EMERGY ANALYSIS OF HUMAN CARRYING CAPACITY AND REGIONAL SUSTAINABILITY: AN EXAMPLE USING THE STATE OF MAINE

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Abstract. The human carrying capacity for a region at a specified standard of living depends on the economic and environmental resources of the region and the exchange of resources across regional boundaries. The length of time that a human population living at a given standard can be sustained depends on the rates of use and renewal of the resource base. All environmental, economic, and social resources are produced as a result of energy transformations; therefore, the energy required for their production can be specified and evaluated in common terms by converting their energy values into emergy. Emergy is defined as the available energy of one kind, previously used up directly and indirectly to make a product or service. Its unit is the emjoule. Emergy values and indices are used to evaluate the resource base for Maine, a politically defined region, and to estimate its human carrying capacity at the 1980 standard of living and for possible future resource bases. Emergy indices for Maine are compared with similar indices for Florida, Texas, and the United States to demonstrate variations in human carrying capacity and sustainability among different regions. The 1980 standard of living for Maine, Florida, Texas, and the Nation as measured by emergy use per person fell within a relatively narrow range of 3.4E16 to 4.3E16 solar emjoules y^{-1}. The human carrying capacity for a region is considered within a pulsing paradigm for sustainabilty and within the constraints provided by a renewable resource base. For example, in the short-term the developed human carrying capacity for Maine is largely determined by the fuel emergy inflow relative to renewable emergy resources. If purchased emergy inflows relative to Maine's renewable emergy increase to the average ratio for a developed country around 1980, the population living in Maine at 1980 standards could increase to 2.9 million or 2.6 times Maine's 1980 population. In contrast, the human carrying capacity based on Maine's renewable resources alone was 0.37 million people at the 1980 standard of living or 33% of the 1980 population.

1. Introduction

The assessment of regional systems is complicated by the need to evaluate the network of interactions occurring between human beings and their environmental support systems. Traditionally, the disciplines that address human activities, principally economics and sociology, have been pursued separately from the disciplines of physics, chemistry, biology, and ecology that provide the context and constraints for human socio-economic activities (Hall 1992). Hall (1992) has documented the need for an alternative integrated approach to understand systems of humanity and nature with their environmental-economic interfaces. The alternative analysis system used in this paper to make regional assessments is the energy systems approach of H.T. Odum (1983, 1994) which integrates ecology and economics within the context of thermodynamics and general systems theory.

The assessment of regional systems defined on scales from tens to thousands of kilometers and tens to hundreds of years is addressed in this paper. A region is generally defined as a part of a larger system that may have naturally or arbitrarily determined

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boundaries. For the purposes of environmental assessment, a region is usually considered to be a large continuous area within a larger defined surface. A state or ecological region within the United States of America, or a county or group of counties within a state, (e.g., the coastal counties of Maine or the potato growing region of northern Maine) are examples. Regional systems are complex networks composed of climatic, physiographic, biogeochemical, socio-economic, and cultural components and processes. Looking through a space-time window at these systems forces us to see the environmental and economic subsystems as parts of the same whole (Figure 1) because it views the scales of time and space over which human and environmental processes are co-dominant in their effects. Using a window of smaller scale usually leads to the view that human activities are forcing functions from the larger scale and gazing through a larger scale window often focuses our attention on human systems as they are constrained by long-term environmental patterns.

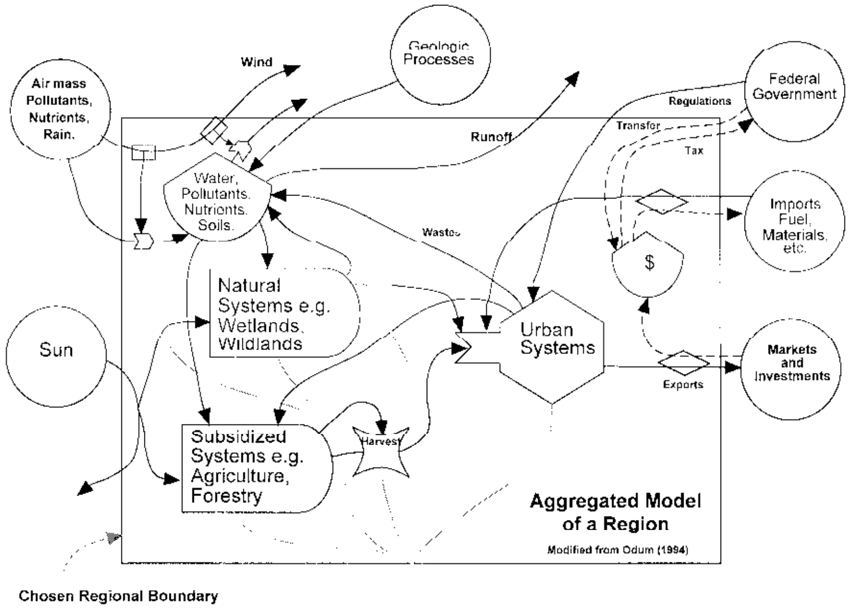

Fig. 1. An aggregated model of a regional system diagramed using Energy Systems Language (modified from H.T. Odum 1994).

An aggregated energy systems model of the components of a regional system at the environmental-economic interface is shown in Figure 1. Energy systems language (H.T. Odum, 1994) uses symbols (e.g., circles for external energy sources, bullets for producers, hexagons for consumers, rectangular arrowheads for interactions and diamonds for economic exchange, etc. (H.T. Odum, 1994) to represent the interactive network of a system diagrammatically. The regional system in Figure 1 is composed of components representing the human social and economic systems, the subsidized systems of agriculture, forestry, and aquaculture that feed and support the urban systems, and the natural ecosystems such as wetlands and wildlands that provide life support services to the human dominated and human subsidized subsystems (E.P. Odum, 1997). This regional system is constrained by the total available energy obtained from both the environment (circles on the left) and from the economy (circles on the right labeled fuel, etc.). Other aspects of a regional system shown in Figure 1 that determine its dynamic performance include (1) balance and recycle of materials, (e.g., water, waste etc.), (2) hierarchical relationships, (e.g., urban control of the subsidized systems), (3) control mechanisms from the next larger system, (e.g. inputs from the federal government and control of exchange by market prices), and (4) the thermodynamic limits on energy transformation efficiency, represented by the energy flows to the heat sink shown in gray as a fraction of the total energy transformed (H.T. Odum, 1987). These design characteristics determine the dynamic behavior of regional systems and they serve as a starting point for constructing simulation models to predict changes and trends in the environment and the economy of the region.

Identifying and assessing the ecological significance of risks to the human and environmental subsystems of a region requires that we evaluate both the economic and environmental components in equivalent terms. Traditional economic analyses are usually not broad enough in scope to adequately address the complex problems of regional systems which include environmental components (Pillet and Odum, 1984; Hall, 1992). The boundaries of most economic studies are fixed so that the creative and supportive work of the environment is external to the economy (Pillet and Odum, 1984). Environmental work is not valued by our monetary market system because money is paid to people for the human labor and capital investment in obtaining a product and not for the work of the environment which also contributes to the creation of the product. Since the products and services of nature are not given their true value by the economy, the ecological systems which produce them are like capital investments subject to depletion without provision being made for their eventual replacement or rehabilitation (Repetto, 1992). Emergy Analysis is an alternative means of determining worth which provides some unique insights into value not available by using monetary evaluation alone.

EMERGY ANALYSIS

Emergy Analysis (H.T. Odum, 1996) is a new method of environmental accounting which may be used to assess the complex relationships between the economy and its support environment because the work of both is expressed in equivalent terms. In this system of evaluation, emergy serves as a common denominator to express the value of environmental work as well as economic work in the manufacture, mining, growing, or creation of anything. Emergy is defined as the available energy of one kind previously used up directly and indirectly to make a product or service. Its unit is the emjoule (H.T. Odum, 1986). Available energy is potential energy capable of doing work (exergy). Emergy was originally called embodied energy but a new word was needed to distinguish it from other quantities also called embodied energy which were calculated in a different way (Odum 1996). The prefix em- comes from the words "energy" (e) "memory" (m) which captures the essential distinguishing characteristic of emergy which is that it is a physical quantity expressing the past use of energy upon which the form of present energy depends (Scienceman 1993). For example, a joule of sunlight, electricity, and human thinking have the same energy content but very different form and emergy content and thus different abilities to do work in a system.

The difference between emergy and energy can be illustrated by considering a small woodlot owner who fells a tree and cuts it into firewood for his wood stove. When the logs are burned over the course of the winter they yield a certain number of joules of heat which is the energy content of the logs. However, the emergy lost as the logs are burned includes the summation of all the solar emjoules (sej) of rain, fertilizer etc. without double counting, that supported the growth of the tree that produced the logs over the period that it stood in the wood lot and the solar equivalent joules required for harvest and processing the tree into firewood. The ratio of the solar emergy of a log to the heat energy it contains is the solar transformity of the log. For example, Doherty *et al.* (1995) calculated a solar transformity of 3846 sej per joule for spruce logs produced in Sweden. If the transformity and energy content of a product or service is known, its emergy can be immediately calculated.

Emergy, unlike dollars, is a true measure of relative importance because the total economic and environmental requirements for an item are accounted for in the same units by a scientific estimation process. The dollar value of a thing is receiver based and subjective because it depends on what individual humans are willing to pay for the thing. In contrast, emergy measures are donor based and objective because they are tied to measurements made on an efficient production process. Emergy expresses the true importance of a thing in the context of its system because it accounts for everything that was required for that thing to be a part of the system in which it occurs. Emergy is not a substitute for dollar values in market transactions; however, it is useful in determining the relative importance of things on the macroeconomic scale for public policy decision making. Both economic and environmental data and analyses are needed to make an emergy accounting. Therefore, emergy analysis is not a substitute for economic analysis, but a complement to it.

Emergy Analysis has been developed over the past 25 years by H.T. Odum and his collaborators. Since 1983 a great deal of research effort has been concentrated on this subject, and this work has culminated in the publication of a book describing the method (H.T. Odum, 1996). Emergy analysis has been used to characterize many regional systems including (1) nations such as, the United States (H.T. Odum and Alexander, 1977), Ecuador (H.T. Odum and Arding, 1991), Brazil (E.C. and H.T. Odum, 1984), Thailand (Brown and McClanahan, 1992), Switzerland (Pillet and H.T. Odum, 1984), and New Zealand (E.C. Odum, *et al.* 1982); (2) ecological regions such as the coastal region of Texas (H.T. Odum, *et al.* 1987a), the sea of Cortez (Brown *et al.*, 1991), Narayit, Mexico coastal region (Brown *et al.* 1992), south Florida (H.T. Odum and M.T. Brown, 1975), the Mississippi River region of the U.S. (H.T. Odum, *et al.* 1987b), and the Amazon Basin (H.T. Odum,. *et al.* 1986); and (3) the states of Florida (H.T. Odum *et al.*, 1986), Texas (H.T. Odum *et al.*, 1987a), Alaska (Brown *et al.*, 1993), and Maine (this paper).

This study applies Energy Systems Theory and Emergy Analysis to gain a better understanding of human carrying capacity and regional sustainability than can be obtained from using traditional environmental monitoring indicators alone. Emergy can be used to show the relative importance of environmental indicators and energy systems diagrams, and quantitatively capture the interrelationships between traditional indicators. Emergy indices calculated for a regional system network can be used to integrate information from different types of traditional environmental indicators. From an anthropocentric perspective the central question to be answered in a regional assessment is "What is the sustainable human carrying capacity for a region?" This paper first explores the ecological concepts of carrying capacity and sustainability and the special conditions that apply to human carrying capacity. Energy Systems Theory (H.T. Odum, 1994) is used to evaluate the concept of sustainability and to apply a new paradigm of pulsing (W.E. Odum *et al.*, 1995) to examine the patterns of development that may be sustainable in regions. The results of an emergy assessment of the environmental-economic system of the State of Maine, a politically defined region, are presented to examine the concepts of human carrying capacity and regional sustainability and to illustrate the Emergy Analysis method.

2. The Energy Basis for Human Carrying Capacity

The idea of a carrying capacity for animal populations derives from the logistic growth curve first investigated by Verhulst in 1838 (E.P. Odum, 1971). In the logistic growth model for animal populations, the population size, Q in Figure 2a, approaches an upper asymptote, K or the carrying capacity, because the negative effects of interactions among the individual population members increase with population size (Figure 2c and d). Many different premises can be used to derive the mathematical forms that have logistic growth dynamics as their solution (H.T. Odum, 1987). Two of these forms in which interactive unit effects limit growth are diagramed in Figure 2a and b using Energy Systems Language (H.T. Odum, 1983). Energy Systems Language is a visual mathematics which can be used for conceptual thinking, quantitative evaluation, and mathematical simulation. Energy systems diagrams and their mathematical translations are shown for the models simulated in the this paper (Figures 2a, 2b, 3a, 4a). Figure 2a shows the form of the logistic growth equation familiar in biology illustrating the intrinsic growth rate, r, and the carrying capacity, K. Energy resources are not explicitly considered in this form of the logistic equation; however, by comparison with Figure 2b, r is seen to be equivalent to a constant, k_1, times the energy source, E (Odum, 1987). This formulation results in exponential growth when the negative effects of population size are not density dependent. Theoretically, population growth can be constrained by limitations in the supply of energy resources as well as from interactive population unit effects (Odum, 1987). In the real world energy sources are never unlimited, so commonly observed logistic growth forms may result from limitation of the energy supply as well as from negative density dependent effects on growth e.g., crowding.

