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Environmental Vulnerability Indicators for Environmental Planning and Decision-Making: Guidelines and Applications

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ABSTRACT / Environmental decision-making and policy-making at all levels refers necessarily to synthetic, approximate quantification of environmental properties such as vulnerability, conservation status, and ability to recover after perturbation. Knowledge of such properties is essential to informed decision-making, but their definition is controversial and their precise characterization requires investments in research, modeling, and data collection that are only possible in the most developed countries. Environmental agencies and governments worldwide have increasingly requested numerical quantification or semiquantitative ranking of such attributes at the ecosystem, landscape, and country level. We do not have a theory to guide their calculation, in general or specific contexts, particularly with the amount of resources usually available in such cases. As a result, these measures are often calculated with little scientific justification and high subjectivity, and such doubtful approximations are used for critical decision-making. This problem applies particularly to countries with weak economies, such as small island states, where the most precious environmental resources are often concentrated.

This paper discusses frameworks for a "least disappointing," approximate quantification of environmental vulnerability. After a review of recent research and recent attempts to quantify environmental vulnerability, we discuss models and theoretical frameworks for obtaining an approximate, standardizable vulnerability indicator of minimal subjectivity and maximum generality. We also discuss issues of empirical testing and comparability between indicators developed for different environments. To assess the state of the art, we describe an independent ongoing project developed in the South Pacific area and aimed to the comparative evaluation of the vulnerability of arbitrary countries.

The issue of ecosystem fragility or vulnerability to exogenous and endogenous stress factors has been the subject of long and intense debate. Along with the related discussion around the determinants of community and ecosystem stability, this debate has deeply influenced the development of modern ecology and produced enormous insight into ecosystem structure and function. Nevertheless, the debate has not led to agreement on the definition of these properties and has not produced general and practical conceptual models to calculate corresponding indicators (e.g., De Leo and Levin, 1997). Instead, a synthesis of the current knowledge could lead us to conclude that, due to the complexity, nonlinearity, and multiplicity of temporal and spatial scales typical of natural systems, a sufficiently general conceptual model of this kind will probably never be developed.

Nevertheless, environmental decision-making and policy-making are based on the quantification of environmental properties such as vulnerability, status of conservation, and ability to recover. In recent years, explicit demand has been put on the scientific community to produce such indicators to direct conservation investments. The need for answers in short time frames has led scientists to attempt surrogate measures calculated on the basis of available or easily measurable indicators, which have been and are being developed to serve as a basis for critical decision-making, often involving some of the most important ecosystems on Earth.

Ecological risk assessment initiatives are being funded at various scales by environmental agencies in many developed countries. Most notably, the United States Environmental Protection Agency (EPA) has started a comprehensive risk assessment project that

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has produced important results (US EPA 1998, Williams and Kaputska 2000). Most attempts to quantify environmental vulnerability to date refer to specific systems and particular stressors or classes of stressors. Examples include vulnerability to sea-level rise and climate change (e.g., IPCC 1992, Yamada and others, 1995, Sem and others, 1996, Pernetta, 1990), oil spills in tidal zones (Weslawski and others 1997), groundwater contamination by pesticides at the regional scale (Loague 1994) and sea-level rise at the national scale (Hughes and Brundrit 1992). Elrich and Elrich (1991) deal with anthropogenic risks to ecosystems, estimating the impact of human intrusion within a given ecosystem. These studies make no attempt to aggregate the scores into a synthetic indicator. Pantin (1997) developed a vulnerability indicator incorporating economic vulnerability to natural disasters. Environmental indicators such as these treat the human system rather than the ecological system as the responder.

System vulnerability and its measure has long been a concern in economics, particularly in reference to small island developing states (SIDS) (Crowards 1999). To date, economic vulnerability indicators tend to use a small number of indicators and simple aggregation models. Methods of ranking have been developed using statistical regression techniques, as in Atkins and others (1998), or simple weighted averaging of country-level indicators to achieve the composite vulnerability score (Briguglio 1995, 1997, Wells 1996, 1997, Pantin 1997).

The US EPA is producing the most comprehensive risk assessment framework to date. EPA's program, as described in Linthurst and others (2000), involves four subprograms dedicated to: (1) ecological monitoring research, including development of indicators and monitoring design; (2) processes and modeling research, dedicated to producing the understanding of system dynamics necessary to assess responses to stressors; (3) risk assessment research, dedicated to producing methods, guidelines, and pilot studies to perform ecological assessments; and (4) risk management and restoration research, involving prevention of pollution, control technologies, remediation and restoration. Most of the research promoted or stimulated by the EPA's effort has involved the regional scale, particularly watersheds. EPA's contributions have led to the publication of risk assessment guidelines that could provide practical standards (US EPA 1996, 1998).

All these studies are good starting points for identifying a general framework for a vulnerability indicator. However, some of them (notably the ones grounded in economics), employ frameworks that are too simple to deal with the complex interactive nature of ecosystems. Others (notably the ones based on EPA's risk assessment framework) involve huge research investments and a data resolution that is only possible for wealthy states and for specific small-scale systems. This article deals with a necessary compromise approach: producing the least disappointing quantification of ecosystem vulnerability with the resources available to most countries and in the time frames typical of environmental policy-making. This problem is too complex to be solved in general with simple indicator aggregation, and at the same time it cannot be approached by following guidelines such as the EPA's, due to the amount and cost of the research involved and the wide range of scales and situations that the nations' demand encompasses.

