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Restoring the health of the earth's ecosystems: A new challenge for the earth sciences

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Ecosystem Health takes the health concept to a new dimension. Traditionally the concept of health has been restricted to individuals and populations. However, it has become apparent that ecosystems also can become dysfunctional, particularly under stress from human activity. The International Society for Ecosystem Health has provided a forum for the evolution of methods of assessing ecosystem health, and for applications to environmental management. This emerging field requires collaboration from many areas, including importantly, the earth sciences. In this paper we articulate the concept of ecosystem health, review the history of the International Society, and illustrate the role of the earth sciences in ecosystem rehabilitation with a case study from Ostrobothnia, western Finland. Several of the rivers in the region suffer from acidification due to drainage and other alteration of sulphide rich soils. The study illustrates how limited areas with special geochemical characteristics can dominate the health of large systems.

Introduction

When it comes to assessing the health of natural systems, intuition is often an unreliable guide. To be sure, the most severely degraded ecosystems are easily recognised, e.g. the "moonscape" landscape that was created downwind of the smelter activity at Sudbury, Ontario (Gunn 1995). However, when it comes to the early stages of ecosystem degradation, intuition is often misleading. Emissions of toxic substances, particularly at sub-lethal levels does not immediately "register" in changes in the ecosystem, and often goes unnoticed until the long term effects are manifest in human and animal pathology and other deleterious changes; subtle alterations in the composition of fauna and flora may well signal the early stages of ecosystem degradation in regions subject to multiple stresses from human activity — but here too, unless there are obvious human health or economic consequences, this may not be a cause for public concern. Yet, by the time that ecosystem pathology becomes obvious it may be impossible to reverse (Rapport and Whitford, 1999).

It is within this setting, that ecosystem health has emerged as a transdisciplinary science (Rapport 1995a). And although the field is in its early stages of evolution (Rapport et al., 1999a), it has articulated methods of analysis, and illuminated the relationships between human activity, the state of ecosystems, and human consequences (Rapport et al., 1998a).

Ecosystem health is a new frontier which integrates ecology, economics, health sciences and many other fields by extending the

notion of "health" from a traditional focus at the level of the individual (clinical medicine) and the population (population medicine/public health) to the functions and structure of the ecosystem as a whole. What has emerged is a new vision of human interaction and integration within nature and a methodology that bridges human values and natural system function (Rapport, 1995b and 1995c; Rapport et al., 1999b). In a nutshell, ecosystem health brings into view a new perspective on nature and sets new goals for environmental management.

In this paper, we review the concept of ecosystem health, the motivation for the formation of the International Society for Ecosystem Health, and illustrate the relevance of ecosystem health to the earth sciences through a case study.

The concept of ecosystem health

The development of a set of new principles that effectively integrates the concepts of "health" and "ecosystem" brings into play both "subjective" and "objective" elements. Health assessments, whether they focus on the individual, population, or ecosystem, necessarily involves an element of subjectivity, for what is "healthy" depends in part upon human values and goals. When it comes to ecosystem health, the relevant values and goals are those of the human community (Rapport et al., 1998b) whose lives and livelihoods are dependent on the condition of the ecosystem. Healthy ecosystems are supportive of economic, social, health, spiritual, aesthetic, and other needs of the community.

The "objective" aspect of the assessment lies in the determination of the state or condition of the ecosystem—as measured by a host of indicators, including primary productivity, nutrient transport, biodiversity, community structure, disease burdens in human and non-human populations, economic activity, etc. Progressively over the past 10,000 years, from the time when agriculture became a permanent feature of the landscape, human activity has increasingly "disabled" ecosystem functions to the degree that many ecosystems have lost their capacity for supplying renewable resources on a sustainable basis (Vitousek et al., 1997; McMichael et al., 1999).