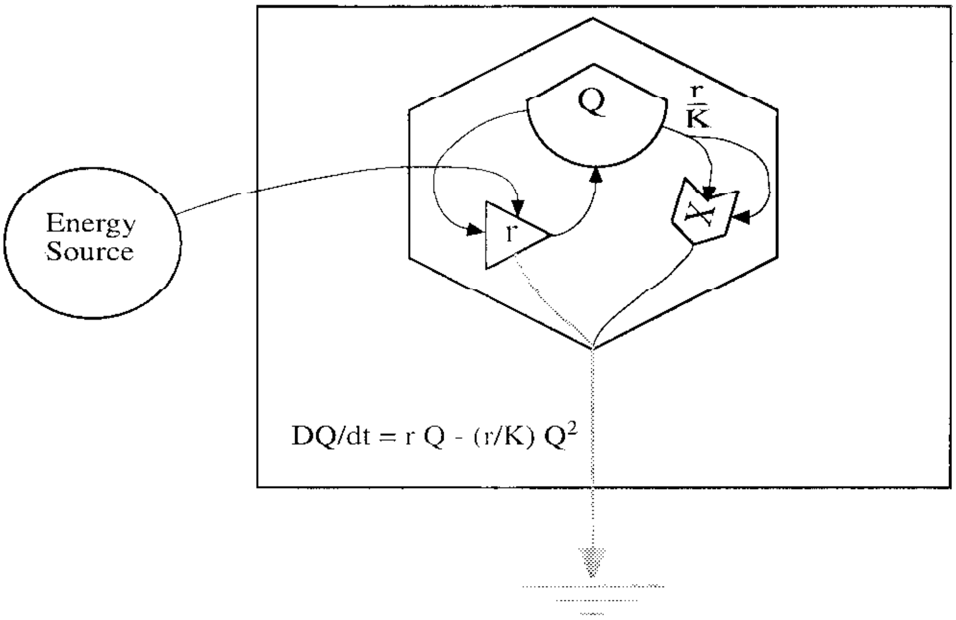

Fig. 2(a)-(d). Energy systems diagrams and the equations for two versions of the logistic equation (a) the standard equation familiar in biology, (b) an equation showing the relation of r to the energy source (Odum 1987), (c) solutions for (b) when the available energy E is changed in increments of 25%, (d) solutions for (b) when k_2, the intensity of negative population unit interactions is changed in increments of 25%. The dotted line in (b) indicates that the fluxes on the two indicated arrows are taken as the net flux.

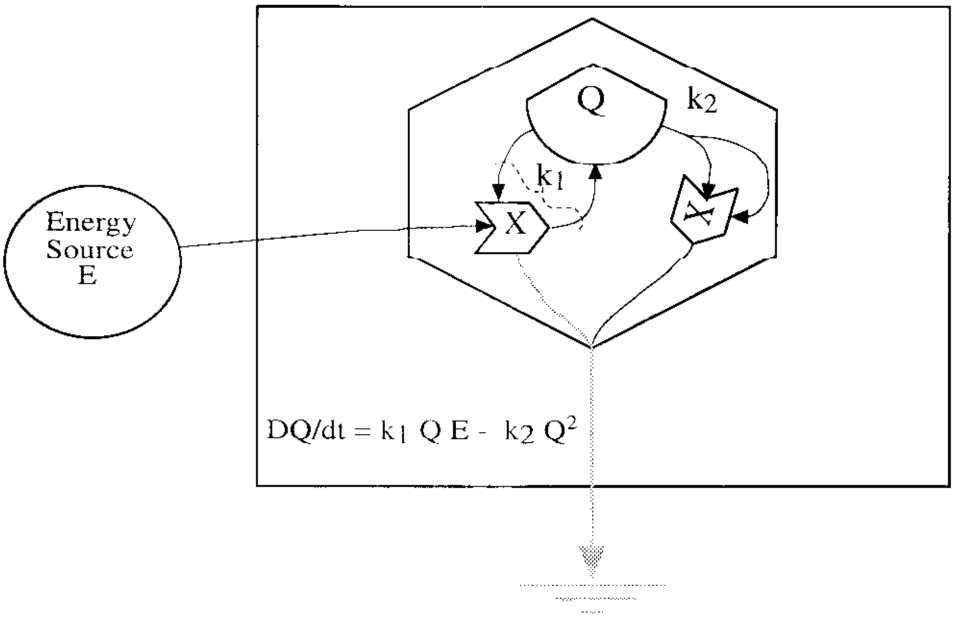

Fig. 2b

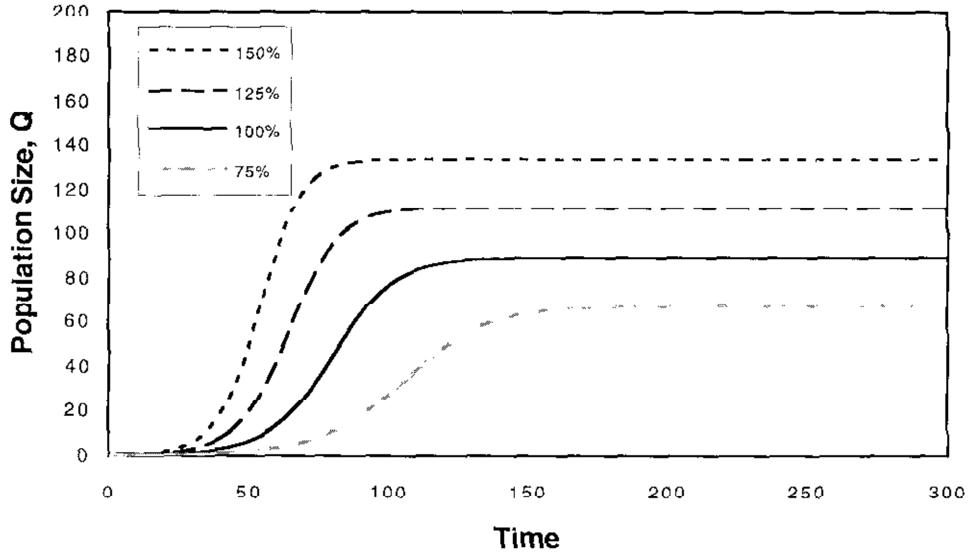

Fig. 2c

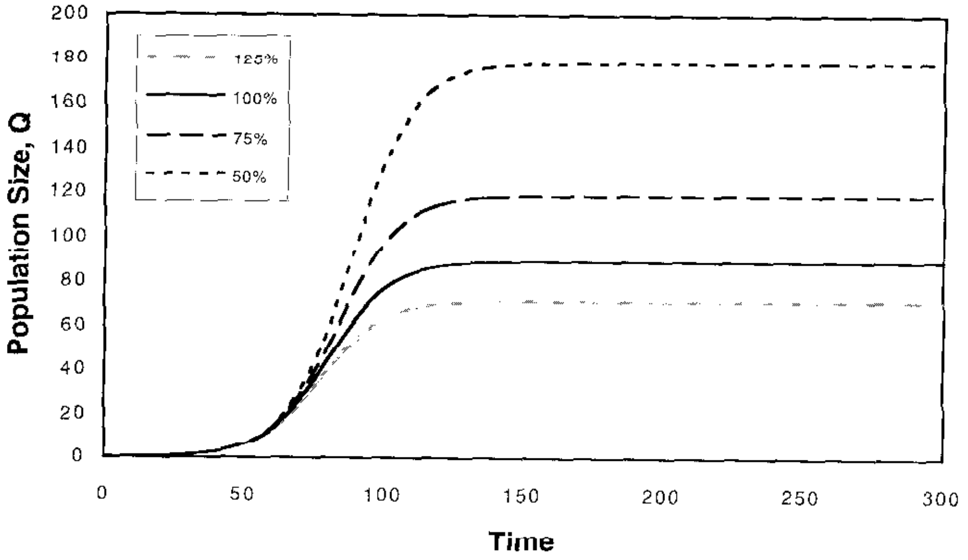

Fig. 2d

The model in Figure 2b was simulated using Extend™, an advanced simulation tool, to illustrate some aspects of the solutions to the logistic equation that are helpful in thinking about human carrying capacity. Figure 2c shows that when k_1E or r is increased in percentage increments of 25% while all other factors are held constant, the population adjusts to progressively higher asymptotes for K. These new values for K represent progressively higher subsistence or maximum values for the population density, as contrasted with the safe or optimum density which is usually between 1/2 to 2/3 of the maximum (E.P. Odum, 1997). Some animal populations unregulated by predation tend to rapidly approach K and overshoot it, damaging their habitat, thereby diminishing the available energy resources and causing K to descend to a lower population density (McCollough, 1979). In contrast, animal populations under sufficient pressure from predators exist at densities closer to the optimum where their food supply is more secure and their resistance to the fluctuations of the environment is greater (E.P. Odum, 1997). The logistic model implies that the carrying capacity, whether the maximum or the optimum, is a level of population size that can be sustained indefinitely into the future.

Human populations can increase to the maximum or subsistence level, but this pattern of behavior is not obligatory as it is with other animal populations. Given sufficient understanding human societies can choose to put some of their energy resources into increasing the assets of the society, thereby, improving the quality of life rather than allowing all the additional energy to go into supporting additional people. Attaining an optimum or safe population density for humans depends on the societal and individual choices which determine how much of the available energy goes into subsistence versus how much goes into increasing some measure of societal assets per individual or the quality of life. The social choices of individual countries in the world represent a wide variety of solutions to the trade-off between more humans beings at a lower standard of living and fewer humans with more assets per person. Thus, carrying capacity for humans can not be defined unless a standard of living is also specified. In the social sciences, human carrying capacity is usually qualified in this manner (E.P. Odum, 1997).

Figure 2d shows the effect of decreasing the intensity of the negative density dependent interaction among individuals in a population. When all other factors are constant, the carrying capacity, K, increases exponentially as interactive effects are decreased. Humans can choose to apply the effective increase in energy resources gained through increased efficiency to improving their quality of life instead of increasing the subsistence carrying capacity of the population. The former kind of change in K is dependent on developing better or more efficient systems designs and it illustrates R. Buckminster Fuller's injunction to human society to learn how to get more for less (Fuller, 1981). Getting more for less is a good strategy for improving our standard of living but its efficacy is limited by the total energy available to support societal organization and by the thermodynamic optimum efficiency for maximum power (H.T. Odum, 1994) production in the system.

The intrinsic rate of increase, r, for a population has been shown to implicitly include ($r=k_1E$) the energy resources for that population (H.T. Odum, 1987). A better understanding of human carrying capacity can be gained by separating the energy resources for society into renewable and nonrenewable components and observing the growth patterns that each produces (Figure 3a). The distinction between renewable and nonrenewable resources is somewhat artificial because all resources on earth are renewed by the global web of ecological processes; however, those that are being renewed very slowly compared to their rate of use are said to be nonrenewable. The large space-time scale patterns in the development of human populations and societal assets for nations and hence regions within nations are almost always controlled by the dominant energy sources available to support development (Watt, 1992). Almost all present economic development is based on the use of these energy resources in a nonrenewable manner (Hall, 1992). This insight alters our view on the possibility of sustaining present population sizes and states of development.

The simple model shown in Figure 3a (Odum, 1987) may be used as the basis for an overview of the regional development process based on available energy. When this model is simulated using Extend™ the patterns shown in Figure 3b result. The nonrenewable resources, F, are depleted because they are being used at a rate that exceeds their rate of replacement. Their use builds a peak level of societal assets that is not sustainable. The human population depends on the assets produced to maintain its standard of living, and therefore, it must decline as assets decline to maintain the same standard of living. C.A.S. Hall (this volume) has presented examples of some inherently unsustainable agricultural, industrial and social activities practiced in the world today. The level of development supported by renewable resources can also be found in Figure 3b, as evidenced by the lower asymptote approached by the assets of society as nonrenewable resources are depleted. This asymptote is the K of the logistic curve produced by a renewable or flow limited energy source, e.g., sunlight is a flow limited resource because only a fixed quantity is available for use per unit area and time (the solar constant is approximately 2 g cal cm^{-2} min^{-1}).

