AN ECOSYSTEM APPROACH TO THE INTEGRITY OF THE GREAT LAKES IN TURBULENT TIMES

Proceedings of a 1988 Workshop
Supported by the
Great Lakes Fishery Commission
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Clayton J. Edwards and Henry A. Regier

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PREFACE

A "Workshop on Integrity and Surprise" was convened in Burlington, Ontario, on 14-16 June 1988 under the auspices of the Great Lakes Fishery Commission's Hoard of Technical Experts (GLFC/BOTE) and the International Joint Commission's Great Lakes Science Advisory Hoard (IJC/SAB). The Workshop was supported by funds from the SAB and BOTE. In addition, the Donner Canadian Foundation supported the contributions of several Canadian collaborators.

This workshop was a sequel of two earlier initiatives. One of these was the Ecosystem Approach Workshop, convened in Hiram, Ohio, in 1983 under the auspices of IJC/SAB, GLFC/BOTE, the International Association of Great Lakes Research, and Great Lakes Tomorrow. The other was the third series of Canada-U.S. Inter-University Seminars (CUSIS III) of 1983-4, which concluded with a meeting in Racine, Wisconsin. The 1983 Hiram Workshop emphasized practical aspects of ecosystem politics.[1] The CUSIS Seminars emphasized ecosystemic governance.[2]

This 1988 Burlington Workshop emphasized scientific and conceptual aspects of ecosystemic policies in the context of great practical uncertainty. Two working groups were convened to explore the implications for policy and for theory and testing of ecosystem integrity and surprise in the Great Lakes basin. With the exception of the introductory paper providing a range of individual perspectives on ecosystem integrity, the papers in these proceedings are categorized according to the two above-mentioned working groups. The first paper in each category provides an overview of that working group's discussions and conclusions.

This workshop was organized and convened by a joint committee of the SAB and BOTE. A. P. Lino Grima and Richard A. Ryder represented BOTE; Timothy F. H. Allen and Clayton

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[1] J.R. Vallentyne, "Implementing an Ecosystem Approach to Management of the Great Lakes Basin, Workshop Held at Hiram College, Hiram, Ohio, March 22-24, 1983," Environmental Conservation 10:3 (1983): 273-274 and W.J. Christie et al., "Managing the Great Lakes as a Home," Journal of Great Lakes Research 12 (1986): 2-17.

[2] L.K. Caldwell, [ED.], Perspectives on Ecosystem Management for the Great Lakes (Albany: State University of New York Press, 1988).

J. Edwards represented SAB: and Henry A. Regier represented GLFC and SAB. Clayton Edwards and Henry Regier had major editing responsibilities, but all authors assisted with reviewing and editing of papers. Randy L. Eshenroder and Madeline Haslam of GLFC and Martha L. Walter of Ann Arbor, Michigan, helped with the publication process.

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PERSPECTIVES ON THE MEANING OF ECOSYSTEM INTEGRITY IN 1975

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ABSTRACT. We have reviewed and analyzed the proceedings of a Symposium on the Integrity of Water convened in 1975 by the U.S. Environmental Protection Agency. We presupposed that all the participants had at least some minimal commitment to the purpose of the goal of integrity as specified in the U.S. Federal Water Pollution Control Act Amendments of 1972. We perceived a spectrum of interpretations of the term integrity and have divided this spectrum into five classes according to the substance of the goal and supporting strategies with which speakers have invested the term integrity. We have then provided a summary sketch of each of these classes.

INTRODUCTION

The word integrity figures prominently in Section 304 of the U.S. Federal Water Pollution Control Act Amendments of 1972. To clarify the concept of integrity, the U.S. Environmental Protection Agency convened a Symposium on the Integrity of Water in Washington, DC on March 10-12, 1975. The proceedings (U.S. Government Printing Office Stock No. 055-001-01068-1) were published in 1977.

The focus of the 1975 Symposium was on the definition and interpretation of water quality integrity as viewed and discussed by representatives from federal and state government agencies, industry, academia, and conservation/environmental groups. Almost all the participants were American. The Symposium was designed to interrelate two concepts of integrity,

1) as a desirable characteristic of natural ecosystems, and

2) as a moral or cultural principle,

and then apply this combined concept to the real-world pragmatic use of integrity for setting regulatory practices.

During the Symposium, it was noted (by R.B. Robie) that "from the many interpretations presented, it can clearly be seen that integrity, like beauty, is in the eye of the beholder." One way to sort out these differences is to examine the various perspectives of the Symposium participants with respect to the degree of reform deemed necessary to achieve integrity. We discerned five different degrees of reform from the Symposium proceedings and have excerpted text that we consider to be illustrative of each reform objective. We then attempt a general characterization of strategies for each objective. The five reform objectives are: deep reform, partial reform, incremental advances, holding the line, and slowing the rate of retreat.

For each of the excerpts that follow we have given the name of the symposium participant and the page(s) on which the statement may be found. We have classified the statements, not the participants, who made those statements. We emphasize that a statement taken out of context should not be used to infer the degree of reform to which a speaker might be committed.

SYMPOSIUM EXCERPTS RELATED TO FIVE REFORM OBJECTIVES

Deep Reform

Senator Muskie, in the Senate debate on the conference report: "These policies simply mean that streams and rivers are no longer to be considered part of the waste treatment process." And elsewhere: "This legislation would clearly establish that no one has the right to pollute, that pollution continues because of technological limits, not because of any inherent right to use the nation's waterways for the purpose of disposing of wastes."
-- R. Outen, p. 217.

The goal of the Act is the restoration and maintenance of the "natural, chemical, physical, and biological integrity of the nation's waters" by 1985. The House Report defines "that ecosystem whose structure and function 'natural' [as] one whose systems capable of preserving themselves at levels believed to have existed before irreversible perturbations caused by man's activities." Any change induced by man which overtaxes the ability of nature to restore conditions to natural or original is an unacceptable perturbation.
-- T. Barlow and J.G. Speth, pp. 215, 216.

The new program [i.e. the 1972 Act]: . ..assumes that man is a component of the biosphere and that the relationship we seek to achieve with the environment is

what some have called harmony. Under this view, man is an integral, if dominant, part of the structure and function of the biosphere. The intellectual roots of this perspective are found in the study of evolution. The objective of this concept is the maximum patterning of human communities after biogeochemical cycles with a minimum departure from the geological or background rates of change in the biosphere.
-- T. Jorling, p. 10.

The clear unequivocal bench mark statement of biospheric integrity as the objective of the water control effort involves the restructuring of society in accordance with ecological integrity.
-- T. Jorling, p. 9.

It's certainly a value judgement to establish integrity and the value is prudence, I suspect.... We should keep things patterned after natural systems; the more closed the material energy cycles within those systems, the better; so, I think that's another value judgement. It recognizes our limitations.
-- T. Jorling, p. 21.

Similarly, we are faced with the challenge, still poorly recognized, of building closed urban and agricultural systems that mimic in their exchanges with the rest of the environment the mature natural systems they displaced. Here is the current challenge for science and government--not to aid in the diffusion of human influences around an already too-small world, but to speed the evolution of closed, man-dominated systems that offer the potential for a long, stable, and rewarding life for man.
-- G.M. Woodwell, p. 143.

Our basic resources world-wide are not energy or the economy or anything else. The basic resources are biotic resources. These are the resources that are used by all of the people on earth, all of the time.... Much more energy flows to the support of man through biotic resources than flows through industrial systems...by a factor of 20 or so, at least, world-wide.... The basic rule of the game is that everybody eats plants.
-- G.M. Woodwell, p. 147.

I can but assert that the essential qualities of air, water, and land that make the earth habitable for many are maintained by natural ecosystems in a late stage of evolutionary and successional development.
-- G.M. Woodwell, p. 141.

It is tacitly assumed, at least to my mind, that only pristine waters possess integrity, for in these waters time and evolution have inter-played to produce a fauna and a flora adapted to the natural characteristics of their environment. Westman argues that to allow anything short of this leads again to uncertainties of relating effluent composition to effluent effects upon water quality. It was this reasoning which led Congress to state: "It is the national goal that the discharge of pollutants into navigable waters be eliminated by 1985...." The way to meet this goal is closed-cycle technology.
-- D.F. Squires, p. 18.

The 1972 Act, P.L. 92-500, provides a planning and a regulatory mechanism. It provides an opportunity, if we use it, to look at the structure and functioning of human communities as elements in the overall biosphere and make judgments about the life-support requirements of those human communities. This is a tall order. Yet it is the direction in which we must move; it is the legacy of the concept of ecological integrity.
-- T. Jorling, p. 13.

It is not possible at this time to define the integrity objective by any index or system of water quality parameters.... Integrity is thus not a regulatory tool in and of itself.... It is more a statement of philosophy, a statement of national direction,,., We have some good interim goals, which can be translated into effluent restrictions, to achieve first. We should get about the business of doing that.
-- R. Outen, p. 217.

The 1972 Amendments marked a profound change in the philosophy and approaches to water pollution in this country. The point bears reemphasis because even after 2-1/2 years of living under the new law, a discouraging number of the people actually implementing it haven't changed their thinking at all. The fact is you cannot effectively implement the '72 law using the 1965 assumptions. Consider the old law. It was premised on the anthropocentric idea. ..that aquatic ecosystems exist for the use of man. This assumption leads quickly to one perverse result after another. The first order of business becomes the designation of the best use, basically a ratification of the status quo, a legitimization of the ecological abuse that had been previously visited upon the

system.... With the 1972 Amendments...we have, for the first time in the nation's history, a water pollution control law that takes a holistic view of the aquatic ecosystem. For the first time, the objective is the restoration and maintenance of ecological integrity, not the perpetuation of somebody's notion of best use.
-- R. Outen, pp. 216-217.

And so we are asked now to dissect and define a phrase [i.e. to restore and maintain the chemical, physical, and biological integrity of the nation's waters] that should not be dissected. Our interest is in the preservation of the biota including man. The biota is dependent on the physics and chemistry of the environment and affects both. In this case, all is one and one is all. A dissection is inappropriate.
-- G.M. Woodwell, p. 141.

Underpinning the conventional process is the ecologically questionable notion of assimilative capacity, the idea that extraneous materials placed in the water somehow go away. Invoking the theory of assimilative capacity, and to avoid the obvious but unpleasant fact of finding discharges in violation right at their pipe, one is led to the device of defining a mixing zone. A mixing zone is a sort of ecological free-fire zone where anything goes....
-- R. Outen, pp. 216-218.

Further, we will not see real progress until we get ourselves detached from the chlorinate and dump mentality.... More broadly, and here I will compound the heresy, we will not get *there* until we break the death grip that the sanitary engineering and economic professions have on all decisions regarding the way that essential materials circulate through society. The sanitary engineer must make room for the systems ecologist.... We must recognize that the field of economics is unequipped to deal with the broad questions [that affect] the quality of life we want a century, two centuries, from now. Rather than responding to individual treatment crises on an ad hoc basis, we must elucidate fundamental ecological principles, then guide all human behavior by these principles.
-- R. Outen, p. 218.

Benefits and costs should determine means, not ends.
-- T. Jorling, p. 13.

Water quality must be of the highest to achieve water integrity.
-- K.M. Mackenthun, p. 6.

The final point, which I think follows, is that we interpret an implication of the goal of integrity in a pragmatic or enforcing way as zero discharge....
-- D.J. O'Connor, p. 102.

With specific reference to nuclear plants, do we allow this further diffusion of human influences around the world, or do we decide that the estuaries are important, and we can't put reactors on them, that we have to figure out something else to do with the reactors?
-- G.M. Woodwell, p. 154.

In other words, don't underestimate people's intelligence, but never overestimate their information.... What does this mean in terms of the large-scale effort in government, science, industry, and conservation to firmly establish the integrity of water? I think...it calls for one of the biggest public educational campaigns in history.
-- G. Hill, p. 228.

Partial Reform

The 1972 Act contains a basic philosophical shift in water management from one of standards (technological approach) to one of integrity (ecological approach). This is a significant achievement. The 1972 Act, however, clearly states that restoration of the physical, chemical, and biological waterways shall be its goal. This, of course, contrasts with previous definitions, which were couched in terms of man's use of waterways. This change sets a higher goal.
-- D.F. Squires, p. 16.

. ..to me ... the integrity of water [means] the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a composition and diversity comparable to that of the natural habitats of the region. Such a community can accommodate the repetitive stresses of the changing seasons. It can accept normal variations in input of nutrients and other materials without disruptive consequences. It displays a resistance to change and at the same time a capacity to *recover* from even quite major disruptions.
-- D.G. Frey, p. 128.

Cur goal is to nourish our waters and watersheds and their inhabitants back. ..closely to the pattern of variable conditions that existed before man's influences became so paramount.
-- R. Johnson, p. 167.

Basically, this has been a shift away from dependence upon the assimilative capacity of water to one of best practical treatment as a means to manage effluent concentration.
-- K.M. Mackenthun, p. 5.

The intent of Congress was not that we revert each flowing stream and each lake to its jeweled quality prior to the coming of man on this continent, for that can never be.... It was the intent of Congress that these sources be managed to control pollution to the maximum extent possible and to restore and maintain integrity as a result.
-- K.M. Mackenthun, pp. 5-6.

The statutory words wherever attainable provide a degree of judgmental latitude. Prudence dictates that there are some individual waters where a purity akin to integrity is not cost effective. Some cannot be restored feasibly. For all waters, however, P.L. 92-500 has become a basis for a national water ethic. Aldo Leopold's clarion call for a national land ethic slowly is being realized for the water.
-- K.M. Mackenthun, pp. 6-7.

I'm sure that most of us . . . agree with the principles [G.M. Woodwell has] enunciated ... our problems arise, not so much in acceptance of those basic moral issues, as in answering specific problems while we have such time here for ourselves and our future...[we must] incorporate flexibility into our environmental planning.
-- D.J. O'Connor, p. 145.

We should be trying to mesh two dissimilar systems. One is an industrial system operating under, more or less, the market system and the ecosystem which is controlled by environmental variables. We should be trying to get these two systems working together in some optimal way for society's benefit: I feel we can do much better than we're now doing in that respect.
-- J.J. Cairns, Jr., p. 186.

I don't think that the concept of integrity needs to be one of returning to a previous state.
-- D.F. Squires, p. 20.

I have only one way to insure no discharge of the wastes of the human population and of human technology and that is to destroy Homo sapiens. I'm not at all sure that zero discharge is achievable so long as we have human beings on earth.... I think it is possible to achieve a considerable improvement without going all the way and revert man to a hunter in an open field.
-- B.H. Ketchum, p. 32.

I think the water has to be nourished just as the land has to be nourished.
-- D.J. O'Connor, p. 103.

I look at the integrity of my own body for instance, and it isn't a perfect thing. ..we can't have complete zero of anything and we can't have complete perfection. What we have is something in between.
-- Anon., p. 102.

[Let's be] more pragmatic. When we try to look at what we can do, let's be very critical of what we think we can do, and let's be very narrow minded in this sense.
-- D.J. O'Connor, p. 154.

The integrity of water is not an abstract concept. It is a challenge, an obligation, and a necessity.
-- R.B. Robie, p. 213.

Incremental Advances

Maximizing of all potentials, along with minimizing of all damages--the aim is the attainment of a delicate balance.... The critical function in this process is conflict resolution, balancing health interests against economic welfare.
-- J.P.H. Batteke, pp. 205-206.

Biological integrity may be defined as the maintenance of the community structure and function characteristic of a particular locale or deemed satisfactory to society.... We do not know, in any scientifically justifiable sense, the characteristics of aquatic ecosystems which are essential to the maintenance of biological integrity.... If there's no such thing as a natural assimilative capacity, we're in real trouble! That would mean the end of industrial society.... We have no other choice but to assume nature can assimilate certain types of wastes and transform them. Rut if we don't define assimilative capacity more vigorously, the assimilative capacity [may be] exceeded and then the ecosystems will collapse.
-- J.J. Cairns, Jr., pp. 171, 182, 185, 186.

The integrity of natural water systems is high. The important thing is that man learns how to manage the use of such waterways, avoiding overburdening them so that the aquatic life in the streams is able to carry out natural cycling processes and assimilate wastes.
-- R. Patrick, p. 160.

The improvement and control of water quality in a natural water body such as a river or estuary can be achieved by intelligent regulation of municipal and industrial waste discharges . . . and, while it is technically possible to approach zero discharge of wastes, in most cases it is neither necessary nor economically feasible to do so.
-- D.R. Harleman, p. 105.

In my mind, it's simplistic [to think] that you're going to change the structure of society. Now, I fully agree with much of [G.M. Woodwell's points above and problems caused by] our standard of living. Rut it seems to me that the issues are not so much between the environmentalist and the industrialist as with all the other basic needs society has. There's a conflict of those monies to alleviate poverty: there's a whole priority of social needs that have to be put into perspective with the environmental. And I think that is a more critical issue.
-- D.J. O'Connor, pp. 146-147.

We want to do what can succeed with today's knowledge.... We want to do something that's going to contribute to the decisions that have to be made. We also want to give those species that the public considers important more than just haphazard attention.... We don't want to have to solve all the world's problems at once.
-- C.C. Coutant, p. 151.

I am convinced that it's necessary for a balance to be defined between the protection afforded by additional monitoring and the costs which the additional monitoring require.
-- A.E. Greenberg, p. 38.

Idealistically we'd like to do [enforcement], but constraints of our budget do not permit this and we permit tolerance, we permit waivers, we permit nonenforcement.
-- Anon., p. 38.

We will monitor and take legal action ***to the*** best of our technical ability at any time. We will also stipulate that in the enforcement of all of the standards, the analytical capabilities of the present technology will be taken into consideration in the preservation of the

case.... From a pragmatic standpoint, we find it a lot easier to change the analytical method than to change the standards.
-- A.E. Greenberg, p. 37.

First of all, then, it might be well to point out that integrity does not necessarily mean virginity.... I believe that it is meaningless to talk of "maintaining the integrity of water"--the integrity of an inanimate thing? Rather we should be stating it as "integrity in the use of water" .... Another way of describing the integrity of the whole is by simply referring to it as balance.
-- R.M. Billings, pp. 221-222.

Water may be said to have integrity when it directly serves the needs of man and indirectly serves the needs of man by serving the needs of plants and animals that are important to man, by enhancing man's food, and preserving a good and healthy environment in which man can live well over thousands of years. In other words, water being inert has no integrity as we think of humans having integrity, it has a function. I think that man has risen to a point on this earth because he had brains and could think and other things couldn't. I think it's not too self-centered for man to make use of what is available for his own benefit.
-- Anon., p. 168.

We're dealing with a dynamic technology and I would prefer to say that, temporarily at least, we may have to report a [criterion] number which is not as far down as we would like it.
-- A.E. Greenberg, p. 37.

Simply put, applying costs and benefits assures that society will not materially change; for, by definition, any change which would cause a significant alteration in any pattern of the existing society in terms of employment patterns, altered consumer patterns, reducing or limiting the amount of capital or its return, or whatever, is an unacceptable cost.
-- T. Jorling, p. 13. [This comment is a criticism of a strategy of incrementalism.]

Our urban citizens are not being given information concerning the nature of so-called waste material.... Rather, they are simply told that the waste treatment problem is an engineering problem. "Pour concrete on it" is the message.
-- T. Jorling, p. 13. [This comment is a criticism of incrementalism.]

Holding the Line

The critical question is not whether [pollutants] can be introduced into the environment, thus taking advantage of its assimilative capacity, but rather how and where they should be introduced into the environment. If the detractors of the assimilative capacity approach believe that it is possible to have an industrial society without introducing anything into the environment at any place or time, then they should show us in a substantive way how this can be done.... If the antagonists of the concept of assimilative capacity believe that there is no way in which a harmonious relationship between an industrial society and ecosystems can be achieved then they should tell us in more detail what to do next.
-- J. Cairns, Jr., pp. 179-180.

Hence, I am in favor of either reversing the trend toward increasing productivity [i.e. eutrophication] in our natural waters, except where this is specifically desired, or at least sufficiently reducing the rate at which eutrophication is occurring so that the system is not stressed unduly.
-- D.G. Frey, p. 140.

Active steps are being taken to control pollution and ameliorate the impact. Hopefully, it is not too late and we can maintain the quality of our aquatic environment.
-- B.H. Ketchum, p. 30.

Many of these industrial pollution problems cannot be easily solved but controls can be developed so that future problems are minimized.... Obviously it is not possible to prohibit accidents, but it is possible to develop quick cleanup techniques. This should be done.
-- J.H. Lehr and W.A. Pettyjohn, p. 55.

Well, I think with respect to water, [the legal definition of integrity would be] the highest and best use of the water.... The best [use] we can [maintain].... Many of us would like to maintain some streams in the wild state. In other words, don't monkey with them in any way whatsoever. In many cases, however, this just isn't possible.
-- P. Towner, p. 214.

Slowing the Rate of Retreat

The net effect of the [early] program was the application of controls which were fully in accord with, and acceptable to, the interests of the discharge source.
-- T. Jorling, p. 11. [This is a critical comment.]

A program premised upon the establishment of acceptable beneficial uses of water has inherent in it several layers of legal cause and effect relationships that enable easy frustration of enforceable requirements.
-- T. Jorling, p. 10. [This is a critical comment.]

The earlier program included a calculation of the assimilative capacity which can be defined as that volume of pollutants which could be processed, treated, or otherwise disposed of in the receiving waters while still maintaining the designated use...assimilative capacity became a rather rough, negotiated estimate, often made by lawyers and engineers, certainly not by biologists, of what waste treatment services could be rendered by a particular reach of water. This calculation, or more accurately negotiated agreement of assimilative capacity, coupled with a determination of acceptable beneficial use and an agreement on the specific numbers or criteria, created circumstances in which compromise and indefinite delay operated to frustrate enforceability.
-- T. Jorling, p. 10. [This is a critical comment.]

So, in addition to concepts such as beneficial use and assimilative capacity, the central program [prior to 1972] required further logical gymnastics such as the provision of mixing zones which, of course, are defined as those areas of greater or lesser distance around an outfall source in which measurements are not taken. Mixing zones are strictly for the purpose of allowing another layer of negotiation and compromise, always with the burden of proof on the government, the public, and the environment. The net effect of the program was the application of controls which were fully in accord with and acceptable to the interests of the discharge source,
-- T. Jorling, p. 11. [This is a critical comment.]

I do believe that protection of ground water is a reason to impose land use control, no matter how severe the political problem.... I don't like to offend people's rights too much, but I do believe in preserving the land, the greatest good for the greatest [number], that can be done in a non-bureaucratic way, so I think that it takes considerable care and thought.
-- J.H. Lehr and W.A. Pettyjohn, p. 57.

GENERAL CHARACTERIZATION OF *FIVE* REFORM STRATEGIES

Deep Reform

- Deep, comprehensive societal change with a broadly specified end-point, firmly rooted in ecocentric principles.

Protection of water as a moral obligation for its inherent worth rather than as just a utilitarian resource.

Return of polluted systems to a pristine, unadulterated condition; i.e., zero discharge is the goal.

- Indictment of conventional technological development and governmental regulatory regimes as inconsistent with natural/social integrity.

- Partial reforms (see below) may serve as proximate or interim steps.

Partial Reform

Pragmatic, sectoral, step-wise societal change within a specified general direction.

Admission that restoration to pristine conditions is usually impossible but pristine conditions are a useful ideal even if unattainable.

Support for a mosaic approach, with upgraded conventional technocentric management and science programs for ecosystems heavily utilized by humans, and alternative ecocentric management science for near-pristine areas to be conserved.

- Incremental improvements may serve as interim steps.

Incremental Advances

- Cost-effective technical improvements are applied within a society that is evolving gradually, progressively, and appropriately.

- Recognition that integrity is a multidimensional concept that is not value-free and therefore certain tradeoffs may be required, thus economics may sometimes dictate ecologies.

- Solutions are often viewed as engineering problems and the ideal solution is an elegant "techno-fix" which involves only a minor "socio-fix".

- Implicit resourcism with an ultimate goal to return and maintain ecosystems to a state of beneficial use.

Holding the line may serve as an interim measure.

Holding the Line

- No further degradation is permitted, except where society explicitly decides otherwise.
- Simplified and explicit utilitarian objectives in water conservation, with present conditions as the primary reference point.
- Broad application of concepts such as assimilative capacity, carrying capacity, maximum sustainable yield, and acceptable levels of risk.
- Allowing the retreat may serve as an interim measure.

Slowing the Rate of Retreat

- Resistance to emergence of new forms of degradation and commitment to reduction in the rate of intensification and/or spread of current forms of degradation, through processes of private harassment, ad hoc negotiation, and compromise.
- Undertaking inexpensive but visible initiatives to project an image of concern and action with a hope that the major perceived problems will be found to be overblown or will be resolved spontaneously.
- Self-awareness as being realists in the sense of recognizing that postponement of action by polluters is part of the political process.

CONCLUSION

In retrospect, we note that the wording of the U.S. Federal Water Pollution Control Act Amendments of 1972 is ambiguous. Their purpose was variously stated as to restore, maintain and protect the integrity of the nation's water and water resources. The three verbs have somewhat different practical connotations; also the nouns water and water resources may imply quite different objectives.

Presumably, only experts who had exhibited at least some minimal concern participated in the symposium. All five degrees of reform by which we classified the comments reflect concern about the harm done to aquatic ecosystems by improper human activities. We reiterate that the degrees of reform refer to comments that may be found in the proceedings of the 1975 Symposium on the Integrity of Water and do not necessarily refer to the experts who made the comments.

Had a similar symposium been convened in 1988 we speculate that comments would again cover the full spectrum sketched above. It is clear that a consensus for deep *reform* has not emerged among the networks of experts: in fact there are currently few spokesmen for deep reform among the kinds of experts that took part in the 1975 symposium. Most such experts seem to be too busy--trying to make necessary incremental improvements or to limit further degradation--to devote any serious attention to the issue of what would be a sufficient program of reform.

INTEGRITY AND SURPRISE IN THE GREAT LAKES BASIN ECOSYSTEM: IMPLICATIONS FOR POLICY

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INTRODUCTION

In this interpretive essay we have sketched our shared sense of the outcome of the discussions of the Policy Working Group at this workshop. We have selected material from the papers submitted by the working group, from informal discussions among participants, and from the arguments in the working group sessions. This is not a set of minutes of what was said in the sessions, nor a complete synthesis of the information and arguments available to the policy group at the workshop, nor an attempt to crystallize the essence of a consensus attained at the workshop. Rather, it is an interpretive essay.

INTEGRITY IN GENERAL

Since 1972 the term integrity has appeared in a number of legal and policy documents related to human activities within some or all parts of the biosphere. Apparently it was first used in this way in the U.S. Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500); subsequently it was used in the Canada-U.S. Great Lakes Water Quality Agreements of 1972 and 1978 and in some international documents on environmental policy. The use of the word integrity for such purposes was stimulated in 1971 by George M. Woodwell (1977) who divulged his motives at the 1975 Symposium on The Integrity of Water convened in Washington, DC by the U.S. Environmental Protection Agency (1977). Woodwell's position was apparently compatible with those of Thomas Jorling (1977), Walter Westman, Peter Jutro, and others who helped to draft U.S. P.L. 92-500.

From their contributions to the 1975 EPA Symposium it was clear that Jorling and Woodwell were advocates of rapid and deep reform of the ways in which humans interact with other parts of the world, or of the relationship between cultural and natural realities within the biosphere. Their views on reform are generally consistent with those of L.K. Caldwell, J.R. Vallentyne, and colleagues, in their call for ecosystemic practices, where the ecosystem involves both the cultural and natural attributes of a region.

At the 1975 EPA Symposium, Woodwell said the following: "And so we are asked now to dissect and define a phrase [to restore and maintain the chemical, physical, and biological integrity of the nation's waters] that should not be dissected. Cur interest is in the preservation of the biota including man. The biota is dependent on the physics and chemistry of the environment and affects both. In this case, all is one and one is all. A dissection is inappropriate."

Jorling, Woodwell, and others emphasized that reform could not be achieved by incremental advances within the dominant utilitarian traditions of the 1960s. Analysis and detailed specification of integrity by the conventions of bureaucracy would serve to defuse and subvert the necessary reforms, as had been done previously with the concept of conservation. People who share this view may agree that it is preferable to have a strongly evocative banner with some ambiguity as to its proximate, practical meaning than to have an objectively insipid recipe that does not address the ultimate intent and implicitly invites the subversion of that intent.

Some reforms have occurred since 1972 in the Great Lakes basin and elsewhere, but we are still far from the integrity evoked by Jorling, Woodwell, and others. In the 1980s the need for such reform was assigned low priority within the federal political agendas of the U.S. and Canada. Rut interest in integrity has continued in nongovernmental circles, and in some state and provincial government agencies.

Like the terms health and wholeness, integrity has been applied to a broad spectrum of phenomena. Usually, if often implicitly, the underlying paradigm is that of a living system, either in a natural sense, or in a cultural sense, or both. If the underlying paradigm is made explicit, then it is usually some version of general systems theory as applied to evolutionary or successional development in benign environments, and to recessional or crippling degradation in malign environments.

Reformers are oftenwary of the tyranny of the paradigm, especially if the paradigm's protagonists seek to be inclusive of both the biotic and nootic aspects of ecosystemic reality. The history of ideological exploitation of a scientific concept has had its tragic episodes, as with the role of social Darwinism in imperialism, capitalism, and Naziism (Pepper 1984; Stein 1988). Totalitarian Nazis made use of a monistic evolutionary principle that encompassed both nature and culture. Could a monistic principle of ecosystemic integrity help to prop up some other ideology? Cur concept of integrity relates to processes of self-organization in turbulent settings, and thus may be generally supportive of pluralistic democratic practices.

Concepts such as adaptability, vigor, balance, and harmony may be used to describe the meanings of integrity, health, or wholeness of living systems, whether natural or cultural. The connotation of integrity that is appropriate here relates to integrated or integral systemic behavior for which descriptions and interpretations that are ostensibly value-free can be developed; it has been suggested that the term integrality be used for this purpose, but we have not done so here.

Concepts such as sustainable, equitable, and enjoyable have been used to characterize the kinds of cultural-natural interactions that are consistent with a goal of overall ecosystemic integrity (Regier et al. 1988). The terms sustainable, equitable, and enjoyable should be interpreted broadly and not just with respect to the immediate interests of extant humans: humans of future generations and nonhuman features of our ecosystems need consideration.

We recognize two polarities or subsystems within the Great Lakes basin ecosystem: the natural and the cultural. These can only be distinguished in a general way; we see no clear boundary between them. Abstractly, the whole system may be viewed as a dynamic self-organizing network in which the human and nonhuman are connected in countless ways. On balance, these two subsystems in and around the Great Lakes are now interacting adversarially rather than mutualistically.

Use of the term integrity in the 1972 U.S. P.L. 92-500 and in the 1972 and 1978 Great Lakes Water Quality Agreements was intended to relate primarily to the interactions between the cultural and the natural, if we understand Jorling, Woodwell, and other reformers correctly. Integrity should be apparent within the cultural subsystem, the natural subsystem, and the whole basin ecosystem.

Jorling's interpretation of integrity is reflected in his sketch of the intent of the 1972 U.S. P.L. 92-500: "The new program...assumes that man is a component of the biosphere and that the relationship we seek to achieve with the environment is what some have called 'harmony'. Under this view, man is an integral, if dominant, part of the structure and function of the biosphere. The intellectual roots of this perspective are found in the study of evolution. The objective of this concept is the maximum patterning of human communities after biogeochemical cycles with a minimum departure from the geological or background rates of change in the biosphere."

For Woodwell, the basic guideline for integrity is sic utere tuo ut alienum non laedas. Use your own property in such a way that you do not damage another's. The concept may be broadened: Interact with an ecosystem in such a way that you do not adversely affect another's legitimate interactions, where the "others" may include present and future humans as well as non-humans. It is a general form of the golden rule. This guideline refers to both cultural and natural subsystems but the linkages remain implicit; i.e. ecosystemic processes act so as to propagate (to other parts of an ecosystem) some of the influences of what one does to some part of the ecosystem. Article IV of the 1909 U.S.-Canada Boundary Waters Treaty may be consistent with this ancient "sic utere...principle" as interpreted in an ecosystemic context. Article Iv includes the statement "boundary waters and waters flowing across the boundary shall not be polluted to the injury of health or property on the other."

Within a general systems context, any human activity has a variety of systemic consequences and everything is connected with everything else, hence the "sic utere...principle" is not fully achievable in practice. This does not necessarily invalidate the ideal, it implies that humans be accountable and responsible for adverse consequences of their actions. Particularly harmful or dangerous practices may be identified as criminal, as with some recent legislation that incorporates a zero discharge principle with respect to certain chemical contaminants.

The principle of fair and reasonable use as applied within international river basins, as in the Helsinki Rules of the International Law Association (1967, 1979, 1982, 1987), may be a weakened version of the "sic utere . ..principle" that does take note of inevitable systemic connections.

A principle of quid pro quo may seem to be more readily compatible with a general systems paradigm. This calls for the adverse consequences of some harmful action to be mitigated or compensated by some beneficial action. The "user-pay principle" is simply a cultural version of guid pro quo. The currently emerging principle of environmental mitigation relates to quid **pro quo** interactions between culture and nature.

These various principles all relate to harmful interactions between the cultural and natural polarities of ecosystems, and to the integrity within the parts and the whole of an ecosystem.

Incidentally, within a system context, we prefer a perception of the Great Lakes basin primarily as a nested mosaic of ecosystems to complement that of a hierarchically structured set of ecosystems. Within a nested mosaic, the lateral connections are as strong if not stronger than vertical connections. The latter are often presupposed to be relatively stronger in a hierarchically structuredmodel. An emphasis on lateral organization within a nested mosaic is consistent with recent developments in landscape ecology and bioregionalism. An overemphasis on hierarchical structure is consistent with the dominant traditions and interests of conventional bureaucracies and large enterprises.

SURPRISE IN GENERAL

As used here, surprise relates to unforeseen events and phenomena. When quite intense surprises occur frequently the circumstances may be denoted as turbulent. Whether an event will register as a surprise may depend heavily on the scale of observation within a nested mosaic or a structured hierarchy (Allen and Starr 1982). Events that can be predicted from study of a large system may be relatively unpredictable from study of only a small subsystem.

A surprising new event of small to moderate intensity may be followed by frequent recurrence of that event. Living systems find some way to accommodate and adapt, at an appropriate scale of integration, to such phenomena, and may eventually evolve to make some beneficial use of what was originally a harmful new series of surprises (Allen and Starr 1982).

As it happens, both the cultural and natural parts of the Great Lakes basin ecosystem have histories that have contributed to the partial pre-adaptation of both subsystems to the kinds of surprises that have occurred here in recent centuries. The natural part of the ecosystem had survived several massive disruptions as a result of geologically recent glaciation. Both the biotic and abiotic aspects of the natural polarity are still in a rather plastic immature stage of landscape evolution. The dominant culture in the basin originates from European lands that had been subjected to a similar glacial history. The culture of Northern

Europe had adapted to those natural features, which were affected in turn by the culture.

In spite of the existence of pre-adaptation, even the most rapid adaptation processes still require many decades to stabilize, with respect to both natural ecological and cultural sociological phenomena of the basin. Where adaptive capabilities are overridden by the frequency and intensity of new harmful events, systemic disintegration and degradation occurs. This has happened throughout the Great Lakes basin as a result of an apparently endless sequence of new surprises generated rapidly within an invading human culture and imposed on the pre-existing nature and culture. By the late nineteenth century these surprises had caused the degradation of much of the rather adaptable endemic nature and culture. Some of the surprises have even overridden the highly adaptive capabilities within the invading culture, as became apparent in the mid-twentieth century when the southern third of the basin could fairly be labelled as the "rust belt" or the "slum belt." Clearly the invading culture has not exhibited integrity within itself and in its interactions with the pre-existing cultural and the natural parts of the basin ecosystem.

Let us here consider three kinds of surprises as they relate to the Great Lakes ecosystem at present, and as they affect current culture and nature.

1) A surprise may occur due to a new or unique concurrence of normal pm-existing factors in the ecosystem and its environs. Because of the number of factors involved in practical cultural and natural situations, it is inconceivable that all possible combinations can be understood. Examples of such surprises include: the record high water levels in the Great Lakes in the mid 1980s and the sinking of the Edmund Fitzgerald in Lake Superior due to a freak storm. Governments and private groups may organize disaster relief for such acts of God, as a kind of generalized contingency strategy. The more that is understood about the behavior of cultural and natural ecosystems, the smaller the domain that is attributed to God and the greater the expectation for informed prudence on the part of individuals or groups of humans.

2) An event may come as a surprise because of some responsible person's unintended or deliberate failure to act according to a code of practice. Though understanding was sufficient to foresee the harmful event, in actuality it was not foreseen: or if foreseen, it was deliberately ignored. Examples include clandestine dumping of toxic wastes, careless

mismanagement of sewage works, and inappropriate use of concrete and steel to control hydrological phenomena at the cost of exacerbating interconnected harmful phenomena. Education, training, codes of professional ethics, and sanctions for malpractice may reduce the incidence of such surprises. Accident insurance, malpractice suits, and emergency response organizations may correct some but not all of the consequences of such failures.

3) A new surprise may be created knowingly or unwittingly within the cultural subsystem. Scientific/technical innovation and application within the military, industry, and commerce lead to uniquely new surprises within culture and nature. In the creation and application of a new phenomenon, a new domain of ignorance is also created: i.e. ignorance as to the consequences of the innovation within culture and nature. Some of the consequences of such an innovation are inevitably unpredictable, and in fact, this is one of the main considerations that motivate innovation. The subsequent disruption within culture and nature caused by the innovation can be exploited by the opportunistic innovator for private or social gain, at least in the short term. The costs of resolving a newly created domain of ignorance are generally externalized to others within the culture, and the costs of adapting to the consequences of the creative surprise are also generally externalized widely within the cultural and natural subsystems. Much of the benefit, both immediate and longer term, flows to the innovators, many of whom had been subsidized by the culture to create such surprises. The kinds of technology assessment currently under development hardly begin to deal with this issue. Examples of such surprises include: construction of ship canals that led to the invasion of the Great lakes by predacious sea lamprey (Petromyzon marinus), wrong-headed introduction of rainbow trout (Oncorhynchus mykiss), rainbow smelt (Osmerus mordax), alewife (Alosa pseudoharengus), and carp (Cyprinus carpio) into these waters by fisheries experts, inadvertent creation of dioxin and its ill-informed disposal on the shores of the Niagara River, and the thoughtless and widespread use of persistent pesticides. It is clear that such creative surprises threaten the integrity of both the natural and cultural subsystems as well as the joint ecosystem.

Surprises of all three types sketched above will continue to occur. Some will likely interact synergistically to exacerbate each other's adverse effects; a few may interact antagonistically to limit adverse effects. Unless special efforts are taken to create appropriate beneficial surprises, few of those currently created by our culture are immediately advantageous to cultural and natural integrity in the basin.

From a perspective of surprise, consider the following:

1) Natural meteorological forces will continue to act erratically when perceived at the scale of ecosystems within the Great Lakes basin.

2) To limit accidents in our more hazardous facilities, such as nuclear power plants, these facilities are gradually being transformed into high-security domains within a strongly hierarchical system of control. Such organizations tend to become semi-autonomous with limited accountability and come to serve their own interests at the risk of reduced safety to others in the ecosystem.

3) Contaminants created by our culture are entering aquifers by leaching from landfill sites and landscapes drenched with acid and toxic rains. Currents within the aquifers are carrying the contaminants into wells and surface springs to be transmitted eventually into surface water and the biota.

4) Some of our local atmospheric abuses have coalesced within the global biosphere, as with global atmospheric change due to radiatively active gases. These global consequences will become apparentwithin the Great Lakes basin, with inevitable surprises.

Currently there is strong political emphasis on untrammelled industrial innovation in the basin. These innovations will serve the imperatives of international competition, perhaps under the flag of free trade. The rapid and coercive dynamics of the international market will likely limit the effectiveness of suchtechnology assessment programs as exist. The overall consequence may be that innovation-driven science married to market-driven technology will create greater ignorance than it dispels, since each creative act brings with it a brand new domain of ignorance.

On balance, the dominant human culture within the Great Lakes basin may still be augmenting harmful turbulence, both within the natural and cultural aspects of the ecosystem. None of the ways in which surprises are generated, as sketched above, is coming under effective cultural control.

FOSTERING INTEGRITY IN AN AGE OF SURPRISE

In this section we sketch some policy considerations that emerged at this workshop.

Anticipate, Prevent, or Adapt

In the Great lakes basin ecosystem, most surprises are unwelcome in that they cause harm to humans and other species, especially to poor humans and to native species. Their ecosystemic influence is generally disintegrative, and sometimes to a disastrous extent. Heretofore, the cultural emphasis has been on attempts to respond reactively after the fact of an unpleasant surprise by intervening in the natural subsystem. Often such a response is limited to technical and engineering interventions to prevent nature from acting out all the consequences attendant on the surprise. Such responses in turn may exacerbate, through natural connections, the adverse consequences of the initial surprise, or predispose the overall ecosystem to new harmful surprises.

The political emphasis should shift to cultural self-regulation. Cultural activities should be such as not to entrain disintegrative consequences in the natural ecosystems. Where this has already occurred, remedial and rehabilitative activities should foster natural reintegrative processes.

With respect to unpleasant surprises that accompany ecosystemic disintegration, a policy of anticipate-and-prevent should focus on anticipating and preventing harmful cultural practices in the first instance. Many natural ecosystemic surprises, or the effects of cultural activities as mediated by the natural system, will not be anticipated even at best, and for these a flexible, adaptive policy should be developed and implemented. The emphasis should shift away from keeping harm away from people, whatever people may do, to keeping people away from harm, whatever nature may do.

Where reintegrative practices are under way, the occurrence of pleasant surprises should be expected and not prevented. But irresponsible exploitation of pleasant surprises should be forestalled because improper exploitationwould again threaten the ecosystem's integrity.

Upstream-Downstream Problems and Jurisdictional Responsibility

The five Great Lakes are large expansions in area and depth of the Great Lakes River, or the Great Laurentian River. The land in the drainage basin, the tributaries, the lakes, the connecting channels, and theoverlying atmosphere are all integral to the basin ecosystem. It is time now to shift from a view of the basin as being dominated by five discrete lakes and four discrete large connecting channels. The Great Laurentian River and its watershed should now become a primary focus of study and management.

In 1958 the International Law Association, IIA, adopted an "agreed principle of international law" which specified that "a system of rivers and lakes in a drainage basin should be treated as an integrated whole (and not piecemeal)" (International Law Association 1967).

Adverse consequences of uses in upstream jurisdictions often cause harm to the legitimate riparian interests in downstream jurisdictions. But interventions at a point in a river may also cause adverse consequences to upstream interests, as in the prevention of the return of migratory fish species by dams. What would constitute fair and equitable use by particular jurisdictions that possess cultural integrity should be specified more clearly.

Accountability and Responsibility of Actor Groups and Individuals

In the Great lakes basin, many users are partially organized, on an interjurisdictional basis, as actor or stakeholder groups. Such groups include fisheries, ship transportation, off-loading of domestic wastes, and hydroelectric power utilities. Each of these actor groups derives benefits from the use of some ecosystemic features, but each also has adverse effects on the ecosystem's integrity. Synergisms are common, especially between adverse consequences of conventional activities by different groups. For each actor group, the major adverse effects should be discovered, documented, and monitored. To ensure ecosystem integrity, each group should be induced to acknowledge and accept responsibility for such adverse effects. Each should also be credited with any beneficial ecosystemic effects that follow from its activities.

The stress-response approach, as developed for Great Lakes ecosystems at different scales, offers an open and effective way of accounting for harmful and beneficial consequences of actor group activities. In effect, it provides a level playing field for those professionals who, intentionally or not, serve different stakeholders or actor groups. The stress-response approach is centered on concepts of natural and cultural integrity; it should now be extended to encompass the entire Great Laurentian River and its basin.

Natural-cultural ecosystems are complex, hence the acts of one individual will influence the welfare of other individuals, and frequently in ways that are not immediately apparent. When a large area becomes degraded due to some environmental use or abuse, the interests of many people who do not benefit directly from the use/abuse may be harmed. In some jurisdictions the individuals may not have standing in a court to sue those responsible for the degradation. To have standing in such a jurisdiction, an individual must demonstrate that the harm done to her/him is separate and distinct from that done to the rest of the community. Only an appropriate governmental official can start such an action on behalf of the community, but the official need not necessarily do so. Increasingly, such a legal convention and other aspects related to it are understood to imply a gap in the overall legal system in that it does not reflect ecosystemic realities and thus diminishes integrality. The convention also serves to perpetuate some injustices and hence diminishes cultural integrity.

Some jurisdictions (e.g., Michigan) have accepted an environmental bill of rights to rectify these deficiencies. Such a bill of rights and supportive legislation should include provision for standing in a particular jurisdiction's courts to individuals of other jurisdictions who believe that they have suffered harm as a result of environmental abuse that originates within the particular jurisdiction. Clearly such initiatives are consistent with the moral or cultural concept of integrity at the level of the individual user and abuser of the natural features of an ecosystem, and of the individual who suffers harm from such use or abuse.

Governance

Integrity in the Great Laurentian River basin, whether cultural or natural, **cannot be assured simply through the** intervention by the federal governments in Washington and Ottawa. Each level of government, from federal to local, has its own role to play with issues and phenomena of the relevant spatial and temporal scales. The increased interjurisdictional involvement of governmental entities below the federal is to be welcomed and fostered. A particular level of government should not seek to devolve responsibilities primarily as a way of cutting budgets. A government's objectives should be specified explicitly so that progress can be evaluated and accountability is directly assessable.

Inter-jurisdictional commissions and boards are usually invested with some autonomy and empowered to innovate with respect to policy on the condition that effective cooperation continue between the interjurisdictional bodies and the sovereign jurisdictions. Occasionally, inter-jurisdictional bodies forge ahead and lose effective connections with jurisdictions. Occasionally, inter-jurisdictional bodies engage in little more than pro forma activities because the members see their roles as unempowered delegates of the jurisdictions, as apologists for governmental inaction, or as a rear guard to cover the withdrawal of a government's political will. The overall integrity of the inter-jurisdictional governance system is threatened where such extreme behaviors are manifested.

In the transjurisdictional Great Lakes basin much consensus- building is now occurring within an informal general network of more specialized networks. Both the general and some special networks are fostered within the extended organizational families of the International Joint Commission, the Great lakes Fishery Commission, and the Great lakes Commission. Other networks are created by actor groups or sectoral interests (Francis 1986), by Great lakes United as a federation of activist environmental groups, and by the Center for the Great Lakes as a policy-related organization. Integrationwithin the overall network occurs mainly through the participation by numerous individuals in more than one special network and in the less structured general network. Ecosystem stewards, with strong commitment to ecological and cultural integrity, are becoming more active in the overall network (Lerner 1986).

cultural Development

Conventional exploitative development in the Greatlakes basin has been driven by the progress ethic (Pepper 1984) in which overall ecosystemic integrity has often been compromised or sacrificed. New enterprises are encouraged, often with governmental subsidies. As indicated above, they generally entrain some disintegrative consequences to the cultural and natural fabric of the ecosystem, but these adverse impacts are frequently ignored in the interests of progress. Much of the disintegrative impact is externalized to others in the ecosystem, usually to the social groups and natural associations that are already disadvantaged and vulnerable due to adverse consequences of previous enterprises.

The process of cultural development should be reformed so that harm to others (humans and other species) would be prevented by internalizing within the developmental enterprise the responsibility for preventing such harm, and for compensating others for any harm done. The interests of the poor, who have been disadvantaged by previous progress, should receive preferential treatment. This should be an acid test.

Institutional mechanisms are required that reward behavior that promotes ecosystem integrity (e.g., tax incentives and transferable use rights). Government practices that penalize stewardship activities, such as taxing a preserved wetland on a farm as though it were cropland, should be discontinued. There should also be disincentives, including the formal designation of actions that degrade protected features of ecosystems as criminal.

A "principle of net gain in ecosystemic integrity" should be applied to new developmental initiatives. This implies anticipation and prevention of harmful cultural surprises, but goes beyond it.

Balanced Research

The conventional piecemeal approach to economic development and to the protection, partial at best, of the natural environment and renewable resources is served by a tradition in science that is predominantly reductionistic, analytic, specialized, and universalistic. It is conventional reductionistic science that leads to insights that are the basis for new technological creations which engender a new domain of ignorance, as argued above. Though this scientific tradition can and will continue to help dispel ignorance and provide useful insight, it should be de-emphasized in favor of systemic, comprehensive, reflective, transdisciplinary, and contextual research. The latter is more directly relevant to issues of integrity and surprise than the former.

State of the Basin Ecosystem

Much of the Great lakes basin, and especially the southern third of the basin, is now slowly recovering from a seriously degraded state, with respect to both natural and cultural attributes. General progress in this recovery should be monitored and reported periodically. For this purpose, measures of the state of ecosystemic integrity and of the occurrence of degrading forces and surprises are needed. Numerous types of measures are already being used for this purpose, though the set is not fully coherent and not sufficient for our purposes. Several initiatives are now timely.

The 1987 Protocol to the 1978 Great lakes Water Quality Agreement selected the lake trout (Salvelinus namaycush) as an integrative indicator or representative important species for oligotrophic Lake Superior. The walleye (Stizostedion vitreum) and yellow perch (Perca flavescens) provide a basis for a proposed measure of integrity for mesotrophic ecosystems in the basin. The black basses (Micropterus spp.) may be used as indicators for nearshore waters and the introduced Pacific salmon (Oncorhynchus spp.) for somewhat enriched offshore waters. All major limnological types of waters in the lakes and connecting channels should be monitored with the use of particularly relevant integrative indicators.

Semi-isolated small nearshore ecosystems should be selected to serve as microcosms for monitoring the ecosystemic integrity of the entire basin. Such ecosystems should include the degraded areas of concern, some of which are beginning to recover and to reintegrate into their contiguous lakes with the help of degraded area remedial action plans. Most importantly, some relatively pristine heritage areas that still exhibit high ecosystemic integrity should also be selected, preserved, and monitored with the formulation and implementation of site-specific heritage area security plans. Site-specific measures of species diversity and locale-specific measures of mosaic diversity are useful for this purpose.

A concept of a land-river-lake-sea continuum has been developed in which ecosystem dynamics and structure are the focus of attention (Steedman and Regier 1987). Integrative processes that compensate for, and even exploit, various kinds of turbulence are explicated. It is now timely that this concept be adapted to the entire Great Laurentian basin. Appropriate measures of river basin integrity may be related directly to this continuum concept.

The marketplace

The market serves society well only if its role is limited to issues that are not of primary importance. Politicians who become frustrated by the democratic legislative process may seek to delegate important decisions to the marketplace. This may lead to a gross subversion of societal interests, as on ecosystemic issues.

Individuals that serve strong economic interests in the marketplace call for the political process to set the reform agenda. Policy constraints to be placed on the market mechanism relate to important values shared within society. With clearly formulated constraints consistent with reform and a level playing field the market would adapt and continue to serve a useful role. But many of the market-oriented individuals also support the merging of regional and national markets into a global market, primarily to serve the individuals' vested economic interests. With the emergence of a world market, effective constraints (i.e. reform policies) would have to be introduced simultaneously on a global basis, or the world market process could override reform policies in individual countries.

Powerful politicians and economic leaders who ostensibly support both ecosystemic integrity and the global market mechanism are likely to support creation of new parks in a relatively worthless hinterland and implicitly support greater ecosystemic disintegration in and near the worthful heartland. This one-sided policy of long standing is biased against ecosystemic values, of course, and lacks cultural integrity.

Back to Beginnings

The U.S. National Environmental Policy Act of 1969 (P.L. 91-190) as amended (see Caldwell 1982) lists its purposes as: to encourage productive and enjoyable harmony between man and his environment; to prevent or eliminate damage to the environment and biosphere: and to stimulate the health and welfare of man. These purposes are interpreted further in Title 1, the Declaration of National Environmental Policy:

1) fulfill the responsibilities of each generation as trustee of the environment for succeeding generations;

2) assure for all Americans safe, healthful, productive, and aesthetically and culturally pleasing surroundings;

3) attain the widest range of beneficial uses of the environment without degradation, risk to health or safety, or other undesirable and unintended consequences;

4) preserve important historic, cultural, and natural aspects of our national heritage, andmaintain, wherever possible, an environment which supports diversity, and variety of individual choice:

5) achieve a balance between population and resource use which will permit high standards of living and a wide sharing of life's amenities; and

6) enhance the quality of renewable resources and approach the maximum attainable recycling of depletable resources.

If we now consider again the U.S. Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500), we may infer that the term integrity in fact, must encompass the six items listed above. Persons like T. Jorling and G.M. Woodwell implicitly invested the word integrity with strong interpretations of the six items. By 1975, the officials in the relevant federal agency createdby P.L. 91-190, the U.S. Environmental Protection Agency, had invested the word integrity with quite weak interpretations. In this they were supported by researchers expert on regulation and by experts serving polluting interests. Such a process of trimming the commitments to fit the capabilities of conventional experts and the willingness of polluters to cooperate was of course to be expected--it was ever thus! Fortunately new expertise has been developing gradually and collaboration by polluters has grown so that a renewed interest in the commitments of the 1969 and 1972 U.S. Acts may be timely.

The contents of the 1987 Protocol to the 1978 Great Lakes Water Quality Agreement (International Joint Commission 1988) provide encouragement. Annex 2, on Remedial Action Plans and Lakewide Management Plans, states that:

> Impairment of beneficial use(s) means a change in the chemical, physical, or biological integrity of the Great Lakes System sufficient to cause any of the following:
>
> (i) Restrictions on fish and wildlife consumption;
> (ii) Tainting of fish and wildlife flavor:
> (iii) Degradation of fish and wildlife populations:
> (iv) Fish tumors or other deformities;
> (v) Bird or animal deformities or reproduction problems;
> (vi) Degradation of benthos;
> (vii) Restrictions on dredging activities;
> (viii) Eutrophication or undesirable algae;
> (ix) Restrictions on drinking water consumption, or taste and odor problems:
> (x) Beach closings;

(xi) Degradation of aesthetics:
(xii) Added costs to agriculture or industry:
(xiii) Degradation of phytoplankton and zooplankton populations: and
(xiv) Loss of fish and wildlife habitat.