Ecosystem health, both as a concept and an emerging practice can trace its earliest history to seminal ideas in the writings of the famous Scottish geologist, James Hutton (1788) who developed the concept of the earth as an integrated system. It also finds its roots in the writings of the 1940s naturalist, Aldo Leopold (Callicott, 1992). Publications in the late 1970s, early 1980s (Rapport et al., 1979 and 1981) provided fresh perspectives along similar lines and mapped out the great similarities between diagnostic challenges at the level of the individual and the whole ecosystem. The term "Ecosystem Medicine" was coined to describe this new area of investigation (Rapport et al., 1979). Later this evolved into principals and concepts of ecosystem health (Schaeffer et al., 1988; Rapport, 1989).

During the same period and subsequently, advances have been made in the development of methods to measure the health, specifically the biological condition of aquatic ecosystems, and to use that knowledge to diagnose causes of degradation (Karr et al., 1986;

Fausch et al., 1990; Karr, 1993; Karr and Chu, 1995). Those methods have now been applied to assess the condition of aquatic systems and their terrestrial landscapes throughout the world (e.g., Roth et al., 1996; Simon, 1999).

While the concept of ecosystem health has come into widespread use and has formed the foundation for several regional, national and international environmental management programs (Rapport et al., 1995), there continues to be a lively debate as to its meaning and significance (e.g. Calow, 1992; Suter, 1993; Wilkins, 1999; Rapport et al., 1999b). Some critics have argued, for example, that ecosystems do not exist as definable bounded entities and therefore reference to ecosystem functions (which are key indicators in ecosystem health assessments) have no grounding in reality. However, widespread use of the ecosystem concept as a basis for regional environmental analysis (e.g., Chadwick et al., 1999) would refute this claim. Critics have also argued that the concept of "health" has no validity beyond the level of the individual. However, if this were true, it would be delegitimise public health as we know it in relation to human communities and populations. In so doing it would discount many of the now recognised supra-individual influences on human health (McMichael et al., 1999). In general, those that object to the concept of ecosystem health appear to fail to recognise that humans are part of the ecosystem (Bormann, 1996; Rapport et al., 1999a), nor do they recognise that ecosystem services have become seriously impaired under the influence of human activity. Such impairments have resulted in many cases of significantly altered nutrient cycling, primary productivity, biodiversity, changes in trophic organisation and dynamics, increased incidence of disease, and other signs (Rapport et al., 1985; Karr, 1999).

As to the definition of ecosystem health, most proposals share common elements (Rapport, 1995a). Costanza (1992) suggests: "An ecological system is healthy and free from "distress syndrome" if it is stable and sustainable—that is, if it is active and maintains its organisation, and autonomy over time and is resilient to stress". Mageau et al. (1995) suggests that ecosystem health be assessed in terms of three major ecosystem attributes: Vigour (productivity), Organisation, and Resilience. Karr (1999) suggests that simple and direct biological measures of ecosystem condition are more convincing than more elusive system properties and suffice to demonstrate the extent to which human actions have degraded living systems.

It remains a matter of debate as to whether ecosystem health should be considered by itself as a scientific discipline (perhaps within a transdisciplinary framework) or whether it should be considered as a practice that draws upon existing disciplines. On the one hand, it may be argued that ecosystem health is an umbrella field drawing upon the specialized knowledge of other disciplines and putting this knowledge to use in practical ways. On the other hand, it may be argued that ecosystem health is transdisciplinary in nature and is providing new methods and concepts that shed light on the interrelations between human activity, ecological change, ecosystem services and economic and human health risks (Rapport et al., 1998a).

The early history of the International Society for Ecosystem Health

The International Society for Ecosystem Health (ISEH) came into existence at a time when it became all too clear that the earth's ecosystems were failing, both locally and globally. It was 1992, twenty years after the Stockholm conference on the environment, and despite all the pledges made on that historic occasion, the earth's ecosystems were becoming more and more degraded (Tolba et al., 1992). ISEH was conceived as an organization that would engage scholars from a variety of fields to chart a new path and to provide an integrated science basis for managing the health of the earth's ecosystems.

