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Proposal for Including What Is Valuable to Ecosystems in Environmental Assessments

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Assessment scientists and managers depend on social values to identify the goals that will be used to guide environmental assessments. These goals are commonly identified by examining the vested interests of the various social groups that are stakeholders in a region. However, knowledge about what people value represents only part of the information needed to identify comprehensive assessment goals for environmental systems that include both economic and ecological components and processes. All parties also need to understand what is valuable to ecosystems because that determines the ecological patterns and processes that prevail in the long run. The competition among alternate system designs for available energy determines the viability of the choices that people make for their environment. Ecosystems that prevail in competition use the process of self-organization to create system designs that maximize the use of ever-changing sources of available energy. The efficacy of ecosystem designs can be evaluated using the maximum empower principle, which states that ecosystems evolve toward designs that maximize empower (emergy use per unit time). Emergy is an accounting quantity that normalizes the different kinds of energy developed in a system so that they may be compared. The counter-intuitive and sometimes controversial results that come from emergy analyses are illustrated by examining three environmental problems on the interface between ecology and economics. A process for identifying and using social and ecosystem values to guide environmental assessments is proposed using a conceptual energy systems model that shows how these processes might interact within a region. The probability of realizing a given change in system empower production is suggested as a decision criterion that can be used by managers to evaluate the efficacy of alternatives.

Introduction

Under statutes such as the National Environmental Policy Act of 1969 (Public Law 91-190) and the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) and their subsequent amendments, the United States Environmental Protection Agency (U.S. EPA) is broadly charged with protecting human health and the integrity of our environment (*1*). To successfully accomplish this task, scientists must first evaluate the state of the environment (*2*, *3*) as well as the state of the social and economic systems that depend on it (*3*) and then determine what management actions are necessary to ensure the health and integrity (see ref *4*) of the environmental system as a whole.

The ultimate success of our assessment and management efforts depends on our ability to frame the right questions. This paper explores the question “Are we asking the right questions to ensure that our environmental systems are sustainable?” At present, the accepted practice among environmental scientists and managers is to frame assessment questions based on the values of social groups that are users of the environment (*5*). This approach is a difficult one because each social group derives its values from the special interests of the group, which often conflict with the values and interests of other groups. Humans must choose what to value based on limited information and imperfect knowledge about the consequences of their choices. In addition, the reliance on subjective human opinions, based on imperfect knowledge, to direct scientific assessment activities may have a fatal flaw if nature itself has values that conflict with our special interests as humans and to which we are not in tune. In fact, the system states that might be valuable to ecosystems have been largely ignored in our current method of performing environmental assessments and making management decisions.

This paper presents theoretical arguments using Energy System Theory (EST) (*6*, *7*) to support the idea that ecosystems are structured in a manner that allows them to “value” one system state over another. In addition, maximization of the environmental accounting quantity, emergy (*7*), is proposed as a means to determine which system states will be most robust in the long run. Other metrics and approaches to discern ecosystem fitness might be used (*8*), but this approach has a long history of exploration and application that has not been understood and/or has been largely dismissed by many scientists. With the growing realization that environmental problems develop within the context of an interconnected system network, I believe that the time has come for us to consider using the results of analyses derived from whole system methods, such as EST, as a necessary input to the process of choosing goals for environmental assessment and management.

Choosing Assessment Goals and End Points Using Social Values: The State of the Art

Social values are often in conflict, and they do not exist in isolation but rather as value systems in which the relationship between values may be as important as the values themselves (*9*).

To use social values to determine the goals and end points in an environmental assessment, scientists must first determine what these values are (*10*). Because the interrelationships of value systems are complex, public values must be assessed systematically in a way that provides a balanced overview of the issues and gives people time to think about them (*10*). These values are most often identified through surveys or in discussions between managers, scientists, and members of the various social groups. The values that people choose are also determined by the easily available information on a topic or the lack of it. Research into the different attitudes of people toward risks (*11*) indicates that optimizing questions and communication methods for the unique characteristics of each group may be an effective means of drawing out deeper thinking on what different groups value.