Altogether, a good rebeginning!

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VALUES IN INTEGRITY

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ABSTRACT. On one level, integrity is best characterized as a symbolic word for the culturally valued qualities of honesty, consistency, reliability, truthfulness, and autonomy. When we speak of ecosystem integrity, the need for explication of the term integrity is obvious as is the usefulness of placing its various meanings in a values context. Values enter directly into decisions about whether to preserve and remediate specific environments (including ecosystems) and what, exactly, should be done. These decisions are made by people each of whom has a set of values which come into play when choices must be made about allocation of resources. This paper examines the ambiguities of the meanings of integrity, the latitude for disagreement among actors as to the correct meaning, and the central role of actor's values and interests in decision-making processes about preservation and remediation in the Great Lakes basin. It is suggested that large-system models which ignore the actor/value dimension will not deal effectively with how to plan for or react to surprise.

INTRODUCTION

As Rafal Serafin has noted in these proceedings, there are many ways in which integrity might be defined, and no one of them is right. On one level, integrity is best characterized as a symbolic word for the culturally valued qualities of honesty, consistency, reliability, truthfulness, and autonomy. But these are qualities most commonly associated with humans or, in some cases, human organizations. When we speak of "...the need to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes basin ecosystem," where ecosystem is defined as "...the interacting components of air, land, water, and living organisms, including humans...," the need for some explication of the term integrity is obvious, as is the usefulness of placing the discussion in a values context.

In attempting to reach consensus on a compelling, heuristic operational definition for the term integrity as it is used in the Great Lakes Water Quality Agreements, it is useful initially to explore rather freely a number of possible meanings of the term, since the values inherent in standard definitions of integrity and related terms are complex and provocatively dissonant in several ways. This paper is intended as a stimulus to such exploration.

VIRGIN MOTHERS AND OTHER PUZZLES

From the Latin integritas we have the meanings "whole, entire, complete" as well as "chaste, pure, untouched." We also have "unmarred, sound, unimpaired," and "in entire correspondence with an original condition." One additional meaning has a specifically human referent: "an uncompromising adherence to a code of moral, artistic, or other values."

These nuances of meaning suggest several considerations in selecting a useful interpretation of integrity, one of which was voiced somewhat plaintively by a Kimberly-Clark executive who spoke on industry's view of the integrity of water at the 1975 EPA symposium on that topic.[1] Said he: "First of all, then, it might be well to point out that 'integrity' does not necessarily mean 'virginity.' These two words may have the same meaning in a specific instance, but they are not synonymous...." His point, of course, was that we can and should be satisfied with some conditions of water(s) that do not preclude human intrusion, and it directs attention to an interesting core of tension in our attitudes towards nature that centers on two images of nature as female--Mother Nature and Virgin Nature. Mother Nature is life-giving, warm, open, generous, productive, the unending source of good things to meet all human needs. Virgin Nature is pristine, untouched, unsullied, unspoiled, to be protected and revered. While basic Christian dogma offers, in the Virgin Mother, a happy combination of these two images, in western culture generally, these two contrasting images of female nature generate fundamental value conflicts about what nature is for and how natural systems should be treated. A common thread that runs through ecofeminist writings, for example, is the claim that the domination of women and the domination of nature are intimately connected and mutually reinforcing.[2]

By traditional definition, and in the majority of cultures today, women are viewed as unproductive unless and until they produce children and men as not fully mature until they father those children. Thus, outside of imagination, there are no virgin mothers, only former virgins who--under circumstances involving seduction, desire, conquest, artificial insemination, and a variety of other interventions that we describe in many ways, cease to be untouched, pristine, immaculate virgins, and become nurturing mothers.

Without pushing the point further, it seems clear that viewing nature as essentially female, and females as somehow closer to nature--and, paradoxically, equally desirable in both the pristine and the fully productive states--raises some interesting questions about definitions of integrity. By requiring integrity of Great Lakes waters, do we wish to insist on a return to some original, pristine, unsullied state (say, even a relatively known state such as that before the arrival of Europeans)? Could the waters of the Great Lakes basin ecosystem ever return to such a condition? If we say "no" on both counts, then we face the real question, which is: "How can we promote respectful, beneficial, human participation in ecosystem functioning?"

Ecofeminists argue that there can be little improvement in the way humans treat natural systems until there is a profound change in male-female relations, away from patriarchal domination and denigration of women, toward egalitarian relations of mutual respect and nurturing. This may well be; domination and exploitation are not easily unlearned or put aside. Rut it is challenging to attempt to envision and plan for social, political, and value changes in ecosystem-human interaction that would not have to wait in line until a complete revolution occurs in the relations between the sexes.

WHAT COLOR IS A CHAMELEON?

If we define integrity as wholeness, entireness, completeness and then attempt to make this term in the form of normative criteria for restoring and maintaining the waters of the Great Lakes basin ecosystem, we face an interesting problem of determining what constitutes wholeness for this system. Are we discussing characteristics, qualities, or abilities of the system? A variety of answers are given in these proceedings: "The integrity of the system comes from its ability to incorporate what have been disturbances into its normal working" (T.F.H. Allen). "Integrity refers to a rich set of behaviors..." (J.J. Kay). "Harmonic communities of fishes and associated organisms with their internal species linkages, serve admirably in the role of indicators of integrity for aquatic ecosystems" (R.A. Ryder and S.R. Kerr). "Integrity comprises elements of wholeness, self-organization, attractiveness, productiveness, diversity, and sustainability" (R. Steedman and H.A. Regier). "The system integrity, as well as the complementary capacity to adapt to perturbation, can both be assessed from its network of material or energetic exchanges using information theory" (R.E. Ulanowicz). "Integrity implies a state of being complete, sound, or whole. Like health, it can only be analyzed through its absence" (E. Cowan, J.R. Vallentyne, and T. Muir).

The problem, then, is that we have no certifiably correct blueprint of how the ecosystem might look or behave in a whole, complete state. This is a similar problem to that encountered if we attempt to develop criteria based on the meaning of integrity related to what can be termed own-selfness--the idea that a system (or individual) has a certain potential that it can fulfill if allowed to develop, i.e. to self-actualize, in an optimal environment without interference. Rut what the recognizable general characteristics of a self-actualized system or individual would be is open to debate and would undoubtedly vary from case to case.

FREE LUNCH IS OVER

It seems clear that whatever definition of integrity is arrived at with reference to the Great Lakes basin ecosystem, some people will have to cease, or stringently curtail, certain activities that interfere with its natural functioning. Natural functioning (whether we decide it's ceasing, curtailing, or minimizing human interventions) could also arguably serve to reduce the likelihood of system flips that produce unpleasant surprises. To this end, decision-making processes about how humans are permitted to function as a component of the basin ecosystem must be made more transparent and brought firmly under societal (public) control. It must be required that the values and objectives of the system actors (stakeholders) are made explicit, together with the implications for the future sustainable functioning of the basin ecosystem. This is important because of the specific activities that flow from these values and objectives. When processes are in place that mandate such explication, then choice about what activities to pursue in the Great Lakes basin can be examined in an interests framework that highlights social, environmental, and equity impacts together with options and alternatives.

A tragedy of the commons[3] occurs only when it is allowed to occur. The operative values in such a case are unlimited individual or interest-group gain, unbridled competition, and willful ignorance of long-term consequences. If we are to create the fundamental value shift and resultant political will to unconditionally proscribe behaviors that irreversibly impair and degrade natural systems, we require nothing less than a basic reconceptualization and revaluing of earth (or our basin) as something held in common, for its own sake as well as for the benefit of all, now and in the future. Only broadly based political will, implemented through fundamentally changed decision-making processes, can effect the restoration and maintenance of the sound, sustainable functioning of the basin ecosystem.

HEALTH IS WEALTH

With the above considerations in mind, particularly the need to generate the political will to bring about fundamental changes in established institutions, health (derived from a word meaning soundness) would seem to be the most useful definition of integrity. This would allow us to focus on ecosystem health in developing normative criteria for the future of the waters of the Great Lakes basin ecosystem and this would have several distinct advantages. We have a tradition of assessing and dealing with human health concerns and are beginning tentatively to move toward a more holistic vision of health as wellness rather than as only the absence of disease. We have developed criteria and indicators for monitoring human health and could potentially extrapolate some of these to ecosystem functioning.

An additional argument for equating the concept of integrity (as used in the Agreements) with health is that there is very little disagreement (value conflict) about whether health is good. Who is against health? Indeed, who is even against optimum health? A similar advantage is that a focus on maintaining and restoring the health of the Great Lakes basin ecosystem centers public attention on the existing and potential connections between the health of biota in the lakes, especially that of preferred fish species, and human health. And certainly a broad and concerned awareness of the state of the lakes as an early warning system with regard to human well-being cannot but contribute to increased interest in ensuring that Great bakes ecosystem health is restored and maintained.

Using the concept of holistic health as the touchstone in developing normative criteria for Great Lakes basin ecosystem functioning might also strengthen the existing movement toward citizen stewardship and co-management of the basin. Contemporary human health care offers alternatives to the illness-centered, physician-dominated field that remains the dominant paradigm. People have become increasingly aware that their health encompasses a general sense of wellness/soundness and that they themselves have the responsibility and the knowledge to promote this through exercise, diet, abstaining from self-pollution, and vigilance with regard to environmental pollution. Thus, people are increasingly accustomed to valuing their health in a positive sense, to welcome taking some control over it, and to understand the role of prevention in maintaining good health.

Similarly, it is not unrealistic to expect that these same people would be able to:

a) understand the concept of ecosystem health;

b) contribute their own ideas and preferences as to what constitutes such health:

c) provide a growing political constituency for firm societal action in defense of the basin ecosystem, and, most important:

d) welcome opportunities to take measures in their own communities to ensure the health of their own part of the basin.

In summary, with regard to a choice of meaning for integrity, I have suggested that ecosystem health (the exact parameters of which are still to be determined and operationally defined, of course) may be the most unambiguous, most generally understandable, least contentious and, thus, the most desirable from a values point of view. In short, I submit that integrity is customarily and most usefully conceived as a positively valued, intentional human behavior pattern that should be promoted in human interaction with natural and social systems so as to provide consistent nurturing and concern for ecosystem health.

POSTSCRIPT

In a recent provocative article, [5] Barry Commoner argues that the environmental movement has little to be pleased about and that the optimism of many is based on a few relatively modest achievements between 1970 and the present:

> . ..[this optimism] does not necessarily respond to the original thrust of the environmental movement which envisioned not an environment that was a little less polluted than it was in 1970, or holding its own against an expanding economy, but an environment free of mindless assaults on ecological processes. By this standard, the question is whether the movement's goal can be reached by the present spotty, gradual, and now diminishing course

> of environmental improvement or whether some different course must be followed.

Commoner argues that there must be an end to compromise. Why should we settle for anything less than nondestructive technologies and resource utilization? Natural systems such as the Great Lakes basin ecosystem are societal resources, societal capital, societal commons. Commoner again:

> Logically... the decisions that determine the choice of production technology ought to be governed by the constraints inherent in nature. But, in fact, the actual direction of governance is reversed....
>
> So, the environmentalist who wishes to grapple with this illogical arrangement needs to turn from the fairly rigid but harmonious pattern of nature to the more flexible but chaotic realm of human decisions. And this realm necessarily includes not only the choice of production technologies but also the closely related economic decisions.
>
> Perhaps the most profound question raised by environmental issues is to what extent the choice of production technologies should be determined by private economic considerations and to what extent by social concerns like environmental quality. These values are in sharp conflict.

And so they are. To be aware of that value conflict is essential to the development of normative objectives for Great Lakes basin ecosystem functioning that are open to input from all stakeholders, that are uncompromising as to goals but amenable to some flexibility in the governance of their implementation, and that capture the imagination and mobilize the energy of the broadest possible constituency in the basin.

ACKNOWLEDGMENTS

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NOTES

1. U.S. Environmental Protection Agency. 1977. The integrity of water: proceedings of a symposium, March 10-12, 1975, Washington, DC.

2. For a recent overview of ecofeminist thought, see Michael E. Zimmerman. Feminism, deep ecology, and environmental ethics. Environmental Ethics 9(1): 21-40, 1987.

3. For the classic discussion of the tragedy of the commons, see Garrett Hardin. The tragedy of the commons. Science 162: 1243-1248; 1968.

4. The term integrality has been suggested as one that might properly be applied to a natural system. It would, however, still be relatively unfamiliar and puzzling to most people.

5. Barry Commoner. A reporter at large: the environment. The New Yorker, June 15, 1987, 46-71.

REHABILITATING GREAT LAKES INTEGRITY IN TIMES OF SURPRISE

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ABSTRACT. The directive of the 1978 Great Lakes Water Quality Agreement (GLWQA), "...to restore and maintain the. ..integrity of the Great Lakes basin ecosystem," can be interpreted in different ways. This is because the concept of integrity as yet lacks a useful and widely accepted meaning. This paper introduces the concept of integrity as a moral imperative for human conduct. Two scientific approaches that endeavor to interpret the concept of ecosystem integrity in operational terms are compared and contrasted. Attention is drawn to the fact that attempts to implement a concept such as integrity are inextricably immersed in trends of cultural change. Different perspectives on integrity suggest a different mix of rehabilitation activities for the degraded Great Lakes ecosystems. What is perceived as sufficient in terms of one interpretation of integrity may be insufficient in terms of another. I discuss some implications of this for remedial action planning in Hamilton Harbour on Lake Ontario.

GREAT LAKES REHABILITATION AND INTEGRITY

Prompted by U.S. legislation, the purpose of the 1978 Great Lakes Water Quality Agreement (GIWQA) between Canada and the United States became "...to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes basin ecosystem." Interestingly, although definitions of 24 terms used in the Agreement are provided in Article I, integrity is not among them.'

In 1985, the International Joint Commission (IJC) designated 42 areas of concern around the Great Lakes. Each of these areas was considered to be badly degraded and in need of remedial action. The presence of any of 14 undesirable conditions indicates "impairment of beneficial uses" and so defines an area of concern. The 14 conditions are listed in a recently signed amending protocol to the GLWQA. They included presence of fish tumors or other deformities, degradation of benthos, beach closings, restrictions on dredging activities, and added costs to industry and agriculture.[2]

The GLWQA requires that a remedial action plan (RAP) be developed and implemented by relevant agencies in each of these areas of concern. Some of these plans have now been completed while others are still being prepared. Each RAP is supposed to focus and guide human efforts to get rid of the unwanted conditions in an area of concern, restore beneficial uses, and so meet the goal of "restoring and maintaining... integrity of the Great Lakes basin" as demandedby the GLWQA.

Hitherto, definitions of ecosystem integrity have provoked an uneasy feeling of incompleteness. Consequently, attention has shifted instead to the objective of restoring beneficial uses. In part, this situation may have arisen because integrity means different things to different people when translated from a conceptual to an operational context as in the case of remedial action planning.

INTERPRETATION OF INTEGRITY

My aim in this paper is to expose and clarify the moral nature of the concept of integrity and to discuss two operational interpretations of integrity that are common among those studying, managing, using, and living in Great Lakes ecosystems. These are

1) integrity as an intrinsic attribute of nature independent of humans, and

2) integrity as a latent attribute of nature.

The first of these interpretations stems from the conventional study of the ecological sciences, which does not address explicitly the role of humans in nature. The central feature of the second interpretation of integrity is the consideration of ecological changes in relation to human-induced stresses.

This leads me to discuss how a concept such as integrity can come to be abused and brought to serve the interests of dominant social, political, and economic forces of society. I will bring together and summarize the various threads of my essay by discussing the practical implications of different interpretations of integrity in relation to remedial action planning in Hamilton Harbour.

There are probably many other interpretations of integrity and many variations of the ones I sketch here. My intent is not to provide an inventory of possible definitions in order to argue for one best definition. Instead, I hope to show how different views of integrity suggest different operational activities for restoring and maintaining ecosystem integrity. All of these views stem from the wording of the GLWQA. My point throughout is not that one perspective might be more useful than the others. Rather, it is to illustrate the practical importance of embracing many different and often changing perspectives of integrity as an integral part of ongoing efforts to rehabilitate degraded ecosystems of the Great Lakes such as the Hamilton Harbour ecosystem.

In the Great bakes basin, the term rehabilitation has been used to describe the pragmatic human activities involved in remedial action planning. Rehabilitation, as practiced around the Great Lakes, embraces attempts

1) to identify, reduce, and discontinue abuses that have led to undesirable environmental conditions (remediation);

2) to foster natural productive processes (restoration); and

3) if desirable, to intervene directly with corrective measures to accelerate and/or to render more complete an alteration of the ecosystem to some more desirable state (redevelopment).[3]

INTEGRITY AS MORAL IMPERATIVE

The concept of integrity as conventionally used is applied to describe the moral standing of human beings. To have integrity is to be dependable, responsible, and whole, with a clear sense of what behavior is good and what is not. In this way, integrity is linked to moral autonomy and refers clearly to questions of moral good.[4]

With this in mind, Arthur Morgan argued that each person should try to attain personal integrity in order to achieve good living. By this he referred to the

> . ..building of great character, the defining and clarifying of purposes and motives, the development of integrity and open dealing, the increase of self-discipline, the tempering of body and spirit to endure hardship, the growth of courage, the practice of tolerance, the habit of acting for the general good, and the growth of understanding and of neighborly affection and regard.[5]

When applied to nature, the concept of integrity also describes not just what is good and bad about different kinds of human behavior, but also implies what is good and what is not good about different states of nature. For some, what is good about nature is intrinsic to nature and contained within it independent of humans. For others, what is good is latent within nature and only recognizable and meaningful in terms of perceptions, attitudes, and beliefs of human observers. I will discuss these two interpretations of integrity in the next two sections.

The use of nature as a moral imperative for guiding human action has a long tradition. One of the more eloquent protagonists in recent times was the ecologist Aldo Leopold. He was concerned with the difference between those human activities that lead to the breakdown of ecological systems and those that do not. Thus, he did not object to human alterations of nature per se, but recommended that the alterations be accomplished with less violence and rapidity.[6] Thus, he argued:

> Civilization is not. ..the enslavement of a stable and constant earth. It is a state of mutual and interdependent cooperation between human animals, other animals, plants and soils which may be disrupted by the failure of any of them. Land despoliation has evicted nations and can on occasion do it again.... It thus becomes a matter of some importance, at least to ourselves, that our dominion, once again, be self-perpetuating, rather than self-destructive.[7]

Leopold advocated a human use of nature which was compatible with the functioning of ecological systems. This notion lay at the heart of his land ethic, which is embodied in the modem ecosystem concept. Thus, he resolved that, granting that the earth is for man--there is still a question: What man?" He insisted that human culture must be, "...decently respectful of its own and all other life, capable of inhabiting the earth without defiling it."[8]

According to this perspective, humans are inextricably linked to nature and, hence, accountable to nature for their actions. This reasoning has led many to suggest that if we do harm to the rest of nature, we are then harming ourselves. Thus, for many, ascribing the term integrity to ecosystems is tantamount to offering a moral guide for human conduct with respect to nature.[9]

In the two sections that follow, I will describe briefly two approaches which have been used to give operational meaning to the concept of integrity. The first rests on the supposition that integrity in nature is independent of humans. The second argues that integrity is only a latent feature of nature which comes to be recognized when humans intervene in nature.

INTEGRITY AS INTRINSIC PROPERTY OF NATURE INDEPENDENT OF HUMANS

Nature is very complicated. Everything appears to be happening at once, and each part seems affected to some degree by all the others. The science of ecology represents a systematic attempt to make sense of what is going on, and of the implications of human interference. The ecosystem concept has been central to these efforts. It refers to the myriad of interactions taking place among a community of living things and their physical environment within some geographic space.

The ecosystem is the level of organization concerned with orderly, not chaotic, processing of energy and matter in the biosphere, which enables life to persist. In this way, the ecosystem focuses attention primarily on structural and functional properties of organization among living things and their environment in any geographically defined part of nature. This has led to the proposition that, when viewed together, the myriad of interrelationships between living and nonliving parts displays predictable, cybernetic properties not evident in any one of the constituent parts." The levels at which such properties emerge or become apparent have been called levels of integration."

In his outline of general systems theory, Ludwig von Bertalanffy was one of the first to consider the world as

> . ..a tremendous hierarchical order of organized entities, leading in a superposition of many levels from physical and chemical to biological and sociological systems. Unity of science is granted not by Utopian reduction of all sciences to physics and chemistry but by the structural uniformities of the different levels of reality."

Von Bertalanffy saw biological systems as open, and so sharing properties common to all open systems. Thus, according to von bertalanffy, in contrast to closed systems which must attain an equilibrium, open systems may attain time-independent states where the system remains constant as whole and in its phases through a continuous flow of materials. This steady state requires energy to be maintained and undergoes a maturing or development toward greater integration, less temporal variability in key features, and greater adaptive capabilities to common external influences, but less adaptive capability to unusual large ones.[13]

Eugene Odum, among others, has adapted von Bertalanffy's ideas to the study of ecosystems by identifying a set of functional features common to all ecosystems. He has identified 24 such attributes which include indicators of community energetics, community structure, life history, nutrient cycling, selection pressure, and overall homeostasis. Inspired also by the notion of succession introduced by Clements in 1916, Odum recognized that these organizational indicators change in an ordered way over time as unbalanced, unstable assemblages of organisms transform to stable self-organizing communities.[14]

Theoretical ecology has been preoccupied with investigating the organizational properties of ecosystems: how these manifest themselves in structural form in time and space, and how humans interfere with them deliberately and inadvertently. Debates have focused on diversity, persistence, complexity, stability, and resilience over time and space. These were prompted in part by advances in computer modeling and in part by the emergence of systems outside of ecology.

The term integrity has seldom featured in the debates of theoretical ecology. Nonetheless, when used, the term has invoked much of the debate which has taken place. Thus, integrity has the connotation of unimpaired, functional, homeostatic mechanisms of ecosystems. This brings to mind a wholesome, untainted ability of nature for self-organization, which in turn enables self-regulation, renewal, and so, survival. According to Rapport, such autogenic attributes of systems can be characterized by three features:

1) an ability to self-regulate,

2) constancy through change, and

3) persistence of a distinct identity.[16]

Integrity seems to refer to a coherent identity in place and time that persists in spite of external inducements to change. The biogeographical notion of ecosystems is consistent with this functional one. Viewing ecosystems as unique identities in space that persist through time is central to the biogeographical perspective and is shared by many cultures. Thus, there are the English terms carr, moss, fen,' and heath. Each has a precise meaning in terms of kind of plants, habitat factors, and resulting landscapes. Similarly, there are Siberian terms, tundra and taiga, the Spanish chaparral and tomillares, the French maquis and garrigue, Yugoslavian shibliak, Greek phrygana, Brazilian cerrado and caatinga, and Andean paramo and pampas.

In sum then, an ecosystem possesses integrity if its mechanisms of competition and natural selection are functioning, and if it is maturing according to some characteristic interplay of abiotic and biotic processes. Conventionally, species diversity has been regarded among ecologists as an important indicator of the state of an ecosystem's cybernetic properties.

Recently, Henry Regier, David Rapport, and Tom Hutchinson have drawn attention to the consequences of human activities for the functional features of ecosystems. They observed that ecosystems undergo similar sequences of functional response when subjected to a variety of human-induced stresses. These include a reduction in size of dominant species, increased loss of nutrients, unbalancing of the productivity-respiration ratio, reduction of species diversity, and increases in opportunistic short-lived life forms. Taken together, such features represent reduction in an ecosystem's ability to organize and perpetuate itself, which in turn leads to loss of identity. Such retrogression toward disorder and chaos, which may resemble earlier successional stages of ecosystem development, at least superficially, has been called ecosystem distress syndrome. Regier has emphasized that the observed rejuvenescence in stressed ecosystems often represents a crippling impairment of ecosystem structure and function from which autonomous recovery to a normal state may be difficult or impossible.[18]

Many ecologists appear convinced that ecosystems possess intrinsic properties of self-organization. They contend these exist outside and beyond human values. Therefore, they argue, integrity can be studied objectively and quantitatively. For Ulanowicz, for example, integrity is the coherence that emerges from a myriad of complex feedback interrelationships among the various components of an ecosystem[19] (see also these proceedings). Humans are treated as irrelevant unless they distort and disrupt the structure and function of an ecosystem through stress or disturbance.= This view has prompted a great deal of applied study aiming to illuminate how ecosystems degrade and to assess what corrective technical measures can be taken to halt and reverse such undesired trends.[21]

INTEGRITY AS A LATENT PROPERTY OF NATURE

An extended view of integrity is that of a latent feature of the complexity of nature that is only revealed through interaction with observers or users. Just as in baseball, where some pitches are balls and some are strikes, "they ain't nothing" until the umpire calls them. In this sense, integrity cannot be thought of as an intrinsic property of nature because it manifests itself only through some process of human observation, measurement, or manipulation.[22]

More accurately then, integrity is a feature of the interaction of nature with humans. All human attempts to understand and intervene in nature are rooted in abstractions or models. As such, they represent simplifications of a reality external to each of us. This rests on a desire to obtain an equivalent, but reduced, representation of nature. Thus, for example, some aspects are omitted, others aggregated, weak couplings are ignored, and slowly changing features are treated as constant. Features of complex systems such as integrity are irreducible, and attempts to simplify thus lead to a loss of aspects essential to the understanding of ecosystem integrity. This has important implications for human attempts to restore and maintain integrity of ecosystems.

Any attempt to protect ecosystem integrity should rest, therefore, on the explicit recognition that it originates from a two-way interaction of an ecosystem with a human system of observers, managers, and users.[23]

In this spirit, C.S. Holling has suggested that the Great Lakes comprise three interacting subsystems:

1) the set of biological, physical, and chemical interactions;

2) the institutions charged with management; and

3) the socioeconomic system that receives benefits and bears burdens of management.

Mismatches in the time and space dynamics of processes central to each of these subsystems trigger surprises.[24] By surprises, Holling means unanticipated and unpredictable restructuring of the essential character of any or all of the three subsystems.

For example, development of a new salmonid fishery in the Great bakes, while having some immediate benefit, has brought with it economic, ecological, and political problems not foreseen and not yet resolved. These include widespread concern about increased risk to humans from contaminants and the replacement of a commercial fishery by a sports fishery.

In such a view, integrity is a property of the interactions of human systems with natural ones. Integrity refers to the extent that changes in some systems can lead to reverberations within others. Integrity is high when human and natural systems each display a capability to accommodate changes occurring in the other. Integrity of the human nature ecosystem is low when rigidities in management institutions, such as a preoccupation with fish hatchery technology, lead to increasing the fragility of natural systems through limiting natural variability. In turn, socioeconomic systems, such as the sports fishing industry, become fragile as they come to be more dependent on an increasingly homogenized and simple natural system. In this case of low integrity of the whole, consequences of change in one part are likely to emerge as crises in others.

To enhance integrity, therefore, human management should augment renewal mechanisms in both natural and social systems by fostering natural variability, encouraging learning among the public, and creating diversity among institutional arrangements.

Put another way, issues of human enjoyment, equity, and sustainability of human uses, together with associated restructuring of institutional arrangements, which inevitably arise from improved ecological conditions, are as important to restoring integrity as the remediation of important biological and physical processes. This is because success or failure of rehabilitation activities lies as much in human perceptions, attitudes, and beliefs as in the ecological changes themselves.[25]

People recognize when an ecosystem is impaired and requires rehabilitation. They determine when a particular rehabilitation strategy has succeeded and when it has failed. History suggests these decisions are rooted as much in demands for various human uses as in the state of ecological knowledge. Thus, remedial action plans which focus on choices and schedules of technical activities, as described in the previous section, are important, but unlikely to prove sufficient to restoring ecosystem integrity.

Some have pointed out that by focusing on linkages between variously defined subsystems, Holling's perspective neglects issues of goals and purpose which are peculiar to human systems. Put simply, they argue, human systems are not like natural systems. Therefore, they cannot be analyzed according to some commensurate materialistic scale of measurement as proposed by Holling. Applying such an analysis leads to amoral interpretations of integrity which are not consistent with the fundamentally moral nature of the concept of integrity outlined earlier."

THE CULTURAL CONTEXT OF REHABILITATION INTEGRITY

So far I have described the moral nature of the concept of integrity and two approaches endeavoring to provide operational guidelines for implementing it. In this section I draw attention to the milieu of Western culture. This is because remedial action planning or any other attempt to implement operationally a concept such as integrity is inextricably immersed in trends of cultural change. Operational activities or rehabilitation can become ineffective or even subserved, if they ignore or cannot contend with societal change.

In this section I do not argue for another interpretation of integrity. I try to show what can happen when a concept such as integrity is used to guide operational activities of rehabilitation. I emphasize how the concept can come to be abused and brought to serve the interest of dominant social, political, and economic forces of society.

Many believe science cannot be separated from human values and cultural history. Scientific ideas are thus products of specific cultural conditions, and scientific truths are little more than issues of personal and social needs.

Since nature is experienced only through a cultural framework which in turn builds culture, it is important to understand what social role a notion of integrity might have come to serve. Taking this view seriously requires a systematic understanding of the dynamics of social and cultural change."

Alvin Toffler has suggested science is embedded in society and so is not wholly independent. Thus, Newton's science reflected an emergent industrial society based on order, uniformity, and equilibrium. Toffler has speculated that Prigoginian science reflects today's revolutionary world of instability, disequilibrium, and turbulence.[28]

Donald Worster has tried to demonstrate that, although many ecologists recognize their views about society to be consistent with their ecological discoveries, few are willing to admit that their views of ecology are in fact reflections of their own cultural experience. Thus, he regards Darwin's ideas of natural selection as products of Victorian society and Aldo Leopold's ecological conscience as an expression of social changes in Roosevelt's United States.[29]

Similarly, many might treat the concept of integrity as merely another reflection of the perceptions and values of those trying to make sense of nature, rather than a portrayal of some intrinsic or latent property of nature. This observation has sparked a lively debate between those who contend nature has intrinsic value and those who regard nature solely in terms of instrumental value.[30]

Most of us would readily admit that humans do prefer some manifestations of nature to others. Humans particularly value configurations which yield a sustained stream of benefits. Thus, we might value wilderness for such benefits as protecting biological diversity, providing a laboratory for scientific study, and providing for recreation, human solitude, moral uplift, and aesthetic experience, in addition to providing the conventionally construed benefits of consumption of natural resources.

Today, large numbers of ecologists are engaged in managing fisheries, wildlife, or landscapes in order to ensure a constant stream of utility from nature. Their activities are usually referred to as conservation, a formulation of Bentham's "greatest good for the greatest number over the longest time." For many, therefore, a notion of integrity has come perhaps to refer to nature's ability to maintain its usefulness to humans.

Thus, to be useful, nature may well require not just active manipulation, but transformation to ever more useful, desirable, productive states. Such a view appears common among environmental managers.

Interpreted in this way, the maintenance of ecological integrity is equated to enhancement of currently recognized human benefits at local, regional, and global scales. This rests on a view of the earth as a collection of resources or potential commodities. An image of earth as machine is invoked. It is for humans to tinker with and improve upon. The challenge of better resource management, then, is to transform the earth so that it can better meet human needs. This philosophy underlies the writings of Julian Simon and Rene Dubos, for example.[31]

If considered at all, the maintenance of life support mechanisms at local, regional, and global scales is treated as a human need and, hence, a commodity just like any other. It thus falls within the realm of human manipulation and control. If nature cannot assure life support, then humans will simply engineer it. Thus, for example, Lovelock appears to believe humans will shortly have the knowledge and wisdom to control the earth's homeostatic mechanisms. He has even suggested that humans export life to Mars by engineering that planet's homeostatic mechanisms to reconstitute the atmosphere in order to make it habitable and, so, useful to humans.[32]

Others maintain that any major human-induced change in natural systems or mechanisms is likely to be detrimental because the workings of nature remain beyond the comprehension required to engineer them successfully. Put simply, nature knows best. What is more, they say, nature will always know best. This is Barry Commoner's third law of ecology.[33] In a similar vein, Edward Goldsmith has called scientific efforts deployed to replace nature as superscience gone mad.[34] This dimension of integrity is further explored by Vanderburg and Lerner in these proceedings.

The contrast between the technological optimists and pessimists sketched above is intended to suggest that the concept of integrity can be harnessed to play an important role in legitimizing values, attitudes, and beliefs as to humanity's role in nature. What is more, interpretations of integrity may be used to legitimize current industrial, agricultural, and bureaucratic practices. This is because such interpretations serve to maintain interests which hold disproportionate amounts of economic and political power. The argument here is that the concept of integrity is embedded in a social and cultural rationale and, thus, plays an instrumental role in perpetuating the dominant values which permeate contemporary society.

Dominant values in society today center on the economic imperative to exploit not just nature but also the economic potential of individuals and nations. Consequently, technical adjustments or institutional rearrangements are unlikely to prove sufficient to avert the continuing destruction of nature. In fact, tinkering without regard to a wider cultural dynamic will likely only reinforce the pervasiveness of the utilitarian view of our surroundings and so guarantee further disruption of nature.

Interestingly, the philosophy and practice of utilitarianism which I have described here has no place in any concept of integrity among humans and human society, let alone nature. For this reason, the discussion in this section has not been directed to providing a definition of integrity that can be set beside those discussed earlier. Rather, my concern here has been with the role an interpretation of integrity might play in contributing to social inertia and change. This is important because cultural forces shape the institutions through which humans strive to either destroy or heal nature. Such issues are seldom addressed in the design of ecosystem rehabilitation strategies. Stein's argument that Haekel's ecological ideas (many of which would be endorsed by contemporary ecologists) provided a scientific basis for Nazism is consistent with the process of subversion described here. I use the term subversion to indicate that neither Haekel nor contemporary ecologists would endorse Nazism or utilitarianism.

INTEGRITY AND REMEDIAL ACTION PLANNING IN HAMILTON HARBOUR

In this section, I use the example of remedial action planning in Hamilton Harbour to summarize my discussion of integrity.

Each of the perspectives on integrity sketched above emphasizes a different kind of knowledge and suggests a different approach to rehabilitating the degraded parts of Great Lakes ecosystems, such as Hamilton Harbour, located at the western end of Lake Ontario, in Ontario, Canada. In fact, what is perceived sufficient in terms of one perspective of integrity may be considered insufficient in terms of another.

Few disagree that Hamilton Harbour is badly polluted and in need of remedial action. However, there is considerable disagreement and debate as how best to design, implement, and maintain remedial action. Since July 1985, a group of stakeholders and technical advisors has been meeting periodically and wrestling with these issues in an ongoing effort to develop a Hamilton Harbour remedial action plan. To date, the stakeholder group has produced a series of reports, discussion papers, and a periodic newsletter in an effort to bring precision to practical goals, problems, and options which are to be addressed by the remedial action plan.[37] The formal remedial action plan for Hamilton Harbour was to be unveiled in the spring of 1989. In the rest of this section I will bring together the various aspects of integrity discussed so far in relation to remedial action planning in Hamilton Harbour.

Excavating contaminated sediments or oxygenating the water column may be sufficient to rehabilitate the ecological integrity of Hamilton Harbour from the vantage point of ecological science. This is because such measures, if undertaken properly, will allow people to drink, fish, and swim in the waters of the harbor. In this case, integrity is a label used to describe the state of biophysical processes operating in the ecosystem.

For protagonists of this ecological science view of integrity, remedial action plans offer an opportunity to marshall sufficient scientific resources and technical expertise, together with sustained funds and political commitment, to undertake successful rehabilitation. In the case of Hamilton Harbour, the challenge is to select and schedule the most appropriate mix of remediation measures. There is a belief that decisions as to what is appropriate and what is not can be made by ecological scientists with reference to current scientific understanding.

According to the second interpretation--the human-nature interaction view of integrity--technical measures, however applied, will never prove sufficient to rehabilitate the integrity of the Hamilton Harbour ecosystem. In this view, integrity stems from the interactions between a changing biophysical system and changing human activities in, and human uses of, that biophysical system.

Thus, in addition to technical measures, rehabilitation of Hamilton Harbour must also involve termination of destructive agricultural and industrial practices, increased regulation of human activities that translate into environmental stresses, and encouragement of those that do not. This may also require redesign of institutional arrangements and management practices for environmental and economic management of Hamilton Harbour. Thus, in terms of this interpretation, the goal of integrity would be attained once desired human activities can take place in Hamilton Harbour without causing undesired ecological changes.

Remedial action plans are thus conscious attempts to design a deliberate configuration of ecosystem integrity which is a latent property of human-nature interaction. Protagonists believe that this can be achieved by relating a growing understanding of what makes nature function to changing human activities, desires, and aspirations. In this view, rehabilitation activities endeavor to modify the interaction between human activities and nature. This may be achieved as much by deliberate intervention into socioeconomic trends and institutional arrangements as by interventions into ecological processes. This is because, in effect, the challenge of rehabilitation is not the re-creation of some historic arrangement of plants and animals or landscape but the design of a sustainable and desirable human-nature system that has not previously existed.

Implementing technical measures or addressing ecological responses in relation to human stresses on ecosystems may not be sufficient to rehabilitate Hamilton Harbour. This is the view of those who believe that, in practice, concepts such as integrity can easily come to serve the dominant political and economic forces in society. This subversion can be deliberate, as conspiracy theorists would have us believe, or inadvertent, as students of bureaucracies often argue. Subversion takes place because the goals of rehabilitation are determined not just by those living and working in Hamilton Harbour. Various government agencies and industries play important and influential roles in goal setting. These are often motivated by concerns lying beyond the immediate objectives of making the Harbour waters drinkable, fishable, and swimmable.

Their motivations are rooted in a utilitarian attitude to local economy and ecology which has no place for any meaningful definition of integrity. This in turn allows preservation and expansion of prevailing political and economic power structures. As long as rehabilitation efforts focus on utilitarian objectives such as drinkable, fishable, and swimmable, bigger questions of equity, control, and responsibility can be avoided. This allows perpetuation of industrial practices and institutional arrangements that are exploitative not just of nature, but also of local people. Thus, if not openly and honestly discussed, the goal of integrity can become little more than a tool for those with the most power and influence to preserve and expand their power and influence over those with the least.

Thus, to avoid the subversion of integrity and to truly rehabilitate Hamilton Harbour, remedial action planning must address explicitly questions of equity, control, and purpose of rehabilitation activities: Who decides on the purpose of rehabilitation? Who benefits and who loses? For whom is the Harbour rehabilitated? Who decides whether rehabilitation activities have succeeded *or* failed, and according to what (and whose) criteria?

These kinds of questions strike at the heart of the moral nature of the integrity concept. Thus, if rehabilitation is considered an activity imbued with moral purpose and justification, amoral interpretations of integrity are likely to prove insufficient to restore and maintain the integrity of Hamilton Harbour. This is because rehabilitation of integrity is not merely a question of repairing biological processes, adjusting human activities and institutional arrangements, or indeed, redistributing political and economic power within society. Integrity is something much more fundamental which relates to values, ethics, and morality.

Degradation of Hamilton Harbour represents yet another symptom of a deep-rooted malaise of contemporary society that disrupts our relations with nature, with one another, and our very selves. To treat causes rather than symptoms, remedial action planning must provide an opportunity for reassessing codes of ethics that guide our individual actions as well as the actions of our communities, industries, and governments. Hamilton Harbour pollution, like the crisis that afflicts our contemporary society, will continue unless each of us faces up to the deep-rooted deficiencies in how we each relate to our surroundings.

To rehabilitate the integrity of Hamilton Harbour's ecosystem is thus a question of reexamining our attitudes and beliefs at a fundamental level of ethics. Looking to what makes nature function allows each of us the opportunity to conduct such a reexamination and so embrace a more sustainable and equitable ethic to guide our behavior. By doing so, not only might we heal Hamilton Harbour, but we may rediscover our own humanity. Integrity is thus not some characteristic of the natural or human world, but a spiritual sense of rightness and belonging which can be found in each of our hearts. In sum, rehabilitation of integrity involves propagation of an ecological ethic of human behavior. If a remedial action plan does not do this, then it will never prove sufficient to restoring and maintaining ecosystem integrity.

CONCLUSIONS

My purpose in this paper has been to show how interpretations of integrity and subsequent attempts to make these pragmatic and operational can lead to quite different prescriptions for remedial action planning (Table 1). I have tried to illustrate my arguments by referring to current efforts to rehabilitate Hamilton Harbour.

TABLE 1. Interpretation of integrity and associated requirements for rehabilitation.

INTEGRITY	REHABILITATION REQUIRES	REHABILITATION GOALS STEM FROM
1. Conventionally interpreted ...as moral imperative	...deliberate transformation of values through adoption of ecological codes of conduct.	...spiritual and pragmatic needs for new ethical guides for human behavior in relation to nature.
2. As interpreted by ...ecological science	...intervention into ecological processes.	...scientific knowledge of the functioning of nature.
3. As interpreted by the model of ...human stress and ecosystem response	... intervention into ecological, economic, social, and institutional processes.	...understanding of the interplay of human activities and ecological change.
4. And the threat of ...utilitarian subversion	...normative reevaluation and readjustment of societal goals and objectives.	...debate as to the nature and purpose of social, political and cultural change.

My point here is not that one perspective might be more useful than others in guiding Great Lakes rehabilitation. Rather, it is to illustrate the practical importance of embracing many different and often changing perspectives of integrity within the context of a cultural milieu which itself is undergoing fundamental change. Such sharing of perspectives appears to lie at the heart of the so-called stakeholder process at the Hamilton Harbour RAP, which has brought together representatives of local industry, government, and citizenry.

Remedial action planning activities, such as those currently under way in Hamilton Harbour, are long-term undertakings of fifty years or more. They are also a step into the unknown. The ambiguity of a legally enshrined imperative to guide rehabilitation strategies, such as restoring and maintaining ecosystem integrity, offers opportunity for ongoing and evolving reinterpretation of the meaning of integrity.

Current legislation and much of the debate that centers on rehabilitation has little to say about the end state towards which rehabilitation activities currently strive.

Legally enshrined terms such as integrity allow the opportunity for exploring and distinguishing end states that are desirable from those that are not.

Perhaps our challenge in the Great Lakes basin should be not a pinning down of some widely acceptable and enduring definition of integrity so we can get on with rehabilitating degraded ecosystems. Rather, we might recognize the importance of continuing a debate into the future as to the meaning of integrity. In fact, we might do well to treat such an ongoing debate as an integral part of the implementation and evaluation of various rehabilitation activities. This is because if people cannot come to share perspectives on integrity with one another they can hardly be expected to behave with integrity towards nature.

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NOTES

1. Protocol amending the 1978 Agreement between the United States of America and Canada on the Great Lakes Water Quality Agreement, as amended on October 16, 1983, signed in the Fall of 1987.

2. Great Lakes Water Quality Agreement of 1978, signed by Canada and the United States at Ottawa on November 22, 1978.

3. Regier H., and G. Francis. 1986. Ecosystem restoration and redevelopment. A Report to UNESCO-MAB on ecosystem restoration and redevelopment as a major cross-cutting theme to the ecosystem-focused projects.

4. McFall, L. 1987. Integrity. Ethics 98: 5-20.

5. Morgan, A. 1936. The Long Road. Yellow Springs, Ohio: The National Home Library.

6. Nash, R. 1987. Aldo Leopold and the limits of American liberalism. In T. Tanner, [ed.]. Aldo Leopold: the man and his legacy. Ankeny, Iowa: Soil Conservation Society of America.

7. Leopold, A. 1933. The conservation ethic. Journal of Forestry 31: 635.

8. Leopold, A. 1979. Some fundamentals of conservation in the southwest. Environmental Ethics 1: 141.

9. This kind of thinking is central to the approach of deep ecology. See Devail, B., and G. Sessions. 1984. Deep ecology. Peregrine Smith Press. See also Devail, B., and G. Sessions. 1984. The development of natural resources and the integrity of nature. Environmental Ethics 6: 302-303. The view also lies at the heart of J. Vallentyne's efforts to popularize the concept of the biosphere. See Vallentyne, J. The necessity of a behavioral code of practice for living in the biosphere, with special reference to an ecosystem ethic. In N. Polunin [ed.]. 1986. Ecosystem theory and application. Chichester: Wiley. 406-414. See also Polunin, N. 1982. Cur global environment and the world campaign for the biosphere. Environmental Conservation 9(2): 115-121.

10. The notion that ecosystems are dominated by complex interactions between species and their environment has been hotly contested over the years by those who believe ecosystems to be fortuitous melanges of independent species' autoecologies. For example, see Patten, B., and E. Odum. 1981. The cybernetic nature of ecosystems. American Naturalist 118: 866-895. See also Engleberg, J. and L. Boyarsky. 1979. The non-cybernetic nature of ecosystems. American Naturalist 114: 317-324.

11. The notion of different levels of organization or integration in biophysical systems was introduced in Rowe, J.S. 1961. The level-of-integration concept and ecology. Ecology 42(2): 420-427. More recently, hierarchy theory has been used to apply mathematical analysis to the notion of characteristic time and space scales of pattern, behavior, and organization of ecosystems. The attempt rests on the supposition that organized systems can be decomposed into discrete functional units operating at different scales that can be related to one another in well-defined ways. See Allen, T. and T. Starr. 1982. Hierarchy: perspectives for ecological complexity. Chicago: University of Chicago Press. See also Urban, D., R. O'Neill, and H. Shugart. 1987. Landscape ecology. Bioscience 37(2): 119-127.

12. Von Bertalanffy, L. 1950. An outline of general systems theory. British Journal for the Philosophy of Science 1: 164.

13. See von Bertalanffy, L. 1950. The theory of open systems in physics and biology. Science 111: 23-28. Von Bertalanffy suggested that if living things are open systems, they must be subject to quantitative laws. Through his investigation of thermodynamics and non-equilibrium systems, Ilya Prigogine has elaborated and popularized such ideas, proposing a unified perspective on biological, chemical, and physical systems. See Prigogine, I. and I. Stengers. 1985. Order out of chaos. London: Flamingo, Fontana Paperbacks. Anatol Rapoport is a contemporary proponent of general systems theory. See Rapoport, A. 1986. General systems theory. Cambridge: Abacus Press.

14. The full list of Odum's ecosystem attributes includes: gross production/community respiration (P/R ratio), gross production/standing crop biomass (P/B ratio), biomass supported/unit energy biomass (P/E ratio), net community production (yield), food chains, total organic matter, inorganic nutrients, species diversity (variety component), species diversity (equitability component), biochemical diversity, stratification and spatial heterogeneity (pattern diversity), niche specialization, size of organism, life cycles, mineral cycles, nutrient exchange rate between organisms and environment, role of detritus in nutrient regeneration, growth form, production, internal symbiosis, nutrient conservation, stability (resistance to external perturbations), entropy, information. See Odum, E.P. 1969. The strategy of ecosystem development. Science 164: 264.

15. A summary can be found in Van Doben, W.H., and R.H. Lowe-McConnell, [ED.]. 1975. Unified concepts in ecology. The Hague, Netherlands: Junk. See especially Orians, G.H. Diversity, stability, and maturity in natural ecosystems. 139-150. To get a flavor of the controversies, see Woodwell, G.M., and H.H. Smith [ED.]. 1969. Diversity and stability in ecological systems. Brookhaven, New York: Brookhaven National Laboratory BNL-50175. C.S. Holling's classic paper on resilience has been very much at the center of these debates. See Holling, C.S. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4: 1-23.

16. Rapoport, A. 1986. General systems theory. Cambridge: Abacus Press.

17. For a full discussion of this point, see Major, J. 1969. Historical development of the ecosystem concept. In G. Van Dyne, [ed.]. 1969. The ecosystem concept in natural resource management. New York and London: Academic Press. 9-22.

18. The ecosystem distress syndrome is discussed in Rapport, D., H. Regier, and T. Hutchinson. 1985. Ecosystem behavior under stress. American Naturalist 125(5): 617-640. The concept is built on earlier analogies with human health and sickness explored in Rapport, D., H. Regier, and C. Thorpe. 1985. Diagnosis, prognosis and treatment of ecosystems under stress. In Barrett, G. and R. Rosenberg, [ed.]. 1981. Stress effects on natural ecosystems. Chichester: Wiley: 269-280. See also Odum, E.P. 1985. Trends expected in stressed ecosystems. Bioscience, 35(7): 419-422.

19. See R. Ulanowicz in these proceedings. See also Ulanowicz, R.E. 1986. Growth and development: ecosystems phenomenology. New York: Springer-Verlag.

20. Perturbation of ecosystem structure and function as a result of disturbance has been an important ecological theme. Human generated disturbance such as overfishing, overcutting, or overgrazing has tended to be treated homologously to natural sources of disturbance such as fire, storm, or flooding. See Money, H.A. and M. Gordon, [ed.]. 1983. Disturbance and ecosystems. Berlin: Springer-Verlag.

21. For example, see Jordon, III, W.R., M.E. Gilpin, and J.D. Aber, [ed.]. 1987. Restoration ecology: a synthetic approach to ecological research. Cambridge: Cambridge University Press.

22. Through much of this section, I draw on John Casti's analysis of complexity of systems to discuss integrity. See Casti, J. 1985. On system complexity, identification, measurement and management Working Paper, WP-85-22. Laxenburg, Austria: International Institute for Applied Systems Analysis.

23. This approach underlies the stress response concept developed by H. Regier and G. Francis. See, for example, Francis G. 1986. Great Lakes governance and the ecosystem approach: where next? Alternatives 13(3): 61-70.

24. Holling, C.S. Ecosystem design: lessons from the Great Lakes, biosphere newsletter (prototype). September 1985. See also Holling, C.S. The resilience of terrestrial ecosystems: local surprise and global change. In W.C. Clark and R.E. Munn, [ed.]. 1986. Sustainable development of the biosphere. Cambridge: Cambridge University Press: 292-316. See also Holling, C.S. 1987. Simplifying the complex: the paradigms of ecological function and structure. European Journal of Operational Research 30: 139-146.

25. Bonnicksen, T.M. 1988. Restoration ecology: philosophy, goals, and ethics. The Environmental Professional 10: 25-35.

26. C.P. Snow, among others, has argued that social and ecological systems differ in terms of fundamental definitions and so must be studied differently. Methods and techniques developed in natural systems are unlikely to prove useful in understanding social systems and vice versa. See, for example, Checkland, P. 1981. Systems thinking, systems practice. Chichester: Wiley. Also see Vickers, G. 1983. Human systems are different. Journal of Applied Systems Analysis 10: 3-13. Also see Jantsch, E. 1975. Design for evolution. New York: George Brazillier. Also see Eccles, J. and D. Robinson. 1984. The wonder of being human. New York: The Free Press.

27. This is the essence of Willem Vanderburg's argument in his work, The Growth of Minds and Cultures. 1985. Toronto. Toronto University Press.

28. Toffler A. A foreword: science and change. In I. Prigogine and I. Stengers. 1985. Order out of chaos. London: Flamingo, Fontana Paperbacks. Thomas Kuhn triggered much of this kind of thinking through his work, The Structure of Scientific Revolutions, 2nd ed. Chicago: University of Chicago Press. 1970.

29. Worster, D. 1977. Nature's economy: the roots of ecology. San Francisco: Sierra Club Books.

30. See especially, Naess, A. 1973. The shallow, and the deep, long range ecology movement. Enquiry 16: 95-100. See also Rolston, H. 1975. Is there an environmental ethic? Ethics 85: 93-109.

31. See, for example, Dubos, R. 1980. The wooing of the earth. New York: Scribner's. See also Simon, J. 1981. The ultimate resource. Princeton: Princeton University Press.

32. Lovelock, J., and M. Allaby. 1984. The greening of Mars. New York: St. Martin's,

33. Commnoner, B. 1971. The closing circle. New York: Knopf. 41.

34. This dimension of integrity is further explored in W. Vanderburg's and S. Lerner's papers in these proceedings.

35. Stein, G. 1988. Biological science and the roots of Nazism. American Scientist 76: 50-58.

36. Goldsmith, E. 1981. Superscience--its mythology and legitimization. The Ecologist: 228-241.

37. The formal Remedial Action Plan for Hamilton Harbour was to be unveiled in the spring of 1989. An ongoing stakeholder process, comprising periodic meetings of interested parties, concerned citizens, and technical experts was initiated in 1985 to develop a remedial action plan for Hamilton Harbour. For a recent summary of developments, see Rogers, K. et al. 1988. A report of the goals, problems and options for the Hamilton Harbour Remedial Action Plan (Ontario Ministry of Environment), and issues of the stakeholders' newsletter, Dialogue on Hamilton Harbour, sponsored by Environment Canada and the Ontario Ministry of the Environment.

ECOSYSTEM INTEGRITY AND NETWORK THEORY

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ABSTRACT. The observed structure of the interactions among ecosystem components results in autocatalytic feedback that occurs within the network of such exchanges. This feedback sets not only the overall rates at which the system functions but also engenders competition and selection for the more effective pathways. As a system grows more highly defined and better articulated, it also becomes more vulnerable to surprise perturbations, i.e. the integrity and reliability of a system are, to a large degree, mutually exclusive. The system integrity and the complementary capacity to adapt to perturbation can both be assessed from the network of material or energetic exchanges using information theory.

Estimating the networks of exchanges within a system provides the manager with one of the most versatile and reliable diagnostic tools available today. For example, with such information one can, in turn, assay all indirect bilateral influences between any components, elucidate the underlying trophic structure, make explicit the routes and magnitudes of recycling, and quantify the status of overall system functioning.

INTRODUCTION

There is a major difficulty in applying the word integrity to any living, non-cognitive system. In one sense, the term conveys the idea of wholeness, completeness, and coherency. At the same time, the noun also connotes soundness and incorruptibility (Webster's New Collegiate Dictionary, 1981). Unfortunately, when describing living, evolving systems, the first set of attributes is incompatible with the latter. For the sake of argument, I will take completeness as being representative of the first set of properties and incorruptibility to characterize the second. Below, I will consider the causal agencies behind completeness on one hand and incorruptibility on the other. I will argue that these underlying causes are distinct and bear a dialectic relationship to one another. Although most of my exposition will be highly abstract in nature, I believe that the exercise nonetheless will lend significant insight into how systems evolve and should interest anyone seeking to manage ecosystems.