The number of recent international programs that have requested similar quantifications proves the interest in this topic. For example, the Nature 2000 project of the European Community (EEC 1992) requested a numerical scoring of the status of conservation, vulnerability, and ability to recover relative to a high number of ecologically relevant sites, identified by all member nations. How to reach such quantifications was never clearly explained. Nevertheless, many countries produced indicators that were used as an important component of a knowledge base on ecotypes and sites located across much of Europe. In 1994 the United Nations expressed the need of country-level environmental and economic vulnerability indicators in the Barbados Plan of Action (UN 1994). As a result of that, various small island nations started programs to produce such indicators, usually characterized by limited budgets and data availability, but dealing with some of the most precious ecosystems on Earth. More recently, the European Union Statistics Department has started producing a comprehensive listing of indicators of environmental pressures to apply in different European countries for comparison purposes (Eurostat 1998).

Governments and policy-making institutions tend to use estimates provided by local scientific communities with limited independent review. Such indicators often consist of linear aggregations of indicators, chosen by local experts or committees, then ranked and weighted according to ad-hoc schemata. As discussed later, no rigorous experimental testing of vulnerability estimates is possible given our current state of knowledge of the structure and functions of the environment. Lack of good quality historical data, time constraints, and funding availability would probably challenge even a much more advanced ecological theory.

These considerations call for a theoretical framework ensuring at least the completeness of the information collected and that the inevitable error and subjectivity can only cause more conservative, rather than optimistic, estimates. The environmental responsibility associated with the application of such indicators is even greater when properties are compared across different systems in order to decide where to direct conservation effort. In this paper we attempt to indicate a path towards a measure that accepts the inevitable oversimplification, but can nevertheless serve a better-informed environmental decision-making process. We will refer to vulnerability in general, with reference to the whole system of factors that can affect a system, and try to develop a general indicator framework that can be applied to a wide range of situations and system conceptualizations. We will discuss aggregation methods that allow keeping the unavoidable error and approximation on the safe side. We will pay attention to the important issue of comparability between indicators developed for different environments and briefly outline our very limited options to validate such indicators. Finally, we will discuss where and how the unavoidable subjectivity can be encapsulated and how repeatability and comparability can be achieved, to the extent possible, through standardization of procedure.

Theoretical Frameworks for a Generalized Vulnerability Indicator

A theoretical framework capable of producing a general vulnerability indicator (VI) needs to include three components. The first is a model of vulnerability, identifying its components and their mutual dependencies in terms of properties that can be associated to indicators. The second is a model of the system, defining a way to decompose the target system in a way that makes it practical to relate the view of the system to the definition of vulnerability and ensures that different systems interpreted according to a common system model are comparable. The third component is a mathematical model, used to aggregate the information defined by the system model into a hierarchically organized set of indicators, whose higher-level aggregation is the VI. In order for different VIs to be comparable across different environments, all three components must be compatible, i.e., adopt the same model of vulnerability, the same system model, and the same mathematical model. Each component should lend itself to being published as a set of guidelines for data collection and elaboration. The following three sections outline the aspects that generic guidelines should address in each component and identify practical decompositions and algorithms to guide the development of a vulnerability indicator.

The Vulnerability Model

Williams and Kaputska (2000), reporting the conclusions of a symposium dedicated specifically to ecosystem vulnerability, define the latter as ". . . the potential of an ecosystem to modulate its response to stressors over time and space, where that potential is determined by characteristics of an ecosystem that include many levels of organisation, such as a soil, a bioregion, a tissue, a species, an organism, a stream reach. It is an estimate of the inability of an ecosystem to tolerate stressors over time and space." It is clear from the generality of this definition that finding a decomposition of the concept of vulnerability that can effectively guide the development and measurement of indicators is not easy. It is productive to start with a brief analysis of the concepts of value, resilience, risk, and scale, which are central to most definitions.

Value. When planning conservation efforts, the notion of what is valuable in the environment is always central, whether explicitly defined or not. Value can come from functional knowledge of the role of a process in determining environmental dynamics, but also from the appeal of the element to decision-makers and stakeholders or from the popularity of a single threatened species that makes the entire environment valuable for the simple fact of sustaining it. It is important here to enforce a holistic vision, so that the set of indicators includes, but is not excessively biased by, elements that have a higher value in nonscientific terms.

Resilience. Holling (1973), in an attempt to overcome the limitation of the common equilibrium-centered definitions of resilience, defines it as the ability of a system to maintain its structure and pattern of behavior in the presence of stress. As mentioned, no easy and rigorous indicators of resilience can be described in general, but it is often possible to identify proxy indicators whose characterization depends on the definition of the system.

Risk. The US EPA (1998) defined risk as being dually composed by hazard and exposure. This distinction reflects a fundamental difference in treatment and measure between actual and potential pressures on the environment. To develop a simple but generic model of vulnerability that fits the purposes of this paper, we believe that more articulation is needed. In the following we describe a generalized reinterpretation of these components.

Scale. Even in semiquantitative studies it is risky and unwise to mix differently scaled information. Our understanding of hierarchically organized complex systems has greatly improved, and scale is now almost

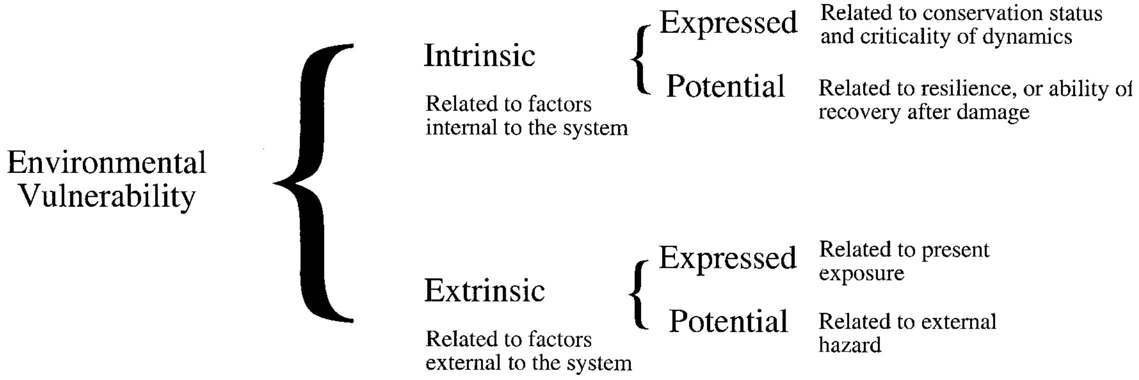

Figure 1. A possible operational conceptual model of environmental vulnerability.