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Gregory and Slovic (*12*) have proposed an innovative multivariate method, the constructive preference technique, for identifying stakeholder values. This method helps people depict complex environmental issues in terms of common sense values and attributes that the affected people generally use to think about the problem. The analyst helps people build their values by increasing their knowledge of the environmental problem and themselves rather than by trying to uncover them as in economic methods such as contingent valuation.

If the conflicting values of various social groups are to be used to frame assessment questions, it is imperative that all voices are heard and that the process of framing questions is open and fair. Scientists and managers have not always been good listeners in the past. This weakness in the current method of framing assessment questions has not gone unnoticed. The U.S. EPA's current emphasis on community-based environmental assessment (*13*) is designed to bring the concerns and values of all interested people into the process of determining environmental assessment goals. A comprehensive knowledge of social values is necessary to carry out environmental assessments, and various methods (*14*) have been proposed to ensure that all perspectives are considered and that legitimate concerns about openness and inclusiveness are met. This is a crucial first step to ensure the success of environmental assessments; however, I contend that stakeholders, managers, and scientists must also understand what is valuable to ecosystems if they are to make decisions that are in the best interests of society and the environment. The purpose of this paper is to focus attention on an alternative paradigm for the environmental assessment process and to outline a practical method for identifying comprehensive goals and end points that include what is valuable to ecosystems, society, and the system that includes them both.

Environmental Assessment Methods and the Use of Values

Environmental systems are ecosystems that are composed of interactive hierarchical networks containing social, economic, and ecological components and processes (*15, 16*). Societies depend on natural ecosystems for goods and services such as raw materials and waste processing. Because economic goods and services are not produced without using ecological resources, scientists and managers need methods to assess the effects of social and economic activities on ecosystems. One such method that recognizes the fact that we must make decisions based on limited and imperfect information is ecological risk assessment or ERA (*5*). ERA quantifies the environmental effects of stressors by determining the probability that damage or harm will be inflicted on a valued attribute of an ecosystem. Because ecosystems are networks of components and processes organized hierarchically over multiple spatial and temporal scales (*17, 18*), an overwhelming number of components and processes could be the subjects of an ecological risk assessment. The first task for the ecological risk assessor is to determine which components and processes might be significantly affected by a stressor.

Ecological risk assessors commonly use societal values to determine which of the many important ecosystem structures and functions that might be damaged by a stress will be assessed (*19*). In ecological risk assessment, social values are evaluated quantitatively by representing them as formal statements called assessment end points (*19*). The process is completed by measuring attributes of an ecosystem that allows the assessment end points to be quantified. Measurement end points used to evaluate the risk to a valued ecosystem structure or function should be determined by science alone (*19*). The practice of identifying assessment end points based on social values and formulating problems and choosing measurement end points based on scientific analysis sets up a false boundary between science and policy that may be intended to ensure the objectivity of scientific analysis. Power and McCarty (*18*) point out that ecological risk assessment is under considerable pressure to bridge this de facto gap. However, ecological risk assessors may fail to recognize and evaluate comprehensive assessment end points because they lack an objective method for identifying the significant attributes of ecosystems.

Energy Systems Theory and Emergy Analysis

In this paper, EST (*6*) is used as a conceptual means for bridging false boundaries such as those historically recognized between science and policy or economics and ecology. EST is based on principles of irreversible thermodynamics (*20*, *21*), general systems theory (*6*, *22*), and ecology (*23*, *6*). Emergy Analysis (EA) (*7*) is a method of environmental accounting derived from EST that uses the energy (in units of the same kind) required to produce a good or service as a nonmonetary measure of the value or worth of components or processes within ecosystems and the economy.

EA often leads to counter-intuitive results that provide answers to environmental and economic questions that differ from the prevailing points of view. Case studies (*24*−*26*) presented in Table 1 show how EA has been used to address three broad public policy questions: (a) In a time of frequent environmental disasters, "How can we evaluate and respond appropriately to catastrophes with extensive environmental, economic, and social effects"? (b) In a time of declining world petroleum reserves, "How can we determine which underused energy sources can support economic growth"? (c) In a time when developing nations regularly default on their debts, "How can we ensure that economic exchange is equitable"? In Table 1, the results of EA may be contrasted with the conventional answers to these policy questions and then compared to the outcome that has resulted in the course of history. The relative merits of EA have been compared to other approaches (*7*) and debated (*27*).