To say that something is complete is to infer that the final state is known, can be described, and is the result of some process that transformed it from a disorganized or inchoate state toward its final, ordered form. Unlike machines, or to a lesser extent organisms, ecosystems never can be considered complete in any absolute sense of the word. The result of succession usually is either unknown or cannot be agreed upon. However, ecosystems are observed to undergo a regular series of transitions called succession resulting in more mature configurations (Odum 1969). Therefore, it makes some sense to speak of the completeness of an ecosystem in the relative sense of the configuration of an ecosystem at a particular time being more mature or complete than its predecessor states. The description of this tendency toward more complete forms has been a fundamental goal of ecosystem theory and, more generally, of biology and philosophy.

The difficulties these disciplines encounter in describing the development of living systems stem from a consensus among modern scientists to limit the designation of causes of phenomena to strictly material and mechanical agents. While this structure has contributed significantly to the rigor of physical and chemical explanations, I submit that an overly zealous adherence to minimalism could blind us to a very natural rational and highly useful description of evolving systems.

In contrast to the modern tendency to restrict the nature of causality stand the ancientwritings of Aristotle, who suggested that causes in nature are almost never simple. A single event may have several simultaneous causes and Aristotle taught that any cause could be assigned to one of four categories: material, efficient, formal, or final. For example, in building a house the material cause resides in the bricks, lumber, and other tangible elements that go into its structure. The efficient cause is provided by the laborers who actually assemble these materials. The design or blueprints are usually taken as the formal cause:' and the need for shelter on the part of those who contracted for the construction is considered to be the final agent.

I am suggesting that autocatalytic feedback is an example of formal cause at work in living systems. By autocatalysis is meant a cyclical configuration of two or more processes or entities wherein the activity of each member positively catalyses the activity of the next element in one direction around the loop.' At first glance, it might appear that autocatalysis can be readily decomposed into its material and efficient mechanical components, but further reflection reveals otherwise.

Autocatalysis (AC) possesses at least six properties that reveal its stature as a formal agency:

1) As the prefix auto- suggests, AC is to at least some degree autonomous of its composite parts. Whenever the network of causal influences can be mapped, it becomes feasible to identify and enumerate all the circular causal routes. Furthermore, if the individual links can be somehow quantified, it is then possible to separate abstractly the autocatalytic nexus from the supporting tree of causal events upon which it remains contingent (Ulanowicz 1983).

2) If one observes only a subset of the elements in an autocatalytic cycle, these components form a distinctly non-autonomous chain. However, if one increases the scale of observation to include all the members of the cycle, AC is seen to emerge as a phenomenon.

3) By its very nature, AC serves to accelerate the activities of its constituents, i.e. it is growth enhancing.

4) Chance perturbations in any element of a loop that enhance AC are themselves enhanced and vice versa. That is, AC exerts selection pressure upon deviations in the loop to foster only those characteristics which contribute to the ensemble behavior. It is a short step from selection for character traits to selection among possible replacement components.

   Once one recognizes that the ensemble exerts selection upon its replacement parts, it becomes clear that the characteristic lifetime of the configuration exceeds that of any of its parts and selection becomes a key element of the autonomy mentioned in (1) above. In particular, changes in any element that result in its drawing increased resources into the loop will be rewarded, giving rise to a central tendency, or, as Denbigh put it, a form of chemical imperialism.

5) Both selection and central tendency result inevitably in competition for resources among multiple AC loops. The result is an ever more

streamlined or articulated topology (network structure) of interactions.

6) Finally, AC is manifestly the result of a dynamical structure, thereby making it formal in nature.

The six properties of AC constitute a strong case for it to be considered a formal agent. In the absence of major destructive perturbation, AC serves to increase the level of activity of the system (an extensive, or size-dependent, effect) while at the same time it prunes the less effective pathways from the causal network (an intensive, or size-independent, effect). The system at any time can be said to be more complete than in its earlier forms. It remains to quantify the dual (i.e. extensive and intensive) effects of the unitary agency (AC) behind this tendency. Toward this end, it is useful to turn to networks of material or energy transfer as they occur in ecological communities. Thus, the activity level of the ecosystem becomes synonymous with the magnitude of the aggregate transfers occurring in its underlying network. This latter sum is known in economic theory as the total system throughput (TST), a term which has carried over into ecology (Hannon 1973). In the early stages of development, when only the extensive properties of AC are manifest, rampant expansionism (or growth as sheer increase in system size) is adequately gauged by the rise in total system throughput.

Quantifying the tendency toward an ever more articulated network topology of fewer but stronger connections is a slightly more difficult proposition. Suffice it here to note that in more articulated or highly defined networks, there is less uncertainty as to whether medium at any given mode will flow next. Less uncertainty implies more information, and Rutledge et al. (1976) have shown how the average mutual information, as estimated from the relative magnitudes of the flows, captures the degree of articulation inherent in the flow topology.

However, the average mutual information, being an intensive attribute, lacks physical dimensions. It is, nonetheless, multiplied by a scalar constant which can be used to give dimensions to the measure (Tribus and McIrvine 1971). Thus, scaling the average mutual information by the total system throughput gives rise to a quantity known as the network ascendancy--a surrogate for the efficiency with which the system processes the medium in question. because any increase in the level of activity can be characterized as growth (e.g., the increase in the gross national product of a country's economy) and because the augmented definition (or completeness) of its topology may be termed development, any increase in the product of the total system throughput by the average mutual information (the ascendancy) serves to measure the unitary process of growth and development (Ulanowicz 1986a).

Of course growth and development can never continue unabated, and it is in the discussion of the limits to increasing ascendancy that one discovers the basic incompatibility between completeness and incorruptibility. To begin with, average mutual information is bounded from above by the Shannon-Wiener index of uncertainty. Scaling this latter measure by the total system throughput yields a quantity called the development capacity--a measure of the size and complexity of the network. The limits to rising development capacity (and also to ascendancy) are recognizable from the mathematical form of the development capacity. One constraint is the finitude of each external source available to the system. A second limitation exists in the number of compartments. Disaggregation cannot continue beyond a point where the finite resources become spread over too large a number of categories. Otherwise, some compartments would come to possess so few resources that they would be highly vulnerable to chance extinction by the inevitable perturbations to which any real system is always subjected.

Even if the development capacity has leveled off, the ascendancy may continue to increase by diminishing the amount by which it falls short of the capacity, a difference called the overhead. The overhead, in turn, can be traced to four sources:

1) the multiplicity of external inputs,

2) the exports of usable medium from the system,

3) the dissipations inherent in the activities at each node, and

4) the average redundancy among various pathways joining any two arbitrary compartments.

Rather than being an unmitigated encumbrance upon the system's performance, the overhead is seen at times to be essential for system persistence. That is, diminishing any term in the overhead beyond some unspecified point will eventually place the given system at risk. For example, relying completely upon a single external source of medium makes the system highly vulnerable to chance disruptions in that source. Similarly, it would be counterproductive to cut back on exports which might be coupled autocatalytically to the system's inputs at the next higher hierarchical level. Furthermore, the resources that are dissipated at each node often underwrite structural maintenance at a lower level of the hierarchy. It would be detrimental to decrease such support to very low levels, even if such arbitrary cutbacks were thermodynamically feasible (which they are not). Finally, a channel of flow between two nodes or species having no redundant backup is susceptible to disruption by exogenous perturbation in the same way as discussed above for the external sources[3].

In an abstract but cogent way, overhead represents the system's incompleteness. At the same time it embodies the ecosystem's strength-in-reserve, soundness, and potential to resist corruption. Therefore, the dialectic nature of the two aforementioned connotations of integrity becomes manifest. The eventual stasis and possible breakdown of the drive toward completeness (or higher ascendancy as driven by AC) is inevitable. The only uncertainty is how or when such limits will be encountered. In very regular, stable, physical environments, such as occur in many tropical rain forests, the balance between ascendancy and overhead appears rather quiescent.

At higher latitudes, however, there appears to be a tendency for the ecosystem ascendancy to overshoot its virtual balance point with the overhead. In such systems, there is more uncertainty (and hence, potential for surprise) concerning when the particular external perturbation will occur that will send the system ascendancy plummeting below its average value. From its underdeveloped status after the crash, the system gradually builds toward another overshoot. Such cyclic behavior has been well-described by Holling (1986) and it is characteristic of boreal and cold temperature ecosystems.

It should be evident that in order to evaluate the organizational status of an ecosystem and to follow its system level dynamics, it is necessary first to quantify at least one of the networks of material and energy flows. Once all the flows of a particular medium are known, it is a routine matter to calculate the information indices that characterize each of the properties mentioned above. One can then determine with some quantitative confidence when a system retrogresses as the result of some environmental insult or when it goes eutrophic in response to elevated inputs of nutrients (Ulanowicz 1986b). The reader is cautioned that any prediction that whole system indices might provide will be valid only at the level of the entire system. Statements about the behaviors of system ascendancy, capacity, or overhead do not translate into prognostications about the future dynamics of particular ecosystem elements of interest: e.g., favorite sport or commercial fishes.

If one wishes to go beyond keeping an eye on the pulse of the whole ecosystem, the data assembled to quantify the network of ecosystem exchanges can either be applied to conventional simulation modeling or be subjected to additional network analyses. For example, one may assess all the bilateral indirect influences occurring in the system: i.e. how each species contributes to or depends upon any other species over all indirect pathways that connect them (Patten et al. 1976). One may construct a picture of the underlying trophic structure and efficiencies (Ulanowicz 1988). All of the pathways for recycling of the given medium can be identified and quantified (Ulanowicz 1983). Finally, the data in the networks can be used, if one desires, to construct a conventional simulation model of the system. (One should remember, however, that such models by their limited nature usually exclude the actions of formal agencies.)

The measurement of ecological networks should provide the background that will allow ecologists better to understand and to evaluate the integrity of ecosystems. It is hoped that from a deeper understanding of ecodynamics will follow the capability to keep the magnitudes of ecological surprises within reasonable bounds.

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NOTES

1. Aristotle actually believed that the final form of any developing object is imminent in its inchoate stages and drives the system towards completion. In every blastula resides the mature form striving to express itself. The neo-Darwinian notion of genome portrays such formal agency as residing in the material locus of the DNA molecule. However, only the most recalcitrant of sociobiologists are willing to accept such a reduction as sufficient. In ecology, one is unhampered by either final forms or material loci. Here it is sufficient to regard formal cause as the effect that the present juxtaposition of component processes has on the system at a later time. Why such identification need be made at all should become clear presently.

2. The details of positive feedback are complex. No attempt is made here to discuss such matters as time delays and phasing as they affect autocatalysis, in the belief that such digression would detract from the treatment of the attributes presented here. Similarly, there are other ramifications of positive feedback, such as the cross-catalysis inherent in nucleotide synthesis and transfer-RNA dynamics, which provide variations on the theme discussed in this paper (Joel Fischer).

3. As the system achieves network states of higher mutual information, it becomes internally more self-consistent. In a sense, one might say that mature systems are less likely to collapse because of indigenous disharmonies: e.g., astatic fish communities (R. Ryder). However, this increasing resistance to disruption by internal dissonance belies an enhanced vulnerability to external disruptions towards which the system is unadapted.

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INTEGRALITY, CONTEXT, AND OTHER INDUSTRIAL CASUALTIES

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ABSTRACT. It is argued that the loss of integrality in both the social and natural ecologies has its roots in a way of life dominated by making things better in a piecemeal microlevel way which does not translate to the whole. The advances on one level are undercut by problems on another because this approach cannot deal with the integrality and context of what is made better. The systems approach cannot be expected to pick up the weakened role of a contextualizing culture. A different intellectual division of labor in the sciences and change in the deep structures underlying our modem way of life are blocked by the influence technology has on human minds and cultures. A widespread recognition of this situation could lead to a more sustainable way of life.

INTEGRALITY AND TURBULENCE

The growing prominence of the concept of integrity is undoubtedly the result of a widespread perception that the integrality of the natural ecology is being undermined by our modem way of life. Public concern about the matter is substantial and warning bells have been sounded by international agencies (World Commission et al. 1987). Despite this, little decisive government action appears to be forthcoming in the near future, nor is the general public insisting on radical changes. I will argue that this contradiction stems in part from the fact that the whole issue of the integrality of the natural environment is not sufficiently connected to the modem way of life and its cultural roots. Of course, we all know about consumerism, the international economic race (potentially as deadly as the arms race), and the despair of many Third World countries. But the problem goes much deeper. This is symbolized in a small way by the fact that integrity is simply not a value of modem civilization.

The processes that contribute to a loss of integrality of the natural ecology are in fact identical to the ones occurring in the social ecology of any modem society. They both derive from the same orientation that characterizes our way of life, and both are rooted in contemporary culture. By culture I mean the basis on which the members of a society interpret their experience and structure the relationships with one another and the world (past, present, and future) into a coherent way of life (Vanderburg 1985). Thus the social ecology of a society is a cultural creation which characterizes an historical epoch of a society and civilization.

By cultural roots I do not mean that culture is some kind of ultimate cause. Apart from the well-known factors contributing to the environmental crisis are phenomena that have deep cultural roots. The roots of a plant do not "cause" the plant, but they make a vital contribution to it. In the same vein, the deep cultural roots of the environmental crisis constitute and nourish the lack of integrity first of all in the social ecology itself.

In the past two hundred years, what used to be the basic systems of the social ecology (namely, the extended family, the neighborhood, the village, and religious communities) have been progressively weakened, thereby creating mass societies (Ellul 1965; Bellah et al. 1985). These are characterized by large, impersonal institutions (particularly the state, as well as national and international markets). The lack of integrality in the social ecology has led to a lack of integrity through the reification of human life. The local and largely self-regulatory character of the social ecology has been undermined, as it has in the natural ecology.

What has created these two parallel developments in the social and natural ecologies on a worldwide and historically unprecedented scale? A significant part of the answer lies, I believe, in the changing role of culture brought on by the technical way of life. This way of life relies not primarily on customs and traditions rooted in a culture for its evolution, but on research designed to find the one best way of doing things. This fact has been almost entirely overlooked in discussions about the nature of contemporary societies, and yet it is a decisive one. The research begins when an area of life is examined in relation to a perceived problem. The results are used to build some kind of model which is necessarily a partial and simplified representation concentrating on those aspects relevant to the pursuit of the original intention. The model is then manipulated to find the set of parameters that yield the most effective and efficient way of dealing with the problem. Guided by this knowledge, the area of life originally studied is reorganized. This research yields techniques by which everything is constantly improved. The difficulty is that this process makes no essential reference to how the researched area fitted into, and, after its reorganization, will fit into its context.

The dominant values of our civilization, such as efficiency, productivity, cost-effectiveness, and risk-benefit effectiveness are all essentially output-over-input ratios, with no consideration of context as expressed in other values, such as harmony, coexistence, and compatibility, or appropriateness of scale. Also, this technical way of life often separates knowing, doing, and managing, thus destroying the essentially self-regulating character of many activities (we now have to read how-to books to engage in the most basic human activities successfully engaged in by people for thousands of years). Since I have developed these themes in detail elsewhere (Vanderburg, in progress), I will put it briefly and thus somewhat simplistically: the technical way of life embodies a contextless rationality in which rationality on the microlevel does not translate to the macrolevel, because it does not respect the integrality of what is technically improved, nor the context in which it operates. Thus, advances on one level (better chemicals, computers, weapons) are undercut by problems on another (contamination of the ecology, unemployment, and omnicide).

The technical way of life imposes an extreme level of turbulence on the social and natural ecologies to the point that it is almost impossible to define integrity and integrality except by their absence. As such, however, the turbulence constitutes a signpost by which new orientations in the modem way of life may be conceptualized and acted on in order to, for example, not exclusively regulate what is relatively abundant (cars, televisions) but what is increasingly scarce: clean air, water, uncontaminated food, and a better quality of life. We will also have to learn to say **"no"** to undertakings involving major surprises with unforeseeable consequences (such as genetic engineering) or those which, because of their complexity, invite major normal accidents.

INTEGRALITY AND SCIENCE

Unlike an engineering drawing in which each view or cross-section is carefully labeled so that it is clear how taken together they constitute a representation of the whole, scientific disciplines do not indicate how their specialized knowledge relates to that of the others or how together they constitute a representation of reality. It would appear that science with its reductionistic heritage produces a rational way of knowing with a minimal dependence on or reference to context. It is unlikely, therefore, that science can be counted on to give context to the technical way of life whose patterns it reinforces. The rationality of many highly detailed and specialized studies does not translate to the macrolevel to create a coherent knowledge base, yielding a comprehensive understanding of the integrity of human life, society, and the natural ecology, nor of how these coexist or conflict on this planet. In proclaiming universality, science rejected context and contextual knowing. It was hoped some time ago that the systems approach would bring about a radical change in this situation, but it has made only modest progress. I will set out what I believe to be the problem by pushing this approach to its limits.

The systems approach begins with the abstraction of a particular system for the purpose of analysis. It can then be studied using three different frames of reference. The first analyzes a system from the vantage point of its environment to examine phenomenological qualities that the system exhibits toward its enviroment. The second frame of reference places the observer within the system to examine its internal structure as it interrelates the constituent components into the whole. The third frame of reference involves the disorganization of the system into its constituent wholes to examine the properties that these wholes have in isolation from the system, and to compare these to those they have within the system according to the findings obtained by means of the second frame of reference.

Thus, an important aspect of the system's organization emerges, namely, how the whole makes use of certain properties of the constituents and suppresses others. For example, the socialization of a human being into the culture of a society suppresses certain instinctual characteristics but creates others that make people a part of their time, place, and history. To create a diversity within the unity of a whole, there must be a dialectical tension between diversity and unity. Too great a diversity would destroy the system, while too great a unity would collapse the unique properties of the whole that emerges as a result of the diversity within the unity. In the same way, the organization of the whole must balance the complementarity and antagonisms of the constituents.

There cannot be complementarity without antagonisms, and thus the organization creates both order and disorder. The latter is frequently used for self-regulation and feedback. Disorder thus contributes to the maintenance of order. Of course, we must remind ourselves that what may be order for one whole may be disorder for another. For example, the extraordinary diversity of relations that human beings are capable of are a source of disorder on the assembly line, but at the same time account for everything that we would call human. It is impossible to absolutize the terms unity, diversity, order, disorder, complementarity, and antagonism. This shows the dialectical and context-dependent character of the human interpretation of the whole.

The above does not, of course, complete the study of a system. A loss of information has occurred by disconnecting the system from reality, either through a process of abstraction or by isolating it in a laboratory. In order to complete the analysis of the system and assess the loss of information, the analysis must be continued in two directions. First, the larger wholes within which the system was a constituent element must be examined. Secondly, the system under consideration was itself made up of smaller wholes, which themselves are constituted of still smaller wholes. The analysis begun by means of the second and third frames of reference must therefore be continued and this is where the difficulties arise.

The results of these analyses are not cumulative because they are interdependent. The findings of the analysis of one whole are inputs into the analyses of adjacent wholes in the network of reality, including the next larger and smaller wholes. In other words, the knowledge we have of a specific whole depends on the knowledge of the context into which it is embedded. It furthermore depends on the knowledge of the observer, his or her past training and experience, including any scientific or technical training, and the instruments used for making the observations.

This raises three further issues. First, the knowledge with which we approach the study of an organized whole is always necessarily partial. Yet no observer treats it as such. Reality as it is known by an individual observer and a community of specialists to which he or she belongs, or the culture of which he or she is a part, is typically taken for reality itself. Yet it is important to make a distinction between reality as it is known by a particular community, and the reality beyond it, which is the source of an endless flow of new discoveries.

Thomas Kuhn (1970) has clearly shown that nothing can be said about the relationship between what I call reality as it is known by a scientific community and the reality beyond it. Reality as it is known by a particular community is not cumulative since gestalt switches occur from time to time, which have been called scientific revolutions. Similarly, but on a cultural plane, reality as it was known during the medieval period was different from the reality characterizing the next historical epoch in Western civilization. Yet the members of a culture or scientific community behave as if their conception of reality is fundamentally correct, and as if it cannot be called into question by future discoveries. It is considered utterly reliable, so that all ultimate questions, such as "Am I really here?", "Am I really seeing what I'm seeing?", or "Am I really doing the right thing?" are eliminated.

The implication is that reality as it is known by a society or scientific community is extrapolated across the unknown to reality itself. In other words, reality is implicitly assumed to have the same gestalt as the reality as it is known. Hence, the unknown is no longer threatening, no longer a source of potential disorder, but simply a reservoir of missing bits and pieces that can be added to the basic gestalt of reality as it is known. Elsewhere, I have shown how these assumptions are never made explicitly in the history of a society (Kuhn 1970). They are generally matters that are so self-evident and so obvious that it is simply inconceivable that things could be otherwise. These are what anthropologists call the myths of a society. It is only much later that observers with hindsight wonder how, during a particular epoch in the history of a society, no one saw through these myths.

What I have suggested about some aspects of the role of science in society has important implications for what Kuhn has called a paradigm or disciplinary matrix. It is not a neutral or symbolic medium through which a community observes and acts on the world. Rather, it is a paradigm, a filter through which a relatively coherent microworld is derived from a complex interrelated reality, by means of explicit, as well as hidden, assumptions and myths. Through connecting macro- and microlevel studies of the modern scientific knowledge base, it is possible to analyze some of the properties of these filters and discover why they produce relative, isolated islands of knowledge while extending the sea of ignorance around them. Science is a study of reality with minimal reference to context. We need to find ways in which specialization can be given a context as the ground against which specialties are configured. It is not a simple task, however, to change an intellectual tradition shaped for centuries by the myths of a mechanistic world view. Even today it is not generally recognized that the fragmentation of the scientific knowledge base is not in keeping with the expectations of a mechanistic world view.

A second implication has its roots in the fact that the above third frame of reference cannot be applied to living wholes. There is a fundamental difference between living and nonliving wholes. Living wholes are never constituted from separate and independently existing parts the way nonliving systems are. A living whole comes about by progressive internal differentiation through which parts are created. Something of the whole is present in each part, so that the part-whole relationship is very different in a living whole from what it is in a nonliving one. Actually, some physicists, like David Bohm (1980), have suggested that this is true even of physical matter. Bohm has proposed the implicate order, suggesting that the fundamental reality is an indivisible whole from which the explicit order of our observations is, derived. In the implicate order, each part is internally connected to all the others and to the whole. It is only in the explicate order that we see them as distinct elements. He suggests that some of the current difficulties in physics may be overcome if the hypothesis of a mechanistic world is abandoned.

A similar case applies to society as a living system. In my study of culture, I have made a detailed study of the enfolded, nonmechanistic nature of a society and its implications. I will therefore limit myself to a few details. Human beings do not experience the categories and divisions imposed on their world through scientific and technical specialization. A person's life is not lived in separate sectors with labels such as the scientific, technical, economic, social, political, legal, moral, religious, and artistic. When we consider a particular action, these are dimensions of that action. Some of them may be more crucial than others, but all of them are enfolded into the action. The same is true for any institution or way of life in a society. There are no distinct social, economic, political, and other subsystems. These are but dimensions of a way of life individually and collectively lived in an enfolded manner. In order to create a less fragmented scientific knowledge base, scientific specialization will have to collaborate to achieve a common base map other than the mechanistic one used thus far. This map would be elaborated by each community of specialists in both general and specific features in an ongoing attempt to superimpose all of them. On the macrolevel this approach would search for a consistent and coherent map of society and the world.

A third implication derives from the relationship between the observer and the observed. If we recognize that our world is in part composed of wholes that are enfolded into others, then the relationship between observer and the reality observed becomes more complex than traditionally assumed. Observers internalize something of their social and physical environments into their minds, so that they are internally related to their world. Hence the facts are affected by the presence of the observer, as has been recognized in subatomic physics, and is becoming recognized in other disciplines (Devereux 1967).

If we are not to contribute to the above problems, our knowing must be based on at least two distinct but interdependent modes of knowing. The first derives from frontier research of the kind customarily encountered in any modem scientific and technical discipline. This approach produces an ever-greater level of specialization, trading off breadth for depth. Questions of context and broader interrelationships thus play, at best, a minor role.

Frontier research must be complemented by contextualizing research, where breadth is emphasized over depth, including the integration of the findings of frontier research by contextualizing them in relation to each other and their human, social, and environmental significance. In so doing, other aspects, implications, and significance will be unveiled which may complement, negate, or challenge some of the finds of frontier research. Hence, the two levels of analysis are in dialectical tension with one another. Each one has consequences and implications for the other. We need to go far beyond the systems approach. What I am arguing has significant implications for the university as well as other scientific institutions. Reflective research must be institutionalized and nurtured by structures parallel to disciplines and invisible colleges.

To imagine a new scientific intellectual division of labor, and the institutional structures supporting it, is not so difficult. What is next to impossible, however, is to move in that direction. Our culture has placed such a high value on science that a critical awareness of its limitations is minimal. We have as a society lost track of the fact that science, like all human creations, is good for certain things, useless for others, and irrelevant to still others. In the knowledge business today we have put ourselves in a position summed up by an unknown author as follows: "If your only tool is a hammer, all your problems look like nails." Too many of our problems today are not the "scientific nails" we generally think they are. I will give one example. The effective regulation of the tens of thousands of chemicals in our environment, to ensure that they do not threaten the integrality of life and life-supporting systems, requires a knowledge of the overall impact these chemicals have. This cannot be a linear combination of the influences they have one at a time because of complex positive and negative synergistic effects. The best scientific tests (possible for only high-dosage, short-term exposure) and unlimited funds cannot begin to answer the question about the extent to which life is threatened. It is not a matter of more studies. An altogether different approach is required, and this brings me back to the technical way of life.

CHANGING THE TECHNICAL WAY OF LIFE?

What stands in the way of changing a reductionistic science and a reifying technical way of life is much more than the powerful vested interests of large modem institutions. It is at least as much the result of the cultural roots and orientation that lives deeply within our beings and which legitimatize the scientific, technical, social, economic, legal, and political organization of modem societies. In all the studies of the influence science and technology have on human life, society, and the natural environment, one of the most decisive influences has been almost entirely overlooked, namely culture. This influence is crucial when considering to what degree society can direct science and technology in accordance with human values rather than technical ones. I am not speaking of all the present attempts to create closer links between government, the university, and industry in order to make the nation-state into a single all-pervasive and efficient enterprise. This is simply doing more of the kinds of things that helped produce many of our present problems in the first place. What I am concerned with is quite different and more fundamental.

The culture of a society is acquired by each new generation through a process of socialization. While much is learned explicitly, even more is acquired implicitly because the internalized experiences are interrelated into structures which are grafted onto the genetically provided organization of the brain. The structure of experience implies a great deal of metaconscious knowledge, to which human beings have no direct access, but which nevertheless fundamentally affects their being by getting at the deeper levels of meaning associated with contextualizing each experience in the whole of a person's life. From this perspective it is clear that a modem society, like all others, has a profound effect on the mind and culture. The high density of machines, devices, and relationships structured by means of techniques of all kinds, the fact that many such relationships are mediated by machines (telephones, computers, televisions) or by techniques (public relations, operations research, political advertising), and considering that these relations take place in an industrial-urban information context--all these permeate our experiences the way nature did in prehistory, and society did until recently. If, through this retroaction of the modem way of life on the mind and culture, human beings become oriented in their perceptions, ideas, actions, and values by the system they create, then questions of individuality, freedom, democracy, justice, and other Western aspirations may well be under siege once again (Ellul 1978). In fact, this would explain how the values related to technology have permeated the culture of every modern society. We need to understand the exact scope and nature of this technical bondage that would make a fundamental reorientation of science and the technical way of life extremely difficult. What is required is a detailed examination of the relation between technique (the phenomenon constituted by the search for efficiency and effectiveness in every area of life) and culture, a task which would take us far beyond the scope of this article.

I will limit myself to one crucial aspect of the influence of technique on modem culture, and thus, on the deepest levels of being, thinking, and acting of the members of a society. I have already suggested that communities metaconsciously create myths by absolutizing reality as it is known to them. This process of absolutization is accompanied by one of sacralization because of the following dilemma. During each epoch in its historical development, a society is generally placed before one or more related phenomena, which so permeate the society that its very existence and the lives of its members become inconceivable without them. For the prehistoric group, such a phenomenon was nature: and for the societies that began to constitute themselves at the dawn of history, the phenomenon became society itself. The structure of experiences in the mind identifies such phenomena in a metaconscious way. This places a community before a dilemma. It could decide that such a phenomenon is so all-determining that the community has little or no control in the face of this fate. On the other hand, and this is in fact what happens, it could sacralize the phenomenon by metaconsciously bestowing an ultimate value on it. Necessity is thus transformed into the good, and the social order based on it is the expression of the community's members freely striving for that good. The freedom and cultural vitality thus metaconsciously created eventually permit the sacred to be transcended as an all-determining force, and make human history possible. At the dawn of history, natural determinisms were slowly transcended, although social ones eventually took their place. The bestowing of an ultimate value on that which is most central in determining the life of a community metaconsciously orders all other values implied in the structure of experience of its members. Thus, this metaconscious operation creates a sacred system of myths and a hierarchy of values, which together constitute the basis for cultural unity.

The metaconscious recognition of the centrality of technique and the nation-state would show them to be something very special, to be given a high value--a decisive consequence of the retroaction of the modem way of life on the human mind and, via it, on culture. When this happens, the members of a society lose a clear sense of the limits of technique and the nation-state because they have become good in themselves rather than human creations serving specific values. This paves the way for contextless technical values (such as efficiency) to permeate the whole culture. The myths of human rationality and a secular society have hidden the existence of a commitment associated with technique and the nation-state (Ellul 1973, Stivers 1982). The present intellectual division of labor makes specialists dependent on, and sensitive to, daily life (i.e. cultural) knowledge of science and technique. Hence, the retroactive effect of the modem way of life has a profound effect on all members of society, including scientists and technical specialists. We find ourselves plunged into a secular mythical universe with all the negative implications for thought and action not unlike theories we know from earlier historical epochs. However, the power of our means is growing, along with our inability to respect the integrality of the social and natural ecologies.

CONCLUSION

If my brief sketch of our present situation is pointing in the right direction, then the formulation of a clear sense of what integrality and integrity can mean today must be coupled with a more iconoclastic attitude about where we are going as a civilization. It is not a question at all of being anti-technique, for without it we could not support the world's population, but it is a question of reestablishing limits for technique--to give it its proper place, like any other human creation, and to use it only where appropriate. In other words, it must be guided by human values. The old warnings of the Jewish and Christian traditions against the dangers of idolatry must not be forgotten by the West in this so-called secular age.

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NOTES

1. The ideal type of technique for understanding the nature of the modem way of life was first advanced by Jacques Ellul. For an introduction to his numerous works, see Vanderburg, W.H. [ED.]. 1981. Perspectives on our age. Toronto: CBC.

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EVALUATING THE BENEFITS OF ECOSYSTEM INTEGRITY

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ABSTRACT. Current approaches to evaluating the nonmarketed goods and services of nature in economic terms are discussed from an ecological viewpoint. Three approaches to generating shadow prices are reviewed: estimation of value of lost ecosystem benefits: use of economic surrogates for the value of intact ecosystems: and hypothetical valuation methods (bidding games). Different methods result in different economic estimates for the same resource. The degree of incompleteness of each estimate is unknown, making it difficult to choose among them. The incompleteness of estimates derives, in part, from incomplete knowledge about ecosystem structure and function itself. Also, because people value money differently, a price fails to reflect the differing weights attached to the economic evaluation unit. Further, because people value natural resources differently but prices reflect aggregated or average social utilities, the differing values attached to a resource by different publics are not separately indicated. Despite the problems associated with environmental cost-benefit analysis, the conduct of an explicit economic evaluation of costs and benefits of a development project, including at least some ecological attributes, can have heuristic value.

INTRODUCTION

> I enter some glade in the woods, perchance, where a few weeds and dry leaves alone lift themselves above the surface of the snow, and it is as if I had come to an open window. I see out and around myself...
>
> -- H. Thoreau, Walden

Aided in part by the small size of the basin, Thoreau was able to observe the linkages among water, land, air, and biota at Walden Pond with remarkable acuity. What he observed in qualitative terms was a lake ecosystem still only mildly affected by the people who used it. The adaptations of the resident plants and animals to the regimen of nature's stresses in this virtually pristine water body resulted in the appearance of ecosystem self-maintenance.

When the framers of the 1972 U.S. Federal Water Pollution Control Act Amendments (FWPCA) first used the term integrity to refer to the quality of interactions Congress sought to restore and maintain in the nation's aquatic ecosystems, it was with an explicit recognition that most of these systems were already significantly modified by human agency. Thus, while the integrity of a pristine water body was taken as a standard for definitional purposes, the ecosystem integrity that was to be restored by cessation of pollution was functional rather than structural (U.S. Senate 1972, p. 76). The concept promoted was that if the functional integrity of surface water ecosystems could be restored or maintained, such systems would at least be able to support "a balanced population of fish, shellfish, and wildlife, and permit recreation in and on the water." Full integrity implied that potability and the remaining uses of highest-quality water would also be restored. Equally importantly, by restoring physical, chemical, and biological integrity to these ecosystems, the ecological processes themselves would provide the necessary homeostasis to the system, minimizing human management costs (Westman 1972; U.S. Senate 1972, p. 76-77).

Throughout the 1970s, the philosophy guiding U.S. environmental laws was that ecological goals and standards set on scientific grounds were to be the primary focus. Regulations and incentives were designed to move society toward eventual achievement of those goals. The costs of achievement were viewed as potentially limiting only after best practicable, and later, best available technology was applied, and the fishable, swimmable standard was still not achieved. In those cases, the Environmental Protection Agency Administrator could weigh economic and social costs against benefits in setting more stringent technological standards (U.S. Senate 1972, Sec. 302). States and municipalities that failed to raise their share of costs of water treatment, and thus failed to meet treatment standards by certain deadlines, faced heavy fines. By the early 1980s, as treatment plant construction neared completion, focus increasingly shifted to weighing the costs and benefits of meeting more stringent water quality standards. This focus was intensified by a new Administration concerned about the heavy monetary costs of pollution clean-up. This emphasis on budgeting created a renewed challenge to find accurate tools for evaluating the true costs of environmental pollution.

ENVIRONMENTAL COST-BENEFIT ANALYSIS

Despite the existence since at least the 1930s (e.g., Kaldor 1939, Hicks 1939) of a well-developed theory of social utility that underlies cost-benefit analysis (CBA), the application of CBA to environmental problems has remained largely unsatisfactory (see e.g., McAllister 1980, Westman 1985, Ch. 5). This has been so both because of problems inherent in the assumptions underlying CBA, and because of particular difficulties associated with assigning monetary values to the nonmarketed goods and services of nature.

Many authors have discussed the problems in assumptions underlying CBA as applied to environmental problems (e.g., Anderson 1974, Ghiselin 1978, McAllister 1980, Mishan 1976, Muller 1974, Price 1977, Westman 1985). The basic rationale for cost-benefit analysis is that social welfare will be maximized if resource managers compare the costs (including potential compensation to losers) and benefits from alternative actions and choose the action in which the net stream of benefits over the lifetime of the project will be greatest.

As noted by Westman (1985, p. 171), however, the use of the social welfare test assumes that:

1) losers are willing to accept financial compensation for their losses, and the full value of losses can be expressed in monetary terms:

2) losers know the value of what they are losing at the time of the transaction; and

3) there does not have to be equity in the distribution of gains and losses; the benefits may accrue to one party, the losses to another.

Westman also noted that there are at least four problems with these assumptions that are not directly addressed by CBA.

1) Future generations of losers may not value the loss in the same way.

2) Species and objects other than people cannot be compensated directly for their losses, nor can they be consulted on whether they are willing to partake of the transaction.

3) Even in the case of people, compensation for losses may not actually occur.

4) Different members of society will value the losses (or compensation) differently: for example, the poor and the rich may place a different value on obtaining an additional $100.

The second set of problems associated with the application of CBA to environmental issues arises from efforts to quantify ecological attributes in economic terms. Farnworth et al. (1981) propose a three-part classification for resources, depending on the ease with which a market value can be assigned to them. Items directly marketed are termed Value I goods. A nonmarketed item for which a surrogate price can be obtained by a shadow-pricing technique (e.g., Hyman 1981, Westman 1985) is termed a Value II item. Nonmarketed items for which shadow-pricing techniques appear inappropriate or inapplicable (e.g., pain from illness), and which are therefore nonmonetizable, are termed Value III items. The problems with CBA center on finding appropriate techniques for ascertaining Value II items. The incompleteness of economic analyses arise in art from exclusion of Value III items (Westman 1985).

Shadow pricing is a general term for a range of techniques devised to produce a hypothetical estimate of the unit cost of a nonmarketed good or service were the item subject to market forces. For example, estimates of the cost of adverse health effects of water pollution have sometimes been made by tallying the value of wages lost due to illness. Before discussing shadow pricing in detail, it will be useful to review the benefits of nature's goods and services in a system whose integrity is intact.

THE GOODS AND SERVICES OF INTACTECOSYSTEMS

One component of the economic value of ecosystem integrity consists of the direct benefits to the marketplace from the harvest of economic products from the ecosystem (Value I items). Typically such goods derive from the structural features of ecosystems, including, in **the case of the Great Lakes basin, the value of commercial** and sport fishery industries, timber, crops, livestock and fur harvested, water sold for drinking or irrigation, hydroelectric power derived, fees for water transportation,' and the value of minerals mined. For example, 5% of the value of U.S. agriculture is produced in the lakes region, and pine production and iron and copper ore extraction remain important.

Other structural features that do not enter the marketplace (Values II and III) nevertheless have value to society (non-harvested terrestrial and aquatic organisms, soil, and clean air), and their worth must be evaluated using other means.

While the nonmarketed structural features of ecosystems are at least tangible, ecosystem functions themselves are not, since they consist of fluxes of energy and materials, rather than standing stocks. As a result, they are even more easily ignored when assessing the worth of ecosystems (Westman 1977).

One ecosystem function that has an obvious connection with the economy is the radiation flux function, since this feature is used by at least 30 thermoelectric power plants in the Great lakes basin that use cooling water from the lakes. Other functions, such as species regulation, often become obvious in the breach. Thus damming and pollution of tributaries by the 1880s led to the elimination of the Atlantic salmon (Salmo salar) and reductions in whitefish (Coregonus clupeaformis), while overfishing of sturgeon (Denser fulvescens), and introduction of carp (Cynrinus carpio) further species composition. These changes helped lay the basis for the successful establishment of the sea lamprey (Petromyzon marinus) in the 1930s, which led to the collapse of lake trout (Salvelinus namaycush) in lakes Huron and Michigan by the 1950s. The loss of large predatory species to the lamprey also permitted the establishment of the alewife (Alosa pseudoharengus), which rapidly increased in abundance during the 1930-1955 period (Beeton 1986; Regier and Hartman 1973).

DAMAGE, REPAIR, AND REPLACEMENT COSTS

The economic value of the above mentioned changes could be estimated by the economic damage they caused (loss of commercially valuable salmon and trout) or the costs to repair the damage (costs of reintroduction of salmon and trout and associated water quality cleanup: costs of removal of alewives from beaches during fish kills). A third possibility is to estimate the cost of replacing the lost function of species regulation. The replacement costs are estimable in part as the administrative costs of operating relevant parts of the numerous governmental agencies (Environment Canada, U.S. Environmental Protection Agency, International Joint Commission) charged with monitoring species changes and finding management tools to regulate species numbers in the Great Lakes.

The estimates derived from damage-, repair-, and replacement-cost approaches will not be the same, except by coincidence, since they refer to quite distinct aspects of dealing with the problem. Furthermore, each of the approaches is likely to provide only a partial estimate of total costs of ecological damage or repair, since many features may be damaged that have no market value (e.g., sediment decomposers), and many features that are lost may not be repaired or replaced (e.g., lost planktonic species).

An illustration of the difference between damage and repair costs due to the effects of air pollution on terrestrial ecosystems can be drawn from the ozone-damaged pine forests of the San Bernardino Mountains in southern California. By 1972, 57% of the trees in a 4000-ha area of these mountains were in a declining phase due to ozone-related damage. Westman (1977) calculated a repair cost estimate for the loss of soil-binding function from the damaged trees by assuming that 50% of the area would be replaced by herbaceous successional vegetation. Using erosion figures from a comparable hillside nearby where native shrubland had been replaced by grasses (Rice et al. 1969, Rice and Foggin 1971), and partitioning the estimated sediment runoff equally between debris basins, sewers, and street edges, he applied current estimates of sediment removal costs from each such structure (Ateshian 1976) to the sediment totals. The resulting estimate of the annual repair cost from loss of the soil-binding function in the San Bernardinos was $27 million/yr. This figure was substantially larger than the amount actually being spent by the flood control district for sediment cleanup in the region, implying that dams, sewers, creek beds, and estuaries were filling with sediment. The year after the calculation was published, the San Bernardino Mountains were subject to floods. The clogged creek beds overflowed, causing $5.2 million in damage to houses and other structures at the base of the mountains (U.S. Army Corps of Engineers 1978). This damage cost estimate is at least in part attributable to smog damage to the pines and the resulting erosion (Westman 1985, p. 180-181).

Another example of estimating a lost ecosystem function by calculating damage, repair, or replacement costs can be illustrated by considering the effects of using lake water for industrial cooling. While the industries around the Great Lakes enjoy the radiation flux as a free service of nature, the cumulative effect of such utilization by all 30 utilities can be a net increase in water temperature in the lakes. Furthermore the evaporative cooling will result in the water discharged having increased solute concentration. The specific heat of this water is decreased, so that a given change in heat input will induce a greater net change in water temperature. As one result, the ability of the lake water to buffer changes in air temperature in the region is reduced. The damage costs of this effect could be estimated by crop or timber losses resulting from earlier snowmelt, altered growing seasons, increased evapotranspirative stress, and other climatic extremes. A parallel set of estimates could be derived for the known increases in human health-related effects as a result of increases in climatic extremes. A repair-cost approach would involve estimating the costs for water treatment plants to remove solutes from the water (either before or after discharge), and the cost of building tall cooling towers to reduce ground-level changes in air temperature. A partial replacement cost estimate could involve estimating the incremental costs of home heating and air conditioning to buffer the temperature extremes induced by the reduced climatic buffering of the lakes. An additional replacement cost might involve increased irrigation of crops to compensate for heightened evapotranspirative stress. Further, these costs do not reflect the costs associated with thermal pollution effects on aquatic organisms, which are myriad (see e.g., Westman, 1985, p. 300-305).

ECONOMIC SURROGATES

Ancillary goods and services purchased by people in the process of enjoying nature's free goods and services may be used as a surrogate or artificial measure of the true value of these nonmarket items (Hyman 1981, Westman 1985). One of the more extensively developed approaches, used for estimating the value of recreational facilities, has involved estimating the dollars people expend to gain access to the recreational area (travel costs, entry fees) (e.g., Smith and Kavanagh 1969; Usher 1973, 1977). Everett (1979) expanded the travel-cost approach to estimate the proportion of the total value of a visit to a national park (Dalby Forest) in England that was attributable to the presence of wildlife there. By a questionnaire, visitors were asked the extent to which their trip was motivated by an interest in the area's wildlife. The mean proportion of the recreational experience attributable to wildlife (25%) was then applied to the total value of the forest as computed by travel costs to determine the fraction attributable to wildlife. Everett attempted to account for consumer surplus (i.e., undervaluation of the park resource) by determining the number of trips visitors would be willing to make to the park under various entrance fee schedules, assuming that people making shorter trips would be willing to pay higher entrance fees. The resultant information permitted the estimation of a demand curve for forest visits; the area under the curve represented an economic valuation of the forest to visitors.

As noted by Everett (1979), this approach assumes that willingness to pay is proportional only to distance from the amenity, yet factors such as visitor income and occupation are likely to affect response. Further, the approach assumes that people will react to an increase in entrance fee in the same way as an increase in travel cost.

Indeed, the problems associated with ascertaining accurate consumer behavior from hypothetical questionnaires have been the subject of considerable study. Inatypical approach to hypothetical valuation (bidding-game approach), the interview gives the consumer a starting bid and asks whether the consumer would be willing to pay that amount for the amenity (e.g. healthful swimming in Lake Erie). If the answer is "yes," the bid is raised, and the question repeated. When a price is reached that the consumer is not willing to pay, the bid is lowered slightly to fine tune the estimate. Such interview situations, however, can easily introduce inadvertent biases in the answers obtained. The level of the starting bid influences the nature of responses obtained (Hyman 1981), as does information on how the money is obtained--direct entry fee vs. federal grant (Westman 1985).

People will also give quite different answers about access to an amenity if the question is posed, "How much are you willing to pay to gain access?" vs. "how much would you be willing to accept in compensation for denial of access?" This is because in the first case people must have the disposable income to purchase a free good, whereas in the second they are relinquishing a free good at no economic expense. Also the answer will often differ depending on whether the parson already enjoys the resource (ability to swim in a clean Lake Erie) which is being taken away, or is being offered a resource not previously enjoyed.

Meyer (1976) asked residents near the Fraser River in Canada about their hypothetical economic preferences regarding maintenance of environmental amenities in the region. Each respondent was asked the following in relation to fishing, boating, swimming, and other amenities:

1) What would you be willing to pay (to enjoy fishing and boating)?

2) What would I have to pay you to give it up?

3) If you were making a community decision, how would you reallocate the budget for recreation on the Fraser River?

4) If you were a judge and someone had been arbitrarily excluded from the activity listed for one year, what dollar damages would you award?

The answers showed marked differences, depending on source of funds. When funds were communal (questions 3 and 4), a very similar level of funding ($11,700-$11,800) was assigned on average. When individuals had to pay directly (question 1), they were willing to pay 10 times less ($1,100); when offered compensation for denial of access, they required 10 times more ($21,000) on average. Which of these estimates to use as a shadow price is unclear. Further, whether any estimatewill reflect ultimate consumer behavior is unknown, and will depend in part on whether those questioned were an unbiased sample of the relevant consumers.

CONCLUSION

The discussion of approaches to shadow pricing serves to emphasize some of the difficulties in evaluating nonmarket goods in economic terms. As noted by Westman (1985, p. 188-189), there are at least five general problems encountered:

1) Different methods (e.g. damage costs vs. repair costs) result in different economic estimates for the same resource; the degree of incompleteness of each estimate is usually unknown, making it difficult to choose between them.

2) Because nature's goods and services are free to begin with, and their ecological value not fully appreciated, any shadow-pricing methods underestimate the true value of the resource to people.

3) Because people value money differently, a price fails to reflect the differing weights attached to the evaluation unit (money).

4) Because people value natural resources differently but prices reflect aggregated or average social utilities, the differing values attached to a resource by different publics are not separately indicated.

5) Some of nature's goods and services are not readily evaluated in economic terms by existing methods either because they are too complex and incompletely known (e.g. global climate) or because they are not considered exchangeable for money (e.g. human life): these items are often excluded from economic analyses, making such analyses incomplete.

> The net result of these problems is that the person conducting an environmental cost-benefit analysis can make the ratio favor, or not favor, a development project, depending on how many benefits of nature the analyst estimates, and what methods he or she uses in deriving the shadow prices. As a result, the bottom line of a cost-benefit analysis is much too arbitrary to be of use to a decision maker. The disaggregated information on the costs and benefits, however, may be of some use in providing the decision maker with a basis for discussion regarding attributes of values on both sides of the ledger. The use of sensitivity analysis and of several different evaluation methods simultaneously can help to reveal the assumptions and limitations more graphically (Westman 1985). As noted elsewhere, the ever present danger with any evaluation method is that decision makers will accept numbers as an objective rationale for a decision, when such numbers merely reflect a quantification of particular human values (Westman 1985, p. 193).

Given the difficulties with economic evaluation methods, there is a natural temptation to avoid the exercise altogether. Noneconomic, quantitative evaluation methods are fraught with similar difficulties (e.g. McAllister 1980, Westman 1985, Ch. 4). Nevertheless, in the absence of an explicit evaluation of costs and benefits, the decision maker will make an implicit evaluation. Such evaluations are often incomplete, and more importantly, are not subject to independent evaluation by other interested parties. Consequently, one of the principal merits of any explicit, quantitative evaluation technique is its ability to display the values of particular goods and services, as estimated using particular, explicit assumptions. These then can serve as a basis for discussion by parties to the decision. Hopefully, the inherent incompleteness and arbitrary element of such analyses will be understood by the decision makers. This is important if the illusion of objectivity is not to be used to strangle the participatory, political process which is an appropriate part of any decision on the use of common resources.

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INTEGRITY AND SURPRISE IN THE GREAT LAKES BASIN ECOSYSTEM: IMPLICATIONS FOR THEORY AND TESTING

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About half of the workshop participants were convened as a Theory and Testing Working Group to examine the implications of the papers and discussions with respect to the theory of ecosystem integrity and how the concepts could be tested scientifically and practically in a rapidly changing Great lakes basin. This paper reports on the findings of the working group.

By definition, a system that has integrity is one which is complete, or can be seen as an undivided whole. It is also a system which is seen to be in an unimpaired state, one which exhibits soundness and purity. In approaching discussion of these definitions applied to the background of management of the Great Lakes ecosystem, the working groups had available to them a number of papers presented at this workshop. In one of them Vanderburg suggested wryly #at: "the growing prominence of the concept of integrity is undoubtedly the result of a widespread perception that the integrity of the natural ecology is being undermined by our modem way of life." It is clearly in this context that a section of the workshop, termed "Theory and Testing," was given the task of reviewing the more conventionally scientific side of the question of developing criteria of integrity that may be applicable at the short or intermediate time scales.

Specifically, the problem exposed to examination at this workshop was the question of whether or not the occurrence of unpredicted events, subsumed under the general designation of surprise, are indicative of some essential flaw, either in scientific knowledge or the management which has been put in place, or in our understanding of the entire basis for relating management of natural and social systems in the context of integrity to some larger, difficult to discern, reality.

Vanderburg helped to place these concerns in perspective:

> We have as a society lost track of the fact that science, like all human creations, is good for certain things, useless for others, and irrelevant to still others. In the knowledge business today we have put ourselves in a position summed up by an unknown author as follows: "If your only tool is a hammer, all your problems look like nails." Too many of our problems today are not the scientific nails we generally think they are. I will give one example. The effective regulation of the tens of thousands of chemicals in our environment, to ensure that they do not threaten the integrality of life and life-supporting systems, requires a knowledge of the overall impact these chemicals have. This cannot be a linear combination of the influences they have one at a time because of complex positive and negative synergistic effects. The best scientific tests (possible for only high-dosage, short-term exposure) and unlimited funds cannot begin to answer the question about the extent to which life is threatened. It is not a matter of more studies. An altogether different approach is required.

In an unpublished background paper for this workshop, Grima (1988) succinctly summarized the situation as follows:

> Public decisions need to be made, whether the data are in or not. Lack of information is compounded by surprise. Adaptive management would help. Its aim is to implement policies in such a way as to generate information that is not available under current policies. The success of adaptive management depends on (a) how flexible the governance is in responding to new information, and (b) the time lags in the ecosystem response to new stresses or relaxed constraints.

In responding to this large need for discovery and evaluation of the necessary methodology, it was pointed out by Allen in these proceedings that the integrity that is the manifest property of self-organizing systems is a reflection of their nature as evolving hierarchies. Within such hierarchical systems what must be recognized is:

> . . . that integrity is scale dependent, and there is no one integrity, even for a system so clearly specified as the Great Lakes ecosystem. Hierarchy

theory as it is most often applied in ecology is a theory of observation. It is a body of ideas concerned with scale, which is a matter of how data are collected, analyzed, and interpreted. It can also address the evolution of complex systems. However, I hasten to add that complexity is not an attribute of the world but is rather a matter of system description.

As Vanderburg further expressed the problem:

The technical way of life...relies not primarily on customs and traditions rooted in culture for its evolution, but on research designed to find the one best way of doing things.... The difficulty is that this process makes no essential reference to how the researched area fitted into, and after its reorganization, will fit into its context. The dominant values of our civilization, such as efficiency, productivity, cost-effectiveness, and risk-benefit effectiveness are all essentially output-over-input ratios, with no consideration of context as expressed in other values, such as harmony, coexistence, compatibility, or appropriateness of scale. Also, this technical way of life often separates knowing, doing, and managing, thus destroying the essentially self-regulating character of many activities.

Living wholes are never constituted from separate and independently existing parts the way nonliving systems are. A living whole comes about by progressive internal differentiation through which parts are created. Something of the whole is present in each part, so that the part-whole relationship is very different in a living whole from what it is in a nonliving one. Actually, some physicists, like David Bohm (1980), have suggested that this is true even of physical matter. Bohm has proposed the implicate order, suggesting that the fundamental reality is an indivisible whole from which the explicit order of our observations is derived. In the implicate order each part is internally connected to all the others and to the whole. It is only in the explicate order that we see them as distinct elements.

Human beings do not experience the categories and divisions imposed on their world through scientific and technical specialization. A person's life is not lived in separate sectors with labels such as the scientific, technical, economic, social,

> political, legal, moral, religious, and artistic. When we consider a particular action, these are dimensions of that action. Some of them may be more crucial than others, but all of them are enfolded into an action.... In order to create a less fragmented scientific knowledge base, scientific specialization will have to collaborate to achieve a common base map other than the mechanistic one used thus far. This map would be elaborated by each community of specialists in both general and specific features in an ongoing attempt to superimpose all of them.

In the opinion of the meeting, the need for such a properly comprehensive and holistic approach is not a simple neutral one, nor can it be removed from the urgency conferred by the danger of conflict. As Francis put it in these proceedings:

> If integrity can only be meaningfully defined in socio-ecosystemic terms, then a wider range of substantive criteria has to be determined and translated into operational guidelines. It is likely then, that this would pose a greater challenge to the paradigms underlying the existing arrangements for governance, and in so doing, begin to deny their basic legitimacy. This in turn could put ecosystemic integrity on a collision course with the major institutions of society, and raise questions about the prospects for peaceful transformations or success.