universally considered in ecological theory (Allen and Starr 1982, O'Neill and others 1986). Yet we do not know enough to develop theoretical models of how properties such as vulnerability vary across scales. For this reason it is wise to develop VIs that are specific to particular organisational levels and adapt the mathematical model (see below) to deal with different subindices calculated at different scales if this is necessary.

Figure 1 shows how the concepts described can be mapped onto a general model of vulnerability to use as a basis for the development of indicators. It is reasonable to assume the existence of two main components in environmental vulnerability. Intrinsic vulnerability is the resultant of the internal dynamics and structure of the undisturbed system. Extrinsic vulnerability incorporates the two components of risk—exposure and hazard—acting on it. Both components can be said to have potential and expressed subcomponents.

Intrinsic expressed subcomponent. This relates directly to the well-debated concepts of ecosystem health and ecosystem integrity. As discussed in the next section, these concepts, despite their appeal, are hard to quantify practically by means of indicators. A further decomposition of this component discloses conservation status and the intrinsic criticality of the dynamic processes going on in the system as subcomponents. As an example, indicators for this latter property could include the genetic resilience of a population as measured by its size and genetic diversity. Both components are difficult to quantify exactly, but they can be ranked by experts, using a ranking scheme that they agree upon. Villa (1995) discusses a framework for evaluation of similar properties through organized survey forms to be used by local experts.

Intrinsic potential subcomponent. This relates to the ability of recovery of the undisturbed system after stress has been applied. Quantification of this aspect is probably the most problematic and should refer to published perturbation studies, which are likely to be highly specific.

Extrinsic expressed subcomponent. This results from the system's measurable exposure to stress factors. The resultant of these factors is obviously not just the sum of the effects of each since each stress will most likely make the system more vulnerable to another. Qualitative definitions of this aspect are reasonably easy, while quantification can be more difficult. For the purposes of developing an indicator, semiquantitative rankings of exposure to stress are easier to produce: the published EPA guidelines (US EPA 1986, 1996, 1998) provide useful indications for a variety of stressors and systems.

Extrinsic potential subcomponent. This results from hazard, which for our purpose we can define as the likelihood of stress that is not being currently applied on the system to be applied in the future, or as the likelihood of change in the level of stress currently applied. Quantification in approximate rankings would need probability estimates for stress situations occurring and appropriately chosen thresholds. Probabilities can be assigned on the basis of historical indicators for factors that have a recurring nature, or careful extrapolation of trends such as development and pollution.

All of these properties, whether potential or expressed, are more easily and justifiably evaluated relative to the moment of time when the estimates are made, no matter if they use historical information or not. They should be regarded as indicators of a current tension of the system towards a more degraded state, not as a state itself, and should be interpreted as rates rather than measures of system state variables. This should be made clear in the guidelines to avoid misinterpretation of the indicators.

It is also not necessary to consider all the components above in an indicator of vulnerability. As an example, we might want to characterize only the expressed components for a given system, based on considerations of precision or on the difficulty of supporting the theoretical arguments upon which other components should be measured. This would yield legitimate VIs as long as the vulnerability definition is explicit and we only compare VIs based on the same model.

The System Model

The system model defines a way to map arbitrary system characteristics onto the identified components of vulnerability. A system model defines a hierarchical decomposition of the notion of a system where particular system definitions (e.g., based on structure and/or function or ecosystem services provided) can be fitted in order to allow consistent calculation and aggregation of indicators. Many existing studies have devoted most energies in developing appropriate system models. An explicit system model ensures completeness, coherence, generality, and scale compatibility. A specific system conceptualization is applied to the model to define notions and specifics of "responders," "stressors," and "indicators."

A suitable system model should: (1) be able to accommodate different system concepts under a common vision; (2) provide a generic layout and a coherent system of constraints to develop guidelines to serve as a base for a VI; and (3) be suitable to the calculation of a VI according to a model of vulnerability like the one outlined above. To reach these goals, it is productive to use a hierarchical conceptualization, where the highest-level decomposition of the system identifies categories corresponding to high-level interacting compartments. These need to be general enough to be applicable to widely different systems. As an example, a functional system conceptualization could define these categories as secondary production, primary production, decomposition, and so on. In the definition of such categories, it is critical that generality is maintained, redundancy is minimized, and the set of categories defines a complete general system rather than just particular aspects of it.

These categories can be further subdivided into responders, which are the entities subject to vulnerability. In the definition of responders, redundancy is a desirable property, as it should ensure that at least one responder is defined for any category no matter which system it is applied to. When the decomposition in categories is defined, responders can be added to accommodate specific environments with no loss of generality. In defining responders within a category, relative independence is also important and should be kept in mind as a goal. The same responder can appear in different categories without affecting the generality of the model.

For each responder, indicators should be defined to quantify properties of responders that are relevant to the calculation of vulnerability. Redundancy is desirable at this level also, since some indicators may be applicable to the measurement of a property in a certain environmental context and not another. Indicators should be characterized according to their role in quantifying the components of vulnerability. In other words, we should know whether an indicator applies to any of the system properties causing each of the components of vulnerability outlined in a vulnerability model, by expressing, e.g., how much a property is inherently at risk of losing its role in the maintenance of the responder's function or how well it is performing its role.