EST Leads to a New Paradigm of Ecosystem Value

The principles of EST lead to the view that environment and society are a single system composing an inseparable whole (*28*, *29*). In this whole, human beings and their social structures exist within the ecosphere and are sustained by it while simultaneously providing important services in the form of controlling feedbacks (*28*, *29*). In this paradigm, comprehensive assessment goals and end points cannot be identified without analyzing the priorities of both humans and their supporting ecosystems.

What Is the Ultimate Value for Humans and for Ecosystems? The usefulness or value that people attribute to things depends on the ultimate values chosen by an individual, group, or society, e.g., individual freedom in the United States (*9*). This idea leads to the question "Is there a single value underlying all other values upon which all rational people can agree?" Regardless of whether the values chosen are spiritual, intellectual, or material, it is an axiom that all rational people must agree that the individual, group, society, or civilization must survive in order to achieve their goals in life. The ultimate values chosen by a society in the past have not always ensured that society's survival, as evidenced by past civilizations such as the Mayan (*30*), which appears to have declined in part because environmental limits were exceeded—perhaps exacerbated by the natural cycles of climate change (*31*). Ecosystems, unlike organisms, do not die; therefore, the equivalent fundamental value for an ecosystem is to prevail over other designs in evolutionary competition (*7*).

TABLE 1. Three Examples of Problems That Have Been Analyzed Using Emergy Accounting[a]