During a recent conversation with Grima (1988) the author discovered:

> Ecosystem integrity in the context of surprise will almost certainly result in conflicts among various stakeholders. The reasonable resolution of conflicts in a democratic society requires that stakeholders have access to information and to expertise. This will require more analysis than the usual synoptic rationality (e.g., benefit-cost analysis and multi-attribute utility analysis) so that the process by which decisions are reached is seen to be fair and reasonable. Public participation needs to move beyond information, education, and consultation to negotiation, mediation, and empowerment.

It was clearly seen as the central task of the Theory and Testing Working Group to help to move existing scientific knowledge of ecosystem integrity and surprise to a position beyond information toward the understanding that is the basis for negotiation and agreement.

DISCUSSION

Meetings of the working group had as their immediate context the Great Lakes Water Quality Agreement of 1978 (GLWQA) as amended by the Protocol signed November 18, 1987. This Agreement exists for the purpose of "maintaining and restoring the chemical, physical, and biological integrity of the Great Lakes basin ecosystem." While expressing the need for a technical definition of integrity in terms of chemistry, physics, and biology, the Agreement clearly invites consideration of the very difficult technical problem of establishing benchmarks to describe integrity in a rapidly changing environment, and of defining criteria by which progress toward the goals of the Agreement can be measured. The establishment both of benchmarks and an expected trajectory of various features of the system involves consideration of both its present state and its history. The longer existing human societies are removed from experiencing what is often defined as a pristine state, the more desensitized are the perceptions that would sustain endeavors aimed at its recovery. It was therefore agreed that restoration of the natural ecosystem to its pristine condition is not an attainable goal of the Agreement.

There was consensus, however, that restoration of a state of healthy ecosystem functioning that could be comparable to the unperturbed condition is a reasonable goal and one that can be objectively defined (Kay 1983; Kerr and Dickie 1984). Fundamentally, integrity entails a full set of coherent living systems and environmental relationships at ecosystem, subsystem, and supersystem levels. The purpose of the discussion was, therefore, to develop criteria by which observed phenomena could be judged as consistent with reasonable expectations of maintenance and rehabilitation.

SCIENTIFIC CHARACTERIZATION OF ECOSYSTEMS

Until recently, ecological analysis has assumed smooth, continuous change in variables. However, it has become clear that the internal dynamics of some systems cannot be adequately described in this manner. Some systems are characterized by abrupt transformations, and with this recognition, the analytic and mathematical tools necessary for their study have begun to be developed. Thus, for example, a phenomenon known as a cusp catastrophe has been precisely defined mathematically. When such abrupt transformations occur among biological populations they are referred to as cases of ecological surprise. It is clearly the job of those having technical-scientific expertise to put such events into the larger holistic perspective of healthy ecosystem functioning.

How surprise is viewed depends upon time scale, because it involves an interaction of fast and slow variables of the system. Slow processes embody (or engender in the observer) anticipatory behavior with which the faster perturbing events are grossly mismatched. Disturbance in a system is a subset of surprise. There are three types of surprise which may be described approximately as follows:

1) change due to disturbance in the environment (e.g., a chemical spill),

2) change in the system composition (e.g., extinction or extirpation of a species),

3) internal catastrophe (e.g., a population collapse or epidemic).

In the setting of the larger ecosystem, models of system behavior provide a means of judging the normal field of variations and the significance of particular deviations from the average expectations. It is also true that by increasing the historical component of our monitoring we enlarge our window of perception, thereby increasing our anticipatory power and reducing the chance of surprise.

Workshop discussions brought out the recognition that, on the basis of experience, these putative surprises fall into a restricted number of categories in the possible range of observed change. For example, they are often identified simply because they represent a marked change in the time scale of an apparent progression. Such events are expected as outcomes in the analysis of certain aspects of system behavior. When they reflect the actual trajectory in a nonlinear system that shows bifurcation behaviors, they are technically referred to as surprise in the sense that the particular event is not precisely predictable in the short term--even while remaining within the normal behavior of the integral large-system functioning (Holling 1987).

From the point of view of ecosystem research these perturbation events become important reference points which help to define stages in system development that need to be identified and observed as aspects of the analysis. They do not represent a loss of integrity of either the natural system or of the larger management system which observes them. From the point of view of the application of science in management, their nature needs to be better appreciated. Proper anticipation of the actual occurrence of such events should permit management to capitalize on the long-term advantages which can accrue from short-term changes. These concepts of surprise, in the context of system development, need to be distinguished from the occurrence of accidents which arise through carelessness or reactions which are attributes only of the observer's ignorance.

In defining the present state of the system, it is necessary to bear in mind that a number of different criteria need to be used. Thus, while the present state of the biological dynamics may appear to fall within bounds of normal expectations, an accumulation of various substances in the basin, or a deterioration of the physical environment, may pose a threat which would completely vitiate the value of the favorable biological index. "Policy design should begin with a dynamic description of the physical and biological system" (Holling 1978). In this same connection, there were serious questions raised as to whether, in view of immediate and long-term deleterious effects of certain pollutants, the concept of an assimilative capacity was any longer to be regarded as generally valid (cf. Cairns 1986). For some compounds, such as tributyl tin, the apparently safe loading level is so low as to prohibit any practical usage.

EVALUATION OF MEASUREMENT CRITERIA

The group undertook to identify and evaluate various measurement criteria by which the present state of ecosystem integrity can best be defined. These measurement criteria constitute a hierarchy of methodologies which are complementary from the point of view of their costs, the ease and accuracy of data collection, the requirement for detailed observations, and their value as bases for simulation modelling and for practical prediction of system behavior.

These methods were exemplified by the following classification:

I. Simple Point Indicators

a) Morpho-edaphic or physical habitat indicators
b) Presence or absence of key species
c) Incidence of pathology or disease
d) Satellite imagery of productivity types

II. Community Topological Indicators

a) Measures of species richness
b) Identification of harmonic communities
c) Patios of components in typical linkages, e.g., predator-prey, species-habitat, food-chains

III. Community Descriptors

a) Production/biomass measurements
b) Particle-size spectra

Iv. Energy Flow Networks

a) Topological food-chain/web charts
b) Analog flux systems
c) Community component compartment systems
d) Detailed functional networks of community interaction

V. Ecosystem Models

a) Complex interaction images
b) Special-purpose simulation modelling and sensitivity analyses

Some of the measurement and analysis systems have shown significant recent development and commanded particular attention from the working group:

I. Simple Point Indicators

This class of measurement system has been more fully discussed in the "Assessment of Stocks and Prediction of Yield" (ASPY) Symposium recently sponsored by the Great Lakes Fishery Commission (Leach et al. 1987), and has been specifically recognized in the Annexes of the 1987 revised protocols of the GLWQA of 1978. It was noted in the working group discussion that the use of satellite imagery for indexing productivity gradients within and between the lakes and across the surrounding land basins appears not to have been exploited to its present potential.

II. Community Topological Indicators

Attention was drawn to the apparently successful application of relative biological indicators of system integrity (Karr 1981; Karr et al. 1987). In general, the approach is to compare identified subsystems within a given type of environment with a selected standard chosen from the group. The standard may be studied in detail and other subsystems compared with it by selected criteria such as numbers of species per unit space.

The technique has the advantages of simplifying observation requirements, particularly when applied to small lakes and streams. It may have particular value in relationship to studies of tributary streams in the Great bakes Basin and vicinity. There are, however, uncertainties in relation to the functional or cause-effect significance of the indicators chosen.

III. Community Descriptors

Attention was drawn in particular to the growing field of study of biological particle-size distributions. In both small and large water bodies, this is an alternative to the traditional detailed specied topology. There is some evidence (Sprules and Munawar 1986) that particle-size spectra may be characteristic of different subsystems such as individual Great Lakes, but such spectra have not yet been studied extensively or intensively enough.

The methods of study, which employ recently developed electronic instruments for survey, hold out the promise of being effective point measures of biological system dynamics. As such, they would greatly speed up and simplify questions of dynamic interaction and lower the costs of ecosystem sampling. Until the more detailed work is undertaken, we cannot verify the significance of second-order variations in the body-size scaling of the parameters of the spectra.

IV. Energy Flow Networks

At present, the construction of complete energy transfer networks is the only system of ecosystem study for which there is an unequivocal theoretical foundation. In practice, differences arise between investigators in the elementary system description (parsing), but this does not appear to be a problem for measuring or observing systems change as long as techniques for measuring energy flow are carefully controlled. Investigators of the patterns of flow and their significance as whole-system indicators of ecosystem state are now well-advanced in specific instances.

The working group devoted particular attention to the well-developed system of analysis described by

Ulanowicz and his associates (Ulanowicz 1984, 1988). Based on the analysis of the many trophic pathways that can be measured in an ecosystem, this method develops a technically defined measure of development capacity which appears to exhibit features that index the state of development and integrity of the whole system. It has been applied to Chesapeake Bay and to a comparison between it and the Baltic Sea. It appears to provide a powerful comparative device for studying the degree of deterioration of ecosystems from their productive, non-polluted states. While requiring an extensive suite of data, these techniques of analysis are completely known and have been thoroughly tested. It appears that application to measurement and analysis of the Great Lakes is highly desirable--with the recognition of the possible need for new data collection in identifiable areas.

A great advantage of these energy-flow network methods of analysis is that the data base used is common to a number of the different analytical systems that have been developed. They therefore provide a special opportunity to chart the expected trajectories of ecosystem change. They are also amenable to study in simulation models and to generalization with respect to the behavior of the hierarchical systems that may be envisioned in relation to various ecological management objectives.

V. Ecosystem Models

Note was taken of the disappointing aspects of the outcome of the large ecosystem models developed during the International Biological Program. Aspects of the possible application of such models to the Great Lakes research programs have been described in some detail in the ASPY Symposium papers (Leach et al. 1987).

In the workshop discussions, attention was focused on the growing sophistication and experience with simulation modelling and its role in both sensitivity analysis and in the characterization of system behaviors. These more recent simulation models are particularlywell-suitedto interactionwith the energy-flow network studies described above.

CONCLUSIONS AND RECOMMENDATIONS

With limited resources and time the participants in this working group have attempted to choose from the multidimensional universe of scientific possibilities those particular techniques and ecosystem perceptions that seem best developed and appropriate to Great bakes problems. In the immediate context of scientific analysis Kerr (1976), more than a decade ago, outlined the nature of the difficulties of drawing conclusions:

> Essentially, the variables that we observe can be chosen either as emergent system variables, or as suites of internal variables. The distinction becomes important when we recognize that real objects of any kind possess an unlimited number of variables that are potential candidates for observation: the problem is, therefore, one of selection. Faced with an unlimited number of variables, together with a corresponding number of possible interactions among these, the problem of adequate system description is clearly intractable unless the representation or model of the system can be formulated so as to encompass some appropriate subset of possible system behaviors. It is my contention that appropriate selection of variables is quite unlikely unless a satisfactory description of the system is first derived in terms of its emergent properties. That is, successful internal analysis of a system is necessarily preceded by observation and theory at the external level of analysis.

For this workshop, Vanderburg expressed much the same view in its fuller philosophical setting:

> If we recognize that our world is in part composed of wholes that are enfolded into others, then the relationship between observer and the reality observed becomes more complex than traditionally assumed. Observers internalize something of their social and physical environments into their minds, so that they are internally related to their world. Hence the facts are affected by the presence of the observer, as has been recognized in subatomic physics, and is becoming recognized in other disciplines.
>
> If we are not to contribute to the...problems, our knowing must be based on at least two distinct but interdependent modes of knowing. The first derives from frontier research of the kind customarily encountered in any modern scientific and technical discipline. This approach produces an ever-greater level of specialization, trading off breadth for depth. Questions of context and broader interrelationships thus play, at best, a minor role.

> Frontier research must be complemented by contextualizing research, where breadth is emphasized over depth, including the integration of the findings of frontier researchby contextualizing them in relation to each other and their human, social, and environmental significance. In so doing, otheraspects, implications, andsignificance will be unveiled which may complement, negate, or challenge some of the finds of frontier research. Hence, the two levels of analysis are in dialectical tension with one another. Each one has consequences and implications for the other. We need to go far beyond the systems approach.

In the presence of such an important challenge, the working group on Theory and Testing chose to specify as concisely as possible their collective conception of the potential of certain frontiers that can be discerned in the state of modern ecological theory, and need to be considered in Great bakes scientific research programs. For simplicity, we adopt (as the format for the rationale of our agreements) the framework suggested by the workshop organizers in their invitation to the workshop: what is known, what is not known, what could be known, and what should be known about certain features of the Great bakes ecosystem in our continuing drive to understand and protect its integrity.

Conclusion/Recommendation #1: addressing a matter of measurement. What is known is that the energy network systems approaches applied in Chesapeake Bay and in the Baltic Sea have proven useful in typifying the state of system development.

What is not known is the extent to which such approaches would be applicable and useful in the Great Lakes.

What could be known is what constitutes the data gaps that stand in the way of placing a relative measure of integrity on the various Great Lakes subsystems.

What should be known is the variability and statistical accuracy of values for the various system linkages which could be employed in sensitivity analyses of the Great Lakes ecosystem energy networks.

Accordingly we recommend a concerted endeavor to develop within the research programs of the Great Lakes basin a broader suite of the energy network systems approaches to investigation and indexing of the ecosystem integrity. In particular we were attracted by the potential of Ulanowiczt's technical index of developmental capacity in relation to definition of integrity of an ecosystem. We commend the comparative study of several such analytic techniques in relation to data sets that could be developed for at least two of the Great Lakes or representative embayments in them. There is no theoretical obstacle in the way of also employing these methodologies for elucidation of the dynamics of the Great Lakes ecosystem in macroeconomic terms, which would include a greater appreciation of interaction with the human population.

Conclusion/Recommendation #2: addressing a matter of characterization. What is known is that certain of the simpler indicator measures of ecosystem state, including key species and harmonic species group identification, have been among the most practically useful in Great bakes research. Other measures exist but have not been explored: their applicability is not known.

What could be known, through application of a wide suite of indices, is a more comprehensive comparative picture of the state of the different Great Lakes themselves. Considering the need for reliable information for implementing the revised Great Lakes Water Quality Agreement, this more comprehensive comparative picture should be known.

Accordingly, we recommend that a selection of the point and community structure indicators of ecosystem state be investigated as special projects within the ongoing research programs. Two techniques were seen to hold particular promise as interim, yet more nearly real-time, indices of ecosystem development. These are:

1) New developments in remote sensing technology, offering an opportunity for analyses between and within lakes, and throughout the adjacent land masses.

2) Particle-size spectra for the Great Lakes themselves. The techniques are well known, but require special effort for equipment acquisition and the design and operation of surveys.

Conclusion/Recommendation #3: addressing a matter of cooperative studies. In the normal course of events, scientific studies utilize various methodologies and compare results among scientists and laboratories, and through the medium of publications and symposia. In the situation of the Great bakes, however:

1) What is known is that there is some sense of urgency in obtaining the balanced comparative picture of the lake productivity systems.

2) We do not yet know the power of some of the techniques that have been developed elsewhere, nor can we judge their usefulness to management concerns without application to the systems in question.

3) We could and should be able to apply the latest knowledge available without the delays which arise in the absence of institutional support.

Finally, we recommend that the IJC and GLFC further encourage the cooperative development of the aforementioned special technical studies through devices such as the joint evaluation of the techniques by scientists and laboratories both within and outside the immediate Great Lakes area. Such data and technique evaluation should be specifically supported by the development and study of ecosystem simulation models, designed to examine questions of stability, resiliency, and potential trajectories of the various lakes, in relation to the likely scenarios of development in the adjacent land basins.

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INTEGRITY AND SURPRISE IN THE GREAT LAKES BASIN ECOSYSTEM: THE PERSPECTIVE HIERARCHY THEORY

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ABSTRACT. Integrity and surprise represent opposite sides of the same coin. The integrity of a system comes from its ability to incorporate disturbances into its normal working. Surprise comes when the system is not prepared to deal with those disturbances. For the system, the surprise is a disturbance that uncouples some relationships and couples other new ones. For us, the observers, the surprise is not the disturbance itself, but the unexpected behavior that follows the changes in system relationships. The surprised system remains as an out-of-equilibrium subsystem inside an integrated upper level that emerges to incorporate the surprise. Subsequently, new surprises destroy the integrity of the present system, and a new integrity must be established. From repeated cycles of surprise and integration, a complex hierarchy of contained surprised subsystems emerges as the present integrated system.

Understanding surprise and integrity is, therefore, a matter of scaling one's observation so as to address the system at the appropriate level of integrity. Managing for integrity has to face the irreversibility of the surprise/integrity cycle. The integrated Great Lakes fishery that existed before the introduction of the sea lamprey (<u>Petromyzon marinus</u>) remains for the most part, but as a subsystem held out of equilibrium by different predation pressures on different species and the consequences of that on competition. Since the lamprey surprise, the lamprey population itself has been surprised by human intervention and by parasites and diseases. However, the original integrity of the primeval fishery has not been reestablished, because there was something irreversible about the first lamprey surprise. It is the new integrity, the one that constrains the lamprey, which is the integrity of consequence now.

INTRODUCTION AND DEFINITIONS

This paper intends to give an outline of ideas from hierarchy theory that are pertinent to the relationship between surprise and integrity. It is possible to express the ideas of other theories that are relevant in terms of hierarchy theory. Self-organizing systems can be described as evolving hierarchies. The insights of hierarchy theory into unpredictable systems and disturbance can be woven together into the notion of surprise. The bottom line will be that integrity is scale dependent, and there is no one integrity, even for a system so clearly specified as the Great Lakes ecosystem.

Hierarchy theory as it is most often applied in ecology is a theory of observation (Allen et al. 1984). It is a body of ideas concerned with scale, which is a matter of how data are collected, analyzed, and interpreted. It can also address the evolution of complex systems (O'Neill et al. 1986). However, I hasten to add that complexity is not an attribute of the world but is rather a matter of system description (Allen and Starr 1982). Before we go any further it is necessary to define some of the words that I have used above.

Scale

Scale is determined by the manner of observation. The largest scale entity that can be observed in a given set of observations is determined by the extent in time and space of the whole set of observations. For example, studies conducted only in summer cannot address entities as large as the annual cycle. The smallest scale entities that can be distinguished are determined by the grain of the finest difference between individual observations. It is the level of resolution. Distinctions between plankton behavior at different times of day cannot be made if samples are taken at daily intervals.

Levels of Organization

Levels of organization are populated by entities of a given scale. Thus, the observation protocol determines the level of organization that appears.

Complex Systems

Complex systems are those that require several disparate levels of organization for their adequate description. Larger systems are not necessarily more complex. For example, a model of the whole globe may require only one number for the entire atmosphere. Perhaps a simple statement of carbon dioxide as an average from several sites would be good enough. That description would be simple. On the other hand, that one number may be a projection of global carbon at a particular time in the future, with implications for global warming. That could involve knowing gas balances for the ocean divided into more than two layers, models of fossil fuel burning, models of deforestation, not to speak of global circulation patterns and volcanic activity. Then the atmosphere alone would be a complex system. Complexity is a matter of the question that is posed and the disparate scales of the observations that are required for an answer.

THE EMERGENCE OF COMPLEX SYSTEMS

The involvement of several levels of organization in a question requires the linking of differently scaled entities. Just because we can look at the world at different scales, it does not mean that we will find entities at all scales, and does not mean that there is any link between differently scaled entities. Thus, although complexity is a matter of the question asked of nature, only some questions are valid or have answers, because only some questions involve configurations and links that are observable. If the world is never in the required configuration, no matter how we look at the nature, we will never see the levels implied in the question. How do these systems involving differently scaled linked entities, namely complex systems, come to exist so we can observe them? The answer brings into play an interaction between integrity and surprise.

The apparent discrete scales between the levels of organization in a complex system arise through discrete surprises that break the integrity of the system in its primitive state (Allen and Starr, 1982). The surprises are symmetry-breaking events that occur in the evolution of nonequilibrium self-organizing systems discussed in other papers in these proceedings (Prigogine and Nicolis 1971). The course of this evolution through perturbation generates successively larger and longer term entities, the things at the top of the evolving hierarchies.

Integrity comes about through the establishment of negative feedbacks. Every entity is the manifestation of a negative feedback. Negative feedbacks return a signal to the source so as to nullify the effect that generated the signal in the first place. They are self-correcting loops that engender stability. Positive feedbacks destabilize the system because the returning signal amplifies the deviation that caused the original signal. A stronger signal is then transmitted and so on. Surprises set in motion positive feedbacks.

The destruction of the old negative feedback equilibrium condition is generally effected, not by the force of the original disturbance, but by the old system conducting business as usual from an unstable configuration. For example, gravitational force and center of gravity hold the cup on the table: it is those same considerations which tip the cup over when it is placed too close to the edge (Allen and Hoekstra 1986). Often it is a delay that is introduced into the negative feedback that destabilizes the system. A negative feedback with a delay will oscillate because the stabilizing signal returns through the loop too late to bring the system back to equilibrium. With a long enough lag introduced, the signal that should have been a stabilizing influence returns at exactly the wrong time and causes a further deviation from the set point. The oscillations themselves get into positive feedback.

The different parts of an equation and the processes which they represent, have different degrees of responsiveness and different relaxation times. The most sluggish parts of the system are therefore lagged in their response relative to the fastest, most reactive parts of the system, even in a stable negative feedback. Holling and Swing (1971) showed how greater displacement from equilibrium tends to increase that intrinsic relative lag by making the fastest part of the system ever more responsive. With a big enough displacement, this usually brings about unstable oscillations. The displacement is brought about by the surprise. Sometimes the surprise is the introduction of a critical component of a new positive feedback. The introduction of the sea lamprey (Petromyzon marinus) is a case in point. A few individuals exploded in positive feedback to result in epidemic populations of the parasite and the collapse of the fishery.

Once the amplifying positive feedback is set in motion, the old regime is pushed further and further from equilibrium. In the evolution of complex systems, this is only the beginning of the emergence of a new level. Sometimes the substance of the system is destroyed and the system loses the integrity of its upper level entities and becomes a simpler, less hierarchical system. Alternatively, the system may discover a new boundary condition that constrains the raging positive feedback. That constraint becomes the new negative feedback, which embodies the new emergent upper level entities. Inside every negative feedback is a positive feedback trying to get out. The boundary is a negative feedback that returns the system to some condition inside its domain every time there is a tendency to exceed its limits. The tendency to exceed the limit comes from the contained positive feedback. The boundary becomes a new equilibrium. Meanwhile the old system is held out of equilibrium inside the new system. The old system is held as a constrained positive feedback. A new integrity has been established.

The technical phrase for the process described above is: collapse to a higher level of organization through incorporation of disturbance (O'Neill et al. 1986). Consider a vegetation that has never burned. The first fire destroys all that is susceptible to the blaze. Some plants like tall trees, however, will not burn, while others like some grasses, may have their growing point below ground, protected from the fire. Other plants may be able to invade quickly into the openings that have been created. When the next fire comes, it addresses different vegetation than did the first fire. Repeated burning selects the vegetation so that it is now very resilient in the face of fire. At this point, the fire is a friend to the plants that are present, for it takes out the opposition. Fire ceases to be a disturbance and has been incorporated into the system. Allen and Wileyto (1983) showed how the disturbing effects of fire pertain only to short-term aspects of fire-adapted vegetation, and that fire is also important for the long-term maintenance of prairies. The longer-term considerations involve a higher level of organization, which is large scale enough to co-opt the perturbation and make fire part of the system. The first fire is a surprise. The last fire is a reflection of integrity.

PREDICTION AND SURPRISE

There are three sorts of systems that are pertinent here: small-number, large-number, and middle-number systems. Analysis of small-number systems involves writing an equation for each part. A planetary system is a case in point. Large-number systems are also predictable because they have so many parts that the parts can be subsumed in a small set of reliable means. The gas laws work in this way on the reliable average particle. The troublesome systems are those called middle-number systems, where there are too many parts to model each one, but not enough parts to subsume their individuality in any representative value, such as a mean. In middle-number systems the patterns of constraint are unreliable. Any individual part can affect the outcome of the whole. This is again a matter of the question being asked, for being a middle-number system is a matter of how the system is specified. As we shall see, middle-number systems are surprising in the technical meaning of the word surprise.

When a system becomes unstable, the old constraints are broken by some part getting into positive feedback. Being system parts, the entities involved in the positive feedback behave rapidly relative to the whole. That is why the collapse of unstable systems is fast: some critical part gains control. Surprises are by definition unpredictable. Middle-number systems are unpredictable because the whole system is surprised as it loses control to some high-frequency system part. An important characteristic of surprise is that it involves disparate reaction rates (C.S. Holling).

INTEGRATED MANAGEMENT

Even at its most degraded, shallow Lake Erie had integrity, in the terms defined above. Erie had incorporated devastating disturbances of toxic substances and nutrients. True, its biota had become simplified, but what had survived formed an integrated system. The pathways of cleansing remained intact, and in a remarkably short time after the load was diminished, the larger, relatively unaffected deep lakes flushed through bake Erie, part of the integrated system, and brought about a significant recovery.

If integrity is manifested by a Great bake ecosystem in a degraded state, then clearly a simple demand for integrity is not what the International Joint Commission's mandate is intended to mean. Somehow integrity must involve health: the organization that emerges to deal with disturbances should not be degraded. Also, the integrity should significantly involve the human creature with its wishes and needs as an integral part of the system. We are not, therefore, asking for an integrated pristine ecosystem.

Consider the issue of water level control in the Great Lakes. Although we have recently come through a crisis of high water, low water is becoming a significant factor expected to remain for the next few years. Climatic fluctuations appear to influence lake levels on approximately a ten-year cycle. A principal source of water removal is evaporation, which is a major driver in the climatic influence. We cannot conceivably do anything about it, so we must turn to other avenues of control. We have done our calculations and discovered that our potential ability to control levels through increased flow is minimal--two-tenths of an inch here and a quarter-inch there, if we are lucky and thoroughgoing. Therefore, an integrated approach using all possible diversions alternated with conservation would be necessary to control lake levels. Furthermore, these efforts would have to occur over many years time and in anticipation of problems which have not yet come to pass. Note how such a large-scale force as climate over decades demands a response integrated over a very large scale. If the integrated Great bakes with their human component is to contain the influence of the extrinsic climatic force, then long-term management applied over years across the entire system is the only hope. Cur management must become an integral part of the entire system.

INTEGRITY SURPRISE AND IRREVERSIBILITY

Each manifestation of integrity is predicated upon an old surprise. Each surprise goes to work on an old integrity. The important point to note here is a critical irreversibility in this process of alternating positive and negative feedback. Should a new higher level itself become destroyed and give way to a lower level configuration, there is no reason to suppose that the primitive, small-scale system that was contained in the recently collapsed system will be reestablished. Some other lower level configuration will in all likelihood emerge instead. Remember that the old, primitive system will have been made unstable some time in the past, only to be saved from total obliteration by the higher level, which has itself now disappeared. Remove the saving constraint, and the old order will be left naked and unstable, ready to decay to a yet lower level.

This has profound consequences for the mandate of the International Joint Commission to restore and maintain the integrity of the Great Lakes ecosystem. The irreversibility of the process of evolution in complex systems means that we cannot return to some desired earlier system state. Cur only option is for new highly integrated states, set in the history of past events. For example, we cannot restore the integrity of the Great Lakes fishery so that it is returned to the state before the invasion of the sea lamprey. We can, however, integrate the lamprey into the system, and we have made significant progress in this regard. Instead of epidemic populations which devastate the fishery, it is now a relatively low-grade endemic consideration. Presumably humans are not entirely responsible for the improvement, because it is characteristic of invaders that they explode in the absence of their own pest load, only to acquire new Rests or have old virus loads catch up with them. However, we can take some of the credit for integration of the lamprey into the system, with programs like those that minimize breeding sites.

It is not an option to remove the lamprey completely. First, it would be very expensive to do so by any means. Second, there probably exists no means whereby **total** extermination of the lamprey could be achieved without huge damage to other parts of the ecosystem. To imagine that extermination is possible is to misunderstand the process of achieving constraint over system parts and disturbances.

Integrity comes through constraint. Constraint is not a matter of control in fine detail of the behavior of the thing which is constrained. Rather, the upper-level constraint operates at a low frequency, and is intransigent in the face of the constrainee. Constraint does not say what will happen in particular; it only says that such and such will not happen. Constraint of the lamprey does not mean driving it to exactly one prescribed state, namely zero. We have to live with the history of the canal that let the parasite into the system. Applying a constraint that will contain the lamprey at zero everywhere in the entire system involves something which is too particular given the scope of the problem. Such a constraint would necessarily be a devastating perturbation in its own right. We could poison every one of them, but that would kill everything else, including some of us.

Living with history is not that bad. We have made major advances in the fishery, particularly as an integrated part of the whole. It appears that the clarification of the waters of Lake Michigan is in significant part due to top-down control of the system from the introduction of salmonids. The big fish prey on the small fish. The depressed small fish fail to contain the growth of zooplankton. The abundant little animals crop down the algae, and clarify the lake beyond our hopes (Kitchell et al. 1988). Now that is what I call integrated control.

CONCLUSION

From the foregoing discussion, I hope the reader has come to understand that integrity is a matter that changes its case-specific characteristics when a new question is asked. There is no one integrity, even for something as explicitly stated as the Great Lakes ecosystem. If we try to find the one true integrity of the system, we will become quickly mired in exceptions and unwarranted, unhelpful details of special cases. Tempting as it may be to intuit a real Great Lakes ecosystem, such a reification is counter-productive. As scientists we rely upon observations. The value of a hierarchical approach to questions of integrity and surprise in complex systems is in the way hierarchy theory tethers the scientist to his observations. All science is ad hoc. Just because it is a big system, there is no reason to be vague about the Great Lakes ecosystem. The integrity we seek in our management of this part of our world will change depending on the questions we wish to ask and the management goals we have. Certainly integrity should be part of our management, but it will be a different integrity depending on the surprises around which we manage.

With the coming of powerful computers, the quantitative aspects of prediction and modeling are, for the most part, workable. The hard part is not quantification but identification. If we do not model the right things with the right things as parts, we can never solve our problems. I mean more here than "garbage in gives garbage out." True, inaccuracy will lead us astray, but that is not the problem we face most often. What is hard to put into the computers today is smart system specification. First, know the question you are asking. Second, find out if is of the type that has no answer. If so, ask something else. Know that the questions we ask, and the surprises we and the system specify, will be scale- and level-specific. Given that surprise and integrity are linked, the integrity of the system is level- and question-specific.

It is a mistake for natural scientists to be self-satisfied about their knowledge of the working of their physical and biological systems. When it comes to management of a large ecosystem, the human and political system is critically integrated into the system. The biologist, chemist, or engineer who works in the context of human activity must focus his efforts on what is politically tractable. A model that tells us what would happen to levels of toxic substances in fish if we cut back the source will do very little good if we have no means to effect the cutback. The integrity and surprise of the Great bakes ecosystem require us to wrestle with the human cultural beast as well. The qualitative, flexible, and general approach of hierarchy theory may help.

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THERMODYNAMICS AND ECOSYSTEM INTEGRITY

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ABSTRACT. This analysis introduces some ideas from nonequilibrium thermodynamics: the maximum entropy formalism, the chemical reaction analog method of modeling physical and biological processes, near-equilibrium and far-from-equilibrium systems, and the origin of dissipative structures. Then, thermodynamic approaches are applied to some specific and increasingly complex situations: free energy transduction and minimization of entropy in biochemical cycles as a principle of biological organization, a principle of parsimony in the optimization of an organism's biochemical machinery to accomplish energy transduction, cooperative behavior (cooperativity) in biological processes at several levels, switching processes, entropy-enthalpy compensation as a mechanism to enhance low energy penalty switching of biological and ecological processes, and the hypercycle and fitness criteria as a means of studying evolutionary systems. Finally, an ecosystem-level problem related to the carrying capacity of the environment and the exploitation of resources by species communities is briefly discussed. This leads to some thermodynamic speculations on niche theory and a reinterpretation of embodied energy for ecological systems. From these discussions, a brief list of what thermodynamics and its methods can and cannot do, is provided.

INTRODUCTION

This paper examines some aspects of thermodynamics which might assist in gaining some insights into the issue of the integrity of ecosystems. The author was asked originally to discuss two topics, embodied energy and dissipative energy structures. Considering the thermodynamic nature of both topics, the author felt a more unified discussion of topics from thermodynamics that might assist in an understanding of ecosystem integrity was preferable to separate presentations on embodied energy and dissipative energy structures. Other workshop papers address the important topic of dissipative structures in greater detail, and only the most general references to the topic are provided herein.

HISTORICAL PERSPECTIVE

In the classical heat-power thermodynamics of mechanical engineering and thermal physics, entropy was defined as the integral of the ratio of embodied energy to temperature. Neither definition conveys the philosophical basis of the concept of entropy nor gives insight into the term embodied energy.

By combining the definition of entropy with the Second Law of Thermodynamics, embodied energy becomes a form of internal energy. Unfortunately, internal energy is not a convenient parameter in biological studies, but further mathematical manipulations of the energy balance equations for a given system yield relationships between internal energy and other more useful thermodynamic parameters.

Thermodynamic approaches in biology occur in Lotka's early papers (1925), but the author considers the modem applications of thermodynamics in ecology to have begun with Lindemann's (1942) work on the energy flow and trophic structure of ecosystems. Odum (1971) followed with a circuit language from analog computer methods and then considered biological and sociological applications. He emphasized the calorimetric or power production aspects of the analysis as a common currency in evaluating systems. He also popularized the term embodied energy in biology within the context of the ecological power production. Morowitz (1968) introduced linear noneguilibrium thermodynamics.

A DEFINITIONAL PROBLEM

Applications of thermodynamic approaches and methods to all levels of biological organization depend on formulating chemical process and reaction analogs for the biological processes. This achieves a critical purpose: a modeling context with an extensive and refined theory, including the immediate formulation of many biological processes as density-dependent rate laws (the analogs invoke the Law of Mass Action).

The goal is to examine the integrity of ecosystems, a concept without a coherent inclusive definition. Ecosystem integrity is currently described by its collective parts or attributes with the comment, "and more." By removing the "and morel" and treating integrity like an undefined term in mathematical logic and predicate calculus, then as theory develops, the undefined term becomes whatever the axioms, definitions, and theorems make it--the product of its attributes, "and nothing more."

Integrity implies some form or structure such that one can recognize a change. Hutchinson (1953) was one of the first biologists to discuss a concept of pattern, and his views could assist here.

Early concern with integrity followed the passage of amendments to the U.S. Clean Water Act. That legislation called for protecting the integrity of indigenous biota, a concept intuitively different from protecting the integrity of ecosystems. To protect biota, one first documents the existing biota of a region to establish a baseline, and then formulates strategies to maintain those biota in their various communities. Unfortunately the resulting perspective is limited. It freezes a system's state, ignores evolutionary possibilities, and sometimes intellectually separates biota from ecosystems--especially if the baseline is mainly a list of native plant and animal species. By themselves, species lists suggest random species assemblages which a priori cannot be assumed to have recognizable structure.

THE MAXIMUM ENTROPY STRATEGY OR FORMALISM

Entropy ranks foremost among the thermodynamic functions used in analysis. One very useful entropy-based method of analysis is the maximum entropy strategy, sometimes called the maximum entropy formalism (Montroll and Shlesinger 1983). The formalism exploits the Boltzmann equation, a mathematical relationship between the entropy of a system and the statistical probability distributions underlying the system's descriptive parameters. Using the calculus of variations (Pontryagin's approach) the Boltzmann equation is maximized, subject to certain constraints of the problem being investigated. The formalism has had many successful applications and appears to be receiving some renewed interest.

Boltzmann did not conceive his entropy formula as a thermodynamic entity. As Dr. Michael Shlesinger has so charmingly pointed out to the author, Boltzmann considered entropy as a purely mathematical tool to address problems having great uncertainty. Boltzmann wanted to infer the probability distributions associated with certain parameters of the systems of interest in order to address the statistical properties of the system. He lumped uncertainties and unknowns together, interpreted them as entropy, and using brilliant intuition, decided to maximize (in a mathematical sense) this entropy and examine the results. J. Willard Gibbs' ensemble methods of macroscopic statistical thermodynamics revealed that the Boltzmann formula was the thermodynamic entropy for systems having particular properties, but differing only from the desired numerical results by a mathematical coefficient with appropriate units. The coefficient was the Boltzmann constant. All entropy formulae isomorphic to the Boltzmann formula differ by a coefficient which determines the units.

The formalism works best if the statistical probability distributions inferred possess finite second moments (finite variances) and preferably finite higher even-moments, and mathematical differentiability. A few probability distributions, such as Cauchy and Levy distributions, violate the former requirement, and the Weierstrass distribution violates the latter requirement. One can study systems having these probabilities by the maximum entropy formalism, but the constraints required by the formalism entail some esoteric and difficult-to-justify mathematical forms.

The Levy and Cauchy distributions are both highly skewed with long tails, and are of interest because they have recently been associated with data structures having fractal properties. Some recent work has begun which examines the fractal aspects of biology including the fractal properties of ecosystems. Such properties are being analyzed directly from the appropriate probability distributions without using the formalism.

SOME NONEQUILIBRIUM THERMODYNAMICS

This section provides background information, and could be skipped by the knowledgeable reader. Nonequilibrium thermodynamics concerns systems not at equilibrium. The entropy of any system, equilibrium or nonequilibrium, can be split into two parts:

1) entropy originating internally from a system's processes, or the entropy production; and

2) entropy originating externally and flowing in the system, or the entropy flow (the nomenclature favors entropy exchanges even though it retains the terminology of entropy flow).

Ecologists usually deal with energy production and transfer (flow) rather than entropy production and flow. The relationships between energy production and flow and entropy production and flow depend on the specific situations. Most of the discussions in this paper refer to entropy production rather than entropy flow because of the concern with internal cellular processes.

Organisms accomplish many tasks through biochemical reactions. Each reaction and process theoretically has an inverse (back reaction), but an organism's needs may block some inverses and cause other reactions to operate irreversibly. The thermodynamic driving force for all processes is a function called the affinity, originally derived by the French physicist deDonder as a weighted combination of the chemical potential functions for all contributing reactions and processes to the system being analyzed. At thermodynamic equilibrium, the affinity is zero (chemical potentials are balanced) and all processes and reaction rates are zero (reactions and inverses are equal--a condition called detailed balance). At nonequilibrium steady states, the affinity is nonzero and only the process and reaction rates are zero. In *other* states, the affinity, and process and reaction rates are nonzero.

Many systems obey a local equilibrium rule, which means simply that the system behaves as though it were in thermodynamic equilibrium on a microscale, but the overall macroscopic system is not at equilibrium. Local equilibrium permits the use of ideal forms of thermodynamic equations on a microscale and highly simplifies the analyses. Noneguilibrium thermodynamics is most highly developed for systems which obey a local equilibrium assumption, and indeed, this condition must often apply for certain kinds of thermodynamic analyses to be valid. Local equilibrium is assumed in this paper.

Noneguilibrium thermodynamics considers the problems of time-dependent entropy. The analysis begins with the time derivative of entropy as a sum of appropriate entropy flow and entropy production terms expressed as a summation over products of forces and fluxes. Thermodynamicists call such products force-flux relationships. Considerable leeway exists in selecting and describing appropriate sets of forces and fluxes, but a basic requirement for any given choice is that a force and its associated flux be of the same tensor rank. For chemical processes without vector properties (e.g., most reactions in a gas phase or solutions), the force is the affinity function divided by the absolute temperature, and the flux is the rate law expressed according to the Law of Mass Action. For chemical processes with vector or tensor properties (e.g., reactions which can occur only on biological membranes in a specific conformation), the same forces and fluxes apply, but they must be expressed in appropriate vector or tensor form rather than simple algebraic form.

Force-flux relationships do not always provide an explicit separation of entropy production components from entropy flow components. The separation occurs directly if the forces and fluxes are expressed by appropriate Taylor series expansions in a common variable. For specific models, the coefficients of the linear terms of the Taylor series must obey a special rule known as a reciprocal relationship (Onsager 1931). From the valid possible choices of expressions for forces and fluxes, one picks (often by clever guess) the forms which yield the desired reciprocal relationship.

A process operates irreversibly if it has a high affinity from either the continuous inputs of energy and/or materials or continuous removal of products, or both. Biotic communities operate at high affinity through their dependence upon continuous inputs and cycling of energy and nutrients. Systems operating at high affinity are far from equilibrium. The distance from equilibrium (near or far) is a basic idea which delimits the power of thermodynamics in evaluating the evolution of systems. Systems near to equilibrium evolve predictably toward that equilibrium, and evolution is said to follow the trajectory (pathway) of the thermodynamic branch. Predictions about evolution along the thermodynamic branch are independent of the modeling context, and specialized models of system behavior, such as chemical reaction analog models, permit generalized comments about near-equilibrium behavior. Systems far from equilibrium do not always evolve predictably. Initial states, modeling context, and mechanisms matter. This is again seen in the force-flux relationships where reaction mechanisms define the mathematical form of the flux expression. Stability is also important, as stochastic and chaotic events (e.g., climate changes, epidemics, chemical spills) affect systems.

Thermodynamic analyses of systems far from equilibrium may reveal multiple evolutionary trajectories and outcomes, of which the thermodynamic branch and its outcomes comprise only one choice. The actual pathway may differ from the thermodynamic branch, and the favored trajectory and its associated outcomes may not even be predictable. The Second Law of Thermodynamics prescribes that entropy production have a zero or positive value, but does not restrict entropy flow, which may assume zero, positive, or negative values. Theoretical estimation of entropy flow depends on a knowledge of the system dynamics forming the force-flux relationships, a situation occurring mainly in a few model systems. The author gratefully acknowledges Professor Robert Ulanowicz's comment that physical measurement or estimation of entropy flow in ecosystems is comparably impractical if not impossible. Without a knowledge of the entropy flow, the total value of the time-dependent entropy is unknown, and that means it is impossible to predict favored trajectories and outcomes. Thus, thermodynamics does not provide a general theory of evolution in far from equilibrium situations.

A few systems have predictable evolutionary trajectories and outcomes no matter how far from equilibrium they are. These include

1) the isolated system (system exchanges neither energy nor materials with the surroundings): and

2) the closed and open systems (a system exchanging energy but no materials with the surroundings, and a system exchanging both energy and materials with the surroundings, respectively) in which all the rate processes have linear phenomenological (rate) laws.

An isolated system has no entropy flow, and evolves to a state of maximum entropy whereupon it ceases to change. Ecological examples are organism death and species extinction in isolated environments. Closed and open systems with only linear rate laws evolve through a suite of predictable steady states to a final steady state of minimum free energy (not always a thermodynamic equilibrium) consistent with any external constraints on energy and material flows. An analysis of force-flux relationships in systems with linear phenomenological laws shows that both entropy flow and entropy production are positive. All final states are stable and withstand perturbations or fluctuations in various parameters. Ecological examples include autotrophic growth in a nutrient-limited environment and diffusional processes in marine plankton leading to patchy and nonpatchy biogeographic distributions.

Most ecological systems of interest are open and have some nonlinear dynamics. What happens then? A unique thermodynamic equilibrium still exists. Near to equilibrium, the force-flux relationships are linear, a consequence of truncating the Taylor series expansions of these relationships at the linear terms. Thus, nonlinear systems have linear dynamics and behave like linear systems: they follow the thermodynamic branch. Far from equilibrium, the force-flux equations are nonlinear. Depending on the nonlinearities, the analysis may reveal one or more of the following:

1) multiple evolutionary trajectories,

2) multiple steady states, or

3) a critical point (a bifurcation) at a certain value of the thermodynamic affinity at which the evolutionary pathway can change.

For systems of interest, the evolutionary pathway changes at the bifurcation from the thermodynamic branch to a new branch, leading to a new structure. That new structure, called a dissipative structure, explains why systems far from equilibrium and highly disordered can produce new and unexpected ordered structures. This is the new order out of chaos (Prigogine and Stengers 1984) studied intensively by Prigogine and his co-workers.

For mathematical models of the biological systems in the required chemical analog format, Glansdorff and Prigogine (1971) provide a method to locate the bifurcation, if one exists. They examined the excess entropy function, a special form of the second-time derivative of entropy for a given system, expressed in terms of fluctuations in the force-flux relationships;

Evolutionary trajectories shift at the bifurcation because the original pathway becomes unstable with respect to a perturbation or fluctuation in some factor. The study of dissipative structures is the study of the evolution of system stability, with stability here being what ecologists call resilience--the ability of a system to attenuate a disturbance.

To amplify the previous ideas, note that ecosystems are open systems, and several important ecological processes have nonlinear rate laws. A prime example of a nonlinear rate law is the Lotka-Volterra model for predator-prey dynamics (Montroll 1972, May 1973).

A thermodynamic study of a mathematical model of a biological system uses Glansdorff and Prigogine's method to extract the evolutionary trajectories and their associated steady states. A system having a single trajectory and one steady state requires no further analysis. For systems with multiple trajectories and/or possible steady states, then stability and fluctuation analyses can sometimes be used to assess the relative likelihood that a particular trajectory is favored under assumed external and internal conditions.

BIOCHEMICAL CYCLES

A few important biochemical reactions occur alone, but most reactions are parts of reaction chains and cycles to accomplish some task related to growth, reproduction, movement, foraging for food, detoxification. Free energy transduction--direct energy conversions of stored chemical energy for various uses--fuels all life-sustaining processes. These processes have frictional losses (entropy terms).

Hill (1977) showed that cycles; not individual reactions, accomplish free energy transduction in biological systems. The study of a single reaction is simple and often important, but the study of cycles is more appropriate for analyzing higher *order* processes or phenomena. Thus, cycle entropy (the sum of the stoichiometrically weighted entropy contributions of the reactions and reactants in a cycle) is the main entropy to analyze. When the cellular environment can be approximated as a closed system, entrophy production dominates the total time-dependent entropy. Most of Hill's analyses concern an organism's internal dynamics: thus, entropy flow is zero. Where entropy flows occur, he provides specific models of the force-flux relationships. For example, when individual reactants or products enter or leave a cell, an entropy flow term arises in accordance with the physiology of the organism. Biological systems at all levels of organization evolve to maximize free energy transduction (maximum efficiency in energy use and conservation) and minimize the frictional losses. This can be accomplished through managing the entropy production of organic processes as well as taking advantage of appropriate entropy flows where possible. This is a basic strategy of biochemical and ecological organization.

Biochemical cycles are coupled; the products of one feed into another via common reactions. The small number of common chemicals (e.g., ATP, acetylcoenzyme-A, succinate, glutathione) observed through these various reactions suggests a principle of parsimony in chemical reaction processes to guide the minimization of cycle entropy. Each reactant and reaction contributes entropy terms to the cycle entropy. Organisms can minimize the cycle entropy by evolving in ways that:

1) reduce the number of different chemical entities needed in all biochemical reactions;

2) reduce the number of different chemical reactions utilizing a specific chemical:

3) reduce the total number of reactions forming a specific cycle:

4) reduce the number of cycles needed to accomplish a given task; and

5) maximize the use of components which recover, store, or conserve energy between steps.

In the above ways, organisms optimize biochemical aspects of their physiology. The sequential or systematic application of the above strategies illustrates Bellman's Theorem of Dynamic Programming applied to the optimization of biochemical pathways.

The optimization of biochemical pathways produces cycles that are either strongly coupled or weakly coupled. Strongly coupled cycles have a critical step, a common intermediate and chemical reaction, which acts as a control or switch. Weakly coupled cycles often induce biochemical redundancy, the development of multiple cycles capable of accomplishing the same task, or multiple uses of common reactions and intermediates to create bypasses and shortcuts between cycles. Redundancy is sometimes an evolutionary basis for defense and repair mechanisms when something goes wrong biochemically. Consequences of specific optimization results are discussed later.

STRONGLY COUPLED SYSTEMS AND COOPERATIVE BEHAVIOR

Strongly coupled systems tend to exhibit a property called cooperative behavior or cooperativity which thermodynamics is well-suited to analyze. The treatment of cooperative phenomena is identical to the analysis of chemical equilibria involving two or more distinct, co-existing, highly organized structural states or phases. Phase transitions are classical physical examples of cooperativity, and some scientists designate cooperative behavior in biochemical systems as higher-order phase transitions. Thermodynamic analysis very often reveals that systems increase in organizational complexity as their subsystems increase in cooperativity. Poland (1978) provides an extensive review of cooperative biochemical systems.

Cooperativity occurs in processes at all levels of biological organization and, thus, ultimately affects ecosystem integrity. Individual cooperative reactions include the oxygen transport in various animal systems through binding to blood pigments. The electron transport chain of oxidative phosphorylation provides an example of cooperativity in a series of interlocking reactions.

Ascending a hierarchy of levels, cooperativity in a unicellular organism underlies the development and use of pseudopodia for movement in Amoeba, and cooperativity in a multicellular organism underlies the function of organs. cooperativity is manifested in species-level processes such as encysting or colony formation in unicellular species, and herding and mass migration in multicellular species. At the population/community level, cooperativity is manifested in commensal and symbiotic processes. Finally, at the community/ecosystem level cooperativity is manifested in the dynamics of nutrient and energy cycling in trophic levels. cooperativity is not cooperation, although the germ of the idea is present. At the ecosystem level, cooperativity produces cooperation.

Systems with strongly coupled cycles are especially *vulnerable* if the coupling unit is disrupted. The disruption of a coupling unit in one cycle permeates every *other* cycle which has that common entity, even if that entity does not control other cycles. Thus, disruption may extend beyond the immediate to jeopardize an organism's entire biochemical machinery and even result in organism death. When cycle disruption does not involve an immediately critical function, the organism may adapt to the disruption by activating biochemical systems dependent on only the remaining undisrupted biochemical reactions. This incomplete biochemical system sometimes produces undesirable effects, like tumor formation, disease, *or* uptake and accumulation of toxic residues, especially if the disrupted biochemical machinery involved the defense or repair systems (immune systems) needed to block the undesirable effects.

Existing biochemical systems reflect evolutionary adaptation to a specific chemical environment. The discharge of new chemicals as well as the unchecked build-up of otherwise nonproblem chemicals represent stresses not anticipated and therefore not factored into the evolution. Preserving ecosystem integrity entails, among other things, preserving the biochemical systems which maximize free energy transduction in organisms and maximize energy flow through an ecosystem with minimum biochemical disruption.

SWITCHING, ENTHALPY-ENTROPY COMPENSATION, HYPERCYCLES

Common chemical intermediates and reactions not only couple cycles, they act as switches to activate cycles, change their direction, or deactivate them. At certain critical temperatures, some switches are chemical equilibria with zero Gibbs free energy, and permit switching to occur without an energy penalty. Excess reactants or products, as well as their relative rates of input, removal, or accumulation, control switching (Le Chatelier's principle). If temperature changes, switching without energy penalty may no longer be favored, even in the presence of excess input materials or products. This is a situation where the entropy flow becomes a critical determining factor.

Thermodynamic methods treat switching without energy penalty as a competition between process enthalpy and entropy (both terms in the free energy equation are equal at the switching temperature). For small temperature fluctuations, either enthalpy or entropy can control. If the temperature dependencies of enthalpy and entropy of cycles near the switching temperature are damped, switching is enhanced. The damping process creates a range of temperatures within which no energy penalty or very low energy penalty switching can occur.

Some biological systems and several purely chemical systems have an important damping mechanism called enthalpy-entropy compensation, which is a linear relationship between the enthalpy and entropy of a switching process over a small temperature range around the switching point. The temperature at the switching point is called the compensation temperature. An enthalpy-entropy compensation equation is extrathermodynamic as it cannot be derived from fundamental laws of thermodynamics except in some mathematically trivial cases. The observation of such behavior is usually correlated with some aspect of the dynamics and behavior of the water molecule, either as a reaction constituent or as a solvent, in a cell or as part of an external life support medium. The evidence for and theories about enthalpy-entropy compensation rules are discussed in the papers of Lumry and Rajender (1970) and Drost-Hansen (1971).

Fisher (1979) examined the enthalpy-entropy compensation possibilities in aquatic biological communities. He noted that many species had nearly identical compensation temperatures, and that the statistical distribution of compensation temperatures correlated with the thermal limits on biogeographic distributions of species in various climate zones. As environmental temperatures approach the compensation temperatures of various species in a biotic community, the species composition of the communities changes, sometimes abruptly--an ecological switching of community structure. Because compensation temperatures are below the upper lethal temperatures and above the lower lethal temperatures for the species being replaced and/or doing the replacing, thermal death rarely accompanies ecological switching during natural temperature changes unless there are other factors. The temperature damping effect of enthalpy-entropy compensation around the switching temperatures provides a temperature transition zone for the species changes.

Some investigators have used biochemical information to propose an overall cycle which defines life itself. One attempt, the hypercycle (Eigen and Schuster 1979), has selected biochemical cycles which cross-catalyze each other to maintain the organism as a living entity. Crosscatalysis, like autocatalysis, is a positive feedback mechanism and thus, destabilizing for an evolutionary trajectory. If an alternate trajectory is available, then dissipative structures may arise. Eigenls special contribution was fitness criteria: relationships which explain the enhanced desirability or success of given evolutionary trajectories. Fitness criteria are constraints on the equations of an evolutionary trajectory and may originate from any biological top-down, bottom-up, or at-level controls on a evolutionary trajectory. These criteria permit a study of the competition among evolutionary trajectories far from equilibrium at several levels of biological organization.

WEAKLY COUPLED SYSTEMS

Weak coupling permits organisms to decouple some systems if convenient or necessary. Weak coupling encourages biochemical redundancy, a strategy organisms can use to select among alternative systems to accomplish the same task. Such choices enable an organism to minimize the damage from disrupted cycles and to evolve mechanisms to repair any damage to disrupted systems, while still accomplishing the tasks of the disrupted systems.