From this analysis it is clear that a human carrying capacity at a specified standard of living is not sustainable unless it is based on the use of resources in a renewable way. Once the patterns dictated by energy use are recognized, some critical questions arise: "What is the total amount of nonrenewable resources available to a nation or a region and what are their rates of use?" For example, ancient ground water in many arid regions such as the southwest U.S. is being pumped at a rate exceeding its recharge to make the deserts bloom (Bowden, 1977). For a given set of technologies the quantity of the nonrenewable resource will determine the timing of the assets rise and fall and the duration of its peak. Technology determines the rate of use and the completeness of exploitation for a resource, but unless it can alter the rate at which the resource is produced that resource will continue to be nonrenewable if it is being used faster than it is being replenished.

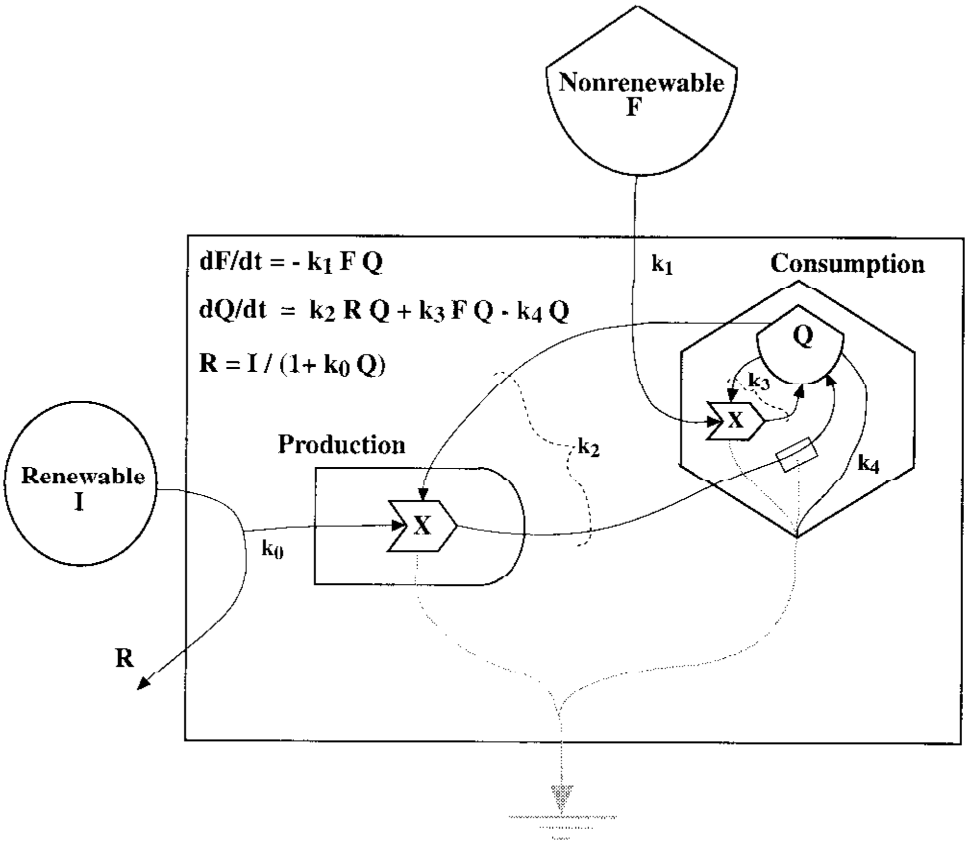

Fig. 3. (a) An energy systems diagram and equations showing the dependence of human populations and their assets on renewable and nonrenewable resources. (b) The solution to these equations showing the expected pattern of societal assets with time as nonrenewable resources are depleted. The dotted lines are net fluxes as in Figure 2.

3. Maximum Power and Sustainability

Models based on logistic growth such as the ones presented above reach a constant value for carrying capacity at steady state and contain the idea of sustainability in a familiar form, i.e., sustainability is the prolongation or maintenance of a state desired by humans. However, the word "sustainability" also means to keep an entity in existence and in this sense it is related to survival of a system. The prolongation of a certain state and the survival of the system that is in that state are two different things and each may require a different systems design. The survival of systems in evolutionary competition with others is hypothesized to depend on creating designs that maximize empower (emergy production and use per unit time) within the system network (Lotka, 1922; Odum, 1996).

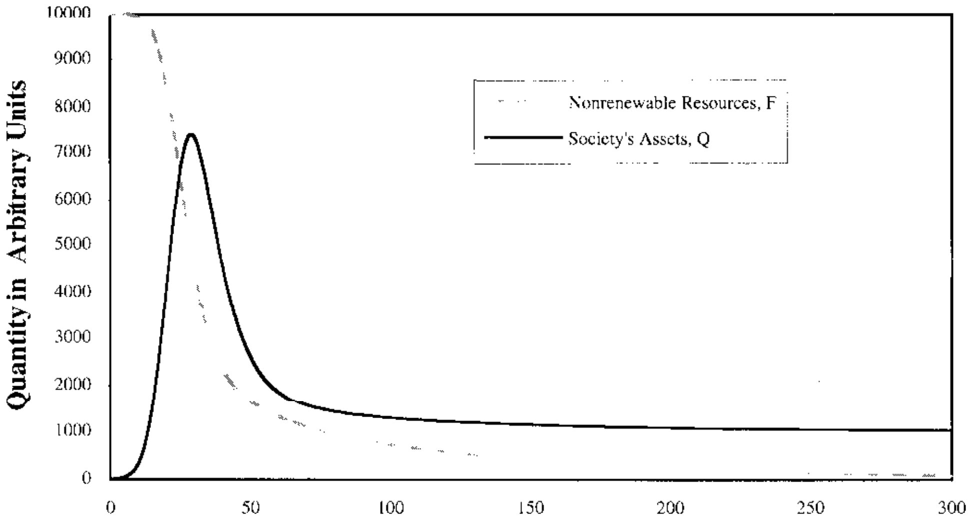

Fig. 3b

System designs that pulse are observed to be ubiquitous in nature occurring from the scale of biochemical reactions to the scale of the galaxies (Odum, 1994). W.E. Odum *et al.* (1995) and H.T. Odum (1996) present evidence and theory to support a new pulsing paradigm for understanding the patterns of humanity and nature that are required for survival in ecological systems. A working hypothesis to explain the broad occurrence of pulsing in nature is that systems which pulse will attain higher performance (i.e., develop greater empower) in the long run than those which maintain steady levels (W.E. Odum *et al.*, 1995).

Pulsing in regional systems can be investigated with the help of EMPULSE (H.T. Odum, 1996), a model illustrating a general pulsing mechanism, which is presented in Figure 4a. In this model Environmental Resources, Q, accumulate at a slow rate and are exploited both linearly (the box with k_2 entering and k_5 leaving), and autocatalytically (interactions symbols marked with an X where a feedback, k_7, from A, the economic assets of the region increases the use of environmental resources nonlinearly). This model includes both renewable, I, and "nonrenewable", Q, resources, but the space-time dimensions of the window of attention in Figure 3 have been widened to include scales which show the slow renewal of the formerly "nonrenewable" resource. Figure 4b shows the pulsing pattern of economic assets that occurs as a consequence of the rapid exploitation of slowly replaced environmental resources. The total material, T_m, in the system is a constant of which the dispersed fraction, M, is available for creating new environmental resources on the pathway indicated by k_1. The money circulating in the regional economy, G, is represented by the dotted line. The dashed box shows the

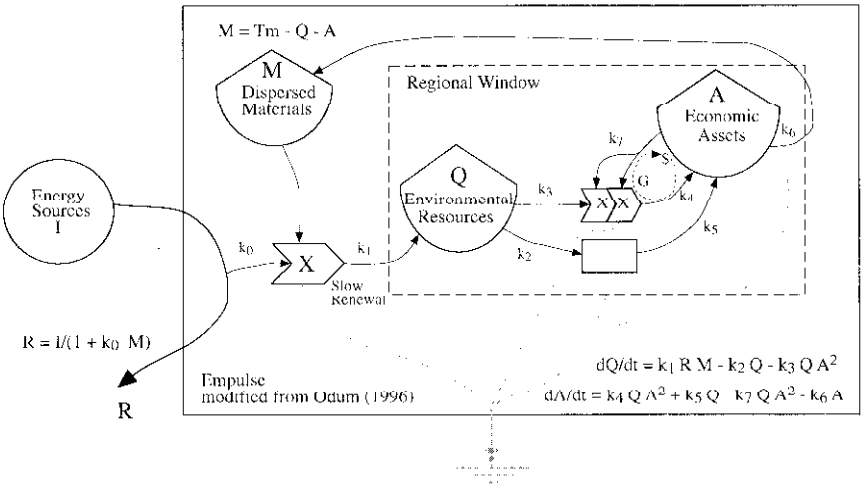

Fig. 4. (a) An energy systems diagram of a regional system emphasizing the environmental-economic interface. The Empulse model (H.T. Odum, 1996) was slightly modified and simulated using Extend to obtain the pulsing patterns for environmental resources and economic assets shown in (b).

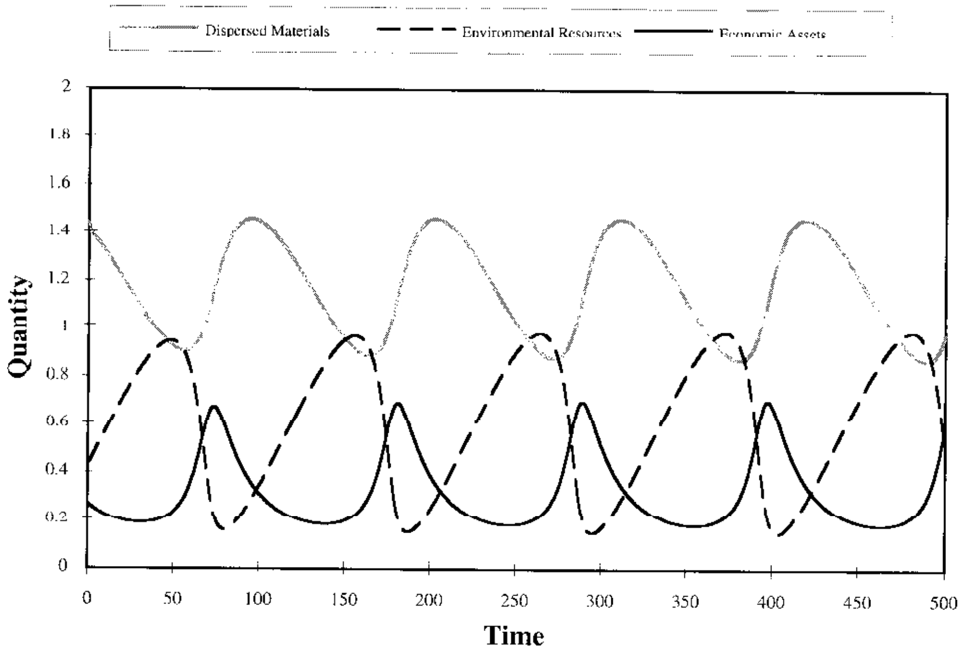

Fig. 4b

boundaries of a regional system which includes environmental resources, human assets and the processes by which humans utilize the environment (H.T. Odum, 1996). The region's environmental and economic assets (Figure 4b) go through a repeating oscillation that represents the only pattern that is sustainable in many cases. Processes of succession and climax that are part of the constant steady state idea of sustainability can be identified within the repeating cycles of environmental and economic assets (W.E. Odum *et al.*, 1995). However, the pulsing steady state paradigm requires that a period of descent or regression and a low energy period be added to the build-up period of succession and the peak period of climax to complete the cycle of change. The key to long-term sustainability of human populations and the economic assets determining their quality of life in a nation or a region may well lie in acquiring the knowledge and understanding to manage the pulsing of subsystems within the constraints of the cycle of change determined by the fundamental energy drivers from the larger system.

4. Human Carrying Capacity and Sustainability for Maine

The State of Maine can be considered as a politically defined region within the larger system of the United States of America (Figure 5). Other means of defining regional boundaries could have been used depending on the research questions to be answered (e.g., biogeographic zones, spheres of regulatory control or spheres of economic influence, etc.), but for the purpose of this paper Maine will serve to illustrate the method of regional environmental-economic assessment using emergy. The emergy analysis of Maine performed in this paper is a static analysis based on evaluating storages and flows in the regional system for the year 1980. Human carrying capacities, standards of living, and their sustainability will be considered in the context of the energy resource constraints illustrated in Figure 3b. Also, the role of pulsing (Figure 4b) in sustaining the patterns of human population and assets in the long-term will be considered as a conceptual basis for understanding what human carrying capacity may be sustainable in a region. Simulation models will be introduced in the methods section; however, they were not employed in this paper to dynamically consider the implications of pulsing to sustainability. Emergy indices were calculated for Maine and employed to provide insight into the nature of economic, environmental, and social interrelationships. These indices were compared to similar data from the states of Florida and Texas as well as from the nation as a whole. Finally, the assessment of human carrying capacity as an indicator of regional sustainability is discussed and recommendations for ensuring optimum patterns for human carrying capacity and standard of living in the future are given.