Problem, conventional wisdom, outcome	Results of emergy analysis
Question 1: What is the appropriate response to an environmental disaster such as the *Exxon Valdez* oil spill? Conventional wisdom: Relief funds can solve any problem. The more money given the better Outcome: A local disaster was transformed into a national issue.Public reaction to images of the oil spill transmitted to televisions in homes throughout the United States resulted in Exxon paying $3.6 billion dollars in cleanup, relief, and reparations (*7*). In 1994, a jury awarded 5 billion more in punitive damages which was appealed. On October 2, 2000, the U.S. Supreme Court refused to throw out the punitive damages case. An initial assessment of long-term ecological effects and recovery has been reported (*41*) in a series of studies supported by Exxon. These studies indicate that recovery of populations and ecosystems is well under way and that long-term affects of the spill are probably minimal. However, in the affected area, controversy continues over the long-term effects of the oil spill on wildlife populations, ecosystems, the economy, and the human psyche.	An emergy analysis of the environmental and socio-economic effects of the *Exxon Valdez* oil spill on the Prince William Sound region of Alaska showed that economic losses were 2−20 times greater than the damage done to the marine environment (*24*). The large range calculated for environmental damage is due to uncertainty in the fractional mortality and nonlethal productivity loss suffered by widely distributed lower trophic level groups (*24*). In emergy units, the response of Exxon and the U.S. government was 33 times larger than the petroleum emergy lost and 5−50 times greater than the environmental damage done. The social disruption caused by the massive amount of money sent in relief aid to the Prince William Sound area was as great as the highest estimate of environmental damage and 10 times greater than the lowest estimate. Results of the emergy analysis indicate that the national response to local disasters should be commensurate with the environmental and economic damage done.
Question 2: Is there net energy in the vast quantities of shale oil? Net emergy? Conventional wisdom: Penner and Icerman (*42*) calculate a net energy ratio of 8.79 for extracting oil from shale. Outcome: An analysis showing that there was no net emergy in shale oil was presented in testimony before the U.S. Congress (*25*); however, a joint project of the Federal Government and private industry was authorized despite this evidence. After spending several billion dollars on synfuels projects, shale oil was found to be uneconomic, and research efforts and pilot projects were abandoned in the late 1980s (*7*). At present, a Canadian company and two Australian companies are using new technology to demonstrate that shale oil can be commercially viable at the Stuart Shale Oil Project in Queensland, Australia. Greenpeace has led active protests against this operation, principally because of concerns that oil from shale will produce more greenhouse gases than other kinds of fuel. Despite diminished global fuel supplies and vast quantities of oil in shale worldwide, significant quantities of oil from shale have not been produced commercially.	The net emergy ratio for an energy source is the emergy output of the production process divided by the inputs that are fed back from the economy to obtain that production. Emergy analysis includes the contributions of human labor, energy, and materials expressed in solar equivalent joules. Many net energy calculations do not count human labor. A competitive net emergy ratio for present energy sources in the United States is about 6:1 (*7*). An emergy analysis of shale oil produced at the Pilot Plant at Anvil Points, CO, in 1944 gave a net emergy ratio of 0.025 (*7*). Penner and Icerman (*42*) and Odum (*7*) are in close agreement on the joules of organic matter in the shale and on the joules of oil and other products produced from processing the rock. The difference in yield ratios comes from determining the energies necessary for processing. The question then becomes which inputs are required for processing the rock and that in turn determines whether oil from shale can be a viable part of our long-term energy mix. On the basis of the shale oil experience recounted on the left, net emergy rather than net energy may be the best indicator of this technology's potential for long-term commercial success.
Question 3: Why is Ecuador unable to pay its debts to the developed world? Does accounting for value in international trade using monetary measures ensure that the trade is equitable? Conventional wisdom: Markets will ensure that trades are equitable. If the monetary value exchanged is equal, then the trade is fair. Outcome: Economic and political conditions in Ecuador have continued to deteriorate during the 1990s. Gross inequities in exchange have led to extreme inflation, exorbitant debt payments, and political unrest. There is a growing realization among many people and some nations that world resources must be fairly exchanged and rightly shared to ensure a prosperous and peaceful future for all. Emergy provides an accurate accounting method to ensure equitable exchange of real wealth, i.e., the products and services of nature and the economy.	Emergy analysis of the international exchange of shrimp and oil between Ecuador and the United States (*26*) showed that the exchange of emergy or real wealth between these two countries was not equal even though the dollars exchanged balanced. This was true because more of the value of products and services in Ecuador's economy is contributed by the free work of the environment without money being exchanged. The emergy-to-dollar ratio in Ecuador in 1986 was 3.6 times the emergy-to-dollar ratio of the U.S. in that year. Thus, money borrowed by Ecuador from the U.S. to buy products in the United States and later paid back in sucres at the international rate of exchange actually returned 3.6 times the buying power of the money borrowed. Who can afford to pay 360% interest on their loans? Emergy analysis indicates that countries should evaluate their foreign exchange in emergy as well as dollars and pick trading partners in a manner that ensures that trades are equitable. The emergy in foreign aid, debt forgiveness, and support for transnational environmental protection programs also contributes to addressing the inequities in current trade balances.

[a] The results of emergy analysis are contrasted with the prevailing viewpoints, and historical outcomes are reported.

How Can Ecosystems Determine What Is Valuable? To understand how ecosystems can attribute value or usefulness to a thing or a condition, we must consider the fundamental nature of the process of valuing something within the context of the evolutionary process that affects all living systems. For example, in the human valuing process, one identifies usefulness in an object and then expresses a desire for that object by seeking to attain it. Seeking an end or goal is the practical manifestation of the attribution of usefulness or value to a thing. If ecosystems have a mechanism to alter their design and if those variations in design can be tested against a criterion for success, they have the prerequisite

