E6).
6. Fish catch: (total yield herring, sardine, anchovies, mackerel) 826.1 E3 mt. (EYB, 1988).
   (826.1 E9 g)(.5)(.2 DM)(5800 cal/g)(4.186 J/cal) = 2.00 E15 J.
   Export value of seafood products ($ 72.5 E6).
7. Cocoa products (EYB): $77.1 E6.
8. Petroleum derivatives (EYB): $70.1 E6.
9. Services exported (EYB): $440 E6. EMERGY/$ ratio for Ecuador is used here appropriate for service of Ecuadorians.

Table 3
Summary Flows for Ecuador, 1986; See Figure 13.

Letter	Item	Solar Emergy E20 Sej/yr	Dollars E9 $/y
R	Renewable sources - rainfall, tide etc.	481	
N	Nonrenewable flows	652	
N0	Dispersed rural	289	
N1	Concentrated use	132	
N2	Exported without use	231	
F	Imported fuels and minerals	19.4	
G	Imported Goods	19.7	
I	Dollars paid for imports		2.58
P2I	Emergy value of goods and services imports	61.9	
I3	Dollars paid for imports minus goods		0.95
P2I3	Imported services	22.9	
E	Dollars paid for exports		2.62
P1E	Emergy value of goods and services exports	228	
B	Exported products transformed within country	44.5	
E3	Dollars in exported service		1.49
P1E3	Exported service	130	
X	Gross national product		11.13
U	Total EMERGY use within Ecuador	964	
P2	U.S. EMERGY/$ ratio used for imports	2.4 E12 Sej/$	
P1	Ecuador EMERGY/$ ratio used for exports	8.5 E12 Sej/$	
	EMERGY/Sucre ratio	7.1 E10 Sej/Su	

Footnotes for Table 3:

R Renewable sources (see Table 1): Rain, tides, and offshore current.

N Nonrenewable sources: NO + N1 + N2 = 641.

NO Dispersed rural: Mangroves lost 0.6 E20, soil loss 283 E20 Sej, and wood consumption 5.72 E20 Sej.

N1 Concentrated use: (Table 1, E20 Sej/yr) hydroelectricity 10, natural gas 10.9, 31 % of oil 111, steel 0.3.

N2 Exported without use: 65% petroleum production 231 E20 Sej. $ services in N2, US $ 912 E6.

F Imported Fuels and materials: (Table 1, E20 Sej/yr) Fuels 1.97, Raw material for ag and industry 17.45. Sum, 1942 E20 sej/yr; dollars in fuel, F, $82 E6. raw material (including construction) $727.2 E6.

G Imported goods: (Table 1, E20 Sej/yr) capital 9.60, transport equipment 4.87, consumer 5.26. Dollars in G: Capital $399.5 E6, transport $203 E6, consumer $219 E6.

I	Dollars paid for imports (Table 1): US $ E9 2.58.
P2I	EMERGY value of goods and services imports: 2.58 E9 x 2.4 E12 Sej/$ = 61.92 E20 Sej.
I3	Dollars paid for imported services: $ 0.95 E9.
P2I3	Imported services: 0.95 E9$ x 2.4 E12 Sej/$ = 22.75 E20 Sej.
E	Dollars paid for exports: 2.62 E9 $/yr
P1E	EMERGY value of goods and services exports: (262 E9)(8.7 E12 Sej/$) = 228 E20 sej/yr.
B	Exported products transformed within country (see Table 2) (E20 Sej/yr) Petrol derivatives 7.92, Fish products 2.6, cocoa 10.8. Dollar values: petrol ,$70.1E6, cocoa products $77.1 E6, seafood products $72.5 E6; total, $0.22 E9.
E3	Dollars paid for exports, 2.62 E9, minus dollars in goods (B) $ 0.22 E9, and raw exports $ 0.91 E9 = 1.49 E9.
P1E3	Exported services: (1.49 E9)(8.7 E12 Sej/$) = 129.6 E20 Sej.
X	Gross national products 1986: 11.1 E9 $ = 1.366 E12 Sucre/yr.
U	Line 5, Table 4
P2	U.S. EMERGY/dollar ratio (Odum & Odum 1983): 2.4 E12 Sej/$.
P1	EMERGY//dollar ratio for Ecuador: EMERGY used (R+NO+N1+F+G+IP2) = U = 964 E20 Sej/yr EMERGY/dollar ratio = U/GNP = 8.5 E12 Sej/$. EMERGY/sucre ratio =964 E20 Sej/1.366 E12 sucre = 7.1 E10 sej/sucre.

Table 4

EMERGY Indices for Ecuador based on Table 3 and Figure 13.

Item	Name of index	Expression	Quantity
1	Renewable use	R	481 E20 Sej/y
2	Use from indigenous nonrenewable reserves	N	421 E20 Sej/y
3	Flow of imported EMERGY	F+G+P2I3	62 E20 Sej/y
4	Total EMERGY inflows	R+N+F+G+P2I3	1195 E20 Sej/y
5	Total EMERGY used, U	NO+N1+R+F+G+P2I3	964 E20 Sej/y
6	Total exported EMERGY	N2+B+P1E3	314 E20 Sej/y
7	Fraction of EMERGY used derived from home sources	(N0+N1+R)/U	0.92
8	Imports minus exports	(F+G+P2I3)-(N2+B+P1E3)	-252 E20 Sej/y
9	Ratio of exports to imports	(N2+B+P1E3)/(F+G+P2I3)	5.0
10	Fraction used, locally renewable	R/U	0.49
11	Fraction of use purchased	(F+G+P2I3)/U	0.06
12	Fraction used, imported service	P2I/U	0.06
13	Fraction of use that is free	(R + N0)/U	0.80
14	Ratio of concentrated to rural	(F+G+P2I3+N1)/(R+N0)	0.24
15	Use per unit area (2.8 E11 m2)	U/area of country	3.4 E11 Sej/m2
16	Use per person (9.6 E6 population)	U/population	10.0 E15 sej/p
17	Renewable carrying capacity at current living standard	(R/U)(population)	4.7 E6 people
18	Developed carrying capacity at same living standard	8(R/U)(population)	37.6 E6 people
19	Ratio of use to GNP, EMERGY/$		
	(GNP: $ 11.13 E9 $/yr))	P1 = U/(GNP)	8.5 E12 sej/$
	(GNP: 1.366 E12 Su/yr	P1 = U/(GNP)	7.1 E10 sej/s

Table 5
EMERGY Self Sufficiency and Exchange

Nation	EMERGY from within %	EMERGY received / EMERGY exported
Netherlands	23	4.3
West Germany	10	4.2
Switzerland	19	3.2
Spain	24	2.3
USA	77	2.2
India	88	1.45
Brazil	91	0.98
Dominica	69	0.84
New Zealand	60	0.76
Poland	66	0.65
Australia	92	0.39
Soviet Union	97	0.23
Ecuador	94	0.20
Liberia	92	0.151

Table 6
EMERGY Use and Population

Nation	EMERGY used E20 sej/yr U*	Population E6	EMERGY use per person E15 sej/person/yr
Australia	8850	15	59
USA	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
Poland	3305	34.5	10
Spain	2090	134	6
World	180000	5000	3.6
India	6750	630	1

* U, see example in Table 4, Line 5.

Table 7
Concentration of EMERGY Use

Nation	Area E10 m2	Population* density people/km2	Empower density# E11 sej/m2/yr
Netherlands	3.7	378.	100.0
West Germany	24.9	247.	70.4
Switzerland	4.1	154.	17.7
Poland	31.2	111.	10.6
Dominica	0.075	107.	8.8
USA	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
Brazil	918.	13.2	2.08
India	329.	192.	2.05
Soviet Union	2240.	11.6	1.71
Australia	768.	1.9	1.42

* Population from Table 6 divided by national area where 1 km2 = 10 E6 m2.
# Rate of EMERGY use (Table 6) divided by national area.

Table 8
National Activity and EMERGY/$

Nation	EMERGY used/yr* E20 sej/yr	GNP E9 $/yr	EMERGY/$ E12 sej/$
Liberia	465.	1.34	34.5
Dominica	7.	0.075	14.9
Ecuador	1029.	11.13	8.5
Brazil	17820.	214.	8.4
India	6750.	106.	6.4
Australia	8850.	139.	6.4
Poland	3305.	54.9	6.0
World	188000.	5000.	3.8
Soviet Union	43150.	1300.	3.4
New Zealand	791.	26.	3.0
USA	66400.	2600.	2.6
West Germany	17500.	715.	2.5
Netherlands	3702.	16.6	2.2
Spain	2090.	139.	1.6
Switzerland	733.	102.	0.7

* Calculated as in Table 4 line 5.

Overview Indices for Ecuador

Overview indices calculated for Ecuador in Table 3 and 4 used data from Tables 1 and 2.

Different EMERGY in Exported and Imported Services

Money is paid only to people, not nature. When payments in local currencies are expressed in international dollars for a particular year, there may be large difference between the EMERGY that was contributed to a dollar's services of one country compared to another. The total EMERGY used per year in Ecuador was divided by the gross economic product in U.S. $ at the time to obtain the EMERGY/$ ratio--also illustrated in Figure 13b.

For the period evaluated here, the EMERGY/$ for Ecuador was 8.7 E12 sej/$, almost four times larger than that for the USA (2.4 E12 sej/$). For more rural nations, more of the basis for life comes to people direct from nature without payments. Thus, more of the real wealth used to support their labor is represented per dollar earned.

National Comparisons

The pattern of environmental resources in Ecuador can be put in perspective with comparisons to similar analyses of other countries (Odum and Odum, 1983; Pillet and Odum, 1986). See various indices compared in Tables 5-9. As might be expected, Ecuador is similar in many indices of development to Brazil, with high degree of self sufficiency (Table 5). Half of the economy was based on renewable resources and half on non-renewable usages (fuels, soils, mature forest wood). Non-renewable resources are those that are very slowly renewed by natural processes of earth cycles, but are being used much more rapidly than they are being replaced.

The EMERGY use per person indicates a moderate EMERGY standard of living (Table 6), even though the income per person is low. The concentration of EMERGY use per area is lower than the developed countries (Table 7). People receive environmental products and services free.

Regional EMERGY Investment Ratios

The ratio of purchased EMERGY to free Environmental EMERGY within Ecuador (Table 9) was only 0.09, much less than the values of 7 or more in developed countries. This ratio is a measure of intensity of development. It indicates a high degree of environmental matching to investments, typically. In part the very low value reflects the large areas of undeveloped Amazon forests.

For consideration of shrimp pond developments, an EMERGY investment ratio was calculated for the coastal region only where populations are more concentrated. The coastal region's investment ratio was 2.3, more than for the whole country but still less than in developed countries. (50% of the nation's population is present in the region and was assumed to purchase half of the national energy use and 75% of the imports.)

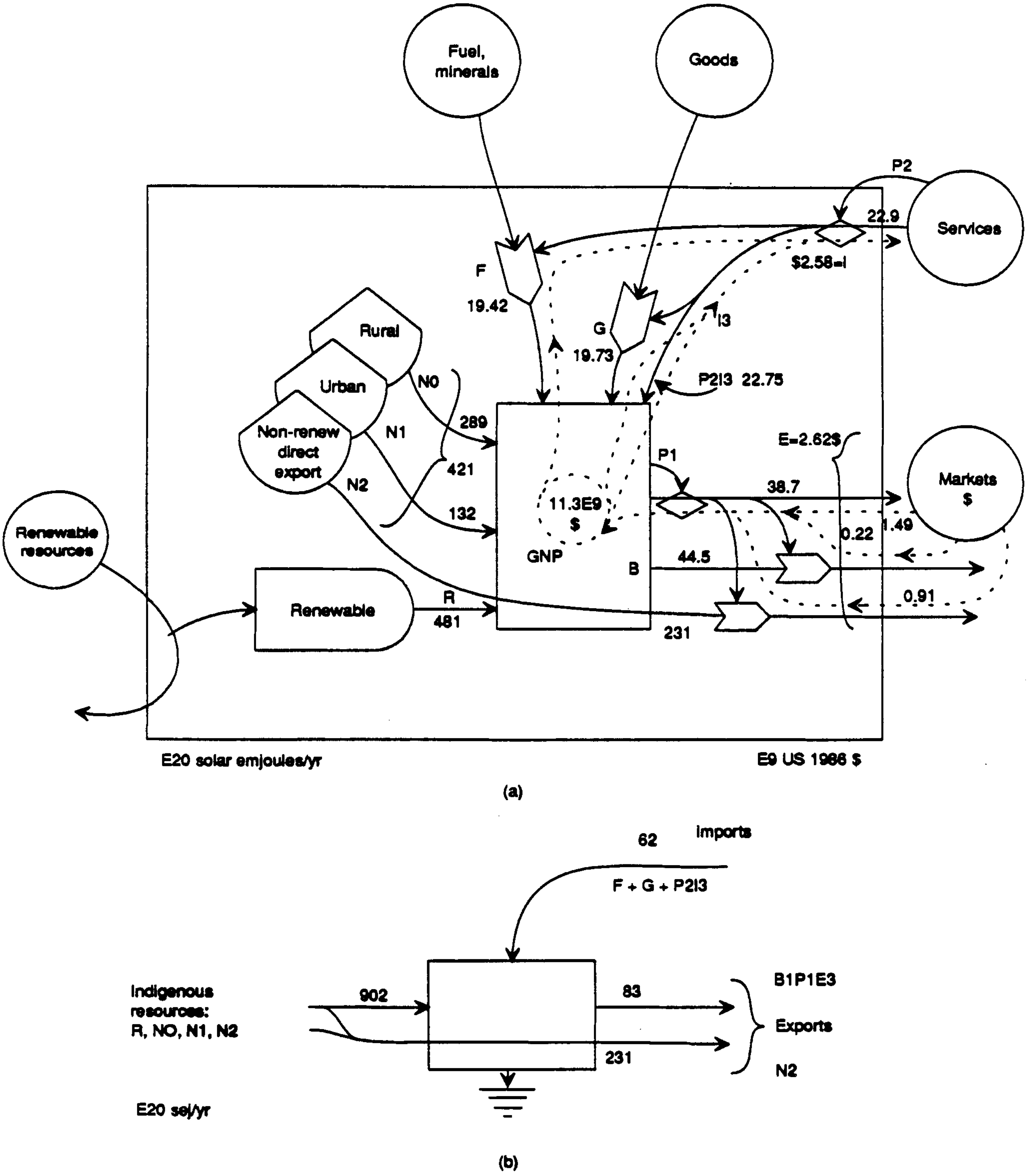


Figure 13. Aggregated summary diagram of the Ecuador national system used to calculate national EMERGY/$ ratio for the year. (a) Flows from Table 1; (b) summary.

SHRIMP AND INTERNATIONAL EXCHANGE

Commercial shrimp production, mainly exported, constitutes 35% of the exports on a dollar basis. Because of the high EMERGY content of exported oil, the shrimp export (Table 2) constitutes only 10% of the total EMERGY exported. The export of oil and shrimp is very bad for the economy of Ecuador compared to the development that would occur if these products were used internally. Consider the inequity in real wealth of the exchange (Table 5) and the reasons.

High EMERGY of Currency of Ecuador in International Exchange

The EMERGY per international dollar converted from the local currency in sucres (Table 8) was much higher than dollars converted from currencies in developed countries because more of the EMERGY was consumed directly without market transactions. International U.S. dollars had much higher buying power in Ecuador than in the United States (EMERGY/$ was 8.7 E12 in Ecuador and only 2.4 E12 in the U.S.).

Typical of underdeveloped countries, the EMERGY/$ ratio of Ecuador (Table 3) is much higher than that of the United states and other developed countries. This is because more EMERGY of the environment is used directly without any money being involved. Thus, more of the basic needs that are required for human service are free and thus the costs of labor are less. When money is converted on international currency exchange, no credit is given for the free EMERGY contributions to the labor and services. In effect, the buying power of international U.S. dollars in Ecuador is many times higher than in the United states. The EMERGY/$ ratio in Ecuador was 8.7 trillion emjoules per dollar (TREMS/$) compared to 2.4 TREMS/$ for the U.S.A. for the same year. The EMERGY/$ ratio of Ecuador in 1986 was 3.6 times that of the U.S in that year. The EMERGY buying power of a dollar in Ecuador is 3.6 times that in the U.S.

If money is borrowed by Ecuador from the U.S. and used to buy products in the United states and later paid back from Ecuadorian currency converted on international currency exchange, 3.6 times more buying power is paid back. This is equivalent to an interest rate of 360%. Little wonder that investments by developed countries in underdeveloped countries have caused financial depression in underdeveloped countries.

If the shrimp development projects are started with foreign loans, the effect of paying back interest and principle is a huge drain of EMERGY from the local economy. In the EMERGY analysis this is an additional EMERGY requirement of the system, but one not essential to the most efficient production of shrimp.

EMERGY Exchange with Foreign Sales of Shrimp

Consider the EMERGY exchange due to sales of shrimp, even if no foreign investments, loans, or debts are involved. Figure 14 shows the balance of EMERGY when the shrimp from Ecuador are sold on the international market for U.S. dollars. The EMERGY in the shrimp going to foreign buyers is 4 times more than the EMERGY they receive back in buying power of U.S. products. This difference has two reasons. First, the commodity has large EMERGY of environmental work for which no money is paid. Second, the human labor in Ecuador has more EMERGY per dollar because

Table 9
Environmental and Economic Components of EMERGY Use

Nation	R Environmental* component, renewable EMERGY E20 sej/yr	Economic# component of EMERGY E20 sej/yr	Economic/ environment ratio
West Germany	193.	17300	90.
Poland	159.	2946	18.5
Holland	219.	3483	15.9
Switzerland	86.8	646	7.4
USA	8240.	58160	7.1
Spain	255.	1835	7.2
Dominica	1.75	4.8	2.7
World	80000.	188000	2.35
Australia	4590.	3960	1.1
India	3340	3410	1.0
USSR	9110	9110	1.0
New Zealand	438.	353	0.8
Brazil	10200.	7600	0.74
Ecuador	891.	483	0.09
Liberia	427.	38	0.09

---

* As calculated for Tables 5 and 6.

Total EMERGY (U in Table 4) minus renewable component = U-R-No.

more of the EMERGY to support a person comes directly from the environment without involving money, as previously discussed. Drawing shrimp into international markets reduces their contribution to the local economy in real terms, as measured by EMERGY, by 4 times. The effect on the buying country is more than four times, contributing to the wealth and standard of living of the developed country at the expense of the underdeveloped country.

EMERGY Trade Balance for Ecuador

Because of the export sale of raw fuels, shrimp, and other environmental products, much more EMERGY goes abroad than is received in payment (Table 5). Five times more EMERGY was sent abroad than received. Ecuador was contributing to the largesse of developed countries, stripping its wealth from its own people, 75% from its non-renewable soils and oil, i.e. its future. Equity might be arranged by balancing the higher EMERGY in the exported shrimp with feedbacks to the shrimp-producing economy in some other products, services, or information.

EMERGY Feedback Reinforcement of Environmental Work

Because of the heavy drain of environmental resources for wild shrimp stocks and other estuarine-dependent species by the highly intensive shrimp mariculture, the necessary nursery and reproductive system is being diminished. The past history of exploitation of marine fisheries where there has not been reinforcing feedbacks to the food chains of economic value has lead to their displacement by other food chains not subject to economic use. The equity feedback of EMERGY from the world economy needs to be passed on to the environmental processes if the system is to be sustainable.

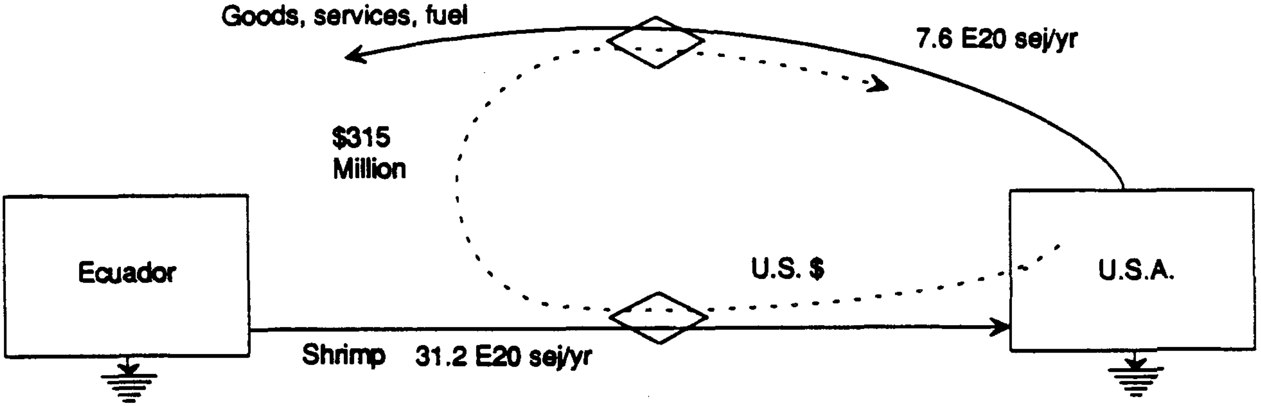
Where agriculture is successful and sustainable for an extended period, the environmental processes of soil and plant production are aided by feedbacks of EMERGY from the economy, often mislabelled "subsidies". For example, New Zealand provided fertilizer at government expense. These feedbacks have been scarce in marine culture efforts.

Shrimp Culture Isolation from the Local Economy

As the configuration "shrimp ponds" in Figure 6 shows, the shrimp production system can be operated as a branch of the international economy without much relationship to the local economy of Ecuador if most of the money received from international sales is spent back in the developed countries. The local economy is reduced to the extent that the EMERGY of the environmental resources for the ponds is diverted from the previous local use. Local use of labor at local wage rates subsidizes the product without returning much of the EMERGY to the local economy. The EMERGY of old and new shrimp production systems is considered next.

Buying power to Ecuador

(3.15 E8 \$/yr)(2.4 E12 sej.US 1986\$) = 7.6 E20 sej/yr



Shrimp from Ecuador:

(3 E10 g/yr)(0.2 dry)(6.7 kcal/g)(4186 J/kcal)(18.2 E6 sej/J) = 31.2 E20 sej/yr

Figure 14. Diagram of the exchange of EMERGY and money with foreign sale of 30,000 metric tons (fresh weight) of shrimp from Ecuador. Transformity benefit ratio to U.S. is 4.0..

Simulation of Price Effects on Sale of a Renewable Resource

The sensitivity of shrimp exports to foreign market prices is illustrated with a simulation model. Figure 16 is a much aggregated interface model typical of the economic use of an environmental production system. Environmental work is generating products on the left. At the interface with the economy, more inputs of labor, materials, information, etc., purchased from the economy interact to generate the economic product that goes for sale to the right. Depending on the price, money is received that goes into storage of money on hand M. Money is then paid out for inputs, some of which go to maintain the capital asset storage A.

In this model the environmental production is limited by its input energies, but there are no competing units present to take over the resources when an economic load is placed. In other words, this model has sustainability built into it. It has carrying capacity limitations but cannot crash due to displacement of alternative environmental species and systems. So long as the input energies are held constant, the main variables are the market prices. It is an appropriate minimodel for isolating the effects of exchange prices on a source limited product..

If the simulation starts at low state, the system grows in assets and money until it is limited by the environmental production process, which is based on renewable, limited flow sources. Changing the relative price of purchased inputs simulates the price of oil and oil-based products on the world market, ultimately affecting how much one can stimulate the economic interface. For example, a gradual increase in price in successive years (Figure 16a) causes fishermen's assets (boats, nets, information) or pond assets to decline, eventually to a place where there is no net yield. At first, however, there is little effect on the sales because there is compensation in rebound of the resource availability (R) as the fishing intensity decreases. There is little to fear from less intensive environmental use in this range of properties. See simulation in Figure 16a.

The simulation in Figure 16 held sales price constant. If the sales price is arranged to rise with decrease in supply, the simulation in Figure 16b results, which has even more stable sales over wide range in the purchased inputs. This system caused environmental loading to increase in spite of decrease in resource when fuels and the goods and services on which they are based were becoming cheaper. When fuels become more expensive, the environmental loading will become reduced without affecting the sales over a wide range.