The advantage of a similar hierarchical breakdown is that the high-level divisions provide a common ground that ensures the comparability of systems, while the more specific, lower-level responders provide the grounds for application to particular environmental realities. Using a hierarchical decomposition, we make sure that different systems, which are not comparable at the responder level, can be compared when the response indicators are aggregated at the category level, since the categories are chosen with sufficient generality to make this possible. No matter which particular system view is adopted, the decomposition must have the properties of completeness and generality. By completeness we mean that an ecological system must be completely characterized by describing elements in each category. By generality we mean that the decomposition should be general enough to make any local specificity disappear, i.e., any system can be defined according to the decomposition, having at least one element of description for each category. The mathematical model, as discussed below, can recognize the different roles of redundancy and use the appropriate aggregation algorithms at different levels.

Very sophisticated system models are sometimes built as a phase of integrated risk assessment. The papers by Cormier and others (2000) and Gordon and Majudmer (2000) provide examples of physical and probabilistic system models for assessing vulnerability on specific environments. When the system is well known, extensive, spatially explicit simulation models such as that presented in Voinov and others (1999) can be used to illuminate the details of how it responds to change. Even in low-resource studies, adopting a sufficiently general system representation is key to the reuse and comparability of indicators calculated for different systems. Nevertherless, many existing studies aggregate available information with little consideration of the fact that the set of indicators should give a complete picture of a system that functions as an interconnected whole (e.g., Eurostat 1998). Below, we identify some possible system conceptualizations that have inspired or can inspire the choice of indicators.

Ecological structure and function. Perhaps the most obvious system conceptualization starts with an inventory of ecological structural attributes at different levels (such as species, communities, ecotypes) and key processes of generally accepted relevance (such as primary and secondary production, *decomposition, or nutrient cycling). Stress factors acting on such responders could be categorized, and factors such as structural redundancy in each component or rates of processes that counter loss of function could be used as indicators of resilience. A hybrid structural/functional conceptualization is preferable to a simply structural one for a number of reasons, most notably because a purely structural vision does not explicitly include time. This reduces its relevance since a measure of vulnerability should be sensitive to the time scale chosen and to the dynamics of natural change. Functional characterizations relate directly to the provision of ecosystem services that humans value (see below). The purely structural conceptualization is nevertheless relevant, since most attempts to estimate the value and the vulnerability of natural systems have concentrated on system's components (particularly key species) rather than processes.

Ecosystem health and integrity. The concepts of ecosystem health and integrity, at the center of the major conclusions of the Earth Summit (Rio Declaration on Environment and Development in 1992), combine structural and functional aspects of ecosystems with human needs and expectations in a higher-level synthesis. Ecosystem integrity can be defined as "the maintenance of the community structure and function characteristic of a particular locale or deemed satisfactory to society" (Cairns 1977). It can be said to reflect the capability of the system to support services that humans value (De Leo and Levin 1997). The decomposition of the ecosystem health concept operated by Costanza and others (1992) can also serve as a basis for the definition of indicator categories. The health of an environmental system is defined as composed of three properties: (1) vigor, a measure of activity such as metabolism or primary productivity; (2) organization, referring to the structure of interaction among system components; and (3) resilience, as defined above. The definition of such properties is closely related to vulnerability. It must be noted, however, that many of these properties have no easily measured corresponding indicators. Furthermore, the debate on such definitions is intense, and the meaning of concepts such as health and sustainability is far from stabilized (Gatto 1995).

Ecosystem services. Costanza and others (1997) have developed a categorization of the services provided by the world's ecosystems to human society as a whole, with the purpose of identifying an approximate global monetary value of these services. Their categorization can be a base for a system conceptualization on which to base a choice of indicators, which concentrates explicitly on the perception and exploitation of services provided by the Earth's natural processes in sustaining life across the globe. The advantages in adopting such as framework, which is based on a broad functional system characterization, lie in its easily understandable conceptual appeal and the explicit consideration of human-specific values such as recreation and culture, which have an obvious importance in decision- and policy-making.

The system model dictates the list of indicators used. As mentioned, adopting an explicit system model helps to ensure that all components of a generic system are characterized, a necessary condition for enabling comparison between synthetic indicators calculated for different environments. Using at least a two-level system model ensures that all categories of indicators defined are represented; within each category, only the indicators that apply to the specific reality under study can be chosen without losing generality. In the next section we will discuss how a mathematical model can be used with a hierarchical system definition to maintain compatibility between VIs calculated for different systems and to account for the environment as a system of interacting components.

The Mathematical Model

The mathematical model is a strategy to standardize and aggregate indicators through the levels identified in the system model, yielding estimates of system vulnerability as defined in the vulnerability model. Different aggregation methods reflect different assumptions on the nature of the aggregated entities and their mutual interactions. In general, linear aggregation is appropriate for noninteracting entities, and multiplicative aggregation methods are best when it is known that the aggregated entities influence each other as parts of an interactive system. The following issues are relevant to the definition of a suitable mathematical model.

Standardization. Indicators express properties of responders that relate to their intrinsic or extrinsic vulnerability. The process of standardization must remap, when necessary, the measurable (raw) value of the indicators as values that can be correlated with the chosen meaning of vulnerability for each property of each responder. It is common to employ an integer ranking scale with enough levels to be expressive of a fairly wide range of values, but not so many that it becomes impossible to attach a verbal description to each level, similar to what is done in commonly adopted earthquake rating scales. The explanatory power of such a description is particularly important for purposes of raising awareness and enabling the use of indicators by policy-makers.