There are many examples of weakly coupled systems. Only a few of the 21 basic amino acids are absolutely essential to most animal species. Many animal species can convert one amino acid into another if there is a shortage and bypass biochemical systems that depend on specific availability. Assuming lack of food is not a problem, a threat to survival arises when there is a shortage of those amino acids which cannot be produced by interconversion. At the ecological level, a trophic level in a biological community might exhibit weak coupling through natural fluctuations in species diversity when the community is subjected to mild external influences. High-diversity systems contain many species having various roles and balanced species populations exhibiting a range of ages, sizes, and classes. These systems can usually utilize resources more effectively than low-diversity systems. When external perturbations remove a species without replacement, the species diversity theoretically declines, but the remaining species may still be able to maintain the previous level of resource utilization and energy cycling with no damage and little or no observed difference. Such systems have species assemblages with redundant roles and cycling pathways to confer an overall resilience to external disturbances.

If, however, a removed species is a critical linkage, then the system was strongly coupled, and survival of the remaining species requires a change in the evolutionary trajectory. A bifurcation occurs and the new ecological arrangement is a dissipative structure. As R. Ulanowicz has pointed out to the author, this suggests that evolution reflects an essential tension between strongly and weakly coupled systems.

Thermodynamic analyses of weakly and strongly coupled systems rely on mathematical models, but most of the models of coupled biological systems pertain to rather unrealistic situations. The existing analyses reflect what is mathematically tractable but not necessarily what is ecologically important. Generally, strongly coupled systems have intractable mathematical representations, and therein lies a problem.

THE DIVERSITY INDEX - A NONTHERMODYNAMIC ENTITY

The preceding discussion raises a problem about an improper use of thermodynamics--the diversity index. Without spending a great deal of time discussing them, diversity indices comprise a counterexample in thermodynamic applications and methods that is important in scoping limitations of thermodynamics.

Pielou (1969) has warned that things that look thermodynamic or use thermodynamic nomenclature do not always have thermodynamic significance. Her concern was the Shannon-Weaver index of information theory used to study the species diversity in a biological collection. This index has the same mathematical form as the Boltzmann entropy formula and is an example of applying the maximum entropy formalism to a theory. The biological problems of interpreting diversity thermodynamically were extensively discussed in a major monograph by Goodman (1975). The main point is that the coincidence of a diversity index formula and an entropy formula are not sufficient to assume the former is a thermodynamic tool or has thermodynamic significance.

Information theoretic entropy has no thermodynamic counterpart in the discussions of this paper at the ecological level. Pielou (1969) questioned whether ecological diversity ever has a thermodynamic counterpart, but information theoretic entropy is essential to discussions in molecular biology of the structure and synthesis of proteins and DNA and RNA, and in various aspects of biochemical genetics (Gatlin 1972). A recent volume on information theoretic entropy and ecosystem organization and evolution updates some of the discussions (Weber et al. 1988). These papers, often speculative, strongly hint at an important role for information theoretic entropy in elucidating a number of evolutionary aspects of ecosystem theory. Successful applications of the theory seem to depend on ways of measuring the information content in ecosystems using approaches and analogies different from the ecologically unfavored and thermodynamically questionable original proposals from communication theory.

Ecological diversity is important; its preservation enhances ecosystem integrity. Nothing previously discussed negates or contradicts that view. Where diversity indices are concerned, however, insight into the subject requires a perspective other than thermodynamics.

CARRYING CAPACITY AND SPECIES POTENTIAL

It is now desirable to consider an ecosystem-level topic: the species-area relationship--the relationship between the size of a region and the number of species it contains. Depending on its size and the nature of its resources (all expressed through area), a region can potentially accommodate some maximum number of species able to maintain themselves successfully. This notion is part of a hierarchy of ideas about environmental carrying capacity. The bottom level of the hierarchy prescribes a population limit for a single species occupying a given region and exploiting the resources either as sole species occupant or at the expense of all other species.

In general, investigators observe fewer species in a region than are theoretically possible. The introduction of a new species to a system at maximum species occupancy often results in elimination of a prior species. Biological succession is one form of introduction and elimination, but typically occurs at levels below maximum species occupancy. A cyclic succession has certain species always replacing or following others in a repeated manner. A noncyclic succession has each replacement leading to a new community structure on an evolutionary trajectory toward some biological climax system.

The numerical difference between a region's maximum number of species and the actual number present scales the region's attraction of new species and is called its species potential. This definition has two major implications:

1) Species potential does not presume the mechanism for species colonization and resource exploitation.

2) Species potential can confer integrity to an ecosystem by assuring that the number of species in biotic communities and ecosystems cannot be made arbitrarily large. Combined with cooperativity, this notion suggests that species are forced to interact to achieve ecosystem structure and cannot behave independently at all levels of population density and species number.

MacArthur and Wilson (1967), in developing the stochastic version of a model of species colonization of islands, studied species-area curves and carrying capacity of habitats in great detail. Their excellent model ignored edge effects (the special problems of certain classes of models when parameters approach maximum permissible values). Hill's (1968) small thermodynamic lattice models offer a more comprehensive approach and already have the appropriate chemical-reaction analog form. Species potential expresses the thermodynamic affinity for the colonization process and is a possible candidate for the ecological chemical-potential counterpart of embodied energy.

In Hill's and in MacArthur and Wilson's models, the rates of species colonization are linear functions of the species potential, and the rates of species loss are linear functions of the number of species already in the region. These simple density-dependent rate laws yield a unique steady-state number of species that is less than the maximum and is determined by the rate coefficients of the colonization and loss processes. Rate coefficients do not depend on the number of species present but may depend on species identity, habitat type, and climate.

Hill's models have interesting evolutionary trajectories. A region treated as a one-sided lattice has only one possible steady state: thermodynamic equilibrium. The evolutionary trajectory, a simple decreasing exponential function, is MacArthur and Wilson's initial case. A region treated as a two-sided lattice also has as its evolutionary trajectory a simple decreasing exponential function. The trajectory passes through a series of predictable steady states, the end one being thermodynamic equilibrium. Evolution is a transition between adjacent states along this trajectory. Modeling context dictates how to treat systems. A one-sided lattice is a simple population model: a two-sided lattice might entail colonization of an area from a species pool outside, then internal development in the colonized area, and finally emigration from that colonized area to a third system. The colonized area becomes a stepping stone in a migration chain between two external systems.

Although for modeling purposes the maximum number of possible species is usually assumed a constant, in reality it can change. The assumption of a constant maximum species number is valid when the time scales of population processes capable of changing that number are orders of magnitude slower than the time scales for population processes of interest in the immediate analysis of the species-area problem. First consider mechanisms which can increase maximum species number. One such mechanism is mutation, the production of a new species within a region without outside sources. This has a time scale far slower than that for immigration and removal processes. Other mechanisms which can increase maximum species number are various interspecific processes like predation, parasitism, and certain kinds of symbiotic and commensal behavior. There are also mechanisms which can reduce the maximum species number. Notable are inhibitory mechanisms: the production by one species of chemicals or toxicants to restrict the activity or presence of another species. changes in maximum possible species number can produce changes in species potential and the steady-state number of species. All mechanisms which can change the maximum number of possible species have thus far been found to be cross-catalytic in nature and collectively provide an ecosystem level example of cross-catalytic behavior (recall Eigen's hypercycle). These mechanisms partially account for dissipative structures at the ecosystem level.

The species-area relationships found in the ecological literature were derived from studies with small numbers of species (order of magnitude of 10-103). Because most thermodynamic equations derive from studies of large-number systems (order of magnitude of 10^{15}-10^{20}), thermodynamic analyses of models with species-area relationships should proceed using the methods of Hill (1963, 1964), which call for a careful choice of variables and thermodynamic equations. Small-systems thermodynamics forego the luxury of interchangeability associated with all of the equations of macroscopic thermodynamics, which permit the user to choose thermodynamic equations based on mathematical convenience: small system thermodynamics does not permit that choice.

Certain choices of environmental variables accommodate the analysis of stochastic influences (e.g., climatic effects) and this author favors stochastic rather than deterministic modeling styles. An important concern is how to represent populations of various species: as numbers (direct census), or as chemical potentials. The actual choice prescribes both the form of the thermodynamic equations for the ecosystem and the form of the rate laws governing such processes as colonization, immigration, and emigration.

Chemical potential is theoretically more advantageous in the thermodynamic calculations because it is related to the average population level rather than the instantaneous population level, although typical data on chemical quality of the environment often come expressed as concentrations. Some difficulty arises in working with thermodynamic equations having one group of parameters expressed as chemical potentials and another group expressed as concentrations.

By a careful selection of environmental variables, the ecological species-area relationships can be studied using the Grand Canonical Ensemble of statistical thermodynamics. It is necessary, however, to interpret the differences in the thermodynamic equations between Grand Canonical Ensembles for macroscopic systems and small systems. Small-systems equations contain all of the terms of macroscopic system equations, as well as additional correction terms. These correction terms become zero in the limit of large populations--species and individuals, as appropriate. How does one interpret these correction terms ecologically? The author's proposal is to treat them as energy factors associated with unoccupied and partially occupied ecological niches. Thus, embodied energy may be more than the chemical potential representation of the species potential, it may also include the potential energy associated with unoccupied components of niches and is separable from the energies associated with available niches having no species occupants. Rather than species potential or embodied energy, one could now talk about niche energy. The approach becomes a model thermodynamic analysis of the ecological niche.

A thermodynamic perspective on the ecological niche offers additional insight into ecosystem organization as follows:

> Ecological niches are postulated to possess a particular potential energy partitionable into terms associated with unoccupied niches (species absent), niches occupied by a species at a population level

below that associated with maximum resource utilization available in the niche, and niches occupied by species at the maximum resource utilization level available. The energy associated with unoccupied niches scales the species potential to attract new species, while the energy associated with partially occupied niches scales potential expansion of resource utilization.

The specific distribution of niche types (empty, partially occupied, fully occupied) reflects instantaneous maximization of community resource utilization, not necessarily that of an individual member species, through maximization of energy transduction and energy flow through the community. Some species interactions are ecological analogs of cross-catalytic biochemical cycles, raising the possibility that ecosystems will develop organizational structure through dissipative processes.

PUTTING IT ALL TOGETHER

Thermodynamics and its methods are powerful tools for evaluating aspects of ecosystem integrity. They provide:

1) some principles or strategies, which operate at all levels of biological organization, for the development of structure and associated integrity. These are:

   -maximization of free energy transduction,
   -a principle of parsimony in the chemical bookkeeping of a cell's biochemical system,
   -cooperativity, and
   -switching and control mechanisms.

2) ways to extract from mathematical models of ecosystem behavior the number and form of evolutionary trajectories and their associated steady states and tests to judge their stability.

3) explanation of the development of dissipative structures in far-from-equilibrium systems--the order out of chaos.

4) the use of fitness functions which, when combined with derived evolutionary trajectories and stability analyses, are measures of integrity.

5) reasons for rejecting proposals for biotic communities of unlimited species number.

On the other hand, thermodynamics and its methods do NOT provide:

1) a definition of ecosystem integrity.

2) a theory predicting the actual number and identity of species forming a given biotic community, or a general theory of evolution applicable far from equilibrium.

3) information on how long it takes for systems to evolve along their trajectories to stable or unstable steady states.

4) which cycles will evolve to maximize free energy transduction and resource utilization.

With the above ideas in mind it follows that thermodynamics offers one particular perspective for analysis of ecosystem integrity, but that other perspectives and approaches are both possible and needed.

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TROHIC DYNAMICS AND ECOSYSTEM INTEGRITY IN THE GREAT LAKES: PAST, PRESENT, AND POSSIBILITIES

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ABSTRACT. The Great Lakes are perhaps unique among large lakes of the world in the degree to which fish population dynamics and water quality resources can be influenced by management at the bottom of the food web or from the top of the food web. Nonmanagement factors known to affect fish quality and quantity and water quality include toxic contaminants, short-term weather events and long-term climatic changes, exotic species invasions, and evolutionary changes of existing species. Because fisheries-based revenues to the Great Lakes region are presently estimated at $2-4 billion per year, it would seem prudent to determine the extent to which management and nonmanagement factors influence fish quality and quantity, as well as water quality. Here we present a comprehensive, yet preliminary, conceptual and mathematical modeling approach that describes causal relationships among fish food web, nutrient cycling, and contaminant processes in the southern basin of Lake Michigan. Our approach identifies weaknesses in the data base that are important to the predictive usefulness of such a model. We suggest that our comprehensive modeling approach will be useful in transforming some surprises into expected events. For instance, the model predicts that contaminant concentrations in salmonines will decrease by nearly 20% if <u>Bythotrephes,</u> an exotic carnivorous zooplankton, successfully establishes itself in Lake Michigan.

PREDICTION OF GREAT LAKES ECOSYSTEM DYNAMICS

our ability to predict Great Lakes ecosystem dynamics with simulation models is proportional to our combined understanding in four subject areas.

1) We must know what is there: biomass of biotic compartments, numbers of individuals and age-class distribution of important fish species, and physical and chemical characteristics of water masses.

2) We must understand basic cause-and-effect linkages among biotic, chemical, and physical factors.

3) We must quantify water movement and rates of material transfer (e.g., carbon, nutrients, contaminants) among biotic and abiotic compartments.

4) We must know system inputs (e.g., solar, nutrient, contaminant, fish-stocking inputs) and outputs (chemical, biological, and hydrological) that affect system behavior.

Yet even with perfect knowledge in these four areas, simulation models cannot be expected to be 100% accurate, since they are abstractions of the system under study. In addition, models are more retrospective than truly predictive (Holling 1987); the predictive power of models is constrained by the domain of existing knowledge. For example, it is unlikely that anyone could have predicted, before the fact, the invasion of the Great Lakes by alewives (_Alosa pseudoharengus_) or sea lamprey (_Petromyzon marinus_). and their subsequent impacts on Great lakes ecosystems. Therefore, not only is the efficacy of predictive models limited by data availability, but in a larger sense, by our inability to predict many system-modifying events that lie ahead. Thus, surprise, as defined by Holling (1987), "...when perceived reality departs qualitatively from expectation [e.g., a model prediction]" should really be of no surprise to anyone who uses or builds models.

Fortunately, significant and truly unpredictable system-modifying events can be spaced widely over time. It is during these time windows that the worth of predictive simulation models can be greatest, especially with regard to understanding and predicting the impacts of management actions on existing ecosystem characteristics. Here, we present work under way on a simulation model that may be useful for understanding lake Michigan ecosystem dynamics now and in the future. We use the model to test the hypothesis that the effects of ecosystem management actions are not independent. That is, one management action might affect the anticipated outcome of another management action (a potential surprise?). We also use the model to test the hypothesis that successful establishment of the exotic zooplankton species, _Bythotrephes_, in the Great Lakes will short-circuit contaminant transfer to salmonines. Through these simulation experiments, we suggest that models may help transform some potential Great Lakes surprises into expected events.

Prediction Uncertainty and Its Relationship to Surprise

The usefulness of a model relies on proper matching of models with well-defined questions and proper model parameterization. The first aspect of model reliability is a conceptual issue; the second is a data issue. Without appropriate conceptual grounds, a model will be of little use regardless of how well it is parameterized. On the other hand, the usefulness of a model that is conceptually superior can be limited by parameterization with uncertain information.

Uncertain information can be categorized in four ways:

1) There are data that are variable, but well-defined statistically (e.g., some model coefficients).

2) There are needed data that are presently unknown (e.g., many contaminant loading functions), but can be defined given proper resources.

3) There are events that we know can happen but we are limited in our ability to quantify their magnitude, importance, and probability of occurrence (e.g., toxic chemical spills).

4) There are events that are totally unexpected, but amenable to being understood after the fact (e.g., the successful invasion of the Great Lakes by alewives, sea lamprey, and *Bythotrephes*).

When an exotic species successfully invades a system and alters it, models must be redesigned so that future predictions incorporate new information. It is impossible for modelers to predict something that is not initially accounted for in a model unless the model has the ability to self-evolve (Fontaine 1981).

The first two categories of uncertainty are easily accommodated in modeling projects. Performing sensitivity and uncertainty analyses can help identify the possibility and probability, respectively, of events occurring in an ecological system. These analyses also can help identify research and monitoring that is needed to minimize uncertainty (Bartell et al. 1983). Uncertainty analysis provides a method for predicting the probability that a particular environmental event will occur. By conducting an uncertainty analysis, future events that might be perceived as surprises can now be identified as having some probability of occurrence. Probabilities are calculated by incorporating statistical information about input and parameter variability into simulations. For example, Fontaine and Lesht (1987) used statistical distributions of basin-specific Great Lakes phosphorus inputs and settling rates in a simulation model to forecast the probability of basin-specific phosphorus concentrations. In Lake Michigan, the predicted distribution of steady-state phosphorus concentrations was between 4 and 7 ug/L, given phosphorus load reduction capabilities specified in the United States and Canada 1978 Water Quality Agreement. While the probability of measuring a concentration near the mean value of 5 ug/L was higher than that of measuring an extreme concentration, the probability of encountering a near-extreme value could be predicted and would no longer be viewed as a surprise when it occurred. Thus, if the proper analytical tools are applied to models, they can be used to transform what would normally be perceived as surprises into expected events.

Uncertainty analysis techniques would not have predicted the recent appearance in the Great Lakes of the carnivorous zooplankter Bythotrephes. Successful invasion of such an exotic species can bring about dominance shifts in existing species, altered functional attributes in existing species, or little change at all. At best, the predictive modeler can incorporate new species into a model, as necessary, to speculate upon their impact. For example, Scavia et al. (1988) evaluated the impact of Bythotrephes and predicted that it could cause Lake Michigan's plankton community to revert to a species composition observed during the 1970s.

Dominance shifts in species composition can also occur if a nonbiological perturbation is of sufficient magnitude. For example, a series of unusually severe winters (Eck and Brown 1985), coupled with predation by stocked salmonines (Stewart et al. 1981; Kitchell and Crowder 1986) greatly reduced alewife recruitment and subsequent population size in Lake Michigan. The decline in alewives led to decreased predation on zooplankton populations. This led to a shift in the species composition of both zooplankton and phytoplankton populations, and a decrease in phosphorus concentrations. The occurrence of this type of surprise might have been predicted if models had incorporated statistical information about the variability of winter severity and the relationship of alewife recruitment to it.

Management Actions and Their Relationship to Surprise

Whenever the objectives of Great Lakes ecosystem management are discussed, the following are most often mentioned:

1) Grow large numbers of trophy-sized sport fish.

2) Reduce basin-specific total phosphorus concentrations to those specified in the United States and Canada 1978 Water Quality Agreement.

3) Reduce contaminant concentrations in fish, water, and sediments to safe levels.

4) Obtain enough money and knowledge to predict how to do 1, 2, and 3.

The Great Lakes are perhaps unique among large lakes of the world in the degree to which the fisheries and water quality resources can be influenced by management at the bottom of the food web (nutrient load reductions) or at the top of the food web (fish stocking and harvesting allowances, and sea lamprey control). For example, the bow tie symbols in Fig. 1 represent control points available to managers for influencing the characteristics of major food web pathways and water quality in southern Lake Michigan.

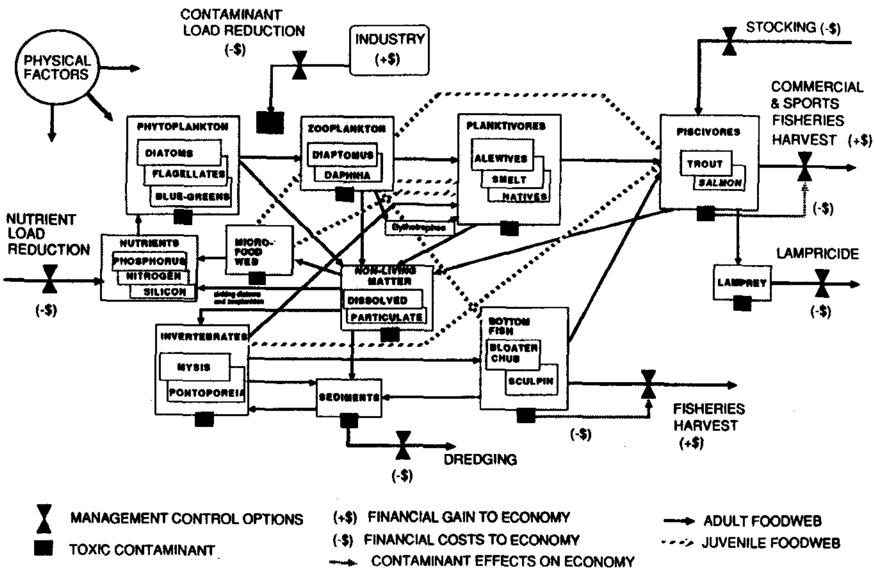

FIG. 1. Conceptual diagram of major food web and contaminant processes in southern Lake Michigan (>100 m depth contour only). Bow tie symbols indicate management options. Note that there is a financial cost associated with each management action. If management actions in the Great Lakes are not independent, then implementing one action will affect the costs of other actions. As cost minimization is a goal of managers, potential management synergisms should be understood and used advantageously.

We suggest that exercising control at these points in attempts to manage the Great Lakes ecosystem may lead to surprises, but only because mental and mathematical models may not be comprehensive enough. A recent example of a Great Lakes surprise is the observation that improved regulation of pollution inputs to the Great Lakes has improved water quality to such an extent that it is now possible for sea lampreys to spawn in areas that they previously could not (Moore and Lychwick 1980, J. Heinrick, U.S. Fish and Wildlife Service). Unfortunately, some of the additional spawning will be difficult to control through conventional means, especially in areas such as the St. Marys River. This raises concerns as to whether lamprey attacks on desirable sport fish will increase. With a more encompassing conceptual approach, perhaps this surprise could have been anticipated.

Management-induced changes in one part of an ecosystem may bring about changes in other parts of the ecosystem. For instance, Scavia et al. (1986, 1988) present a strong case for top-down control of epilimnetic plankton and water-quality dynamics by alewives (whose dynamics are controlled to some extent by stocked salmonines) during the summer in Lake Michigan. Their model strongly indicates that decreased zooplanktivory resulting from the decline in alewives, rather than phosphorus load reductions, was the major cause of the observed water-quality changes. The latter is an example of cascading food-web effects (Carpenter et al. 1985). McQueen et al. (1986), however, suggest that the relative importance of bottom-up versus top-down control will depend on the trophic status of lakes. They found that the impact of top-down effects are quickly attenuated at the top of the food webs of eutrophic lakes. In oligotrophic lakes, however, top-down effects appear to be weakly buffered, and significant impacts are seen at the phytoplankton level. Carpenter and Kitchell (1988), on the other hand, emphasize that the magnitude and duration of top-down pressure on food webs (e.g., from stocked salmonines in the Great Lakes) is of overriding importance compared to nutrient loading effects on food-web structure. Thus, the relative importance of top-down, bottom-up, stochastic events, and management activities on the structure and function of Great Lakes ecosystems deserves clarification.

Surprises may result when the use of one management tool unexpectedly affects the anticipated outcome of another management tool: effects of separate management actions may not be independent. Examples of the nonindependence of management actions abound in many fields. For instance, in the medical field it is well known that certain pharmaceuticals will enhance or negate the intended purpose of other pharmaceuticals. Other examples of the interdependence of management activities are reported by Gall (1986).

A PRELIMINARY MODEL OF SOUTHERN LAKE MICHIGAN ECOSYSTEM DYNAMICS

Goals

The conceptual framework represents a working hypothesis of how ecological and related economic factors are linked in southern Lake Michigan (Fig. 1). Shown are the major ecological, contaminant fate, and management characteristics of the lake. Using this conceptual framework and a simulation model based upon it we initiated a program to accomplish the following:

1) Improve our understanding of the underlying causal mechanisms of observed fish-community dynamics and year-to-year variability in southern Lake Michigan.

2) Understand the relative importance of benthic and pelagic food-web pathways to the numbers and biomass of economically important fisheries and their bioaccumulation of contaminants.

3) Identify data inadequacies and needs for field and laboratory experiments through the process of attaining objectives 1 and 2, above.

4) Determine if (and to what extent) fisheries, phosphorus, and contaminant management strategies affect (enhance or negate) each other's success.

5) Identify cost-effective methods for attaining fisheries, contaminant, and phosphorus management goals.

6) Determine which fisheries management techniques can produce results (e.g., increased yield or recruitment) that are distinguishable from expected variability of the natural population.

Model Description, Assumptions, and Limitations

Our model builds on that developed by Scavia et al. (1988), with the exception that aggregated alewife and aggregated Salmonine populations were included. A bioenergetics approach was used to model the dynamics of these fish populations, using parameters derived from Stewart and Binkowski (1986) and Stewart et al. (1983). Because alewife and salmonine populations are treated as aggregates, age-class specific stocking and harvesting strategies cannot be evaluated yet. Bloater chub (*Coresonus* hoyi) and *Mysis* are also included in the model, but at this time are represented as constant biomass storages available for consumption by salmonines and alewives, respectively. Dynamic representation of bloaters and *Mysis* awaits development of bioenergetic models for them and improved definition of their role in the food web. Accomplishment of the latter should improve our understanding of the dynamics of material fluxes between the pelagic and benthic zones and the importance of these materials to benthic food webs.

Pathways describing the behavior of a persistent contaminant were overlaid on the ecological model and include processes such as uptake, depuration, trophic level transfers through consumption, and sorption reactions with particles. Because ecological processes that affect particle formation are usually ignored in toxicant fate models, this coupled ecosystem-contaminant dynamics model can be used to determine the importance of ecological processes to the prediction of contaminant dynamics. Coupled ecosystem-contaminant pathways that remain to be defined include contaminant dynamics of benthicinvertebrates and bottom fish and resuspension and biological-chemical dynamics of settled, particle-associated contaminants.

Simulation Conditions

The model of Scavia et al. (1988), with the modifications noted above, was initialized with mid-1970s nutrient and plankton conditions. Because estimates of Great Lakes fish biomass range widely, a matrix of possible mid-1970s alewife and salmonine biomass values (both lakewide and individual weights) was initially tested in the model to determine a combination that would reproduce plankton and nutrient dynamics that have been observed at the >100 m depth contour. The fish biomass estimates that produced the best match of model and data (according to criteria specified in Scavia et al. (1988) were 15,000 metric tons (MT) and 10,000 MT of lakewide alewife and salmonine biomass, respectively. Average initial wet weights of alewives and salmonine that yielded the most realistic results were 7 g and 454 g, respectively. Therefore, these lakewide and individual fish biomass values were used in all subsequent simulation experiments.

To test for potential management- and nonmanagement-induced surprises, the model was run with a variety of phosphorus loading, lamprey control, and *Bythotrephes* initial conditions. In all simulations a persistent, nondegrading, highly partitioned (k_{oc} = 2 X 10^{7} lw kg. org. carbon (C).') contaminant was loaded to a contaminant-free system at a hypothetical, steady rate of 1 unit per cubic meter per day to determine how differing conditions would affect contaminant concentrations in salmonines. Phosphorus (P) was added at three levels: 0.0055, 0.0035, 0.0015 μg P per liter per day to simulate the effects of relaxed, present, or more-stringent phosphorus load regulations. Lamprey control was set as either present or absent by increasing salmonine mortality by an additional 12.7% per day in the latter case. _Bythotrephes_ was programmed as either initially present (0.005 mg carbon per liter) or absent. If present, it was programmed to either strongly prefer _Daphnia_ over _Diaptomous_ or to show equal preference for both prey. The former case is believed to be the most plausible. _Bythotrephes_ was assumed to be a preferred prey item for alewife. All told, 18 different simulation conditions were evaluated and together represent a very limited sensitivity analysis of the model. An uncertainty analysis of the model has not been performed yet.

RESULTS AND DISCUSSION

Under all simulation conditions, predation pressure on alewives by salmonines caused alewife biomass to decline from an initial 15,000 MT to a steady-state value of about 3,000 MT. These results apply only to fish dynamics at the >100 m depth contour. Before declining, alewife biomass increased 6% and 7% from their initial biomass, with and without existing lamprey control, respectively. The absence of lamprey control led to decreased salmonine biomass and less predation pressure on alewives. Declines in alewife biomass brought about changes in phytoplankton and zooplankton composition, and dissolved phosphorus concentrations, (Figs. 3-7; Scavia et al. 1988). At the time that alewife biomass began to decline, lakewide salmonine biomass had nearly doubled to about 18 MT. After that point, salmonine biomass decreased, leveled, or increased in direct relationship to the preference factor setting for salmonines feeding on bloater chub. Determination of this preference factor is, therefore, central to our ability to extend predictions of salmonine biomass and contaminant concentrations further. If the major percentage of salmonine diets shift from alewife to other species and if salmonine feeding rates remain the same as before the decline in alewives, it is these other species that will primarily dictate future salmonine biomass and contaminant dynamics. Since there is considerable uncertainty about how salmonines would adapt to low alewife availability, the results reported here correspond to the point in time that salmonines are at their peak biomass, just before the decline in alewives.

Effects of Bythotrephes

The model was used to explore the effect of the presence (two feeding preference scenarios) or absence of the exotic species Dythotrephes on salmonine contaminant concentration. The most striking finding was that the presence of Dythotrephes brought about reductions in salmonine contaminant concentrations (Fig. 2). Greatest reductions (17%) were predicted when Dythotrephes preferentially fed on Daphnia over Diaptomous, the scenario thought to be most likely. If Dythotrephes preferred Daphnia and Diantomous equally, predicted reductions in salmonine contaminant concentrations were about 8%. These predicted changes in salmonine contaminant concentration represent a field-testable hypothesis. In addition, the predictions transform what could have been viewed as a surprise into an expected event.

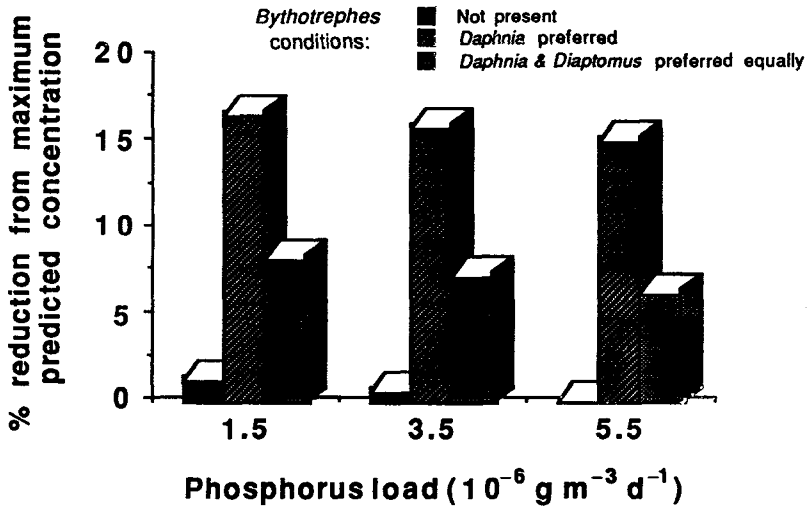

FIG. 2. Predicted differences in salmonine contaminant concentrations under three phosphorus loads and three Dythotrephes conditions. Note that the ordinate expresses the percent of maximum simulated contaminant concentration.

Why did salmonine contaminant concentrations decrease when Dythotrephes were present in the model? The model suggests that Bythotrephes will short-circuit the transfer of contaminants up the food web, primarily by affecting Daphnia dynamics. Changes in Daphnia biomass dynamics, in turn cascade down the food web and affect algal and particle dynamics. All of these changes in food-web dynamics affect the amount of contaminant predicted to reach the alewife. *Bythotrephes* directly competes with alewives for *Daphnia* biomass and thereby reduces alewife consumption of *Daphnia*-associated contaminants. Although alewife consume *Bythotrephes* the alewife do not receive the same contaminant flux from them that they would have from direct consumption of *Daphnia*. This is because *Bythotrephes* do not assimilate all of the *Daphnia*'s biomass and associated contaminants; the unassimilated portion is shuntedto the particulate organic carbon pool.

A secondary effect of *Bythotrephes* on ecosystem contaminant dynamics is suggested by the model. In simulations with *Bythotrephes*, *Daphnia* biomass is suppressed because total predation pressure on *Daphnia* increases due to the presence of two predators instead of one. The decrease in *Daphnia* biomass leads to an increase in the biomass of their preferred food items, green and blue-green algae. As a result, the flux of sinking algal biomass and associated contaminants to hypolimnetic sediments increases. This model prediction represents another hypothesis that could be field-tested. Unfortunately, the model is not at the stage of development where the subsequent fate of the increased contaminant flux to the sediments can be predicted. It is likely that most of this increased contaminant flux would end up in benthic invertebrates and bottom-feeding fish. If so, it should eventually become available to salmonines if they shift their diets from alewife to bloaters as alewives decline.

Effects of Management Actions

We hypothesized that the effects of individual or multiple management actions might lead to surprises. This hypothesis was tested by determining the effects of three phosphorus load scenarios and the presence or absence of lamprey control on salmonine contaminant concentrations. The model predicted that control of phosphorus loads and lamprey would have little effect on salmonine contaminant concentrations. Only a 1% change in salmonine contaminant concentration was predicted for sizable increases or decreases from present phosphorus loads (Fig. 2). Eliminating lamprey control led to a 5% decrease in peak salmonine biomass and a small increase (<1%) in salmonine contaminant concentrations. Therefore, over the period from initial to peak salmonine biomass, simulations indicate that management-induced surprises will be minimal. However, preliminary simulations of all ecosystem state variables to steady state show that management-induced surprises can be quite large. Unfortunately, steady-state solutions to the model are extremely speculative because of insufficient information on coupled benthic-pelagic food web and contaminant dynamics.

LOOKING FORWARD

Refinement and improvement of this comprehensive model for southern Lake Michigan contaminant and ecosystem dynamics will continue. At the present stage in model development, however, simulation experiments suggest that the successful establishment of an exotic zooplankton species might provide more surprises than the effects of one management activity on another. It cannot be emphasized enough, however, that the model is in an early stage of development; present results may change as the model is improved. by using this comprehensive modeling approach, we may transform some potential surprises into anticipated events. The key to facilitating the transformation is to ask well-focused questions and to build models that recognize and incorporate the fact that "surprise emerges from coupling of human time and spatial scales with smaller and larger ones in nature" (Holling 1987).

Data Needs and Model Uncertainty

Future work should address the data inadequacies that limit the predictive capability of the model. better estimates of fish biomass across age-class distributions are needed, and better understanding of coupled benthic-pelagic carbon flow is required. Improved understanding is also needed regarding the role of lipids in food web bioenergetics and contaminant transfer from prey to predator. In addition to these data needs, future modeling and monitoring work should address the following question: "Given present conditions, what is the expected variability of Great Lakes water quality constituents (e.g., phosphorus, PCBs) and the biomass, quantity, and characteristics of Great bakes organisms?" Without knowing this, it will be difficult to say whether a surprise has actually happen& since the range of expected behavior is unknown. As demonstrated by Fontaine and Lesht (1987) and Bartell et al. (1983), probabilistic models can help define expected behavior ranges of ecological variables and their dynamics. Given the ability to define the range of expected ecological behavior, the question that should then be asked by ecosystem managers is: "What management techniques will produce results that can be distinguished from the expected variability of the system?" In other words, why manage if an effect cannot be demonstrated at some point?

Economic-Environmental Trade-Offs

Politicians, managers, scientists, and end users of Great Lakes resources undoubtedly support the fish and water quality management objectives listed earlier. However, the priority assigned to each objective may vary depending on the user's perspective. This results in a classic multi-objective optimization modeling problem. It is a multi-objective optimization problem because more than one goal is desired, but all goals more or less compete for money from a common, limited environmental funding base. It is also a modeling problem since predictions are desired. Identifying a solution that is acceptable to all interested parties is complicated by the fact that the optimization (whether mathematically or intuitively based) has to be performed with uncertain information regarding the future of short-term weather events, long-term climatic change, exotic species invasions, evolutionary changes of existing species, politics, management activities, and toxic contaminant spills. An approach that combines results from comprehensive environmental models, such as discussed here, with uncertainty analysis and "surrogate worth tradeoff" techniques (Haimes 1977) is needed by decision-makers to holistically understand, manage, and anticipate surprises in the Great bakes.

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THEORETICAL FRAMEWORK FOR DEVELOPING AND OPERATIONALIZING AN INDEX OF ZOOBENTHOS COMMUNITY INTEGRITY: APPLICATION TO BIOMONITORING WITH ZOOBENTHOS COMMUNITIES IN THE GREAT LAKES

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ABSTRACT. A pragmatic approach is presented, outlining the rationale and necessary questions which must be addressed in the development of an Index of Zoobenthos Community Integrity for biomonitoring in the near-shore Areas of Concern in the Great Lakes. Abalanced perspective documenting the notable strengths and weaknesses in the use of such indices by aquatic managers is discussed. It is demonstrated that the integrity indexmethodology can serve an important, if not vital, function as an empirical link in a hierarchical framework of comparative nested integrity.

INTRODUCTION

Living organisms provide convenient full-time, integrative monitors of environmental perturbations in that they are not affected by temporary amelioration, nor usually by transient deterioration of an effluent or a transient activity that degrades habitat. Further, the use of living organisms as early warning indicators is an important means for reducing the degree of surprise as new problems emerge. Ryder and Edwards (1985) discuss the strategy and utility of selecting different types of indicators to reflect different manifestations of human impact in the Great Lakes.

Bioassessment consists of both bioassay-toxicology (laboratory) studies and biomonitoring (field surveillance), and has received increasing recognition as a means of identifying, understanding, and even ultimately predicting, perturbation stress (Levin and Kimball 1984; Herricks and Cairns 1982). Thus, there is a need to mesh new concepts of maintaining biological integrity with the established, diverse tradition of biomonitoring.

The integrated toxicity test design (Buikema and Benfield 1979; Lehmkuhl 1979; France 1986), although heralded as a most valuable tool in ecotoxicological research, is still little used. It is very important, however, because the relationships between life histories and environmental disturbances are usually subtle and difficult to interpret. Laboratory studies provide precise dose-effect information concerning the effects of single pollutants, but can never successfully duplicate all the interacting variables characteristic of natural environments. On the other hand, field studies often cannot provide the sensitivity necessary to detect adverse effects before they reach crisis proportions. The failure to assimilate both laboratory and field information in concert produces studies that may have limited utility in solving contaminant problems. Combining field monitoring and laboratory bioassays is necessary to understand whether legislative criteria are over- or under-productive in mitigating environmental disturbance. A method is needed for integrating laboratory and field data, based on reciprocal objectives of increasing or decreasing relevance (prediction) and identification (understanding) of mechanisms (Fig. 1)'.

	ECOSYSTEM	
	COMMUNITY	
MECHANISM	POPULATION	**RELEVANCE**
(UNDERSTANDING)	INDIVIDUAL	**(PREDICTION)**
	ORGAN	
	CELL	
	MOLECULE	

FIG. 1. Hierarchical integrated toxicity test design.

The result of dilution and dispersion in the natural environment of pollutants from point source inputs and the resultant chronic exposure of organisms to sublethal concentrations of such substances is likely to affect a much greater biomass than exposure to lethal concentrations (Klerekoper 1976; France 1986). The affected community may continue to exist but usually in some modified or crippled form. As the Food and Agriculture Organization (FAO) (1976) stated: "Not very sophisticated indices will be required to diagnose acute continuing stress. Death is easily recognized. It is of more interest to determine where the boundary lies between acute and chronic and between chronic and no significant practical effect." This is our goal in the recognition and management of human by-products in the Great bakes basin.

BIOINDICATOR OBJECTIVES IN THE GREAT LAKES

The 1972 Great Lakes Water Quality Agreement stated that the waters of the Great Lakes system should be "maintained and, as necessary, restored to a condition where a balanced and stable community of organisms is present which resembles as much as is feasible and practical the community that existed before the advent of anthropogenetic intervention." Recognizing that no single organism (or chemical constituent or physical feature) is capable of reflecting satisfactorily all of the cultural stresses affecting the Great Lakes, the International Joint Commission's Water Quality Board (IJC/WQB) reiterated in 1985 the need for biomonitoring to embrace the ecosystem approach, and as a result, to give more consideration to the integrative and holistic interpretation of health at the ecosystem level of organization (Schaeffer et al. 1988). Attempts to regulate one stress in isolation from the effects of other stresses won't work (Cairns 1975). Natural communities summarize and integrate all the perturbations and therefore provide a cumulative response. Despite the acknowledgment that use of complementary indicator organisms is the most effective avenue for assessing ecological integrity, the 1987 IJC/WQB Report stated that such techniques had yet to be systematically developed.

In view of the fact that the near-shore zone is the most intensively used area of the Great Lakes, and the region most likely to assimilate nearly all of the pollutant inputs, the WQB recommended that more emphasis be directed toward the remediation of near-shore problems. Changes in open lake quality are much slower, but represent better indicators of progressive and longer term alterations that might be obscured by the often degraded and rapidly variable water quality found within the near shore (Ryder and Edwards 1985).

Surprise events, however, will be first felt in the barometer areas of concern (AOC), where the mix of perturbations display a cumulative ecological impact. Indeed, a history of the problems within the AOCs suggests that these areas can be characterized as being surprise-rich environments. Importantly, because the near-shore areas can be conceptualized as centers of organization for the functioning of the Great Lakes ecosystem (see Steedman and Regier, these proceedings), the IJC/WQB cautioned that it is erroneous to perceive the so-called AoCs as merely localized problems, as they can and probably do affect more extensive regions. The benthic environments within littoral zones can be regarded as open systems both chemically and biologically. They provide a strong and continuous flow of matter/energy to the pelagic lake, which, based on the hydrodynamics of Legendre and Demers (1984), is, in a sense, the end point of the watershed continuum concepts of Steedman and Regier (1987).

The remedial action plans (RAPs) for the AOCs were criticized by the IJC in 1985 because they lacked conformity in identification and assessment of perturbations, and were plagued by inconsistencies in data collection and reporting. There is a strong and urgent requirement, therefore, for the AOCs to be evaluated with uniform criteria. As the management of contaminated sediments (the most prevalent problem in the AOCs) often entails expenditures of many millions of dollars, ample justification is needed to proceed with the preferred management strategy. According to the National Research Council (1985) report on Great Lakes water quality, evidence of biological damage attributable to in-place pollutants does not exist for many AOCs because of the ineffectual nature of the biomonitoring approaches presently being utilized.

Additionally, RAPs should be designed, not only to monitor and evaluate existing environmental problems, but, most importantly, also to survey emerging (both expected and surprise) problems, particularly through employing "a systematic and comprehensive ecosystem approach." This, unfortunately, has not yet been done. The need is, therefore, to move from diagnostic understanding to prognostic prediction in our assessment of anthropogenic stress in the Great Lakes. How can concepts of integrity help us to make this epistemological shift, this necessary refocusing, if ecotoxicology/applied ecology is to develop as a mature science?

INDEX *OF* BIOTIC INTEGRITY

Great emphasis was placed in the 1978 Great bakes Water Quality Agreement on not just reaffirming the determination of the two countries to restore and enhance the water quality, but also on assuring that the "biological integrity of these waters is maintained." Before the present workshop, only Regier (1987) had discussed Great Lakes environmental quality issues in such terms. Philosophically, the term integrity is central to the land ethic of the pioneer American conservationalist Aldo Leopold (1947): "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise." The present manuscript addresses the objective scientific meaning of integrity: the subjective ethical implications of this precept are discussed in a complementary paper

(France 1990). In the broadest sense, integrity refers to the wholeness, diversity, or degree of connectiveness within a biotic community and can be viewed as an emerging property of ecosystems, one that is clearly within the mandate of the IJC/WQB. In this respect, ecosystems are only a special example of general systems, which Paul Weiss has defined as "a complex unit in space and time whose sub-units cooperate to preserve its integrity and its structure and its behavior and tend to restore them after a nondestructive disturbance" (Goldsmith 1988). As Fisher states in these proceedings, "ecological integrity is currently described by its collective parts or attributes" (Table 1) .

TABLE 1. Ecosystem integrity argot generated by workshop members.

balanced indigenous populations	complexity
identity	species redundancy
predator-prey coupling	cooperatively
persistence	constraint development
hierarchical framework	negative feedback
resilience	stability
internal species linkages	corruption resistance
community nuclei	cohesion
inertia	harmonic entities
disturbance incorporation	nonchaotic processes
constancy	cybernetic properties
perpetual dynamic equilibrium	coherency
ascendancy	self-organization/ renewal
autocatalysis	homeostasis
fitness criteria	inherent diversity
stress resistance	recursive nesting
internal organization maintenance	species differentiation

Problems may arise, nevertheless, in developing techniques for operationally defining and practically applying concepts of emerging ecosystemic properties for gauging environmental quality within the AOCs (Ryder and Edwards 1985). The ambiguous interpretations which frequently characterize assessments of ecosystem status and thereby hamper progress in biological monitoring, prompted the National Academy of Science as early as 1975 to explicitly affirm that "...indices are needed for such goals as the integrity of ecosystems..." (Council for Environmental Quality (CEQ) 1975). Despite this, it was not until a half decade later that Karr (1981) developed the Index of Biotic Integrity (IBI) as a tool to help managers, through the interpretation of biological data, to quantify river health or integrity.

Because human uses can affect the biota in many ways, such a measure of biotic integrity must incorporate a broad array of ecological characteristics which are sensitive to various (both chemical and physical) forms of degradation. Karr developed a series of parameters (called metrics) that reflect individual, population, community, and ecosystem attributes in an integrated framework. The five types of metrics are: species richness and abundance, local indicator species, trophic composition, fish abundance, and fish condition. Together these metrics provide information about a range of structural and organizational aspects of the ecosystem. Individually, each metric explains a specific attribute of the sampling site. It is important to note that although no single metric is always a reliable indicator of degradation, in aggregate they appear responsive both to changes of relatively small magnitude and to broad ranges of perturbation. Some metrics are sensitive across the entire range of investigation, others to only a portion of that range. Later testing by Karr and associates (e.g., Miller et al. 1988) revealed that no single metric is consistently best or worst at detecting degradation and that none appeared redundant with respect to one another. Indeed, the great strength of the IBI is its multiparameter assessment ability.

Measuring the biotic integrity of a body of water is analogous to measuring human health from a suite of different techniques (cardiograms, x-rays, blood pressure, blood and urine chemistry). The major aim, therefore, is to construct an agglomerate index that summarizes this diversity of biological information into a single value considered synonymous with community health (Steedman 1987). Communities lacking integrity in this respect are often already degraded, and when further perturbed, are likely to change rapidly and frequently unpredictably (either linearly or through a catastrophic flip: (see Kay, these proceedings)), to even more undesirable states (Frey 1975). In some cases integrity may be more evident from its absence than from its presence.

ZOOBENTHOS COMMUNITY INTEGRITY

An important question is whether the integrity of zoobenthic communities can be conceptually determined and then empirically utilized as a sensitive and predictable finger-printing biomonitor for the AOCs. Heuristically, the use of benthic invertebrates in such a fashion is appealing, in contrast to fish, due to their sedentary behavior and localized distribution, relative ease of being sampled quantitatively, and recognized sensitivity to a wide range of cultural stresses. Perhaps most significantly, because zoobenthos species associations in benign environments are heterogeneous, with numerous phyla and trophic levels being represented, the chances are high that at least some groups, and therefore the community integrity as a whole, will respond to environmental disturbance.

The major disadvantage in using benthic invertebrates as biomonitors is that they are susceptible to both micro- and macro-environmental factors. Seemingly minor changes in substrate particle size, organic content, and even texture, can influence the associated community structure. Close attention is therefore essential to discriminate between anthropogenic and substrate influences at all stages in the development of an Index of Zoobenthos Community Integrity.

Multivariate analyses have identified different zoobenthos community types in relation to anthropogenic stress within the Great Lakes. This suggests that

a) long-term consistency of nonrandom zoobenthos species associations may exist as harmonic entities (Ryder and Kerr, these proceedings) under pristine environmental conditions (Tyler 1974); and

b) a series of multiple equilibria states may exist on a localized scale in response to stress.

The goal, as Holling (1985) identified, is to be able to detect the point at which the sharp discontinuous changes in community structure become inevitable, and how to predict these in a surprise-filled environment. Other important questions which need to be addressed concern:

1) How does the initial integrity of a zoobenthic system (in terms of species richness, size spectra, functional respiration or feeding guilds, proportion of oligochaete to insect biomass, trophic connectiveness, etc. (see Table 2)[3] predetermine the final outcome of perturbation?

2) Does, in fact, a generalized stress response toward different perturbative agents exist?

3) What are the particular aspects of those communities which are already preadapted to surprise events?

TABLE 2. Potential metrics of zoobenthos community integrity.

(A) <u>Non-Great bakes Research</u>
percentage of total abundance composed of chironomids
chironomid trophic status index
oligochaete species assemblage composition
species abundance curves
insect/tubificid ratio
alterations in predator-prey ratios
differential sensitivity responses of feeding, respiratory and reproductive functional groups
body size or shape analysis
autotrophic/heterotrophic functional group analysis
novel approaches using K-dominance curves of relative abundance/biomass
(B) <u>Great Lakes Examples</u>
log species richness distributions
mean total community biomass
density of oligochaetes
ratio of amphipods to tubificids
mean individual weight
various trophic indices based on the relative abundance of oligochaetes or chironomids

Prior to the formulation of an Index of Zoobenthos Community Integrity (ZCI) for the Great Lakes, several important preliminary areas upon which the selection of metrics for the final index resides must be thoroughly examined. These are briefly discussed in Appendix A.

INDEX THEORY AND CONCERNS

There is a need for a catholic biological scale of water quality that compares and contrasts the biotic communities in all locations and habitats under all circumstances (Truett et al. 1975). Section 102(2) of the 1969 U.S. National Environmental Policy Act directed all federal environmental agencies to "identify and develop methods and procedures. . . which will ensure that presently unquantified environment amenities and values may be given appropriate consideration in decision-making." This was reaffirmed in 1975 by the National Academy of Science, which at that time concluded that the efforts of federal agencies to develop and use environmental indices have been inadequate. The same criticism could equally apply to Canada.

An index (such as the IBI) is a number, usually dimensionless, whose value expresses (in a linear or simple curvilinear function) a measure or estimate of the relative magnitude of some condition, such as the pollution load of a body of water or the estimated effectiveness of a proposed pollution abatement program. Such a system for rating water quality offers promise as a useful tool in the administration of water pollution abatement programs and has a number of benefits. The CEQ (1975) distinguishes between two types of indices:

1) goal indices, which measure progress toward broad societal reforms: and

2) programmatic indices, which relate to a specific program designed to maintain or change some aspect of an immediate environment under consideration.

The nature and complexity of an index is dependent upon its subject, the purpose it is designed for, and the rigor of the requirements it should have in order to be scientifically defensible. Several biological indicators may be integrated into one index for complex problems. There are precedents for such techniques with respect to the well-known and accepted indices used by economists to communicate trends in the cost of living, unemployment, and GNP.

Once defined, understood, and accepted, indices can be guickly grasped and compared in many cases where assimilating and comparing a complicated set of data would be too time-consuming and confusing to be practical or useful (Truett et al. 1975). By providing a convenient format for summarizing and handling data, indices allow for direct analysis of biotic communities without the need for referring to cumbersome tables, curves, or multivariate outputs. By depicting trends through time in relation to pollution abatement and by comparing environmental quality among geographic areas, indices are one of the most effective ways to communicate information to policy makers and the general public (Landwehr and Deininger 1976).

The selection of indices can be regarded as a two-stage process, involving first the selection of stimulus-response factors appropriate to the problem, and second, the selection of appropriate measures of these factors (FAO 1976). The major end point in development of any index should be the translation of a scientifically defensible analysis of the many components of the environment into an optimum number of terms with maximum information content. To do this, we must accept some reduction in precision, but in turn gain the ability to communicate. In current times of strict funding, public accountability, and increased concern by all with regard to pollution problems, environmental scientists and policy makers must develop techniques, such as indices of biotic integrity, to express complex concepts to lay people in as uncomplicated a fashion as possible.

An important concern is the need to examine the use of the Index of Zoobenthos Community Integrity (ZCI) in light of the extensive and diverse literature on the theoretical rationale for developing environmental indices based on a comprehensive understanding of the causal mechanisms that relate response type to stimulus type (Table 3). For example, what are the trade-offs between communication facilitation and ecological acumen within the ZCI index? Is community integrity the best means of abstracting and communicating changes in Great Lakes environmental quality? How can the a priori selection of parameters be best undertaken to form an effectual monitor of health in relation to both recognized/expected stresses and as yet unconceived/unanticipated surprises?

As the CEQ (1975) identified, the utility and shortcomings of indices should be examined by lay people and specialists alike. Attention should be directed toward identifying and accepting some point of balance between the accredited managerial advantages in using agglomerative indices (Thomas 1972; CEQ 1975), and the noted, and perhaps not insignificant, weaknesses in such indices (FAO 1976).

TABLE 3. Stages needing to be addressed in the development and application of biotic indices.

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a) Marshalling of insights concerning the stimulus-response system under study.

b) Application of preexisting indices that are sufficiently general in their nature that immediate application can be made.

c) Rapid development of new indices on an ad hoc trial basis.

d) Empirical observation of new community responses or properties, including initiation of statistical studies to develop correlations and causal mechanisms.

e) Synthesis of the hypotheses into a larger conceptual framework; i.e. modelling in the broadest sense. Computer simulations are likely to be valuable at this stage to explore the dynamics of causal hypotheses.

f) Formulation of new indices from the models. In a sense, simulations and other models may be abstracted into indices.

g) If computer simulation models have been developed, the new indices may be tested on the dynamics of the simulation. The cost structure of index application may be modelled and added to the simulation, and a benefit cost analysis may be done.

h) New indices developed through conceptual processes should be field tested. At this stage, iterations are desirable, and the investigator may want to return to stages (a), and (d) through (h).

Source: FAO 1976.

The managerial advantages in such indices include:

1) Communication ease among those segments of society concerned with environmental quality. In this respect, indices serve a vital educational function.

2) Resulting increased public sensitivity and participation in decision making. For example, environmental impact statements are prime candidates for application of such indices.

3) Encouraged accountability of public officials. For example, the use of indices summarizing changes in the economy has raised the whole level of political discussion about such concerns, since these indices have achieved widespread recognition.

4) Distillation and standardization of voluminous data in an objective format such that the efforts of special interest groups (Pollution Probe, Sierra Club, and Greenpeace) become more efficient, to the benefit of all concerned.