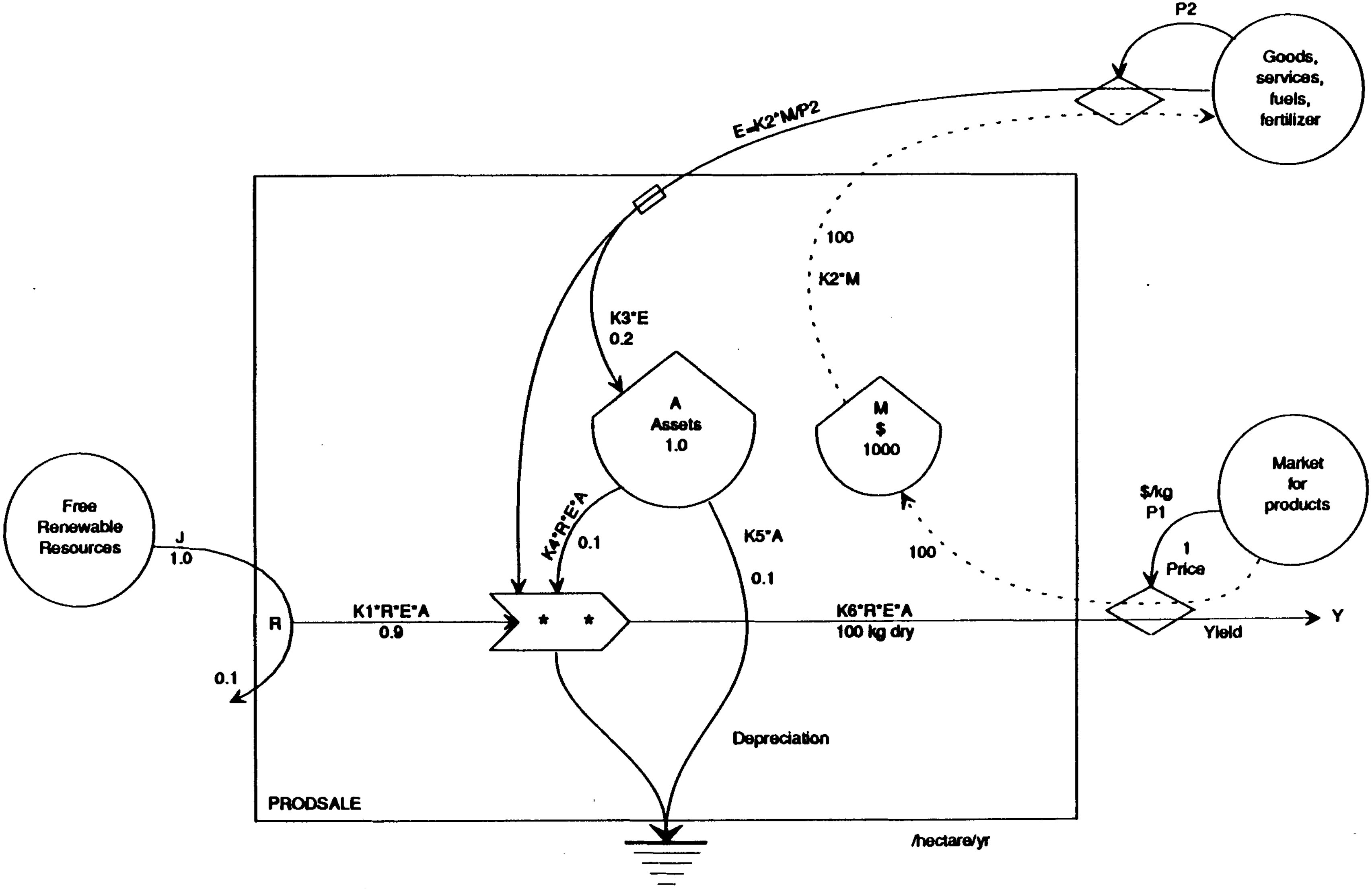
Table 10

Spreadsheet Calibration Table Used to Calculate Coefficients of the Simulation Model PRODSALE.BAS Using Numbers from Figure 15

Data:						
SOURCES						
Renewable Sources, J	=	1				
Price of sale product, p1	=	1				
Price of purchased inputs, p2	=	1				
Unused source, R = J/(1 + k1*E*A)	=	0.1				
STORAGE VALUES:						
Assets, A	=	1				
Money on hand in $, M	=	100				
COEFFICIENT CALIBRATIONS:						Coeff:
Resources used, K1*R*E*A	=	0.9	Therefore	K1	=	0.09
Money spent, K2*M	=	100	Therefore	K2	=	1
Goods, services to assets, K3*E	=	0.2	Therefore	K3	=	0.002
Assets into production, K4*A	=	0.1	Therefore	K4	=	0.1
Assets depreciation, K5*A	=	0.1	Therefore	K5	=	0.1
Yield, K6*R*E*A	=	100	Therefore	K6	=	10

Table 11 BASIC Program PRODSALE.BAS for IBM PC. See Model in Figure 15

```
10      REM IBM
20      REM PRODSALE: PRODUCTION ON RENEWABLE SOURCE
30      CLS
40      SCREEN 1,0: COLOR 0,0
50      LINE (0,0)-(319,180),3,B
60      LINE (0,90)-(319,90),3
70      REM External sources:
80      J = 1: REM Environmental source
90      P1 = 1:REM Price of product
100     P2 =.5:REM Price of purchased inputs
105     PC = .1*P2:REM 1% price change
110     REM Starting conditions
120     A=.1: REM Assets
130     M = 200:REM  Money
140     E = 100:REM  Purchased Inputs
150     Y = 100:REM  Product yield
160     REM Scaling factors for graph
170     A0 = 20
180     M0 = .6
190     T0 = 3
200     DT = .5
210     K1 = 9.000001E-02
220     K2 = .1
230     K3 = .002
240     K4 = .01
250     K5 = .1
260     K6 = 10
270     REM Equations
280     REM Plotting instructions
290     PSET (T * T0,180 - A * A0),3
300     PSET (T * T0, 90 -JM * M0),1
310     LOCATE 2,23: PRINT "Sales, $/ha/yr"
320     LOCATE 13,23: PRINT "Assets,A"
325     REM  Equations
327     P1 = 100/(Y +20)
340     R = J  / (1 + K1 * E * A)
360     E = K2 * M / P2
370     Y = K6 * R * E * A
375     JM = P1*Y: REM sales, $
380     DA = K3 * E - K4 * R * E * A - K5 * A
390     DM = P1 * Y - K2 * M
400     A = A + DA * DT
410     IF A < 0 THEN A = 0
420     M = M + DM * DT
430     T = T + DT
440     REM Instruction to return and repeat
450      IF T * T0 < 320 GOTO 270
460     P2 = P2+PC
470     T = 0
480     X = X +1
490     IF X <15 GOTO 110
500     LOCATE 1,1
600     END
```



R = J/(1 + k1*E*A)
DA = K3*E - K4*R*E*A - K5*A
DM = P1*Y - K2*M

Figure 15. Simple simulation model PRODSALE, an example of an economic interface calibrated for shrimp ponds.

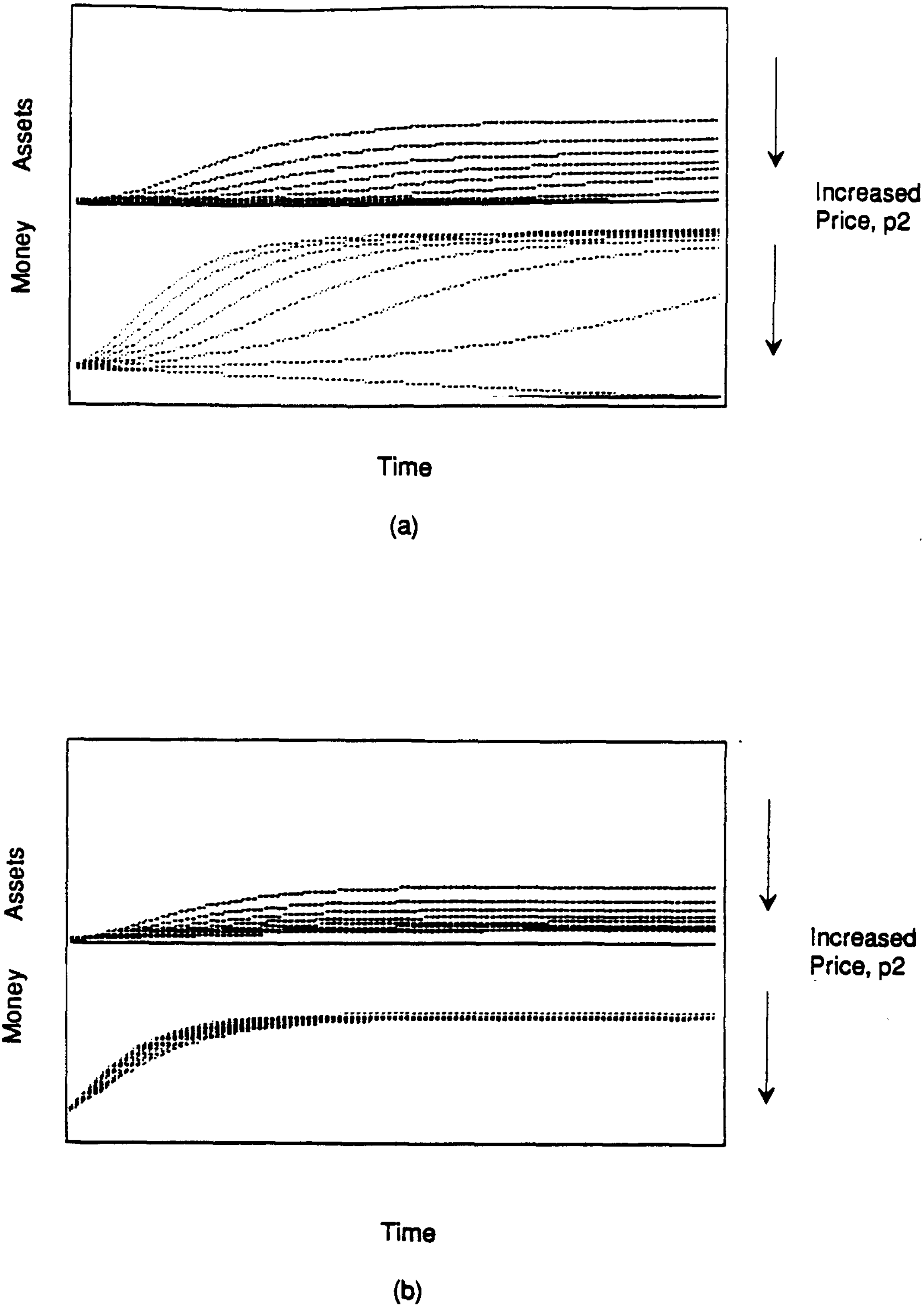


Figure 16. Results of simulating the model of economic yield PRODSALE in Figure 15. Assets are built up from sales income (without capital investment). (a) successive runs with price of purchased inputs p2 increased with each run; sales p1 constant; (b) same as (a) except sales price responding inversely proportional to yield, Y with inelastic limit = 5: $p1 = 100/(20 + Y)$.

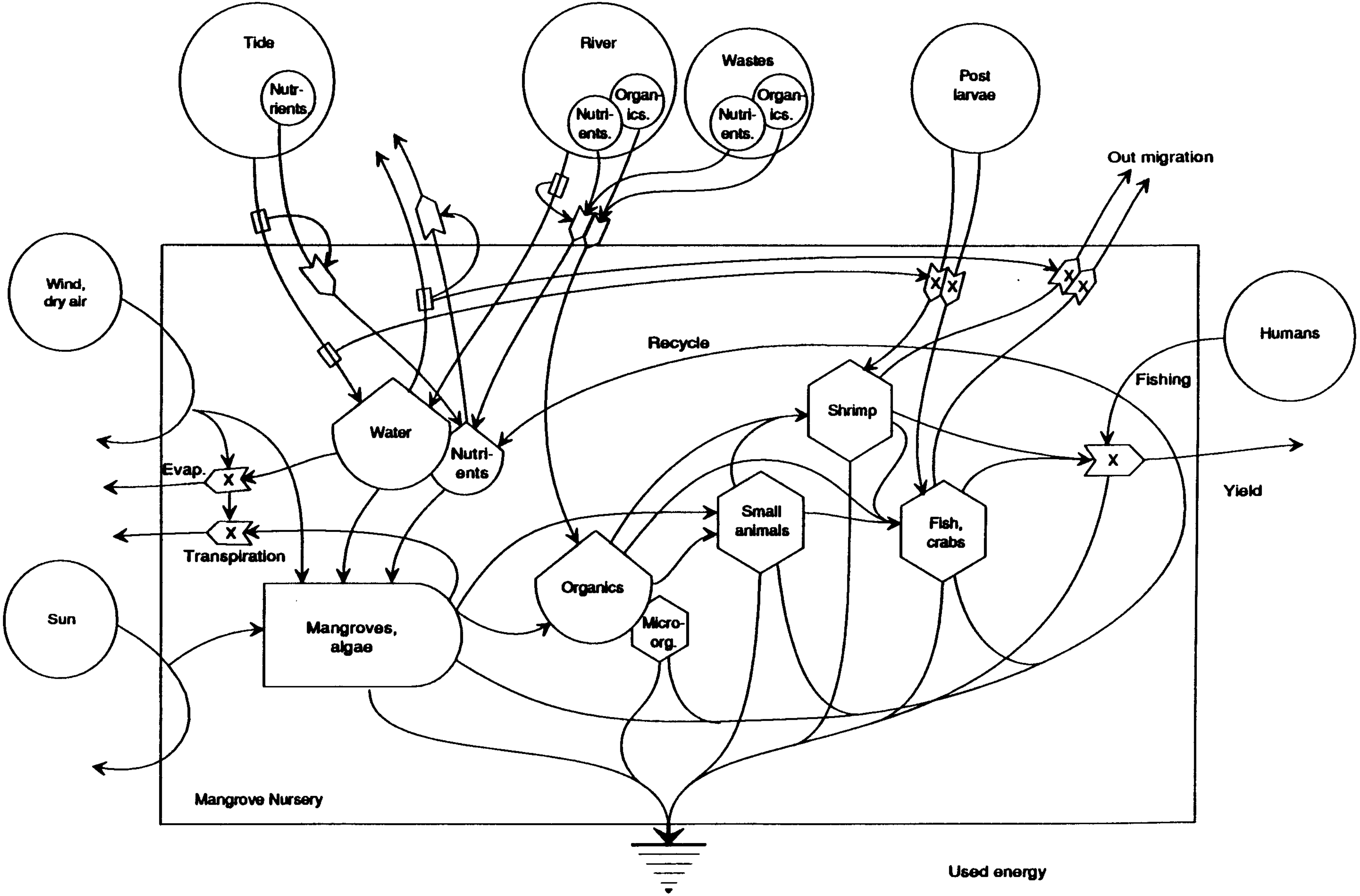


Figure 17. Energy systems diagram of the mangrove nursery ecosystem.

SHRIMP ECOSYSTEMS OF COASTAL ECUADOR

In order to evaluate the new shrimp pond systems in relation to the environment and previous pattern, coastal systems supporting shrimp were examined including the inshore gulf and estuary, the offshore pelagic waters, the mangrove nursery areas, and the shrimp ponds.

Ecosystems Supporting Reproduction, Recruitment, and Growth of Shrimp

Much of the coastal zone contributes to the environmental shrimp production including the mangroves, the estuarine waters, the continental shelf and offshore waters which are productive with phytoplankton due to upwelling (Figure 2).

The normal life cycle of the commerical shrimp starts with release of larvae from reproduction out in the open sea. The microscopic larvae released into the open sea plankton ecosystem, grow into post larvae (macroplankton) depending on the phytoplankton. Tides, currents, and the transport generated by waves bring the post-larvae to shore, into the Gulf of Guayaquil, and into the mangroves (Figure 1). Thus, the small shrimp are "recruited" into the shrimp fishery. The mangrove areas generate shrimp food, organic matter and small organisms, much of it derived from the mangrove production, so that the mangrove waters and adjacent estuary are called a "nursery." Here, the shrimp reach half size, "bait shrimp size," in several months. Aided by the tides, they migrate out into the open seas, growing to full size there, later reproducing and releasing larvae again.

The pattern of inshore and offshore reproduction and inshore nursery growth is used by some species of crabs and fishes as well as several species of shrimp. The offshore plankton ecosystem yields plankton-eating fish, pelagic herring, sardines, and anchovetta, especially in the upwelling zones just off the shelf to the southwest. Periodically, in some years, the upwelling and its contribution to the productivity offshore is interrupted by the change in the worldwide east-west wind-current regimes. Warm waters displace the cold, nutrient-rich regime and its species.

Traditionally, fisheries based on the shrimp, crabs, and fish supplied local and international markets. Some of the half-size shrimp and fish were caught in the estuary and larger ones caught offshore. The EMERGY in the fishery products high in the food chain was contributed by the several kinds of energy driving the coastal system.

As of 1989, shrimp pond development was spreading through the coastal zone, often displacing the mangroves and other ecosystems that contribute to the estuarine nursery. Even though many of the ponds were built on former salterns, the briny, algal-dominated salt flats, these also reduced the organic matter made there by algae and flushed into the estuary at time of floods.

The energy systems diagram of the coastal system (Figure 4) has the offshore plankton ecosystem above and the inshore mangroves and estuarine ecosystem below. The new ponds are included. The yields of shrimp and other products from ponds and from trawl fishing are on the right. The sources of EMERGY are the resource inputs represented in the diagram by the external circular symbol. Especially important are the high quality sources, the physical circulation energies, rivers, and nutrients, which have high transformities (high solar EMERGY per unit energy).

EMERGY Inputs to the Coastal Ecosystems

The EMERGY inputs to the coastal ecosystems were evaluated with EMERGY analysis Table 12 as drawn in Figure 4. For the purpose of evaluating the coastal system used by the shrimp life cycle, an offshore boundary was drawn to include the continental shelf out to 100 meters depth contour (Figure 2).

Table 12a.

Annual EMERGY Flows of the Coastal System of Ecuador. See Figure 4.

Note	Item	Raw Units J,g,$	Transformity Sej/unit	Solar Emergy E20	Macroeconomic US $E6
Offshore - Contintental Shelf and Coast Area: 18500 E6 m2					
1	Sun	6.88E+19 J	1	0.688	34.40
2	Wind	6.69E+15 J	663	0.044	2.22
3	Rainfall	1.46E+17 J	6380	9.315	465.74
4	Current energy	1.07E+14 J	8.0E+06	8.560	428.00
5	Deepwater nutrient - N (g)	3.70E+11 g	9.00E+08	3.330	166.50
6	Deepwater nutrient - P (g)	1.02E+11 g	8.10E+09	8.262	413.10
7	Tide	1.06E+17 J	23564	24.978	1248.89
8	Pelagic trawl - fuel used	3.17E+13 J	53000	0.017	0.84
9	Pelagic trawl - G & Services	1.13E+06 $	8.80E+12	0.099	4.97
10	Pelagic fishery landings	4.15E+15 J	1.31E+05	5.437	271.83
11	Shrimp trawl - fuel used	5.48E+14 J	53000	0.290	14.52
12	Shrimp trawl, goods,services	3.58E+06 $	8.80E+12	0.315	15.75
13	Shrimp fishery landings	2.08E+13 J	4.0E+06	0.832	41.60
Inshore - Estuaries and beachesArea: 6330 E6 m^2					
14	Sun	2.36E+19 J	1	0.236	11.80
15	Wind	2.29E+15 J	663	0.015	0.76
16	Waves	7.76E+16	25889	20.090	1004.49
17	Rainfall	5.00E+16 J	15444	7.722	386.10
18	River - chemical potential	5.13E+17 J	41068	210.679	10533.94
19	River - total N (g)	1.29E+11 g	9.00E+08	1.1573	57.87
20	River - total P (g)	1.42E+10 g	8.10E+09	1.1522	57.59
21	River - Organic load (COD)	2.77E+16 J	62400	172.536	8626.80
22	Tide	7.27E+16 J	23564	17.131	856.55
23	Inputs to Shrimp Ponds (Table 14)	–	–	21.84	1092.00
23	Shrimp pond yield				
	Minimum efficient value	1.68E+14 J	4.00E+06	6.720	336.00
	Resource used in ponds	1.68E+14 J	1.30E+07	21.84	1092.00

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* Solar EMERGY divided by 2 E12 sej/$ for U.S.A.
Some of these are included in others.

Table 12b
Indices of Coastal Ecuador

Environmental EMERGY Inputs from Table 12a;
See Note 1, Table 12 about what to include:

Offshore EMERGY inputs: tide absorbed offshore and the largest of the climataic-oceanic system, the Humboldt current (See Table 12,note 4): 33.6 E20 sej/yr (25.0 E20 + 8.56 E20 sej/yr)

Inshore EMERGY inputs: tide absorbed inshore and river water and detritus,
126 E20 sej/yr [(17.1 + 54.1 + 55) E20 sej/yr].

Indices of Offshore Fishery:
Sum of solar EMERGY of input fuels 0.017 E20 sej/yr) and goods and services (0.099 E20 sej/yr) purchased by pelagic fishery: 0.116 E20 sej/yr. (Fuels underestimated? EMERGY of boat materials not included).

Solar EMERGY of fishery landings, item 10. 5.4 E20 sej/yr

Environmental Input to pelagic fishery calculated by subtracting purchased input(fuels,0.29 E20 & goods and services, 0.099 E20) from EMERGY of landings(item 10): (5.44 E20 - 0.39 E20) = 5.05 E20 sej/yr

EMERGY investment ratio of pelagic fishery:
(0.39 E20/5.44 E20) = 0.07 (very low).

Net EMERGY yield ratio of pelagic fishery (Yield divided by purchased):
(5.83 E20/0.39 E20) = 14.9 (very high).

Environmental input to coastal zone system including inshore and offshore EMERGY above: (33.6 + 126) E20 = 160 E20 sej/yr; offshore to inshore ratio = 3.8

EMERGY indices of shrimp trawl fishery:
EMERGY of yield (item 13) using minimum (efficient, low intensity) solar transformity from Table 15: 0.832 E20 sej/yr

Purchased inputs to shrimp trawl fishery fuels (0.29 E20 + goods and services 0.315 E20) = 0.605 E20 sej/yr

Calculation of environmental inputs: (Yield minus purchased):
(0.832-.605) E20 = 0.227 E20 sej/yr

EMERGY investment ratio (purchased over environmental):
(0.605 E20/0.227 E20) = 2.7

Regional investment ratio for comparison: 2.3

Footnotes for Table 12

Direct sun, rain, pacific circulation, wind, and waves are all mutual by-products of the same EMERGY sources. Therefore one subtracts each from the largest before adding back to eliminate double counting.

Offshore - continental shelf to 100 m depth; see Figure 2. Area, 1.85 E10 m2.

1. Sunlight: area 18500 E6 m2, av. solar radiation 127 kcal/cm2/yr, .7 absorbed. (.7)(18500 E6 m2)(127 E4 kcal/m2/yr)(4186 J/kcal) = 6.88 E19 J.

2. Wind kinetic energy: using diffusion and gradient values for FL. (1000m)(1.23 kg/m3)(18500 E6m2) ((.5)(3.154 E7 sec/yr)(2.8)(2.3E-3)^2 + (.5)(3.154 E7 sec/yr)(1.7)(1.5E-3)^2) = 6.69 E15 J/yr.

3. Rainfall chemical energy: (1.603 m)(18500 E6 m2)(1 E6 g/m3)(4.94 J/g) = 1.46 E17 J.

4. Physical current energy transferred from the Pacific Ocean Circulation. The Humboldt current sweeps over the continental shelf of the southern half of Ecuador half of the year (Cucalo'n, 1988). See Figure 2; half of shelf area: 9.3 E9 m2). Assume water current 0.3 m/s with 10% absorbed.
   Kinetic energy over the shelf during the half year:
   (9.3 E9 m2)(50 m avg. depth)(1.025E3 kg/m3)(.5)(.3 m/s)(.3 m/s) = 2.14E13 J
   Rate of replacement turnover from velocity and entry cross section:
   (0.3 m/s)(1.55 E7 seconds/halfyear)((50 m)(100 E3 m)/(9.3 E9 m2)(50 m)
   = 50 times per half year
   Energy absorbed: (2.14 E13 J)(50/yr)(.1 absorbed) = 1.07 E14 J/yr
   Solar transformity that of Mississippi River current at New Orleans
   80 E5 sej/J (Odum, Diamond, and Brown, 1987)

5. Nutrients nitrogen inflowing from deepwater on half of the area half of the year: 0 .3 microg-at/m2/s av. flux, 40% exported (Carpenter and Capone, 1983).
   (0.5)(.6))(.3 ug-at/m2/s)(14E-6 g N/u-at)(3.154 E7 sec/yr) = 39.7 g/m2-yr.
   (39.7 g/m2/yr)(9.3 E9 m2) = 3.7 E11 g/yr .
   Solar transformity of marine nutrient nitrogen, 9.0 E8 sej/g was derived from world annual EMERGY flux divided by world oceanic nitrogen flux.

