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Evaluating ecosystem health*

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Abstract. In the past decade, metaphors drawn from human health are finding increasing application in environmental assessment at ecosystem levels. If ecosystem medicine is to come of age, it must cope with three fundamental dilemmas. The first stems from the recognition that there are no strictly objective criteria for judging health. Assessments of health, as in humans, inevitably are based on some combination of established norms and desirable attributes. The second stems from the irregular pulse of nature which either precludes the early recognition of substantive changes or gives rise to false alarms. The third is posed by the quest for indicators that have the attributes of being holistic, early warning, and diagnostic. Indicators that excel in one of these aspects, often fail in another.

Advances in ecosystem medicine are likely to come from closer collaboration with medical colleagues in both clinical and epidemiological areas. In particular the time appears ripe for a more systematic effort to characterize ecosystem maladies, to validate treatments and to develop more sophisticated diagnostic protocols. These aspects are illustrated with comparisons drawn from studies of environmental transformation in the Laurentian Great Lakes, the Baltic Sea and Canadian terrestrial ecosystems.

1. Introduction

Much that can and does go wrong with nature is linked in some way to the activities of humankind. Examples abound — the acidified lakes and rivers in Canada's Boreal forests have lost valued fish stocks, and some no longer support fish at all; the same is true of similar areas in Scandinavia. To speak of ecosystems as 'dead' or 'dying' is, unfortunately, no longer merely a matter of poetic license.

Disturbance *per se* is not the culprit. Indeed, perturbations are often essential in order to maintain vigorous and healthy ecosystems. For example, periodic fires in the Boreal forests serve to rejuvenate the forests by recycling nutrients and freeing space. Many ecosystems have been shown to be entirely dependent on such natural perturbations for their continued vitality (Vogal, 1980).

This is not to suggest, however, that all types of disturbance are beneficial for the sustainability of natural systems. Ecosystems have become severely crippled as a result of stress imposed directly, or as a by product, from human activity. Even in ancient times, there are records of local pathologies in aquatic ecosystems resulting from human abuses. For example, Aristotle remarked on the abundance of 'small red threads' (apparently tubificids) growing out of 'foul mud' in proximity to human settlements (Leppakoski, 1975, p. 12), an observation suggestive of the impacts of organic waste discharge.

Today, environmental concerns have spread from the local through to the regional and global levels. At the global level, the increasing concentrations of carbon dioxide in the atmosphere (with the attendant risk of rapid global warming), and the depletion of the ozone layer (promoting the risk of skin cancer and deleterious mutations) are grave concerns.

There is no single process that has lead to the current predicament, unless one speaks of the imprudence of our own species. Rather, a multitude of stresses, (many of them interactive), has resulted in widespread ecosystem degradation. Sometimes a single causal factor, such as sulphur dioxide emissions, has rendered large regions practically barren of life, e.g., parts of the Boreal forest downwind of smelters. More often, the combined effects of numerous stresses: e.g., harvesting,

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*** Dedicated to Prof. J. Stan Rowe whose pioneering work in formulating a holistic perspective on ecosystem health has substantially contributed to the development of these ideas.**

introduction of exotic species, generation of waste residuals, physical restructuring, in concert with extreme natural events, deals nature its mortal blows. (Regier & Hartman, 1973; Rapport & Friend, 1979; Rapport & Regier, 1980; Rapport, 1983).

We have barely begun to understand how ecosystems function and now we are grappling with describing and defining their health. This, however, seems a relevant and worthy enterprise, for today many ecosystems have been rendered pathological. Such transformations have often occurred with little warning. This phenomenon of repeatedly being caught unaware poses the greatest challenge to future managers of ecosystem health.

There is a double challenge here: humans were concerned about deleterious changes in their environment long before the term 'ecosystem' came into our vocabulary. With a growing awareness of the long-term cumulative impacts of stress on environment, the transmission of stress effects within and between ecosystems, and the complex interactions between stresses, the importance of developing a holistic or ecosystem perspective becomes self-evident. The continuing challenge is two-fold: (1) increase our understanding of ecosystem behaviour under intensification and relaxation of multiple sources of stress, and (2) developing true early warning indicators identifying and then heading off irreversible impacts of human activity on the integrity of natural systems.