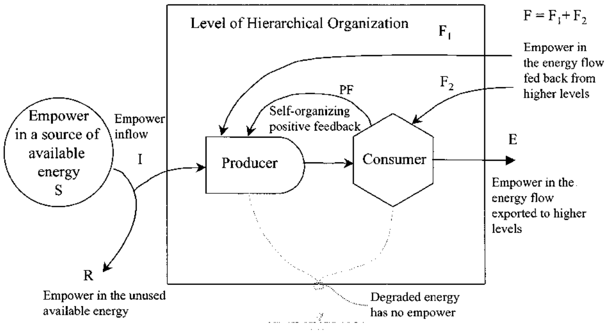

FIGURE 1. System design with positive feedback (PF) that maximizes empower production in hierarchical systems. Over time I + F is maximized throughout the hierarchical system. Empower is determined from the underlying energy flows multiplied by their transformity. The Energy Systems Language symbols (*6*) used in Figures 1 and 2 are as follows: bullets and hexagons are hierarchical symbols for producers and consumers, respectively; circles are energy sources; tanks are storages of matter, energy, or information; rectangular arrowheads indicate workgates or interactions; solid lines with arrowheads carry a flow of energy, matter, or information in the direction indicated; used energy flows on gray lines to the ground symbol or heat sink; dashed lines indicate money flows; diamonds show the exchange of money for goods and services; and rectangular boxes show the boundaries of systems and subsystems.

abilities needed to seek a useful goal, and this is the practical essence of the valuing process.

The conceptual model in Figure 1 shows a self-organizing positive feedback (PF) as a general design feature of hierarchically organized systems (*6*). Such PF loops are self-reinforcing or "learning loops" by which a system can move toward designs that maximize power, because more system resources are dedicated to the loops that generate more power. Higher power pathways are selected by winning the competition among alternatives for a common resource base. It can be demonstrated using mathematical models that when two units are in competition for a single limited energy source, the system that captures the greatest amount of the available energy and uses it to create a structure that feeds energy back in a manner that results in capturing more available energy from the source will prevail in competition with other systems that lack such feedbacks or that process and feedback the energy captured in a manner that is further from the optimum efficiency for maximum power than the system that prevails (*6*, *32*, *33*).

This idea has deep historical roots in science beginning with Boltzmann (*34*), who first characterized the struggle to prevail in nature as a competition for available energy (*6*). Lotka (*20*) extended Boltzmann's thought when he formulated the "maximum power principle" to identify a general criterion for success in the evolutionary competition for available energy. This principle states that ecological designs that process more useful energy will prevail over competing alternate designs. Useful energy creates system components and feedback that increase the intake of available energy (*7*).

Choices for pathways to change ecosystem design are generated through mutations among species reinforced by differential reproduction as well as from the existing pool of species that can be transported to the system. The ultimate reproductive success of a species depends on the contribution it makes to building a pathway in the larger ecosystem that reinforces a PF loop operating to gain more power for the larger system as well as for itself. Thus, the selection of species is linked to the success of pathways that maximize power at the ecosystem level. This process is illustrated by peat bog ecosystems that have developed an unusual pathway, i.e., carnivorous plants, that conserves nutrients and keeps gross primary production higher than it would be ordinarily in a nutrient-poor environment. The pitcher plant, *Sarracenia* spp., found in peat bogs of the northeastern United States is the obligate host to at least 16 arthropod species, many of which play a role in facilitating the transfer of nutrients along this PF pathway (*35*). The useful energy flow (power) developed by an ecosystem is hypothesized to be the fundamental measurement end point for evaluating the condition of ecosystems. All characteristics of ecosystems, such as the abundance of organisms, the diversity of species, the biogeochemical cycling of materials, etc., exist only as a consequence of the transformation of energy and can be quantitatively evaluated in terms of energy transformations. Thus, maximizing useful energy flow in a system network is the first key to understanding what ecosystems "value".

However, the raw energy flows are not sufficient to determine equality in the ability to do work, because different types of energy have different abilities to do work depending on their position in the hierarchical network of a system (*7*, *36*). For example, a joule expended by a beaver in a woodland pond ecosystem does a different kind of work (dam building, wood cutting, etc.) than a joule expended by pond algae (fixing carbon, producing oxygen, etc.). The kinds of work done by the beaver and by the algae depend on their respective positions in the hierarchical network of the pond ecosystem. Odum (*37*) showed that the maximum power principle implies that the amount of work (defined as a useful energy transformation) done by a component in a hierarchical network should be commensurate with the work that was required to produce that component. If this were not true, the contribution of a new component to producing power in the system would not completely compensate for the power used to produce that component, and another system that developed a new component that contributed more to the power produced by its system would be more competitive. Therefore, over time, selection among alternate pathways gradually changes the structure and function of systems so that the components retained do work at least equivalent to the work required to produce them. Odum (*38*) used these realizations to define a new quantity, *emergy*, which can be used to evaluate indirectly the contributions that components, processes, and alternate system designs make to the general welfare of a system. Emergy is the available energy of one kind, previously used up both directly and indirectly, to make a product or service (*7*). Available energy is *exergy* or energy with the potential to do work. A new unit, the *emjoule* (emj) was required because emergy is defined by energy used in the past. E_m is a mnemonic for energy memory (*39*). Emergy measures in equivalent units (solar emjoules or sej) the energies of all kinds that are required to have a component or process as a part of a system. Emergy measured in solar emjoules is commonly used to compare economic and environmental energy flows of many kinds and to develop criteria for making public policy decisions (*7*).