6. Nutrients phosphorus inflowing from deepwater on half of the area half of the year: P values 1/8 of N values observed (Walsh, 1981), est. 0.0375 microgram-at/m2/s.
   (0.5)(0.6)(.0375 ug-at/m2/s)(31 E-6 g P/ug-at)(3.154 E7 s/yr) = 11 g P/m2/yr.
   (11 g/m2/yr)(9.3E9 m2) = 1.02 E11 g/yr.
   Solar transformity of marine phosphate phosphorus, 8.1 E9 sej/g was derived from world annual EMERGY flux divided by world oceanic phosphorus flux. Nitrogen and Phosphorus are cycle by-products representing the same EMERGY

7. Tidal energy: average height 1.8 m. (Twilley, 1986), 50% absorbed on shelf, 1.85 E10 m2 area.
   (706/yr)(.5)(9.8 m/s2)((1.025 E3 kg/m3)(1.85 E10 m2)(0.5)(1.8 m)(1.8m) = 1.06 E17 J/y.

8. Pelagic trawl - fuel consumed (1986) (Banco Central del Ecuador, Div. Tecnica, 1988) 9.54 E6 Su (1975 prices adjusted). (9.54E6 Su)/(41.2 Su/gallon) = (231.5 E3 gallon)(137 E6 J/gal) = 3.17 E13 J.

9. Pelagic trawl - goods and services (1986) 138 E6 Su (as above 1975 prices adjusted). (138 E6 Su)/122 Su/US $ = US $ 1.13 E6.

10. Landings of Pelagic Fishery; 826 E3 tonne/yr; also see Calculon(1986);
   (826 E3 tonne/yr)(1 E6 g/tonne)(.2 dry)(6 kcal/g)(4186 J/kcal)
   = 4.15 E15 J/yr
   Solar transformity for landed fish 3.36 E5 sej/J; see note 9, Table 14.

11. Shrimp trawl fuel consumed: see notes in Table 16; 4 E6 gallons diesel/yr.
   (4 E6 gallons)(137 E6 J/gal) = 5.48 E14 J/yr.

12. Shrimp trawl goods and services: 547,055 Sucre/mo per vessel (McPadden, 1986), 266 vessels, est. 3 months operations per year.
   (547,055 Sucre/mo-vessel)(266 vessel)(3 months)/(122 Sucre/US) $ = US $ 3.58 E6.

13. Shrimp fishery landings in 1985 (McPadden,1986) 3710 tonne;evaluated with solar transformity 4 E6 sej/J from other studies.
   (3.71 E3 tonne/yr)(1 E6 g/tonne)(.2 dry)(6.7 kcal/g)(4186 J/kcal)
   = 2.08 E13 J/yr

Inshore - estuaries and rivers:

14. Sunlight: (6330 E6 m2)(127 E4 kcal/m2/yr)(.7)(4186 J/kcal) = 2.36 E19 J.

15. Wind kinetic energy: values as #2 above.
   (6330 E6 m2)(1000 m)(1.23 kg/m3) ((.5)(3.154 E7 sec/yr)(2.8)(2.3 E-3)^2 + (.5)(3.154 E7 sec/yr)(1.7)(1.5 E-3)^2) = 2.29 E15 J/yr.

16. Waves: See Table 1, note 7.

17. Rain chemical energy: (1.603 m)(6330 E6 m2)(1 E6 g/m3)(4.94 J/g) = 5.0 E16 J/yr.

18. River chemical energy: 750 TDS (Ariaga, 1986). Gibbs free energy relative to sea water: 138.8 * ln((1 E6 - 750)/965000) = 4.48 J/g.
   Coastal river discharges: 11.5 E10 m3/yr
   (4.48 J/g)(1 E6 g/m3)(11.5 E10 m3/yr) = 5.13 E17 J.
   Solar transformity is that of average world river flow.

19. River total N (Solorzano, 1986): 80 mg-at/m3 average concentration at surface. (80 mg-at/m3)(.001 g-at/mg-at)(14 g/g-at)(11.5 E10 m3/yr) = 12.86 E10 g/yr.

20. River total P (Solorzano, 1986): 4 mg-at/m3 surface average.
   (4 mg-at/m3)(0.001 g-at/mg-at)(31 g/g-at)(11.5 E10 m3/yr) = 14.22 E9 g/yr.

21. River organic load, 115 ppm organic matter (mean of 5 measurements of chemical oxygen demand from Rio Chone: 21,28,10.6, 308.6,212.9,21 mg/litre).
(115 mg/l)(1 g/m3/mg/l)(5 kcal/g)(4186 J/kcal)(11.5 E10 m3/yr)= 27.65 E16 J/yr.

22. Tidal energy in estuaries: av. height 1.8 m, all absorbed:
(706/yr)(.5)(9.8 m/s2)(1.8 m)(1.8)(1.025 E3 kg/m3)(6330 E6 m2)= 7.27 E16 J/yr

23. Shrimp ponds, environmental and purchased inputs from Table 14.

24. Shrimp pond yield from Table 14. Two EMERGY values are used in estimating EMERGY. The first uses the least transformity from less intensive systems (Table 15)--the ultimate thermodynamic value; the second transformity is that used in the intensive and inefficient shrimp ponds (Table 14).

The inshore system includes the beaches, estuarine waters, mangroves, and shrimp ponds.

Note the high EMERGY contributions for the tide, currents, the river fresh water, the river organic matter, and the nutrients. Much of the extraordinary marine productivity of the area is due to the converging contribution of so many resources, especially the river flows in wet season. The sharp seasonal variation due to alternation of dry and wet seasons organizes and channelizes net productivity.

The high levels of detritus organic matter flowing into the coastal zone are apparent from aerial reconnaissance. This is the EMERGY of land production, some from the past in erosion of soils and some from current land production utilizing the rain that was transpired in the present. The total value contributed by the rivers to the estuaries is very large, 19.1 billion U.S. $/year (sum of $10533 E6 and $8626 E6 from items 18 and 21 in Table 12a).

If one adds tide and waves to river inputs, total annual macroeconomic $ value for the coastal waters is about $21.4 billion/year. The EMERGY of the pelagic fishery and shrimp landings is substantial but a small part of the total works of nature there.

EMERGY Inputs to the Mangrove Nursery Areas

In Table 13 are EMERGY evaluations of the inputs to the mangrove nurseries considered separately. Shown in Figure 1, the system includes the mangrove forest, the waters within the mangroves, and their tidal channels. It is these areas that are being displaced by pond construction or diminished by diversion of the estuarine waters into the ponds. For the later calculations it was convenient to evaluate this ecosystem separately. Figure 17 is an aggregated systems diagram of the mangrove system and the input pathways evaluated in Table 13. The evaluation was made per unit area and multiplied by the mangrove area for totals.

Some of the products generated as concurrent byproducts within the mangrove system include live mangrove biomass, organic litter fall, and medium sized shrimp migrating out. The solar transformities of these products were calculated by dividing the total EMERGY contributions of independent sources by the energy flux of each item.

EMERGY Evaluation of Daule-Peripa River Diversion

A dam being filled at the time this report is written, will store some water from the Daule tributary, making the wet season flow less and the dry season flow greater, divert water to agriculture, inland growth and evaporation. Many highly productive shrimp ecosystems occur where fluctuating or very high salinities reduce diversity and channel energy into a few species. Examples are the white shrimp of the Mississippi delta and the brown shrimp of the briny Laguna Madre of Texas. The main shrimp cultivated in the ponds of Ecuador, *Penaeus vannamei*, is a species that is adapted to wide ranges in salinity and temperature. Evidence that the annual river surges favor high shrimp production was the 1983 year when exceptional El Nino runoff was accompanied by exceptional shrimp production and post-larvae.

The damming of the river will cause estuarine salinities to be higher and uniform. Higher diversity marine organisms will displace many of the shrimp populations. In an analogous situation, oysters based on wide salinity fluctuations develop diseases and disappear when salinities are made uniform by human reduction of flood run-off.

Table 13

Annual EMERGY Flows in the Mangrove Nursery System of Ecuador.
119,500 Hectares. See Figure 17.

Note	Item	Raw Units J,g,$		Transformity Sej/unit	Solar EMERGY E18 sej/yr	Macroeconomic 1989 US E6 $/yr
1	Solar energy	4.4 E+18	J	1	4.44	2.22
2	Wind energy	4.4 E+14	J	623	0.27	0.14
3	Mangrove transpiration	4.4 E+15	J	41068	179.06	89.53
4	Rain chemical potential	5.2 E+15	J	15444	80.31	40.15
5	Tides	4.2 E+15	J	23564	99.91	49.96
6	Total solids from sewer	5.8 E+10	J	62400	0.00	0.00
7	Total N from sewers	4.2 E+08	g	9.0 E+08	0.38	0.19
8	Total P from sewers	5.15 E+07	g	8.1 E+09	0.42	0.21
9	Biomass growth	1.9 E+16	J	14684	279.00	139.50
10	Litterfall	2.1 E+16	J	13285	278.99	139.49
11	Shrimp produced	2.1 E+12	J	2000000	4.20	2.10
12	Independent total	—		—	278.97	139.48

Footnotes for Table 13

1. Solar input: 1195 E6 m2, 127 kcal/cm-yr average solar insolation.
(1195 E6 m2)(127 E4 kcal/m2-yr)(.7 absorbed)(4186 J/kcal) = 4.44 E18 J/yr.

2. Wind energy: 0.19 available inshore system (areal ratio) - see Table 12, note #2.

3. Mangrove transpiration:
(2.5 mm/d)(365 d/yr)(1000 g/mm/m2)(4.0 J/g)(1195 E6 m2) = 4.36 E15 J/yr

4. Rain chemical potential energy: Av. precipitation in Guayaquil 885 mm/yr (Twilley, 1986): (1195 E6 m2)(.885 m)(1 E6 g/m3)(4.94 J/g) = 5.2 E15 J/yr.

5. Tidal energy range absorbed in mangroves, 1.0 m;
(706/yr)(9.8 m/s2)(1.025 E3 Kg/m3)(11.195 E9 m2)(1.0 M)(1.0m) = 4.23 E15 J/yr

6. Total suspended solids in sewer effluent: 6456 E6 g/yr. 0.2 of area;
(0.2)(6456 E6 g)(.002 organic)(5.4 kcal/g)(4186 J/kcal) = 5.84 E10 J/yr.

7. Nitrogen concentration in sewer effluent 2.1 E9 g/yr; 0.2 of estuary area (Twilley, 1986).
(2.1E9)(.2) = 4.2E8 g/yr

8. Phosphate concentration in sewer effluent 2.58 E8 g/yr (Twilley, 1986); 0.2 area. (2.58 E8 g/yr)(.2) = 5.15 E7 g/yr

9. Mangrove biomass growth: 2.8 g/m2-day (observation from Snedaker, 1986 and Sell, 1977).
(1195 E6 m2)(2.8g/m2-d)(365 d)(3764 cal/g)(4.186 J/cal) = 1.9 E16 J/yr.
Transformity:(279 E18 sej/yr in footnote 12)/(1.9 E16 J/yr) = 14684 sej/J.

10. Mangrove litter fall: 957 - 1032 g/m2-yr (Sell, 1977); av. 995 g/m2-yr. (995 g/m2)(1195 E6 m2)(4139 cal/g)(4.186 J/cal) = 2.1 E16 J/yr.
Transformity: (279 E18 sej/yr)/(2.1 E16 J/yr) = 13285 sej/J

11. Medium sized shrimp produced (70 individuals-tails per pound) Turner(1985): 10 kg commercial yield of adults per hectare of vegetated nursery.
(10 kg/ha)(2.2 lb/kg)(.7 tails)(35 tails/lb) = 539 individuals/Ha
(539 ind./ha)(1195 E6 m2)(/70 ind/lb)/(1 E4 m2/ha) = 9.2 E5 lb
(9.2 E5 lbs)(.2 dry)(454 g/lb)(6.0 kcal/g)(4186 J/kcal) = 2.1 E12 J/yr
Transformity for estuarine shrimp, half of larger offshore adults:
(0.5)(4 E6 sej/J in Table 15) = 2 E6 SEJ/j

12. Total omitting double counting: sum of transpiration and tide:
(179 + 100) = 279 E18 sej/yr

We did not do a full evaluation of the dam and its economic consequences, but only of its effect on the estuary and the shrimp as follows. Data from Arriaga (1986) were used. The average flow of the Guayas River is 974 m3/s (307 E8 m3/yr). The solar EMERGY of the water purity (Gibbs free energy) was evaluated using solar transformity for average world rivers as follows:

(3.07 E10m3/yr)(1 E6 g/m3)(5 Gibbs J/g)(41068 sej/J) = 63 E20 sej/yr

Add to this the EMERGY of organic detritus using 115 parts per million (=g/m3) (similar to the calculation made for the coast as a whole in Table 12, line 21).

(3.07 E10 m3/yr)(115 g/m3)(5 kcal/g org.)(4186 J/kcal)(62400 sej/J) = 46.1 E20 sej/yr

Dividing the sum, 109 E20 sej/yr (63 E20 +46 E20) by U.S. solar EMERGY/$ ratio gives macroeconomic $ contribution:

Macroeconomic 1989 US $ = (109 E20 sej/yr)/(2 E12 sej/$) = 5.45 E9 $/yr

Similar evaluations are made in the text table below for the Daule-Peripa dam situation. The reservoir area will be 27,000 hectares. If the evaporation rate is 6 mm per day there is a 2% loss/yr.

The new dam is reducing flow on the Daule River, one of the main tributaries of the Guayas River. According to the plan, the annual discharge of the Daule river (333 m3 /sec) will be reduced to 100 m3/sec, a 70% diversion.

EMERGY and macroeconomic dollar values for the diversion follow:

Annual Flows of Guayas River affected by Daule-Peripa dam Project

Name	Flow E8 m3/yr	Solar EMERGY/yr E20 sej/yr	Macroeconomic $/yr sej/yr E6 1989 US $*
Average flow	307	109	5,450
Evaporation	5.9	1.21	60
Diversion	73.5	26.1	1,305
Loss of wet season river surge	78	27.7	1,385

* EMERGY divided by 2 E12 sej/1989 U.S. $.

These figures are tentative, since there were few data on organic detritus content. Figures during flood are likely to be higher than those used in these calculations:

The mean flow in 6 months wet season is 599 m3/s and in 6 months dry season 68 m3/s.

The difference between the wet season and the future planned discharge is:

599 -100 = 499 m/s (78 E8 m3.yr)

This is the surge of freshwater that dominates the estuarine productivity, lowering diversity and channelizing energy to the shrimp and other estuarine values. See EMERGY evaluation in text table above with macroeconomic value of 1.35 billion US $ threatened by water diversion. This does not include the $1.134 macroeconomic dollars in purchased inputs to the shrimp industry (Table 14) which may be decreased with water diversion. The shrimp ponds are based on several sources of detritus and on pumping in waters of variable salinity that keep the competitors and weed species from becoming established. Diversion of the waters may bring on algal blooms, animal competitors, carnivores, and diseases normally prevented by the river surge. The mangroves are also based on the freshwaters and their productivity will be much reduced without as much freshwater to transpire. Insect infestation has been observed there in 1990.

From Table 12a and 14 the shrimp systems, ponds and trawling, were EMERGY evaluated, and an annual macroeconomic $ value was found of 1.5 billion U.S. $/yr ($1.06 E9 + $0.42 E9). The diversion of the rivers and their surges is likely to remove much, if not most, of estuarine resource and the shrimp industry. Whether the values transferred inland by diversion of the river can equal the coastal resources lost was not analyzed in this study. The agricultural alternatives now being developed should be evaluated in the same way urgently. Certainly, the principle used in this development was wrong, destroying a developed system without bringing in competent knowledge of what may be lost.

Evaluating Pelagic Fishery Landings

Relating the EMERGY of the oceanic production to the landings of pelagic fisheries from offshore is difficult because the boundaries fished for the boats landings included in Ecuador statistics are not known. Also, the estimates of physical energy inputs are very preliminary. Part of the EMERGY basis is the colder upwelling ecosystem beyond the continental shelf south of 2 degrees south latitude (Figure 2). The web of energy transfers is not worked out to show how much of these energies are in support of the pelagic fishery.

A tentative solar transformity for this fishery was estimated from food chain calculations by Walsh (1981) in Table 14, note #9. The transformity is appropriate for consumers low in the ecosystem trophic web. Based on this, the EMERGY content of the fishery landings (Table 12a, item #10) is very high, with macroeconomic value of 272 million US $. From the data available, the investment ratio was very low and the net EMERGY high. In other words, the landings appeared to be high value for little input. Much more can be done with these fish than is the case now. These indices need verification.

Evaluating Shrimp Trawl Landings

The trawl fishery for shrimp on the continental shelf and Gulf waters receives its environmental support from the mangrove nursery, the shallow open water estuary and the continental shelf. These, in turn, receive their EMERGY basis from the river, tides, and oceanic currents sweeping the shelf as evaluated in Table 12a. The total solar EMERGY contributed by offshore and onshore areas (Table 12b) is 160 E20 solar emjoules/yr with macroeconomic $ value of 8 billion $.

There is not a full energy web worked out for the interaction of the physical energies with geologic and biologic processes in this complex estuary. Thus, it is not clear how much of the solar EMERGY supports the shrimp food chain hierarchy.

Another approach was used. EMERGY of landings contains that from purchased inputs and the environment. By calculating the landings with a transformity from Table 15 and subtracting the purchased EMERGY, the environmental component was estimated. From this an investment ratio of 2.7 was obtained similar to the regional ratio 2.3, as would be expected for an operation economically viable in that local economy (see previous section: "Regional EMERGY Investment Ratio").

Some part of the solar EMERGY of the coastal waters supports a food chain web of populations converging to a few dominant larger species, including the Penaeid shrimp. The shrimp and other larger species are byproducts of each other, feeding back their services to the food web, continuously self re-organizing. The solar EMERGY per unit energy of one species (solar transformity of that species) measures what was required with all the division of labor operating to develop an efficient system, presumably of maximum production and utilization by consumer populations.

When an economic interface is attached to such a system without a feedback from the economy to augment the ecosystem, higher level consumers and their services are diverted and basic production may be reduced. Then the ecosystem may reorganize with energies going into other consumers of less human use. Development of the ponds diverted mangrove nursery areas, waters, and post-larvae without feedback reinforcement to the wild system to compensate for the resources drawn off for human consumption. The low proportion of the solar EMERGY of the coastal ecosystem that is going into shrimp trawl landings under the 1986 conditions may be due to the disturbances and diversions of the wild system by the new developments.

SHRIMP MARICULTURE DEVELOPMENT

The many new marine shrimp ponds like those in Figure 1 are intensive developments based on international sales of shrimp at high price. Shrimp ponds capture the shrimp growth process within the pond dikes. Everything has to be supplied. The growth is based on fertilized aquatic plant production plus added shrimp food. The critical inputs which are now in short supply are the post-larvae.

Energy Diagram of the Shrimp Pond Systems

An overview energy systems diagram showing main inputs to the shrimp ponds is Figure 5. Note the many more inputs that have to be purchased in the pond systems compared to the system of natural shrimp production and trawl harvest in Figure 4. The system resembles intensive agriculture with high levels of purchased inputs per area. Estuarine waters are pumped into the ponds to keep up with evaporation and seepage. The estuarine waters are generally low enough in salinity due to river inflows to keep the ponds from becoming too briny for optimum growth. Plans to dam and divert the river upstream may affect this.

The pumps also transfer inorganic fertilizer elements, organic matter to support the food chain, and some living components, as shown in Figure 5, from above. However, the pumps destroy many organisms that would otherwise contribute to the estuarine nursery system. Post-larvae are obtained from pumping in waters, from catching and transporting larvae, and from physiological treatments of adult shrimp previously raised or captured. In some areas in dry weather, the ponds mainly pump each others' waters around and around.

The food for the shrimp comes from the pumped-in waters containing detritus, from purchased organic matter, and from the algal-based food chain stimulated by high levels of nutrients. Nutrients are added by the pumps, especially when the outside waters are enriched with wastewaters; other nutrients are purchased fertilizers. Thus, the ponds may have higher concentrations of nutrients, organic matter, and shrimp post larvae than adjacent waters. Considerable fuels, electricity, machinery, and goods and services are required, all relatively high EMERGY inputs.

Shrimp are harvested and few get back to the estuary for reproduction. Ponds that receive food and larvae from the wild environment have less costs than those with more purchased inputs.

EMERGY Inputs and Investment Ratio of Shrimp Pond Mariculture

EMERGY evaluations of typical pond inputs are given in Table 14a. The EMERGY of fuels, services, and the post-larvae are largest. Indices are given in Table 14b. Economic developments displace undeveloped environmental resources, because development supplies additional EMERGY resource use consistent with the maximum power principle that reinforces such arrangements because it is a design principle of self organization.

The degree of development is measured by the EMERGY investment ratio defined as the ratio of purchased EMERGY to local free EMERGY (Figure 8). See Table 9. An investment ratio is normally between 1 and 7 during development, where fossil fuel based inputs are available to interact and amplify environmental resources. The ratio for Ecuador as a whole is about 0.25 (Table 9) and for the coastal region about 2.3 (Table 14b), which is lower than the same index for the United states, Texas, and Florida (7.0). Because undeveloped resources are more abundant in Ecuador, there is more free resource available to match investments. More EMERGY of environmental resources can be obtained for the same EMERGY investment. Developments require more free matching to be competitive.

The shrimp pond systems EMERGY investment ratio is 3.4, indicating more economic purchased inputs than environmental ones. In contrast, the shrimp ponds are more intensive than the preceding direct uses of the mangroves for fisheries, crabs, and shrimps, wood, etc., and more typical of the developed countries to which they sell. The higher the investment ratio (the more inputs are bought), the higher the costs and prices. An industry with higher investment ratio than the general one for the region has products too expensive for local sale.

With less intensive operations, less feeding, fertilizing, labor, pumping, etc., the yields would be less but so would the costs (as indicated by the investment ratio). Less intensive shrimp operations could be sold within Ecuador.

Shrimp Transformities and System Efficiency

The total resource required for a product is measured by the solar transformity in solar emjoules per joule (Solar EMERGY/energy). We believe there is an ultimate lowest transformity thermodynamically possible for conditions of maximum production. These lowest, most efficient transformities may be approximated by low intensity, long-standing utilization practices. The solar transformities of commercial Penaeid shrimp calculated from other studies are given in Table 15 so they can be compared with that of the new shrimp ponds. Values of less intensive ways of obtaining shrimp are generally 4 to 8 E6 solar emjoules per Joule, similar to other protein foods such as mutton and beef.

The SOLAR transformity of the pond yields (13.0 E6 sej/J, Table 14b) is much higher than the less intensive systems of harvesting from the coastal systems. This may indicate a wasteful process that uses too much resources for the results obtained. It may mean the system is vulnerable to being replaced by less intensive, older systems when prices vary.

The new shrimp system is using the older system for its reproductives (Figure 4), but undermining its basis by displacing the mangrove nursery and removing the post-larvae from the cycle that leads to continued reproduction.

Pelagic Fish Meal Supplements to Shrimp Ponds

In the more intensively managed ponds, fish meal from offshore fishing is added. The added feed makes a big difference in efficiency where everything else has been provided. The fish-food supplement containing 25% protein increases yields 2 to 5 times. The solar transformity is higher (more resource required per unit shrimp) where fish meal is absent, indicating a low efficiency situation. In Table 14b, the EMERGY amplifier ratio, the increased yield due to added fish meal, was 2.8. (See Figure 11.)

The fish meal has a moderately high transformity and increases the investment ratio from 2.6 (the regional value) to 3.4 making costs high for local consumption but still cheaper than food in developed countries where investment ratios are higher.

The solar transformity of herring, sardines, and anchovettas used to make the meal, although less than the shrimp, is high enough to be used as food. It may not make sense to divert a food product just to make a lesser quantity of luxury food for enriching a foreign economy. Money required to catch and process the fish is small relative to the EMERGY from the open seas upwelling system that is contained in the fish.

Table 14a.

Annual EMERGY Flows of Shrimp Pond Mariculture in Ecuador, 1986
53,000 Hectares; 1.5 m deep; see system diagram in Figure 5.