2. Ecosystem: a nebulous concept?

We might remind ourselves that the very term 'ecosystem' is ensconced in ambiguities. While ecosystems can be described in the context of General Systems Theory (Rapoport, 1986), non-systemic thinkers complain about difficulties, such as the impossibility of delimiting precise boundaries on the basis of conventional observations. This is best illustrated in aquatic ecosystems where the concept of a continuum (Vannote *et al.*, 1980) is well appreciated. That is, ecosystems are not isolated, but intimately connected, or nested within adjacent or larger systems. Thus, we find a continuum from rivers to lakes; from estuaries to the sea; from the sea to the world's ocean. And transcending this is the embedding of aquatic ecosystems, including groundwater, within terrestrial systems and the significant interactions between them at the land-water interface. Seemingly superimposed, but actually part and parcel of all this, is human activity with its own important influences on the character of ecosystems and, as we know, one of the now often dominant engines of ecosystem transformation (Bird & Rapport, 1986).

Yet for management and assessment, 'ecosystem' constitutes a relevant macro-level unit for describing the environment (Rowe, 1961, 1989; Bird & Rapport, 1986). As dynamic, complex, and open systems that are in constant change over ecological, evolutionary, and geological time (Rapport & Regier, 1992), ecosystems exhibit chameleon-like properties; that is, they might exist in a number of alternative forms, the particular composition being very much influenced by internal dynamics and by interactions with neighboring systems (Holling, 1985; Rapport & Regier, 1992).

3. Towards an ecosystem health model

In the quest for a more comprehensive understanding of the process of ecosystem breakdown and recovery, it has struck me that we are engaged in the practice of some form of ecosystem medicine (Rapport *et al.*, 1979). Introducing the medical metaphor suggests that, like physicians, ecosystem practitioners are in need of systematic procedures by which to recognize illness, devise protocols to 'rule-in' or 'rule-out' possible causes, and prescribe treatment. When it comes to treatment, medicine suggests several options: following internal medicine, ecosystems may be treated by regulating the 'blood chemistry' of the system; following surgery, ecosystems may be treated by wholesale physical and biological restructuring. The latter may involve both removal of undesirable elements and introduction (grafting) of desirable ecosystem components.

I should hasten to add that we are concerned here with the application of scientific methodologies developed in medicine in order to assess the state of ecosystem health. In so doing I neither subscribe to the view that ecosystems can be considered as organisms (for clearly there are substantive differences in both the mechanisms and degree of integration as well as in the dynamics of these two systems) nor do I suggest that clinical medicine with its emphasis on 'cure the disease' is an appropriate model for environmental ills. In both human and ecosystem medicine, far more emphasis deserves to be placed on preventing system breakdown than the more costly and less effective option of attempting to restore health once the damage has been done.

With help from several colleagues, I suggested a systematic basis for assessing ecosystem health in terms of ecosystem level properties (Rapport *et al.*, 1979; Rapport *et al.*, 1981; Rapport, 1989a, 1989b, 1990, 1991; Rapport & Regier, 1992). The original essay (Rapport *et al.*, 1979) was written at the request of John B. Calhoun whose purpose was to stimulate new thinking and cross-fertilization among a number of traditional disciplines (Calhoun, 1983). Apparently Calhoun sensed our interest in the self-organizing capabilities of open thermodynamic systems, because he listed our contribution under 'negentropy' rather than under other categories used to classify the various contributions, such as 'stress', 'environment', and 'complexity'.

4. The subjective nature of health assessments

If we accept the notion advanced by Rene Dubos (1968) describing health as a *modus vivendi*, enabling imperfect man to achieve a rewarding and not too painful existence, health assessments, at least in the human context, require judgements that are not only rooted in systematic observations, but also that incorporate explicit value judgements. Porn (1984) suggests that health be defined in the context of subjective judgements by the individual in relation to his or her life goals. The extraordinary life of Hellen Keller (1954), provides a well-known example. Although blind and deaf from birth, Ms. Keller described her own life as extremely rewarding. Her life story provides testimony to the sensibility of Porn's definition of what is health.

With its roots in tribal medicine, folk practices, quasi-religious practices of shamanism, and quasi-scientific practices of acupuncture, the practice of modern medicine retains as much of the character of an art as of a science. It has been said that medicine is a conjectural art; it has almost no rules. Clearly, in many cases, the diagnosis and treatment of illness is governed as much by the intuition of the practitioner as by scientific principles. Inevitably, there enters a degree of subjectivity in evaluating the health status of an individual or an ecosystem.

