The dynamics of lake acidification as indicated by a 30 years old conceptual model

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Introduction

The acidification of lakes has been divided into three main processes, atmospheric, terrestrial and limnetic acidification (Grøterud 1981). The lakes used in this investigation are typical soft-water lakes lying in an area underlain by granitic rocks with very shallow overburden, a so-called sensitive area with poor neutralizing capacity of the lakes and their catchments. The rocks are in many places directly covered with lichens, mosses or humic matter with vegetation mats. Therefore, the geological sources of alkalinity are small and other forms of alkalinity produced may also be of importance. One such form is a biologically produced alkalinity by reduction of SO_4 and NO_3 by chemotrophic bacteria or photosynthetic organisms, which use them as nutrients (see Goldman & Brewer 1980, Schindler et al. 1980, Kelly et al. 1982, Kilham 1982). These processes contribute to the maintenance of the acid-neutralizing ability of the lakes, and changes in this mechanism should therefore be of crucial interest in connection with the limnetic contribution to the acidification dynamics.

Conceptual Model

A conceptual model was made as an attempt to approach the dynamics of acidification, by synthesizing the knowledge from many complex phenomenon that, in addition, has demanded comparison of photos from earlier and recent times, interviews and observations not recorded here. The author used the research area for recreational activities since childhood, and is therefore quite familiar with the locality. The model presented in figure 1 is a smaller modification of a previously published model (Grøterud 1987). The boxes depict changes in the ecosystems and the arrows the effects these changes can make. The central box with the increased acidity of the lake water (the final result) is marked with bold letters. The heavy arrows indicate processes of much greater effect than the thin arrows, i.e. the terrestrial and atmospheric contribution to the acidification. The limnetic acidification, on the other hand, consists of many effects, which are weak when considered separately, but not necessarily when combined. Broken arrows denote great uncertainty in evaluation of the effect.

Such a model needs some comments even if many formulations are self-explanatory. It seems pedagogical and practical to start with the acidified lake water (the central box). This is relatively strongly affected by increased acidity of the runoff, which is an integration of increased acidity of the soil and the precipitation, including dry deposition. The change in soil acidity is coupled to change in the vegetation, which again is determined by the cessation of grazing and associated activities (e.g. Rosenqvist 1977, Rosenqvist et al. 1980). The climate may possibly also be of importance in this regard. Changed precipitation pattern and the yearly mean air temperature seems to have increased during the latest years. Important to note is that the increased acidity of the precipitation does not only include strong acids, but also salts of these acids. By contact with the humic matter in the catchments, these salts may produce strong acids by cation exchange with the hydronium ions from the humic acids.

The central box also receives one thin arrow from the precipitation box, which describes the direct acid deposition on the lake surface. In addition, six thin arrows (two broken) lead into the box constituting the limnetic contribution to the acidification dynamics. Five arrows also point out of the same box, indicating feedback mechanisms. One key mechanism in the limnetic acidification is the decreased availability of P in the limnetic ecosystem. This may lead to an oligotrophication of the lakes, which may subsequently result in a decreased lake metabolism rate (see e.g. Grahn et al. 1974, Anderson et al. 1978) with an increased redox potential, especially in the sediments. The reduced availability of phosphorous (P) is related to decreased supply from the catchment through the cessation of waste products from cattle grazing, the human activities connected to grazing and an increased sorption of P by the changed vegetation (which decomposes more slowly). P is possibly also indirectly determined by the assumed increased leaching of iron from the catchment in response to increased acidity of the runoff. This iron may be precipitated with P in the lake. Further, P may be regulated by an interaction between increased acidity and decreased metabolism rate in the lake through an increased sedimentation of humic matter, or possibly by a feedback mechanism acting through an increased re-oxidation of iron during lake turnover. This effect is denoted with great uncertainty because the oxidation feasibility decreases with reduced pH. According to well-known simple experiments, the solubility of humic matter decreases with an increased acidity (see also Gjessing 1976). The decreased metabolism rate may increase the amount of undecomposed humic matter normally exposed for sedimentation. P is incorporated in the lake sediments by adsorption to the sedimenting humic particles and as an inherent part of the humic matter.

The precipitation of FeS in the lake sediments will prevent iron from re-oxidizing when lake turnover occurs (see e.g. Ohle 1955, Grøterud & Hongve 1980, Kelly et al.1982, Cook et al. 1986, Davidson & Finlay 1986). This FeS precipitation also seems to be of importance in preventing the re-oxidation of sulphide to sulphate, which is a direct acidifying process. The precipitation of FeS is affected by two processes, consisting of decreased reduction of sulphate and increased acidity of the lake water, and may consequently be another key factor in the limnetic acidification dynamics. The pH-effect may be involved in a feedback mechanism (solubility curves of FeS calculated for different values of pH and H_2S). However, the supposed long-term production of organic sulphur (S) from the sulphide formed (Rudd et al. 1986) makes the situation somewhat unclear.

Nitrate may also take part directly in the acidifying process by decreased reduction to inactive gasses (N_2) normally escaping to the atmosphere. Indirectly the presence of NO_3 will provide a relatively high redox potential in the lake water, and possibly the sediments, and will prevent SO_4 from being reduced. Consequently, by a continual increase in NO_3 emission and SO_4 reduction, this part of the model will be of growing importance in the future.