The 1st International Symposium on Ecosystem Health and Medicine (Ottawa, Ontario, Canada) was held in June of 1994. The opening Keynote Address was delivered by the late Henry Kendall (a Nobel Prize Laureate in Physics and the founding president of the Union of Concerned Scientists). Collectively, participants represented a wide range of disciplines including anthropology, economics, ecology, environmental management, epidemiology, ethics, law, philosophy, public health, sociology, and veterinary medicine. Although participants came from varied backgrounds, a shared belief emerged that collaborative efforts were likely to yield a deeper understanding of regional environmental challenges (Shrader-Frechette, 1994). Understanding the forces of transformation of the earth's ecosystems clearly requires an integrative approach drawing upon the natural, social, and health sciences, in which humans are considered as "part of" and not "apart from" the ecosystem (Cairns, 1994; Bormann, 1996).

One of the major goals of ISEH is to encourage understanding of the critical linkages between human activity, ecological change and human health (Cairns, 1997; Rapport et al., 1998a and 1998b; McMichael et al., 1999; Rapport and Whitford, 1999). This involves the development of methods of assessing the degree to which the functions of complex ecosystems are maintained or impaired by human activity. It also involves formulating new strategies which take account of societal values and bio-physical realities to manage human activities so that ecosystem health is enhanced and not compromised further (Farnsworth, 1995; Vitousek et al., 1997; Gaudet et al., 1997; Cairns, 1998).

The following general tendencies in the evolution of the concept of ecosystem health and ISEH have been noted (Rapport et al., 1999a).

1. A progression in the discourse from arguments that initially were largely philosophical in content (e.g., ecosystem health as a societal goal; ecosystem health as a metaphor (e.g., Costanza et al., 1992) to questions of quantitative methods of assessment at a variety of scales, e.g., indicators of ecosystem health using ecological, public health and socio-economic data) (e.g., Johnson and Patil, 1998)
2. A progression from consideration of how human activity impacts the biophysical functions of ecosystems to complex representations wherein ecological change is shown to be a prime determinant of human health and economic viability. This requires taking into account societal inputs and or impacts and public health components (Levins et al., 1994). Paramount here is increasing recognition given to the role that human values play in the system (Gaudet et al., 1997; Salim and Ullsten, 1999; Ullsten, 1998; van Ierland et al., 1998).
3. A development of practical applications of the concept to concrete cases moving from the identification of problems towards developing rehabilitation and restoration (Rapport et al., 1998c). This conceptual development has been reflected in the development of innovative curricula in medicine, veterinary medicine and public health.
4. A growing interest by international societies is having ISEH co-sponsor their events. ISEH has participated in a number of international symposia sponsored by academic societies. These have included meetings of: The Soil Science Society of America (St. Louis, Missouri 1996), The American Phytopathological Society (Rochester, NY, 1997), The International Society for Ecological Economics (Santiago, Chile, 1998), The European Union of Geological Sciences (Strasbourg, France 1999) and the upcoming 31st Congress of The International Union of Geological Sciences (Rio, Brazil 2000).
5. The development of curricula in ecosystem health in professional schools. In Canada, and in the USA, programs in ecosystem health have been initiated in veterinary colleges and within a major medical school. In Canada, for example, an elective field course in ecosystem health has been offered jointly by all four veterinary colleges since 1994 (Ribble et al., 1997). These offerings were partly in response to the recognition that ecosystem health was a logical context for veterinary medicine to address

health issues involving non-domestic species (Nielsen, 1992). The veterinary ecosystem health program engages students in problem solving real cases in an ecosystem health context; for example, urban wildlife problems, lead pollution of marshes, agricultural pollution of estuaries, sour gas leaks in oil fields, etc. At each site, a problem or set of problems are identified, and students begin to seek solutions by applying their veterinary skills. They soon recognise, however, that the solution is embedded in a wider circle of expertise and interests. This experience provided "fast track" learning as to the relevance of ecosystem health to the health of domestic animals, wildlife, and people.