To be sure, some ecosystem transformations are so debilitating that assessments are easily made without recourse to societal values or limitations of scientific understanding, e.g., the demise of the forest downwind of a smelter. Yet in many, perhaps the large majority of situations, social value-judgements and the limitations of science conspire to give ecosystem medicine more the stamp of a conjectural art. To cite just a few examples: In New Zealand, highly diversified indigenous forests are being converted to plantations of radiata pine (*Pinus radiata*). To foresters, this transformation is desirable, constituting an improvement in ecosystem health, since the yield of merchantable timber is higher in the plantations than in the natural forest. To conservationists, however, the change is decidedly negative, as it results in the wholesale loss of native flora and fauna.

Another example of the importance of societal values in judging the health of ecosystems is found with respect to recent changes in the Great Lakes fishery. Here the Pacific salmon was purposefully introduced to control runaway populations of smelt and alewife. The rich food supply produced a thriving sports fishery, though it is not self-sustaining and relies on hatchery production and stocking of young. From the sports fisherman's perspective, these changes constitute an improvement, despite the fact that the catch is inedible owing to high concentrations of toxic substances. From an ecological perspective, the health of the Great Lakes ecosystem appears further compromised by fostering an exotic species which is not self-reproducing and which might preclude the re-establishment of a sustainable fishery comprised of native species.

Perhaps I am leaning, for the sake of argument, to the other extreme: suggesting that judgements concerning the state of health of individuals or ecosystems are based on largely subjective criteria. Particularly in humans, judgements about the state of health of an individual are based on seemingly objective comparisons of individual physiology against norms derived from population statistics. But this only side-steps the issue, for what is most relevant, as Porn (1984) and Dubos (1968) suggest, is whether a particular condition or change advances or hinders individual aspirations.

In defining ecosystem health, Calow (1991) proposes to evaluate ecosystem health by reference to its optimal state. Calow argues that just as natural selection yields an optimal genetic state, it also yields an optimal ecosystem state. Yet in this and other applications of optimization principles to economics and ecology, the elegance of the mathematical apparatus cannot compensate for overly simplistic assumptions about the nature of the evolutionary process and human and ecosystem behaviour. Optimization models foster more a mythology than a science if the assumptions are either weak, untested, or moulded more in the service of mathematical solutions than in the service of understanding natural process (Rapport, 1991).

If, as in human medicine, ecosystem health is less an objective state than a subjective judgement, then the use of optimization principles appear even more inappropriate as an analytical framework. For it turns out that it is not a single configuration that satisfies social needs, but a range of configurations. These configurations are not wholly objectively determined, but contain much by way of value judgement as to what is desirable. The fact that a variety of alternative states might be considered healthy does not, of course, give licence to any environmental transformation that might be set in motion by a political/economic process. Rather, recognizing that there is not a uniquely defined optimum state implies only that a healthy nature need not conform to a specific structure. However, a healthy system must embody certain basic features, both structural and functional, to manifest ecosystem integrity (Rapport, 1990, 1992).

5. Early warning signs of pathological ecosystems

There are a number of obstacles in providing early warning of ecosystem pathology. Firstly, basic processes such as nutrient cycling and primary productivity are highly cyclical and irregular, varying from year to year, seasonally and diurnally. Such variability and seemingly random behaviour raises havoc with detection of the onset of many pathologies that beset aquatic ecosystems. Secondly, early symptoms of ecosystem degradation may be missed or discovered only after pathology is well advanced. Thirdly, false alarms are easily sounded owing to a still far from adequate understanding of the long-term dynamic behaviour of ecosystems.

The failure to recognize the significance of symptoms is illustrated by the disappearance of the mayfly larvae in the central basin of Lake Erie (Rapport, 1989b). Although the exact cause of the disappearance remains controversial, (perhaps it was the combination of occasional anoxia in the central basin and bio-accumulation of organic pesticides, especially DDT) the disappearance of this species appears, only long after the fact, to have signalled the onset of severe cultural eutrophication.

An example of the ease of sounding false alarms concerns the sudden die-back of macrophyte beds of *Fucus vesiculous* along the SW Finnish coast in the late 1970s (Ronnberg *et al.*, 1985). This die-back was at first thought to signal coastal-wide environmental degradation owing to cultural eutrophication. However, the subsequent partial recovery of *Fucus* in the mid 1980s, despite continuing high nutrient loadings, suggested a more complex chain of events with less long-term risk to coastal ecosystems.