Note	Item	Raw Units J,g,$		Transformity Sej/unit	Solar Emergy E20	Macroeconomic US $E6
1.	Sunlight	1.97 E18	J	1	0.0197	0.99
2.	Rain	2.65 E15	J	15444	0.41	20.5
3.	Pumped sea waters	7.33 E15	J	15444	1.1	55.
4.	Post larvae	3.2 E9	ind	1.04 E11	3.4	170.
	Sum of Free inputs, direct sun omitted				4.92	246
5.	Labor	1.32 E14	J	2.62 E6	3.79	189.
6.	Fuel	2.34 E15	J	5.3E4	1.24	62.
7.	Nitrogen fertilizer	1.14 E9	g	4.19 E9	0.048	2.4
8.	Phosphorus fertiliz.	2.62 E8	g	2.0 E10	0.053	2.6
9.	Feed protein	3.29 E15	J	1.31 E5	4.3	215.
10.	Other services	3.56 E7	$ US	8.5 E12	3.0	151.
11.	Costs of post-larvae	3.56 E7	$ US	8.7 E12	3.0	151.
12.	Capital costs	1.93 E6	$ US	8.5 E12	0.164	8.2
13.	Interest paid back in sucres or sucre-converted-to $	11.2 E6	$ US	8.5 E12	.95	47.6
	Sum of Purchased Inputs				16.9	845
	Sum without organic feed				12.7	635
	Sum of all Inputs				21.82	1092
	Sum without organic Feed				17.6	880
14.	Shrimp yield using organic feed					
	Efficient value	1.68 E14	J	4.0 E6	6.72	336
	Resource used	1.68 E14	J	13.0 E6	21.80	1092
15.	Shrimp yield without organic feed					
	Efficient value	0.93 E14	J	4.0 E6	3.72	186
	Resource used	0.93 E14	J	18.9 E6	17.58	879

Table 14b. Indices from Table 14a

EMERGY investment ratio:
With organic feed = (16.9 E20 sej/yr)/(4.92 E20 sej/yr) = 3.4
Without organic feed = (12.7 E20 sej/yr)/(4.92 E20 sej/yr) = 2.6
For comparison, regional EMERGY investment ratio = 2.3

Solar transformity of Shrimp from shrimp ponds:(Input EMERGY)/(yield energy)
= (21.82 E20 sej/yr)/(1.68 E14 J) = 13.0 E6 sej/J.
Solar transformity in ponds without organic feed
= (17.6 E20 sej/yr)/(9.3 E13 J) = 18.9 E6 sej/J.
For comparisons, Peneid shrimp transformities elsewhere = 4 - 8 E6 sej/J (Table 15).

Net EMERGY yield ratio (Yield EMERGY/Purchased EMERGY):
With organic feed = (21.82 E20 sej/yr)/(16.9 E20) = 1.3
without organic feed = (17.6 E20)/(12.7) E20) = 1.4

EMERGY amplifier ratio explained in Figure 11; using an average transformity before and after amplifying production, 16 E6 sej/J.

EMERGY increase due to feeding with fish meal
16.0 E6 sej/J * (1.68 -.93) E14 J/yr

$$\text{amplifier ratio} = \frac{12.0\text{ E20 sej/yr}}{4.3\text{ E20 sej/yr}} = 2.8$$

EMERGY in added fish meal (Table 14a)

Footnotes for Table 14a

1. Direct solar energy:
   (127 E4 kcal/m2/yr)(4186 J/kcal)(0.7 absorbed)(530 E6 m2) = 1.97 E18 J/yr
2. Rain into ponds:(1 m/yr)(530 E6 m2)(1 E6 g/m3)(5 J/g) = 2.65 E15 J/yr
3. Pumped sea water to maintain water levels and salinity; evaluated freshwater content:
   (0.1 vol/d)(365 d)(1.5m)(5.38E5 m2)(.08 fresh)(1E6 g/m3)(3 J/g)=7.4 E15 J/yr
4. Input of post-larvae estimated from pond yield 3.0E4 tonne (Aquacultura de Ecuador, 1988):
   (30 E6 kg)(2.2 lbs/kg)(.70 tails))(35 tails/lb)/(.5 mortality) = 3.2 E9 ind./y
   Larvae can be thought about as information packages with little energy. When a shrimp releases many larvae, this represents a split of the EMERGY. Each tiny new individual carries an information copy. If the population is at steady state the larvae grow and are depleted in number by mortality eventually replacing two adults. This is a closed life cycle dependent on all the inputs necessary for the whole sequence. The EMERGY per individual is a transformity that grows reaching a maximum with the reproducing individuals. For a mortality commensurate with growth of the surviving, post-larvae with 50% further mortality represents 2 individuals that will finally restore 1 adult. Thus a transformity for the post-

larvae is half that of the reproducing adult before harvest (.5 * 4 E6 sej/J). On an individual basis the solar transformity is:
(0.5)(4 E6 sej/J)(10 g/ind)(.2 dry)(6.2 kcal/g)(4186 J/kcal) = 1.04 E11 sej/ind

5. Transformity of Labor in Ecuador estimated as national EMERGY/person/yr from Table 6.
Energy/person = (2500 kcal/d)(365 d/yr)(4186 J/kcal)(4186 J/kcal) = 3.82 E9 J/yr.
Solar transformity = (10 E15 sej/ind/yr)/(3.82 E9 J/ind/yr) = 2.62 E6 sej/J
90,000 fisherman 5 days a month; 20,000 people full time
(12.7 E6 person-days)(2500 kcal/person-day)(4186 J/kcal) = 1.32 E14 J/yr
6. Fuel: estimated as a percent of operating cost of pumped pond; price (Aquacultura del Ecuador, 1988):
($.10/lb shrimp)(26.4 E6 kg/yr)(2.2 lbs/kg)/($.34/gal fuel) = 17 E6 gal//yr
(17.1 E6 gal/yr)(137 E6 J/gallon) = 2.34 E15 J/yr
7. Nitrogen fertilizer for each 6 month start; 1.3 g/m3 N;
Volume: (1.5 m deep)(2.91 E8 m2) = 4.365 E8 m3
(4.365 E8 m3)(1.3 g/m3)(2/yr) = 1.135 E9 g/yr
8. Phosphorus fertilizer for each 6 month start: 0.3 g/m3;
(4.365 E8 m3)(0.3 g/m3)(2/yr) = 2.62 E8 g/yr
9. Feed; Fish meal from offshore herring, sardines; See text figure.
Total feed = sum of 23,600 Ha of semi-extensive ponds, fed for last 60 days.
(45 kg/ha/d)(1 E3 g/kg)(2.36 E4 ha)(60 d)(5.7 kcal/g)(4186 J/kcal) = 1.52 E15 J /yr
and 5500 Ha of semi-intensive ponds, fed for 300 days:
(45 kg/ha/d)(1 E3 g/kg)(5500 ha)(300 d)(5.7 kcal/g)(4186 J/kcal) = 1.77 E15 J/yr
Total feed supplement: (1.52 + 1.77 = 3.29 E15) J/yr
Much of the fish meal came from herring, sardines, etc mostly beyond the continental shelf. A solar transformity was estimated using organic carbon per square meter in herring sardines and anchovettas yield from the pelagic upwelling system published by Walsh (1981) divided by the solar EMERGY of the current. EMERGY of direct solar energy, and chemical energy of rain were also evaluated, but were less than the physical energy of the Humboldt current. As lesser by products of the world weather system direct sun and oceanic rain were omitted to avoid double counting.
Fish yield was 6.71 grams Carbon/m2/year with energy content:
(6.71 g C/m2/yr)(2.5 g org./g C)(5.7 kcal/g)(4186 J/kcal) = 4.00 E5 J/m2/yr.
Solar Emergy input per square meter of pelagic ecosystem generating this meal includes direct sun, rain, and the physical energy being used from the several sources driving the Humboldt current, the waves, and upwelling. The circulation of the east Pacific gyral includes wind energy transferred from the large scale circulation of the atmosphere wind plus large scale pressure gradients maintained by density differences due to temperatuare and salinity differences. In this pelagic system unlike the inshore ones, the tidal absorption and river contrtibutions are less. The physical energy was estimated by assuming a fraction of 1% of the kinetic energy used up per day in steady state with the sources. As the calculations below show, the EMERGY of the direct sun and direct rain are small by comparison.
EMERGY of direct solar Energy under offshore stratus::
(1 m2)(1.00 E6 kcal/m2/yr)(4186 J/kcal)(1 sej/J) = 4.19 E9 sej/m2/yr

Physical energy (tentative pending better sources);
(0.5)(.3 m/sec)(.3 m/sec)(100 m deep)(1 m2)(1025 kg/m3)(.01/day)(365 d/yr)
= 1.68 E4 J/m2/yr physical energy
EMERGY flux using solar transformity of river current at New Orleans: (4.67 E4 J/m2/yr)(80 E5 sej/J) = 1.34 E11 sej/m2/yr
Rainfall chemical energy on the open sea:
The solar transformity of rain falling over the ocean is different from that over land. Land is at a higher level in the geological hierarchy in which the solar energy falling on the seas is part of the basis for converging atmospheric processes to interact with continent building processes to generate rain on land. Solar transformity of rain over land was calculated as the quotient of the earths annual EMERGY divided by the Gibbs free energy of the rain over land relative to sea water. Rain over the sea is a necessary by-product feedback lower in the hierarchy with larger volume for the same earth EMERGY budget. Rain over ocean was assumed 71/29 of 1.05 E14 m3/yr rain over land in proportion to the ocean/land areas.

$$\begin{array}{l}\text{Solar transformity}\\ \text{of oceanic rain}\end{array} \quad \frac{8.1\text{ E }24\text{ sej/yr/earth}}{(2.57\text{ E14 m3/yr})(1\text{ E6 g/m3})(4.94\text{ J/g})} = 6380\text{ sej/J}$$

(1.0 m)(1 m2)(1 E6 g/m3)(4.94 J/g) = 4.9 E6 J/m2/yr
Solar Emergy: (4.9 E6 J/m2/yr)(6380 sej/J) = 3.13 E10 sej/m2/yr
Solar transformity of the fish meal based on 1 m2 of pelagic offshore; see Figure. EMERGY sum (1.34 +. 014 = 1.35) E11
(5.24 E10 sej/m2/yr)/(4.00 E5 J/m2) fish meal = 1.31 E5 sej/J
Costs (services) of feed supplement for 1986 from Camara de Productores de Camaron (1989)
EMERGY value added in fishmeal preparation:
(17% cost for supplementary feeding)(150 E6 $) = 25.5 E6 $
(8.7 E12 sej/$)($25.5 E6) - 2.2 E20 sej/yr

10. Operating costs given as $2.70 (1986 U.S. $) per kilogram of shrimp yield.
($2.70 US /kg)(26.4 E6 kg/yr yield) = 71.2 E6 U.S.$;
Half of this is for post larvae (note 11) and half for other services:
(0.5)(71.2 E6 US $) = 35.6 E6 US $.
For evaluating EMERGY, use 8.7 sej/$ within Ecuador calculated in Table 3.

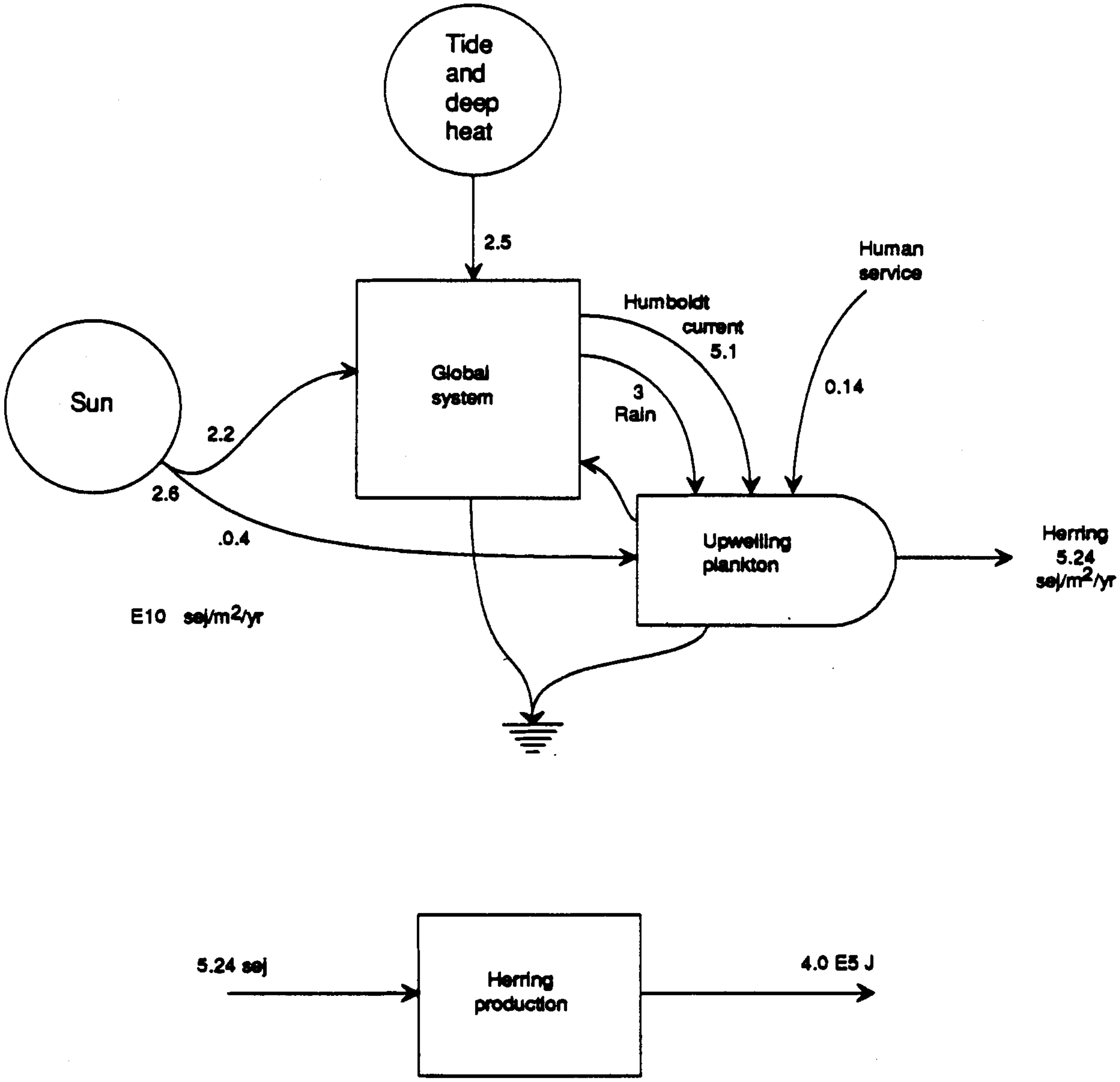
11. Costs of post larvae: 50% of total operating cost (note 10): 35.6 E6 US $.

12. Capital costs: (235 E3 sucre/ha)(2.91 E4 Ha)/(122 sucre/$) = 58 E6 $US
Assume 30 year life of ponds; annual cost = 58 E6 $US/30 yr = 1.93 $US/yr

13. Interest on loans for capital investment at 20% of principal
(.2)(58 E6 $US/30 yr) = 11.6 E6 $US. Whether aid to an investor within Ecuador or one in the U.S., the sucres when converted to international $ represent EMERGY according to the Ecuadorian EMERGY/$ ratio (8.5 sej/$).

14. Yield: 30,000 tonne/yr:
(3.0 E10 g/yr)(0.2 dry)(6.7 kcal/g dry)(4186 J/kcal) = 1.68 E14 J/yr

15. Yield without organic feed: 598 lb/Ha (Camara de productores de Camaron, 1989)
(5.3 E4 Ha)(598 lb/Ha)(454g/lb)(.2 dry)(6.7 Kcal/g dry)(4186 J/kcal)
= 9.28 E13 J/yr



Solar transformity of herring: $\frac{5.24 \text{ sej}}{4.0 \text{ J}}$ = 1.31 E5 sej/J

Figure for footnote 9, Table 14.

Table 15

Comparisons of Solar transformities of Penaeid Shrimp

Location and Source	Solar transformity sej/J
Shrimp, Gulf of Mexico (Fonyo, 1983)	3.77 E6
Shrimp Panga, Sea of Cortez, Mexico (Brown, Tennenbaum and Odum 1989)	3.99 E6
Upper consumers, Mississippi River delta (Odum, Diamond, and Brown, 1987, data from Bahr, Leonard, and Day, 1982)	8.0 E6
Ecuador shrimp ponds with organic feed, Table 14b	13.0 E6
Ecuador shrimp ponds without organic feed, Table 14b	18.9 E6

Neither costs nor market prices of environmental resources measure their ability to generate gross economic product dollars. Line 9 of Table 14a evaluates the contribution to the economy if the pelagic fish landings are used appropriately at home (215 E6 $/yr).

Net EMERGY of Shrimp from Ponds

The net EMERGY yield ratio of the shrimp from the ponds (1.3, Table 14b) indicates little contribution beyond what is required for its processing. Adding feed had little effect.

Compared to fuels or shrimp processed with low intensity means, pond shrimp cannot stimulate an economy much more than they do already. One would not expect a food to be much net EMERGY since food is one of the things an economy does with the net EMERGY it gets from its primary energy source, currently fossil fuels.

Regional EMERGY Change Accompanying Pond Development

The EMERGY evaluation of the present coastal systems supporting shrimp production in Tables 12 and 13 included some of the older natural pattern of producing shrimp in the sea and some new ponds. To simplify the comparison of the original system and the system after shrimp pond development, an EMERGY "change table" was prepared (Table 16), omitting those items not much changed by the development. This table was used to evaluate the benefits of alternatives shown in Figure 1 and 18. Since many inputs continue unchanged, the EMERGY change Table 16 has fewer line items than the general analysis. Included are totals for the EMERGY diverted from Ecuador to the U.S.

The ponds have a big contribution to the outside developed economy and a heavy negative drain on the local economy (Table 16), partly because of the differences in EMERGY/$ ratios of undeveloped and developed economies. On a worldwide basis there is a net increase in rate of generating EMERGY because the economic development of Ecuadorian resources draws on the available fuels and other resources.

Comparison of EMERGY Benefit of Alternatives

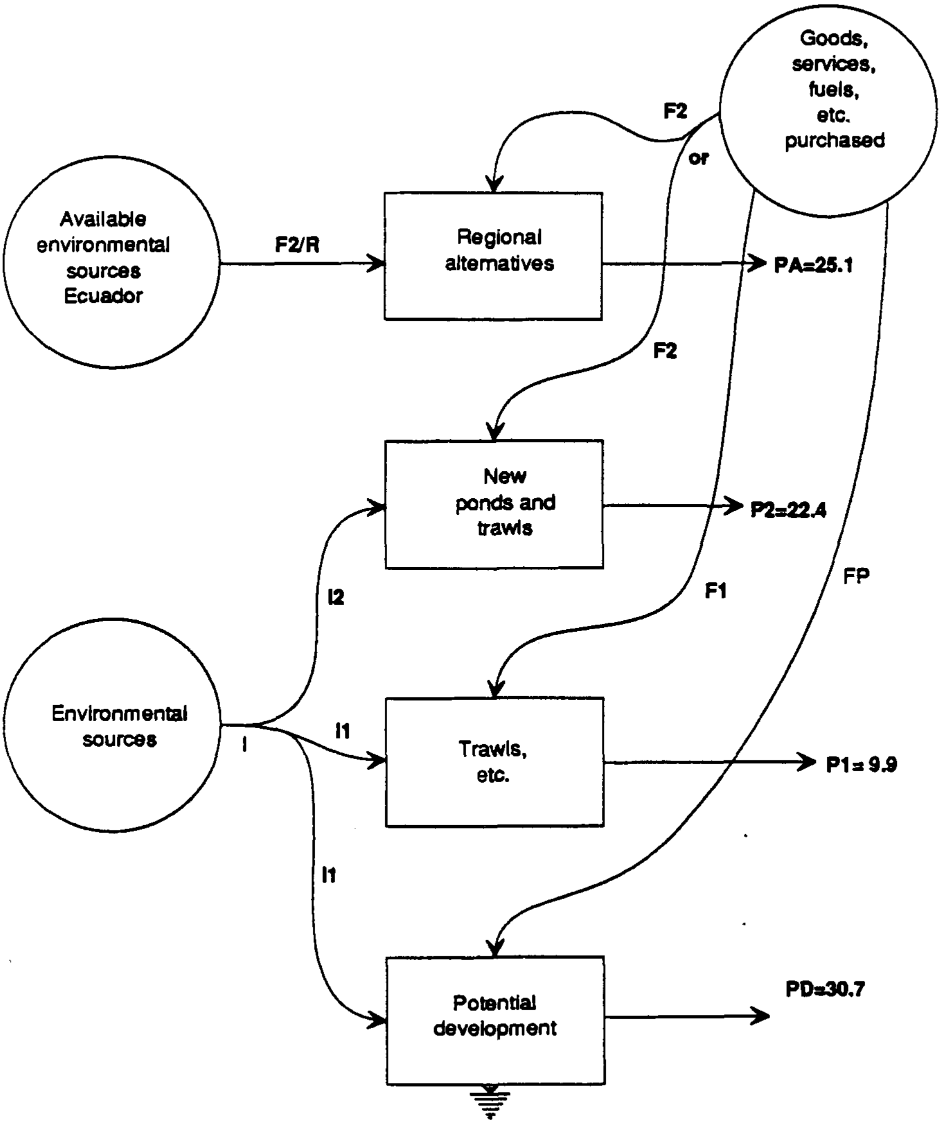
The concept of comparing the EMERGY benefit of alternatives was shown in Figure 3. This diagram was evaluated (Figure 18), comparing the natural shrimp production and trawl harvesting with the present shrimp pond system still based on post-larvae from the natural cycle. Also included is the EMERGY produced when the same amount of purchased EMERGY is invested in an alternative with the typical regional matching of environment. The best possible alternative is evaluated fourth, the original environmental contribution plus the EMERGY of purchased inputs matched at the regional investment ratio. (More matching is not economical.)

Optimum Development for Maximum Benefit

In any environmental development there is an optimal intensity which generates maximum EMERGY, part from the environmental work and part from purchased inputs. There are several maxima of concern:

1. The development intensity that maximizes pond shrimp yield and profit.
2. The development intensity that maximizes the region's shrimp yield including trawls and ponds.
3. The development intensity that maximizes the total EMERGY availability to the home country.
4. The development intensity that maximizes the EMERGY of investing countries.
5. The development intensity that maximizes the total EMERGY production and use worldwide.

Table 16 showed that shrimp pond developments contributed to developed economies by diverting resources of Ecuador without receiving payments of equal buying power.



E20 sej/yr

Figure 18. EMERGY benefit comparison of original system with trawls (P1), new system of ponds and trawls (P2), typical alternative investment (PA) and potential development (PD).

		E20 sej/yr
Environmental inputs to trawl fishery (0.227 E20 in Table 12B and environmental later displaced (9.1 E20 in Table 16:		I1 = 9.3
Environmental inputs to ponds (Table 14A, line 1-4):		I2 = 4.92
Purchased inputs to trawl fishery(Table 12a, line 11,12):		F1 = 0.61
Purchased inputs to ponds (Table 14a 16.9) and trawls:		F2 = 17.5
Old shrimp system (trawls and local fishing) :	P1 = I1 + F1	= 9.9
New shrimp system (trawls and ponds)	P2 = I2 + F2	= 22.4
Alternative regional development where investment ratio R = 2.3	PA = F2 + F2/R	= 25.1
Potential development, matching original I1	PD = I1 + I1 * R	= 30.7

Table 16

Change in Annual EMERGY Flows of Coastal System with Shrimp Pond Developments

	Item	Solar EMERGY E20 sej/yr	Macroeconomic $ E6 US 1989 $/yr*
Change in purchased inputs for pond development:			
1	Pond Labor and services added	+9.95	+498.
2	Pond fuel use added	+1.24	+62
3	Debt & profit lost	-0.71	-35.5
Changes in environmental resources to develop shrimp ponds:			
4	Loss of Mangrove area	-0.04	-2.0
5	Lost Areas of organic runoff	-0.22	-11.0
6	Shrimp Post-Larvae diverted	-3.4	-170.
7	Estuarine Waters diverted	-1.1	-55.
8	Fish diverted to feed shrimp	-4.3	-215.
9	Shrimp Trawl decrease	-0.046	-2.34
10	Environmental losses (items 4-9) =	-9.1	-455.
11	Exported pond shrimp =	-21.5	-1075.
12	Purchased gains & losses (items 1,2 & 3) (+10.17+1.24 -.71 E20) =	+10.7	+535
13	Buying power from exported pond shrimp	+7.56	+378
14	Net benefit to the local region: (7.56 +10.7 - 9.1 - 21.5 E20)	-12.04	-602
15	Net benefit to foreign economies: (21.2+.58 -7.56 E20)	+14.2	+710
16	EMERGY increase for the planet (21.2 - 9.1 E20)	+12.1	+600
17	Developed potential (U.S. level)	+9.4	+470
18	Sustainable potential (Long range)	+3.86	+193

Footnotes for Table 16

*Solar EMERGY change in sej/yr divided by 2 E12 sej/U.S. 1989 $

1 Labor, new services, costs of post-larvae, and capital costs in Table 14.
items 5, 10, 11, & 12 (3.79 + 3.0 + 3.0 + 0.164)= 9.95 E 20 sej/yr

2 Fuel, item 6 in Table 14.

3 Interest and profit assumed to leave the local area; item 13, Table 14.

4 Mangrove loss: 6000 hectares; Transpiration rate, 2.5 mm/day
(2.5 mm/d)(365 d/yr)(1000g/m2/mm/d)(4.8 J/g)(6.0 E7 m2 loss)(15444 sej/J)
= 4.05 E18 sej/yr

5 Organic runoff diverted by 46,600 hectares ponds on salterns and other areas contributing organic matter. 1 g/m2/day net production
(1 g/m2/d)(365 d/yr)(4.6 E8 m2 lost)(5 kcal/g) (4186 J/kcal)(6000sej/J) = 0.22 E20 sej/yr

6 Post larvae diverted: item 4 Table 14

7 Estuarine water (its fresh water content) diversion, item 3, Table 14.

8 Shrimp feed, item 9, Table 14.

9 (2000 pounds less/boat-McPadden, 1986)(249 boats) = 498,000 pounds
(4.98 E5 lb/yr)(454 g/lb)(.2 dry)(6.2kcal/g) (4186 J/kcal)(4 E6 sej/J) = 4.68E18 sej/yr.