6. In recent years, both schools of public health and schools of medicine, have initiated teaching programs on ecosystem health topics. Within the Faculty of Medicine and Dentistry at The University of Western Ontario (London, Ontario, Canada) for example, ecosystem health topics have been introduced into the first, second and fourth years of under-graduate medicine. Students in the fourth year course are exposed to a variety of case studies (e.g., asthma, ozone depletion, changing distribution of vector borne diseases, antibiotic resistance). Students actively participate in the development of the case materials. Within Schools of Public Health (e.g., Harvard School of Public Health, and Johns Hopkins School of Public Health) programs on climate change and infectious diseases, as well as other aspects of regional ecosystem health have been introduced. In the spring of 1999, a workshop organized by the Center for Conservation Medicine (a newly established environmental health collaborative between Tufts University School of Veterinary Medicine, Harvard Medical School's Center for Health and the Global Environment, and Wildlife Preservation Trust International) was held at White Oak Conservation Center (near Jacksonville, Florida). The workshop explored the potential for integration between the fields of Conservation Biology and Medicine.
7. Initiation of national and international programs in ecosystem health. The International Development Research Centre (IDRC) in Canada has an ongoing program in ecosystem health with a focus on the human health impacts of ecological change. IDRC now sponsors research in this area in a number of developing countries. The United States Department of Agriculture (USDA) Natural Resource Conservation Service has initiated a program in "Rangeland Health" that incorporates the biological, social, economic, anthropological, and human health aspects of ecosystem health. That program was initiated by a workshop held in Las Cruces (in early 1999) on integrating what is known about ecosystem health into a comprehensible framework that can be made available to resource managers and users. The workshop also considered applications of Geographic Information Systems to assessing, monitoring and recovering ecosystem health.

An illustrative case study: Acidification in Ostrobothnia in Western Finland

An important feature of ecosystem health assessments is that they are highly contextual. While common behaviors under stress have been demonstrated among very different types of ecosystems (Rapport et al., 1985; Rapport and Whitford, 1999), it has also been shown that there are also unique features that are contextually determined (Hildén and Rapport, 1993; Huq and Colwell, 1996; Kevan et al., 1997; Yazvenko and Rapport, 1997; Buckingham, 1998; Kevan and Belaousoff, 1998; Karr and Chu 1999). In all cases one encounters the general properties of complex systems; i.e., non-linearity, positive and negative feedback loops, the interplay of societal values with bio-physical change, uncertainty, and mutual causality (Levins, 1995).

To illustrate the range of considerations, we examine, as a case study, the evolving situation regarding the acidification of Ostrobothnian rivers (a region containing several catchments which are

located on the eastern shore of the Gulf of Bothnia) (Figure 1). This area has a long history of human settlements and signs of ecosystem degradation have been apparent for many decades in several major river and estuarine systems. This case study focuses on the attempts that have been made to rehabilitate these systems and the role of the earth sciences in developing methods to reduce the acidification damage to the receiving waters.

The geological conditions in Ostrobothnia: We focus our interest on the middle part of Ostrobothnia in western Finland, with the River Kyrönjoki, the largest catchment in the area, and the River Lestijoki (Figure 1). One peculiar feature of the Ostrobothnian catchments affecting their health status is the abundance of acid sulphate soils.

The acid sulphate (AS) soils: Sulphide-rich sediment soils are abundant worldwide (Brinkman, 1982). Soils with very high sulphur contents are generally referred to as acid sulphate or AS soils but they can have different origins. In the Baltic Sea area they originate from marine sediments that were deposited during the early stages of the Litorina Sea, 7600–5800 B.P. This was an exceptionally warm period in the history of the Baltic Sea, characterised by high sulphate concentrations, a large supply of organic material and the existence of dissolved iron. The conditions yielded anaerobic sediments with extensive formation of iron sulphides in contrast with early post-glacial freshwater clays, which are poor in sulphides.