Biological changes like fish extinction and a different community structure of the invertebrate fauna in the lake may affect both the metabolism rate and possibly the lake acidity directly by a decreased rate of base release. These changes are induced by the increased leaching of aluminum (Al) from the catchment and the increased acidity of the lake water. In addition, invasion by mosses, fungi and periphytic algae is involved in a feedback process with the acid lake water. This invasion may also be affected by increased transparency in the lakes. Changes in the decomposition of organic acids will possibly

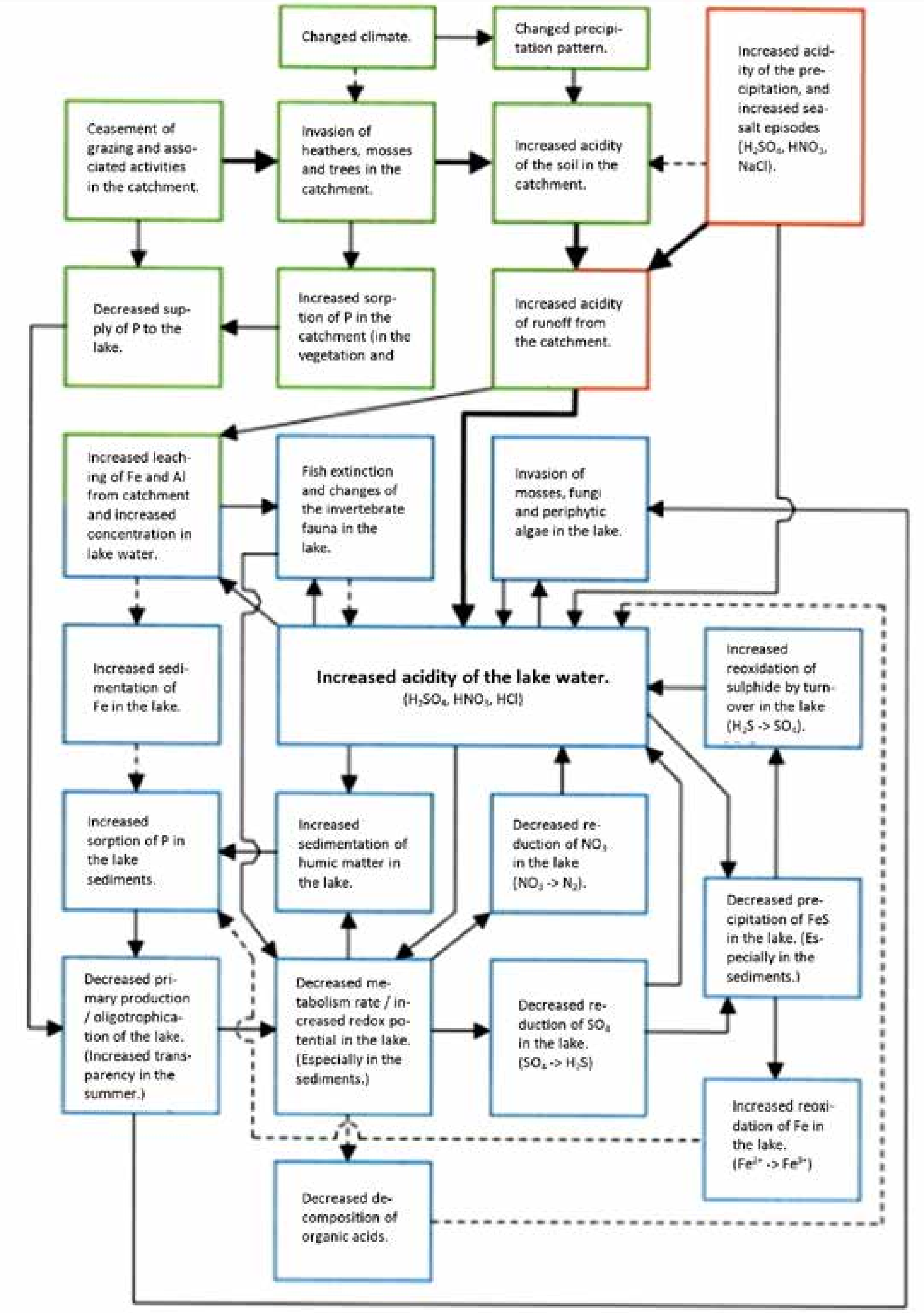

Figure 1. Conceptual model of lake acidification. Bold, thin and broken arrows depict strong, small and uncertain effects respectively. The boxes have three different colors. Red associated with atmospheric, green with terrestrial and blue with limnetic phenomena.

affect lake acidity. However, these complex mechanisms have been ventured in the model as a possible effect.

In general, limnetic acidification with its many possible feedback mechanisms is liable to be less stable than the two other main acidification processes (atmospheric and terrestrial). For example, a change in the vegetation cover of the terrestrial catchment may induce a feedback mechanism in the limnetic system, thus giving rise to a stronger acidification than it should merit alone. It is also of interest that acidification of lakes is not necessarily only initiated by an increased supply of acids, but also by, for example, a decreased supply of P.

Although this model describes the acidification dynamics of lakes in Finnemarka in southern Norway, the processes, interactions and feedback mechanisms should also be of general importance where the natural conditions are roughly the same. For example, the indicated processes and mechanisms contributing to acidification of Lake Gårdsjøen (Nilsson 1985) and to water acidification more generally (Schnoor & Stumm 1985) partly support these considerations.

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