Odum (*7*) formulated a more general statement of Lotka's Maximum Power Principle by using emergy to account for the different amounts of work that are done by energies of different kinds. The Maximum Empower Principle states that in the competition among self-organizing pathways, network designs that maximize empower or the emergy per unit time will prevail (Figure 1). The empower produced at any level in a hierarchy is maximized when emergy is fed back (PF) within a hierarchical level so that the incoming emergy (I + F) approaches a maximum. This assumes that (F) is carrying some emergy from a source other than (S); if it does not, then it is sufficient to maximize I. The theory implies that ecosystems on all hierarchical levels will simultaneously evolve toward designs that maximize the production of empower for a given set of external conditions.

Choosing Assessment End Points Based on Ecosystem Value

Human beings control society's feedbacks to the environmental system by making economic and political choices. One problem for managers in exercising the power of their office is deciding whose evaluation of risks and rewards will be taken into account in identifying and setting priorities for environmental assessment and management (*40*).

A comprehensive set of values for guiding environmental assessments might be developed through an iterative, collaborative process (*12*, *14*) in which people first identify what they really value both individually and as part of various social groups. Next, the complete list of values is examined, interpreted, and used as one input to the design of a multilevel model of the environmental system. Ecosystem scientists work with a self-consistent set of hypotheses about ecosystem structure and function to build models that can serve as heuristic tools to help identify holistic assessment end points (*3*, *24*). For example, a group of experts with different specialties who are asked to identify the valued attributes of an environmental system would probably come up with a list that included many economic and ecological components and processes on several hierarchical levels. In this case, a consensus among scientists on a single assessment end point is unlikely; however, if the group was asked to list the primary factors one needed to measure to characterize the environmental system, there would be more agreement. This broad agreement among scientists on the primary components and processes that must be measured to characterize an environmental system is the starting point for building a comprehensive model.

The first step in the energy systems method for determining what is valuable to an ecosystem is to construct a detailed energy systems model using the characterization developed by consulting experts, stakeholders, and published studies. Next, the detailed energy systems model is simplified by aggregating components and processes into functionally similar groupings in a manner that captures the salient characteristics of system behavior. This results in a set of working hypotheses that represent the interrelationships among components and processes. These relationships are documented in the process of constructing and evaluating the model. A sensitivity analysis of the empower produced in such a model and its components, when simulated over a specified period of time, can be used to identify assessment end points that are representative of the overall condition of the ecosystem (*4*).

Proposed Model for Environmental Assessment and Management within a Region

A conceptual energy systems model (Figure 2a) is proposed to show how the processes of environmental assessment and management might be organized within a region. This regional model has been discussed in detail by Campbell (*15*). Figure 2b gives the details of the environmental assessment and management module shown in Figure 2a. This module (Figure 2b) shows how ecosystem values (V_e) and social values (V_s) can be identified and joined to develop a comprehensive set of i assessment end points (A_i) to guide environmental assessment and management. The assessment and management module in Figure 2a is linked to the larger regional system through a set of measurement end points (M_i) that are matched to the assessment end points and evaluated based on the data collected in regional monitoring programs. Managers make decisions (D_i) and implement solutions to problems related to these values and end points.