Finnish AS soils contain about 1 % sulphide, although as high amounts as 3.5 % have been measured (Palko, 1994). Under anaerobic conditions sulphide soils are more or less neutral. Acidification occurs as a consequence of aeration when the ground water is lowered due to land uplift and subsequent drainage. The exposure to atmospheric oxygen initiates a gradually accelerating microbially catalysed oxidation of the sulphide minerals. The oxidation process is composed of several intermediate steps and releases large amounts of acidity, metal cations and sulphates to the soil and the soil water. Existing soil buffering systems, such as cation exchange and silicate weathering, are generally unable to neutralise the acidity, which leads to a dramatic drop in both soil and drainage water pH. Typical drainage waters from acid sulphate soils are furthermore characterised by very high concentrations of toxic metal cations such as

Figure 1 The catchment areas of Middle Ostrobothnia.

aluminium. Such waters will inevitably lead to ecological damage in the recipients.

The quantity of acidity that is released as a consequence of the oxidation of the sulphide minerals is a function of the sulphide contents. A 10 cm lowering of the water table releases theoretically 625 keq acidity per hectare for each percent of sulphide that is oxidized. This can be compared to an annual load of 0.2 keq acidity per hectare due to acid rain (Palko and Wepppling, 1994).

The acid sulphate soils are particularly abundant in Ostrobothnia. Flat, fine-textured soil areas below the past Litorina Sea level combined with a relatively rapid land uplift of 0.4 to 0.9 m per century has created suitable conditions for the formation of acid soils. The total extent of acid sulphate soils in Finland has been estimated to be 3360 km², of which nearly 2500 km² is found in Ostrobothnia (Puustinen and Palko, 1991).

The state of the catchments: A superficial view of many of the Ostrobothnian catchments would suggest relatively slow flowing, silty, humic and nutrient rich rivers, especially in the lower reaches. Typical features would be extensive reed belts in the estuaries, a fish fauna dominated by cyprinids (i.e. minnows that thrive in disturbed and nutrient rich habitats) and large populations of ducks, waders and gulls. This is the picture that suggests itself from aerial photographs of the Kyrönjoki. The acid sulphate soils make the picture more complex.

A large part of the acid sulphate soils have been cultivated and are thus drained. Much of the drainage is nowadays based on the use of subsurface drainage, which significantly speeds up the oxidation process and the release of acidity in and from the soil. In areas exposed to recurrent flooding, the drainage has been concentrated to and intensified by pumping stations. In some areas pumping is necessary, because dykes have been constructed along the river banks in the Kyrönjoki to reduce the risk of flooding. In these areas the water table is kept at a suitable level by pumping. The drainage water can be very acidic, in some cases pH levels of around 3 have been observed (Hildén and Hirvi, 1987; Wepppling, 1993). Sulphide clays have also been exposed to oxidation during historical times when lakes have been lowered and the river beds have been altered in water development activities (Hildén and Rapport, 1993).

The soils and bedrocks of the catchments give the waters low buffering capacity (alkalinity) (Edén and Björklund, 1993). Thus the acidic drainage water from sulphate soils causes pH levels to drop rapidly. If the amount of AS soils in the catchment is high, the drainage water can cause the pH of the down stream river water to fall below 5. In addition the run off regularly contains high levels of metals, including toxic concentrations of aluminium (Wepppling, 1993; Palko, 1994). The acidification of the river water is not constant. It follows an annual cycle with high levels of acidity generally observed towards the end of the snow smelt in May and during heavy autumn rains.

The presence of the acid sulphate soils and the temporary acidification mean that health of the river system is disturbed in a rather peculiar way. For example, despite an abundance of epiphytic algae in the estuarine areas, rivers that occasionally become acidified are devoid of snails and other molluscs. The fish fauna, which in nutrient rich low land rivers tend to be dominated by cyprinids, is impoverished because many cyprinids are sensitive to acidification (Braekke, 1976). The crayfish, which has thrived in many Ostrobothnian rivers as a successful introduced species, can only live in the upper reaches of the rivers, which do not become acidified.