The weaknesses in such indices include:

1) Lack of transparency in discrimination of the sensitivity of reactant components of the index. For example, during aggregation, the primary measurement data need not and should not be lost. The information conveyed by indices should be accessible for more detailed examination if the need arises; i.e. "indices should be capable of being disaggregated as well as aggregated."

2) Difficulty in identifying the agents of perturbation (an important concern in the AOCs, which are characterized by a complex milieu of pollutants). For example, recognition that index answers are at best largely correlative and that cause-and-effect relations, although often indicated, would not be referred without further testing.

3) Practical questions relating to the spatial bounds and temporal variability (including seasonal stratifications) which must be considered. For example, because no biological measure remains constant in a turbulent environment, the concept of baseline is misleadingly oversimplified. We must therefore recognize that there exists a spectra of values which encompass the normal range of responses.

4) Mathematical naivete and possible statistical artifice at best, or obfuscation at worst, between environmental variables and biotic responses. For example, the lack of logical methodology in constructing of some agglomerative indices is almost legendary, i.e. solving problems of scale by converting each separate factor into a dimensionless index number often does not solve the problem of assigning subjective weights to each of the component metrics, due to the existence of multiplicative effects (e.g., synergisms) and dependence on human values.

Emphasis should be placed on recognizing such concerns during the screening of potential parameters for measuring the effects of stress upon the integrity of zoobenthos communities in AOCs. Finally, it should be remembered that the credibility of any index is only as good as the supporting data base which, in the case of the current Great Lakes zoobenthos, may be marginal (Appendix A).

As Kerr identified, a long-term goal in the use of the IBI and related biomonitoring tools should be the treatment of the index as a statistic that has sampling and other sources of variability. The distributional properties of the ZCI or IBI indices must therefore be documented, perhaps using sensitivity or uncertainty analysis (see Fontaine and Stewart, these proceedings). Once this is done, such indices can be used in the design of research programs (as in Jackson and Resh 1988), or as functional vehicles for predicting the effects of anthropogenic perturbation on natural systems through extrapolation, rather than through retrogressive assessment on a system-by-system basis of damage already manifest (Rosenberg et al. 1981). Further, using index information to calculate the cost-effectiveness of different management decisions should be investigated through use of gaming approaches via computer simulations (FAO 1976). Questions of interest might include time to stress detection, financial cost of index application, level of pollutant reached before affirmative action, and the full degree of degradation that occurred at the time the decision was made. By undertaking such analyses, some of the trial and error can be removed before the biomonitoring program is applied to the field.

Still, the major worry some justifiably have about indices is fear of information loss through oversimplification. In fact, by definition, an index represents a condensed form of understanding, a stripped-down model, in which factors of secondary importance are intentionally deleted (FAO 1976). Patrick (1975), drawing upon the analogy of an environmental doctor, stated: "Just as in medical treatment, you get what you pay for. The more thorough and competent the examination, the better the diagnosis. The more you try to reduce things to a single number, the more you lose in the measurement.... In other words, you ought to have different degrees of information, just as we do for medical examinations, depending on your questions." To continue with this analogy, consider the Canadian physician, Norman Bethune, who was nearly deified in china during the second Sino-Japanese War when at one time he was the only qualified doctor among 13,000,000 people, once operating "without thought of self" (Mao 1939) on 115 cases in 69 hours while constantly under heavy artillery fire. Obviously, in such a situation, considerable hedging was required. The number of environmentally diseased areas warranting our attention as environmental physicians (Schaeffer et al. 1988; Rapport 1989) is increasing at an alarming rate. As in Bethune's dilemma, often detailed diagnoses are possible on only a limited number of these systems. Ignoring others because of lack of time or money is tantamount to euthanasia. Trade-offs, in the form of integrity indices, are therefore required in the interim. By design, then, such empirical biomonitoring procedures can compensate for recognized sacrifices in descriptive precision and detail by greatly expanding the frame of reference from which general inferences can be drawn (Peters 1986).

In conclusion, it is important to remember that use of biotic integrity indices is neither the panacea that some would believe, nor the spreading cancer that others would suggest. Such indices are designed as managerial, not ecological tools. This is an important distinction worth keeping in mind. Facile and naive use of biotic index procedures by government managers has unfortunately begun. As the FAO (1976) emphasized, although relevance and high scientific precision are often incompatible goals, development of indices of low relevance and precision (e.g., diversity measures) can be "misleading and worse than useless." Further, the danger implicit here is in the ascription of an inaccurate number to system health, which may be unscrupulously regarded by some as license to pollute to a particular level. Setting of directions rather than end points may be a wiser management strategy.

Alternatively, as Cairns (1975) has elaborated, prejudicial dismissal of index approaches by ivory-tower academics is equally as dangerous (as someone in this workshop said in defense of such iconoclastic techniques as indexing: "if you're not offending at least fifty percent of the people, you're not making progress").
statistical acumen needed to use and explain complicated multivariate techniques is, more often than not, unavailable to policy makers. The time lag involved in

educating such individuals precludes the widespread use of multivariate approaches. Indices should not, however, be generated as a replacement to detailed ordination procedures by researchers (if for no other reason than that such procedures are needed to identify representative community types for the indices). It is important to remember that the usefulness of any index depends greatly upon the manner in which the component metrics are aggregated (CEQ 1975). Indices should be supported by mathematical models that characterize environmental interrelationships in vigorous quantitative fashion. Frequently, benthologists working on the Great bakes fall into lengthy arguments about why they consider an area to be polluted or pristine, based on observed community patterns (some of which, unfortunately, are analyzed by statistical techniques of dubious merit). Dy using indices of community integrity, objectivity will replace subjective rhetoric in the assessment of shifts in environmental quality. Indeed, we will be able not only to define our goals, but also to measure how we progress toward them (remember, however, the previous cautionary caveat about the setting of end points). Indices are susceptible, as Thomas (1972) correctly states, to misuse, just as all information systems are, but their use can actually promote open discussion and retard misleading environmental information which may appear when only selected raw data or complicated statistical procedures are available to a limited number from the ranks of a select scientific priesthood. Again, a biotic index of integrity is but a tool.

COMPARATIVE NESTED INTEGRITY

Because of the legal need for operationally defining ecosystem health, the overall mandate of this section of this workshop was to grapple with ways of linking empirical integrity with the theoretical backgrounds from each of our independent disciplines. The take-home message from the three-day workshop was that we do not require any single approach to measure integrity, but would rather benefit from a plurality of integrated approaches. This is recognized in several of the papers in these proceedings: a composite integrity [is needed] which includes each hierarchic level of the system" (Ryder and Kerr); "integrity is scale dependent and there is no one integrity even for a system so clearly defined as the Great Lakes..." (Allen): and "integrity should be seen as an umbrella concept which integrates these many different characteristics of an ecosystem which, when taken together, describe an ecosystem's ability to maintain its organization (Kay 1990). Fig. 2 represents an attempt to interpret the varied integrity monitoring approaches in an epistemological hierarchy. This is essentially an expanded dissection of the top-level organizational strata from Fig. 1.

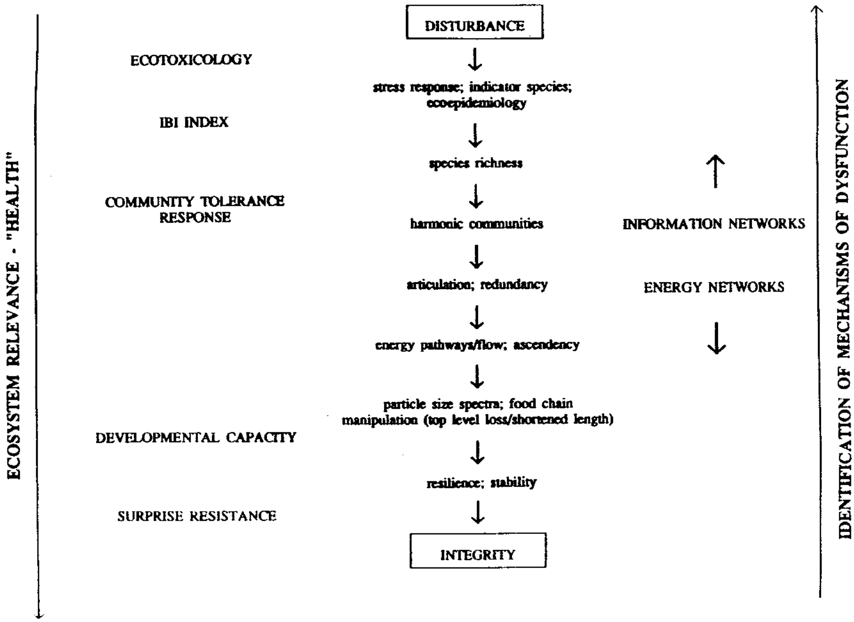

FIG. 2. Interpretation of varied integrity monitoring approaches in an epistemolcgical hierarchy.

An interdependence of the complementary methodologies is evident in that, although different in their final interpretation, they all draw largely upon the same data base for their formulation. For example, Kerr's analysis of particle-size spectra is really a linear mapping of Ulanowicz's articulation measure described in these proceedings. One level's prediction becomes another level's understanding. As Kay illuminates in these proceedings:

Before such theoretical power will be available, a much better understanding of ecosystems as self-organizing dynamic systems is required. In this regard, second law/energy analysis and rework theory hold much promise. However, such approaches require time-series data of a detail which is available for only a few systems. In the interim, we will have to depend on an empirical and intuitive understanding of ecosystems for the prediction of ecosystem response to environmental change.

Integrity index approaches function as just such an empirical link in a hierarchical framework of comparative nested integrity. Not only are the different methodologies complementary, but they can also be co-requisite; for example, the IBI indices suggested by Steedman and Regier in these proceedings depend upon the identification of the species assemblages described by Ryder and Kerr in this volume. In a sense, all the methodologies need each other. That is, energy networking is firmly grounded in ecosystem theory, but suffers from a restricted data base. IBI indices, in contrast, are rich in data but short on the ecological ground-truthing of some of their representative metrics. No single approach is going to be the most adequate in all situations. There is a strong need to facilitate vigorous cross-calibration among the various techniques to determine the situations in which each is best suited for biomonitoring the diverse scope of insults characteristic of Great Lakes environments. What we require, therefore, is an integrated toolbox, not one full of just hammers (Vanderburg, these proceedings). The best strategy should be one of adaptive management of integrity biomonitoring for the Great Lakes system. As Cairns (1975) similarly concluded, What is needed is a protocol indicating the way in which one should determine the mix of methods that should be used to estimate and monitor threats to biological integrity."

In this sense, the final assessment should be one of comparative nested integrity, one that enthusiastically embraces the IJC recommendations for ecosystem focus.

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APPENDIXA

GENERATIONOF BACKGROUND DATANECESSARY FOR DEVELOPMENT *OF* AN INDEX OF ZOOBENTHOS COMMUNITY INTEGRITY

Assessment of the Quantification of Zoobenthos Data

The primary concern in optimizing design of any sampling program is to gain an accurate measurement with high precision with the least effort. The ability to detect future changes in zoobenthos populations is obviously one of the most important issues needing to be examined in environmental monitoring. Unfortunately, the efficacy of zoobenthos as indicators of environmental change within the Great Lakes is greatly hampered by sampling design and data interpretation techniques that are frequently embarrassing at best, and possibly of extreme limited usefulness at worst. Subject areas needing investigation include the effects of sampling intensity on both the precision of density estimates and the ability to detect species compositional changes, data transformation procedures, and analysis of sampler efficiencies. As several of the proposed metrics involved in compilation of integrity indices are dependent on the accurate and precise quantification of zoobenthos density and species composition, such critical appraisal of existing methods is essential.

Investigation of the Appropriateness of Diversity Indices

Diversity indices have been widely used for assessing the impacts of perturbations on zoobenthos communities in the Great lakes. Literally dozens of diversity indices now exist, and the choice of which to use is seemingly dependent upon the whims/biases of the investigator (although some individuals circumvent the difficulty of justifying their choice by calculating an entire suite of indices). Few subjects in applied ecology are as controversial as the use (and misuse) of diversity indices. Despite numerous papers whose very titles appear to be designed as a form of reality therapy, many benthologists (including several prominent Great Lakes researchers) still persist in the belief that diversity indices must serve a prominent role in biomonitoring protocols. Regardless of whether the cause is innocent ignorance or myopic determinism, there is an obvious need to review, synthesize, and generate advisory statements to government managers on this issue before such indices become further entrenched in the soon-to-be-developed RAP/AOC surveillance programs. Due to the reticence of some to trust strictly theoretical arguments, one of the most profitable methods of critically assessing diversity indices is to actually test their effectiveness in identifying noxious conditions in the Great Lakes as compared with integrity indices or more traditional multivariate techniques. Studies with fish have shown that when compared with conventional diversity indices, the IBI consistently provides a better means of quantitatively ranking sites in relation to perturbation.

Harmonic Communities and Development of an Index of Community Tolerance

In addition to the acknowledged problems inherent in diversity indices in terms of numerous theoretical and mathematical constraints, perhaps the most serious difficulty restricting their use in water quality assessments involves their dismissal of organism identification in the place of simple integer values. Obviously, useful knowledge revealed by the kinds of animals present is lost in such a technique (in effect, as has been stated numerous times, it may equate an oligocheate-chironomid community with a mayfly-amphipod community and thereby ignore a wealth of information on the environmental adaptations of such invertebrates). Because of this, diversity indices are notoriously inefficient in discriminating between pollution-induced stresses and nonanthropogenic influences, such as substrate characteristics. Due to this weakness, several researchers have attempted to combine the indicator-organism and community-richness approaches to provide a method of data analysis and valid criteria for evaluating zoobenthos communities as markers of water quality. Although, as previously discussed, severe limitations may exist in the use of quantitative zoobenthos data from previous Great Lakes research efforts, the qualitative presence/absence data bank is quite good. By carefully screening the multivariate data, determinations of the occurrence of nonrandom assemblages of species may become overt. such associations, or harmonic communities, are thought to exist for Great Lakes fishes. Tolerance rankings could then be assigned to all zoobenthos species endemic to the Great Lakes and a mathematical algorithm designed to summarize such information into a statistic of integrated community tolerance. This in turn could be utilized as a metric in development of an Index of Zoobenthos Community Integrity.

Hierarchical Nomenclature

Aristotle was the first to comment on the association of tubificids (described as small, red threads) and contaminated sediments. Some have feared that because several of the investigators studying Great Lakes zoobenthos have been little more specific than Aristotle in their species identifications, by inference these individuals may not have conducted the most useful research. Recent thinking, however, has seriously challenged such paradigms with respect to zooplankton in general and Great Lakes limnetic communities in particular. Throughout the development of the integrity indices, close attention should be paid to such questions as: How much information about community structure is lost if lower taxa levels are not discriminated? Is species-level identification a retrogressive approach?

NOTES

1. Unfortunately, most studies operate at only the lower levels, yet attempt to make predictions about top-level processes. For example, "a complete understanding of the physiological response is, in particular, needed to predict how far degradative activities have to be lowered to prevent or to overcome ecosystem damage." This is not only overoptimistic, but erroneous. It can only be hoped, at best, to use one level's understanding to predict the next level's behavior. The problem is, therefore, that because few researchers have comprehensively studied attributes of Great Lakes communities, we still have relatively little power to empirically predict ecosystemic dysfunction. It is also important to note that, to be identified at all, certain system responses must be observed or sought at the community level and that these responses may not be predictable from a synthesis of research on lower-level components (FAO 1976). Achieving an appropriate study design is a matter of proper definition and bounding before research is undertaken. There is a need to integrate applied research with basic research to avoid what Vallentyne (1978) has referred to as *'band-aid, fire-fighting efforts."

2. Obviously, as Kay these proceedings) identified, "the concept of integrity must be seen as multidimensional and encompassing a number of ecosystem behaviors." Integrity terms are also not value free. Although Leopold (1947) never explicitly defined exactly what he meant by integrity, he did provide some clues:

   1) All ethics rest upon a single premise that the individual is a member of a community of interdependent parts.

   2) We must realize the indivisibility of the earth--its soil, mountains, rivers, forests, climate, plants, and animals, and respect it collectively not as a useful servant but as a living being.

   3) The land is one organism. Its parts, like our own parts, compete with each other and cooperate with each other. The competitions are as much a part of the inner working as the cooperations.

   4) These creatures are members of the biotic community and if (as I believe) its stability depends on its integrity, they are entitled to continuance.

Integrity, therefore can be defined in many ways, be it a property either intrinsically or latently applied to ecosystems by humans (see Serafin, these proceedings), with no one definition being right. As a contributor to the 1975 EPA Integrity Symposium remarked, "from the many interpretations presented, it can clearly be seen that integrity, like beauty, is in the eye of the beholder." (Regier and France, these proceedings). The interlinking of integrity and beauty as a moral precept is further developed in France (1990). Although important in describing a paradigm, words can also be used as jabberwocky or in monistic totalitarianism (Regier et al. these proceedings). Recall the World State's motto in the opening lines of A Brave New World: "COMMUNITY, IDENTITY, STABILITY." Despite being the same words as those used by members of this workshop, few would argue that for Huxley (1932) they described an environment characterized by integrity. Caution should therefore be always applied in the use of any lexicon.

3. Effective application of a Zoobenthos Community Integrity Index requires not only careful consideration of those factors most descriptive of biological integrity, but also numerous judgments based on scientific expertise. Thus, integrity indices cannot be used in a cookbook fashion, as can those of species diversity. Instead, an adaptive strategy is required to tailor the integrity index to each zoogeographic region of study. Whether a common ZCI Index can be constructed for the entire Great bakes basin, or whether a series of lake-specific indices must be developed, is not yet known.

4. (From FAO 1976). The essential formal characteristics of indices can be explained in relation to an ideal case where R, a quantifiable response, is some function; f, of a quantifiable stimulus: S, that is:

$$R = f(S)$$

An index of response is selected such that a given level of response determines a definite value of the index. The response is thus represented by an index, Ir, as a function; g, of the response:

$$Ir = g(R)$$

Similarly an index of the stimulus, Is, may be selected so that:

$$= h(S)$$

$$\text{since } r = f(S),\ Ir = g(f(S))$$

that is, the index of response is also determined by the value of the stimulus. In practice, it will often happen that the magnitude of the response is not uniquely determined be a specified level of stimulus owing to variability characteristic of biological systems. Similarly, the value of an index may be subject to errors of observation, and not uniquely determined by the factor it purports to measure. Further, several levels of stimulus may yield the same response, or a single value of an index may result from several levels of an observed factor. These complications may severely limit the strength of an inference which attempts to identify the cause (stimulus) of an observed response. Annotated abstracts of biological indices of environmental quality are found in Thomas et al. (1973).

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FLEXIBLE GOVERNANCE

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ABSTRACT. The institutional structure for governance over the Great Lakes is outlined and recent trends are described. Compared with the situation ten or so years ago, there is now a better balance between governmental and nongovernmental organizations, and among organizations working at local, lakewide and basinwide levels. Governance is now more complex, but it is also more firmly rooted in regional and local constituencies. With more organizational centers and networks available, there is a greater inherent flexibility within the overall system of governance to respond to surprises. However, continued evolution of governance through reactive responses to various trends and events is unlikely to promote ecosystem integrity and sustainability. Governance for the Great Lakes can also be seen in terms of different sets of actor systems which use different components of the ecosystem. Given the common property characteristics of the lakes, these actor systems should be encouraged to become responsible self-governing communities of interest groups. Issues to consider for guiding governance viewed in terms of self-governing actor systems include:

1) translating ecosystem integrity into a set of standards that can provide management objectives and constraints for each actor system,

2) determining the extent to which a biocentric value system may be a prerequisite for achieving integrity and sustainability,

3) assessing the pro-active initiatives needed at international levels as well as at regional and local levels,

4) developing anticipatory capabilities so that not everything new comes as a surprise,

5) establishing institutional ground rules based in ecosystem integrity and sustainability as a fundamental right,

6) fostering societal learning as integral to the further development of governance itself.

AN ORIENTING PERSPECTIVE

Governance is generally defined as the exercise of authority and control. Flexibility means susceptibility to modification or adaptation. As do ecosystems, governance exhibits both structure and process, with the only real difference between structure and process being the rates of change. Legal systems and institutions change relatively slowly, and usually incrementally, while informal networks of people can often respond swiftly to changing circumstances. Flexible governance becomes an issue of how quickly arrangements for governance can be modified. In the context of "restoring ecosystem integrity in times of surprise," it is also a question of whether or not the modifications are compatible with or enhance certain properties of the ecosystem.

The basic structure for governance of the Great Lakes is provided by the two constitutional federalisms which meet in the middle of the water. The constitutions define the appropriated functions of government vis-a-vis other sectors of society, and they divide responsibilities for governance between central and state or provincial authorities. The latter, in turn, assign rights and responsibilities to local (municipal) governments. In both countries, governing structures have also been created at levels above the municipal but below the state or provincial level, so that most citizens in the Great Lakes basin ecosystem now live under four layers of governing authority. Fig. 1 sketches this structure for governance.

CANADA		UNITED STATES
FEDERAL		FEDERAL
	International Joint Commission Great Lakes Fishery Commission	
FEDERAL PROVINCIAL Federal-provincial agreements		FEDERAL-STATE (Great Lakes Basin Commission, 1965-1981)
		INTER-STATE Council of Great Lakes Governors; Great Lakes Commission
PROVINCIAL		STATE
	Great Lakes Charter Toxic Substances Control Agreement	
REGIONAL MUNICIPALITIES		MULTI-COUNTY PLANNING COMMISSIONS
CONSERVATION AUTHORITIES CONSERVATION		SOIL AND WATER DISTRICTS; WATERSHED COUNCILS
MUNICIPAL		MUNICIPAL
	International Great Lakes-St. Lawrence Mayors Conference	

FIG. 1. Basic framework of governance for the Great Lakes. The IJC reports to the two federal governments. The GLFC reports to federal, state and provincial governments. The Great Lakes Charter and Toxic Substances Control Agreement were signed by the eight governors and two premiers of the Great Lakes-St. Lawrence Basin. In Canada, federal-provincial cooperation is established by formal agreements. In the U.S., federal-state cooperation used to be fostered by the GLBC. Interstate cooperation is carried out through the Council of Great Lakes Governors and the GLC. The Mayors' conference fosters municipal involvement in Great Lakes issues.

The scope of the governance to be understood depends considerably on some interpretation of what an ecosystem approach must entail. At the very least it should embrace matters being dealt with under binational agreements that concern the Great Lakes. Nine such agreements have been made over the years, ranging from formal treaties and conventions to good faith statements of intent (Table 1). The administrative arrangements for implementing these agreements constitute an important component in the overall governance for the lakes.

TABLE 1. Binational agreements concerning the Great Lakes.

Boundary Waters Treaty, 1909
- International Lake Superior Board of Control, 1914
- International St. Lawrence River Board of Control, 1953
- International Air Quality Advisory Board, 1966
- Great Lakes Water Quality Agreement, 1972; 1978; 1987
- International Great Lakes Levels Advisory Board, 1979

The Migratory Birds Treaty, 1916
- The North American Waterfowl Management Plan, 1986

The Niagara Treaty, 1950
- International Niagara Board of Control, 1953

Convention on Great Lakes Fisheries, 1955
- Joint Strategic Plan for the Management of Great bakes Fisheries, 1981

St. Lawrence Seaway, 1959

Great Lakes Charter, 1985

Michigan-Ontario Agreements
- Air Pollution Agreement, 1985
- Joint Maritime Advisory Committee, 1988

The Great Lakes Toxic Substance Control Agreement, 1986
- Great Lakes Protection Fund, 1988

Declaration of Intent (for the Niagara River and Lake Ontario), 1987
- Lake Ontario Toxics Management Plan, 1989

In addition, there are different configurations for governance over major ecosystem components of the basin; i.e. the atmosphere (or "atmospheric region of influence" over the basin, which can be of continental or even biospheric scale): the lakes and connecting channels (rivers); tributary rivers and watersheds; groundwater aquifers: and coastal zones. Arrangements are also organized around seven distinct water uses: commercial navigation, hydropower generation and cooling water; domestic and industrial water supply; effluent disposal; sport and commercial fisheries: wildlife; and water-based recreation other than hunting and fishing.

SOME TRENDS IN GOVERNANCE

Throughout most of the 1970s, Great Lakes concerns were addressed almost exclusively by governments, mostly through programs of binational cooperation overseen by the International Joint Commission (IJC) and the Great Lakes Fishery Commission (GLFC). Local governments and land use agencies were essentially not involved. The International Association for Great lakes Research (IAGLR) had been serving an important role for information exchange among the scientific community since the mid-1960s. Except for a quite innovative process for public consultation developed by the IJC's Pollution from Land Use Activities Reference Group (PLUARG), citizen involvement in lakes issues was low. Great Lakes Tomorrow (GLT) was created in the latter part of the 1970s, originating as a spin-off from the Lake Michigan Federation. Academic proposals to strengthen the capacity for governance were addressed mainly to expanding the functions of the IJC. By the end of the 1970s it was clear that neither the Commission nor the two federal governments wished this to happen.

In 1981, the Reagan administration abolished the Great Lakes Basin Commission, which had been established in 1965. The Commission was the only forum whereby U.S. state and federal officials met regularly to consider a range of land and water management issues pertaining to the U.S. portion of the Great Lakes basin. Combined with federal budget cuts and a general withdrawal of political will to deal with environmental issues generally, the new federalism left responsibilities for Great Lakes matters much more on the shoulders of the eight Great Lakes states. In Canada, the provinces constitutionally have major responsibility for resource and environmental matters, so Ontario already had a leading role for the Great Lakes. Nevertheless, the federal government played important supporting roles, and had lead responsibilities for the international aspects of Canada-United States cooperation. Early moves by the Mulroney government in 1984 to downsize Environment Canada gave the same impression of withdrawal of political will to deal with Great Lakes and other environmental issues.

Probably both governments had seriously underestimated the strength of public concern about the lakes and public support for environmental protection measures. Several initiatives came from various U.S. sources in the early- to mid-1980s. Through the Council of Great Lakes Governors, the Great bakes Charter (1985) and the Toxic Substances Control Agreement (1986) were signed as good faith agreements by the governors of the eight lake states and the Premiers of Quebec and Ontario. Quebec began to take direct interest in the Great Lakes as an affected downstream jurisdiction following a change in provincial administration in 1985. Mayors of some cities and local municipalities began to express interest in Great lakes issues, and following a 1987 International Great Lakes-St. Lawrence Mayors' Conference (sponsored by the Great Lakes-St. Lawrence Maritime forum), the mayors raised the possibility of holding such conferences on a regular basis. The Mayors' Conference is now an annual event.

In 1983, from an initiative taken by a former Governor of Michigan, a Center for the Great Lakes was established in Chicago, and it opened a Toronto office in 1985. The center undertakes policy analyses on matters of interest to governors and some business groups. It has convened conferences to facilitate discussion of broad issues by representatives of diverse interest groups, it holds briefing sessions for state and provincial legislators, and it performs a public information role through distribution of its periodic newsletter, "Great lakes Reporter." In 1986, Great Lakes United (GLU) was formed as a loose coalition of diverse citizen interest groups. Now, with a membership of over 200 environmental, conservation, small business, union, and local government groups and individuals, almost a third of whom are Canadian, GLU has become an important force for building a binational constituency for the Lakes. This was recognized by governments when they took the unprecedented step of including GLU representatives on both the U.S. and Canadian teams for negotiating the 1987 Protocol amending the 1978 Great lakes Water Quality Agreement. Great lakes Tomorrow continues to perform the modest but important role of sponsoring extension courses on Great bakes issues at colleges and universities around the lower lakes.

In response to the high water levels and winter storm damages during 1985-1986, riparian landowners have formed the International Great Lakes Coalition (IGLC). The coalition has a number of local chapters in both countries and a 1988 membership in the order of 20,000 people. It promotes further regulation of lake levels and is closely following the work of the five functional study groups convened by IJC in response to the Great Lakes Levels Reference it received in 1986.

The bake Michigan Federation was the first organization of public interest groups to form around one of the bakes. In 1987, Lake Superior International became the first binational network of groups sharing concerns about a particular lake. In Toronto, GLU is working with Pollution Probe, the Canadian Environmental Law Association, and other groups to develop a lake Ontario Organizing Network (LOON) to strengthen the involvement of nongovernmental organizations in lake-wide issues. Review of the lake Ontario Toxics Management Plan draft is one of the first priorities.

The main result of these developments in the 1980s is that, while the institutional framework for governance has remained the same, the number of agencies and other organizations involved with policy and program issues, and taking initiatives, has increased considerably. There is now a better balance between the involvement of governmental and nongovernmental organizations and among different organizations working at local, lake-wide, and Great Lakes basin levels. Governance may have become more complex, but at the same time it is more firmly rooted in growing regional and local constituencies. It has also developed considerable networking capabilities. Nongovernmental groups in particular often go beyond immediate local concerns to develop an interest in larger questions about the policy directions being taken by governments and the longer term goals being sought. There is every reason to expect this will continue and give rise to a much stronger sense of bioregionalism.

Thus, with more organizational centers and networks available to take initiatives, using a wider range of strategies and tactics to address problems and issues, a great inherent flexibility has emerged within the overall system of governance to respond to surprise. This flexibility should then be able to give rise to more innovations in governance. It is a moot point as to whether or not some dialectical relationship exists between initiatives taken by governmental and nongovernmental bodies, as one reviewer of this paper has suggested.

TOWARDS UNDERSTANDING THE FLEXIBILITY

From an ecosystem perspective the governance of the Great bakes is still inadequate. It remains fragmented and incomplete, with major discontinuities among the different arrangements that have developed independently for the different ecosystem components. It also remains ineffective in achieving the "virtual elimination of persistent toxic substances in the Great Lakes system" (a goal agreed upon ten years ago), and in controlling the atmospheric fallout of contaminants. Governance will continue to evolve through reactive measures in the face of compelling or fortuitous circumstances in an overall context of turbulence. Rut such a random and reactive process for the development of governance is unlikely to promote ecosystem integrity, with or without surprise.

Some kind of guidance for strengthening governance in appropriate ways seems called for, but it requires more insightful understanding of the processes that are to be guided and the bases for their flexibility. Two concepts are helpful for this intellectual endeavor.

Actor System Dynamics

The term actor is used in its sociological sense to refer to any category of organization (i.e. corporation, government agency, public interest group) or key individual involved in decisions pertaining to a domain. A domain is anything perceived as important or a matter of concern to an actor, be it an issue, an economic or social sector, or a particular place. Actors seek to influence decisions about their domain, and the dynamics are the communications and transactions that go on among them to do so. These may involve competition, collaboration, or conflict resolution, all of which are guided in turn by sets of rules. Some of the rules are formal, such as laws, regulations, or boards of enquiry; and others are informal, arising from custom and cultural rituals. Actor system dynamics are directed to matters of substance concerning a shared domain and to the system of rules which some actors may wish to change (Bums et al. 1985).

Governance over the Great bakes can be conceived in terms of different sets of actor systems that direct their attention and efforts toward the different components of the ecosystem. In the case of water, there are actor systems for the seven major uses of the lakes. These actor systems have varying degrees of formal organization and connectivity among their members. Fisheries and navigation interests seem particularly well organized into actor systems, whereas recreational interests are much less so, at least on a whole-lake or basin-wide basis. There seem to be relatively few connections among the different actor systems, and those that do exist appear to be loose and informal.

Rights and Common Property Resources

The degradation of the Great lakes would seem to confirm the worse case scenario of common property resources; i.e. the "tragedy of the commons." Yet the growing commitment to restoring the commons without at the same time calling for its privatization or conceiving some basin-wide supernational authority for top-down management by professional experts suggests there is a healthy realization of the limits to these two systems for coordination and resource allocation.

The alternative ground rules for allocating the use of resources can be defined in terms of whether or not rights to use resources (i.e. the lakes) are exclusive and whether or not they are transferable rights as in a free market system; exclusive nontransferable rights, as in regulation by governments; nontransferable, nonexclusive rights, exemplified by common property resources with their vulnerability to abuse: and nonexclusive transferable rights, a situation in which attempts to transfer are unethical or illegal (Regier and Grima 1984). Since there are considerable limitations on the extent to which governance by regulation and market forces can be counted on to achieve ecologically sustainable and equitable use, other options need to be developed in addition to these prevailing either/or choices.

Self-governing communities of user groups exercising private stewardship is an arrangement that has evolved under a wide range of cultural, institutional, and ecological circumstances. Although apparently more prevalent in traditional than in modem societies, this arrangement could emerge in the Great lakes context in the form of nongovernmental organizations engaging in various kinds of co-management roles with government agencies. To some extent, this has already happened with fish and wildlife management programs. The voluntary sector of society has considerable potential, and with the right incentives, could be mobilized to support and contribute to a wide range of co-managed activities. This in turn could help individual actor systems develop into self-governing communities of user groups. To the extent they do this, they will likely take on some responsibility for measures that help assure sustainability.

GUIDING THE DEVELOPMENT OF GOVERNANCE

Because governance will continue to change in response to the events of turbulence, there is a challenge in finding out how this change might be guided in ways that will achieve ecosystem integrity and enhance the overall flexibility for coping with systemic surprise. This is a formidable exercise in institutional design. The flexibility criterion itself rules out preconceived blueprints in favor of very general guidelines. A number of issues have to be addressed in order to develop and propose plausible guidelines for governance that would be acceptable.

Ecosystem Integrity

If ecosystem integrity is the prerequisite for sustainable development, it must become a major goal for governance and must be defined clearly. Ecosystem standards need to be set with reference to integrity and interpreted to provide management objectives and constraints for actors and actor systems. This will be challenge enough if only ecosystemic criteria need be considered.

If integrity can only be meaningfully defined in socio-ecosystemic terms, then a wider range of substantive criteria have to be determined and translated into operational guidelines. It is likely then, that this would pose a greater challenge to the paradigms underlying the existing arrangements for governance, and in so doing, begin to deny their basic legitimacy. This in turn could put ecosystemic integrity on a collision course with the major institutions of society, and raise questions about the prospects for peaceful transformations or success.

Beliefs and Values

The common strategy for avoiding political conflict (which collision courses ultimately can give rise to) is to urge major changes in personal and cultural values. Public opinion polls in the Great Lakes basin repeatedly find strong support for environmental quality, and for measures (in general) to restore and maintain it. Current debate in environmental ethics raises doubts about whether or not environmentalism and the policies it gives rise to, such as regulatory pollution control and environmental impact assessments, can achieve what it sets out to do.

Values associated with biocentrism are being promoted as a deeper and more authentic belief system (Devall and Session 1985). An issue to be resolved then, is whether or not integrity and sustainability require a biocentric base, and if so, what this would imply for governance. Can biocentrism be inculcated as governance itself evolves, or is it the prerequisite?

Global Interdependence

The driving forces of Great bakes regional economics are linked to global economic interdependence in sectors such as automobiles, steel, communication technologies, and financial institutions. Biosphere integrity would be a concept of equivalent scope to the economic realities.

Ecosystem integrity for the Great lakes, however it is defined, would be a regional goal affected by events that occur elsewhere in the world. If integrity is to be achieved, then it may require pro-active efforts at international levels, as well as mitigative efforts at regional and local levels to counter the impacts of actions taken elsewhere. Thus, ecosystem integrity for the Great Lakes cannot be based entirely (or even mainly) on self-reliance. The implications of this, however, are not very clear.

Anticipatory Capabilities

Not all surprises have to be surprises. The need to develop anticipatory and preventative strategies for dealing with issues and events has been recognized, but so far these strategies are absent from the governance for the Great bakes. For example, despite the considerable work being done on climate change (e.g., Sanderson 1987; Meisner et. al 1987), no policies or strategies have been proposed to respond to it in the Great bakes. Shorter-term demographic and economic changes in the Great lakes basin are more uncertain, but even the relevant data are not being compiled and analyzed on a systematic basis for the whole basin.

Anticipatory capabilities should be linked with pro-active measures to help bring about preferred futures which are sustainable. Future imaging, adaptive environmental management, and policy exercise games are some of the techniques used to enhance the anticipatory capabilities of small groups of actors. They have been tried out as academic exercises on occasion, but have no permanent role in policies and decisions concerning the lakes.

Institutional Ground Rules

All actors and actor systems must be involved in measures to achieve ecosystem integrity and sustainability. No major players should be allowed to exempt themselves to seek personal gain at the expense of the collective good. Yet the existing ground rules for enterprise encourage and support competition for individual gain, and within bounds this has societal benefits. Ecosystem integrity and sustainability should be viewed as fundamental rights for humans and other living things. Human rights serve to guard against the violation of persons by institutions and other people. Something comparable is needed to guard ecosystemic integrity from violation by institutions and individuals. Ecological rationality should have priority over rationalities inherent in social-choice mechanisms (Dryzek 1987). An ecosystem charter should be able to articulate these ideals with a view to exploring how they might become incorporated into the constitutional framework for governance over the lakes. Eternal vigilance will be required to monitor, challenge, and, where necessary, sanction transgressions.

Societal Learning

The directions of change indicated above will require considerable learning. Societal learning is that which is incorporated into the collective memory of organizations as well as in the individuals who learned. Leadership is needed to promote this learning, and negotiating skills are required to act upon its results.

Arrangements for governance should foster societal learning as part of further development of governance itself. The most appropriate style for this kind of leadership is one that exercises influence throughout governance rather than competing for authority in some one situation. Networking arrangements have this kind of capacity, as well as the flexibility that will be needed.

TAKING SOME FIRST STEPS

Ecosystem integrity and the prerequisites for sustainability need first to be defined and clearly presented. Their implications for the existing and nascent actor systems need to be discussed with, and by, all involved. Sufficient common ground needs to be established so that the self-governing capabilities of various actor systems develop in ways that foster integrity and sustainability. This is the process for societal learning. Are there networks to take the lead?

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A NONEQUILIBRIUM THERMODYNAMIC FRAMEWORK FOR DISCUSSING ECOSYSTEM INTEGRITY

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ABSTRACT. During the last twenty years our understanding of the development of complex systems has changed significantly. The two major developments have been that of catastrophe theory and noneguilibrium thermodynamics and its associated theory of self-organization. These theories indicate that complex system development is nonlinear, discontinuous (catastrophes), not predictable (bifurcations), and multivalued (multiple developmental pathways). Ecosystem development should be expected to exhibit these characteristics. Traditional ecological theory has attempted to describe ecosystem stress response using some simple notions such as stability and resiliency. In fact, stress response must be characterized by a richer set of concepts. The ability of the system to maintain its current operating point in the face of the stress must be ascertained. If the system changes operating points, there are several questions to be considered: Is the change along the original developmental pathway or a new one? Is the change organizing or disorganizing? Will the system return to its original state? Will the system flip to some new state in a catastrophic way? Is the change acceptable to humans? The integrity of an ecosystem does not reflect a single characteristic of an ecosystem. The concept of integrity must be seen as multidimensional and encompassing a number of ecosystem behaviors. A framework of concepts for dealing with integrity is presented in this paper.

INTRODUCTION

The purpose of this paper is to explore the type of organizational and developmental pathways available to ecosystems and the relationship of these pathways to system integrity. The theory of dissipative structures suggests that a number of different pathways *are* available and that these pathways are nonlinear and may be discontinuous and multivalued. Any discussion of integrity, therefore, will encompass a rich set of ecosystem behaviors, some of which will be considered to be consistent with integrity, and some which will not. This paper will discuss the different types of pathways open to ecosystems and their relationship to integrity, but will not discuss the specific conditions which will lead to one type of pathway being followed rather than another.

Integrity of a system refers to our sense of it as a whole. If a system is able to maintain its organization in the face of changing environmental conditions, then it is said to have integrity. If a system is unable to maintain its organization, then it has lost its integrity.

There is an important difficulty with this definition. Ecosystems are not static, their organization is often changing. As well, any loss of organization is often gradual. Thus it is not possible to identify a single organizational state of the system which corresponds to integrity. Instead there must be defined a range of organizational states for which the ecosystem is considered to have integrity. Such a definition would necessarily have an anthropocentric component.

The discussion of the notion of stability in the literature has led to quite a number of conceptual terms, such as resiliency, elasticity, vulnerability, and catastrophe (see Appendix). All of these ideas describe some aspect of an ecosystem's ability to cope with environmental change. Integrity should be seen as an umbrella concept that integrates these many different characteristics of an ecosystem which, when taken together, describe an ecosystem's ability to maintain its organization. What is presented below is a description of ecosystem development and organization that will serve as a framework for connecting these concepts.

How does nonequilibrium thermodynamics suggest that systems develop? Prigogine (Prigogine, Nicolis, Babloyantz 1972; Nicolis, Prigogine 1977) has shown that under certain conditions, open systems with a gradient across their boundaries will move away from equilibrium and will establish new stable structures. (The point is that this is the opposite of the behavior one would normally expect, given the second law of thermodynamics.) Such systems are characterized by rates of energy dissipation which increase as the system moves from equilibrium and becomes more organized. Hence the name dissipative structures.

The development of such self-organizing systems is characterized by phases of rapid organization to a steady-state level, followed by a period during which the system maintains itself at the new steady state. The organization of the system is not a smooth process, but proceeds in spurts. These spurts are sudden accelerations in the change of state of the system. The state change may be continuous or catastrophic (see Appendix). The change in the state is accomplished by the addition of new dissipative structures to the system. These new structures can consist of new pathways for energy flow which connect old components or of new components and their associated new pathways. Each spurt results in the system moving further from equilibrium, dissipating more energy, and becoming more organized. Each spurt occurs when random environmental conditions exceed a catastrophe threshold for the system. The path through state space which the system follows as it develops is called the thermodynamic branch (see Appendix). Ecosystem succession is an example of this kind of process. Each of the seral stages corresponds to one steady-state plateau. The displacement of a previous seral stage by the next is an example of a spurt, the reorganization of the system to a new level of structure which dissipates more energy.

The gradient which drives ecosystem development is the solar energy impinging on the ecosystem. As ecosystems are driven away from equilibrium they become more organized and effective at dissipating solar energy. At the same time as this self-organizing process is occurring in ecosystems, environmental fluctuations are tending to disorganize the system. The point in state space where the disorganizing forces of environmental change and the organizing thermodynamic faces are balanced is referred to as the optimum operating point (see Fig. 1).

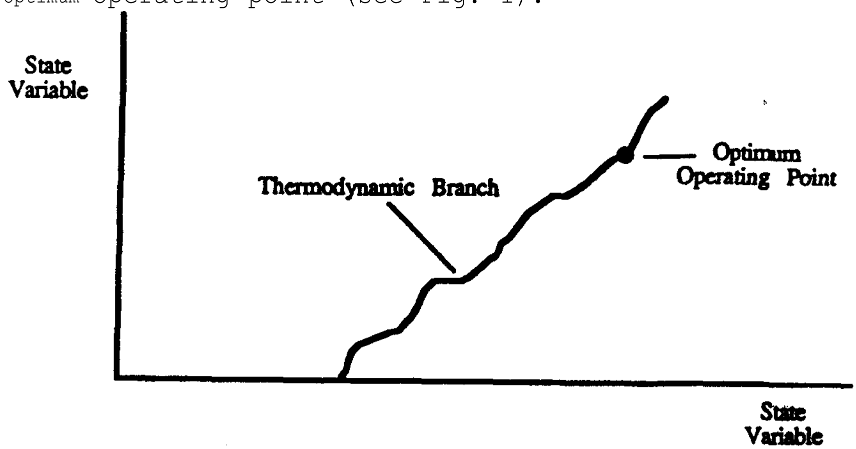

FIG. 1. An ecosystem develops along a thermodynamic branch (a path in state space) until it reaches an optimum operating point.

For any real ecosystem, a particular point will be an optimum operating point only temporarily. This is because the environment will be changing and evolution will be occurring, thus changing the balance between the organizing and disorganizing forces. However, it is useful over short time periods to treat the optimum operating point as if it were stationary. The climax community in ecological succession would be an example of an optimum operating point for an ecosystem.

RESPONSE TO ENVIRONMENTAL CHANGE

Let us assume that the ecosystem has developed along a thermodynamic branch in the way described above and that it has reached its optimum operating point. Suppose some change occurs in its environment. (The change may be short term with the environment returning to its previous condition, or the change may persist.) What effect will this have on the ecosystem's organization and hence its integrity? There is a series of questions which must be asked. These are:

1) Will the system be moved away from its optimum operating point?

NO: Then organization and integrity are not directly affected, and the analysis ends.

YES: Then the question becomes:

2) Does the system return to its original optimum operating point?

NO: Then the system does not return to its original optimum operating point. This leads to two possibilities:

1) a new optimum operating point exists, or

2) it does not.

In the latter case the organization breaks down and the system loses its integrity. In the former case there are three possibilities:

Case 1: The new optimum operating point is on the original thermodynamic branch.

Case 2: The new optimum operating point is on a bifurcation from the original branch.

Case 3: The new optimum operating point is on a different thermodynamic branch and the system undergoes a catastrophic re-organization to reach it.

YES: Then there are three issues:

a) How far is the system moved from its optimum operating point before returning?

b) How long will it take to return to its optimum operating point?

c) What is the stability of the system upon its return?

In any case the system is able to re-organize itself to cope with the environmental change, and its integrity is preserved.

Examples and Elaboration

The system does not move from its original optimum operating point. For example, a terrestrial system may be exposed to a temporary flood or drought which the system is adapted to. If the disturbance is not particularly intense, the system will not be affected. Another example is the ongoing spraying of fenitrothion on Canadian forests to control spruce budworm. This appears to have no immediate effect on the forests but it does interfere with the ability of the forest to regenerate itself (Weinberger et al. 1981). Thus the ability of the system to deal with some future stress which requires regeneration may be impaired.

The system moves from its original optimum operating point but returns to it. Fire in a temperate forested ecosystem is a short-term event that moves the system well away from its optimum operating point. However, the forest regenerates back to the original system. Oil spills along the shores of Great Britain have had similar effect with a regeneration time of about 10 years (Nelson-Smith 1975).

Rutledge (1974) showed that a short-grass prairie ecosystem subjected to continuous drought will, after about 20 years, reorganize itself to return to its pre-drought state.

The system moves permanently from its original optimum operating point:

Case 0: the system collapses. The environment changes in such a way as to be uninhabitable. An example is the process of desertification. Another is severe prolonged drought in mangrove systems, which leads to the total collapse of the system (Lugo et al. 1981). A third example is the result of acid rain which, in the extreme case of the Sudbury area in Canada, has led to the rocky equivalent of a desert, and in the Laurentian Shield, has led to dead lakes.

Case 1: the system remains on original thermodynamic branch. See Fig. 2 for an illustration of this case. The ecosystem maintains its original set of dissipative structures, or moves back to some set which represents an earlier stage in development. The level of operation of the individual structures has changed, perhaps even catastrophically. Overall, the dissipative system is recognizable as the original, but its operation has been modified.

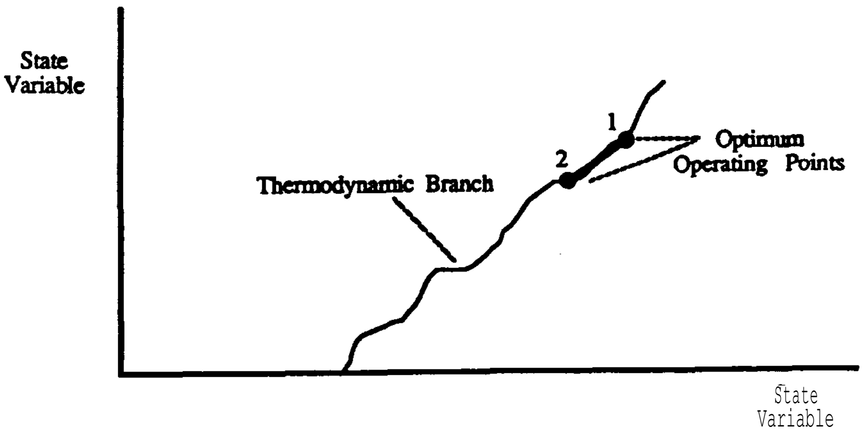

FIG. 2. The environmental change causes the ecosystem to move from its original optimum operating point (1), to a new optimum operating point (2).

In this case, there are four issues:

1) How far is the new optimum operating point from the old?

2) How long does it take to reach the new optimum operating point?

3) What is the stability of the system about the new optimum operating point?

4) If the environmental conditions return to their original state, will the system return to the original optimum operating point?

While the system's organization has changed in this case, it will probably return to the original optimum operating point if the environmental conditions return to their previous state. This is because all the original structures exist to some extent. The system's integrity has been affected in the sense that its organization has had to change. This is only noteworthy if the new optimum operating point (level of operation) is considered undesirable.

As an example, consider the practice of spraying terrestrial ecosystems with the end product of secondary treatment of municipal waste water. Pine forests subjected to such spraying are shifted back to an old field community (Shure and Hunt 1981). As another example, consider maple forests subjected to acid rain. They are shifted to a state of less productivity and lower biomass. (Unfortunately the level of acidity in the rain is increasing with attendant further changes in the ecosystems. The question is whether the response of the maple forests will remain as in Case 1 or become one of the other cases discussed here, which would imply the loss of some the characteristics of these forests which we value.) A final example is that of a cold snap in 1962-63, during which the shoreline systems in southern England were driven back to an earlier stage of development. Recovery to the original state seems unlikely (Nelson-Smith 1975).

Case 2: system bifurcation to an new thermodynamic branch. See Fig. 3 for an illustration of this case. In this case, some new dissipative structures are added to the system and/or some of the original ones disappear. The new structures can be new pathways for energy flow connecting old components or the emergence of new components and their attendant pathways. Also, the level of operation of the system is changed. The system is seen as slightly different than the original.

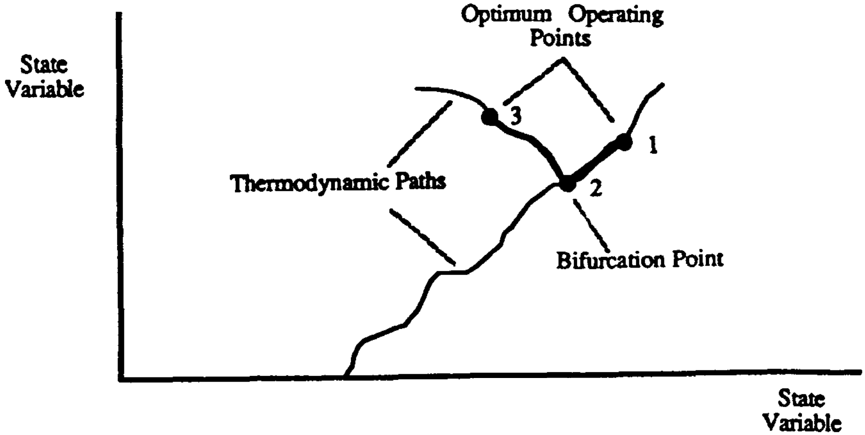

FIG. 3. In response to changing environmental conditions the system moves away from the original optimum operating point (1), through a bifurcation point (2), and onto a new path and then to a new optimum operating point (3).

The same four questions apply here as apply to Case 1. However, the answer to the fourth question is probably different. The system is not likely to return to its original optimum operating point, unless the bifurcation point is the original optimum operating point.' If it is not, then the organization of the system has probably been permanently altered by the addition of new dissipative structures. However, bifurcations represent variations on the original theme. Thus the new ecosystem's organization will not be extraordinarily different from the original. The integrity of the system has been affected in the sense that the organization has been permanently altered, although not dramatically. Again, this is only noteworthy if the bifurcation branch and the new optimum operating point are considered undesirable.

An example of this case is the change in a marsh gut ecosystem, Crystal River, Florida (see Ray 1984; Ulanowicz 1986). The system is stressed by warm water effluent from a nuclear power station (6^0C increase in water temperature). The result is the loss of two top predators, the addition of a species, and a dramatic change in the food web in terms of cycling and trophic positions. These are examples of changes in the dissipative structures in an ecosystem. Odum's state variables (such as net productivity) decrease, thus the overall functioning of the system has changed. Overall, however, the ecosystem is clearly a variation on the original. It is not clear that a cessation of the effluent would result in a return to the original system. Similar results have been found for Par Pond on the

Savannah River in South Carolina (Sharitz and Gibbons 1981). Another example of this case is the introduction of exotics into the Great bakes. New species associations (dissipative structures) occur, the sea lamprey (Petromyzon marinus) being a case in point. It appears that the system has been permanently altered, but it still resembles the original.

Case 3: the system moves to a new thermodynamic branch. This case is illustrated in Fig. 4. In this case, the system undergoes a catastrophic change that leaves the system so reorganized that it is clearly recognized as being different from the original system. There is no possibility of the system returning to its original optimum operating point, even if the environmental conditions return to their original state. (This is an hypothesis. In this case the system is made up of very different dissipative structures than existed in the original. The author has been unable to find a single example of an ecosystem flipping back after undergoing such a dramatic reorganization.) In one sense the integrity of the system has been seriously undermined, as the system will be quite different from the original. However, the fact remains that the ecosystem still exists, so in some sense, it has been able to maintain its integrity.

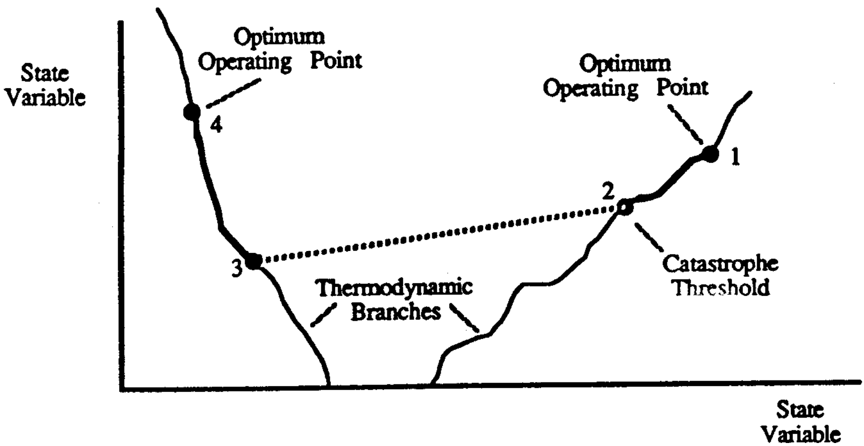

FIG. 4. The environmental change drives the ecosystem from its original optimum operating point (1), through a catastrophe threshold (2), to a new thermodynamic branch at (3), and eventually to a new optimum operating point (4).