Response scaling. In order to be aggregated successfully, all indicators should have a similar response over their allowed range. As an example, a linear response implies that the doubling of the indicator value corresponds to approximately twice the effect it estimates. In environmental properties it is very common to refer to nonlinear responses or threshold effects; indicators exhibiting such behaviors must be made compatible by adopting a common response model (linear is best for easier interpretation by nontechnical audiences) and defining appropriate transformations to map the raw indicator values onto the chosen scale and the chosen response.

Weighting. Implicit equal weighting is done every time no weighting scheme is employed, so it is important that a weighting scheme be built into the mathematical model to force consideration of the issue and enable incorporation of priorities. Care must be exerted in doing so as different weighting schemes at certain organizational levels can make different VIs incompatible for purposes of comparison.

Two approaches to weighting are commonly used: (1) the direct attribution of weights, and (2) their calculation on the basis of a pairwise comparison matrix. In the first case, the experimenter specifies a numeric weight for each entity, describing its relative importance in the context of the system, or assigns each entity to a predefined importance category. In the second case, the weights are mathematically extracted from a matrix specifying relative importances for each possible combination of two entities. The latter approach, described by Saaty (1980) as a phase of the analytical hierarchy process, eliminates the difficulty of comparing a potentially large number of entities at the same time. It allows exact relative weighting and provides a measure of coherence in the priority structure that constitutes important feedback in a group decision process. Villa and others (1996) describe the application of this technique jointly with multivariate statistical analysis to analyze and solve opinion conflicts among different decision-makers. Weights can be assigned individually by experts in a team and processed statistically to reflect overall tendencies and identify controversial issues.

Aggregation. Once the indicators have been chosen and the weighting scheme established, system vulnerability can be calculated by aggregating indicator values in progressively higher levels as mandated by the system model. Each aggregation step can employ different methods. Simple system models reduce the number of aggregation steps; nevertheless, it is crucial for maintaining comparability of VIs to use at least two levels and incorporate any system specificity only in the lower levels.

In general, the aggregation algorithm should reflect the dynamic view of the system at each level of aggregation. Linear aggregation (e.g., weighted averaging) reflects a view of the system as noninteractive: it is in fact appropriate for nonsystems, as adopting it is equivalent to assuming that the whole equals the sum of the parts. Nonlinear aggregation reflects functional relationships between the system's components, and as such it is usually safer than linear aggregation when "cost" criteria are considered, as in the case of vulnerability. For example, it would be inappropriate to use averages to evaluate the health of an organism on the basis of functionality indicators for its vital organs. Even (and particularly) if the exact dynamics of the interaction are not known, a conservative indicator should be drastically influenced by the fact that even just one (no matter how many organs are in the system) is very dysfunctional or subjected to high risk.

Multiplicative algorithms are often used for nonlinear aggregation. Their high sensitivity to extreme values makes their application difficult in the presence of missing data or with high uncertainty. For this reason the system model should allow for at least two hierarchical levels and only the properties calculated for the highest level should be aggregated with nonlinear algorithms. By doing so, the system specificities and the effects of data uncertainty are absorbed by the linear aggregation at the lower levels and optimal criticality can be obtained.

Simple mathematical aggregation is not the only option available. Statistical techniques such as multiple-criteria analysis (Voogd 1983) can be used as a base to devise sophisticated aggregation schemes involving not only indicator values, but also their concordance or discordance with explicitly stated goals. Economic studies have used regression techniques instead of simple aggregation of indicators (Atkins 1998). As the complexity of the objectives increases, however, the applicability and clarity of the overall indicators obtained decrease. Simplicity and ease of understanding are important goals that are best met by simple aggregation schemata.

Using a maximal articulation of the system model as discussed previously, a four-step aggregation scheme is required. No matter how many steps are involved, it is possible to identify general guidelines only for the first and last step.

The first step is the aggregation of indicator values into vulnerability or criticality of the responder's property. In this phase a weighted average scheme is probably most appropriate. It is one of the phases where the weighting is most important, and the use of weights does not hamper comparability at this stage since it refers to the lowest level of aggregation. A linear aggregation reflects the assumption that indicators contribute independently to the calculation of the property's criticality, which should be enforced by the system model.

The last step is the aggregation of per-category vulnerabilities into the final VI (system-level vulnerability). At this stage it is critical to employ a nonlinear aggregation scheme, since by definition a system is composed by interacting entities, at least at the highest level of aggregation. It is also important that the weighting is equal at this stage unless there are important arguments for an unequal weighting; if so, this weighting should be stated in the system model and not be modified in specific applications, in order to preserve the high-level comparability of the VIs calculated according to this scheme.

The intermediate steps—if using a maximally articulated system model—are the aggregation of property values into the responder's vulnerability and the aggregation of the responder's vulnerabilities into category vulnerabilities. The aggregation model at these stages depends on the vulnerability model and the system model and little can be said in general. It could be argued that potential and expressed vulnerabilities are not independent since a compromised system is more at risk of subsequent stress than a pristine one, and as such they should multiply each other in order to describe the whole responder-level vulnerability. In this case it might be useful to add an intermediate organizational level to account for these different components.