10 Items 4-9 are losses from the environmental system but transferred for the most part to the pond system, thus being retained in the area. However, their use here is grossly inefficient, generating one fourth of the EMERGY yield compared to the enviromental and purchased inputs utilized. See Table 15.

11 Shrimp pond yield, item 14 Table 14.

12 Interest and profit removes EMERGY, especially if financed from the developed countries with much smaller EMERGY/$ ratio. See section on "Shrimp and International Exchange".

13 Shrimp exports item 2 Table 2. Buying power of US $, with US EMERGY/$ ratio
(315 E6 US $/yr)(2.4 E12 sej/US $ in 1986) = 7.56 E20 sej/yr

14 Buying power earned from shrimp sale plus purchased inputs of EMERGY used minus environmental losses minus the EMERGY of exported shrimp.

15 Benefit to foreign developed economy from shrimp received plus EMERGY of Ecuador's EMERGY/$ value of interest and profit (assuming half financed from developed country) minus purchases made with shrimp earnings.

16 Change in annual rate of EMERGY production and use considered on a world basis without regard to where it goes or is used or where the money goes:
Shrimp Pond production (which includes EMERGY in new fuel use and new items purchased from fuel-based economy (items 1 & 2) and some environmental inputs) minus environmental loss (item 10).

17 Temporary potential to developed economy using investment ratio of 7 (U.S.A.). For calculations in footnote 18.

18 Sustainable contribution was estimated as the sum of the renewable environmental input plus the economic development for the present regional investment ratio 2.3 which is similar to the world ratio.
The environmental EMERGY input(Table 13) per unit coastal area is:
(279 E18 sej/yr)/(1.195 E9 m2) = 2.33 E11 sej/m2/yr

The environmental EMERGY input for the coastal area is calculated as if all that shrimp pond area was calculated as if all converted into tidal mangroves even that which was originally upland.

(2.33 E11 sej/m2)(5.3 E8 m2) = 1.17 E20 sej/yr

Investment ratio 2.3 multiplied by environmental EMERGY is

(2.3)(1.17 E20 sej/yr) = 2.69 E20 sej/yr)

Environmental and sustainable economic matching:

(1.17 E20 + 2.69 E20) = 3.86 E20 sej/yr

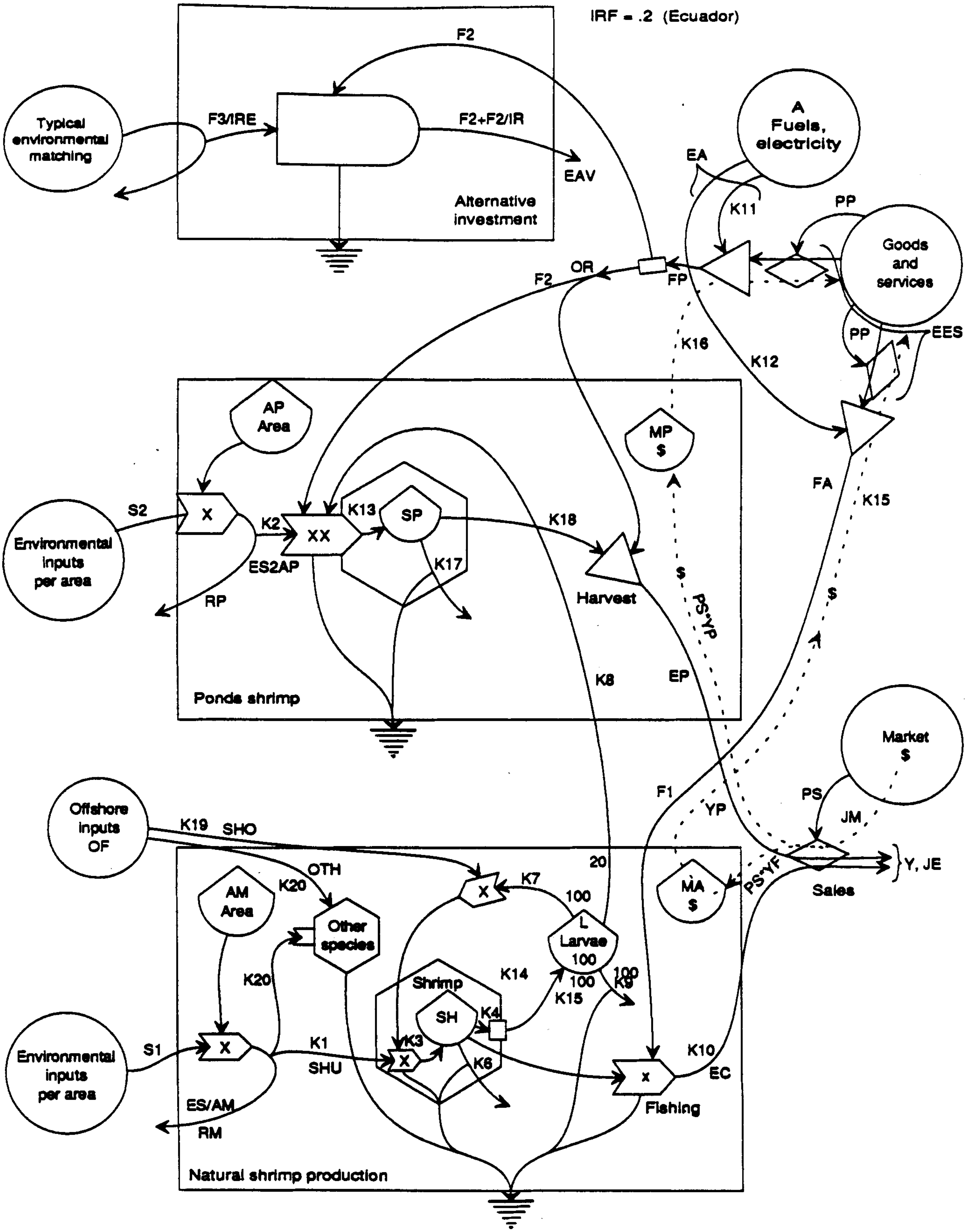


Figure 19. Overview simulation model MAXSHRIMP for determining the benefits of production of shrimp for various areas of pond development. Systems diagram includes variables and coefficients, EMERGY flow designations, and numerical values used for calibration.

A SIMULATION MODEL OF SHRIMP PRODUCTION SYSTEMS AND SALES

In order to study the effect of increased development of ponds on the shrimp production of the region as a whole, a model of two linked subsystems was prepared as shown in Figure 19. At the bottom is the original shrimp production system including estuarine and mangrove nursery. This includes offshore Shrimp using offshore resources for growth and generating larvae, some of which are exchanged back to shore and swept into the estuaries with the tide.

Figure 19 is an aggregated version of the more detailed systems overview in Figure 4. Table 17 contains the equations for this model and its program in BASIC is Table 18. Figure 19 also has the three alternatives to be compared arranged from top to bottom as in Figure 18.

At the top of Figure 19 are shrimp ponds which pump larvae from natural water where they grow on a food chain from solar energy and environmental inputs of waters and purchased inputs of food, fertilizers, and management by pond managers as already diagrammed in Figure 5.

Simulation of Benefits as a Function of Developed Area Using MAXSHRIMP.BAS

To study the way the shrimp system generates maxima, a BASIC microcomputer program MAXSHRMP.BAS was developed to simulate the model in Figure 19 with old and new shrimp production systems and the interfaces with markets abroad.

The program also calculates the EMERGY flows by multiplying the flows of energy, materials, or energy by the appropriate solar transformity. Figure 19b identifies the letter abbreviations for various categories of EMERGY that the program calculates during the simulation. The model is very sensitive to the rate of production of larvae (K14). More larval availability causes much wider oscillations in magnitudes.

Calibration of MAXSHRMP

Data on storages and flows used for calibration of MAXSHRMP are given in Table 20. Calibration numbers for flows and storages per square meter in Figure 19 were obtained from data assembled for EMERGY analysis (coastal area in Table 12 divided by 1.2E9 m2 area of mangrove nursery, and shrimp ponds in Table 14 divided by 5.3 E8 m2 area). Environmental inputs into the subsystems are represented by solar EMERGY S1, S2, and OF in solar emjoules per square meter. Money from sales is shown spent on inputs from the economy.

In this calibration, shrimp in the greater coastal area were represented per unit of mangrove nursery area that produced them. Then, when proportions of the mangroves are assigned to ponds, there is a proportionate loss of freshwater coastal shrimp and larvae. The pond and the undeveloped area parts of the model were both calibrated as if the mangrove nursery area was 100% in original mangroves or ponds, respectively.

Simulation Results

For the calibrated conditions and pond area, Figure 20 has the results of the simulation graphed with time. When the program is run and variables graphed with time (Figure 20), the system builds up to its carrying capacity and levels off, after some oscillation. Fluctuations of market prices from the larger economic system would cause additional oscillations, but were not included in these runs.

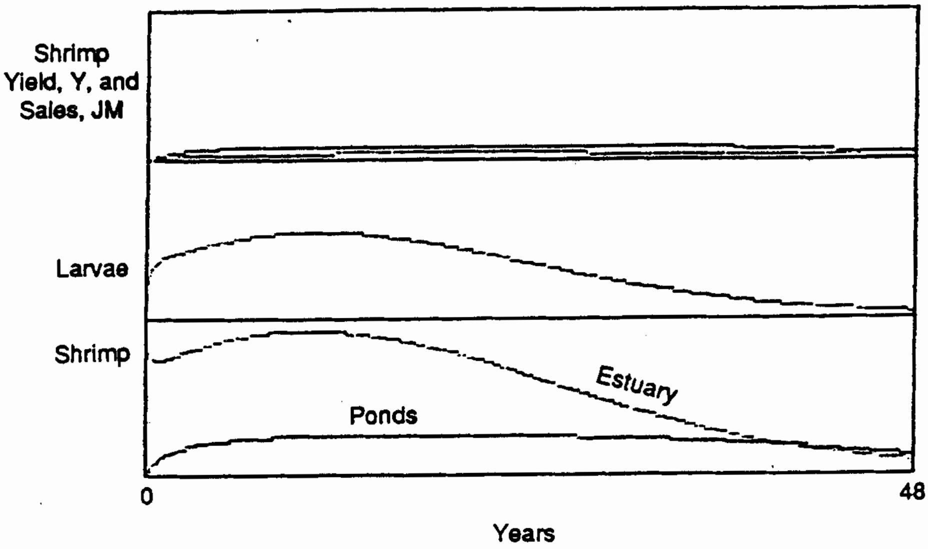


Figure 20. Results of simulating the program MAXSHRIMP.BAS Diagrammed in Figure 19, graphing variables with time for 10% of mangroves converted to ponds.

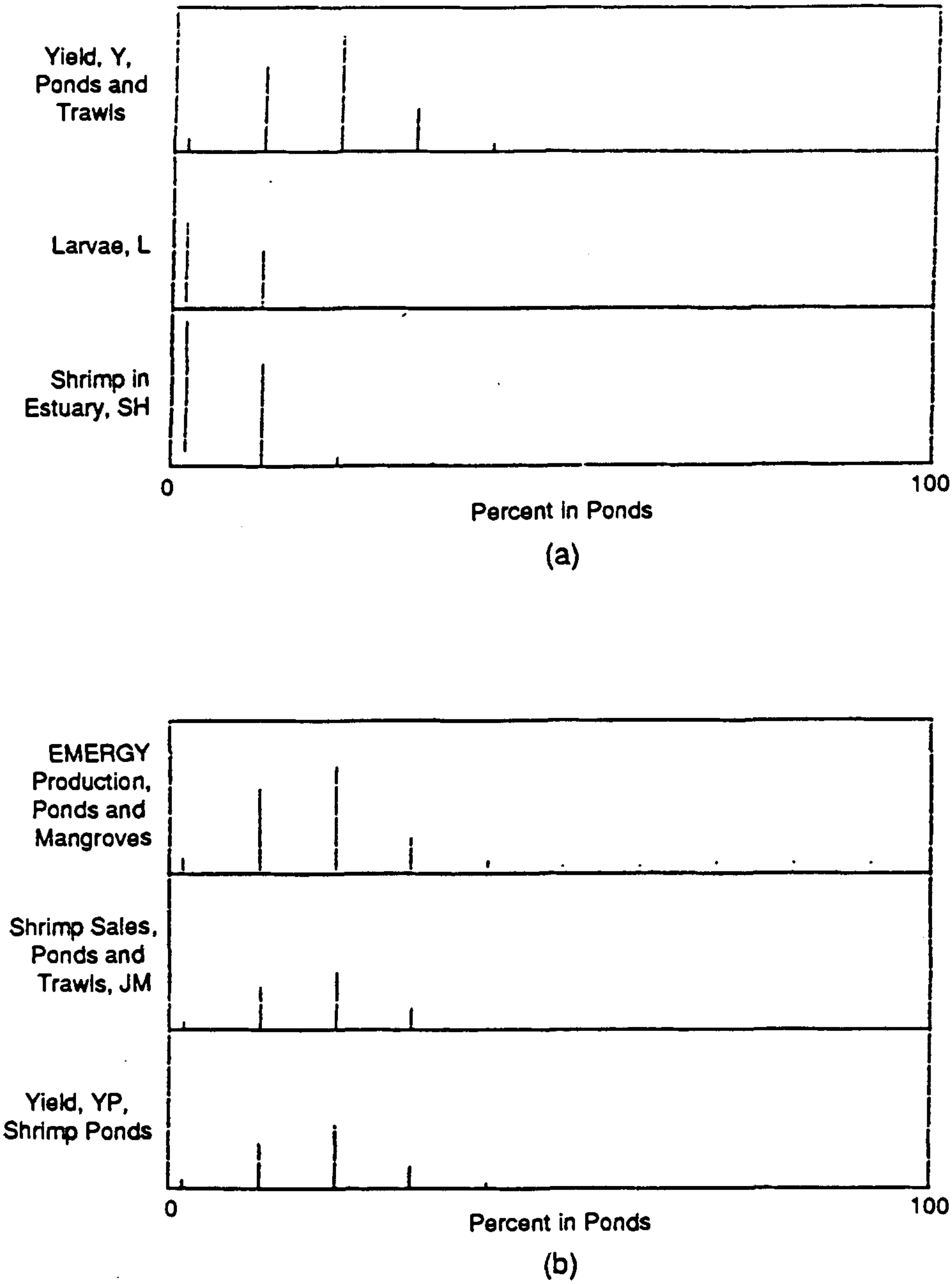


Figure 21. Results of simulating the program MAXSHRIMP.BAS (Figure 19), graphing stocks and EMERGY flows as a function of mangrove area developed into shrimp ponds. (a) Upper panel: yield of shrimp in ponds, Y; middle panel: shrimp larvae, L; lower panel: shrimp in estuary, SH (b) upper panel: total shrimp EMERGY production of ponds and mangroves, JE; Middle panel: total sales of shrimp, JM; lower panel, yield of shrimp from ponds.

Table 17

Equations for Simulation Program MAXSHRMP.BAS for the model in Figure 19.

Available environmental resources not used in the intertidal area	RM = S1*AM/(1 +K1*L*OF)
Available environmental resources not used in the ponds	RP = S2*AP/(1 + K2*L*FP)
Shrimp stock in estuary and outside waters	DSH = K3*RM*L*OF -K4*SH - K5*SH*FA
Shrimp stock in ponds	DSP = K13*RP*FP -K17*SH - K18*SP
Shrimp larvae	DL = K14*SH - K7*RM*L*OF - K9*L -K8*RP*FP
Fishing input efforts	FP = K16*MP/PP
Pond processing	FA = K15*MP/PP
Shrimp caught	YF = K10*SH*FP
Pond shrimp yield	YP = K18*SP
Total shrimp yield	Y = YP + YF
Total shrimp sales	JM = PS * Y
Shrimp pond money	DMP = PS*YP - K16*MP
Fishing money	DMA = PS*YF - K15*MA
EMPOWER use	JE = TRS*(K1*RM*L*OF) +TRS*(K2*RP*L*E) +TRA*K11*E +TRA*K12*F +TRM*PP* (K15*MA + K16*MP)

Rather than use a spread sheet, this program has the calculation of coefficients in the front part of the program. See Table 18.

Table 18

BASIC Program MAXSHRMP.BAS for the Model in Figure 19.

```
10      REM IBM
20      REM MAXSHRMP (Optimum  land use for maximum EMPOWER)
30      CLS
40      SCREEN 1,0: COLOR 0,1
50      LINE (0,0)-(319,180),3,B
70      X = 1:REM x=0 for time graph; x=1 for variables with area as abscissa
75      E = 0:REM E=0 and z = 0 for yields,larvae,and coastal shrimp with area
76      REM E=1 and Z=0 for total empower, sales, and pond yield with area
78      Z = 0:REM Z = 1 for alternative investment and overall investment ratio
80      LINE (0,120)-(320,120),3
90      LINE (0,60)-(320,60),3
100     REM Outside sources for calibration
110     S1 = 2.34E+11
115     S2 = 2.8E+11
120     PS = 1.88E-06:REM $/j
130     PP = 1 :REM service effort expressed in $ per year cost
135     OF  = 1
140     RM = 4E+10
150     RP = 8.2E+10
200     REM Calibration values
210     SH = 8000
215     SP = 700000!
220     L = 100
230     AM = 1
240     AP = 1
250     FP = .14
260     FA = .001
285     MA = .1
290     MP = 1!
300     REM Coefficients
310     K1 = 0.1*S1*AM/RM/L/OF
320     K2 = 0.9*S2*AP/RP/L/FP
330     K3 = 8000/RM/L/OF
340     K4 = 4000/SH
350     K5 = 2000/SH/FA
360     K6 = 4000/SH
370     K7 = 100/RM/L/OF
375     K8 = 20/L/RP/FP
380     K9 = 100/L
385     K10 = 866/SH/FA
387     K11 = 4000000!/FP
390     K12 = 400000!/FA
395     K13 = 1660000!/RP/L/FP
397     K14 = 200/SH
400     K15 = .001/MA
410     K16 = .14/MP
420     K17 = 800000!/SP
430     K18 = 800000!/SP
440     K19 = 1.9E+10/RM/L/OF:REM Shrimp use of offshore EMERGY
450     K20 = 0.8*S1*AM/RM/OF:REM Other species use of Mangrove EMERGY
460     K21 = 1.5E11/RM/OF:REM Other species use of offshore EMERGY
```

```
500     REM Solar transformities: sej/J
515     TRM = 8.7E+12: REM Sej/$ for Ecuador
525     TRA = 50000!: REM sekcal/kcal for fuel
600     REM External Sources
610     OF = 1
630     YP = 800000!
640     YF = 866
650     PP = 1
660     PS = 1.88E-06
665     S1 = 4.4E+11:REM sej/yr
670     S2 = 8.6E+11:REM sej/yr
690     IRE = 2.5: REM Investment ratio-Ecuador
700     REM Starting storages
705     TA = 1
710     AP = .02*TA
720     AM = TA-AP
725     L = 200
755     PP = 1
760     MA = .01
770     MP = .01
780     SH = 50000!
790     SP = 500
800     REM Scaling factors
805     DT = .03
810     T0 =  .15
820     SH0 = 1000
830     L0 =  10
840     Y0 = 10000
850     JE0 = 2E+11
860     JM0 = .04
870     SP0 = 3000!
880     YP0 = 20000!
890     REM Equations
900     FP = K16*MP/PP
905     AM = TA-AP
910     FA= K15*MA/PP
920     RM= S1*AM / (1 + K1 * L*OF+K20)
930     RP = S2*AP/(1 +K2*L*FP)
940     DSH= K3 * RM* L*OF - K4 * SH- K5 * SH*FA-K6*SH
950     DSP = K13*RP*L*FP- K17*SP - K18*SP
960     DL = K14 * SH- K7 * RM*L*OF -K8*RP*L*FP-K9*L
970     DMA = PS*YF - K15*MA
980     DMP = PS*YP -K16*MP
1000    REM EMERGY flows:
1005    ESIAM = S1*AM
1007    ES2AP = S2*AP
1010    SHU=K1*RM*L*OF:REM Inshore resource use by shrimp
1020    ES2 = K2*RP*L*FP:REM ponds
1030    SHO = (K19*RM*OF*L):REM part of offshora resource used by shrimp
1035    OTH = K21*OF*RM:REM Other nursery species use of offshore resource
1040    EA = TRA*(K11*FP +K12*FA):REM Fuels
1050    EGS = TRM*(K15*MA +K16*MP):REM Service
1052    F2 = TRA*K11*FP + TRM*K16*MP:REM Ponds purchased
1055    EAV = F2 + F2/IRE:REM Alternate investment
```

```
1058   EP = ES2AP +F2:REM Ponds total emergy
1060   JE = ES1AM +ES2AP +SHO +EA +EGS +OTH:REM Empower total (ponds &
       freewaters)
1070   IRF = (TRA*K12*FA +TRM*K15*MA)/(SHU+SHO):REM Fishery investment ratio
1075   IRP = F2/ES2:REM Ponds investment ratio
1080   IR = (EGS +EA)/(ES1AM +ES2AP +SHO):REM Overall inmvestment ratio
1100   REM Change equations
1110   SH= SH+ DSH*DT
1120   SP = SP +DSP*DT
1130   IF SH < .0001 THEN SH = .0001
1140   L = L + DL * DT
1150   IF L < .00001 THEN L = .00001
1160   MA = MA +DMA*DT
1170   MP = MP +DMP*DT
1180   YF = K10*SH*FA
1190   YP =K18*SP
1200   Y = YP + YF
1210   JM = PS *Y
1220   REM Plotting
1230   IF X = 1 GOTO 1295
1240   PSET (T / T0,180 - SH / SH0),1
1250   PSET (T / T0,120 - (L / L0)),2
1260   PSET (T / T0, 60- Y / Y0),3
1270   PSET (T/T0, 60 - JM/JM0),1
1280   PSET (T/T0, 180 - SP/SP0),3
1290   IF X = 0 GOTO 1410
1292   IF T/T0 < 300 GOTO 1410
1295   IF Z = 1 GOTO 1350
1296   IF E = 1 GOTO 1310
1297   PSET (320*AP/TA, 60-Y/Y0),3
1299   PSET (320*AP/TA, 120-L/L0),2
1302   PSET (320*AP/TA, 180-SH/SH0),1
1304   IF E = 0 GOTO 1400
1310   PSET (320*AP/TA, 120- JM/JM0),1:REM Tolal sales
1320   PSET (320*AP/TA,  60- JE/JE0),2:REM Total EMERGY (ponds and freewater)
1330   PSET (320*AP/TA, 180 - YP/YP0),3:REM Pond yield of shrimp
1340   IF Z =0 GOTO 1400
1350   PSET (320*AP/TA,  60 - EAV/JE0),2:REM Alternative investment of F2
1370   PSET (320*AP/TA, 120 - IRP),3:REM overall EMERGY investment ratio
1400   IF T/T0 >310 GOTO 1440
1410   T = T + DT
1420    IF T / T0 < 320 GOTO 890
1430   IF X =0 THEN END
1440   T = 0
1442   MA =.01: MP = .01
1444   SP = 1: SH = 5: L = 10
1450   IF AP > TA THEN GOTO 1490
1460   AP = AP +.1*TA
1470   IF AP > TA GOTO 1490
1480   GOTO 890
1490   END
```

Table 19

Calibration of the Simulation Program MAXSHRMP in Table 18

STORAGES (state variables):

(SP)	Pond shrimp storage per unit area estimated: (50,000 ind/1E4m2)*(.5 survival)*(454g/70 ind)*(5.7 kcal/g)(4186 J/kcal) = 0.7 E6 J/m2
(SH)	Shrimp storage in mangroves per unit areas (539/ ind./1E4 m2)(454 g/70 ind)(5.7 kcal/g)(4186 J/kcal) = 8000 J/m2
(L)	Plankton stage individuals free in coastal waters (Order of magnitude from Guzman de Peribonio et al, 1981) 10 ind/m3 * 10 m = 100 ind/m2 coastal area;
(MP)	Cash on hand for pond operations equivalent to 5 times annual costs; per area of shrimp ponds (5)*($111 E6)/(5.3 E8 m2) = $1/m2
(MA)	Cash on hand for trawl operations per unit area of nursery mangroves (5 * $ 2.58 E6)/(1.19E9 m2) = $.01/m2
(A)	Total area of mangroves & ponds = 1.0

SOURCES & FLOWS: For environmental inputs, annual solar EMERGY was used.