Social values (V_s) are determined by a process of facilitated interaction (Figure 2b) among all social groups (*34*), i.e., the general public (P), managers (P_m), assessors (P_a), teachers (P_t), scientists (P_s), and facilitators (P_f). All social groups participate in the assessment and management processes, but environmental assessments are led by the assessors, the management process is led by the managers, the education process is led by teachers, and the process of developing shared values is led by facilitators. Scientific analysis of the environmental system is conducted by scientists with input from others, and it provides a basis for creating models that allow us to formulate expressions for the things that are valuable to the ecosystem. The information that people use to determine values can be modified by education based on the results of the research carried out by natural and social scientists. In this case, the scientific analysis looks at empower production (M_e) in sej yr^{-1} in the region, defined as the sum of empower generated through economic (M_m) and ecological (M_n) processes, as an indicator of the overall well-being (V_e) of the system.

In the hypothetical environmental system shown in Figure 2a, people have chosen to value three environmental processes V_a,V_c, and V_p, which are respectively the assimilative capacity of the environment for urban wastes in MT yr^{-1}, agricultural yield in MT yr^{-1}, and economic productivity as measured by exported goods and services in \$ yr^{-1}. Assessment and measurement end points (A's and M's) quantifying each social value are specified by using the same subscript (Figure 2a,b). For example, the measurement end point, crop yield (M_c), could be measured in metric tons of corn produced per year, and the probability that crop yield will fall below Y tons per year could be specified as the assessment end point (A_c). The empower gained or lost as a consequence of changes in the corn yield is determined by converting MT yr^{-1} of corn to J yr^{-1} and then multiplying by the appropriate transformity for corn to get the empower in sej yr^{-1}, which represents the contribution of this end point to the well-being of the whole system. The evaluated assessment end point can be compared to its parent social value (V_c), e.g., provision of a sufficient food supply, and to the ecosystem value (V_e), e.g., no net loss of system empower due to corn production to determine if society's goals for crop yield and system well-being will be satisfied for a given management alternative. The other measurement and assessment end points can be expressed in a similar manner.

Management decision-making is shown as a box in Figure 2b that receives the results of the environmental assessment and contains the decision criteria, logical programs, and other information needed to make management decisions (D_a, D_c, D_e, and D_p). In this conceptual model, management decisions are made on the basis of the ecological importance (EI) attached to a particular change. EI is a new index that is presently under development. It is defined as the product of ecological significance (ES) and ecological risk (ER). The ecological significance of an impact is here represented by the change in empower production ($\Delta \mathrm{em}_i$) in sej yr^{-1}, which results from the direct and indirect effects of a change on the environmental system. ER is the probability (p_i) that a given change in empower will be realized. The decision criteria for managers is then to compare the ecological importance of alternatives taking into account the uncertainties, u_i and v_i associated respectively with the measurements of $\Delta \mathrm{em}_i$ and p_i, respectively, as follows:

minimize:

$$\sum_{i=1}^{n}((\Delta \mathrm{em}_i \pm u_i)(p_i \pm v_i))$$

for the impact of stressors and maximize this quantity for any proposed improvements. The EI index is proposed as a