Aggregation algorithms. For linear systems, the simple weighted average is an obvious choice, as used often in economic vulnerability studies. The choice of nonlinear aggregation algorithms is less obvious and should be evaluated with care. The literature on evaluation of land resources is rich in examples of linear and nonlinear aggregation algorithms. Among these, the most widely used is the Storie (1976) indicator, originally developed for equitable assessments of land value for taxation purposes and used since then in various environmental applications (Leamy 1974, Lal 1989). The general formula is

$$\Omega(k; A_1, A_2, \ldots, A_n) = \left[\prod_{i=1}^{n} A_i\right] \frac{1}{k^{(n-1)}} \qquad (1)$$

where k is the highest score obtainable in a scale 1 to k, A is the individual score, and n the number of scores taken into consideration. The indicator in this form lends itself to the evaluation of benefit situations: high values will contribute to determine the overall value more than low values, and the presence of many low values will influence the overall indicator, but never to the point of compensating the effect of a high one completely. In the evaluation of environmental vulnerability, it is more common to need a cost formulation that gives higher importance to low values. Its formulation in this case can be modified as follows:

$$\Omega(k; A_1, A_2, \ldots, A_n) = k - \left[\prod_{i=1}^{n} (\mathrm{k} - \mathrm{A_i} + 1)\right] \frac{1}{\mathrm{k}^{(\mathrm{n}-1)}} \qquad (2)$$

The indicator in this form has the same behavior discussed above but reverses the dominance structure: low values will dominate the overall value. It is thus safe to use when it must be ensured that the effects of a dysfunctional system component are not entirely compensated by the number and relative health of the others. Koreleski (1988) discusses modifications to the Storie indicator that reduce its very high sensitivity to extreme values. Villa (1995) originally proposed the cost formulation of the Storie indicator for the evaluation of conservation status, vulnerability, and potential of recovery for the BioItaly/Nature 2000 program of the EEC (1992). Case studies and comparisons with other indicators are described in Villa and Antonietti (1996).

In general, applying nonlinear aggregation requires particular care, since they tend to have unwieldy statistical behavior. Algorithms should be carefully evaluated through bootstrap studies and their distribution and properties compared before adoption, particularly when good statistical behavior is important (e.g., when the indicator must be postprocessed or compared statistically).

Validation

Validation of approximate indicators of environmental properties with controversial definitions is obviously impossible in exact scientific terms. The hypotheses leading to the development of such aggregated indicators are normally not falsifiable. The problem of validating vulnerability indicators is at least twofold: on the one-hand validation methods need to be assessed, and on the other appropriate time scales need to be identified. Large-scale systems will need to be observed at proportionally large time scales, which limits the ability of invalidating the vulnerability estimates through observation and measurement.

A further problem is the inherent stochastic nature of the very concept of vulnerability, and the lack of replication at the larger scales. Together, these properties make the whole issue of validation almost entirely nonapplicable in conventional terms. It can be argued that peer review (possibly aided by conflict-resolution techniques and statistical analysis) is the only way to obtain a reasonable level of confidence in such indicators. Of course, the results of peer review cannot be conclusive. In particular, cross-system comparisons are the most difficult aspect since experts with the breadth of knowledge necessary to compare widely different environments are rare.

In the example discussed in the next section, a procedure was suggested as an "acid test" for determining when the VI could be considered globally operational. This would involve detailed country vulnerability assessments being carried out on a number of countries across the world by consultants not initiated in the work of the VI. These assessments would be ranked and then compared with the vulnerability indicator values to ascertain their correlation. This is, of course, a costly process, but small compared to the cost of conducting detailed vulnerability assessments of individual countries by on-site visits as is the procedure at present. Furthermore, the cost of testing an indicator should be measured against the possible costs of using an untested indicator that is faulty in its results.

Given the difficulties in validating high-level synthetic indicators, it is very important that a peer review process is built into their development from the initial phases and that general guidelines are prepared by teams of experts using appropriate conflict analysis techniques and statistical characterization of priorities and agreement for each sub-goal. The decomposition of the problem into different, relatively independent models operated above can be a base for the development of such guidelines. In the following we briefly describe assumptions and preliminary conclusions characterizing the first of such attempts, aimed at the definition of a generic framework to evaluate vulnerability at the country level, in response to internationally identified, long-term goals.

An Example: SOPAC's Environmental Vulnerability Index (EVI)

No case studies inspired by the theoretical principles outlined above are currently available. However, the EVI project, led by the South Pacific Applied Geosciences Commission (SOPAC), a regional organization based in Fiji, currently leads the way towards a generally applicable environmental vulnerability indicator, which will get as close as possible to a validation process by being applied and compared in widely different countries and biotas. Both authors of this paper have been involved, either as an independent scientific advisor or as part of the core research team, with the development of the EVI, which is funded by the New Zealand Overseas Development Assistance (NZODA). The EVI is a work in progress and current details are published in reports that are available on the Internet (Kaly and others 1999a,b, Kaly and Pratt 2000, http://www.sopac.org.fj/Projects/Evi). While not all of the principles outlined above are incorporated in the current EVI formulation, we consider it productive to briefly describe the published features of what is currently the most ambitious VI framework, with the aim of: (1) showing how the theoretical framework we outlined can be used as a context to develop and discuss a VI, and (2) illustrating an important ongoing development in the field.

Preliminary EVI Model

In this section we briefly describe the salient aspects of the published EVI formulation with reference to the framework outlined above. We discuss separately the EVI interpretation of vulnerability, the model of the system, and the preliminary aggregation strategy as published in the literature cited.

Vulnerability model. Environmental vulnerability in the EVI formulation is seen as resulting from the combination of exposure to stress and system resilience. Resilience is, in turn, divided into an intrinsic component, viewed as functioning as an immune system in the environment, and a component directly related to the state of environmental degradation. A risk exposure component reflects the historical occurrence of natural impacts, such as droughts and cyclones, and anthropogenic impacts, including resource exploitation and pollution. Vulnerability is assumed to increase with the intensity and frequency of impact. Intrinsic resilience can be viewed as similar to a human being's genetic immune system. Some systems are interpreted as being more capable of bouncing back due to faster recovery, and the EVI formulation identifies a number of environmental properties that can correlate to this ability.

As an example, one indicator used for relative comparisons of resilience in systems where coral reefs are present was the rate of coral reef accretion, for which data are easily available and show wide differences in the test environments.