An example of this case is the clear cutting of a terrestrial system to the extent that soil erosion is so severe that it effectively changes the soil type and precludes the original system from reappearing. (The loss of tropical rainforests is a case in point.) Another example is a burn in a spruce hardwood forest (on thin soils). This has resulted in a new bare rock-shrub ecosystem appearing as the climax (Bormann and Likens 1979). A final example is the irreversible change of savanna ecosystems to woody vegetation brought on by cattle grazing (Walker et al. 1981).

The above discussion systematically lists the issues which need to be examined when considering the possible direct responses of an ecosystem to environmental change, and the implications of these responses for ecosystem integrity. This framework encompasses all of the stability-related concepts discussed in the Appendix and identifies other issues which need to be examined.

COMMENTARY

An important observation is that this framework indicates ways in which an ecosystem might reorganize in the face of environmental change, but not which reorganizations constitute a loss of integrity. It could be argued that any environmental change which permanently changes the optimum operating point affects the integrity of the ecosystem. In this case, there would be four distinct types of loss of integrity: i.e. cases 1 through 3 above and the possibility of there being no optimum operating point. It could also be argued that any time that the system can maintain itself at an optimum operating point, it has integrity. In this case, loss of integrity would only occur if the system is unable to maintain itself at an optimum operating point. Between these two extreme positions, there is the possibility of defining some optimum operating points as being undesirable changes in the system, and therefore representing a loss of integrity. This would inject an anthropocentric component into the definition of integrity. Which set of system changes we decide constitutes a loss of integrity will ultimately depend on the utility of the definition in a regulatory and management context.

Some researchers are uncomfortable with definitions which are not objective, that is, which reflect the viewpoint of an observer. Physicists, during this century, have come to realize that there are no preferred observers. Each observer brings a unique viewpoint of, and interaction with, that which he observes. As long as the reference frame of the observer and his interactions are clearly defined, there is no problem. The observations will be reproducible, assuming that they are accurate to begin with. In the study of complex systems, the exercise known as systems identification is equivalent to the exercise of defining the observer in physics. What is proposed here would be part of a systems identification exercise for studying the integrity of ecosystems. It would explicitly involve defining why the observer is examining integrity and what he would consider a loss of integrity in terms of changes in the optimum operating point.

While the above framework identifies a number of types of ecosystem organizational change in response to environmental change, it tells us nothing about which type of organizational change to expect for a given environmental change. before such theoretical predictive power will be available, a much better understanding of ecosystems as self-organizing thermodynamic systems is required. In this regard, network theory and second law/exergy analysis, in which analysis of the irreversibilities in the system are measured by entropy production and decreases in the quality of energy (exergy), hold much promise. However, such approaches require time-series data at a level of detail which is available for only a few systems. In the interim, we will have to depend on empirical and intuitive understanding of ecosystems for the prediction of ecosystem response to environmental change.

A third point about this framework is that it only deals with immediate changes in an ecosystem caused by an environmental change. Some environmental changes will not immediately affect an ecosystem. Rather, they affect the ability of the system to cope with other future environmental changes. An example is the spraying of forests with fenitrothion to control spruce budworm. As mentioned earlier, this has no immediate impact, but interferes with the ability of the forest to regenerate itself in the face of other environmental changes. Similarly, forest fire suppression now appears to interfere with the ability of the forest to cope with fires at later times. The impact of environmental change on the integrity of an ecosystem is not just immediate, but has implications for its ability to maintain its integrity in the face of future environmental changes.

SURPRISE

This discussion of integrity would be incomplete without a discussion of surprise (Holling 1986). Surprise is an interaction of fast- and slow-system variables. Surprise happens (only) in anticipatory systems when the sampling rate of the monitoring system is too slow and something big happens in between samples. (For example, if you are detecting forest fires by checking forests once a month, you will be surprised because a fire may have happened and run its course in between your observations.) The point is, the effect being monitored must be monitored at a rate that is significantly faster than the rate at which the effect occurs. The problem is that we cannot always predict a priori what effect will happen, and thus we cannot know the correct monitoring sampling rate. Surprise will always be a fact of life because we can not monitor systems continuously. Even if we could monitor systems continuously, developments in self-organizing systems (dissipative systems) can proceed in spurts during which changes in the system suddenly accelerate very rapidly or even occur catastrophically, independent of environmental changes. The onset of such spurts may not be predictable, and this is surprising. (An example is a pest outbreak, such as spruce budworm.) Also continuous environmental changes can drive ecosystems past catastrophe thresholds. (For example, an algae bloom in response to nutrient loading beyond a threshold could be a surprise.) Finally a catastrophic event in the environment (such as a lightning strike) may be the source of surprising change in the ecosystem (a forest fire).

As this discussion illustrates, we should expect the rate of change in ecosystems to accelerate or decrease very dramatically with little or no warning. Hence we should expect to be surprised. Better historical information about an ecosystem can help us to better design our monitoring techniques so as to reduce some surprises. However, the only real solution to surprise is to have human systems which are adaptive and prepared to respond appropriately to surprises.

CONCLUSION

In this paper, the relationship between ecosystem integrity and its ability to maintain its organization has been explored from the perspective of dissipative structures. An enumeration of the possible organizational changes in response to environmental change was made. The ways that such changes might be associated with changes in integrity of the ecosystem were examined. There are four points of note.

1) Dissipative systems can respond to environmental change in qualitatively different ways. One response is for the system to continue to operate as before, even though its operations may be initially and temporally unsettled. A second response is for the system to operate at a different

level using the same dissipative structures it originally had (for example, a reduction or increase in species numbers). A third response is for some new structures to emerge in the system to replace or augment existing structures (for example, new species or paths in the food web). A fourth response is for a new dissipative system, made up of quite different structures, to emerge. We must be aware of these different possible responses to environmental change if we are to anticipate the stress response of ecosystems.

2) If the concept of integrity is to be useful, it must have an anthropocentric component that reflects which changes in the ecosystem are considered acceptable by the human observers. Otherwise we are restricted to defining integrity as the ability of an ecosystem to absorb environmental change without any ecosystem change. This would rule out the acceptability of the other three ecosystem responses to environmental change discussed above. This does not seem reasonable to this author.

3) An environmental change has implications for the future ability of an ecosystem to respond to other later occurring environmental changes. Put another way, the response of an ecosystem to environmental change is a function of both the immediate environmental change and changes that the ecosystem has been subjected to in the past. Historical environmental changes can have both positive and negative implications for the ability of the system to cope with current changes.

4) by their nature, dissipative structures exhibit surprising behavior, behavior which cannot be predicted **a** priori, and which may be catastrophic. No matter how much knowledge we have, we will always be subject to surprise when we observe ecosystems. Therefore, any human systems which are meant to deal with ecosystems (or any dissipative systems) must be adaptive in their response, that is, able to cope with surprise.

APPENDIX

Ecological Stability

The following is meant **to give the reader a taste of** the varying definitions related to the term ecological stability which exist in the literature. The discussion is detailed but by no means complete.

When an ecosystem is described as being stable it usually means that it is, in some sense, well-behaved. Many attempts have been made to formalize this definition using mathematics. The most natural approach is to use a definition of stability commonly used in the physical sciences, that is, Lyapunov stability. This requires that some function be found which describes the system and which satisfies Lyapunov's stability criteria (Lewontin 1969; and Harte and Levy 1975).

Many workers have attempted to use the stability of the species population to define ecological stability. Usher and Williamson (1976) state, @*roughly speaking, ecological stability is the strength of the tendency for a population or set of populations to come to an equilibrium point or to limit cycle, and also, related to that, the ability of a population system to counteract disturbances." Many articles and books have been written using this definition of ecological stability (Genero-Porati, Kron-Morelli, Porati 1982), but an equal number of papers and books have been written challenging this approach.

Hirata and Fukao (1977) and others have used the biomass of species as the important function which must be stable. This is a slightly more flexible approach because it allows for fluctuations in populations as long as the total biomass is stable. Others have talked about the stability of the functioning of a species, that is, their niche remains stable. More recently, Bormann and Likens (1979) have discussed stability in terms of the functioning of the entire ecosystem, as measured by stream water input. Another suggestion is that the stability of the structure (i.e. food web) of the ecosystem as characterizing ecosystem stability. Presumably this would be measured using the measures developed by Rutledge (1976) and Ulanowicz (1979, 1980, 1986). Still others have suggested that the stability of the macro (i.e. external) or micro environment are the important characteristics. (This would be measured by such things as temperature fluctuations, rainfall fluctuation, humidity fluctuations). Unfortunately, no one of these system measures is sufficient to characterize ecological stability. Any one of them may not be stable, in a Lyapunov sense, while the system as a whole may be well behaved. In the last few years, the term ecological stability has been used to mean the stability of so many different characteristics of ecosystems that one must be very careful to understand what an author means when he uses the term ecological stability. Clearly such a situation is undesirable. Several authors have suggested that a broadening of the definition of stability is necessary if it is to be usable in an ecological context. What follows is a sampling of the ideas of a few authors. Preston (1969) states:

> Stability lies in the ability to bounce back.... An ecological system may be said to be stable, from my point of view, during that period of time when no species becomes extinct (thereby creating a vacant niche) and none reaches plague proportions, except momentarily, thereby destroying the niches of other species and causing them to become extinct.

This is an interesting definition because it does not require that the populations be stable in the Lyapunov sense, only that they be non-zero.

Rutledge (1974) identifies three different properties of ecosystems, all of which should be encompassed under ecological stability. The first is the sensitivity of the components of the ecosystem to perturbation. The larger the sensitivity, the less the stability. The second is the persistence of the ecosystem over time. The longer it has survived the more stable it is. The final property is the ability of the ecosystem to return to its equilibrium state after being perturbed from it.

May (1974) identified three tributaries to the stream of ecological stability theory.

> One draws inspiration and analogies from thermodynamics, and is concerned with broad patterns of energy flow through food webs. A second theme ,...deals with the physical environment, and the way it limits species' distributions and affects community organization. A third tributary concentrates on the way biotic interactions between and within populations acts as forces moulding community structure.

Margalef (1975) is a little more pessimistic and suggests that "it is perhaps questionable whether the term stability should be retained, as it has been used too much in different and divergent speculation." Wu (1974) suggests that perhaps it is more relevant to talk about ecosystem health, where an ecosystem is considered healthy if its state variables are within a certain range.

My own opinion is that the idea of stability should be kept, but only in the narrow confines of the Lyapunov definition. In order to define what is meant by a well-behaved ecosystem, other ecosystem properties, besides stability, must be defined and quantified. A number of authors have attempted to do just this. Many of them work with the idea of an N-dimensional state space. Usually each of the N axes corresponds to the population of one of the N species. However, other state variables can be used as well. There are a number of points in this hyperspace which are stable equilibrium of the ecosystem. About each of these stable points is a cloud. If the system is displaced from equilibrium, but remains within the cloud, it will return to the initial equilibrium points. If it is displaced outside of this cloud it will move to some new stable equilibrium state.

Holling (1973) introduced the idea of resilience. He defines resilience as the minimum distance from the equilibrium point to the edge of the cloud. Thus, resilience is measured by the minimum disturbance necessary to disrupt the system and cause it to move to a new equilibrium state. Stability is the degree of oscillation the system exhibits about its stable equilibrium point. Holling points out that forests which undergo pest outbreaks, such as the spruce budworm, are unstable. They experience extreme oscillations in populations. Yet the system almost always bounces back to its original state. It is resilient. Holling notes that resilient systems normally aren't stable, and vice versa. Hill (1975) expands on Holling's idea and observes that there are two kinds of stability involved. One is no-oscillation stability and refers to the stability of the state variables in the absence of stress. The other, he calls stability resilience. This refers to the stability of the state variables while the system is under stress and after the stress is removed. This latter stability refers to the degree of oscillation (flutter) the system experiences while under stress and how quickly this is dampened out when the stress is removed.

Cairns and Dickson (1977) have examined the stability resilience of stream ecosystems. They have identified four properties of ecosystems which determine the stress recovery characteristics of ecosystems: ecosystem vulnerability, elasticity, inertia, and resiliency.

Vulnerability is defined as the lack of ability to resist irreversible damage (which is defined as damage which requires a recovery time greater than a human life span). Presumably it is measured by the size of disturbance necessary to cause irreversible damage.

Elasticity is defined as the ability to recover after displacement of structure and/or function to a steady state closely approximating the original. Presumably this is measured by the rate of recovery after disturbance.

Inertia is the ability of an ecosystem to resist displacement or disequilibrium in regards to either structure or function. Presumably it is measured by the size of the disturbance needed to displace the system.

Resiliency is the number of times a system can undergo the same disturbance and still snap back. Cairns and Dickson are not clear about how to measure these properties or the difference between them. But, they do point out that the size of the disturbance necessary to displace the system, how far the system can be displaced before it will not bounce back, how long it takes to bounce back from the disturbance, and how many disturbances the system can tolerate, are all properties which influence the reactions of an ecosystem to stress and need to be understood in detail.

Orians (1975) has identified seven properties of ecosystems which are related to their stability:

1) Constancy: lack of change in some parameter of the system.

2) Persistence: survival time of the system.

3) Inertia: ability to resist external perturbations.

4) Elasticity: rate at which the system returns to its former state following a perturbation.

5) Amplitude: area over which the system is stable (the same as Holling's resilience).

6) Cyclical stability: property of a system to cycle about some central point or zone.

7) Trajectory stability: property of a system to move towards some final end point or zone despite differences in the starting points. The factors which increase each of these properties are listed in Table 1.

TABLE 1. Environmental factors and phenotypic characteristics of species that increase different kinds of stability.

A. PERSISTENCE
1. environmental heterogeneity in space and time
2. large patch sizes
3. constant physical environment
4. high resource utilization thresholds of predators

B. INERTIA
1. environmental heterogeneity in space and time
2. greater phenotypic diversity of prey
3. multiplicity of energy pathways
4. intraspecific variability of prey
5. high mean longevity of individuals of component species (Frank 1968)

C. ELASTICITY
1. high density-dependence in birth rates
2. short life cycles of component species
3. capacity for high dispersal
4. strong migratory tendencies
5. generalized foraging patterns

D. AMPLITUDE
1. weak density-dependence in birth rates
2. intraspecific variability of component species
3. capacity for long-distance dispersal
4. broad physical tolerances
5. generalized harvesting capabilities
6. defense against predators not dependent on a narrow range of hiding places

E. CYCLIC STABILITY
1. high resource-utilization thresholds
2. long lag times in response of species to changes in resource availability
3. heterogeneity of environment in space and time

F. TRAJECTORY STABILITY
1. strong organism-induced modifications of the physical environment
2. all factors increasing elasticity

Source: Orians 1975.

Orians believes that an understanding of these properties can only be obtained from an understanding of the interactions of species and an appreciation of the past disturbances and selection pressures which have acted on the species. We must examine stability from this perspective, using a precise definition of the property of an ecosystem we are trying to understand, and in the context of a specific type of disturbance.

Robinson and Valentine (1979) review the idea of stability and introduce their version of the concepts of elasticity, invulnerability and invadeability. Van Voris, O'Neill, Emanuel, and Shugart (1980) introduce the notion of functional stability.

Holling and his colleagues have introduced the use of catastrophe theory in ecological systems (Ludwig et al. 1978; Jones 1975; May 1977; Holling 1986). The last of these references is an excellent! readable overview of Holling's ideas about dynamic stability and surprise.

Clearly, before any real understanding of ecosystem response to environmental change can be obtained, the confusion about concepts which fall under the umbrella of stability or well-being must be dealt with. Hopefully, the discussion of the concept of integrity in these proceedings will aid in the resolution of this confusion.

Some Systems Notions

Throughout this paper some notions from systems theory are used. These are described in this Appendix.

A state variable is a variable which describes some aspect of the system we are interested in. In population modelling the number of individuals of a species would be the state variable. Ulanowicz's ascendancy measure (1980, 1986) is a state variable for ecosystems. Photosynthesis and respiration rates, net productivity, total biomass, (see Table 2) are other examples of state variables for ecosystems.

TABLE 2. A tabular model of ecological succession: trends to be expected in the development of ecosystems.

	Ecosystem Attributes	Developmental stages	Nature stages
		Community Energetics	
1.	Gross production/community respiration (P/R ratio)	greater or less than 1	approaches 1
2.	Gross production/standing crop biomass (P/B ratio)	high	low
3.	Biomass supported/unit energy flow (B/E ratio)	low	high
4.	Net community production (yield)	high	low
5.	Food chains	Linear, predominantly grazing	weblike, predominantly detritus
		Community Structure	
6.	Total organic matter	small	large
7.	Inorganic nutrients	extrabiotic	intrabiotic
8.	Species diversity - variety component	Low	high
9.	Species diversity - eqitability component	low	high
10.	Biochemical diversity	low	high
11.	Stratification and spatial heterogeneity (pattern diversity)	poorly organized	well organized
		Life History	
12.	Niche specializations	broad	narrow
13.	Size of organisms	Small	large
14.	Life cycles	short, simple	long, complex
		Nutrient Cycling	
15.	Mineral cycles	open	closed
1b.	Nutrient exchange rate, between organisms and environment	rapid	slow
17.	Role of detritus in nutrient regeneration	unimportant	important
		Selection Pressure	
18.	Growth form	for rapid growth ("?-selection")	for feedback control ("K-selection")
19.	Production	quantity	quality
		Overall Homeostasis	
20.	Internal symbiosis	underdeveloped	developed
21.	Nutrient conservation	poor	good
22.	Stability (resistance to external perturbations)	poor	good
23.	Entropy	high	low
24.	Information	Low	high

A state space is a space whose axes are the state variables. In a predator-prey system, the state variables would be the population of each and the two-dimensional space with the number of predator on one axis and the number of prey on the other would be the state space. There would be a curve (a path in state space) which describes the relationships between the predator and the prey (see Figs. 5a and 5b).

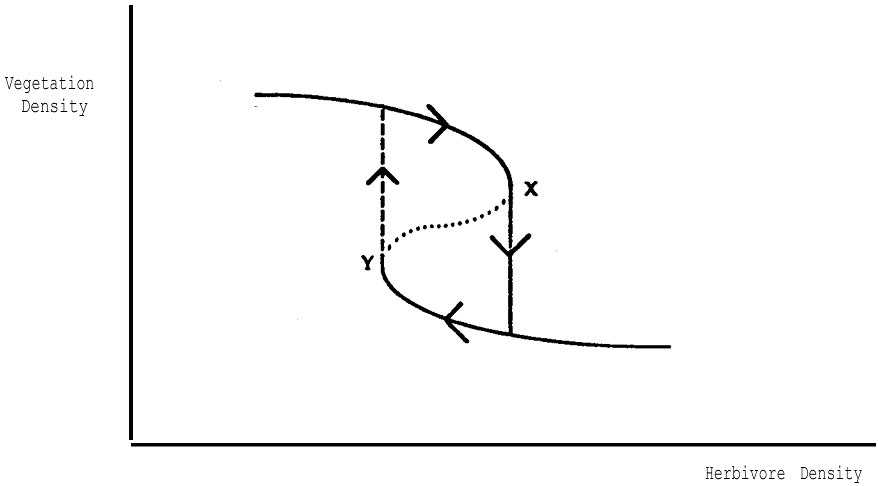

FIG. 5a. The herbivore-vegetation system follows the equilibrium path through its state space as indicated by the arrows. At point X the equilibrium path becomes unstable and the system drops from the upper solid curve to the lower solid curve. At point Y the system is again unstable and moves from the lower to the upper solid curve.

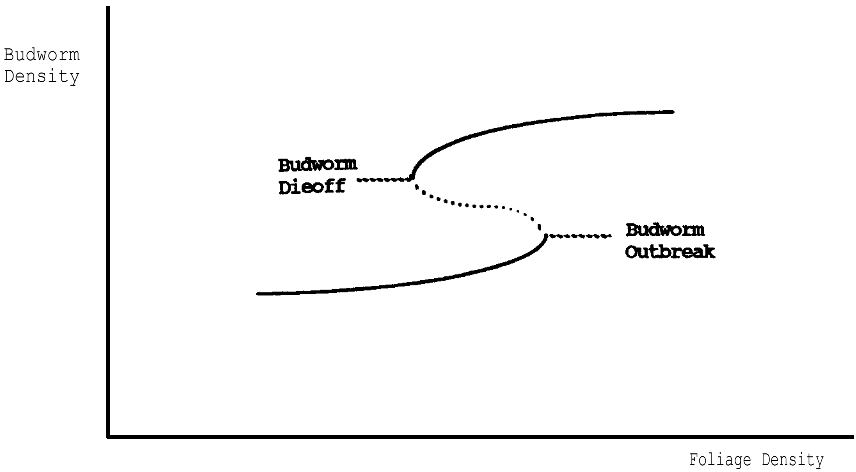

FIG. 5b. The spruce budworm is an example of the type of catastrophe illustrated in Fig. 5a.

Another possibility is that the state of the system does not return to the equilibrium point after a disturbance but oscillates about it with a maximum amplitude. Consider a perfect pendulum. The equilibrium point is at the bottom of the swing. The system oscillates about this point with a maximum amplitude after it has been disturbed. In the case of a real pendulum, it eventually comes to rest at the equilibrium point. Both the ideal and real pendulum are consider& stable.

For a given set of forces acting on a system, there will be at least one point in state space where the forces are balanced. This is known as the equilibrium point. (For example, the equilibrium point for a population is the point where the mortality and birth rates balance.) The issue of importance is the stability of the equilibrium point. That is, is the system able to stay in equilibrium? Consider a cone that has a very narrow blunt top. If it is placed upside down on its top, then a small disturbance will cause it to fall over. On the other hand, if it is placed with its top up and its broad base down, only a very large disturbance will cause the cone to topple over. In the former case, the equilibrium is said to be unstable and in the latter it is stable. In a strict mathematical sense an equilibrium point is stable if after a disturbance the state of the system returns to the equilibrium point.

These two types of stability are mathematically defined by the Lyapunov stability criteria (see Lewontin 1969; Harte and Levy 1974). The key question is whether the state of the system will return to the equilibrium point or oscillate about it when the system is disturbed, or if the state of the system is permanently moved to another point in state space (the cone falls over). It was through a Lyapunov stability analysis of thermodynamic systems, with specific entropy production as the state variable, that Prigogine discovered the self-organizing phenomena for which he was awarded the Nobel prize.

The optimum operating point for an ecosystem is an equilibrium point in state space which represents a balance between the forces acting on the system. Examples of state variables (see Fig. 1) could be respiration rate, biomass, and number of species. Odum (1969) identified a set of ecosystem state variables (see Table 2) and how they change with succession. Ulanowicz (1986) has identified a set of variables which describe the state of the ecosystem's energetics. Some of these are ascendancy, number of cycles, cycling index, and effective trophic levels. Which state variables are looked at depends on the questions posed by the researcher.

In the real world, the environment is not static. The forces acting on an ecosystem are constantly changing. Therefore, the equilibrium point is constantly changing. For the purpose of discussion in this paper, the optimum operating point has been treated as being stationary. In reality it is constantly changing and would be more realistically represented by a distribution in time. This distribution would reflect the distribution of environmental parameters.

Notwithstanding this variability, it is possible that the ecosystem has cyclic stability much like a pendulum. Holling (1986) has shown this to be the case for some pest outbreaks that happen with a fixed frequency in forested ecosystems. The forested ecosystem swings between maximum foliage just before an outbreak and minimum foliage just before the outbreak ceases. Another example is ecosystems driven by phytoplankton blooms.

A final and very important system's notion is that of a catastrophe. Catastrophe theory was brought to prominence by Thorn (1969) and an analytical basis for it was discovered by Huseyin (1977, 1980). The importance of catastrophe theory is that it shows how systems can exhibit behavior which is discontinuous and occurs without warning. Usually the phenomena is very dramatic. A simple example is shown in Fig. 5a. As the herbivore population increases, the vegetation decreases (more is eaten). Eventually a point (X) is reached where the vegetation crashes (the system becomes unstable) because of overgrazing. As the vegetation regrows, the herbivore population drops off sharply until a second point (Y) is reached (the system becomes unstable again) and a vegetation bloom occurs. The vegetation crash and bloom are catastrophes in the mathematical sense of the word. X and Y are known as critical thresholds. The spruce budworm population shows this type of behavior with the herbivore following the crash and outbreak pattern (see Fig. 5b) (Ludwig et al. 1978). This type of catastrophe is called a fold (see Fig. 6). For P1 and P3 there is one value of X (Xl, X3) but for P2 there are two possible values, X2 and x4. Which value the system takes at P2 depends on its history, i.e. depends on the path that the system is following.

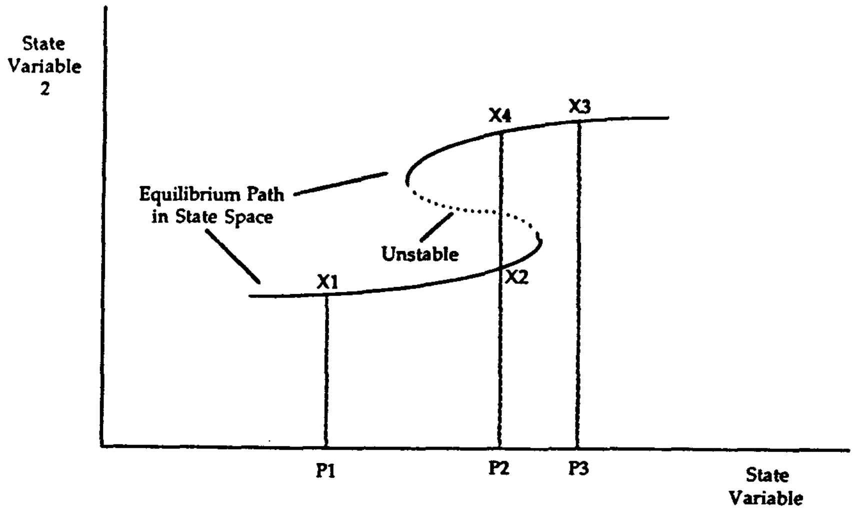

FIG. 6. The basic fold catastrophe. There is an equilibrium path through state space. The solid curves represent the stable part of the path. The dotted curve represents the unstable part of the path. (The system cannot stay on the unstable path, only on the stable path.) For points P1 and P3 there are single values of X possible. The value of X at P2 depends on which curve the system is currently following. The catastrophe occurs when the system jumps from the upper to the lower curve, or vice versa. This occurs at the thresholds (X and Y in Fig. 5a).

A more complicated form of catastrophe is shown in Fig. 7. This is the Riemann-Hugoniot catastrophe. This behavior is more complicated than the fold because the system may move along an equilibrium path with a catastrophe threshold (A to B) or one without (C to D). It may also exhibit bifurcations, divergences, or multiple paths. The Riemann-Hugoniot catastrophe is still quite simple, being of order 3. There are examples up to order 7 (swallow tail and butterfly being orders 4 and 5 respectively). The point is that systems can exhibit very complicated and dramatic behavior, even when they are deterministic. The lesson is, be prepared for surprise. To explore these notions in more detail see Holling (1986) or Jones (1975) for excellent discussions.

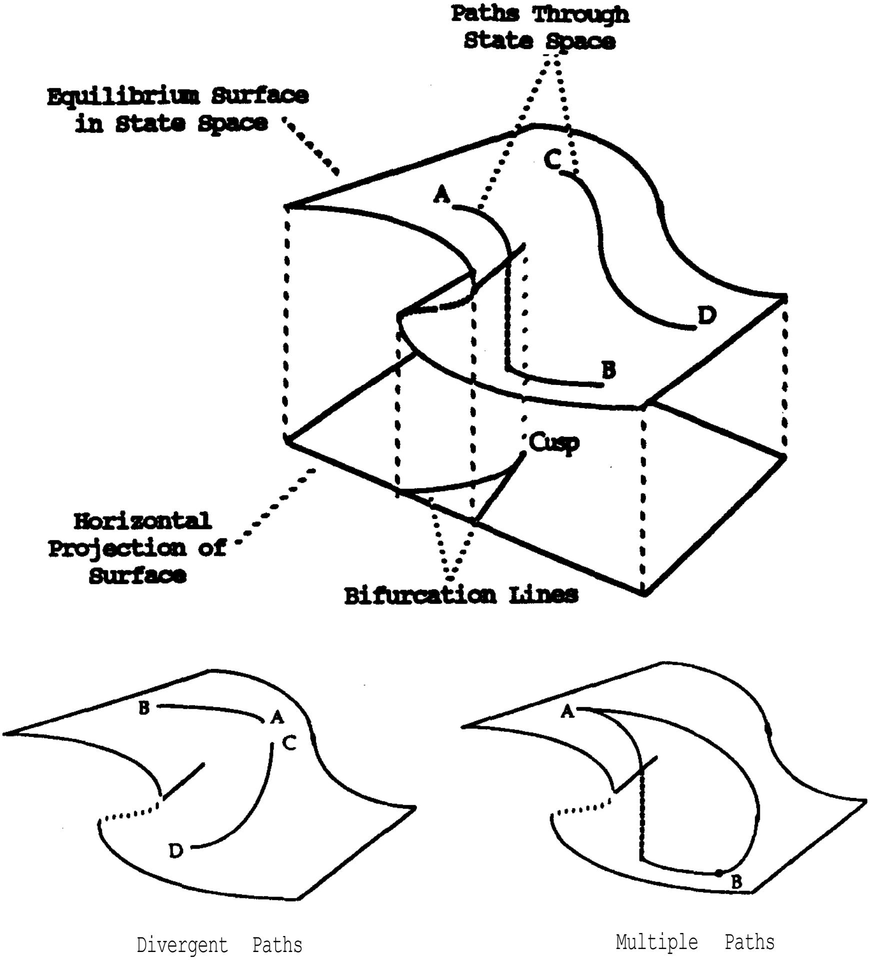

FIG. 7. The Riemann-Hugoniot catastrophe. The set of equilibrium points for the system is a surface in state space. The path followed by the system may pass through a catastrophe threshold (from A to B above, the dotted part of the curve corresponds to the jump) or it might not (from C to D). The system may hit a cusp, which is a bifurcation point. (The systemmay follow either bifurcation line after the cusp: which one it follows is not predictable). Two points in state space (A and C lower left) may be very close, but the system may diverge quite dramatically later on in its development (from A to B versus C to D). Also there may be different paths that the system can follow from A to B (lower right). One path may involve a catastrophic system change (the dotted line) while another does not.

NOTES

1. It is theoretically possible by manipulating environmental conditions to return to the original optimum operating point.

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AQUATIC HARMONIC COMMUNITIES: SURROGATES OF ECOSYSTEM INTEGRITY

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ABSTRACT. Harmonic communities of fishes and associated organisms have been variously described. Their major components include a predominant keystone organism that acts as a principal controller of other community members, usually through terminal predation. Complementary guilds of fishes that fill essential ecological roles complete the integration necessary to ensure the long-term persistence of a moderately constant, identifiable community of organisms under a natural environmental regime.

The level of integration among species of a harmonic community varies from low, in the loose associations found in phoresy, mutualism, commensalism, and predation, to high, in obligate associations found in symbiosis and parasitism. The level of integration is most often determined by internal species linkages, such as a tight coupling of a dominant predator with an abundant prey species. Other species within the community remain steady state at a secondary level, dependent upon the major interaction between the keystone predator and its principal prey.

Harmonic communities, with their internal species linkages, serve admirably in the role of indicators of integrity for whole aquatic ecosystems. Any excursionbeyond the normal variability of community production will usually be indicative of one or more anthropogenic interventions at a local, regional, or global scale.

INTRODUCTION

A succinct and unequivocal fisheries management goal has been aspired to by virtually every fisheries administrator who has ever faced an unexpected environmental exigency or emergent surprise (Kerr 1974; Holling 1985). Under these somewhat stressful circumstances, the urgency of the moment often promotes an inappropriate knee-jerk reaction by the manager, resulting in the application of band-aid treatments of short-term effect, but often ineffective or even counter productive to rational, planned management goals over the long term. Such purportedly therapeutic measures often result in the introduction of nonindigenous fish species, known to grow rapidly to maturity, ultimately reaching a large asymptomatic stock size, the latter of which may be perceived as desirable to the majority of the human populace. This scenario is so prevalent in North America that further detail would be superfluous beyond the need to explain why such reactive management usually results in inappropriate responses to an ecological crisis in virtually any given situation.

A more reasoned approach to a similar sequence of events would ensure that a modicum of planning had taken place, at least to the extent of measuring the major natural system variables over time, and from these, providing a detailed description of the ideal natural system from an anthropocentric viewpoint. Having established this benchmark, predictions of ecosystemic responses to any environmental perturbation may be made, followed by recommendations for their amelioration in the spirit of adaptive environmental assessment and management (Holling 1978), or alternatively, the natural system may be considered as an idealistic goal to be re-attained. On the basis that man may not easily counteract the effects of two-and-one-half billion years of evolution (e.g., Johnson 1981), we will retain our bias and persist with the notion that the natural ecosystem and the natural communities contained therein provide not only the best basis for determining the extent of man's impingement on the system, but implicitly, at least, provide a benchmark of ecosystem quality for which managers might strive (Ryder and Edwards 1985). In most instances this benchmark will never be reached, but if a management trajectory directed towards the benchmark is ambitiously pursued, at least partial system restoration might be attained, and the direction to total restoration will be clearly indicated as an extension of the initial trajectory. Hence, rehabilitation goals may be retained in focus throughout the restoration process.

In the recent past, balance has been perceived to be an effective benchmark for which fisheries managers should strive. In simple systems such as largemouth bass (*Micropterus salmoides*) and bluegill (*Lepomis macrochirus*) farm ponds, balance has been defined as the maintenance of an appropriate predator-prey ratio, such that the predators always retain control of the prey through predation, and the prey species, accordingly, become neither superabundant nor stunted (e.g., Swingle 1951). It was assumed that when these conditions were first attained, and subsequently maintained over time, modest and proportional harvests of both predator and prey could be taken in perpetuity, provided that the productive potential of the system was not exceeded.

Despite this reasoning based on popular ecological principles of the day, balance was rarely attained and even then, never sustained for any appreciable length of time. It wasn't until a couple of decades later that the futility of the balance approach became evident, especially the notion of sustaining into perpetuity, harvests emanating from complex, multispecies ecological systems (e.g., Larkin 1977).

On large lakes, the concept of balance was not only never attained, but it was always unclear what the balance was in a multispecies system. Therefore, the ultimate attainment of such a vague and ambiguous property was always moot. Presumably, balance denoted a perpetual dynamic equilibrium among all of the community components. Despite these difficulties of interpretation, the term balance continued to be used, often in an imprecise and indeterminate sense, suggesting a desirable goal, even though the latter had never been defined.

Extensions to the balanced species concept have been recently explored in the proportional stock-density approach and slot-limit sizes, the first of which (Anderson and Gutreuter 1983) proposes an index of relative species abundance, while the latter (Brousseau and Armstrong 1987) provides a management mechanism for retaining this desired proportionality. While these slightly more sophisticated extensions of the balance concept have had a modicum of success in manipulating species and size ratios within certain multispecies fish assemblages, this rather inflexible and somewhat arbitrary approach allows no leeway for addressing system surprises or other unexpected management dilemmas.

THE HARMONIC COMMUNITY

The original description of harmonic communities was largely intuitive, following more than 20 years of personal observation of percid communities in the Precambrian Shield lakes of Ontario (Ryder and Kerr 1978). We defined a percid harmonic community on the basis of a common pattern that emerged following close examination of catch data from more than 200 lakes, supplemented by more than 1,000 hours of diving (Ryder and Kerr 1989). On the basis of this information, these communities were originally described as having consistent properties of identity, persistence, and integrity. The essence of all harmonic percid communities was the presence of four key species: walleye (*Stizostedion vitreum*), northern pike (*Esox lucius*), yellow perch (*Perca flavescens*), and white sucker (*Catostomus commersoni*). The presence of other species varied but didn't markedly affect the output properties of the system, such as community production or community mortality. Each of the four key species played a vital ecological role within the assemblage that contributed to community integrity. The walleye, chiefly a terminal predator and piscivore which often fed on young yellow perch, was also highly opportunistic, adapting readily to preying on the subimages of *Hexagenia* during emergence (Regier et al. 1969). The walleye was considered to be a keystone organism in the sense used by Paine (1966), in that it provided the principal biological control, through predation, over the remainder of the aquatic community.

The northern pike was a large accessory piscivore that increased control of the yellow perch and white sucker populations through additional and complementary predation. The yellow perch, as a small predator, fed opportunistically on large zooplankters, insects, crustaceans, and small fishes. The white sucker complemented the other three key species through its role as a large benthic predator, specializing on invertebrate infauna found on soft substrates.

In considering the aggregated hypervolumetric niche space defined by these four species alone, the resources (food and habitat) of a mesotrophic lake would be reasonably well utilized in terms of their individual niche dimensions, especially if the time-dependent ontogenetic niche for each species were taken into account. Accordingly, other species occurring within the harmonic community would contribute but little to the major interactive pathways, but their presence would ensure a Potential for alternative pathways or interactions, particularly if one or more of the key species were under ecological stress.

In a large set of Ontario mesotrophic lakes examined, the four key species co-occurred frequently, thereby suggesting the possibility of a marked degree of integration amongst them, not found in the other species that were part of the same assemblage (Ryder and Kerr 1989). Examination of other discrete sets of boreal forest lakes in both Quebec and Ontario, using different methods than were employed in the present study, also highlighted the high levels of abundance of these same four species (Legendre and Beauvais 1978; Marshall and Ryan 1987).

That all four of the key species originated in the Mississippi Refugium during the Pleistocene (Bailey and Smith 1981) suggested, but did not prove, a possibility for co-evolution (e.g., Jantzen 1980). Yet long-term co-existence must have been a contributing factor to the interactive processes among the four species, and also toward the complementary ecological roles that these species play within a mesotrophic system, in terms of food preferences and particle-size differences of food items, and times and modes of reproduction. All four species differ in their spawning activities, time of spawning, or mode of spawning. In the case of the walleye and white sucker, both of which often spawn in tributary streams in the spring of the year, the differences may seem subtle, but exist nonetheless. Complementary (noncompetitive) reproduction may also emerge following eons of co-existence, if not co-evolution. This inherited complementarity in both food preferences and spawning times and sites suggests, at least, integration by default--that is, a minimized level of niche contention. The latter, through competitive exclusion (Hardin 1960), would preclude the possibility of two species spawning on the same substrate at the same time. In fact, stock-recruitment curves within a single species are often predicated on the fact that there are optimum numbers of brood stock necessary for maximum recruitment to a fishery (Ricker 1954). Implicitly, numbers beyond the optimum level on spawning redds of restricted surface area, inhibit the development of eggs first deposited through suffocation. Whether or not suffocation or some other factor, such as accumulation of hydrogen sulphide, is the major contributing factor, is a moot point. More germane to our argument is the apparent diversity in the approach of the four key species to their reproduction strategies (Balon 1975) that allows them to circumvent this eventuality and thereby retain discrete spawning runs.

Other harmonic communities comprised of different species combinations exist in the northern temperate zone--a salmonid community, for example, that is particularly adapted to oligotrophic lakes (Ryder and Kerr 1989). Within a salmonid community, the same functional ecological division takes place, butgreater ecological flexibility is noted in the capability of some species to occupy outer pelagic waters as well as cold, demersal areas. This flexibility increases the level of persistence for the community through the retention of benign refugia when other parts of the system are environmentally stressed. These refugia are natural sources of organisms for re-invasion of formerly stressed areas following rehabilitation.

Salmonid communities are also highly integrated. The predator-prey relationship between lake trout (Salvelinus namaycush) and lake herring (Coregonus artedii) is well known (Ryder and Kerr 1984), and provides one of the principal linkages contributing to the stability of harmonic salmonid communities.

LEVELS OF INTEGRATION

Levels of species integration within fish assemblages vary, and range from seemingly nonintegrated, sympatric, species pairs such as lake sturgeon (Acipenser lacustris) and emerald shiners (Notronis atherinoides), to the very tight integration which has developed between the Atlantic salmon (Salmo salar) and the parasitic sea lamprey (Petromyzon marinus).

Intermediate levels of integration usually relate to interspecific relationships within communities, such as predator-prey coupling, resource partitioning by organisms in time and space, or the complementarity of the food niches between two species competing for a common food source. This complementarity reaches its zenith in harmonic communities of long standing, and is particularly exemplified by some of the highly specialized species linkages in the ancient African Rift Valley lakes. For example, nine separate cichlid species have independently (via different evolutionary routes) developed scale-eating habits in Lakes Tanganyika, Malawi, and Victoria (Fryer and Iles 1972). As specialized as the scale-eating characteristic itself might seem, it is specialized further as one species eats only a large body scale of a particular cyprinid species, while another scale-eater specializes on the small scales of the caudal peduncle of another cichlid species. Hence, not only is a tight interspecific coupling established by the obligate scale-eating habit, which would seem to be a co-evolutionary trait, but a further Partitioning of this specialty into large and small scales, and scales from different species has taken place! Such tight couplings of species seem to occur in only the oldest of lakes, where the temporal sequence of events has allowed evolution to mold species into complementary forms. Just as a successful parasite must never eliminate an obligate host completely, so a scale-eater must be equally modest in its demands in order to avoid premature extinction.

Similar tight and obligate couplings among fish species do not seem to occur in the relatively young (ca. 8,000-12,000 B.P.) Pleistocene lakes of North America. However, a suite of species exemplified by the bitterling (*Rhodeus* amarus), a native of the unglaciated portions of Eurasia, has developed a symbiotic relationship with a freshwater mussel (Nikol'skii 1961; Muus and Dahlstrom 1971). The bitterling lays its eggs in a species of the mussel Unio, where they derive some protection until hatching. In a complementary and symbiotic fashion, the bitterling is the host of the parasitic larvae of the mussel (Berg 1949). Hence, this tight coupling is a two-way linkage that is most easily explained in co-evolutionary terms.

Two-species couplings, be they one-way or two-way interactions, form community nuclei about which other community components might gravitate. In North American glacial lakes, if we look beyond fishes per se, some extremely tight couplings have developed within percid and salmonid communities. Perhaps best known is the northern pike-lake whitefish (*Coregonus clupeaformis*) - copepod (*Cyclons bicuspidatus*) - tapeworm (*Triaenophorus crassus*) relationship. The tapeworm depends on the predictable behavior of the other three components of this quartet to complete its life cycle. Hence, the northern pike, which preys on the lake whitefish, acquires from the whitefish the plerocercoid stage of the tapeworm, which subsequently develops into an adult within the pike. The lake whitefish eats the copepod which contains the procercoid stage of the parasite, which then develops into a plerocercoid larva within the whitefish. The copepod, in turn, has fed upon the free-swimming coracidia which have developed from eggs released by sections of the adult tapeworm which have broken off and subsequently dropped from the host pike (Miller 1952).

For the casual observer, the pike-whitefish-copepod food pathway might seem to be a simple, elective choice at each node of the path. In fact, this particular pathway must occur on both a frequent and regular basis if the tapeworm is to survive, implying that the pike-whitefish-copepod food chain is a moderately tight community linkage. Artificial disruption of this linkage has only been possible through extremely intensive exploitation of northern pike over long periods of time (Lawler 1961).

THEORETICAL CONSIDERATIONS

Our conclusions are based primarily upon observation of fish communities of a variety of freshwater lakes. For this reason, it is germane to ask whether focus on the larger organisms of these systems, existing more or less at high trophic levels, has prejudiced our view of the salient processes which engender community integrity in the Laurentian Great Lakes. For similar reasons, there is cause to question the role of historical opportunity, in the sense that relatively few fish species had the opportunity to recolonize portions of the recently glaciated areas of North America with which we have been primarily concerned. Do either of these interrelated considerations affect our conclusions? The following comments are addressed to that end.

The stability-diversity controversy has been a feature of the ecological literature for some decades. The pleasingly intuitive notion that species diversity encourages community stability has for a considerable period come under fire from the ecological theoreticians, who could find little support for such a premise (e.g., May 1972). The theoretical conclusion has been precisely the opposite, that diverse communities reflect stable conditions, such as might result from hierarchical organization. Specifically, theoretical considerations for the existence of stability require conditions that support relatively low measures of food-web connectedness and interaction intensity, which are measures inversely proportional to the degree ecological compartmentalization within a system (McMurtrie 1975; Lawler 1980).

The fish communities we focus on are essentially depauperate, owing primarily to their recent (ca. 8,000-12,000 years B.P.) reestablishment from glacial refugia, allowing us to focus in these examples upon a relatively modest list of species. This a priori lack of complexity, following the theoreticians' reasonings, argues by default for potentially stable community structure. More positively, again following the theoreticians' views, the kinds of resource compartmentalization we describe, based on direct observation, adds support to the idea that the fish communities of recently deglaciated lakes should be expected to exhibit the kinds of communal integrity and stability we describe.

The evidence that theory is consistent with ecological observation has recently become more persuasive. Moore and Hunt (1988) have examined data for below-ground components of grassland ecosystems and arrived at some conclusions that are relevant within the present context. Of particular interest here, Moore and Hunt show that relatively weak food-chain interactions (equivalent to low food-chain connectedness and interaction intensity) occur at the base of the food chains they examined, conditions which they associate with system stability. On the other hand, Moore and Hunt find that higher predators tend to link food channels because their feeding habits are based upon prey size and form, rather than species identity. The emergent view, accordingly, is that grassland ecosystems are predicated upon relatively nonoverlapping consumption at the primary food-chain levels, with the compartmental discreteness becoming less discernible at higher trophic levels.

In our set of examples, we have been particularly impressed by the devices exhibited within the fish communities themselves to minimize competition and other interactions. The essential measure, required by the theoreticians, of system compartmentalization appears to persist to higher levels of the food web in the lentic fish communities we describe, than in the grasslands-root ecosystem analyzed by Moore and Hunt (1988), but this is apparently no more than a quantitative difference. The compartmentalization requirement imposed by the theorists exists, but appears somewhat more extensively realized at the higher trophic levels in freshwater lakes, relative to grassland root systems.

The picture becomes considerably more complex, threatening intractability, if we transfer the same considerations to a marine situation at an equivalent latitude. In part because there are fewer barriers to recolonization following disturbance, a comparable marine community is substantially more intricate, involving species complexes (demersal and pelagic fishes or highly specialized fishes such as sharks) and apparently discrete food chains culminating in macroinvertebrates (e.g., squid), sea mammals, and birds. Given this complex of species and food-web structures, the organizational principles to be learned from depauperate freshwater systems seem agreeably simple. Compartmentalization in marine systems appears to involve additional hierarchical levels, involving guilds of functionally related, if sometimes taxonomically unrelated, organisms. But in our view, the essential organizational principles leading to perception of ecosystem integrity remain the same, although the prerequisite conditions are more readily identifiable in the relatively depauperate freshwater systems than we describe.

In terms of both faunal and environmental complexity, the ecosystems of the Laurentian Great Lakes are poised somewhere between the relative simplicity of depauperate inland lakes and the complex structures of most marine systems. The major physical factors affecting Great Lakes ecosystems approach, but do not encompass, the scales of processes (warm-core rings and various large-scale frontal systems) that are known to influence marine fisheries in important ways. Similarly, the faunal diversity of the Laurentian Great Lakes reflects the strictures of their recent glacial history, much like the smaller inland waters we deal with here, as distinguished from the more open, ancient faunal opportunities in marine systems.

For these reasons, perception of ecosystem integration in the Great Lakes should reflect these realities of physical scale and faunal diversity. They are indeed "great" lakes, in the sense that this word conveys the magnitude of system scale and complexity, but they are undeniably not of oceanic dimension: and their recent origin and attendant faunal simplicity implies some further substantial distinctions from their marine counterparts.

The foregoing considerations lead naturally to the question of ecosystem integrity, which is the crux of the matter we have been charged with considering. In simple terms, system integrity in our view is directly equivalent with the stability of what we have described above as harmonic communities, with due allowance for the scale of the system in which they are perceived to exist. Our view, as noted above, appears entirely consistent with ecological stability theory and with direct observation of various kinds of ecological communities.

Ours is a primarily empirical and structural view of natural ecosystems. Others have adopted different perspectives, leading them to emphasize different aspects in their analyses: but we feel all are attacking a common set of considerations. For example, among the contributors to these proceedings, Ulanowicz stresses the connectance patterns observable within real systems and the properties these confer upon the integral ecosystem. Allen's approach through hierarchy theory is concerned with the interaction of structure and dynamics in determining ecosystem integration; Kay, adopting perhaps the most courageous position of all, attempts, as did Johnson (1981), to frame all of the above in the context of recent discoveries in open-system thermodynamics (e.g., Nicolis and Prigogine 1977), a perspective which threatens to revolutionize the ways we think of the integral properties of complex systems. Given this variety of options, appropriate choice of analytical procedure will depend on the scope and scale of the question being asked. The primary value of our empirical approach is its relative simplicity in operational terms.

Holling, (e.g., 1987), who could not be present for our deliberations, was of course very much in our minds, owing to his espousement of the notion of surprise (in the technical, mathematical sense of the term), which is a consequence of the interaction of slow and fast variables in bringing about the dynamics of the system behaviors that we often observe in natural systems, in the Great Lakes and elsewhere. That is, there is the important recognition that ecological change is not necessarily smooth and continuous when observed on human time scales, but can manifest abrupt transformations to new stable states when conditions are appropriate. Recognition of this class of phenomena is not unique to ecology. It is, in fact, the essence of a major transformation of thinking that distinguishes the scientific climate of the late twentieth century from the persistent effect of Lyell's uniformitarianism. For those of us schooled in the smooth, continuous functions of traditional mathematics, adaptation to the analytical tools appropriate to cope with the abrupt transformations that can characterize the real world has not been easy, but it is important that we make that intellectual jump: the ecosystems we depend upon for our survival require that measure of understanding. This is by way of pointing out that a harmonic community is by no means an invariate or immutable entity (Ryder and Kerr 1989), but rather a preferred configuration to be protected, within its normal range of variation, against pathological disturbance.

Our perspective is to commend the approach of harmonic community analysis to the attention of those concerned with the well-being of the Great lakes ecosystems. It is a readily available and meaningful indicator of ecosystem integrity as we define the term. Empiricism, as noted above, is not the only effective approach to the realities of ecosystem management, but it is a powerful approach to coping with the problem of defining and diagnosing system integrity in the context of the Great Lakes ecosystems.

INFERENCES

The foregoing description of harmonic communities is based upon a single ecological subsystem of a much larger ecosystem. We propose that the inferences drawn from aquatic communities may be extended to a much larger ecosystemic scale that will provide a new perspective on ecosystem problems derived from man's interventions. We proffer aquatic harmonic communities as exemplary because they have been intensively studied in the Great Lakes, especially over the last three decades, are easily bounded without the need for arbitrary assignments, and are sufficiently complex to avoid the pitfalls engendered through the use of a single organism (e.g., Ryder and Edwards 1985).

We contend that natural systems may be categorized not only qualitatively, but also quantitatively according to the level of integrity they possess; that is, a composite integrity which includes each hierarchic level of the system (e.g., Allen 1989). While this science has not, perhaps, developed to the level where an "ecosystem integrity index" may be quantitatively assessed and compared with other indices from other ecosystems (e.g., Karr 1981), alternative methods of assessment are possible (e.g., Ryder and Edwards 1985; Marshall et al. 1987). France most appropriately points out in these proceedings that the development of an index of integrity will be neither a panacea nor a spreading cancer. As a management tool, such an index holds promise, however, whereby ecosystem integrity may be rapidly and economically assessed, albeit at a moderately low level of resolution.

Evaluation of total ecosystem health through the subcomponent of aquatic communities is particularly attractive because, through the hydrologic cycle and the biogeochemical cycles, many terrestrial ecosystem qualities of interest are integrated within the aquatic sector. The watershed hydrography, geology, soils, and vegetation, plus the atmospheric fallout, strongly influence water quality of the contained basins, which in turn, determine the structure and kind of aquatic communities that might be present. Degraded or disaggregated aquatic communities showing little community integrity are often indicative of a disturbed terrestrial condition caused by poor agricultural or forestry practices, high levels of aeolian deposition, or inordinately high levels of human development. Even after many terrestrial indicators of system stress, such as raptors, have long disappeared from the system, aquatic communities continue to be indicative of terrestrial stresses.

It is a characteristic of human nature that once a single generation has passed through life on a featureless landscape, the next generation accepts that condition as the status quo, and further attempts to restore the original integrity to the system are lost. After all, how can a perceived level of system integrity be restored, if the erstwhile restorers have never seen a natural, integral system? Should ospreys and bald eagles suddenly appear in increasing numbers where they had been absent for two decades or more, they would be regarded by the new generation, not as an indication of ecosystem restoration, but as an anomaly, or something to wonder at.

We have stressed that the tight couplings of aquatic organisms due to parasitism or symbiosis contribute to the level of integrity of the whole community, but looser linkages of predator-prey relationships and niche complementarity are also important in integrating the parts of a community with the concept of wholeness. Many other ecological structures and functions contribute to ecosystem integrity (see Table 1).

TABLE: 1. Some structural and functional properties of harmonic communities that contribute to their integrity.