5.1. *Health indicators at the ecosystem level*

One of the significant findings to come from a comparison of case studies of ecosystem level response to cultural stress has been the identification of common symptoms of ecosystem degradation. These common symptoms, termed the 'ecosystem distress syndrome' (Rapport *et al.*, 1985) characterize a large number of ecosystems under stresses of various types. The distress syndrome, documented on the bases of comparative case studies, is consistent with indicators of ecosystem dysfunction suggested by Odum (1985), Steedman & Regier (1987) and Godron & Forman (1983). These various frameworks for indicators of ecosystem response to stress have been shown to be roughly congruent (Rapport & Regier, 1992).

With reference to aquatic ecosystems, the ecosystem distress syndrome comprises the following symptoms: (1) alteration in biotic community structure to favour smaller forms; (2) reduced species diversity; (3) increased dominance by 'r' selected species; (4) increased dominance by exotic species; (5) shortened food-chain length; (6) increased disease prevalence; and (7) reduced population stability (Rapport, 1991). While stressed ecosystems do not manifest all the above symptoms, in the vast majority of cases, most of these symptoms do appear (Rapport *et al.*, 1985). Perhaps an important exception to the general pattern is the response of Boreal lakes to experimental acidification (Schindler *et al.*, 1985). In this case, surprisingly, both nutrient cycling and primary productivity remained near reference values, while there was a drastic loss of sensitive species and simplification of the biotic community.

A study of changes in the Gulf of Bothnia (northern Baltic Sea) best illustrates the ubiquity of most signs of pathology comprising the ecosystem distress syndrome (Rapport, 1989a). In this case, practically all symptoms listed above were present at scales ranging from local bays and estuaries to coastal areas, to basin-wide. This suggests that the ecosystem distress syndrome provides a suitable starting point for general health check-ups at the ecosystem level. Unfortunately, however, such symptoms of whole ecosystem dysfunction often fail to signal pathology until the process of degradation is fairly well advanced (Bormann, 1985). That is, the response times of whole ecosystems to stress are often measured in terms of decades if not longer periods (Clark, 1986).

Thus, a major challenge in ecosystem medicine is to identify early warning signs of incipient pathology. To achieve this, recourse may be had to changes in critical components, perhaps analogous to organ systems within humans, which have faster response times than whole system transformation (Rapport, 1984). However, with increased sensitivity often comes increased uncertainty as to the significance of the change at the ecosystem level (Rapport *et al.*, 1985). Natural variability in populations and sub-communities of most ecosystems is little known or quantitatively documented. In the absence of long historical records and a more substantial theoretical framework than now exists, it is difficult to assess the significance of changes in specific ecosystem components.

Some progress in identifying sensitive ecosystem components has been registered. In intensively studied large-scale aquatic ecosystems, a consensus is emerging that the presence of certain species suggests a general state of healthiness (and conversely their absence, suggests ecosystem degradation). I refer here to the identification of indicator species for assessing the health of the Great Lakes (Ryder & Edwards, 1985). For example, for the Upper Lakes, (Lakes Superior and Huron), the lake trout (*Salvelinus namaycush*) has been adapted as an indicator of the health of off-shore oligotrophic waters. The continued presence of this open-water, environmentally-sensitive species in abundant and healthy populations in the Upper Great Lakes, marks the absence of cultural stress from a number of sources including eutrophication, toxic substances, harvesting, and the ravages of the sea lamprey (an exotic but now endemic predator). The inference here is that when these stresses, singly or in combination, begin to degrade the ecosystem, lake trout populations would decline rather early in the degradation sequence.

Thus, the indicator approach has the advantage of shortening the relatively slow signal response time of the whole ecosystem to stress by shifting attention to the much quicker response time of sensitive species. Here one should add that while the signal response time is fast for the degradation sequence, it is slow for the recovery sequence: e.g., lake trout will not reappear in desired numbers until much of the ecosystem is restored. Here is a direct parallel with the development of many human diseases; i.e., certain individuals, target cells, or organ systems, signal the onset of pathology well before the whole community or organism is affected. For the following specific examples I am indebted to Dr John Last of the Department of Epidemiology and Community Medicine at the University of Ottawa.