Lastly, extrinsic resilience was interpreted as the health of a system and assumed to be inversely proportional to degradation by outside impact. As an example, indicators of susceptibility to coastal erosion were devised by considering removal of the natural mangrove barriers.

System model. Like other examples of existing aggregated indexes of environmental properties, the EVI puts a strong emphasis on the system model, defined through a highly articulated choice of environmental indicators. However, the choice of indicators identified for the EVI is directly related to the assumptions set forth in the vulnerability model and does not attempt, at the current stage, a comprehensive description of a general environmental system. Rather, a full description of what makes a system vulnerable is attempted, and indicators are classified a priori according to their contribution to each of the different components of vulnerability.

The EVI focuses on the vulnerability of the natural environment and excludes human systems as a responder. The justification for this was that human welfare is dependent on environmental systems and degradation of these systems leads to a reduction in human welfare. Many people also value the intrinsic benefits of knowing the environment exists in an undegraded form. Lastly as a number of vulnerability indicators were being developed based on human systems, an indicator such as the EVI excluding these systems will not overlap with those in existence, allowing the possibility of aggregation into a composite indicator. The responders would include ecosystems, habitats, populations, and communities of organisms as well as physical and biological processes. In this sense, the EVI system view is a "pure" ecological one with structural and functional components and no concern for human influence as part of the system.

The system was broken down into a number of categories based on structural and functional factors or responders. The responders considered in the current list of indicators can be broadly classified into several categories: (1) ecological entities at the landscape and ecosystem level, (2) populations and communities of organisms (identifiable groupings of organisms and their habitats), (3) physical and biological processes (beach building, reproduction, recruitment), (4) energy flows (nutrient cycling and import/export), (5) synthetic attributes (such as diversity) at different levels (geographic, ecosystem, community, population, species and genetic diversity), and (6) functional redundancy of ecological system components (species which carry out similar functions in an ecosystem). This subdivision reflects conceptual categories rather than ontological differences attributable to different responders or categories thereof. Although the available information has been arranged in order to constitute a hierarchical system model and to enable a multistep aggregation as we have described, no such attempt is made in the published EVI formulation. As we indicate in better detail below, exploring more articulated aggregation strategies is one of the goals for the EVI's future, and the system model may be revised to allow this.

To reach a satisfactory set of indicators, the SOPAC research team used a multistep process that engaged the help of a wide group of national and international experts. An initial formulation was developed (Kaly and others 1999a) by a multidisciplinary team that included regional experts. In a later phase, a conference process was used to correct the focus and provide abundant peer review on the developing formulation. An international forum was held (Kaly and others 1999b) to overhaul the indicator for international applicability and robustness. Many of the ideas expressed earlier in this paper were incorporated into the EVI as a result of this process.

A total of 47 indicators were selected through successive refinements of an initially very large list. The current list of indicators and their values for five test countries are given in Kaly and Pratt (2000). Table 1 gives examples of proposed indicators categorized according to their relationship with the vulnerability model and the system components or processes to which they refer.

The demand that drove the development of the EVI made it necessary for it to be focused at the country level. This requirement, rather typical of government-funded programes, introduces a peculiar and somewhat ambiguous role for the variable area, which becomes not only a proxy indicator for many factors connected to resilience, but also an important scaling factor for cross-country comparison. Land area at this time is a cross-cutting variable that is considered as a major contributor to the intrinsic resilience.

Scaling and standardization of indicators. Indicators were mapped on a scale of 1 to 7, where 7 reflects maximum incidence or effect. In order to obtain approximate linearity of response for each indicator, different response classes were defined, corresponding to different mappings of the indicators' raw values onto the 1–7 scale. The indicators were individually assigned

Table 1. Some examples of factors related to indicators used in the current EVI formulation[a]

Vulnerability component	Anthropogenic	Biological	Geological	Meteorological
Exposure	Touristic pressure Percentage of protected areas	Pathogen outbreaks Species introductions	Earthquakes Volcanic eruptions	Sea surface temperature
Degradation	War or civil strife	Alloctonous species	Mining activity	
Resilience	Land area; Fragmentation indexes; Isolation			

[a] Indicator categories are on the columns. The rows specify the component of vulnerability the indicators refer to. Resilience indicators are not categorised at this stage.

Table 2. Response classes for the indicators considered in the EVI

Response class	Description	Example indicators
Linear	The raw magnitude of the indicator is proportional to its value on the importance scale	Percent protected land area
Marginal	The effect of the indicator varies more or less than linearly with its raw magnitude	Surface sea temperature change
Threshold	The effect of the indicator becomes negligible or catastrophic below or above a given threshold	Human population density

to a class with the help of the consulting team of experts, and a mapping of the raw value onto the 1–7 scale was defined accordingly. The response classes used are described in Table 2. Other response classes were devised for possible future use.

Weighting. Two weighting systems were evaluated to express the relative importance of each indicator within the overall EVI calculation. In all cases the weights are and will be assigned by a team of international experts. An initial set of weights for the 47 indicators was assigned during the 1999 Think Tank meeting as the average of importance rankings (1–4) provided by each of the 30 experts at the end of the four day working group (Kaly and others 1999b). Standard deviations of the ranking for each indicator were used to highlight the most controversial issues and suggest areas for further discussion. This weighting system is the basis for the provisional calculation of vulnerability done for test countries in the South Pacific. The EVI team is also planning to use pairwise comparisons, a longer and somewhat more involved process, to obtain more precise weights, evaluate the overall coherence of the suggested priorities, and identify the main "lines of thought" in the consulting group, as done in Villa and others (1996), through the use of multivariate statistical techniques (Kaly and Pratt 2000).