5. Methods

The method presented here has been used with some success investigating many complex problems which have both economic and environmental ramifications. For example, energy analysis has been used to: (1) develop a method of siting nuclear power plants (Odum *et al.*, 1983); (2) determine the economic and environmental feasibility of tree farming and paper production in the Amazon rain forest (Odum *et al.*, 1986); (3) determine appropriate environmental and economic policy for countries, states and regions as noted above and (4) to determine the net energy available from various energy sources including nuclear power, shale oil, solar technology, ocean thermal heat gradient, and ethanol from biomass production (summarized in H.T. Odum, 1996). Several predictions derived from the application of emergy analysis have proved to be correct (e.g., the lack of net energy in shale oil, H.T. Odum, 1996); however, only the future holds the answers to many of the larger questions that can be addressed now by this technique.

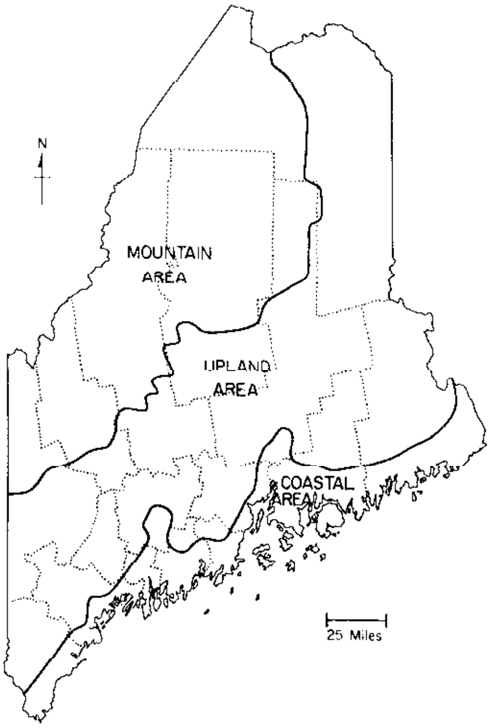

Fig. 5. A map of Maine, showing three regional areas delimited on the basis of their physiography.

The methods and techniques for performing a regional analysis using the energy systems perspective were first published by H.T. Odum *et al.* (1976). The method presented there has been modified and presented in this paper. Emergy analysis can be organized into eight principal steps with useful products produced at each step. The steps in the emergy analysis of a region are as follows:

1) Assemble the information and/or the individuals necessary to define the system boundaries, components, external causal influences, and processes. The product of this step is three lists, one for the main system components, one for the forcing functions or external causal factors, and one for the pathway flows that are generated by the processes through which the forcing functions and components interact. In the initial organizing meeting with knowledgeable individuals this step may be combined with step 3, construction of a detailed energy systems diagram. The diagraming process facilitates

discussion among participants and produces an understanding of what the important parts of the system are and how they work together.

2) Make or obtain land use maps to estimate the areas of the main system components. High transformity elements that create organization such as networks of water flow, transportation, and supply of fuels and electricity are identified and their patterns mapped. All important emergy flows whether of large extent or high concentration are included in the spatial classification.

3) Construct a detailed diagram of the regional system network categorizing the main components and showing the interactions among these components and the external forcing functions. Energy systems language uses mathematically defined symbols (H.T. Odum 1983; 1994) to represent the interactive network of a system. Producer, consumer and rectangle symbols can show a nested hierarchy by indicating intermediate levels of organization. A large rectangle shows the system boundaries and the hierarchy of organization within a system is represented from left to right in order of increasing transformity.

4) Simplify the detailed regional diagram by combining functionally similar components and processes to make one or more aggregated diagrams. This simplification is done not by cutting out pieces, but by combining them into aggregate variables. The aggregated diagram contains the variables that are important in describing major system trends or those which are germane to the analysis of specific problems and policy alternatives. To understand how a system works and to demonstrate these mechanisms clearly, the complex system must be simplified to a few main components and forcing functions. This simpler structure is easier to evaluate and simulate allowing specific research questions to be answered in the most straightforward way. The emergy flows that are large or controlling are guides in the simplification process. Identifying the fundamental external drivers that are changing and their interactions is also a key factor in simplification.

5) Evaluate the sources, storages, and main flows of energy, materials, and money on the aggregated regional systems diagrams.

A. For simulation models tables defining the storages, forcing functions, and flows are made showing their value, giving its source, and linking it to the aggregated diagram with an appropriate symbol.

B. For evaluating the emergy basis for a region a standard table with columns for (1) a footnote detailing the calculation, (2) the item, (3) the item's energy value, (4) the item's transformity, (5) the solar emergy value of the item, (6) the item's emdollar value (the emergy of the item divided by the emergy/dollar ratio for the economy). Emdollars express the value of an item in terms of dollars flowing in the gross state or gross national product, GSP or GNP, as if these dollars were distributed according to the emergy flows. The emergy analysis table provides a template for calculating solar emergy and emdollar value from data on the raw value of energy inputs and there respective transformities.

6) Analyze the emergy basis for the region using emergy indices, spatial plots of emergy use density, emergy power spectra, and other tools (H.T. Odum et al., 1976). Emergy indicators aid in understanding a region and in comparing it to other regions. Several emergy indicators are defined below.

7) Computer simulation of one or more aggregated models can be performed to predict future trends, evaluate policy alternatives, or test the model's sensitivity to critical variables. Step seven has a number of sub-steps related to the construction and analysis of simulation models. (a) Mathematical equations are written from the systems diagram, (see Figures 2a and b, 3a, and 4a). (b) The equations are programmed using a computer language such as Basic, Fortran or a simulation tool such as Extend™. (c) Each major aspect of the model is calibrated by comparing simulation results to the available data on that model output. (d) The model is verified by testing its ability to represent the entire calibration data set in simulation. (e) The verified model is validated using one or more independent data sets. (f) A sensitivity analysis of the effects of varying the forcing functions on predictions of the validated model can be used to evaluate management alternatives. Sensitivity analysis can be used to investigate other aspects of model behavior such as the robustness of model solutions as a parameter value is varied. The prediction of future trends can be enhanced by driving the regional model with a macroscopic minimodel (H.T. Odum, 1976) of the next larger system which dynamically describes the behavior of the fundamental forcing functions. Emergy magnitudes are used as a guide to identify these important forcing factors.

8) Combine all information from the emergy analysis to address issues of concern to public policy. For example, emergy values and their changes are indicators of the ecological significance of ecosystem components and processes. These indicators should be used with determinations of risk (probability of damage or harm) to evaluate the importance of an ecological change for use in the environmental decision making process. An emergy evaluation of environmental impacts and management alternatives allows us to predict those alternatives which have a higher probability of success because they result in a maximum contribution of empower to the regional and national system.

EMERGY INDICES

If maximizing empower production and use in regional systems determines the patterns of development that will survive and prosper in the long run, we may expect many emergy indices to be particularly meaningful for characterizing the condition of a region, for estimating human carrying capacity and its sustainability, and for determining the true relationship between the region and the next larger system. There follows a list and definition of the important emergy indices used in this study:

(1) The solar transformity of an object or resource is the energy in solar equivalent joules that it takes to create a unit of that product efficiently and quickly. For example, a large number of joules from solar heat and deep heat sources in the earth are necessary to warm the land and oceans and produce a joule of chemical potential energy in pure rain water (Odum, 1994). In fact one joule of chemical potential energy in rainfall requires 1.5 E4 solar energy joules for its creation on a global basis. The solar transformity of chemical potential energy in rain is therefore 1.5 E4 solar emjoules (sej) per joule of rain.

Solar transformities for a large number of objects and resources have been calculated by H.T. Odum and E.C. Odum (1983) and H.T. Odum (1996). These transformity calculations are based on the evaluation of subsystems or production processes that result in the creation of the object or resource. When a needed transformity is not available a subsystem analysis of the production process for that object must be performed. This involves summing all the energy inputs in equivalent units required to produce a unit of that type. Solar transformities provide a scale for value referenced to a planetary energy baseline. They are necessary factors for calculating the emergy value of resources from their energy or mass contents. The calculation of a revised solar transformity for tidal energy is presented in Appendix B. The older calculations of the emergy indices for Florida, Texas, and the nation have been modified to incorporate this new estimate of the transformity of tidal energy.

(2) Emergy exchange ratio is the ratio of the emergy received in trade for the emergy given. The trading partner that receives the greater emergy value in a trade will have its economy stimulated more by the exchange. In practice raw materials such as lumber, fish, furs, oil, agricultural products, and minerals have high emergy values relative to the emergy received in trade for them because payment is rendered for the human labor involved in obtaining these products and not for the work of the environment in creating them.

(3) The emergy to dollar ratio is the total emergy used by a country or state in a particular year divided by the gross national or gross state product for that year. The emergy used includes that from renewable environmental energies, sun, wind, rain etc. without double counting (H.T. Odum, 1996); nonrenewable emergy from fuel, soil, and water reserves; and the emergy in imported goods and services.

(4) Several emergy indices of an economy are useful in examining the human carrying capacity and sustainability of regional and national systems. The emergy flow per person is an index of the standard of living which includes environmental and economic contributions to the quality of life. The emergy flow per unit area is an indication of the spatial concentration of economic activities in a state or nation. The fraction of the total emergy inflow that comes from within the region or nation is an index of its self-sufficiency.

MODEL DEVELOPMENT

An energy systems model of the Maine economy at a medium scale of complexity is shown in Figure 6. This model could be evaluated in full but in this study the model is used as a conceptual guide for organizing the emergy analysis and thinking about the Maine regional system. Pathway flows indicated by the k_i's in Figure 6 are defined in Table I. The economic sectors that comprise the various aggregated compartments in the model are defined in Table II. The environmental energy sources that provide the basis for a productive economy are shown by the circles around the edge of the large rectangle which indicates the regional boundary. The regional boundary coincides with the State boundaries and the offshore area to the 100m isobath. The transformity of forcing functions increases from left to right around the outside of the rectangle. Emergy also enters the Maine economy as fuels, goods and services, and through the earth's geologic processes. Tourists, the federal government, and export markets supply money to the Maine economy in exchange for products and services of some perceived value. These external emergy sources for Maine are evaluated in Table III except for the glaciers which contributed to building the present Maine landforms over a time scale not evaluated in this analysis.

The model components include aggregated ecosystem variables for coastal ecosystems, forests and wildlands, and agricultural systems represented by the bullet shapes on the left (Figure 6). Soil, ground and surface water, and landform are storages of environmental resources used by the economy. Wastes are produced as a byproduct of human activities. These effluents some of which are toxic are released into the environment, often in partially treated form, where they impact aquatic and terrestrial ecosystems. The industrial sector is divided into resource industries and other export industries (Table II) according to the classification of Pease and Richards (1983). Commerce and service industries are lumped into a single component that accounts for a large share of the money circulating in the gross state product, GSP, represented by a storage variable in the upper right corner of the model. People and their households are shown by the hexagon symbol on the far right. State, local, and federal government installations are included within the rectangle designated, Government. Electrical power plants within the state are also shown by a multipurpose rectangular box.

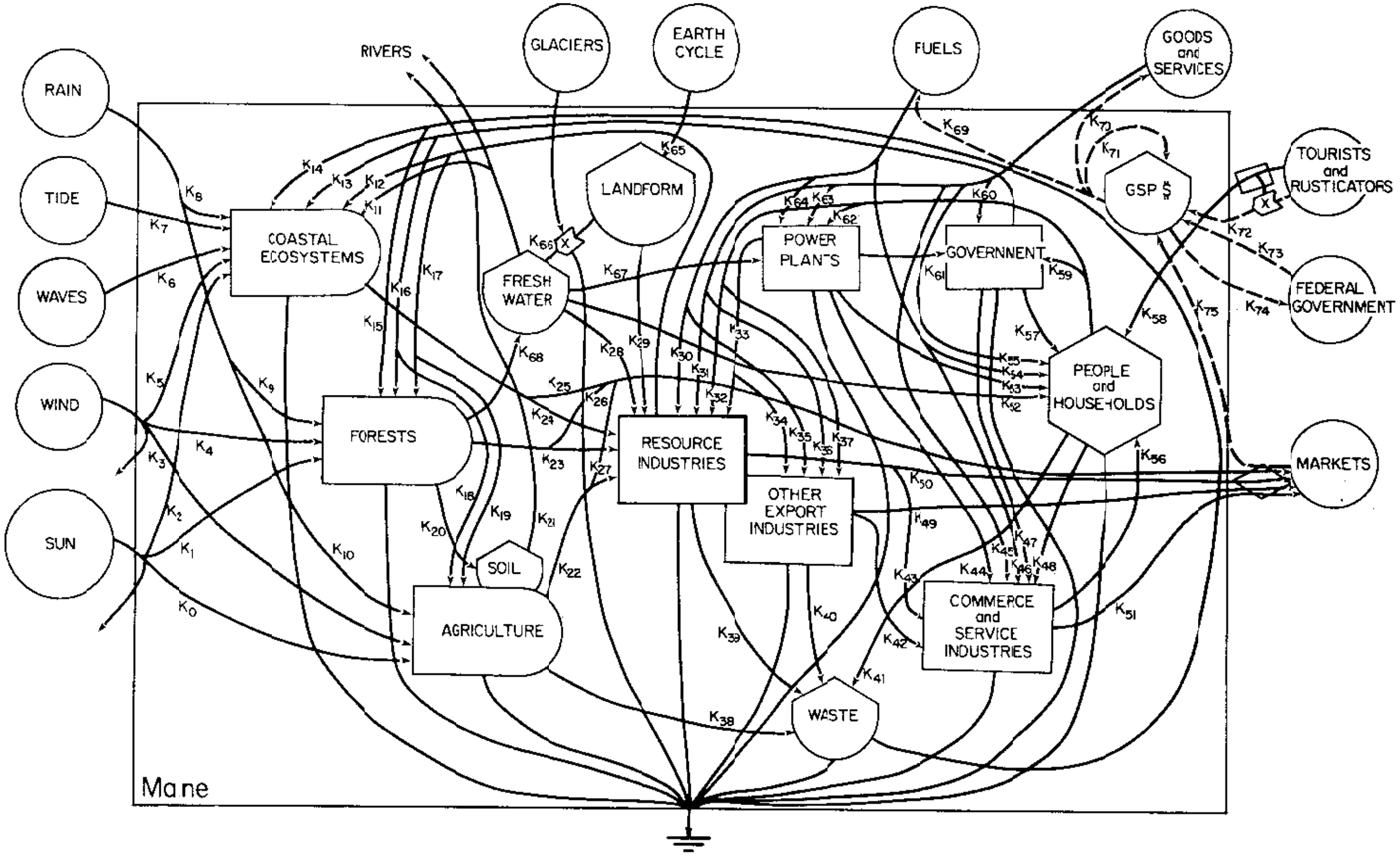

Fig. 6. A detailed conceptual energy systems model of Maine showing the environmental and economic interactions of system components and their emergy basis.