Some epidemiological examples of early warning indicators include monitoring for potential outbreaks of schistosomiasis in a region previously free of it, after a major environmental disruption such as a new dam or irrigation project. In this case, surveillance of high-risk individuals in the exposed population (people who work in water) will disclose the presence of the parasitic infection before it has affected the population at large.

Similarly, the detection of isolated cases of malaria in a previously malaria-free region, after changes that permit mosquito breeding (e.g., building roads that impair drainage and allow stagnant water to accumulate) serves as an early warning of impending community-wide health problems.

At the level of the individual, pathology may be detected early by monitoring target organs. This is particularly the case in the detection of certain forms of cancer before they declare themselves by causing gross disruption of bodily function and/or structure. Specific examples here include preinvasive cancer of the cervix, which can be detected by pap smear when the lesion is not yet even cancerous, but merely dysplastic. Similar microscopic evidence of various other cancers, such as lung and colon, can be obtained, but unfortunately, these are mostly not responsive to early intervention. Other examples of early warning detection with an environmental aspect include many occupational cancers, such as those due to exposure to asbestos and other occupational diseases such as lead or mercury poisoning, which can be detected long before they cause gross disease. Early detection of high blood pressure, before it causes kidney damage, strokes, etc., might be another example of monitoring target systems for early warning of damage to the individual.

5.2. *Ecosystem risk factors*

The identification of individuals at risk for certain types of diseases, e.g., coronary disease, shifts attention from treating illness to prevention. A macroeconomic study of disease prevention in the United States implicated a number of factors, including smoking, diet, occupational hazards, drug abuse, and air and water pollution, as contributing causes to cardiovascular diseases and malignant neoplasms (Gori & Richter, 1978). Some of these results were obtained by following a large cohort of individuals with different lifestyles. Applying similar methods to ecosystems is more difficult, for ecosystems seldom come in cohorts. However, in some situations, the presence or absence of threats which are known to cause ecosystem breakdown coupled with an evaluation of inherent susceptibilities provides useful information on the potential for ecosystem breakdown.

Naturally, this approach works best where a single dominant stress acts to transform ecosystems, such as may occur in the process of eutrophication or acidification of aquatic ecosystems. Much is known about the actions of these two stresses and the vulnerabilities of the recipient aquatic systems (e.g., Vollenweider, 1968; Schindler, 1988; Schindler *et al.*, 1985; Minns *et al.*, 1990). Combining the findings from case studies of impacts of such specific stresses on ecosystems with the knowledge of current stress loadings and sensitivities of recipient ecosystems enables one to arrive at an ecosystem level risk assessment. The development of various factor analyses similar to the manner in which risks of coronary disease are now assessed, is already well underway in ecosystem health evaluations.

Minns *et al.* (1990), for example, have examined the impact of acid precipitation on the loss of fish species in vulnerable eastern Canadian lakes. Such studies, based on statistical correlations between species richness and levels of acidity, require a large sample size. In their study, hundreds of lakes provided the data base upon which to assess the previous impacts of acidity on fish species richness and upon which to project future threats to community integrity from further acidification. There appears much scope here for further studies of other major stresses to aquatic ecosystem integrity, both singly and in combination. The key limitation is one of obtaining the appropriate sample size upon which to base statistical analyses.

5.3. *Validation of treatment*

Validation of treatment is really the bottom line for medical practitioners. That is, following the conventional bio-medical model, once an illness has been diagnosed, the question turns squarely to the most effective treatment. While the diagnosis and treatment of ills remains, as I have earlier stated, more of a conjectural art than a science (particularly within psychiatry and psychotherapy) the need remains to select treatments with the highest likelihood of success. Treatment validation provides a basis for selection among alternative procedures. For example, in evaluating alternative treatments for certain types of cancer (e.g., breast cancer) doctors take into account 5-year posttreatment survival rates. Similarly, in assessing various surgical options for hernia repair, surgeons rely on statistical assessments of previous success rates under alternative procedures (in this case the percentage of patients not requiring follow-up operations).

In comparing medical case histories, and evaluating the success of treatment, it is crucial to take co-morbidity into account. Co-morbidity refers to the negative impacts on effectiveness of treatment for a particular disease should the patient have other health problems. For example, in comparing success rates for various surgical procedures, one should not average results obtained from patients who are otherwise in excellent health with results from patients that are suffering from chronic illness such as cancer, asthma, diabetes, etc. Such complicating factors naturally tend to reduce the success rates of most treatment procedures.