Property	Structure, Function, and Attribute
Resource Partitioning	Food, redds, shelter, space, time
Niche Interactions	Complementary, contentious
Hierarchic Structure	Dendritic, nested, recursive
Diversity	Genetic, phenotypic
Interrelationships	Parasitism, commensalism, mutualism, phoresy, symbiosis, predation
Size Spectrum	Particle-size density
Hysteresis	Lag, overshoot
Energetics	Feeding, spawning
Resilience	Return time, return distance, binding effect

We are, of course, exposing our prejudices by discussing communities as if they were real entities (e.g., McIntosh 1987). Alternative points of view abound, but none that can, with equal facility, describe man's ultimate objective in attempting to manage ecosystems. Harmonic communities persist over time, therefore they have an identity and may be easily perceived. Similarly, they may be managed, especially once the integral nature of their systems is understood and accommodated. Integrity, however, encompasses a wealth of ecological concepts besides identity and persistence. These include hierarchy, the blueprint of integrity: structure, the building blocks: and resilience, the glue that holds it all together. Diversity of form, differentiation within a species, biomass spectra, and various recursive and nesting features, all contribute to the integrity of an ecosystem. Its natural cybernetic state will persist if we attempt to manage with due regard for the output properties of the system, such as its level of integrity, and avoid undue reductionist dissection at any level. Gross analyses of aquatic harmonic communities provides a means of doing so.

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ECOLOGICAL BASES FOR AN UNDERSTANDING OF ECOSYSTEM INTEGRITY IN THE GREAT LAKES BASIN

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ABSTRACT. Use of the word integrity, when applied to natural ecosystems as affected by human cultural activities, may connote health as sketched by Neess (1974):

1) energetic, in that natural ecosystemic processes are strong and not severely constrained:
2) self-organizing, in an emerging, evolving way:
3) self-defending, against invasions by exotic organisms;
4) biotic capabilities in reserve, to survive and recover from occasional severe crises;
5) attractive, at least to informed humans; and
6) productive, of goods and opportunities valued by humans.

Of the six features above, the first four need not relate directly to human interests, as do the last two. Thus the first four may be treated objectively in the sense that subjective cultural interests are absent. The term integrality might be used to refer to the systemic state of a healthy ecosystem, which state can be characterized fully by the objective methods of natural science.

To make operational a concept of ecological integrity (or integrality), ecological phenomena may be related to ideas in system theory and to empiric generalizations about ecosystems. In particular, we should know how ecological integrity develops, how it responds to turbulent or surprising external influences or stresses, how it may be measured, and how it may be managed. Each of these topics will be addressed briefly in the following sections.

MYTHS AND MODELS OF SYSTEMIC AND ORGANIC DEVELOPMENT

Cur perception of integrity (integrality) in ecosystems, organizations, and organisms is usually related to some developmental model that we believe underlies the organization and growth of the system. Our perception may be further limited or expanded by our cultural, scientific, and political perspectives.

Many developmental models, some with ancient origins, have been used to explain or predict biological and cultural processes (Table 1). Some have been used to justify racist, oppressive, or totalitarian regimes (Collingwood 1946; Stein 1988). In some cases, an objective scientific concept has been expanded to encompass subjective aspects of culture, and a monistic (fundamentalistic) ideology may result. A monistic ideology may serve a totalitarian regime, with monistic true believers preferring to settle ideological differences through irrational force mobilized through the totalitarian state. Other developmental models may foster the full potential of human individuality (Davidson 1983; Rapoport 1986). An important and liberating observation with regard to Table 1 is that recent developmental models based on evolutionary or open-systems thought tend to be nonmechanistic with regard to their potential outcomes.

TABLE 1. Developmental myths and models.

Model	Reference	Application
	DETERMINISTIC	
Creation	myths	everything
Phoenix	myths	cultures, organizations
Four Seasons	myths	organisms, ecosystems
Haeckel	(1905)	organisms, cultures
Clements	(1916)	ecosystems
	NONDETERMINISTIC	
Gleason	(1939)	ecosystems
Von Bertalanffy,	Davidson (1983)	organisms, ecosystems, organizations
Maruyama	(1974a, b)	open biological and social systems
Gaia	Lovelock (1979)	biosphere
Prigogine	(1980)	open systems
Holling	(1986)	ecosystems, organizations

Integrity or integrality in such systems is likely to involve aspects of diversity, variety, and self-determination, rather than constrained and mechanistic behavior.

Modern developmental ideas in ecology share some of the organismic ideas that interested Bertalanffy. He was not an ecologist himself, but presumably he was familiar with the systemic concepts of the ecologist Haeckel (1905). Foremost among von Bertalanffy's concepts are:

1) Open systems, which continuously exchange matter and/or energy with the environment. In living systems, structure and organization are developed and maintained only through continuous throughput of energy and matter (the dissipative structures of Prigogine 1980).

2) Anamorphosis or self-organization, the tendency for an open system to develop toward increasing complexity and functional capability, at least in a benign environment (von Bertalanffy 1950; Davidson 1983). This is an important aspect of ecological succession (see below).

3) Equifinality, in that open systems may reach similar end points from different starting points and in different ways. In ecosystems, this may be recognized in the ways that similar environments, e.g., temperate oligotrophic lakes, will develop similar or analogous biotic associations comprised of different species (Loftus and Regier, 1972).

According to von Bertalanffy, development of organization, complexity, and structure in living systems involves four concurrent, complementary processes, described below. We may look for evidence of these in a healthy ecosystem.

1) Progressive integration, in which the parts become more dependent on the whole. In biotic associations we see this in obligative interactions of producer and consumer organisms, linked by food webs and recycling pathways: we also see it in all aspects of symbiosis and commensalism. In an ecosystem context, integration is expressed in the development of mutually dependent geomorphic-biotic structures, such as river channels, wetlands, and coral reefs, and in close linkages of life cycles to seasonal features of the environment.

2) Progressive differentiation, in which the parts become more specialized. This is a simple statement of phenomena related to development of biotic diversity during evolution or succession, such as niche development, genetic and behavioral adaptation, speciation, and stock development.

The first two processes tend to foster the emergence of an ability within the system to adapt to external disturbances, but the remaining two processes tend to increase the vulnerability of the ecosystem's organization to external disturbances.

3) Progressive mechanization, the limiting of some parts to a single function. In ecosystems, habitat or trophic specialists, who are highly dependent on products, behaviors, or structures supplied by other ecosystem components, may lose the ability to function as generalists. It has long been recognized that highly specialized organisms that are stenoecious (of limited niche dimension) thrive in conditions approaching those of a climax association.

4) Progressive centralization in which there emerge leading parts that dominate the behavior of the system with the loss of some control function within subsystems. This is particularly clear in organisms that develop central nervous systems, but is more difficult to visualize in an ecosystem context. Possible examples include keystone species which dominate ecosystem behavior by virtue of their biomass, energy, or nutrient control, predation, or influence on reproduction. Cur concept of ecosystemic centers of organization (Francis et al. 1985; Steedman and Regier, 1987; Regier et al. 1988) is relevant here.

The first two processes and last two processes sketched above tend to act in opposing ways, with respect to overall ecosystemic behavior. A kind of dynamic domain of equilibrium may appear as an end-point of ecological succession. Generally, natural external perturbations are sufficiently intense and frequent that some static equilibrium point is not realized for long.

We argue that these general, qualitative developmental tendencies of healthy organic systems, i.e., integration differentiation, mechanization, and centralization, specified where possible in terms of detailed ecological process and structure, provide a basis for practical understanding, measurement, and management of ecosystem integrity (integrality).

SUCCESSION: A DYNAMIC EXPRESSION OF ECOSYSTEM INTEGRITY

We have outlined some of the ways in which natural ecosystems exhibit processes of von Bertalanffian development. In ecology, this tendency has generally been incorporated into the concept of succession and applies both to primary colonization of areas with inorganic substrates, and to secondary recovery of more mature systems following local or temporary disturbances (Table 2.)

TABLE 2. Trends expected in ecosystems that are perturbed naturally or stressed culturally to a moderate degree.

COMMUNITY STRUCTURE

- species diversity decreases and dominance increases: if original diversity is low, the reverse may occur: at the ecosystem level, redundancy of parallel process theoretically declines
- size of organisms decreases
- lifespans of organisms or parts (leaves, for example) decrease
- food chains shorten because of reduced energy flow at higher trophic levels and/or greater sensitivity of predators to stress

NUTRIENT CYCLING

- nutrient turnover increases
- horizontal transport increases and vertical cycling of nutrients decreases
- nutrient loss increases (system becomes more "leaky")

ENERGETICS

- Community respiration increases
- P/R (production/respiration) becomes unbalanced ($<$ or > 1)
- P/B and R/B (maintenance/biomass structure) increase
- Exported or unused primary production increases

GENERAL SYSTEM - LEVEL TRENDS

- Ecosystem becomes more open (i.e. input and output environments become more important as internal cycling is reduced)
- Autogenic successional trends reverse (organization exhibits some features similar to earlier stages of succession)
- Efficiency of resource use decreases
- Parasitism and other negative interactions increase, and mutualism and other positive interactions decrease

Source: After Odum 1985.

A complementary process relates to reversal of succession, and apparent loss of integrity (integrality). Ideas about changes in the arrangement, complexity, or integrity of an ecosystem faced with disturbance are the domain of stress-response ecology (Steedman and Regier, 1987). Natural disturbances or perturbations generally reset all or part of an ecosystem to a less-integrated, less-organized, and less-complex state (Rapport et al. 1985). Such changes to the ecosystem may include reductions in species richness, changes in relative abundance of species, loss of accumulated biomass or structural complexity, and simplification of feedbacks and nutrient cycles. Such natural resets are sometimes called rejuvenescence; presumably an analogy is implied between somewhat similar phenomena in a primary and a secondary succession.

Natural and cultural disturbances tend to produce similar ecological effects when the disturbances are of moderate intensity, extent, or duration. Under such conditions of moderate disturbance, all key ecological subsystems remain intact, although their composition and function are altered. Severe cultural degradation, however, has some unique pathological effects, often resulting from the loss or inactivation of key ecosystem components. Severe cultural degradation almost always involves a suite of stresses. Each stress will trigger some uniquely diagnostic effects that provide clues about the mechanism of degradation, as well as some more general, nondiagnostic effects.

In the Great Lakes, the following symptoms of systemic disintegration and/or reorganization, in response to human activities in the basin, have been observed (Regier 1979; Whillans 1979; Francis et al. 1985; Steedman and Regier 1987; Regier et al. 1988):

1) shift in dominance from large, long-lived organisms such as lake trout and sturgeon, to small, short-lived organisms such as alewife and rainbow smelt:

2) shift from self-regulatory populations where abundance and age structure is relatively constant for long periods, to populations where abundance fluctuates widely in the short term, in response to weather, predators, food abundance, or other environmental factors:

3) shift from biotic associations dominated by species that relate closely to permanent morphometric features in the water or on the land, such as river systems or spawning shoals, to species that thrive in less-structured open-water environments: and

4) shift from species generally preferred by humans for food or sport, to those that are not.

TURBULENCE AND SURPRISE

The systemic science of surprise and related adaptive management methods under development by Holling and colleagues (Holling 1978; ESSA 1982; Regier 1985) seem to be particularly relevant to the above perspectives on ecological integrity. Interpreted in a somewhat extreme way, Holling's concepts of surprise start from the general inference that long-term equilibrium or steady-state conditions are quite unusual in present-day ecosystems, especially in those that are strongly influenced by humans. Change is now ubiquitous, often in the form of dramatic transformations that occur over relatively short time intervals.

In recent years Holling (1986) has become interested in disequilibria on geographic scales from regionalto global, and on temporal scales from decades to centuries. The concept of ecological integrity that we outline here generally deals with ecological disequilibria of a local scale of some kilometers and of a time scale of some years.

Our perceptions and predictions of ecosystem integrity should be consistent with the turbulent nature of the Great Lakes basin and the people that live in it. To us, this means that models and measures of ecosystem integrity must be of sufficiently large spatial and temporal scales to encompass unusual or surprising ecosystem behaviors, to put them in an appropriate historical context, and to be able to incorporate them into practical ecosystem management. We have not made much progress with respect to the operational specification of integrity (or integrality) at these larger scales of resolution. Developments in landscape ecology are of interest.

In turbulent settings integrity cannot be specified in terms of some equilibrium end-point, since stable equilibrium will not be attained. Perhaps the temporal variability of key components or processes of special interest to humans may be a better measure of integrity than the mean value through time of some systemic features.

MEASUREMENT OF ECOSYSTEM INTEGRITY WITH THE IBI (INDEX OF BIOTIC INTEGRITY)

Practical measurement and monitoring of ecosystem integrity may involve a historical, normative perspective of integrity that is complementary to the conceptual and ecological approaches sketched above. In simple terms, measurement involves establishment of a set of indicators that reflect key aspects of integrative ecosystem structure, preferably relating to several hierarchical levels of organization. A framework is then established by which this extracted image of the ecosystem can be compared quantitatively with historical, high-quality, or some other ecosystemic standard.

Conceptually robust, quantitative measures of ecosystem integrity would be useful for purposes of practical, sustainable ecosystem management. Direct generic measures of the health, organization, or integrity of ecosystems in a political context do not seem practical at this time, since ecological/cultural integrity will almost always be contextual in nature, i.e., regional, in reference to history and intended use. Currently, any single statistic for integrity should be viewed as an indicator or surrogate measure of ecosystem integrity. France (these proceedings) has provided a technical review of biotic indices.

The most widely applied measure of ecological/cultural integrity has been the IBI, or Index of Biotic Integrity. James Karr and others developed the IBI primarily to assess biological integrity in streams and rivers (Karr 1981). This index addressed the need to measure biological integrity as specified in the 1972 Amendments to the U.S. Federal Water Pollution Control Act, and more recently, the 1978 Great lakes Water Quality Agreement. Since then, other workers have adapted the IBI and have tested the approach in regions outside of the U.S. Midwest, where it was originally developed (Miller et al. 1988).

The IBI has been applied mainly to streams and rivers, and has its origins in the application of ecological stress-response concepts to the biology of fish associations in rivers. Key ecological principles of the IBI include: the longitudinal biogeography of fishes in river systems: normative, regional aspects of trophic ecology and productivity; and autoecology of certain fish species.

The components of the IBI generally correspond to key components of ecosystem integrity, as outlined previously. A typical IBI would assess the following attributes of an aquatic system:

1) biotic diversity, scored as a specified function of the number of native fish species, and the number of species in various taxonomic or ecological groups:

2) local indicator species that provide evidence of particular habitats or environmental conditions;

3) trophic composition of the fish association;

4) productivity, scored as a specified function of fish abundance; and

5) condition or health of individuals, scored as a specified function of physical condition, disease frequency, or parasite load.

Most forms of the IBI have been based on 8 to 12 individual measurements, or metrics, with 1 to 4 metrics represented in each of the five categories described above. Calculation of the IBI involves transformation of field data into scores, according to calibration curves. Most authors have followed the lead of Karr (1981), and assigned scores of 1, 3, or 5 points to each metric, with a high score corresponding to healthy or least-disturbed condition (Miller et al. 1988). (Even with variables or metrics for which a continuous scale is available from 0 to 5, only the quantities 1, 3, and 5 are specified: this appears to involve an unnecessary increase in the imprecision of the separate and overall scores.) The IBI is simply the sum of the individual metrics. The additive nature of the IBI implies that the individual metrics are independent, which is usually not the case. In fact, certain ecosystem attributes such as species richness are weighted by virtue of the fact that they occur in different forms in several of the metrics.

The issue of the standard or reference ecosystem used by the IBI is important. By definition, the IBI is adapted and calibrated to regional conditions. The usual practice has been to use the best or least disturbed regional ecosystem as the standard for expected species richness, species composition, trophic structure, productivity, and disease frequency. This has usually provided useful and quantitative classification of ecosystem health for a given region. The implication is, of course, that relatively pristine systems have high ecosystem integrity, relative to systems that have been altered by human activity. This is generally reasonable in that natural, native ecosystems are often more diverse, self-regulatory, sustainable, and attractive than are altered or degraded systems. However, natural systems may not always be as productive as altered or subsidized (i.e. agricultural) systems. For these reasons, there is a clear onus on the practitioner to specify the nature and implications of the standard used to calibrate an index such as the IBI.

Although there is not a one-to-one correspondence between the categories of an IBI and the four processes of systemic development as identified by von Bertalanffy (integration, differentiation, centralization, and mechanization) there are some apparent homologies between the two approaches. Measures of trophic composition and

and consumer organisms. Presence of indicator species such as large, sensitive, long-lived, and predator indicate the long-term persistence and integration of key habitat and trophic features. Measures of species richness or diversity, especially reflecting diversity at an aggregated taxonomic level such as family, index the extent of habitat, resource, and niche differentiation in the system. The IBI as currently developed apparently does not extend to the von Bertalanffian concepts of mechanization and centralization. This may imply that it is biased toward acceptance of moderate cultural transformation or disruption, since the maximal score can be achieved by modified ecosystems.

The nature of the metrics in the IBI is such that they are generally not diagnostic of individual stresses acting on an ecosystem. This may be appropriate for an index that will most often be applied to judge the overall states of systems subject to multiple, interacting, degradative forces. However, there is sufficient resolution and specific ecological information included within the metrics of the IBI that tentative diagnoses of simple stresses may often be made, but the relevant diagnostic protocols have apparently not yet been developed.

The IBI has been shown to respond in a correct and quantitative manner to gradients of cultural degradation along river systems (Karr et al. 1985; Steedman 1988). But we do have misgivings that such an aggregated index is rather opaque as to the causes of relative disintegration (ACMRR/IABO 1976). Also such an index can take on a life of its own in the service of relatively uninformed technicians and suppress the need for ecological comprehension of the causes of ecological degradation. With some further developments, the IBI approach may be adaptable in principle to a wide variety of aquatic and terrestrial ecosystems (see Regier et al. and France, these proceedings).

MANAGEMENT OF INTEGRITY IN GREAT LAKES ECOSYSTEMS

Certain components of Great bakes aquatic ecosystems may be more important than others to the recovery and maintenance of ecological integrity. Relatively small or localized habitats often provide essential conditions for breeding, spawning, rearing, and feeding of fishes and other animals and, thus, have an ecological role far more important than would be suggested by their size alone. Such areas have been called centers of ecological organization (Francis et al. 1985; Steedman and Regier, 1987). Design and management for increased ecosystem integrity in any context must foster regional and local processes of ecological self-organization and succession in these key areas, before sustainable system-wide benefits can be realized.

Recent attempts at rehabilitation and restoration of ecosystem integrity in the Great Lakes have focused on remediation of severely degraded bays. The characteristics that made these areas biologically important (sheltered water and access to river mouths, in particular) also made them centers of settlement and economic activity. Efforts are now under way to rehabilitate such locales ecologically, economically, and socially, but such efforts are not yet being interrelated. Cultural integrity would be fostered by appropriate connections within a locale.

Some parts of the Great Lakes coastal zone, usually distant from cities, are not yet degraded seriously. Healthy centers of ecological organization persist in such settings. These deserve special and long-term attention. A basin-wide system of efforts to preserve such locales could be achieved through the creation of "Heritage Area Security Plans" (Francis 1988). Such a system would complement the current system of Degraded Area Remedial Action Plans.

Many aspects of advancement in ecosystem science are difficult to transfer to natural resource managers, policy practitioners, or legislators. A key benefit of enhanced theoretical and practical expression of ecological integrity is its usefulness as both a medium and a message to aid understanding and management of Great Lakes ecosystems.

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POLITICAL AND ECOLOGICAL SYSTEMS: INTEGRITY?

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ABSTRACT. This paper describes a framework for examining environmental conduct in order to determine whether the intentions of an institution with respect to environmental change in the Great Lakes basin are reflected in its use of the authorities allowed it. The capabilities of governments are identified by listing a set of tools that government has at its disposal. These are the things that government can do and include the powers to tax, regulate, subsidize, expend, create rights, allocate public property, control imports and exports. Examples are examined to determine which tools have relevance for environmental management and whether some of the current uses are positive, benign, or damaging with respect to the environment. This paper also sets out questions or tests for an institution to determine if the use of its tools or powers is consistent with its environmental aims. Congruency between the intentions of the major human moral forces for change (i.e. national governments) which participate in an ecosystem and the changes which occur is treated as an indicator of ecosystem integrity.

INTRODUCTION

> Until the crisis validates itself by catastrophe, the whole concern is an abstraction, in the critical sense of not entering actively into our consciousness, its dreams, fears, fantasies.
>
> \- Richard A. Falk

A lack of ecosystem integrity is evident when there is convincing evidence of ecologically destructive behavior greater than the absorptive or self-correcting capacities of natural systems. Political systems attempt to specify carrying capacities. If they set objectives incorrectly, they will be required (by the ecosystem) to revise them in the future. We assume that man has taxed the natural processes of ecosystem maintenance in the Great Lakes basin. Accordingly, we look for the balance of integrity in man's efforts to enhance his self-control as the ecosystem's capacities for self-renewal are fully subscribed. We have also assumed that governments are the logical focus for organizing and implementing this self-control.

In examining whether the scope of human self-control is sufficient, questions of the following type will be asked:

1) Are the tools of governments or other institutions (taxation, expenditure, subsidy, direct production, moral suasion, regulation, enforcement, creation of property, and civil rights) adequate to mobilize the support of society for necessary actions within available time frames?

2) Are these tools used?

3) Is the framework for solving problems comprehensive enough to prevent reappearance of old problems in new forms?

4) Is there a commitment to integrity at the ecosystem level by people and governments?

5) Are governments preparing for future shock?

When human populations were low in number and technological impact was minimal, growth could proceed on a slash and burn mentality without fear of more than local expressions of nature's revenge. Today, the context is global. The more we stress the biosphere, the greater the frequency of surprises and the intensity of its revenge.

This essay is based on the following premises:

1) "The Earth does not belong to man, man belongs to Earth" (Chief Seattle); alternately, "humans thinking they own the Earth is like fleas thinking they own the dog" (Crocodile Dundee).

2) "Nature to be commanded must be obeyed" (Francis bacon).

3) The Great Lakes basin is not an island unto itself.

4) An ecosystem (social-economic-environmental) approach to managing the human uses and abuses of natural resources is developing in the Great Lakes basin.

5) Resources allocated to improving ecosystem integrity cannot cause harm elsewhere.

THE QUESTION

Are effective mechanisms available in the Great Lakes basin to permit the individual and collective behavior of people to accommodate the needs of the ecosystems that sustain them? Two general mechanisms are possible: enlightened self-control, and forced accommodation to the consequences of past errors.

DEFINITIONS

1) Integrity implies a state of being complete, sound, or whole. Like health, it can be analyzed through its absence, but only when there is an effort to monitor and respond to change. Integrity in an ecosystem context requires political systems that are responsive to the social, economic, and environmental systems that sustain them.

2) Ecosystem is used here to refer to the Great Lakes basin ecosystem as defined in the Great Lakes Water Quality Agreements of 1978 and 1987.

3) The primary subdivisions of the Great Lakes basin ecosystem for the purpose of this discussion are: social, economic, and environmental.

4) Ecosystem approach (Great Lakes Research Advisory Board, 1978) refers to an holistic approach to managing human use and abuse of natural resources. It is based on the presumption that no one of the economic, social, or environmental compartments can be sacrificed for any other without detriment to human interest.

5) Ego-system approach (Vallentyne and Hamilton 1987) refers to a "me first" and a "me only" approach based on personal greed and global indifference. Long-term social and environmental benefits are sacrificed on the altar of short-term gain.

6) Forbidden zone implies a state in which major planetary processes are sufficiently disturbed by human actions to threaten the integrity of the biosphere. In the forbidden zone, signals indicative of a system out of control appear on a global scale. In the broader context of space and time these surprises are comparable to signals of distress preceding the death of a miner's canary.

POSITIVE INFLUENCES

1) The Great Lakes constitute a large, valuable natural *resource* aesthetically, economically, and internationally. This facilitates political attention, especially when the value of the resource is threatened.

2) The Great Lakes basin is unusual in being drained by a river course that is interrupted by large lakes with long 90% removal times (10 years to 550 years) for conservative pollutants. This necessitates long-term planning.

3) The basin is a hive of human activity. There are 38 million people using forms of technology which transform energy and materials at a rate well above the global average. This has resulted in environmental feedback (e.g., pollution) causing people and governments to initiate a shift from ego-systemic to ecosystemic behavior.

4) 23 million people drink water drawn from the Great Lakes. While drinking water is not a major dietary source of toxic chemicals relative to food, it is an important factor in developing social concern. (International Reference Group on Pollution from Land Use Activities 1978).

5) Municipal and industrial wastes are discharged directly and indirectly (via the atmosphere, tributary waters and soils) into the Great Lakes. Because the Great Lakes are used for drinking, governments are more alert to the necessity of waste treatment than are governments in urban centers adjacent to oceans.

6) There is a large and growing body of information on historical trends in respect to anthropogenic changes in the basin. Synthesis and dissemination of this knowledge has the potential to provide a sound basis for social change.

7) People in the basin share a common language, have close cultural and economic ties, and possess a sense of wilderness.

8) An international mechanism is in place for resolving disputes in instances where actions on one side of the border could threaten human health or property on the other side of the border (the Boundary Waters Treaty of 1909). [On the other hand, Article IV of the Treaty (there shall be no transboundary pollution) is being violated].

9) An international mechanism is in place for maintaining and enhancing water quality in an ecosystem context (the Great Lakes Water Quality Agreements of 1978 and 1987 protocol revision). The 1978 Agreement has been cited as first among international agreements in recognizing the necessity for political actions to take account of ecological realities. However, it is generally accepted that management practices have not adequately reflected the intent of the Agreements.

10) There is sufficient income generation within the basin to support necessary measures to reestablish and maintain the integrity of the ecosystem. Furthermore, an investment in integrity has the capability of generating further income.

11) There have been no wars in the region for nearly 200 years.

NEGATIVEINFLUENCES

1) Lack of a holistic perspective. "A holistic perspective demands knowledge of inter-relationships and a focus on cycles and rhythms at various levels of integration and with varying time delays. In contrast, we and our institutions tend to be programmed in a linear, piecemeal fashion" (Christie et al. 1986). Understanding has been overwhelmed with information and has become disembodied from feeling, dulling our capacity to perceive and react to signals reminding us that nature is our home.

2) Predominance of ego-system thinking. "In a world which has become increasingly adversarial, it is difficult to convince people to be even just a little less selfish.... There is a need to balance egocentric and ecocentric views" (Christie et al. 1986). What is lacking is a comprehensive ecosystemic accounting system and an ecosystem ethic based on a concept of Mother Earth.

3) Lack of a preventive approach. "Announcements of newly discovered contaminants in fish and drinking water, each seemingly more persistent or deadly than the last, have become routine in the Great Lakes basin. Each becomes a crisis in its turn. Governmental reaction is often to shift dollars from prevention and research to diagnosis and treatment, mortgaging the future to pay for the past" (Christie et al. 1986). Recycling is limited, future taxing (against known future costs such as reclamation) is not practiced, and the typical response to legitimate environmental concerns is protectionist public relations.

4) Lack of institutional arrangements for resolving ecosystemic problems in the basin. Many private firms have a sufficient volume of capital cost-allowance tax deferrals to never pay tax: hence, there are no tax or production incentives for such firms to install pollution abatement technologies. If society values environmental benefits more than the benefits from new production, it should be willing to pay more for them. However, governmental pricing of money and debt (through the setting of interest rates) does not encompass resource values; hence, conservation efforts (e.g., reforestation, soil protection, environmental protection) are overpriced, overtaxed, and underutilized.

5) Lack of institutional arrangements for resolving ecosystemic problems globally. The Great Lakes basin is likely to be increasingly subject to globally induced change. Problems include excessive industrial and population growth, global climate change, long range transport of atmospheric pollutants, effects of CFCs on the ozone layer, loss of genetic diversity through extinction of geographic races and species, declining quality of human environments, and reduction in the genetic fitness of human populations for survival under harsh conditions. What is lacking is a mechanism for averting global enactment of the tragedy of the commons.

6) Absentee ownership. The separation of power and responsibility and concern is now institutionalized to such an extent that resource owners, managers, and users are subject to few effective legal or cultural restraints to their abuse of major subsystems of the biosphere, with spillover effects on the Great Lakes basin and elsewhere.

7) Educational systems overly focused on linear, piecemeal thinking in a world of interconnected, circular causal systems. In the words of the Brundtland Commission, curricula must include bottom-up, built-in, holistic education in addition to top-down, add-on, specialized forms of instruction.

QUESTIONS AND RESPONSES

1) What processes do we need to look at? The processes that need to be examined are, first and foremost, those that support human life. Broadly viewed, these are processes governing the energy balance of the Earth, the water cycle, the balance between photosynthesis and respiration, the cycles of essential elements, the availability of essential nutritional compounds and the processes of decomposition and energy dissipation.

Among these processes, the compartments most sensitive to change are the following:

a) atmosphere: ozone, carbon dioxide, water in various forms;

b) hydrosphere: dissolved oxygen, phosphorus, nitrogen, pH;

c) soils: water content, organic matter, phosphorus, nitrogen, potassium, calcium, pH, rate of erosion:

d) biota: species composition and health of terrestrial and aquatic ecosystems: demography, with a focus on human health.

New situations have resulted from technological production systems--long-range transport of atmospheric contaminants (SO, and NO, metals, radionuclides, and organic contaminants), erosion of topsoil, contamination of food chains by long-lived industrial chemicals (particularly organochlorines), redistribution of species, extinction of species, and so on. In a disturbing number of instances, new situations are arising in which indirectly reproduced, unintended poisons are being created in the biosphere; for example, the leaching of aluminum from soils, production of carcinogenic halocarbons from the chlorination of water and sewage, erosion of the ozone layer by CFCs, and production of dioxins and furans during the combustion of municipal and industrial wastes.

2) Can we tell when the processes that support human life are being impacted? Obvious signals are instances of gross air and water pollution from point sources, fish kills, population declines, erosion, and the like. New ecosystem objectives are under development and sensitive analytical techniques (gas chromatography-mass spectrometry) are available to detect minute changes in system properties. However, each problem tends to be examined in piecemeal fashion as if it existed alone. Available techniques are adequate to establish early warning signals of the immediate effects of harmful change, but inadequate to provide compelling evidence of harmful long-term effects of change. In terms of planetary behavior, recent changes in the ozone layer and in atmospheric levels of carbon dioxide clearly show that we are in the forbidden zone.

3) When these processes are *harmed,* can the political-economic-industrial system be mobilized to repair them in time? There is no general answer to this question. The fact that technology has resolved individual anthropogenic problems (e.g., shortages in supplies of particular resources) in the past provides no assurance that this situation can continue indefinitely or that more complex issues can be resolved.

   Surprises in the Great Lakes basin during the past twenty years have included the following: toxaphene, dioxins, furans, and a litany of other contaminants in food chains; the long breakdown times of many organochlorine compounds; the seepage of toxic industrial chemicals from old dump sites; new costs associated with acid rain; new exotic species; and the collective lethargy from 1972 to 1985 in administrative actions in the IJC Areas of Concern. Based on the predominance of toxic chemicals that contain chlorine, one might well ask: Can human society in the Great Lakes basin be dechlorinated?

   The political process is in large part the building of commitment to support a course of action or policy. Four preconditions for development by a government of an environmental policy are (Waldegrave 1987):

   a) acknowledgment of a risk:

   b) nonvoluntary exposure of people or property to the risk:

   c) existence of an acceptable, effective remedy: and

   d) existence of public support for action.

Establishing each precondition for policy is time consuming and a major test of how democracies respond to scientific and public concerns. Governments are constrained by law and custom as to what they can do and the tools they can use. Tools available to government include:

a) taxation

b) subsidy

c) expenditure

d) direct production (e.g., schools, roads, public utilities)

e) moral suasion

f) regulation and enforcement

g) intermediation

h) control of creation of money

i) establishment and enforcement of rights

j) import/export controls

For environmental matters, governments tend to rely on regulation and enforcement. Expenditure policy, for example, does not discriminate between purchasing from suppliers that pollute and those that don't. Tax policy provides capital cost allowances at similar rates for pollution control equipment as for new production equipment. The specific rate at which a capital cost allowance is allowed varies from item to item.

The capital cost allowance is a loan from one group of taxpayers to another. The Income Tax Act sets out the permitted uses for capital cost allowances. There are no requirements compelling firms that are not in compliance with environmental regulations to use their capital cost allowances for projects that would bring them into compliance. Public funds (i.e. tax deferred) may be used to expand society's capacity to pollute.

Government is not wholly consistent in its approaches to environmental problems. These inconsistencies reflect both the complexity of the problems and the time needed to build support for change, as well as ongoing differences of opinion, interest, and approach within society.

4) Can go-slow policies be instituted? Co-slow policies can be initiated in situations where learning from error is possible (e.g., Minimata, Love Canal, Chernobyl) or when people perceive that a sudden change of context has taken place (e.g., the many signs of technology out of control in the 1960s), providing that these lead to changes in behavior.

On the other hand, based on the current industrial wait and see philosophy, the turn around time for major industrial activities and human society as a whole is on the order of 25 to 100 years. The continual separation of individual crises as if each existed alone is indicative of a profound state of denial that humanity is well into the forbidden zone. Piecemeal approaches and wait and see attitudes are unacceptable in the forbidden zone.

Perhaps the best answer to this question is the quotation at the start of our paper, for there is as yet little evidence that perception of the problem has entered the consciousness of a significant proportion of leading politicians and industrialists. A recent expression of hope for the future is the Report of the World Commission on Environment and Development (1987).

5) Is research improving the capacity to respond? Research is improving the capacity to detect ecosystemic change; however, new attitudes, perceptions, and behaviors are not developing at rates paralleling the development of new knowledge (Regier et al. these proceedings). There is often public and political pressure for expenditures and efforts that exacerbate existing situations because of the highly technical and specialized nature of research. Communication between the scientific/public/political communities is limited and often subject to suspicion and mistrust. Society is ill-prepared to rationally exchange present growth for future indebtedness and degraded ecosystems (e.g., promoting economic growth while increasing pollution and debt mortgaging the future to pay for the past). Sometimes the need for research is used as an excuse to delay action.

Although research is improving the capability to respond, its findings have neither been fully utilized or well integrated.

6) Is a more benign production system under active development? The seeds of a more benign production system (energy conservation, recycling, and organic farming) have been planted, but show few signs as yet of being able to compete effectively with the existing machinery. In ecological succession, communities create conditions favorable to their successors, thus providing for ecological continuity. In contrast, many of the instruments used by governments (subsidies and resource pricing) encourage wasteful practices that burden successors. Agrochemical industries, debt, and subsidized competition, for example, virtually compel farmers to mine their soils.

7) Are we destroying the carrying capacity of the ecosystem for our species? The extinction of other species is common. It is not clear that this loss has given man more space or time. Carrying capacities of ecosystems for humans are a function of population, life style, and invention. In most instances carrying capacities are only knowable after the fact. Our society's faith in invention as a means for continuously improving living standards for an expanding population ought to be tempered by a practice of vigilantly testing carrying capacity viability. Nobody knows if we are in the forbidden zone. Rather there is a blind faith that whatever damage we cause will be benign or can be reversed after it is found.

OVERALL RESPONSE TO THE PRIMARY QUESTION

Mechanisms are available to governments that could permit the individual and collective behavior of people in the Great Lakes basin to accommodate to the needs of the ecosystem that sustains them. These include taxation, expenditure, subsidy, direct production, moral suasion, regulation, enforcement, creation of property and civil rights, creation of environmental rights, and others. However, these mechanisms are often used in ways that are counterproductive to ecosystem integrity.

While actions taken within can to some extent buffer the Great Lakes basin ecosystem from external change, such actions are inadequate in the face of global influences (climate change, depletion of the ozone layer, long-range transport of toxic contaminants, and economic recession).

Awareness of an environmental crisis in the 1960s arose from the eruption of pollution in centers of technological and population growth. A comparable perception may resurface in the 1990s in ecosystemic (social/economic/environmental) form. This, in turn, could generate cooperative forms of behavior on an international scale--if a sufficient number of leaders from politics, industry, andvoluntary membership associations with global interests were prepared for such an event in advance. However, until the crisis is felt or people see the entire basin as their backyard, business as usual will continue.

We believe that people, corporations, and governments--generally unwittingly, mostly reactively, sometimes cunningly, and with more than occasional kicking and screaming--will accept Francis Bacon's dictum that: "Nature, to be commanded, must be obeyed." If this is done with forethought based on enlightened self-interest, and if basin-wide and international mechanisms for building consensus and commitment are put in place, it is possible that a sufficient degree of integrity could be maintained to characterize the Great Lakes basin as a sustainable ecosystem.

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LANDSCAPE ECOLOGY: ANALYTICAL APPROACHES TO PATTERN AND PROCESS

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ABSTRACT. The interrelationship of ecological history, process and spatial variability is central to understanding system stability and response to disturbance. The concept of landscape in ecology provides a working unit for the study of spatial heterogeneity and its causes. Patterns across a landscape result from the dynamic interaction of biotic and abiotic factors, natural or cultural in origin. Understanding pattern dynamics and disturbance can assist in identifying andmonitoring anthropogenic perturbations which alter system processes.

New strategies are necessary for acquiring and interpreting data relevant to the variability of ecological dynamics across landscapes. In one sense, emergent properties at large scales need to be identified which cannot necessarily be predicted from small-scale variation. The system must be observed at a sufficiently coarse scale to extract lower frequency information associated with landscape-level processes. On the other hand, scale-independent approaches to the landscape (e.g., fractal dimension) allow ecological generalities to be applied across a range of scales. Developments in remote sensing, pattern analysis, geographic information systems, and spatially based ecological modeling provide the opportunity to analyze natural systems over large geographic areas. This paper briefly describes these developments in the context of their contribution of spatial and temporal information to the analysis of natural system dynamics and response to disturbance. The utility of these approaches to management of the Great Lakes basin ecosystem is discussed.

INTRODUCTION

The measurement and analysis of ecosystem dynamics is influenced by scientific methodology and technology as it affects perception at the time of data acquisition and interpretation. The analysis is inherently biased by the choice of variables which are deemed important, as well as by what can physically be measured at the time of study. Consequently, our definition of ecological integrity is a function of scale (what is measurable) and a function of our paradigm (what we delegate as important). Surprise, in the context of ecological integrity, is similarly connected to our perception and our ability to perceive. Holling's (1984) definition of surprise, "perceptions of discontinuous behavior of complex, nonlinear systems," positions us relative to the system. As we step back and increase the scale of what is perceived, we may see that surprises become part of the system and are no longer surprises per se, but are components integral to the fabric (the system integrity). We must recognize the consequence of crossing spatial and temporal scales of processes in our analyses in order to have an integrated understanding of system dynamics and response to disturbance (Allen et al. 1984).

THE LANDSCAPE PERSPECTIVE

The concept of the landscape provides the unit most amenable to studying heterogeneity in space as well as time. Patterns across a landscape result from the dynamic interaction of biotic and abiotic factors, natural or cultural in origin. Analysis of these patterns can lead to greater insights into their causal factors, namely the underlying processes: and time series may suggest sources of natural or disruptive variation. The prediction of future landscapes is dependent on the understanding of how patterns and processes vary in space and time in response to change. It is apparent that if we are to study large-scale ecological phenomena which have been beyond our grasp [our perception and ability to perceive], we must develop new strategies for acquiring and interpreting data pertinent to the variability of ecological dynamics at these larger scales. There is a need to identify emergent system properties which cannot necessarily be predicted from small-scale variation. In a sense, the system must be observed at a sufficiently coarse scale to extract lower-frequency information associated with large landscape-wide processes.

Troll (1939, 1968, 1971) introduced the term landscape ecology in his consideration of relationships between living communities and their environment. He combined the horizontal approach of geography, emphasizing relationships between spatial units, and the vertical approach of ecology, focusing within a unit (Naveh 1982). Analysis of the interdependency among spatial units distinguishes landscape ecology from other, more classical approaches

(Forman and Godron 1981, 1986). Such analyses operate within a large array of temporal and spatial scales and, as a consequence, landscape studies have adopted a hierarchical perspective (Urban et al. these proceedings). landscape ecology explicitly addresses linkages between structure (spatial heterogeneity) and function (ecosystem processes), and, importantly, it recognizes humankind as an influential agent in shaping landscapes (e.g., Vernadsky 1945; Buchwald 1963).

This view that integrates humans into the system is an important one when considering ecological dynamics within the Great bakes basin ecosystem. More than 45 million people live in the region and depend on the Great Lakes for economic, recreational, and aesthetic benefits. Whole-system integrity, its balanced functioning and response to unstabilizing forces, concerns the complex of interrelationships between all *components* of air, land, water, and living organisms, including humans, within the basin. Restoration and maintenance of system integrity in the context of surprise requires an understanding and appreciation of large-scale dynamics. Small-scale natural disturbances, appearing external to the disturbed subsystem, are integral to the greater system functioning. When disturbance is regional rather than local in scope, as are many of the problems confronting the Great Lakes region today, the impact on the greater system will be far less predictable (i.e. more surprising) if anthropogenic influences have not been previously considered.

Concepts developed within the discipline entitled landscape ecology pertain to any natural system since they attempt to understand spatial and temporal patterns under the influence of biotic and abiotic functioning. This paper *reviews* new technologies and analytical methods developed under the umbrella of landscape ecology for study of the integrated properties of ecosystems. The works cited are primarily from terrestrial ecology studies, but the term, landscape, and the associated analytical approaches, apply equally as well to aquatic systems or seascapes. With the terrestrial human creature as an integral part of the system, a set of technologies that have focused on terrestrial systems becomes a perfectly natural approach to the Great Lakes basin ecosystem.

DATA ACQUISITION AND MANIPULATION

Remote sensing technology presents one of few tools with which we can assess and monitor ecosystem dynamics at landscape and regional scales. Observations made from aircraft or satellite platforms expand our viewing field of the surface mosaic. Simple definition of dissimilar patches within the landscape provides information on surface cover types, their spatial interdependency, and the changing mosaic over time. Physical understanding of interrelationships between spectral reflectance and surface biophysical properties allows extrapolations to be made from intensive site-specific research. While remote sensing is not the panacea for large-scale questions, as was suggested early in its development, its utility is unsurpassed in producing a consistent data base at spatial, spectral, and temporal resolutions useful for resource monitoring and management. When coupled with other data bases through the use of information systems, it has the potential to alter our models, our methods of analysis, and, in essence, our paradigms.

Remote Sensing

By definition, remote sensing is the acquisition of information from a distance without physical contact. The technology is based on measurement of different portions of the electromagnetic spectrum as radiation is reflected and reradiated from a surface back to the sensor. Changes in the properties and amount of radiation relay informative data on the properties of that surface with which it interacts. Remote sensing data have been used to categorically describe landscapes in terms of geological structure (Goetz and Rowman 1981; Townsend 1987), vegetative cover (Nelson et al. 1984; Hopkins et al. 1988), and urban development (Bryan 1975; Jackson et al. 1980). Other applications have acquired continuous measurements of landscape properties as they vary in space and time. Available sensors, such as the Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM), and the Advanced Very High Resolution Radiometer (AVHRR), have been used to measure the seasonal course of emergence and senescence of vegetation on a regional-to-global scale (Tucker et al. 1985), to measure changes in conifer leaf area along environmental gradients in the Pacific Northwest (Spanner et al. 1984; Running et al. 1986), and to assess water quality and dynamics (Carpenter and Carpenter 1983; Lindell et al. 1985; Lathrop and Lillesand 1986).

Remote estimates of ecosystem characteristics which are indicative of the system state and functioning create opportunities for testing many ecological hypotheses on landscape and regional scales (Waring et al. 1986, Wessman et al. 1988). Commonly used vegetation indices derived from spectral measurements (R/NIR; NIR-R/NIR+R) utilize the red wavelengths (R) absorbed by chlorophyll and the near infrared wavelengths (NIR) scattered by leaf and canopy structure. Theoretical developments indicate that these ratios are indicative of instantaneous biophysical rates, such as photosynthesis and transpiration within the canopy (Sellers 1985, 1987). The close connection of absorbed photosynthetically active radiation (APAR: .4-.7 **μm)** to chlorophyll density, which can be estimated remotely, leads to near-linear relationships among canopy properties of **APAR,** photosynthetic capacity (P_C), minimum canopy resistance (l/r,), and the two vegetation indices. Theoretically, integrating multitemporal measurements of reflected radiation in a given region should provide an estimate of gross primary productivity (Tucker and Sellers 1986).

Likewise, satellite and aircraft sensors provide a way to observe water body dynamics and biological productivity. The greatest degree of light penetration into water occurs in the visible wavelengths, also the region of chlorophyll absorption. Patterns of surface planktonic biomass and chlorophyll fluorescence can be used to derive estimates of primary productivity. Patterns of phytoplankton pigment groups allow further delineation of the phytoplankton community into some functional group classes (e.g., Carder and Steward, 1985). Pollutants (both inorganic sediments and organic constituents) may affect the reflective or emissive properties of water bodies. Relative turbidity is easily detected as tonal changes in remotely sensed imagery (e-g., Klemans et al. 1973; Strong 1978). Wavelength bands in the thermal infrared estimate the surface temperature (upper few microns) of water bodies, from which plume and circulation patterns can be depicted (e.g., Schott and Schimminger 1981). Numerous ocean studies have shown that at microwave frequencies, where water is opaque to radiation, surface structural features such as currents and eddies are measurable (e.g., Kasischke et al. 1984; Vesecky and Steward 1982).

The task of landscape ecology, as defined by Toth (1988), is to:

1) discover, by way of analysis, which factors are operationally significant:

2) determine how these factors bring about change in the landscape: and

3) describe how these factors define the spatial (form) characteristics of a landscape.

In light of these objectives and the foregoing discussion, the synoptic view of the land and seascape as provided by remote sensing instrumentation is essential to the analysis of large-scale ecological pattern and process. The critical issue is how best to interpret the emergent patterns, as extracted from remotely sensed data, to provide insights on terrestrial and aquatic system structure and function at landscape and regional scales.

Geographic Information Systems

Increasing complexity of ecological problems, availability of large computerized 'data bases, and the increasing demand to work at continually larger scales are factors which, in combination, emphasize the need to automate aspects of ecological research and planning. As a result, geographic information systems (GIS) have evolved as tools for spatial analysis, inventory, and data management (e.g., Burke et al. 1988). In the broadest sense, a GIS permits the integration of data for study of complex interactions from such disparate sources as remotely sensed imagery, simulation model output, digital terrain data, soil surveys, drainage basins, and road networks. Expert systems for GIS are being developed to make data processing and analysis more efficient and to advise on problem solving where a human expert's interpretation is usually required (Ripple and Ulshoefer 1987).

Various analytic and data processing functions can be performed on spatially automated data [vector (polygonal) or raster (grid)]. Some of these functions and related examples include:

1) data retrieval: browsing, windowing, boolean attribute retrieval, and statistical summary:

2) map generalization and abstraction: calculation of centroids, automatic contouring from randomly spaced data, proximal mapping, reclassification of polygons, coordinate conversion;

3) map sheet manipulation: scale changes, distortion removal, projection changes, coordinate rotation and translation:

4) buffer generation: buffer zones around points, lines and polygons:

5) polygon overlay and dissolve: integrating and disintegrating multiple maps or data layers:

6) measurement: line, area, and volume;

7) network analysis: models of flow: linear networks representing streets, waterways, and related phenomena;

8) grid cell analysis: grid cell overlay, area and distance calculation, optimal corridor selection;

9) digital terrain analysis: visual display of cross sections and 3-D view, interpolation/contouring, slope/aspect/sun intensity, watershed computation, visibility;

10) output techniques: hard-copy maps, statistical tabulations, CRT display, computed data files which result from the various manipulations of the data.

Static GIS models can be created internal to the system by simple overlay or statistical calculations using various data layers in combination. These usually represent thematic maps for variables that change slowly over time. At the present, spatial models which require intensive calculations are run outside the GIS; i.e. information from the database is passed out of the GIS for external processing. These so called dynamic GIS models represent the linking of the GIS to an existing ecosystem or process model for simulation studies. In this case, the GIS serves as an archive or display mechanism for the ecosystem model in and output.

ANALYSIS OF SPATIAL HETEROGENEITY

Relationships between spatial pattern and ecosystem processes are not restricted to any one spatial or temporal scale. The effect or importance of processes on pattern will, in fact, vary with scale (Risser et al. 1984). Knowledge of which factors are operationally significant at a given scale or a range of scales assists in establishing the constraint/driving variables of the system. Several methods are being used (and many remain to be developed) for the analysis of landscape mosaics in order to generate hypotheses about the appropriate scales at which to study specific ecological phenomena and how best to interpolate the results across scales.

Patch shape and boundary dynamics are indicative of flows and interactions within the landscape. A patch is identifiable by the high autocorrelation among its components and not necessarily by ecosystem properties per se (Risser 1987). Patch characteristics of size, shape, number, and configuration will affect the available energy and nutrients, species composition, and dispersal and foraging of organisms. (Wiens 1976; Pickett and Thompson 1978; For-man and Godron 1981). The mosaic will be a function of patch boundaries, their location, their effect on ecological processes within patches and across the landscape, and their influence on energy and material flow (Wiens et al. 1985).

The complexity of natural boundaries or patch shapes can be quantified with Mandelbrot's fractal, a mathematical concept describing continuous but not differentiable temporal or spatial phenomena (Maldelbrot 1983). Fractals have the property of self-similarity where patterns at one scale are repeated at another. They can be used to establish domains of scaling defined as "portions of a spectrum of spatial scales within which patterns, and perhaps the patterns which cause them, are repetitive or self-similar" (Wiens and Milne 1988). Some environmental data display self-similarity at all scales, others over a limited range of scales, and still others over a few widely separated scales (Burrough 1981). Such properties describe domains of variation which may be the result of particular ecosystem processes; i.e. the technique offers the potential to quantify the spatial scales over which one can extrapolate site-specific data to larger geographic area. Techniques of fractal analysis have been applied to environmental data to characterize boundaries and patch shapes of land cover types in relation to natural and human processes (Burrough 1983; Krummel et al. 1987; Milne 1988). By looking at fractal dimensions that occur over a range of scales, hypotheses can be developed about the spatial scale of the underlying processes that may control the shape and complexity of the landscape.

Gardner and colleagues (1987) employed methods derived from percolation theory to construct neutral landscape models that can show the effects of patch size and frequency on the landscape without the contaminating influence of factors such as topography, historical disturbance events, and related ecological processes. Percolation theory was originally developed to describe the flow of liquids through material aggregates. Analogically, landscape complexity can be related to organism dispersal and abundance through simulation of their diffusion across percolation networks. The pattern dynamics established in this fashion can serve as a neutral model against which data and hypotheses can be rigorously tested. Again, such analyses make it possible to define the scale or range of scales, at which the interaction of landscape processes affects pattern.

Ecosystem analysis and modeling has, in the past, focused on change in time rather than change in space. Current work has expanded to incorporate spatial heterogeneity in recognition of the fact that interdependency across space is a critical factor in disturbance and landscape dynamics (Risser et al. 1984;

Turner 1987). Models at the individual and population level have considered patch effects on external behavior of organisms without considering patch interaction (Ford et al. 1982) and by incorporating interpatch exchange (Fahrig et al. 1983). Forest growth models based on the individual tree development incorporate the importance of spatial position as it is influenced by physiology and environmental factors (Shugart 1984; Pastor and Post 1986). In such models, landscapes are commonly simulated by distributing independent plots over a grid of physiographic factors. Recent models define spatially interactive plots. Observations of disturbance effects on simulated collections of independent and interdependent plots showed recovery time to be quicker for the former, and dependent on spatial scale of the disturbance for the latter (Coffin and Lauenroth 1988). A scale-independent model by Fahrig (1988) of a general disturbance regime on hypothetical species in a spatially explicit habitat grid shows potential for examining landscapes across several scales.

APPLICATIONS TO THE GREAT LAKES BASIN ECOSYSTEM

The Great Lakes basin is a dynamic system with a variety of processes occurring at different spatial and temporal scales. Recent work with remotely sensed data over the Great Lakes has established that no single satellite remote sensing system is optimal for the study and monitoring of such dynamics (Lathrop and Lillesand 1986; Lillesand et al. 1987). However, the application of imagery in a GIS context from both the Landsat Thematic Ma per [high spatial (30 m), low temporal resolution] and the Advanced High Resolution Radiometer [coarse spatial (1 km), high temporal resolution] presents the possibility for working across scales and to integrate spatial information.

Lillesand et al. (1987) found that the satellite data were strongly correlated to water color, a function of the variables of phytoplankton (chlorophyll), suspended sediments, and dissolved organic matter, all highly intercorrelated. Each one of these three variables was strongly related to reflectance in the visible and near-infrared wavelengths, but the actual source of the reflectance signal was considered a combination of their scattering properties. In Green Ray, a general water turbidity index was used successfully to differentiate levels of terrestrial inputs, primarily suspended sediments and dissolved organic matter. In the mid-lake waters, where terrestrial inputs were minimal or absent, reflectance was highly correlated with chlorophyll. Circulation patterns resolved at the scale of the AVHRR were indicative of thermal upwelling.

Remote monitoring of the Great Lakes will require data from a combination of satellites acquiring imagery in a range of spatial and temporal resolutions. In the case of the studies cited above, the 30 m resolution of TM provided information on intra-lake variability, while the coarser 1 Ion resolution of AVHRR covered the entire Great Lakes system with a view of interlake variation. Initial studies suggest that mapping of such variables as water color and temperature is possible. The next step is to use such maps for the parameterization of lake production models.

ENLARGING OUR VIEW OF THE BASIN

As our influence on the environment increases in intensity and extent, so must our analytical capabilities increase if we are to understand the potential response of the systems we affect. The complexity and size of the Great Lakes basin ecosystem requires a holistic, integrated view which, due to advances in theory and technology, is now possible. Much of what has been presented in this paper is at the theoretical stage only: landscape ecology is in its infancy and has yet to develop practical principles on how to apply this theory to management problems in general. However, we are at the stage where significant advances in understanding large-scale ecological dynamics can be made through integration of the landscape perspective, remotely sensed information, and spatial analysis techniques. Remote sensing offers the first tool to monitor the basin as a whole, and GIS presents the means to manage the vast amounts of data required to work at that scale. Spatial analysis techniques, as they mature, will provide the means to assess the landscape mosaic, be it aquatic or terrestrial, in the context of natural or human disturbance. The establishment and effective application of these techniques to the study and maintenance of the Great Lakes basin ecosystem must be a multidisciplinary endeavor, including institutional, political, and economic considerations as well as scientific and technical issues.

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