Aggregation method. The overall vulnerability is calculated as an aggregation of the appropriately scaled subindicators relative to the three components of vulnerability. The partial scores for risk exposure, intrinsic resilience, and extrinsic resilience are simply averaged to obtain the final EVI. As the EVI is intended for intercountry comparison, the aggregation scheme is of paramount importance. For this reason, the current aggregation scheme is considered limited, and different aggregation algorithms are being evaluated. Teams of local and international experts will compare the EVI values calculated with different aggregation algorithms for a number of test countries to identify the most satisfactory ones. The preliminary results have been obtained with linear aggregation for South Pacific small island states (see below), where direct comparison of indicator values is justifiable because countries share most ecotypes, problems, and are of relatively similar size. As the EVI expands towards more different environmental systems, nonlinear aggregation will be also used to aggregate indicator values between categories, while indicator values within categories will be aggregated linearly using weighted averages with weights obtained as explained above. This will require restructuring the system model in order to account for the specificities of different environmental systems within broader, general categories of responders. For nonlinear aggregation, the EVI team is planning to test the modification of the Storie indicator illustrated in equa-

Table 3. Preliminary EVI results for 4 South Pacific countries[a]

	Fiji	Samoa	Vanuatu	Tuvalu
REI	3.0	2.9	3.0	3.9
IRI	4.2	5.1	3.4	6.6
EDI	3.7	3.3	3.3	4.3
EVI	3.6	3.8	3.2	4.9

[a] Data from Kaly and Pratt (2000). EVI = Environmental Vulnerability Index; REI = score from indicators of exposure to stressors; IRI = score expressing factors causing lack of intrinsic resilience; EDI = score expressing current state of environmental degradation. EVI is a rounded arithmetic mean of the other indexes.

tion 2 along with other formulations to be identified (Kaly and Pratt 2000).

Results and Future Developments.

Preliminary EVI values for four test countries in the South Pacific area have been calculated using simple weighting and linear aggregation (Kaly and Pratt 2000). Vulnerability estimates as of late 2000 are shown in Table 3 and, despite the preliminary nature of the results, are considered to satisfactorily express the nation's comparative vulnerabilities as the common knowledge of the respective ecosystem dynamics suggests. Different weighting schemes are being evaluated which produce different results, and some estimates (most notably the ones for Vanuatu) are considered less reliable because of difficulties obtaining data for a number of indicators. At this time SOPAC's arbitrary criterion for validity is the availability of at least 80% of the indicators, which was met for all countries except Vanuatu. A much more detailed account of these preliminary results and future priorities is given in Kaly and Pratt (2000).

At the present stage, the mathematical model is undergoing the most active conceptual development. The efforts planned for phase 3 of the project concentrate on statistical determination of redundant indicators, scoring of individual indicators, weighting of indicators, mathematical testing, and validation. The latter will involve a collaborative review and evaluation of vulnerability indicators calculated with different weighting schemes and aggregation algorithms as indicated above, performed by an extended team of local and international experts.

A useful by-product of the EVI is the fact that country-level profiles can be useful in their disaggregated form, showing, for instance, the absolute level of degradation and relative level of risk. The various levels of reporting—from the single EVI score to the individual indicators—can be useful to differently focused policymaking, from the international to the interagency national level. Further breakdown of risk into anthropogenic impacts and natural impacts allows further clarification of the causes of vulnerability in a particular country.

The major challenge and most interesting aspect for future EVI development is globalization of the model. The minimum number of different countries set as a goal for evaluation after phase 3 is complete is 15, spread around the globe and not only the Pacific area. Reaching this goal will require that all objectives of phase 2 to be met and major that advances in the system conceptualization be made, possibly following the guidelines indicated in this paper. Countries as different as Fiji, Italy, Ireland, and New Zealand have agreed to use the EVI in pilot evaluations. For this reason, the EVI project provides a unique occasion for determining not only the scientific value, but also the potential of such a measure to become a tool for raising awareness about the vulnerability of the environment. The latter is one of the stated goals of the EVI (Kaly and others 1999a).

Other priorities of the EVI project include the provision of a permanent data collection mechanism, the development of a friendly user interface for data organization and calculation of the indicators, and the formalisation of a feedback strategy from local and international experts. The strengths and weaknesses of the EVI were discussed with the same conference process that defined the list of indicators. As the panel of experts pointed out, strengths include: (1) being the first comprehensive and convenient measure of environmental vulnerability; (2) allowing, in principle, comparison between countries, and (3) being easily explained to and understood by nontechnical decision makers. Weaknesses include: (1) the subjectivity implicit in the weighting and response scaling processes; (2) the fact that complex environmental factors are often represented by proxy indicators, and (3) the fact that the EVI interpretation might not be obvious or unambiguous without specific instruction. Many of the obvious weaknesses of the current model (such as the assumptions of linearity implicit in the choice of a linear aggregation model or the lack of consideration for the amount of controversy in the choice and weighting of indicators) will be overcome by planned development in the near future as outlined above.

Conclusions

The need for synthetic indicators of critical ecosystem properties, such as vulnerability, is clear and strong, as witnessed by the number of worldwide initiatives that have requested them. We have indicated general guidelines and priorities that can help in developing such indicators, based on sets of easily measurable properties, while maintaining realistic requirements concerning time scales, data, research funding, and conceptual accessibility for decision-makers. As the EVI example indicates, we are nearing a phase when such indicators will be available for comparison, providing a tool for policy-making that is likely to become widespread and important. It is our belief that the theoretical points we discuss need to be accounted for in any indicator framework that has pretence of generality. The way we "take the pulse" of the environment, particularly in the conditions of limited resources and understanding that most nations face, has the potential of causing high impact on the world's ecosystems and our own well being. We hope that this contribution can help a discussion that, while recognizing the fact that the scientific community cannot currently handle the issue rigorously, can nevertheless bring as much rigor as possible and make sure that the inevitable mistakes are made on the safe side.

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