Similarly for ecosystems, in which an observed condition is brought about by a variety of co-dominant stresses, success rates for a given treatment cannot be evaluated without factoring out the influences of the other stress factors. For example, in evaluating the effectiveness of harvesting regulations on restoring seal populations in the Baltic Sea, it is necessary to take into account impairments to seal reproductive success owing to the presence of PCBs and related toxic substances (Helle *et al.*, 1976). Here, just as in human medicine, we have the need to develop methodologies to factor out co-morbidities.

This requires at the outset a far better taxonomy of ecosystem ills than we presently have. One currently may describe ecosystem pathologies in terms of air pollution damage to forests, eutrophication of aquatic systems, acidification of aquatic and terrestrial systems, etc. These are very rudimentary categories. For each of these classifications there are many finer subdivisions which need to be categorized before one can readily compare case histories. For example, with respect to air pollution and its impacts on forests, it ought to be possible to establish a fine-grained taxonomy which considers various ways in which toxic substances affect forest canopy structure. This should no doubt involve both ‘splitting’ and ‘lumping’ with respect to the modes of actions of particular sources of pollution on plant physiology and ecosystem structure (Woodwell, 1970).

Validating treatment requires data concerning risks that various interventions pose to the health of the patient. Risks posed by so-called ‘side-effects’ may take years, if not decades, to develop. For example, some decades back, it was commonplace to treat skin blemishes (acne) with radiation. Some quarter of a century later it was discovered that the ‘cure’ was far worse than the disease, in that a significantly higher incidence of thyroid cancer manifested itself in individuals that had undergone radiation treatments.

Remedial actions designed to restore ecosystem health run similar risks. With hindsight, we know, for example, that efforts to control a forest insect pest, the spruce budworm, with pesticides, led perversely to an intensification and prolonging of the infestation (Holling, 1985). This occurred because the pesticides not only killed budworm but also destroyed or weakened the natural predators of the budworm.

6. Reporting on the state of environment from an ecosystem health perspective

For the past several decades, various countries have made attempts to provide a statistical overview of the health of their environment. The first Canadian State of Environment Report (Bird & Rapport, 1986) was somewhat unique among these efforts in that it adopted a holistic ecosystem perspective, rather than the more conventional approach of treating air, water, and land as isolated entities. The Canadian approach is best illustrated by taking a terrestrial example.

For purposes of analysis, Canada was subdivided into 15 ecozones, defined on the basis of physiography, vegetation type, soils/surface materials, climate, and human use. The forests of most ecozones are impacted by a combination of natural and cultural stresses (particularly in the Montaine Cordillera, Boreal Shield, and Atlantic Maritime ecozones). These stresses include fire, insects and diseases, over-harvesting, conversion of forests to agriculture, construction of transportation and utility corridors, air pollution, and climate-induced stresses such as redbelt and windthrow. Documentation of these stresses at a generic level pose little difficulty. However, quantification has proven more difficult, owing to the lack of systematically collected data for such purposes (but see Statistics Canada, 1986). On the response side, several surrogates for indicators of ecosystems distress were readily available from existing data bases. Among the more interesting were series documenting changes over time in disease prevalence (particularly in spruce budworm) and the area of once forested lands that did not recover sufficiently after disturbance caused by either fire, harvesting, insect damage or other stresses.

Disease, being a natural occurrence in most ecosystems, is known to increase in prevalence in stressed systems (Rapport *et al.*, 1985; Rapport, 1989b). It was thus fortunate that there exists a 70-year record of areas impacted by moderate or severe infestation of spruce budworm, for this long time series shows a definite trend. From 1910 to 1980 there were three major episodes of spruce budworm outbreak. Each outbreak was separated by approximately 30 years (roughly the time required for the regeneration of spruce and fir, the main species consumed by budworm). The area of infestation increased during successive outbreaks from approximately 12 million hectares at the peak of the 1910—20 outbreak to approximately 55 million hectares at the peak of the 1975 outbreak. Ironically, one of the reasons for this is the failure of efforts to control budworm by pesticides, which, owing to their non-selective nature (they depressed the budworm's natural predators more than the budworm) had the effect of spreading and prolonging the duration of acute infestation.