The easiest observable effects of the acidifications have been those that have hit the fisheries. Fish kills have occurred with 50-100 tonnes of dead fish in the Kyrönjoki and severe losses of reproductive capacity (Hildén and Rapport, 1993; Hudd and Leskelä, 1998; Kjellman, 1999). The losses have been economic, but they have also altered the structure of the fish fauna due to differences in the sensitivity of different species and differences in the spawning and nursery areas. The burbot, *Lota lota* L., is a prime example of a sensitive

species since its reproductive areas are concentrated in areas influenced by the rivers and the hatching time in spring coincides with periods of high acidity in the river water (Kjellman, 1999).

Rehabilitation and decision making: Water quality in many Ostrobothnian rivers is generally worse than in other regions in Finland, and "poor" conditions are not uncommon (Rautio and Ilvesalo, 1998). The development of strategies for rehabilitation awaited, however, an acceptance of the causes of deterioration of the region's rivers, estuaries and coastal waters. The hazardous impacts of acid sulphate soils on aquatic ecosystems were officially recognised only relatively recently, although the problem of acid soils had been described in the 1920s (Hudd and Leskelä, 1998). In the 1970s spectacular fish kills in a fresh water reservoir in SW Finland and at the lower reaches of river Kyrönjoki were linked to the drainage of surrounding acid sulphate soils (National Board of Waters, 1973).

Rehabilitation activities in Ostrobothnia have focused on the health of the rivers. It is now abundantly clear that the health of the rivers is not only a question of conditions in the aquatic systems, but of conditions in the entire drainage (catchment). Therefore, measures to restore the health cannot be restricted to the traditional measures of reducing waste water inputs. The key problems of the rivers, nutrient and acid loading, are largely the result of land use in the catchment (Hildén and Rapport, 1993; Rautio and Ilvesalo, 1998). Thus the decisions that will have the strongest impact on the future state of health of the Ostrobothnian rivers are those related to drainage activities, land use patterns and agricultural practices.

The efforts to rehabilitate the catchments can be classified in three interrelated groups:

1. Actions to reduce loads of acidity and nutrients to the rivers (Wepppling, 1997);
2. Actions to rehabilitate the biota of the rivers; these activities, which often involve stocking of fish fauna and crayfish, are conditional on first re-establishing acceptable water quality;
3. Actions to restore particular features of the landscape (e.g. forests in the catchment), but which do not directly affect water quality.

The overall strategy is to implement the set of actions that are most likely to result in successful rehabilitation of the river systems of the region. For each action or combination of measures earth sciences play an important role, although the level of detail will vary. The most detailed information is required for activities aiming directly at reducing acidity in the rivers, for which there are several potential measures that can be used (Figure 2).

Figure 2 The use of different kinds of earth sciences information in rehabilitation.

Empirical results of mitigation and rehabilitation in the Lestijoki: The Life Lestijoki - project (Wepppling and Innanen, 1999), a full scale demonstrative restoration project partly financed by the European Union, illustrates one of the attempts to solve the acidification problem. A key observation is that the location and classification of acid sulphate soils in the catchment is vital independently of rehabilitation methods and strategies.

The main objective of Life Lestijoki was to demonstrate the capacity of a new drainage technique, the lime filter drainage, in preventing or at least reducing acidity surges in the recipient when applied on a catchment scale.

(i) **Soil surveys:** The project started with a comprehensive soil survey in order to localize the acid sulphate soils in the catchment, to determine their acidity potential and to define the boundaries of future drainage operations. The main soil type in the Lestijoki catchment is coarse silt, although some fine grained sediments were observed near the river mouth. One fifth of the cultivated soils in the uppermost part of the survey area were sand or sandy loam.

The soil survey showed, that almost 60% of the cultivated soils in the lower parts of the Lestijoki catchment were AS soils ($pH_{min} < 4.5$). The lowest pH_{min} value in the studied soil profiles was as low as 2.68. The survey also demonstrated that there is substantial variation in the soil characteristics and that it would be unwise to use average data when planning concrete measures (Figure 3).