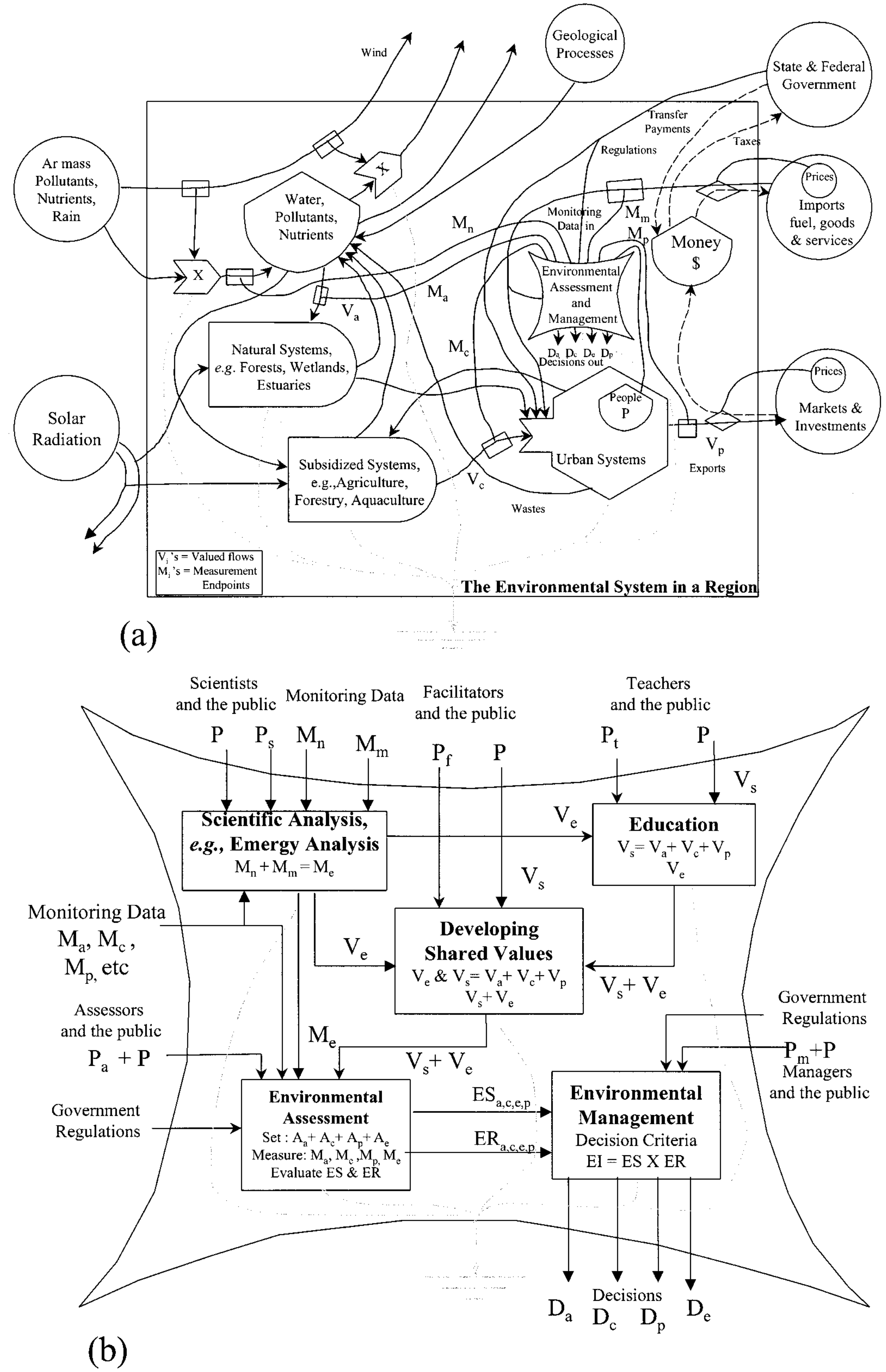

FIGURE 2. Energy systems model of the environmental assessment and management process operating within a region. (a) Conceptual model of a regional environmental system showing the role of the environmental assessment and management process within the region. (b) Conceptual model of the environmental assessment and management subsystem including the proposed system structure for identifying ecosystem and social values and using them to guide the processes of environmental assessment and management.

strong candidate for further development because it is a single, comprehensive, risk-based indicator that represents the condition of a whole system as measured by emergy production and use within the network.

Scientists, managers, and stakeholders that use an open process of interaction guided by energy systems modeling (or another whole system method) to incorporate ecosystem and social values into the assessment process can identify comprehensive assessment goals and end points that lead to a state space where human and ecosystem values intersect. In this space, the welfare of the system as a whole may be the greatest. Managers can avoid much of the controversy, ill will, and expense associated with making decisions based primarily on the narrow views of one or more particular social groups by using emergy accounting to identify the solutions to environmental problems that society will eventually come to regard as correct (if maximizing empower determines success). Decisions based only on the values of social groups, even majorities, should be examined within the context of the state of maximum empower developing in an environmental system to understand the consequences of those decisions for the well-being of the system as a whole, now and in the future.

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