Table I
Definition of pathway flows in the conceptual energy systems model of Maine's environment and economy shown in Figure 6

Pathway Coefficient	Definition of Flow
k_0	Solar radiation absorbed by farm land.
k_1	Solar radiation absorbed by forest land.
k_2	Solar radiation absorbed by the coastal area.
k_3	Wind energy absorbed by farm land.
k_4	Wind energy absorbed by forest land.
k_5	Wind energy absorbed by the coastal area.
k_6	Wave energy absorbed along the shore.
k_7	Tidal energy absorbed by the coastal systems.
k_8	Chemical potential of rain falling on the coastal area.
k_9	Chemical potential of rain falling on the forest.
k_{10}	Chemical potential of rain falling on farm lands.
k_{11}	Chemical potential energy of river inflow to coastal ecosystems.
k_{12}	Environmental effects of commercial fishing and aquaculture.
k_{13}	Government expenditure on programs to help the coastal zone.
k_{14}	Waste discharged to coastal area.
k_{15}	Waste discharged to forests.
k_{16}	Government expenditure to improve forests.
k_{17}	Environmental effects of forest management practices.
k_{18}	Government expenditures for agriculture.
k_{19}	Environmental effects of agricultural activities.
k_{20}	Soil formed by forest land.
k_{21}	Soil lost through erosion
k_{22}	Agricultural products used by resource industries.
k_{23}	Forest products used by resource industries.
k_{24}	Fisheries products used by resource industries.
k_{25}	Fisheries products exported directly.
k_{26}	Forest products exported directly.
k_{27}	Farm products exported directly.
k_{28}	Fresh water used by resource industries.
k_{29}	Mined products used by resource industry.
k_{30}	Fuel used by resource industries.
k_{31}	Goods and services used by resource industries.
k_{32}	Labor used in resource industries.
k_{33}	Electric power used in resource industries.
k_{34}	Electric power used by other export industries.
k_{35}	Fuel used by other export industries.
k_{36}	Goods and services used by other export industries.
k_{37}	Labor used by other export industries.
k_{38}	Waste production by agriculture.
k_{39}	Waste production by resource industries.
k_{40}	Waste produced by other export industries.
k_{41}	Waste produced by people.
k_{42}	Other export industry products sold in the state.
k_{43}	Resource industry products sold in the state.
k_{44}	Electricity used by commerce and service industry.
k_{45}	Goods and services used by commerce and the service industry.
k_{46}	Fuel used by commerce and the service industry.
k_{47}	Government contributions to commerce and service industries
k_{48}	Labor used in commerce and service industry.
k_{49}	Products exported by other export industries.
k_{50}	Products exported by resource industries.
k_{51}	Commerce and service industry exports.
k_{52}	Fresh water used by people.
k_{53}	Electricity used by people.
k_{54}	Fuels used by people.
k_{55}	Imported goods and services purchased by people.
k_{56}	Goods and services purchased locally by people.
k_{57}	Government subsidies given directly to people.
k_{58}	Tourists, seasonal residents, net immigration.
k_{59}	Labor used by government.
k_{60}	Goods and services used by government.
k_{61}	Electrical power used by government.
k_{62}	Labor used by the power industry.
k_{63}	Goods and services purchased by the power industry.
k_{64}	Fuel purchased by the power industry.
k_{65}	Earth cycle energy flow driving land uplift.
k_{66}	Energy flow in glaciers creating landform.
k_{67}	Water used for hydroelectric power.
k_{68}	Fresh water recharge by forests.
k_{69}	Money spent for imported fuel.
k_{70}	Money spent for imported goods and services.
k_{71}	Money circulating in the State GSP.
k_{72}	Money brought into the state by tourists.
k_{73}	Federal subsidies to the state.
k_{74}	Federal taxes paid by the state.
k_{75}	Money received from the export trade.

Table II

Definition of the aggregated components in the energy systems model of Maine's environment and economy shown in Figure 6.

Component	Definition
Coastal Ecosystems	All marine, estuarine, and intertidal ecosystems <100 m in depth; including beaches, marshes, mudflats, estuaries, rocky coasts, coastal shelf.
Forests	All forest land both managed and unmanaged, including maple-beech, spruce-fir and pine forests, as well as, bogs, swamp, and marshes.
Agriculture	All crop, pasture and orchard land.
Soil	The storage topsoils in Maine.
Fresh water	The quantity of fresh water stored as groundwater and surface water.
Landform	The land and the minerals it contains.
Resource Industries	All primary and secondary fishing, farming, forest, and mining industries, including paper, lumber, furniture, and cord wood industries; the various fisheries, aquaculture, and seafood processing; potato, poultry, dairy, and fruit farms and food processing operations; sand, gravel, and limestone mining and cement manufacture.
Export Industries	All other manufacturers of durable and nondurable goods, including leather products, textiles, and apparel; engines, instruments and computers; large insurance carriers; and shipbuilding.
Power Plants	All fossil fuel, nuclear, and hydroelectric plants generating electricity in Maine.
Government	State, local, and federal government.
Commerce and Service Industries.	Retail and wholesale trade, hotels, restaurants, banking, real estate, insurance companies; the transportation industry; health, legal, social, personal, and repair services; waste treatment, schools other government services.
People	The population of Maine and their assets (households).
Waste	Waste products created by industry, people, and agriculture.
GSP	Gross State Product.

Table III

Emergy evaluation of the resource base for the Maine economy in 1980. The transformities are taken or modified from H.T. Odum (1996) except as noted.

Note †	Item	Energy Flow y^{-1}	Transformity SEJ $Unit^{-1}$	Solar Emergy E21 SEJ	Emdollars# E8 1980 $
Renewable Sources within Maine					
2	Sun	4.51E20 J	1 J^{1}	0.45	1.7
3	Wind	5.47E17 J	1268 J^{-1}	0.69	2.7
4	Tides*	1.57E17 J	49383 J^{-1}	7.75	29.8
5	Waves	9.95E16 J	25890 J^{-1}	2.58	9.9
6	Rain, chemical	4.74E17 J	15423 J^{-1}	7.31	28.1
7	Rain, geo-potential	2.06E17 J	8888 J^{-1}	1.83	7.0
8	Rivers, chemical	2.99E17 J	41068 J^{1}	12.30	47.2
9	Earth Cycle	1.42E17 J	34377 J^{-1}	4.88	18.8
10	Fuels, renewable from within the state				
	Hydropower	2.90E16 J	8.5E4 J^{-1}	2.46	9.5
	Wood	2.95E16 J	3.2E4 J^{-1}	0.94	3.6
Imports from Outside Maine					
10	Fuels, nonrenewable purchased out of state				
	Coal	2.00E15 J	4.0E4 J^{-1}	0.08	0.3
	Petroleum	2.54E17 J	5.4E4 J^{-1}	13.7	52.8
	Natural Gas.	2.32E15 J	4.8E4 J^{-1}	0.11	0.4
	Nuclear Elec	2.82E16 J	1.6E5 J^{-1}	4.51	17.4
	Canadian Elec	7.27E15 J	8.5E4 J^{1}	0.62	2.4
11	Tourists	1.07E9 $	2.6E12 S^{1}	2.78	10.7
12	Goods and Services	2.98E9 $	2.6E12 S^{-1}	7.80	29.8
13	Federal Government	0.86E9 $	2.6E12 S^{-1}	2.24	8.6
18	Immigration	7500 people	3.4E16 $p.^{-1}$	0.26	0.9

Solar Emergy in column 5 divided by 2.6E12 sej S^{-1} for the U.S. in 1980.

* Calculated in Appendix B of this paper.

† Note 1 gives the area used in the calculations.

6. Results

Table III gives the emergy and emdollar values for the renewable and nonrenewable emergy base of Maine's economy. The numbers listed in column 1 of Table III and Table IVdirect the reader to a note in Appendix A where the value in column three is calculated and/or documented. The emergy sources generated by solar energy in order of decreasing magnitude are the chemical potential emergy in rain, the emergy in waves, and the geopotential emergy of rain. The emergy of the tides is the largest renewable emergy source, but it is only slightly greater than the chemical potential emergy of rain. The extremely large emergy value for the chemical potential energy in rivers is a further concentration of the large chemical potential emergy in rainfall and as such it is not considered to be a primary emergy source for Maine. The largest emergy input to Maine from all sources is in fuels. Petroleum is the most important fuel for Maine, although nuclear energy and hydroelectric power together supply half as much emergy as petroleum. The emergy contributed to the regional system by imported goods and services is second in magnitude behind petroleum fuels, and it is just slightly larger than the emergy supplied by the tides and in the chemical potential energy of rain.

The emergy and emdollar values in Maine's stored resources are shown in Table IV. The largest emergy value of the stored resources (natural capital) is found in Maine's extensive peatlands which are about 3% of the total state area (Hasbrouck 1979). The emdollar value stored in peat is worth about 50 times the total value of the 1980 gross state product. The second largest storage is in the accumulated talents and experience of the people of Maine (human capital) which has an emergy value that is 81% of the emergy stored in peat. Topsoil contains the third largest emergy storage. Even though the state as a whole is gaining topsoil, agricultural areas such as the potato growing region of Aroostock County are loosing this stored resource faster than it is being replaced. Economic assets, wood, and groundwater are also important stored resources in Maine. When all forest lands are taken into account, timber in Maine grows about twice as fast as it is harvested. However, this is not true for individual tree species which may be over harvested if they are of sufficient value. None of these stored resources were considered as part of the annual emergy basis for Maine's economy because over the whole state their stored values are not being used faster than they are being replaced. As noted above, this situation may change if a more detailed analysis of regions or industries within the state is performed.

Table IV
Evaluation of emergy storages in the environmental and economic resources of Maine in 1980.

Note	Item	Raw Units	Transformity sej unit^{-1}	Solar Emergy E21 sej	Emdollars# E8 1980 $
14	Peat*	6.8E19 J	1.9E4/J	1292	4969
15	Wood*	4.52E18 J	3.2E4/J	145	556
16	Groundwater†	1.71E18 J	1.1E5/J	188	723
17	Topsoil†	1.21E19 J	6.3E4/J	762	2932
18	Population	3.38E7 p-y	3.1E16/p-y	1048	4030
19	Assets	1.86E11 $	2.6E12/$	484	1861

Solar emergy in column 5 divided by 2.6E12 solar emjoules per dollar for the U.S. economy in 1980.
* H.T. Odum (1996)
† H.T. Odum *et al.* (1987)

Figure 7 is an aggregated model of Maine's economy suitable for gaining an overview of emergy flows across state boundaries. Table V summarizes the flows of emergy and dollars that form the basis of the Maine economy. Diffuse environmental resources (e.g., sunlight, rainfall, etc.) total 15.1E21 sej y^{-1} or 33% of the state's total emergy budget. Fuels account for 41% of the emergy use, and imported goods and services excluding fuels accounted for 17%. Renewable fuel resources such as wood and hydroelectric power found within the state comprise 7.3% of the state's total emergy use.