(S1)	Mangrove area (279 E18 sej/yr)/(1.19E9 m2) = 2.31 E11 sej/m2/yr.
(S2)	For ponds: (1.5 E20 sej/yr)/(5.3 E8 m2) = 2.8E11 sej/m2/yr;
(OF)	Offshore environmental availabilities set at unity (1.0)
(FP)	same as (K16) pathway, $.14/m2/yr
(PS)	($315 E6/m2/yr)/(1.68 E14 J/m2/yr) = 1.88 kE-6 $/J
(PP)	= 1.0; Money and costs both in $ units
(RM)	Residual unused environmental availability to mangroves, 10% of S1
(RP)	Residual unused environmental availability to ponds, 10% of S2
(YF)	Trawl yield per area of mangrove nursery: (2.08E13 J/yr)/(2.4E10 m2) = 866 J/m2/yr
(YP)	Mariculture yield per area of ponds: (1.68 E14 J/yr)/(5.3 E8 m2) = 316,981 J/m2/yr
(K1)	10% of S1*mangrove area
(K2)	90% of S2*pond area
(K3)	Shrimp produced, one year replacement time: 8000 J/m2/yr
(K4)	Shrimp used to make larvae as 1/4 ; 4000 J/m2/yr
(K5)	Shrimp harvested as 1/4: 2000 J/m2/yr
(K6)	Depreciation as half of turnover: 4000 J/m2/yr
(K7)	Larvae metamorphosing in Mangroves: 100 ind/m2/yr
(K8)	Post-larvae used or killed by ponds (100,000)/(1E4 m2)/0.5 year) = 20 ind/m2/yr
(K9)	Larval mortality: 100 ind/m2/yr
(K10)	Trawl yield--see YF 866 J/m2/yr
(K11)	Fuel, ponds:(2.39 E15 J/yr)/(5.8 E8 m2) = 4 E6 J/m2/yr
(K12)	Fuel, trawls: (5.4E14 J/yr)/(1.2 E9 m2) = 4 E5 J/m2/yr
(K13)	Pond shrimp production, 6 month replacement: 1.6 E6 J/m2/yr
(K14)	Larval production, half year replacement: 200 ind/m2/yr
(K15)	Trawl costs, goods-services: $1.3E6)/(1.2 E9 m2) = $ .00108
(K16)	Pond costs,goods-services: (25.5 +35.6+2.0+5.8+5.8 = 72.7 E6 $/yr)/(5.3E8 m2) = $.14/m2

(K17) Pond Shrimp mortality, half of production: 0.8 E6 J/m2/yr

(K18) Pond shrimp harvested, half of production: 0.8 E6 J/m2/yr

(K19) SHO Shrimp use of coastal EMERGY from Table 12b: (0.227 E20 sej/m2/yr)/(1.19 E9 m2) = 1.9 E10 sej/yr

(K20) Drain of other species on coastal shrimp availability, 80% of S1 = 3.5 E11 sej/m2/yr

(K21) Loss of offshore EMERGY use by other nursery species (8 • SHO). See coefficient K19.

At the top is the combined yield of shrimp from the new ponds and the old system of fishing in natural waters. The total sales Jm are plotted also. The lower part of Figure 20 has the growth and leveling off of shrimp post-larvae L, shrimp in the environments SH and in the ponds SP. A run with time shows up as a vertical bar. Then the program increases F, the development intensity and runs again, plotting another bar, and so on. The results are graphs of variables as a function of development area. Increasing numbers of ponds reduce the areas supporting the wild populations, reduce the stocks and food supplies in the wild. Costs of operating ponds increase. Shrimp caught in the wild decrease.

Effects of Adding More Shrimp Ponds

Figure 21 has the results of simulations plotted as a function of the area of shrimp ponds developed. First is the total EMERGY use in the system calculated as the sum of the solar EMERGY in environmental inputs S, in the fuels use in the purchased operations and in the goods and services input. The graphs include total EMERGY, sales and yield. In Figure 21 as development increases, the maximum EMERGY benefit and sales of trawl and pond shrimp together for the region as a whole decline because resources are diverted as fast as purchased inputs are added.

The lower panel shows that an intermediate developed area produces maximum yields. The lower panel of the graph is the yield for the ponds only. The maximum for the ponds alone is further to the right than the maximum contribution to the economy of the region. If one continues pond development so as to maximize profit to the shrimp operators, regional economy suffers.

In some runs where environmental resources available to the wild populations were restricted and larvae were adequate, a maximum was found for the EMERGY and regional sales.

Sources of Hatchery Post Larvae

At the time of the study, the shrimp ponds of Ecuador depended on the natural life cycle of the *P. Vannemei* to generate post larvae or to provide gravid females caught offshore. Hatcheries were in extensive use, but female shrimp that supply up to 300,000 eggs each were obtained from the natural population off shore. Since the hatchery post-larvae tend to be clones of a few adults, and not subject to the selective processes of the wild cycle, questions were raised about whether the hatchery post larvae were as viable as those captured during their migration into the estuary. The selection process of natural environment may be an important EMERGY contribution to genetic viability. Culture methods include antibiotics with unknown effects on larval stamina.

In some Asiatic shrimp pond culture, penaeid shrimp have grown to reproduction size in ponds and used to seed the hatcheries. In other words, it is possible to close the life cycle of shrimp aquaculture without the wild system. However , this increases the inputs required in time, labor, feeding, fuels, etc. for the same output. The Ecuador system uses the environmental system to do half the work. An EMERGY analysis of a system that closed the cycle without use of the environmental work would show whether it could be economic or whether the additional inputs would make too-high ratio of purchased to free inputs to compete.

Data Limitations

There are several numbers for which the calculations are tentative for lack of good data or confidence in the aggregation. These include the EMERGY evaluation of the contributions of the offshore Peru current. More data are needed on the trawl fishery costs and fuel requirements, and evaluation of the geological components of the national system. However, refinements are not expected to change main conclusions.

CONCLUSIONS

This report includes EMERGY evaluation of shrimp ponds and the mangrove bordered estuaries in Ecuador, the role of shrimp in the economy of Ecuador and its foreign trade, simulation models of shrimp ponds and their interface with the economy, and public policy recommendations for maximizing sustainable economic use of the environmental resource. These studies illustrate the methodology for evaluations and developing recommendations for sustainable development of environmental resources and economically vital foreign aid.

In the absence of any public policy on managing environmental resource for the public good, the free market economy causes the mangroves and shrimp previously supporting the public generally, to be brought into private shrimp business, the products going overseas with much less real wealth returning in the small buying power of the money received. Those in the shrimp industry in Ecuador become part of the overseas business enterprises with overseas money no longer contributing much to the local economy. The pattern also applies to oil exports. If the pelagic fish, mangrove, river, oil, and shrimp products were utilized within Ecuador, prices would drop, standards of living rise, inflation decrease and more buying power would remain in Ecuador.

The pattern of selling a valuable raw product abroad produces a very large drain from the underdeveloped country because of the differences in EMERGY/$ ratio, because of the large, previously unevaluated contributions of the environment to shrimp, because of over-intense developments of some of the ponds, and because valuable pelagic fish landings are being used as auxiliary shrimp food.

In the rush to develop ponds and agriculture, contributions of coastal environmental systems have diminished. Measures to help the environment generate more wealth could include: decreasing channelization; returning some of the *Peneus vannamei* to the estuary at time of pond harvest to insure larval stocks; returning the coastal areas to mangroves, and changing inland dam development plans to return some of the seasonal flood of the Duale-Peripa river to the estuary.

Decreasing the intensity of pond operation may lower yield but will reduce costs, lower shrimp prices, allow local consumption and generate more net benefit to the region. Using the high EMERGY pelagic fish landings for local food contributes more to the standard of living than feeding shrimp to profit foreign markets.

The simulation of models showed maximum benefit to Ecuador occurs with less area developed in shrimp ponds than that which maximizes shrimp pond profits. In order to substitute home use of products for unequal trade abroad, some existing ponds may be converted to other aquaculture.

To keep environmentally produced wealth within Ecuador to stimulate its own economy, requires that there be less borrowing from developed currencies, less sales to countries with higher EMERGY/$ ratio, keeping intensity of developments from exceeding the local investment ratio, using high EMERGY products for high quality purposes, and matching environmental EMERGY with purchased inputs without diversion of destruction.

General Recommendations for Maximum Success of Economic Development

Guidelines for development that reflect the principles illustrated by these studies on shrimp in Ecuador include the following:

- Value of environmental areas and products should be determined with EMERGY measures and then related to currency and international dollars on a national basis rather than using market values which mainly cover human services, often a small part of environmental products from nature.

- Density of development and amount of area developed should be that which maximizes regional EMERGY and thus direct and indirect contributions to the whole economy. Maximizing market value and profit of the environmental industry may detract from the general economy, especially if there is no feedback from that industry to reinforce the input processes of the environmental systems.

- Intensity of development as measured with investment ratio should not be greater than the typical intensity for the region as measured with EMERGY investment ratio.

- Contribution of an environmental area before and after development should be compared with EMERGY evaluation and these compared with the potential development that has the national EMERGY/$ ratio. Evaluation is made as shown in Figure 18.

- Sales of products should be made to the local economy. If international sales are made, arrangements should be made to obtain equal EMERGY value in exchange for the environmental products or services. This may require that sales agreements include other compensations such as information, service, and military protection. To some extent these exchanges have been part of the exchanges between less developed and highly developed countries, but there has not been an adequate basis for determining equity. Perhaps the EMERGY method provides the means.

- An Emdollar may be defined as the basis for exchange equity with the conversion between each country's currency and the emdollar based on the EMERGY/currency ratios. Manipulations of currencies and exchange rates should be evaluated with EMERGY benefit calculations.

Acknowledgment

We are grateful for the opportunity provided by the Coastal Resources Center to apply new methods of environmental and macroeconomic evaluation. Data were supplied by Gordon Foer, Bruce Epler, Lynne Hale, and John Walsh. Dan Campbell read and criticized the manuscript.

We acknowledge the stimulating leadership of Stephen Olsen in connecting scientific intitiatives with critical problems of the world's economy.

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PRINCIPLES OF EMERGY ANALYSIS FOR PUBLIC POLICY[1]

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This paper explains EMERGY concepts for maximizing public wealth, and gives explanations for why the principles are valid. The viewpoint is that the world economy, the nations, and states increase their real wealth and prevail according to these principles.

A new quantity, the EMERGY, spelled with an "M" measures real wealth. Here we are using "wealth" to mean usable products and services however produced. Maximizing the EMERGY is a new tool for those making public policy choices among alternative programs, resources, and appropriations. Choosing actions and patterns with the greatest EMERGY contribution to the public economy maximizes public wealth. EMERGY analysis is not advocated as a tool for estimating market values. This paper explains EMERGY evaluation and its use to improve public policies.

Human Choices Consistent with Maximum Sustainable Wealth

Many if not most people of the world assume that the economy is not subject to scientific prediction but is a result of human free choices by businesses and individuals motivated by their individual needs. A different point of view is that the human economy, like many other self-organizing systems of nature, operates according to principles involving energy, materials, information, hierarchical organization, and consumer uses that reinforce production.

If those human choices that lead to successful, continuing wealth fit principles of larger scale self organization, then the economy ultimately uses human choices to follow the scientific laws. The human free choices are the means for finding the maximum public wealth by trial and error. Choices that do not contribute to the public wealth are not reinforced in the larger scale. Eventually patterns that do develop more wealth take over and are sustained.

However, if the designs of society that maximize wealth can be determined from scientific principles, then better choices are possible with less trial and error. EMERGY evaluations and designs based on unchanging physical measures may provide an efficient and predictable means for achieving public wealth and sustainable economic patterns.

Scientific Basis for Economic Vitality

More in the education of scientists and engineers than in that of journalists and business people is the recognition that resources and products are wealth. An economy is vital when it has abundant goods and resources and uses them to reinforce productivity. Energy, minerals, and

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[1] Chapter 1. from "EMERGY AND POLICY," J. Wiley

information are the real wealth. It takes energy to concentrate the minerals needed by an economy. It takes energy to maintain and process information. When resources are abundant and cheap, there can be abundant wealth and a high standard of living. If resources and basic products are imported cheaply, abundant wealth is imported.

The Irrelevance of Market Prices to Wealth

Although the market value of products and services is important to individuals and business budgets, it is largely irrelevant as a measure of wealth. A tank of gasoline drives a car the same distance regardless of what people are willing to pay for it. A day of summer sunlight generates so much corn growth regardless of whether a human thinks it's free or not. A nugget of copper concentrated by geological work will make so much electric wire regardless of its price.

When resources are abundant, wealth is great, standard of living is high, and money buys more. But when resources are abundant, market values and prices are small. Prices are not a measure of resource contribution to wealth.

When resources are scarce, prices are high not only because shortages affect demand, but because more human services are required to mine, transport, or concentrate scarce resources. By the time the resources have been collected and used, the net contributions of the resource have been diminished by the extra efforts to process the resources.

Figure 1 shows the economic interface between a typical environmental process that generates the resources and the human economy. Money circulates through the people involved in processing the resources, but no money goes to the works of the environment. The money paid is not a measure of the wealth that comes from nature's work on the left. In other words, prices are not only not a measure of the contribution of resources and commodities to an economy, they are inverse, being lowest when contributions are greatest. Another kind of measure is required for evaluating contributions to public wealth.

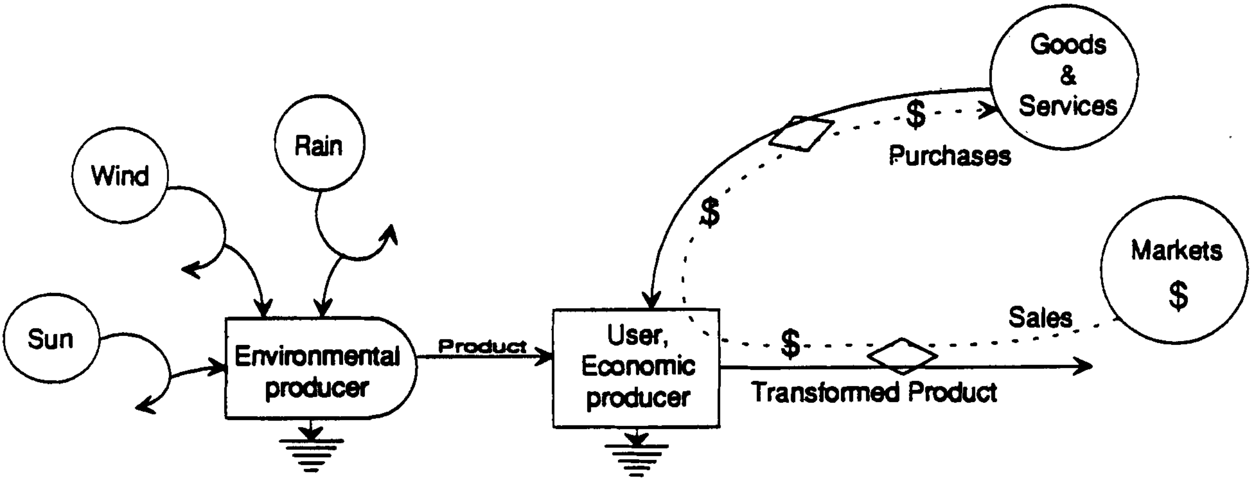


Figure 1. Environmental production process and an interfacing economic user which is also a human-paid economic production process. Notice absence of reinforcement from user to environment producer.

EMERGY Definition

EMERGY of a product is the work which went into making it expressed in units of one type of energy. The unit of EMERGY measure is the emjoule.

For example, a cubic meter of rain water over land has a solar EMERGY content of 7.5 E10 solar emjoules. This means that 7.5 E10 solar joules directly and indirectly were involved in bringing this much rainwater to the land.

EMERGY and Sustainable Uses

Because EMERGY measures what went into a product, it is also a measure of what that product should contribute to the economy if its use is to justify its production.

In the self organizational process of economies and of environmental systems, products that require more work in their manufacture either contribute more to the system commensurate with what was required to make them, or the production is discontinued.

Thus, EMERGY is not only a measure of what went into a product, it is a measure of the useful contributions which can be expected from that product as an economy self organizes for maximum production.

EMERGY goes with a product as it is processed and transported. It is like a memory, since it records what went into that product.

Reinforcement of Production Required for Sustainable Uses

Whereas individualistic human-centered concepts of economic benefit view production as directed to benefit the human consumer, real self organizing systems develop with a different consequence. All uses (by consumers) reinforce production processes or are displaced by those which do. Economies which allow allocation of resources to wasteful luxuries are not sustainable, being displaced by those with better reinforcement of their productive basis. This viewpoint contrasts with the economic view that any expenditure of money is good whether it be for unnecessary products and services or not.

Consumers that use products without contributing to production processes elsewhere in the system divert resources, reducing the wealth of the system below its potential. For example, consumers that use larger cars than necessary for their maximum service to the economy reduce the potentials for economic reinforcement inherent in the products they consume.

Consumers that use products of nature's production such as fisheries without contributing some reinforcement to the natural production process cause that production system to be displaced by alternative systems which are not so exploited. Because marine fisheries have rarely reinforced their stock production processes, many have been displaced. In contrast, most sustainable systems of agriculture apply extensive reinforcement to their soil production processes by applying various fertilizers and other soil improvements. Figure 2 compares sustainable systems that reinforce with an unsustainable design that does not reinforce.

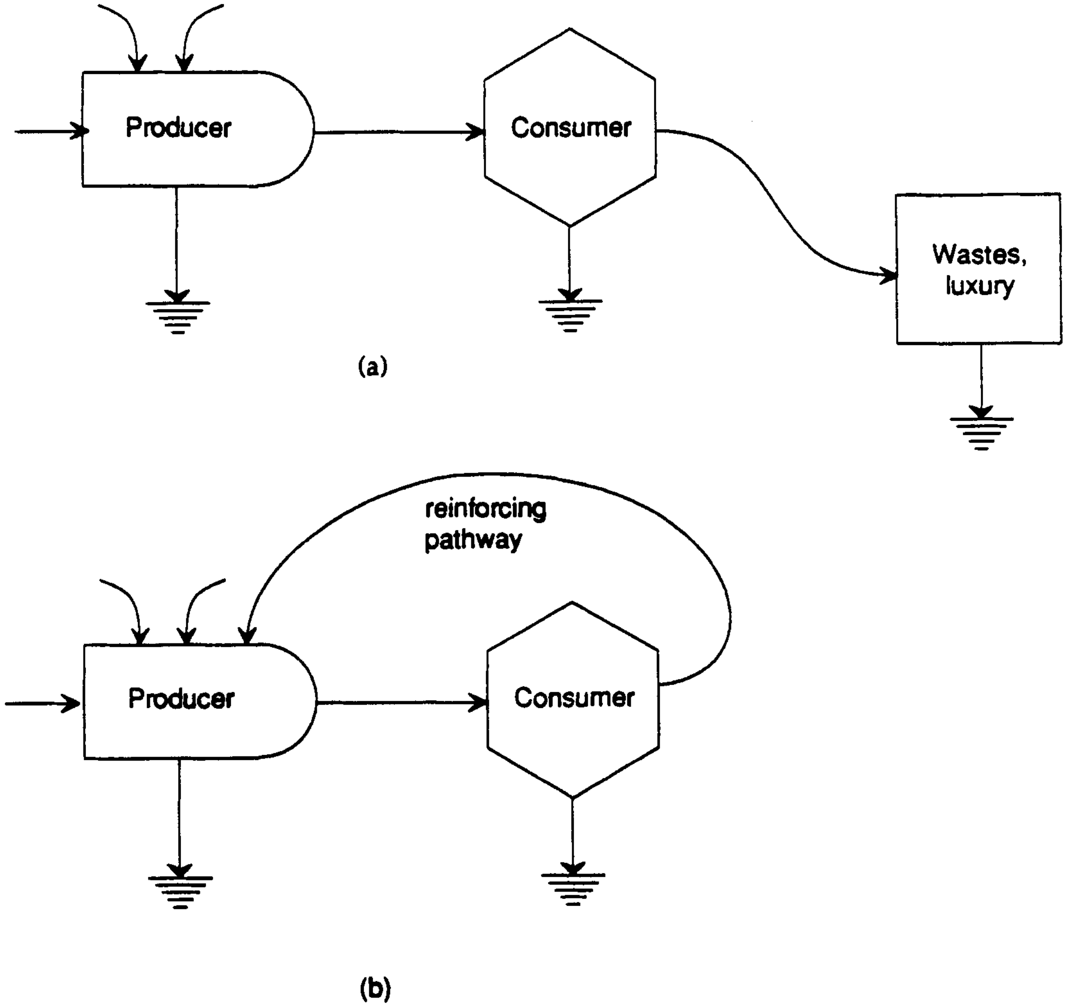


Figure 2. Comparison of consumers which reinforce production with those that don't. (a) Environmental production and consumption with consumer outputs of materials and services that don't reinforce; (b) economic production and consumption with consumer output reinforcing production.

Some of the production processes are those of environmental work such as that of forests, farms, fisheries, and mineral forming processes (geological processes). Other production processes are those within the human economic system of industries. Both kinds of production processes require reinforcement with services and other inputs from the consumers to be sustainable. For example, means for reinforcing fisheries production include release of hatchery stocks, fertilizing food chains, selective removal of competing species, and chumming with extra food suplements.

The circulation of money helps insure that human producers receive reinforcement for their contributions, but the production processes of nature cannot accept money. As Figure 1 shows, money paid to humans to process environmental products with market pricing does not lead to reinforcement. Maximizing human incomes does not include any reinforcement to the environmental systems necessary for sustainable production.

Public Policy to Maximize EMERGY Input and System-reinforcing Uses

From the preceding explanations of EMERGY we conclude that greatest public wealth can be achieved by policies that bring in the most EMERGY and allocate it to uses that reinforce production, including environmental production processes on which the human production systems depend. For example, policy to maximize agricultural production of wealth includes reinforcing natural soil maintenance processes, even if profits are less.

Maximizing EMERGY Is the Old "Maximum Power Principle"

The principle that greatest wealth is achieved by maximizing input and reinforcement may be recognized as a statement of an old concept: "the maximum power principle" sometimes attributed to Lotka (1924). The concept has its roots in writings of theoretical scientists and economists in the last century (Martinez-Alier, 1987).

EMERGY-based Evaluation of Contribution to GNP

The total annual EMERGY use by a nation measures its annual wealth. Many people are used to thinking of national economic vitality in terms of money circulating in that country measured by the gross economic product. However, in different countries money buys different amounts of real wealth even when the currencies are compared on a current international exchange basis. The amount of real wealth that circulating money buys is indicated by the EMERGY/$ ratio. Table 1 has the gross economic products and solar EMERGY budgets of several nations. The last column is the solar EMERGY/$ ratio for each country.

Rural countries have higher EMERGY/$ ratios because more of the wealth goes directly from the environment to human consumer without money being paid. For example, a family in remote rain forest gets most of its food, clothing, shelter, recreation, etc., directly from nature without money being involved.

If some change in global environmental processes reduced the EMERGY budget of a country by 10%, the real wealth would be reduced by 10%. The same money circulation would buy less. This is inflation.

Since public policy people already have values of gross economic product in their minds, it is sometimes useful to express EMERGY in dollars of gross economic product. If one is given a solar EMERGY value, the equivalent gross economic product is found by dividing the solar EMERGY by the solar EMERGY/$ ratio (Table 1).

The dollars of gross economic product estimated from EMERGY evaluation of a product is usually much larger than the money first paid for the product (Figure 1). Sometimes we call the EMERGY-based GNP evaluation "macroeconomic dollars".