The subcatchment of Kinarehenoja ($F=56 \text{ km}^2$) on the northern side of river Lestijoki was found to be the best choice for the experimental construction for several reasons: The cultivated soils in the catchment were most acidic, water quality monitoring data was available, water acidity was high, acidic soils were located in appropriate clusters and the farmers were co-operative. Kinarehenoja is a brook with a catchment containing 12.5% cultivated soils, about 28.5% forests and about 59% low standing crop or peat soils. The

cultivated fields are located along the central and lower reaches of the brook.

The construction area was selected on the basis of a second soil survey to cover most of the acid fields in the central part of the catchment. The field amount in this area was 113 ha. Almost 80% of the studied fields in the Kinarehenoja subcatchment were found to be AS soils. The soils in the area were extremely acid, the lowest pH_{min} value being as low as 2.52. The average pH_{min} for AS soils was 3.62 and for non-AS soils 4.65. The drainage condition, as indicated by soil CDD, was poor or moderate (Table 1).

Table 1 Soil survey results from the Kinarehenoja subcatchment. (AS=acid sulphate soil, CDD=chemical drainage depth).

	AS soils	Non-AS soils
Drilling sites	35	8
Average pH_{min}	3.62	4.65
Average CDD (m)	1.39	1.29
Total field area (ha)	89.7	23.3

A considerable part of the area (74%) was already in subsurface drains when the project started. New lime filter drains were built in October 1997 on fields with open drainage as well as on fields with an existing subsurface drainage. The total amount of lime filter drains was 32 185 m covering a field area of 92.5 hectares, which was about 82% of the cultivated fields in the studied area.

(ii) **Water quality:** Water quality was monitored before and after the drainage construction. Samples were taken from drainage pipe outlets as well as from the brook. The monitoring, which started in autumn 1996, was concentrated to flood periods, i.e. two month periods during spring and autumn.

Runoff water samples were taken twice in spring and twice in autumn 1998 from 48 different pipe outlets connected to lime filter drainage. Simultaneous sampling was made from 15 pipe outlets from the parallel old subsurface drainage system. Titratable acidity, pH and several other components were measured from each sample. The runoff acidity data between new lime filter drains and old subsurface drains were compared.

Water samples were taken twice a week from 3 sampling sites in brook Kinarehenoja. The first sampling station was situated above, the second in the middle and the third station below the construction area. Titratable acidity, pH and electrical conductivity as well as iron, manganese and aluminium contents were measured from each sample. The data from the sampling sites was compared to each other in order to evaluate the effects of the construction on brook water quality.

Daily discharge was measured at the brook outlet in order to obtain calibration data for a hydrological submodel, which was used in a dynamic model to calculate the amount of acidity discharging from the catchment.

(iii) **Key results of the lime filter drainage:** Runoff quality data obtained one year after the drainage showed significant differences in runoff pH and acidity between old subsurface drains and new lime filter drains in each of the four samplings (Figure 4).

The significant difference in water quality between drainage waters from lime filter drains and old subsurface drains was not, however, reflected directly in the water quality of brook Kinarehenoja. According to the monitoring results from 1998, the brook water was clearly acidic despite the lime filter drainage. This might seem strange, as the new lime filter drainage covered as much as 80% of all fields in the area. The controversy was explained, when the response of the recipient was analysed on the basis of drainage water quality and simple dilution calculations. The calculations were later verified by a mathematical model developed during the project. The model showed that the acidity below the construction area was expected to increase slightly from the background value. This was, in fact, the case during 1998, when the mean acidity below the con-

Figure 3 Map of Lestijoki, showing distribution of pH minimum.

Figure 4 Difference in acidity between new and old pipes.

struction area was $0.393 \text{ mmol l}^{-1}$ compared to $0.330 \text{ mmol l}^{-1}$ above the area. The calculated acidity for the lower monitoring site ($0.396 \text{ mmol l}^{-1}$) was very close to the measured mean value.

The calculated water acidity was found to reflect the actual situation very closely, when monitoring results from different seasons of the year were evaluated separately (Table 2).