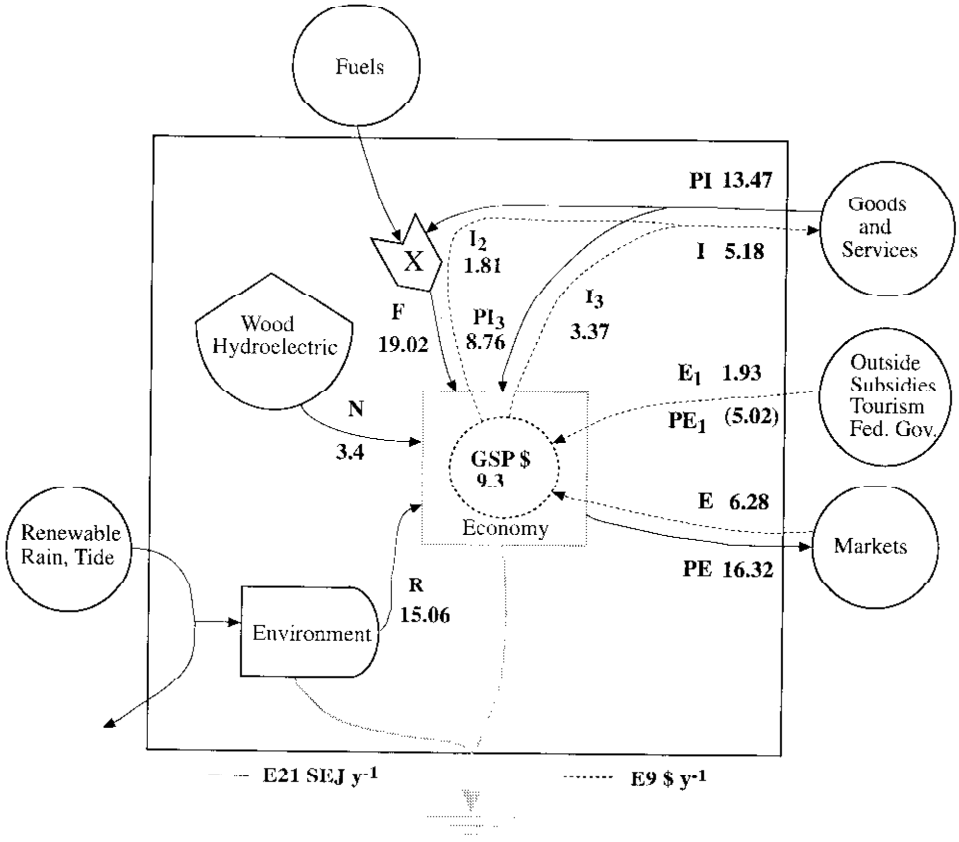

Fig. 7. An aggregated diagram of the Maine State economy and its emergy resource base for the calculation of emergy indices.

The gross state product, GSP, in 1980 was 9.3 E9 $ of which 56% was spent outside on goods and services. Fuels accounted for 35% of imports and 19.5% of the GSP on a dollar basis, whereas, on an emergy basis fuels account for 68% of imported emergy and 41% of the total emergy use by the economy. Twenty-one percent of the GSP or 1.93 E9 $ y^{-1} is attracted to Maine in tourist and net federal expenditures. There is no actual emergy flow which corresponds to all of the money spent; however, something of value is received for these expenditures (e.g., tourists consume resources obtain experiences which are taken with them) therefore, there is a virtual emergy outflow of 5.02 E21 sej y^{-1} corresponding to this monetary influx which is directly or indirectly dependent on the abundance of environmental resources in Maine and the image of attractiveness that they project. This virtual emergy flow is equivalent to 11% of the total actual emergy use, 23% of total exports (including the virtual flows), and 37% of imported goods and services in 1980.

Table V
Summary of emergy and dollar flows for Maine in 1980 (See Figure 7).

Symbol	Item	Solar Emergy E21 sej y^{-1}	Dollars E9 \$ y^{-1}
R	Renewable sources	15.06	
N	Energy sources within Maine	3.4	
F	Imported fuels	19.02	
I	\$ paid for imports		5.18
I_2	\$ paid for service in fuels		1.81
I_3	\$ paid for imports (minus fuel)		3.37
PI_3	Imported goods and services excluding services to fuel	8.76	
PI	Imported goods and services	13.47	
E	\$ paid for exports		6.28
PE	Exported goods and services	16.32	
E_1	\$ attracted by natural resources		1.93
PE_1	Virtual emergy flow representing the aesthetic value of the environment	5.02	
X	Gross State Product		9.3
P	U.S emergy to dollar ratio used for imports.	2.6E12 sej \$$^{-1}$	

Table VI defines a number of emergy indices that are useful in characterizing Maine and comparing its emergy profile to that of other states and to the nation as a whole. Locally renewable emergy (R/U = 0.33) is an indicator of a region's self sufficiency in the long run. At present 40% of Maine's emergy is derived from home sources which also indicates the potential for a region to be self-sufficient; however, 60% of the emergy use is purchased from outside the state which indicates a strong present dependence on national resources. Twenty nine percent of Maine's total emergy use comes from imported goods and services which compose 48% of the total imported emergy, the other 52% is mostly in the fuels themselves. In 1980 Maine had an emergy imbalance with the rest of the nation of 11.5 E21 sej (F+ PI3 - PE), equivalent to 41% of the emergy imported. Therefore, economic conditions in Maine are highly dependent on the conditions in the national economy which determine the availability of emergy for import. Actual exports are only 59% of imports, but if total exports which include the virtual flows are considered exports increase to 77% of imports. During 1980, 4.1 E16 sej per person were used in Maine which is an expression of the people's standard of living in that year. At the 1980 standard of living Maine's renewable resources could support a human carrying capacity of 0.37 E6 people. The developed human carrying capacity for Maine was 2.9 E6 people compared to the 1980 population of 1.13 E6 people.

Table VI
Emergy indices for an overview of Maine in 1980.

Expression	Name of Index	Quantity
R	Renewable emergy flow	15.1E21 sej y^{-1}
N	Flow from indigenous sources	3.4E21 sej y^{-1}
$F+PI_3$	Flow of imported emergy	27.8E21 sej y^{-1}
$R+N+F+PI_3$	Total emergy in flows	46.3E21 sej y^{-1}
$R+N+F+PI_3+N0$	Total emergy used*, U	46.3E21 sej y^{-1}
$(R+N)/U$	Fraction of emergy from Maine	0.40
R/U	Fraction of use locally renewable	0.33
$(R+N0)/U$	Fraction of use that is free†	0.33
$(F+PI_3)/U$	Fraction of use purchased outside	0.60
PI/U	Fraction of use in imported goods and services	0.29
PE	Exported emergy in goods and services	16.3E21 sej y^{-1}
PE_t	Virtual emergy export	5.0E21 sej y^{-1}
$PE+PE_t$	Total emergy export	21.3E21 sej y^{-1}
$(F+PI_3)-PE$	Imports - actual exports	11.5E21 sej y^{-1}
$PE/(F+PI_3)$	Ratio of actual exports to imports	0.59
$(PE+PE1)/(F+PI_3)$	Ratio of total exports to imports	0.77
$(F+N+PI_3)/R$	Ratio of concentrated to dispersed	2.00
U/area	Emergy use per unit area (9.4E10 m^{-2})	4.9E11 sej m^{-2}
U/population	Present emergy use per person (pop = 1.125E6)	4.1E16 sej $p.^{-1}$
R/(U/pop.)	Renewable carrying capacity at the present standard of living	0.37 E6 people
8R/(U/pop.)	Developed carrying capacity at the present standard of living.	2.9 E6 people
P1=U/GSP	Ratio of emergy use to GSP, or state emergy to dollar ratio	5.0 E12 sej $\$^{-1}$
el/U	Ratio of electricity to emergy use el = 10.26 E21 sej y^{-1}	0.22
fuel/pop.	Fuel use per person	2.2E16 sej $p.^{-1}$

* Total emergy use includes that from N0, the stored emergy resources, e.g. soil, groundwater, forest biomass, that are being used faster than their rate of replacement. For Maine initial calculations indicate that replacement rates exceed use of these resources in the state as a whole.

†Since N0 = 0 the fraction of locally renewable emergy is equal to the that which is free.

COMPARISON OF EMERGY INDICES FOR MAINE, FLORIDA, TEXAS, AND THE NATION

Table VII contains a comparison of various emergy indices for Maine, Florida, Texas, and the United States including Alaska. Maine is endowed with a large amount of renewable emergy relative to the average available in the nation. Maine accounts for 1% of the national area but receives 2% of the nation's renewable emergy. Florida is somewhat better endowed with renewable emergy since Maine contains 30% of Florida's land area but only 22% of her renewable emergy. In contrast, Maine receives 39% of the renewable emergy input to Texas over an area 13.4 % the size of Texas. Renewable emergy accounts for a larger fraction of present emergy use in Maine (0.33) than in the other states examined. Renewable emergy as a fraction of total use indicates the present degree of economic development in an area while the quantity of renewable emergy available per unit area indicates the potential for self sufficiency in the long run.

Table VII
Comparison of emergy indices for Maine, Florida, Texas, and the United States circa 1980.

Index	Maine 1980	Florida# 1979	Texas† 1983	U.S.† 1983
Renewable emergy flow*	15.1	66.2	39	773
Indigenous emergy flow*	3.4	2.1	666	5346
Imported emergy flow*	27.8	284	307	1936
Total emergy inflow*	46.3	352	595	8055
Total emergy used*	46.3	380	628	7887
Fraction use from home	0.40	0.18	0.84	0.75
Actual emergy export*	16.3	95.7	501	870
Imports - exports *	11.5	188	-194	811
Ratio exports to imports	0.59	0.34	1.6	0.58
Renewable fraction of use	0.33	0.17	0.06	0.10
Purchased fraction of use	0.60	0.75	0.37	0.25
Fraction that is free	0.33	0.18	0.12	0.22
Ratio concentrated to dispersed	2.0	4.2	7.3	3.5
Area (m^{-2})	9.4E10	3.1E11	7E11	9.4E12
Population	1.13E6	8.8E6	15.7E6	234E6
Use per area sej m^{-2}	4.9E11	12E11	9E11	8.4E11
Use per person sej $p.^{-1}$	4.1E16	4.3E16	4.0E16	3.4E16
Renewable carrying capacity	0.37E6	1.53E6	0.98E6	23E6
Developed carrying capacity	2.9E6	12.3E6	7.8E6	183E6
Emergy to \$ ratio sej $\$^{-1}$	5.0E12	4.3E12	2.6E12	2.4E12
Ratio electricity to use	0.22	0.23	0.18	0.17
Fuel use in sej $p.^{-1}$	2.2E16	2.3E16	2.9E16	1.5E16

* Flows in sej y^{-1} times E21.

\# Data on Florida from H.T. Odum *et al.* (1986) with modified tidal input.

† Data on Texas and the United States are from H.T. Odum and E.C. Odum (1987) with modified emergy input from tides.

Maine, Florida, and the nation import more emergy than they export. Texas alone exports emergy, principally due to the sale of petroleum. Maine exports 59% of the emergy which it imports making it the state most similar to the national average. Florida is the state most dependent on the emergy available nationally because it's exports account for only 34% of the emergy imported. Texas is the state least dependent on the nation in the short run since it exports 1.6 times more emergy than it imports. Florida purchases 75% of its emergy use, while Maine buys 60% of the emergy it uses. Both of these fractions are large when compared to Texas which purchases only 37% of its emergy. The fraction of emergy purchased outside the state is an indicator of the dependence of a state on the availability of emergy in the national economy. The United States is less dependent (25% of its emergy is imported) on foreign emergy compared to the dependence of these individual states on the nation.

The ratio of emergy use in urban systems to emergy use in rural systems is an indicator of the degree of economic development. According to this criterion Maine is much less developed than Texas and less developed than Florida and the U.S. as a whole. This picture is mirrored in the index of emergy use per unit area, where the density of emergy use in Maine is 41% of that in Florida, 54% of that in Texas and 58% of the national emergy use density. Maine has an emergy to dollar ratio 1.9 times that of Texas, 2.1 times the national average, but only 1.2 times greater than Florida. This indicates that a dollar spent in Maine buys twice the emergy of an average dollar spent in the nation. This is true because a large fraction of the total resource base is provided by unpaid environmental work. The greater the emergy to dollar ratio the more competitive an area will be in attracting economic inflows, all other things being equal, because a dollar spent buys more free environmental service than in areas with a lower emergy to dollar ratio.

The emergy use per capita is an indicator of the standard of living which must be specified to describe human carrying capacity. Maine, Florida, and Texas all use more emergy per capita than the national average. Maine and Texas had a per capita emergy use which was 95% and 93%, respectively, of the highest use which was found in Florida. All the standards of living measured fell within a narrow range with Florida only 26% greater than the national average.