Using Diagrams to Visualize Sustainable Systems

For many people the principles already stated for maximizing wealth can be understood better when the self organizing systems of environment in the economy are represented with network diagrams. These are a pictorial way of representing production, consumption, and pathways of input and reinforcement. Figure 3 shows a systems network in which all uses reinforce other parts of the system with materials or services.

Table 1. National Activity and EMERGY/$

Nation	U, ENERGY used/year E20 sej/year	GNP E9$/Year	EMERGY/$ E12
Liberia	465.	1.34	34.5
Dominica	7.	.075	14.9
Brazil	17820.	214.	8.4
India	6750.	106.	6.4
Australia	8850.	139.	6.4
Poland	3305.	54.9	6.0
World	188000.	5000.	3.8
Soviet Union	43150.	1300.	3.4
New Zealand	791.	26.	3.0
USA	66400.	2600.	2.6
West Germany	17500.	715.	2.5
Netherlands	3702.	16.6.	2.2
Spain	2090.	139.	1.6
Switzerland	733.	102.	0.7

The special set of symbols and conventions for drawing a web (Figure 4) has been used for two decades to represent systems networks, gain overview perspectives, and explain concepts. The networks of symbols connect flows of materials, goods, service, and information. These diagrams are an "energy systems language" because all pathways have some flow of energy. Even flows of information have the tiny energy content of the paper, computer disks, electrical currents, sound wave, light waves, etc., that carry messages. Flows of minerals or other materials that are more concentrated than in the surroundings contain the small energy content inherent in being concentrated. As we explain below, the importance of any flow is measured by its EMERGY content, whether the energy flow is large or small.

The second law of thermodynamics requires that any process have some of its available energy be dispersed in degraded form leaving the system unable to do more work. This law also requires that any stored material, energy, goods, or information, depreciate, losing its concentrations (because its energy is dispersing). The flows of used energy leaving the system are shown in the diagrams by pathways that go downward (into the "heat sink"). These pathways represent only degraded heat energy. Any dispersing materials, commodities, services, or energy still concentrated enough to do work are shown leaving the system by other pathways.

Money is exchanged as a counter current to the flow of commodities and services where humans are involved. Money is only paid to people and thus does not flow over environmental pathways. As already said, money flows are not proportional to the input of EMERGY wealth to the human economy.

Note that the designation of producer and consumer is relative. Things on the left are producers passing products to consumers on the right. A consumer in the center of the diagram uses products incoming from the left, but is also a producer passing its products to the unit next on the right.

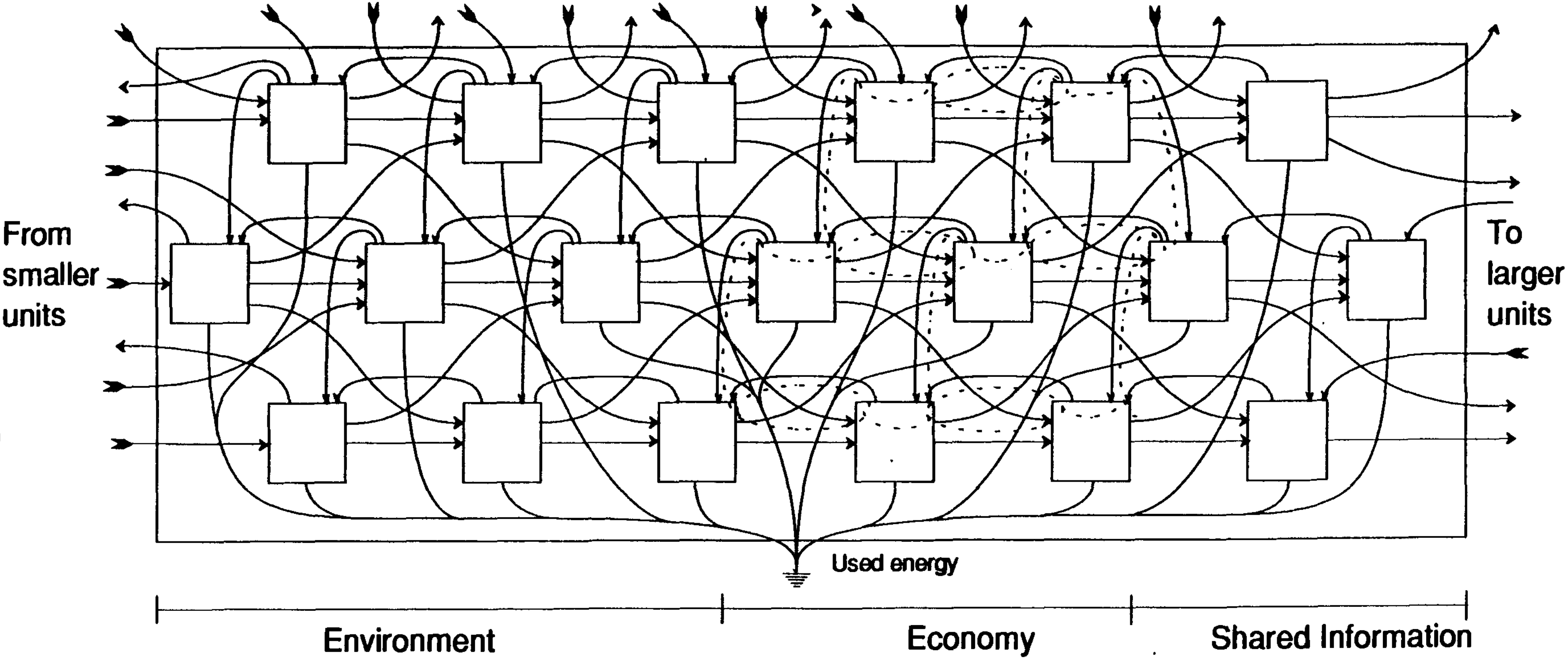
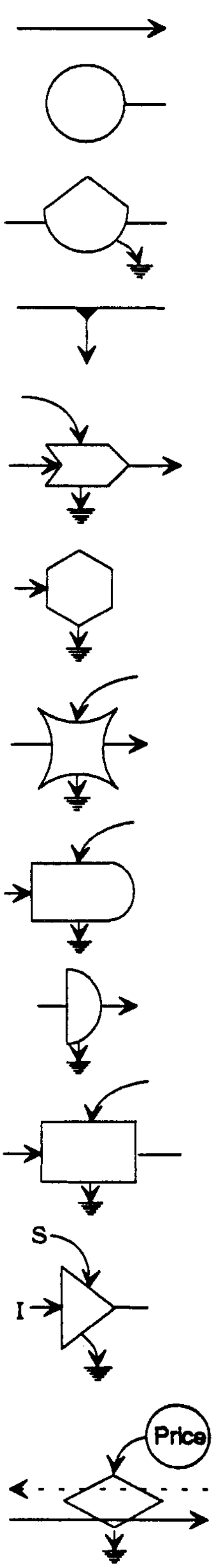


Figure 3. Network diagram of a joined system of environment and human economy. Economic sectors have circulation of money (dashed lines).



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

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

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

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

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

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

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

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

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

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

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

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

Figure 4. Symbols of the energy Language used to represent systems (Odum, 1971, 1983)

Energy Hierarchy Principle

Diagramming the economies of environment and humanity in network form as in Figure 5 makes it easy to explain the important concept of energy hierarchy, which is necessary to understand how different kinds of flows have different EMERGY. Self organizing systems develop a hierarchical division of labor according to size that increases system reinforcement of production. All the processes of nature and of humans are hierarchical. Many small units converge their production flows to form a few units of larger size and territory. These larger units converge flows to fewer units of even larger size and territory. For example, grass is converged into sheep and sheep to the shepherd and shepherd's products to the village and the village products to the town.

As shown in Figure 5, we arrange the hierarchy with converging from left to right (by convention). Items on the right are fewer, have larger size, and take longer to grow, depreciate, or turn over (are replaced). Each use is an energy transformation, changing the form of energy from one unit to the next.

As already explained, consumers of sustainable systems have pathways reinforcing other units of production. In Figures 3 and 5 these reinforcement pathways are the services and materials that consumers on the right pass to the producers they use on the left. Because they go back to the left, we call them feedbacks. Many of these feedback pathways are controls with the application of useful information. Even these information flows have small amounts of accompanying energy flow, since it is not possible to store or transmit information without a small energy flow to carry the information.

Because it takes more of an item on the left to make an item on the right and because a small amount of items on the right control larger amounts on the left, we can describe the right side of the energy hierarchy as of higher quality. In sections that follow we will measure that quality.

As Figure 5c shows, the energy flows on the pathways get less as one goes from left to right in the energy hierarchy. This is because of the second law which requires that some potential energy be degraded into used energy state (no longer reusable) at each use and transformation.

Thus, it takes more energy of one type on the left to support the transformations that make a smaller amount of higher quality energy to the right. Thus, it is incorrect to use energy as a measure of work or value, except where one is comparing energy flows of the same type. A Calorie of sunlight does not contribute as much to the economy as a Calorie of coal. A Calorie of coal does not contribute as much to the economy as a Calorie of human effort.

Energy Flow Decrease Up the Hierarchy

The definition often used in elementary physics and engineering courses that energy is the ability to do work is incorrect. Degraded energy can't do any work. The work that potential energy can do depends on its position in the energy hierarchy (its position in the left-right hierarchy illustrated by Figures 3 and 5).

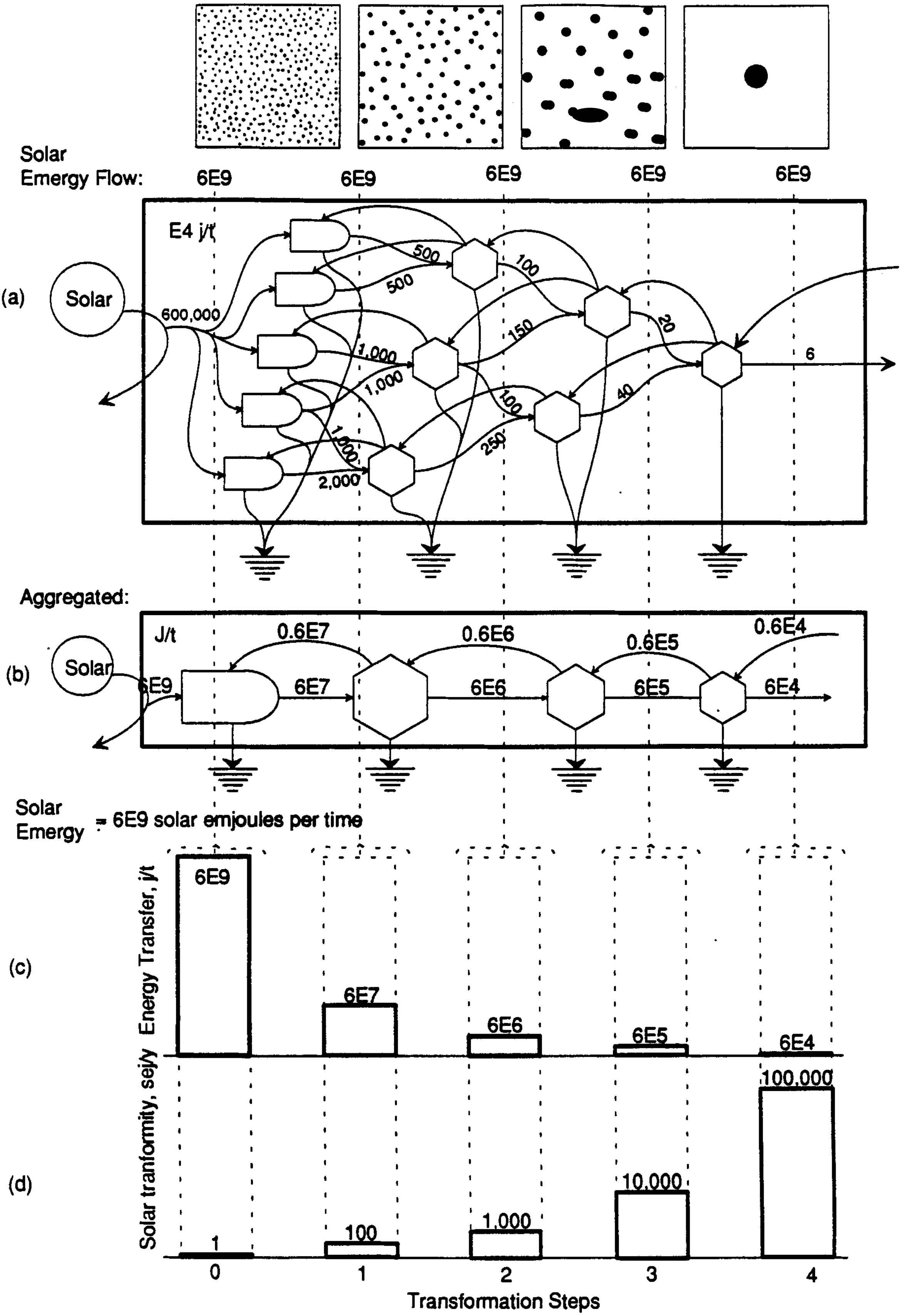


Figure 5. Energetics of a food web. (a) Energy flows on the pathways (feedback control pathways omitted); (b) the energy transformed by aggregating the web; (c) graph of energy flows by position in hierarchy; (d) solar transformity at various positions in heirarchy.

Transformities

By examining the energy transformations in networks that have been proven to be sustainable over long periods of self organization (in nature or in the economy), we can determine the energy of one form required to generate energy of another type under sustainable conditions. We introduce a new term, the "transformity" defined as the energy of one type required per unit of energy of another. For example, if 4 coal Calories are required to generate 1 electrical Calorie, then the coal transformity of electricity is 4 coal emCalories per Calorie. If one uses Joules instead of Calories as the unit of energy, then the same statement using Joules is: the coal transformity of electricity is 4 coal emjoules per Joule.

In order to make calculations easier, we have been expressing all our transformities in EMERGY units of one type, solar equivalents, as solar emjoules per Joule. Table 2 has some representative solar transformities for typical commodities and services.

Consider any product whose energy is known. Its solar EMERGY was already defined as the solar energy required to generate that product. Thus, another way to calculate a solar transformity is to divide the product's solar EMERGY by its energy. As stated before, the solar transformity units are solar emjoules per joule.

Tables of solar transformities make calculations of EMERGY easy. One has only to multiply the amount of a product by its solar transformity. If the product data are in energy units (Joules), multiply by a transformity in emjoules per Joule. If the data are in mass units (grams), multiply by the transformity expressed in emjoules per gram.

Transformity as a Measure of Unit Wealth

Notice in Figure 5 that the solar transformities rise as one goes from left to right in the system hierarchy. The larger the transformity, the more resources were required to make a unit. The further to the right, the higher the quality and the larger the control action if it is fed back to reinforce production.

Observed and Theoretical Lowest Transformities

If one evaluates the transformity of a newly initiated process, which has not been running long enough to develop its maximum efficiencies for full sustainable production, then a higher transformity (lower efficiency) may be found than later after the system is operating at highest output possible. For example, the transformity of steam engine work calculated from steam engines in 1910 was higher than for the better engines that had been developed by 1940.

There is a thermodynamic lower limit for transformities reflecting the inherent differences in quality concentration. For example, to convert dilute solar energy falling on the earth into a concentrated fuel requires that much of the energy be dispersed as part of the concentrating process. If the green plants after a billion years of evolution have achieved the maximum possible sustainable output, then the transformity we obtain from evaluating biomass conversions from solar energy will not be exceeded by new technology.

Each EMERGY analysis generates transformities. As more and more analyses are done, and we obtain many independent values for the same kinds of products, it will become clear which are the consistent lower values. Then we can judge a process to be inefficient if the calculated transformity is much higher than that found in other analyses.

Table 2. Typical Solar Transformities (solar emjoules per joule)

Item	sej/J
Sunlight	1
Wind kinetic energy	623
Unconsolidated organic matter	4,420
Geopotential energy in dispersed rain	8,888
Chemical energy in dispersed rain	15,423
Geopotential energy in rivers	23,564
Chemical energy in rivers	41,000
Mechanical energy in waves and tides	17,000-29,000
Consolidated fuels	18,000-40,000
Food, greens, grains, staples	24,000-200,000
Protein foods	1,000,000-4,000,000
Human services	80,000-5,000,000,000
Information	10,000-10,000,000,000,000+

Transformity Matching in Reinforcement

A product reinforces some other part of its system by interacting as a multiplier. For example, fuel interacts with a tractor to deliver farming work; phosphates interact with green plants to form crop products; computer programs interact with computers to generate information services. In each case something of higher quality with higher transformity reinforces its larger system by interacting with a larger quantity of lower transformity to generate new products. The principle here is that more wealth is generated by production processes that join a smaller quantity of high transformity with a larger quantity of lower transformity.

Experience shows that items with very large difference in transformity cannot interact with maximum effect directly, but need intermediate processes. For example, human bodies cannot use sunlight as an energy source directly; highly educated humans are not well used gathering sticks from the woods; high tech ships are not well used harvesting microscopic plankton; electricity is too valuable for general heating.

The transformities of products and by-products are useful guidelines for developing new systems and assigning resources.

Equivalence of Resources

Because EMERGY evaluation traces what was required for a product back to a common form of energy, it is a way of showing how the requirements for different products compare. As we discussed already, self organization finds uses for products that reinforce some part of the system commensurate with what was required in the products manufacture. After appropriate reorganization, products with similar solar EMERGY requirements can be substituted without changing the productivity of a system. The same original amount of resource is going into the same use and reinforcement.

Thus, EMERGY evaluation of a product can indicate in advance what uses and substitutions are appropriate to continued, sustainable wealth of the economy.

Evaluating Human Services

The average EMERGY/$ ratio for a nation (Table 1) can be used to evaluate the typical services. Data on costs in $ are multiplied by the EMERGY/$ ratio to estimate the EMERGY contribution from the paid services. This method omits the many unpaid services. It probably does not appropriately represent information services. For example, it does not evaluate mothers raising children.

Individual human services have a very wide range of transformities from that of an uneducated youngster to national leaders who have become symbols in the whole population. Some efforts have been made to evaluate EMERGY per person for categories of education and occupation.

Procedure for Making an EMERGY Evaluation Table

The EMERGY flows of a country, city, process, storage, or whatever may be evaluated by the following procedure for making an EMERGY evaluation table. See example in Table 3. It may be convenient to use a computer spread sheet.

1. Assemble people knowledgeable about a system to be analyzed. Together diagram the system, thus identifying the main inputs, system parts, processes, and products yielded.
2. Make an EMERGY analysis table with one line in the table for each input or product to be evaluated. Number the lines, using the same numbers for the footnotes that give the sources of data, references, calculations, or other details.
3. In the first column of data put raw data for each line in Joules, grams, or dollars.
4. Put the appropriate solar transformity in the next column.
5. In the third column multiply data from column 1 by the solar transformity from column 2, thus obtaining solar EMERGY values.
6. In the fourth column divide the solar EMERGY values by the solar EMERGY/$ ratio for a particular economy for a particular year in order to express EMERGY in equivalents of gross economic product (for perspective).
7. Calculate totals and indices for recommending public policies (see below).

Evaluation of Environmental Resources

Decisions on the use of environmental resources cannot be made correctly using money because money is only paid for services, but an EMERGY comparison can be prepared for choosing among environmental alternatives. The management with the largest EMERGY may be chosen to maximize the economy.

A use that fosters environmental EMERGY production also maintains the area's ability to attract more EMERGY from outside sources. The environmental EMERGY contribution serves as an attraction for economic investments that bring in fuels, goods, services, technologies, etc., from outside. Purchased inputs interact with the environmental resource in new production processes. One can multiply the environmental EMERGY by the EMERGY investment ratio of the region (see below) to estimate the potential the environmental use has in attracting the additional EMERGY of outside purchased resources.

Table 3. Emergy Evaluation of Texas Cattle, Grain, and Vegetable Production in 1983*

Note	Item	Raw Units J,g,$	Transformity Sej/unit	Solar EMERGY E20	Macroeconomic 1983 US E9 $/yr
1.	Cattle and Calves	2.98 E16 J/y	1.73 E6	515	19.8
2.	Grains	1.49 E17 J/y	8.6 E4	128	4.9
3.	Vegetables	4.29 E15 J/y	2.6 E5	11.1	0.43

Notes:

*. Odum, Odum, and Blissett (1987)

1. Cattle and Calves 1983; 5.555 E9 pounds production (Texas Livestock, Dairy, and Poultry Statistics for 1983, Texas Department of Agriculture, 60 pp)
(5.555 E9 lbs)(454 g/lb)(2.82kcal/g)(4186 J/kcal) = 2.98 E16 J/y
Transformity of beef products estimated from Appendix 35 as ratio of 0.89 of the solar emergy inputs (beef 89% of yield emergy) to energy in products:
(0.89 *(1132 + 291) E12 sej/yr)/(7.3 E8 J/yr) = 1.73 E6 sej/J

2. Grains, corn, 104,760,000 bushels; barley 2,476,000 bushels; oats 10,730,000 bushels; rye 450,000 bushels; winter wheat 161,000,000 bushels; sorghum 10,730,000 pounds CWT; rice 13,805,000 pounds CWT. (Texas Field Crop Statistics for 1984, Texas Department of Agriculture, 100 pp.)
(11.95 E12 grams/year)(0.9 dry)(13826 J/gram) = 1.49 E17 J/y

3. Vegetables, fruits: production in 1982, 1.74 E9 pounds/year (Texas Vegetable Statistics for 1985, Texas Department of Agriculture, 44 pp.)
(2.82 E9 lb/y)(.2 dry)(454 g/lb)(4 kcal/g)(4186 J/kcal) = 4.29 E15 J/y
Transformity estimated as solar emergy in rain on acreage:
(301,800)(2.1 ft/y rain)(1233 m^3/ac-ft)(1E6 g/m^3)(5 J/g) = 4.29 E15 J/y
(3.9 E15 J/y)(1.54 E4 sej/J) = 0.6 E20 sej/y
plus services estimated from cash receipts (1982): $4.07 E8)(2.6 E12 sej/J) = 0.6 E20 sej/y
Emergy inputs (0.6 + 10.5) E20 sej/y = 11.1 E20 sej/y
Solar Transformity = 11.1E20 sej/y/y/4.29 E15 J/y = 2.6 E5 sej/J.

Evaluation of Primary Energy Sources Net EMERGY Yield Ratio

The Net EMERGY of a source of energy is its EMERGY yield after the EMERGY used to process it has been subtracted. Primary sources can be evaluated with the Net EMERGY Yield Ratio, which is the ratio of the EMERGY yield divided by the EMERGY used for processing (see Figure 6). The developed countries that run on fuels at present prices have fuels available to them with a net EMERGY yield ratio of 6 to 1 or more. In other words, only 1 of the 6 is required for processing, leaving 5 to run the rest of the economy. The higher the yield ratio of an economy's primary energy source, the more can be done elsewhere in the economy besides processing its energy. Good policy selects sources with the best net EMERGY yield ratio even if they have to be bought abroad.