Table 2 Measured and calculated mean acidities 1998 (mmol l^{-1}) at the monitoring sites above and below the construction area.

		above measured	below measured	below calculated
May	(n = 6)	0.32	0.35	0.32
June	(n = 7)	0.29	0.36	0.39
August	(n = 4)	0.41	0.49	0.54
October	(n = 4)	0.34	0.44	0.45
Whole year	(n = 21)	0.330	0.393	0.396

The expected response of different drainage regimes in the recipient waters was evaluated by changing the input values in the calculation. If the study area would have been totally drained into lime filter drains, the mean acidity below the construction would have remained approximately at the background level.

If, on the other hand, the area would have been drained exclusively using ordinary subsurface drains, the mean acidity below the construction area would have risen with almost 50% to 0.56 mmol l^{-1} . This would have a dramatic adverse impact on the health of the recipient waters, in terms of fish kills, loss of key biotic components, etc.

Lime filter drainage is thus a potential method to decrease harmful ecosystem effects caused by drainage projects in catchments containing acid sulphate soils. By this method, the acidity of the recipient water remains low. However to achieve this significant improvement over prevailing water quality, lime filter drains would need to be introduced over a very large area.

Concluding remarks

The rivers of the Ostrobothnia which have been severely impacted by soil acidification demonstrate clearly the importance of specific geological features on ecosystem condition and health. Although the acid sulphate soils are limited, covering some 10–20 percent of the total surface of the catchment (Figure 3), they can have a disproportionate and dominant impact on the state of the system.

One might argue that the catchments of Ostrobothnia are exceptional and therefore do not reveal a general pattern with respect to the health of river systems. However, we would suggest that the case

study shows that geological features can play an important and in this case, a dominant role in determining the state and development of ecological systems, including their susceptibility to human impacts. These features can be related to the geochemistry of the area, topography and soil character. Thus a major task of the earth sciences in the context of ecosystem health is to identify these special features and to provide knowledge on their impact on the whole system. This knowledge is essential in planning the use of catchments and in planning rehabilitation activities (Figure 2).

The implications of localized dominating geological features in Ostrobothnia, i.e., the location of the potentially acid soils, are two fold. First, it is possible to determine critical areas within which human activities should be severely constrained to avoid deleterious change. Second, rehabilitation of whole catchments can achieve visible results faster, if the measures are focused on areas of critical importance. However, as the example of River Lestijoki shows, single measures are rarely sufficient. Some features can be so dominant that even though they cover a limited percentage of the total catchment they can frustrate all attempts at quick fixes. Ecosystem rehabilitation in these and many other cases would thus appear to be a slow process that requires actions at many levels with many different approaches. Each action raises specific demands on relevant knowledge and information. In such cases, the earth sciences provide an important input into the process. Developing collaboration between the sciences and finding relevant information for each type of decision is a challenge in all rehabilitation activities.

Ecosystem Health is becoming a primary societal goal, and a number of agencies (in natural resources, environment and human health) have now introduced major programs in ecosystem health (Rapport et al., 1999a). One can argue, that ecosystem health is the essential condition for human survivability into the 21st century (Rapport et al., 1999b). If the degradation of the earth's ecosystems is to be arrested, one needs knowledge of the ways in which human activity alter ecological systems and the impacts of those alterations of the vital services that these systems provide (e.g. as sources of potable water, renewable resources, breathable air, etc.). Unless ecosystem health is maintained, or restored, there will be no possibility for sustaining economic activity or human health in the very near future (Rapport et al., 1998a and 1998b; Rapport et al., 1999b).

In rehabilitating the earth's ecosystems, the Earth Sciences have a most critical role to play. As well illustrated in the case study, both the analysis and rehabilitation of damaged ecosystems depends on the knowledge of the geochemistry of soils and water in relation to human activity. Collaboration between earth scientists, ecologists, economists, epidemiologists and others, is essential both to understand and mitigate the causes of environmental degradation (Rapport and Whitford, 1999). The urgent task ahead lies in developing improved methodologies for assessing ecosystem health (Rapport et al., 1998a and 1998b). In this a strong participation by the Earth Sciences is needed both to deepen our understanding as to the causes of ecosystem degradation and to suggest strategies for rehabilitation.

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