Maine can support 33% of her present population at their 1980 standard of living in a time when only renewable emergy is available for use. This estimate indicates that for a future similar to that predicted in Figure 3b, 370,000 people could be sustained indefinitely at the 1980 standard of living as defined by emergy use. This percentage is considerably larger than the national average of 9.8%. Florida and Texas could support 17.3% and 6.2% of their present populations, respectively, on their renewable emergy alone. The developed human carrying capacity of Maine and Florida exceeded their 1980 populations. The developed carrying capacity is defined as the number of people a state could support at their present standard of living if its emergy use was 8 times the renewable resource base. The factor of eight represents an average ratio for developed countries in the world circa 1980 (H.T. Odum et al., 1987a). Texas had the highest degree of development since it proved to be supporting twice as many people as expected for an average developed industrial country. Maine's population can be increased 2.6 times and Florida's 1.4 times before they support as many people as an average developed country at the 1980 standard of living.

7. Discussion

Aggregation of variables at the state level obscures regional differences and may lead to a somewhat distorted view of the actual situation in Maine. For example, the entire state area is used to determine the emergy use per unit area when in reality about two thirds of the state's area is sparsely settled forest land and the remaining third supports 85% of the population (Morris 1976). Therefore, an intrastate regional analysis may give different results than those found for the state as a whole. Similar regional differences in the emergy indices for the United States as a whole may exist because the vast hinterland of Alaska has been included in the calculation of national average values. The existence of regional differences within a nation or a state does not necessarily invalidate the whole analysis or the comparison of emergy indices among nations or states because these regional variations are present to a greater or lesser degree in most nations and states. However, these departures from uniformity do point out the need for emergy analysis to be pursued at the regional level within systems to address certain assessment questions.

The state of Maine was divided into three regions, which were used in averaging observations for subsequent analysis (Figure 5). The Coastal area is a zone rich in emergy inputs and popular with tourists, rusticators, and natives alike because of its great natural beauty. The Upland region is the industrial and farming center for Maine which is linked to the rest of New England by Interstate 95 (Barringer 1972), while the Mountain region is a hinterland containing vast forest tracts, recreational facilities, and few people (Barringer 1972). An emergy analysis of these three regions could determine the contribution each area makes to the support of economic activities within the state. The potato growing area in Aroostock County forms an additional subregion within the uplands that should be evaluated as a separate system because of its particular set of problems i.e., soil erosion. For similar reasons, the eastern coastal and upland area is logically combined into the economically isolated "Down East" region (Washington County) for separate analysis. Single sectors of the economy, such as the fishing, transportation, or forest products industries are also possible subjects for analysis using this method.

Several emergy indices show that Maine may have a high degree of self-sufficiency in a future with lower fossil fuel availability, whereas, in today's fossil fuel economy it has a low degree of self-sufficiency. In a low energy future it is probable that Maine would be even better off than indicated in Table VII. Several observations contribute to this opinion. Maine has large quantities of renewable energy which are not being fully exploited at present. For example, Maine forests are growing biomass at twice the present rate of harvest, the potential for using water power is not yet exhausted, and there is a great potential in tidal power that is unutilized. In addition, to these renewable resources, Maine has large quantities of peat stored in bogs that can be an important source of energy in the future whether it is exploited in a renewable or nonrenewable way. These extensive natural resources combined with the ingenuity that the Maine people have historically displayed in mastering the forest and the sea will probably make Maine a state with a standard of living close to the present high level despite lower energy in the future.

Despite some evidence of environmental degradation (Pollard 1973, Larsen 1989), emergy indices show that Maine is a state which at least for the present has both a high standard of living and a relatively unspoiled environment. Fuel, electricity, and emergy use per person are all far above the national average which indicate that the Maine standard of living is a good one. In addition, the fraction of emergy use in free and renewable sources is the highest of the four cases examined which reflects the relatively unspoiled and undeveloped state of Maine lands as a whole. Thus, many people in Maine enjoy the values of a developed economy along with the environmental resources of a state that is yet to become heavily developed. This view is altered somewhat if the regional distribution of development is considered. Southern Maine is within the expanding edge of the greater Boston metropolitan area, and at present is experiencing some of the environmental and social problems that development brings. In contrast, large areas of the state exist as unincorporated townships which lack the organization and infrastructure that we have come to expect as part of a developed country.

The challenge for Maine in the immediate future is to fulfill its development potential without compromising the environmental resources that support a high quality of life. What human carrying capacity will be sustainable in Maine? We have demonstrated using the conceptual model in Figure 3 that the answer to this question depends on the standard of living that is desired by the population and on the renewable energy basis for the region. The human carrying capacities for Maine, Florida, Texas, and the nation at the 1980 standard of living on their renewable environmental resource bases alone were 34%, 17%, 6%, and 10% of their present populations, respectively. The present human populations living in these states and in the United States as a whole indicate that our way of life is not sustainable using present system designs. In the long run human population and/or the standard of living must adjust to come within the range that the renewable environmental resource base can support. This can happen in two obvious ways. Human population size can be decreased given sufficient lead time (e.g., the one child policy instituted by the People's Republic of China) or the rate of resource consumption can decrease to a level which allows the existing population to survive on the renewable resource base. The latter course assumes that present populations can indeed subsist on the renewable environmental resource base. In either case, our standard of living will be ameliorated by testing and incorporating changes in our social, economic, and environmental system designs that improve efficiencies and help us obtain more for less from the existing environmental-economic interface. As mentioned earlier such design changes are not a panacea, but they may considerably soften the shock of a necessary decline in population size and/or standards of living to meet the constraints on the rates of resource use imposed by using our resources in a renewable way.

Pulsing may be nature's strategy for getting more for less. Developing a better understanding of how pulsing maximizes the empower production of environmental-economic systems may increase our ability to recognize system designs that will allow us to choose alternatives that optimize human populations and their standard of living at each stage in the cycle of change including a future time when we are more dependent on renewable environmental resources. For example, by developing presently unexploited renewable resources such as tidal power, and by exploiting renewable peatlands and forest biomass in phase coordinated pulses with other regions, Maine may be able to contribute to supporting a larger fraction of the nation's 1980 population in a future with low fossil fuel supplies than would otherwise be possible.

Optimizing human population and standards of living during the climax of fossil fuel use (in the short run) requires us to consider our present state of development in relation to the expectations for global development (see Wackernagel and Yount this volume). The present populations for Maine (39% of the average) and Florida (72% of the average) were less than the expected value for an average developed country in the world circa 1980, whereas, the populations of Texas (200% of the average) and the United States as a whole (128% of the average) exceeded the world average carrying capacity for a developed country. For the near term future Maine and Florida should focus on carefully managing their remaining growth potentials, whereas, Texas should consider strategies that will reduce its population size and focus research programs on developing system designs (perhaps centering on agriculture, H.T. Odum *et al.*, 1987a) that will maximize the quality of life for a smaller population in the future.

It may be unwise to develop regions more intensely than the average for a developed country at present because the most heavily developed regions may suffer the greatest hardship during a decline in fossil fuel availability. Alternatively, the less developed areas may suffer more because they will have to willingly or forcibly subsidize the developed areas during a period of decline. The pulsing paradigm for sustainability leads to the hypothesis that a climax state of emergy use may be prolonged by the coordinated out of phase pulsing of regions within or controlled by the system that is in climax. Design changes that reinforce this pattern may be successful in optimizing human carrying capacity at a chosen standard of living for regions, nations, and our planet during the portion of the pulsing cycle of change when our nonrenewable fossil fuel resources are peaking.

8. Conclusions

Several conclusions about human carrying capacity and regional sustainability can be derived from the discussion of the overview ideas presented in this paper. They are as follows:

(1) All regional development based on the nonrenewable use of resources is inherently unsustainable.

(2) Human carrying capacity at a specified standard of living represents the anthropogenic load on a given regional environmental resource base.

(3) Because the environmental resource base of a region is varying in a pulsing cycle of change (Figure 4b), human populations and/or standards of living must constantly be adjusted to maintain the same load on the resources.

(4) Pulsing appears to be the pattern that insures survival and maximum performance in natural systems. Therefore, a pulsing steady state with a cycle of change in carrying capacity may be the pattern that is sustainable for a region with a given environmental resource base rather than a steady state with a constant development level or carrying capacity.

These assumptions interpreted in the context of Energy Systems Theory lead to the following recommendations for optimizing the load on environmental resources which results from different human carrying capacity and level of development choices in a region through time.

(1) Identify the pulsing patterns in a region and the fundamental drivers (energy sources) so that we know where we are in the cycle of change, e.g. succession, climax, regression, or low energy steady state.

(2) Use an emergy perspective to assess environmental and economic problems while nonrenewable resources are still high and the range of possible responses to their future decline is correspondingly large.

(3) Search for and incorporate systems designs that will maximize empower production and use at each stage in the pulsing cycle of change.

(4) The key to prolonging a stage in the cycle and to insuring a smooth transition from one phase of the cycle to another may be in learning to recognize and manage the cycles of environmental-economic pulsing on multiple scales.

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Appendix A - Evaluation of Maine Energy Resources

NOTE #1. AREAS

Land area of the state: 86156 km^2, (Maine State Development Office 1985 (our estimate from maps was 84261 km^2 which is 2.2% less than the area above).

Area by physiographic region in Figure 5.

Coastal region:	10596 km^2
Upland region:	42609 km^2
Mountain region:	31056 km^2
Continental shelf headlands to 100 m:	9822 km^2

NOTE #2. DIRECT SUNLIGHT

(area of state) (average insolation)

Area of Maine including the shelf area out to 100 m. = 94083 km^2

Northern Region: Mountains and Aroostook Co. 31056 km^2 + 10059 km^2 = 41115 km^2 = 4.1115 E10 m^2

Remaining land: Uplands and Coastal (land only) 32550 km^2 + 10596 km^2 = 43146 km^2 = 4.3146 E10 m^2

Shelf to 100 meter isobath: 9822 km^2 = 9.822 E9 m^2

Solar Energy Totals: The average daily solar insolation from 1961 - 1971 received at Caribou is used for the Northern region. The remainder of the land and the continental shelf are assumed to receive an average solar insolation similar to that received at Portland during the same time period (U.S. Dept. Commerce 1971).

(4.1115 E10 m^2) (4.643 E9 J m^{-2} y^{-1}) = 1.909 E20 J y^{-1}

(4.3146 E10 m^2) (4.917 E9 J m^{-2} y^{-1}) = 2.1215 E20 J y^{-1}

(9.8220 E9 m^2) (4.917 E9 J m^{-2} y^{-1}) = 4.8295 E19 J y^{-1}

Total Solar Energy = 4.5134 E20 J y^{-1}

NOTE #3 - KINETIC ENERGY IN WIND USED AT THE SURFACE

(height) (density) (diffusion coefficient) (wind gradient)^2 (area)]

Assume an annual average vertical eddy diffusion coefficient of 15 m^2 s^{-1} similar to Albany, NY. the closest station to Maine given in Odum et al. (1983). The annual average vertical velocity gradient was calculated for stations at Caribou and Portland (U.S. Dept. of Commerce 1980). Areas were the same as those used in the solar energy calculation.

Northern Region:

(1000 m) (1.23 kg m^{-3}) (15 m^3 m^{-1} s^{-1}) (3.154E7 s y^{-1}) (3.31E-3 m s^{-1} m^{-1})^2 (4.115E10 m^2) = 2.62E17 J y^{-1}

Uplands, Coast, and Shelf:

(1000 m) (1.23 kg m^{-3}) (15 m^3 m^{-1} s^{-1}) (3.154E7 s y^{-1}) (3.04E-3 m s^{-1} m^{-1})^2 (5.2968E10 m^2) = 2.84E17 J y^{-1}

Total wind energy = 5.47E17 J y^{-1}

NOTE #4 - TIDAL ENERGY ABSORBED

(area elevated) (tides per year) (height)^2 (density) (gravity)

Tidal energy absorbed on the shelf (9.822E9 m^2) assuming an average tidal height over the entire area of 1.5 m (Moody et al. 1984) and that 100% of the tidal energy is absorbed on the shelf or in nearshore waters.

(9.822E9 m^2) (706 y^{-1}) (1.5 m)^2 (1.0253E3 kg m^{-3}) (9.8 m s-^{2}) – 1.568E17 J y^{-1}

NOTE #5 - WAVE ENERGY ABSORBED

(Shore length) (1/8) (density) (gravity) (height)^2 (velocity)

The annual average wave height measured at NOAA's Portland buoy station was 1.0 m for the years 1982 - 1984 (National Climate Data Center 1986). Assume that d, the average water depth in the breaker zone along the Maine coast, is 5 m. The shore length at the headlands is our estimate.

Then wave speed, c= gd = 7 m s^{-1}.

(3.59E5 m) (1/8) (1.025E3 kg m^{-3}) (9.8 m s^2) (1.0 m)^2 (7 m s^{-1}) (3.145E7 s y^{-1}) = 9.95E16 J y^{-1}

NOTE #6 - CHEMICAL POTENTIAL ENERGY IN RAIN:

(Area including shelf) (Rainfall) (Gibbs Free Energy, G) =

The area weighted average annual rainfall is 102.04 cm y^{-1} based on the 1931 -55 average precipitation by area for 26 stations (U.S. Dept. Commerce 1972). G assumes 10 ppm dissolved solids concentration in rain.