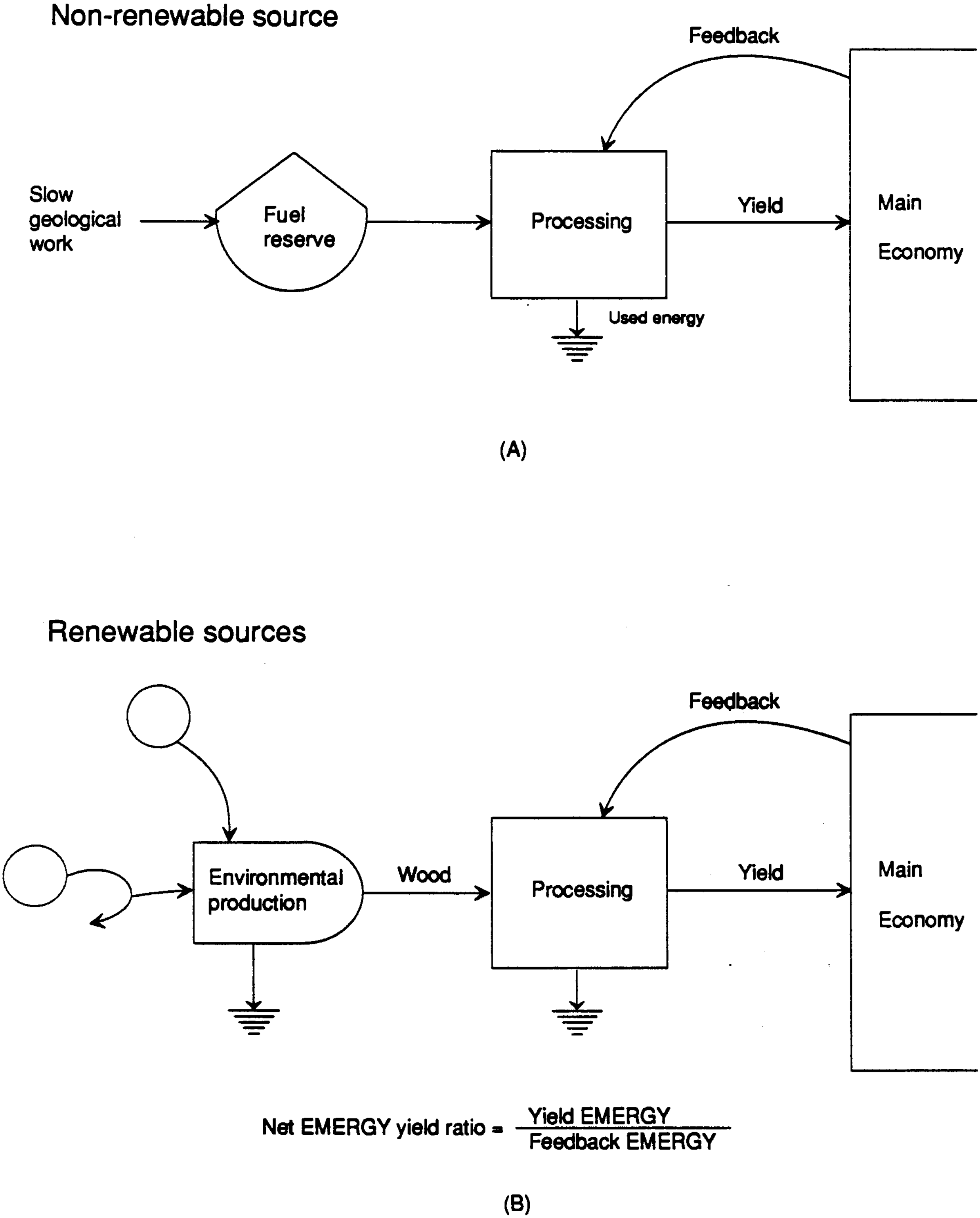


Figure 6. EMERGY yield ratio for evaluating a primary energy source. (a) Nonrenewable source; (b) renewable source.

Compare this policy with the economic view that buying fuels hurts the economy by sending out foreign dollars. The economic viewpoint underevaluates the wealth of the fuel six fold or more.

When fuels are deep in the ground and require more money and services to extract, the typical economic view sees this as more value and more jobs, whereas the EMERGY viewpoint sees less net yield and diminished wealth for everyone except those involved in extracting the resource. Good public policy for a nation is to obtain resources with the highest net EMERGY yield ratio.

Countries that sell their fuels give away their EMERGY 6 for 1 or worse. The benefits to countries that buy their fuels depend on the EMERGY ratio of their trade transaction (see below).

Selecting Taxes with Net EMERGY Yield Ratio

To maximize EMERGY availability and use, taxes should never be put on any commodity that has a net EMERGY yield. Tax tends to discourage use and the effect on the economy is amplified according to the net EMERGY yield ratio. Putting a tax on fuels that have a net EMERGY yield ratio of 7 to 1 inhibits the economy 7 times more than putting the tax on a final product, most of whose EMERGY input is service. Most raw products have high yield ratios including fresh waters, soils, wood, fish, crops, and minerals.

Wastes and luxuries that do not reinforce production are usually from highly-paid consumers. Taxes on these consumers at the top of the hierarchy (on the right side of the diagrams in Figure 3) increase productivity, whereas taxes at the other end inhibit the economy. Traditional economic viewpoints do not recognize the differences, because money is used to evaluate commodities, which it cannot do, since it is paid to the human service part of a commodity only.

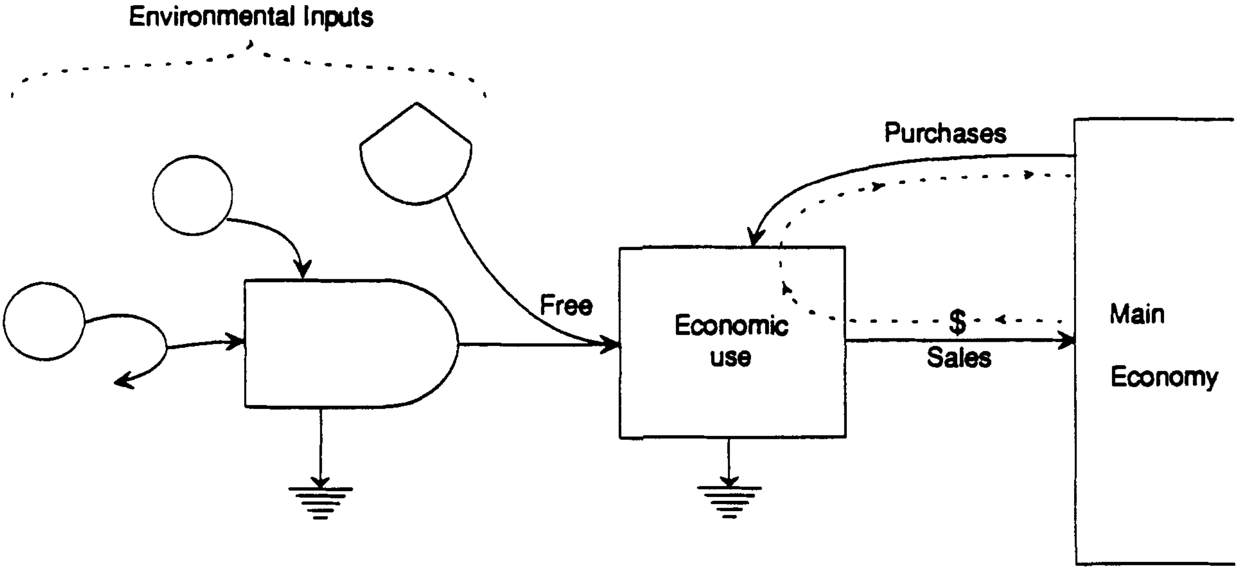
When there are critical fuel shortages, rationing should be of consumer use, not of production industries.

EMERGY Investment Ratio

The net EMERGY from primary fuel sources or products derived from them are moderately high quality (high transformity). Their effective use requires that there be an interaction with lower transformity resources, as we already discussed. Typically, most of the products of urban society use fuels and electricity directly or indirectly. The fuels and their products are fed back to reinforce production processes, interacting with abundant but lower transformity environmental resources. Examples are agriculture, forestry, fisheries, and recreation. In other words, high quality products elsewhere in the economy are brought into a region to form a new economic use industry, usually through economic investment that utilizes environment. How much investment is appropriate for a given amount of environmental lands and waters?

The ratio of EMERGY brought into an area from the economy and the EMERGY of the environmental resources used in the interaction is the EMERGY investment ratio (see Figure 7). This index is useful for determining when a process will be economically competitive and at the same time how much economic activity is loaded on the unpaid environment.

If a product is not the economy's primary source it does not need to yield net EMERGY, but the EMERGY matching should be typical of the region to be competitive. If a proposed project has a lower ratio than the regional average, this means that purchase costs are less than the average economic activity in the region. Costs being less, the industry tends to sell its products for less, capture markets and grow. If the EMERGY investment ratio is higher than the typical regional ratio,



EMERGY INVESTMENT RATIO = $\frac{\text{Purchased EMERGY}}{\text{Free environmental EMERGY}}$

Figure 7. EMERGY investment ratio for evaluating whether an environmental use is economic and its environmental impact.

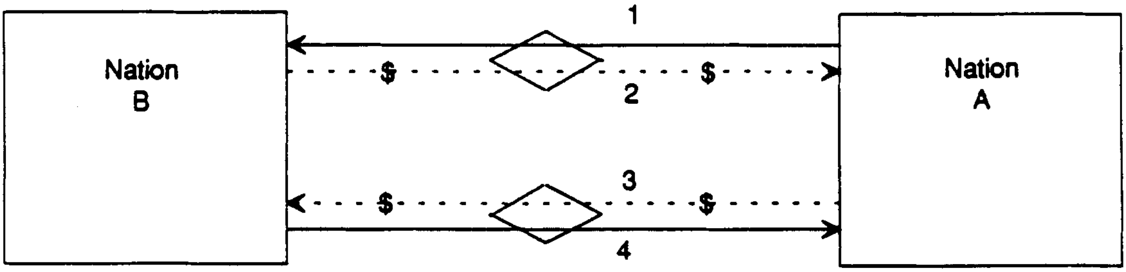
then the project may not be economic, since too much investments and costs will make the product economically uncompetitive. The worldwide EMERGY investment ratio is about 2 to 1, whereas it is 7 to 1 or higher in developed countries.

As the world economy becomes more organized into one system, processes that would be competitive within their own region are forced to compete more with similar processes elsewhere. An industry with an EMERGY investment ratio of 7 may compete within the United States, but not compete with a comparable unit overseas where more free environmental resource is available with a lower EMERGY investment ratio. Planning for economic vitality now may require planning for lower EMERGY investment ratios (less density of economic developments) than a few years ago.

Areas with typically high EMERGY investment ratios have less environment to support each unit of economic activity. Thus, they are impacted more. More of their EMERGY is used up, often not reinforced. The ratio is a measure of economic loading of environment. EMERGY investment ratio is useful to plan new developments to insure that they are economically competitive and that the environmental resources are not overloaded.

Evaluation of Foreign Trade

The benefit from a foreign sale, purchase, or trade depends on the EMERGY exchange ratio of the trade. An EMERGY table should be prepared evaluating the commodities purchased or sold and the monies received (Figure 8). Generally, a country loses wealth if it sells environmental raw products because the EMERGY of nature's work to make them is high, whereas the money received is only for some services to process them. The luxury of developed countries is partly due to importing raw resources without paying anything but processing costs. For example, aluminum ingots made with New Zealand hydroelectric power were sold in Japan for 58 million dollars, even though the contribution to the Japanese economy evaluated with EMERGY methods was close to a billion dollars. For the benefit of New Zealand, the ingots should be kept at home and used to make final products for export, thus making jobs in New Zealand.



$$\text{EMERGY EXCHANGE RATIO} = \frac{\text{EMERGY received}}{\text{EMERGY sent}}$$

Figure 8. EMERGY exchange ratio for evaluating benefits of purchases and sales, foreign trade, or international loans. The ratio may be used for comparing 1 and 2, 3 and 4, 2 and 3, or all exchanges.

Another way to achieve equity in trade is to adjust foreign purchases and trades so that there is EMERGY equity. If EMERGY trade balance is uneven, the difference can be made up in education, military, or technology transfers duly evaluated for their EMERGY contributions.

Allowing individual businesses to maximize their own profits in monetary terms often imbalances EMERGY trade equity. The dollar value of profits may be small compared to the bases for public gross economic product given away to other countries.

Evaluation of Foreign Loans

The EMERGY/$ ratio is larger for rural and undeveloped countries where people are supported from the environment directly. They are using money less than those in urban areas. If one borrows money from a country, the buying power of that loan is given by the EMERGY/$ ratio of that country. When the money is paid back, the buying power in the payback is that of the borrowing country.

If an undeveloped country with 5 times higher EMERGY/$ ratio borrows from a developed country, the undeveloped country ends up paying 5 times more back than was borrowed. Much of the economic plight of undeveloped countries is due to these overpayments that come from using money instead of EMERGY as a measure of public wealth.

Guidelines for Foreign Assistance Projects from EMERGY analysis.

EMERGY concepts provide guidelines for projects from developed countries within under-developed areas. Measures that maximize the EMERGY budget are believed to maximize economic wealth and vitality. However, there are questions of scale. Figure 9 suggests there are five levels of consideration, the economy of the development project and its people, local economy of the development project, the economy of the under-developed nation, the economy of the developed nation, and the world economy. The difficult question is which economies are having their EMERGY increased. Ideally, a project should increase EMERGY of all scales. Unfortunately, past decision-making processes have not considered all these. It is not even clear that foreign aid projects have been managed for the good of the underdeveloped nations. The following are some general guidelines with do's and don'ts:

1. On the scale of the economic activity, market values will tend to guide the business managers towards project profit, but if this is the only guideline involving an environmental resource, it soon pulls down the resource, is not sustainable, and reduces the EMERGY of the local economy and of the underdeveloped country. The damage to the local economy is even worse if international sales or loans are involved as discussed in item below.

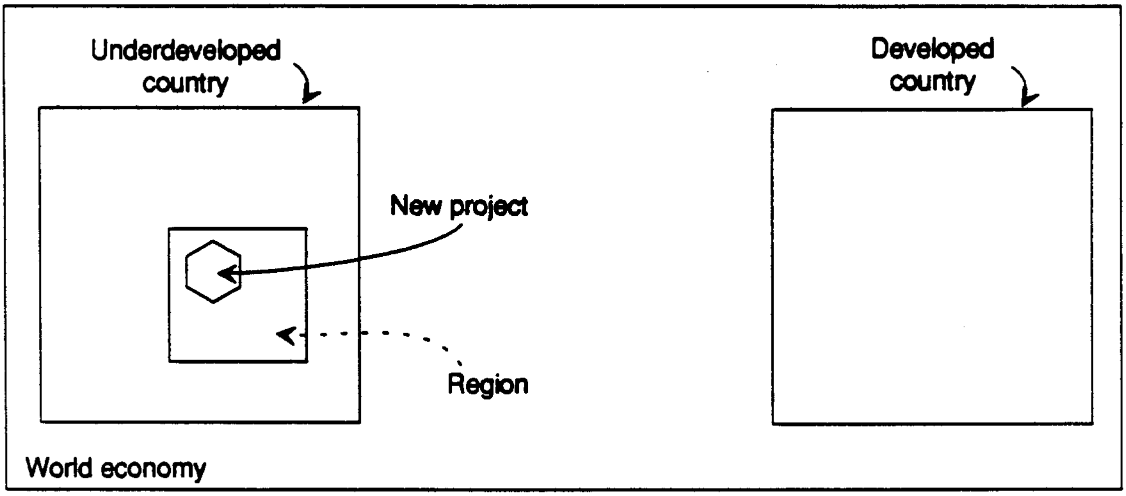


Figure 9. Scales for maximizing EMERGY.

2. On the regional scale, subsidized development of an intensive activity ahead of general development of the region is indicated by the EMERGY investment ratio being too high (higher than the regional value). As a result, the products cannot be used locally (are too expensive for the home people), and the EMERGY tends to be exported usually with less return. The situation is made worse if the profits are changed into foreign currencies because of the much higher EMERGY/$ ratios of underdeveloped currencies. Contrasts in wages disrupt other parts of the local economy, making sharper differences between rich

and poor. Pulling resources from one existing use, however indirect, to make monied income should not be done unless the total EMERGY is much increased (counting the areas disrupted).

3. On a national scale of the underdeveloped country, EMERGY benefit comes when the projects increase the total EMERGY, usually by increasing the use of purchased resources in appropriate match to the environmental resources in a sustainable way. The development must not divert resources from rural users of one region to another. Project developments should not undermine the occupations of part of the country to make profit for another area.

   On a national scale of the developed country supplying the initial funds, the project should not be a means to maintain inflated foreign interest rates. All repayments and interest rates should be adjusted for EMERGY equity, which means that repayments should remain in the currencies of the underdeveloped countries with reinvestment there. Thus, an international project to aid a country should no longer be a means for growth and profit in the developed country.
4. On the international scale, any loans or sales of products between countries should be arranged to maintain EMERGY equity so that both countries benefit mutually. Because of the different EMERGY/$ ratios, loans and sales may transfer many times more value to the developed country making the aid project an exploitation. Interest rates and repayments should be calculated in advance on an equal EMERGY basis.
5. On a world scale, projects that unbalance local economies increase EMERGY inequity between countries, do not maximize the world economy, because they leave major sectors of the world's population in poverty, essentially outside the world economy. This pattern wastes resources into luxury and excess of the developed countries, diverting the resources that used to go directly to population support (without payments). This pattern is not sustainable, does not maximize world wealth and EMERGY, does not reinforce world production, and will not last. These patterns will become discredited as world opinion changes, as revolutions occur, and worldwide resource depletion soon cuts off the largesse of the overdeveloped countries.

Controversy over Acceptance of EMERGY Wealth Concepts

General acceptance of the concepts given in this paper have been slow. Most people concerned with environment and policy have heard something about them, since there have been extensive published reports, papers, and books from time to time as the concepts have evolved.

Opposition has been severe, especially from economists. It's probably safe to say that this group with a handful of exceptions don't understand it. The concept of a donor value is so fundamentally opposite to the "human willingness to pay" concept of value, that those with that training read opposite meanings into words so that what they read seems like nonsense to them.

EMERGY value is a donor value based on invariant physical measures that accompany a product through transformation to its final use until it reinforces another production process. EMERGY only adds and subtracts when flows of products of the same kind are added or separated. When there are by-product flows, they carry the same EMERGY because that is what was required to make them. The by-product flows, while reinforcing other production processes, may come together again. In this case, the EMERGIES are not added, since they represent the same original input. Network diagrams of a larger system are required to avoid double counting the same original source.

Many economists were taught that early efforts to find an absolute basis for value failed, often citing Marx's labor theory. As several authors have pointed out, Marx's labor value concept was also a donor-value concept, using hours of labor as the measure of labor power. But what labor can accomplish depends on the EMERGY inputs of the education, the machinery used, and other aspects of labor. EMERGY measures put labor value on a more scientific basis.

Some confuse EMERGY concepts with the technocrat movement of the 1930's, which used energy as the basis of value and proposed to pay people with energy certificates in place of money. Of course this failed because energy of different types are not of equal wealth and have to be multiplied by their transformities. Technocrats wanted to substitute energy value for money, whereas EMERGY value is not meant to be used for market value, but for larger scale evaluation of the economy. Value to the person is market value. Value to the economy is EMERGY. A free functioning market economy helps to maximize EMERGY values by eliminating shortages. A dollar bill of currency represents about 2 E12 solar emjoules per 1989 U.S.$. It is already an EMERGY certificate for interhuman transactions. (An emjoule is the unit of EMERGY defined as the energy of one kind in Joules required to supply all the inputs necessary for a product or service.)

Input-output embodied energy analysts oppose the EMERGY methods because it does not fit their method which assigns the embodied energy of resource inputs to pathways with an arbitrary matrix inversion procedure according to some other variable, usually money. Assigning embodied energy according to money gives a measure that correlates with money, which is a useless tautology. The embodied energy assigned to commodities depends on the numbers of pathways used in aggregation, so that there is no one value for a commodity. Many who have criticized the input-output approach to embodied energy have assumed that EMERGY analysis was similar, which it is not.

Process analysts adding up energies that go into industrial processes have attacked EMERGY analysis because they do not want to give up the idea that energy (without using transformities) is a measure of work. Nearly all scientists and engineers were trained this way. They trick themselves into holding on to what they were taught in elementary classes by leaving out all items of large or small transformity, only adding items of similar transformity. Their methods are nearly worthless for evaluating contributions and drains to the economy. They omit the EMERGY of service, which is often the largest input.

Many oppose an energy-based theory of value because they think it refers only to medium and lower quality energy (sunlight, fuels, electricity), whereas they correctly recognize that humans, information, and scarce materials are more valuable. They don't wait to hear that transformity and EMERGY evaluation give highest values to these high quality items.

Many in government and industry who have declined to support research or use the concepts in their public policy decisions reject a method which requires that the problem under study be put into the context of the next larger system, which is required for EMERGY evaluation. Going larger puts people into conflict with decision makers on a larger scale and may bring in large scale politics to a smaller scale problem.

The whole education of intellectuals in this century is towards taking things apart, studying parts to find answers to problems. It has been left to experience, vague judgements, and adversary process to make larger scale decisions as if there were no right or wrong for that level of organization. People of wide experience and responsibility may feel threatened if scientific calculations can preempt their judgement. Since few public policy people believe there are any deterministic scientific principles at this level, any effort to provide policies through calculations is rejected as nonsense without any effort to understand it.

Thus, there are many reasons why each kind of background rejects the EMERGY approach, usually before they have heard anything but fragments of it. On any general committee there are usually a mix of backgrounds from different fields, each of which has a different objection. Thus, it is not hard to get a negative concensus. How can someone take an action when his advisory committee doesn't understand it and has members violently against it? People whose security depends on the majority have to avoid being associated with something controversial that is excluded lest he be excluded.

The general accounting office reviewing energy analysis methods said the method was interesting and declined to consider it. A recent author of a book on net energy (Spreng, 1989) referred to the methods as a valiant failed effort even though the last reference he referred to was 1976. Because transformities were not used, many inferences in that book are in error.

Many have said, let's wait and see, because the methods have been evolving, the transformities revised with new data, and new indices offered. We renamed the two main rigorous measures (EMERGY and TRANSFORMITY) in 1982 because the older names (embodied energy and transformation ratio) were being confused with other concepts.

Sometimes there are products for which we do not have a trustworthy value for transformity and must make subsystem evaluations to obtain them. Confidence in transformities comes with many determinations so that we can average values, using some to check others. Training people takes time. A new student who makes an analysis after a few months may have incorrect results because he may not know enough yet about the larger system so that important features are diagrammed incorrectly or omitted. Some have described the system as complex, but that is because the real world being evaluated is complex.

In the meantime, the method is chalking up some successes in predicting what is good public policy in energy polices and environmental development, proven after the fact, when the right answer is agreed upon following years of disastrous trial and error. Probably there will be further progress, but the EMERGY method for arriving at policies may already be the best way to develop a vital economy. It is especially useful to show what's wrong with many economic dogmas now undermining public welfare on the planet.

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An EMERGY Glossary

Dan Campbell

Available energy

Energy with the potential to do work.

Donor value

A value of a product determined by the production process and not by what a person is willing to pay (examples, mass & energy of wood).

EMERGY (spelled with an "M")

All the available energy that was used in the work of making a product expessed in units of one type of energy.

Emjoule

The unit of EMERGY which has the dimensions of the energy previously used (grams-centimeter squared per second squared).

Energy

A property of all systems which can be turned into heat and measured in heat units (Calories, Btus or joules).

Energy hierarchy

The convergence and transformation of energy from many small units into smaller amounts of higher-level types of energy (often in units of larger size) with greater ability to interact with and control smaller units.

Energy systems language or energy circuit language

A general systems language for representing units and connections for processing materials, energy, and information of any system; diagrammatic representation of systems with a set of symbols (Figure 4) that have precise mathematical and energetic meanings.

Gross national product (GNP)

The total market value of all final goods and services produced in an economy in one year.

Investment ratio (EMERGY investment ratio)

The ratio of EMERGY brought into an area from outside an economy to the local, free environmental EMERGY used in the interaction.

Macroeconomic dollar value

Dollars of gross economic product obtained by dividing the EMERGY of a product by the appropriate EMERGY/$ ratio. The dollars of gross economic product equivalent to the wealth measured in EMERGY.

Maximum power principle

An explanation for the designs observed in self organizing systems (energy transformations, hierarchical patterns, feedback controls, amplifier actions, etc). Designs prevail because they draw in more available energy and use it with more efficiency than alternatives.

Net EMERGY

The EMERGY yield from a resource after all the EMERGY used to process it has been subtracted.

Net EMERGY yield ratio

The ratio of the EMERGY yield to that required for processing.

Next larger scale

Larger territorial areas occupied by units with longer replacement times which must be considered in determining system behavior because of the controls larger units exert on smaller scale units and processes. (See Energy Hierarchy)

Reinforce

The action of a unit or process to enhance production and survival of a contributing unit or process, thereby enhancing itself; a loop of mutually enhancing interactions.

Self organization

The process by which systems use energy to develop strucure and organization.

Maximizing EMERGY

The process by which the maximum power principle operates within a system to select from among the available components and interactions the combination that results in production of the most EMERGY.

Second law of thermodynamics

Principle that energy concentrations disperse spontaneously and in all energy transfomations some of the available energy is dispersed in the process.

Solar transformity

Solar EMERGY per unit energy, expressed in solar emjoules per joule (sej/J).

Sustainable use

Resource use that can be continued by society in the long run because the use level and system design allow resources to be renewed by natural or man-aided processes.

Systems ecology

The field which came from the union of systems theory and ecology and provides a world view for energy analysis.

Transformity

The EMERGY of one type required to make a unit of energy of another type. e.g. Since three coal joules and one coal emjoule of services are required to generate one joule of electricity, the coal transformity of electricity is four coal emjoules per joule.

Turnover time or replacement time

The time for a flow to replace a stored quantity. For example, a flow of 10 gallons of water per day will replace a 1000 gallon tank of water in 100 days.

Wealth

Usable products and services however produced.