Failure of an ecosystem to recover after disturbance, which I have referred to elsewhere as a loss of counteractive capacity (Rapport, 1989b), provides a clear indication of ecosystem dysfunction. A surprisingly large area of once healthy forested land in Canada is now classified as Not Sufficiently Restocked (NSR). In 1981, the latest figures available, 22.6 million hectares were classified as NSR (Bird & Rapport, 1986). Most NSR lands were found in ecozones comprising the Boreal forest. The NSR lands represented over 5 percent of total productive forest lands of Canada.

The NSR figures do not tell the whole story. In part they understate the extent of the problem by primarily focusing on areas replanted or stocked, while areas where natural regeneration is taking place may not be classified. In part they may overestimate the problem to the extent that tracts that no longer bear preferred species (but reflect healthy regeneration) may be classified NSR. Despite these biases which may offset each other to some extent, one may conclude that there has been a considerable erosion of ecological capital in terms of once productive forested lands.

Other sections of the 1986 Canadian State of Environment Report relate to aquatic ecosystems, both the Laurentian Great Lakes and other Inland Waters, as well as the three marine systems (Atlantic, Pacific and Northern). Major stresses affecting these ecosystems include: over-harvesting, construction of dams and diversions, contaminants (including toxic substances), and the purposeful or accidental introduction of exotic species (particularly in the Great Lakes and inland waters). Further, in all but the Northern marine ecosystems, land use change (particularly the drainage of wetlands for agricultural and recreational purposes) and sewage inflows added significant additional stress.

The response of these large aquatic systems to stress from human activity is best documented for the Laurentian Lower Great Lakes. Here one can safely infer that phosphorus concentrations were vastly elevated in the 1960s compared with historic (pre-human settlement) levels, but have fallen somewhat over the past 15 years owing to effective controls of loadings (GLWQA, 1987). However, in both Lake Erie and Lake Ontario phosphorus concentrations remain well above historic levels (Bird & Rapport, 1986). Further, in both the Lower Great Lakes, there have been wholesale shifts in the composition of the fish community to favour exotic, shorter-lived opportunistic species (Rapport, 1983). Reproductive failures in waterfowl and fish are also commonplace, and an increased prevalence of tumors and other diseases in fish and wildlife have been reported. Collectively, these symptoms of ecosystem distress suggest that the Great Lakes is far from a healthy ecosystem despite progress in some highly targeted areas (e.g., the elimination or reduction of selected toxic substances). In many respects, the Baltic Sea provides a very similar case history with numerous symptoms of ecosystem distress owing to a combination of cultural eutrophication, toxic substances, and physical restructuring of many bays and estuaries. (Harris *et al.*, 1988; Rapport, 1989a).

7. Summary and conclusion

While it is indisputable that ecosystem behaviour under stress is complex and processes leading to degradation and recovery are only partially understood, nonetheless, ecosystem medicine is coming of age at least as a conjectural art. There remains, however, innumerable challenges. In the present paper I have underscored that the enterprise necessarily has inherent subjective elements, and that a combination of objective and subjective criteria are called into play in rendering judgements as to the health of ecosystems.

To the extent objectivity enters in, there is an emerging consensus as to some of the key features enabling one to distinguish healthy ecosystems, undergoing normal fluctuations, from unhealthy ecosystems which have been crippled by stress from anthropogenic sources (Rapport & Regier, 1992). The presence or absence of symptoms of ecosystem distress provides a useful starting point for assessing health at the ecosystem level (Rapport, 1989b). Further, monitoring populations of sensitive species (Ryder & Edwards, 1985) in some cases can provide early warning of ecosystem breakdown. The development of forecasting and backcasting models relating the vulnerabilities of particular ecosystems to various stresses has proved useful in identifying ecosystems at risk from certain kinds of stress. Further work along these various lines will advance the development of a macro-level health perspectives on the state of environment.

One may argue (in my view, correctly) that many present practices in assessing ecosystem health have occurred without the need to borrow concepts from medical sciences. Even the very concept of ecosystem health does not depend on an explicit reference to medicine. However, one may as easily argue that the use of the metaphor suggests more systematic approaches to the diagnosis and treatment of ecosystem ills, underscores the importance of validation of remedial action interventions, and draws attention to the inherent subjective nature of health assessments. Further, the metaphor provides a language in which the concern for ecosystem health becomes a natural extension of the concern for individual health.

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