The spatial division averages were: Coastal = 114.44 cm y^{-1}, Upland = 101.73 cm y^{-1}, Mountain= 97.66 cm y^{-1}.

(9.41E10 m^2)(1.02 m y^{-1})(4.94 J g^{-1})(1E6 g m^{-3}) = 4.74E17 J y^{-1}

NOTE #7 - GEOPOTENTIAL ENERGY IN RAIN

(area) (mean elevation) (runoff) (density) (gravity)

The mean elevation for Maine is 244m from Odum et al. (1983).

(8.43E10 m^2)(244 m)(1.02 m y^{-1})(1.0E3 kg m^{-3})(9.8 m s^{-2})= 2.06E17 J y^{-1}

NOTE #8 - CHEMICAL POTENTIAL ENERGY IN RIVER

(Volume of Flow) (Density) (G), where G is the Gibbs free energy of river water relative to sea water. The volume of flow is a 30 year average from Bue (1970).

$$G = \left(\frac{(8.33\ J\ mole^{-1}\ degK^{-1})\ (\ 300\ ^{\circ}K)}{18\ g\ mole^{-1}} \right) \ln \left(\frac{1E6\ -\ S}{965{,}000} \right)\ J\ g^{-1}$$

where S = 50 ppm is the dissolved solids concentration in river water.

$$G = 138.8\ J\ g^{-1}\ \ \ln \left(\frac{999{,}950}{965{,}000} \right) = 4.94\ J\ g^{-1}$$

(6.05E10 $m^3\ y^{-1}$) (1E6 g m^3) (4.94 J g^{-1}) = 2.99E17 J y^{-1}

NOTE #9. EARTH CYCLE

(area) (heat flow per area)

53.54 mW m^{-2} average crustal heat flux in Maine estimated from Decker (1987).

Heat flux due to earth cycle = (8.4261E10 m^2) (1.689E6 J $m^{-2}\ y^{-1}$) = 1.422E17 J y^{-1}

NOTE #10. POWER SOURCES

Data in this section were extracted from Maine Office of Energy Resources (1985). The dollar value of Maine's 1980 fossil fuel use was $1.81E9. The use of energy in Maine during 1980 in J y^{-1} for the major sources is as follows: Coal, 2.003E15; Petroleum, 2.548E17; Natural Gas, 2.319E15; Wood, 2.951E16; Nuclear output, 2.825E16; Canadian Electric 7.273E15; Hydropower, 2.899E16.

NOTE #11 TOURISM

Rovelstad and Rovelstad (1987) estimate tourist expenditures in Maine to be $1.69E9 in 1985. A prior study by Arthur D. Little in 1973 (Pease and Richard 1983) estimated tourist expenditures in Maine to be $3.10E8 If tourism increased linearly between these two times, tourist expenditures in Maine for 1980 would have been $1.07E9.

NOTE #12 IMPORTED GOODS AND SERVICES

The U.S. Transportation Census estimated that Maine manufacturers received $3.2E9 worth of goods from all parts of the country in 1977 and shipped $4.2E9 worth of products in return. Intrastate shipments were valued at $0.8E9 which we assume are distributed equally between shipments and receipts. Maine foreign exports in 1977 were around $0.2E9 (Maine State Development Office, 1985). We estimate the total value of Maine manufacturers shipments in 1977 at $4.4E9. By 1981 this value was $7.8E9, if we assume a linear rate of increase, manufacturers shipments in 1980 are estimated to be $6.95E9. Exports to Canada in 1980 were estimated to be $0.22 E9 so about $6.73E9 were shipped domestically in 1980. If intrastate shipments were about 10% of the domestic shipments as they were in 1977, interstate shipments in 1980 were $6.06E9 and a total of $6.28 E9 goods and services were exported. If the trade balance between Maine and the rest of the nation in 1980 was the same as it was in 1977 (imports = 0.76 exports), she imported $4.6E9 of goods from the rest of the nation in 1980. Maine's imports from Canada in 1981 are estimated to be $0.58E9 and total imported goods and services are estimated to be $5.18E9. Data quoted here are from Maine Development Office (1985) and Pease and Richard (1983).

NOTE #13 FEDERAL GOVERNMENT

Total outlay of federal funds to Maine in 1980 was $2.56E9 of which $1.33E9 was direct transfer payments to individuals. Personal income taxes paid in Maine in 1980 were $9.64E8. If Maine's share of all taxes is similar to her share of personal income tax we estimate business taxes, social security taxes, and corporate income taxes paid in 1980 to be $8.25E7, $4.3E8, and $2.43E8 respectively. Therefore, Maine's total contribution to the federal government in 1980 was $1.72E9, leaving a surplus balance of $8.6E8 in government funds that was spent in Maine. Data in this footnote were taken from Pease and Richard (1983) and U.S. Bureau of Census (1985).

NOTE #14. POTENTIAL ENERGY IN STORED PEAT

(volume of material) (density) (organic fraction) (G)

Volume: Average depth of peat = 3.05m, Approximate area of peatlands = 2.53E9m^2, 3.05 x 2.53E9 = 7.71E9 m Density: Peat density = 0.67g cm^{-3}; % Organic: Ash content of peat = 10%; G: Assumed similar to lignite, 6300 Btu/lb, (13.88 Btu/g) (1,054 J/Btu) = 14,629 J/g

Energy stored in Maine peat = (7.71E9 m^3) (1E6 $cm^3\ m^{-3}$) ((0.67 g cm^{-3}) (.9) (14,629 J g^{-1}) = 6.8E19 J

Presently peat is not mined extensively in Maine (about 5000 tons were mined in 1977). The information used to make the peat calculations is from Hasbrouck (1979).

NOTE #15 - POTENTIAL ENERGY STORED IN WOOD.

(Volume of material) (density) (organic fraction) (G) where G = (4.2 kcal g^{-1}) (4186 J $kcal^{-1}$)= 17581 J g^{-1}
Volume: 1.2E9 green tons = 6.97E8 m^3 with density = 0.64 g cm^3 (Maine State Development Office, 1985).
Density: softwoods; 0.56 g cm^3, hardwoods; 0.785 g cm^3 , 35% of Maine timber stock is hardwood and 65% is softwood. Organic fraction: Ash content of wood is assumed to be 10%
Energy stored in wood biomass = (6.97E8 m^3)(1E 6 cm^3) m^{-3})(0.51g cm^{-3})(0.9)(17581 J g^{-1}) = 4.52E18 J
The annual rate of biomass growth for all species in 1984 was estimated at 30-40 million green tons per year, whereas, the annual harvest was 21 million green tons in that year (Maine Office of Energy Resources, 1985).

NOTE #16 - CHEMICAL POTENTIAL ENERGY OF WATER STORAGES

(water volume) (density) (G) where G is the Gibbs free energy of the water relative to sea water. The formula for calculating G is given in Footnote #8.
A) Groundwater. Groundwater volume for the state is estimated as 1.0E14 gallons by Hasbrouck (1985). This converts to a volume of 3.79E11 m^3. An S equal to 132 ppm for Maine groundwater was estimated as the average of five stations given in Haskell et al. (1984). This solute concentration gives a G of 4.467 J g^{-1}.
(3.79E11 m^3) (1.0E6 g m^{-3}) (4.47 J g^{-1}) = 1.69E18 J
B) Surface water. The average capacity for surface water in Maine was estimated as 75% of the maximum capacity calculated from Haskell et al. (1984) as 1.77E11 ft^3. This average capacity converts to 3.77E9 m^3. An S equal to 46 ppm for Maine surface waters was the average of 14 values from 3 stations given in Haskell et al. (1984). This solute concentration gives a G of 4.68 J g^{-1}.
(3.77E9 m^3) (1.0E6 g m^{-3}) (4.68 J g^{-1}) = 1.76E16 J and 1.71E18 J = stored emergy of water

NOTE #17 LAND USE PATTERNS AND TOPSOIL

Table A1 Erosion rates and soil loss from several land use types in Maine.

Land use	Area	Rate of erosion		Soil loss
		m^2	g m^{-2} y^{-1}	g y^{-1}
Cropland		3.67E9	673	2.47E12
Pasture land		1.0E9	67	0.07E12
Forest land		6.69E10	22.4	1.5E12

Data in the table above were found in U.S. Dept. Agriculture (1982).

Total topsoil lost to erosion is 4.04E12 g y^{-1}. Average soil formation rate for the forested area is 650 g m^{-2} y^{-1} assuming that the earth cycle is in steady state and net uplift is balanced by soil formation rate. Net uplift for upland and mountain regions of Maine is about 0.25 mm y^{-1} (estimated from Tyler & Ladd 1980), and the average density of rock is assumed to be 2.6 g cm^{-3}. Topsoil formation on forested land: (6.69E10 m^2) (650 g m^{-2} y^{-1}) = 4.35E13 g y^{-1} balances all erosion.
Estimate of energy storage in Maine topsoil.
(area of crop, pasture and forest land) (depth of soil)(soil density) (% organic) (energy per gram)
Energy storage in topsoil = (7.16E10 m^2) (0.5 m) (0.5E6 g m^{-3}) (0.03) (22604 J g^{-1}) = 1.21E19 J

NOTE #18 POPULATION

The 1980 census estimates the Maine population at 1.125E6 people. The median age of the U.S. population in 1980 was 30 y. Value stored in people of Maine = (population) (average age) 1.125E6 people x 30 years = 3.38E7 people-years

NOTE #19 ECONOMIC ASSETS

Economic assets are estimated assuming a depreciation rate for replacement of 5% per year. Therefore the dollar value of total assets is approximately 20 times the GSP. Economic Assets=20 (9.3E9 $) =1.86E1 $

Appendix B - Calculation of a Revised Solar Transformity for Tidal Energy Received and Tidal Energy Dissipated Globally

D.E. Campbell and H.T. Odum

The solar transformity of tidal energy can be calculated in a manner similar to that used by Odum (1996) to determine the solar transformity of the earth's heat using the following assumptions:

(1) The available geopotential energy of the elevated water in worlds oceans is similar for this purpose regardless of source.

(2) On the time scale of one year the available potential energy of the world's oceans is in steady state, thus all the potential energy that is created in a given year is dissipated in that year. If this assumption is not true on average, there would be an accumulation of potential energy in the global ocean which is not observed.

(3) The elevation of the ocean surface relative to a reference level is primarily caused by the solar heat engine including its effect in delivering fresh water streams or the gravitational pull of the sun and moon. Therefore, almost all the available potential energy of the oceans is created by one of these two sources.

(4) The dissipation of tidal energy in the deep oceans is less than 0.001 of that in shallow water (Miller 1966). This fraction does not take into account recent estimates of the importance of deep ocean internal waves generated by seamounts.

If the solar energy flux to earth is 3.93 E24 joules y^{-1} (Odum 1996), the gravitational energy transmitted to the earth is 8.515 E19 joules y^{-1} (Munk and MacDonald 1960), the tidal energy transmitted to shallow water is 5.2 E19 joules y^{-1} (Miller 1966), and the available potential energy in the top 1000 m of the global ocean is 21.4 E19 joules y^{-1} (Oort et al. 1989), the following calculation can be performed.

The fraction of the available potential energy of the oceans created by solar energy is equal to the total available potential energy minus the potential energy created by the tide. If almost all of the available potential energy produced by gravitational attraction is transmitted to shallow water and dissipated the amount of the global available potential energy produced by solar energy is 16.2 E 19 joules y^{-1}.

21.4 E19 joules y^{-1} - 5.2 E19 joules y^{-1} = 16.2 E 19 joules y^{-1}

If the deep heat energy input from the earth contributes to the formation of geopotential energy in the ocean by creating the continental land masses and coastal shelves, the non-tidal emergy input to this process should be 8.0 E24 sej y^{-1} (3.93 E24 sej y^{-1} from solar and 4.07 E24 sej y^{-1} from deep heat of the earth (Odum 1996). To see that there must be a geologic input to creating the potential energy of the oceans imagine an earth without continents and thus no geologic input to the upper zone. Would the oceanic geopotential energy created by the sun and tide be different? The solar transformity of the available potential energy in the oceans created by the solar heat engine is 8.0 E24 sej y^{-1} / 16.2 E19 joules y^{-1} = 49383 sej/j. Because the available potential energy created by the tides is the same "stuff" as the available potential energy created by solar energy it is logical to assume that it has a similar solar transformity.

The solar emergy used up globally in the dissipation of available potential energy produced annually by the tides is then 5.2 E19 joules y^{-1} * 49383 sej/j = 2.568 E24 sej y^{-1} and the solar transformity of the gravitational energy received by the earth is: 2.568 E24 sej / 8.515 E19joules y^{-1} − 30159 sej/j and the new planetary baseline is 3.93 + 4.07 + 2.57 = 10.57 E24 sej y^{-1}.

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