Acid deposition, critical loads and soil minerals: a historical review with some cautionary comments

Dépôts acides, charges critiques et minéraux des sols : une revue bibliographique historique et des commentaires de prudence

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The ecological damage that could be caused by distant sources of anthropogenic acid emissions, leading to widespread trans-boundary acid deposition, was first understood following numerous studies in southern Scandinavia in the 1970s and 1980s. In this area it was found that literally thousands of lakes had become acidified within recent times and had either completely lost their fish stocks or were in imminent danger of doing so. A study published by various Government bodies in Norway (Overrein, et al, 1980) brought together an impressive and convincing body of evidence showing the linkage between the chemical composition of precipitation and that of the lakes in southern Scandinavia. In particular, it was shown that precipitation was most acid and with the highest content of anthropogenic (non-marine) sulphate in precisely those areas where lakes had become acidified. These lakes, in turn, contained elevated levels of non-marine sulphate, as well as higher amounts of soluble aluminium. The latter, which is toxic to fish, must have been soil-derived, suggesting that the soil must have acidified too and must have transferred its acidity to surface waters. The most plausible mechanism to explain this transfer was described as the mobile acid anion concept. It was envisaged that incoming sulphate anions are transferred relatively rapidly through soil profiles. Accompanying protons are initially adsorbed by the soil exchange complex where they are exchanged for base cations, so that the first consequences of acid deposition would be an increased leaching of base cations to surface waters. However, base saturation of the exchange complex would quickly decrease, particularly where soils are derived from slowly weathering parent materials, and in these circumstances the base cations leached from the exchange complex are not replaced, leading to acidic soils and to the transfer of this acidity, often in the form of soluble aluminium to surface water. The adverse ecological effect of acid deposition was not widely accepted in the UK until after the advent of the Surface Water Acidification Programme (SWAP) which was jointly administered by the Royal Society and equivalent bodies in Scandinavia. The outcome of SWAP (Mason, 1990) was essentially a confirmation of the link between acid deposition and acid surface waters as suggested by the earlier Norwegian and Swedish work, and the necessity for abatement of acidic emissions now became
generally accepted. But on what basis should the extent of this abatement be calculated? First suggestions were in terms of overall percentage reductions from a previously agreed level but later it was accepted that an approach based upon critical loads was more rational. The fundamental process that determines the critical load of acidity to soils is the rate of mineral weathering in the soil so that, in principle, soil mineralogists might be expected to make a major contribution to this area of research.

Critical Loads

The term critical loads was defined by Nilsson and Grennfelt (1988) to mean "a quantitative assessment of one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge". For terrestrial ecosystems, the critical load may be equated with a level of acid deposition from the atmosphere at which soil acidification will not cause harmful effects on the ecosystem that the soil supports. It may be noted here that where the evidence for adverse effects of acid deposition on the aquatic ecosystem is wholly convincing, the same could not be said for evidence of damage to the terrestrial ecosystem. In fact, the SNSF report (Overrein et al, 1980) was rather circumspect upon this point. Nevertheless, mapping of critical loads of acidity to soils has proceeded throughout Europe on the basis of several different approaches.

The first and easiest approach arose from a Workshop held in Skokloster, Sweden in 1988 and simply related the dominant primary mineralogy of a soil to one of five critical load classes defined in terms of a numerical range of acid inputs. Other secondary factors could influence the assignment of a soil to a critical load class but the primary determining criterion was soil mineralogy. The different critical load classes, therefore, reflect the sensitivity of the soil to acid inputs, the most sensitive soils being those that contain a dearth of weatherable minerals, such as ferromagnesian silicates or carbonates. If the soil critical load classes are mapped and current acid inputs are known, then it is easy to see whether or not the critical load of acidity to soil in any particular area has been exceeded. The implication of exceedance is that this will cause chemical changes in the soil, such as a decline in the Base Cation: Aluminium ratio of the soil solution, leading in turn to ecological damage, such as stunting of root growth. Clearly, for this approach to be realistic much depends upon the way in which the actual soil critical load is determined. The Skokloster critical load classes were based upon expert opinion at that time, in the expectation that these critical load classes would be made more precise as research progressed.

A more refined approach to the application of critical loads and which has been widely used in mapping exercises in Europe is described as the Simple Mass Balance method. (de Vries et al, 1993). Here, an equation is used to calculate the balance between sources and sinks of acidity, largely in terms of leaching and mineral weathering respectively. The critical load is set to the pollutant limit at which a critical chemical value, such as the BC:Al ratio of the soil solution is not transgressed. The application of this method still requires a soil mineral weathering rate to be estimated and the critical chemical value also needs to be pre-determined. Sometimes, the soil weathering rate is derived from the Skokloster critical load class of the soil in question and in such an instance the SMB approach must also be regarded as essentially empirical. However, weathering rate can be calculated using rate law equations and independently measured soil properties using the PROFILE model developed at the
University of Lund (Sverdrup and Warfvinge, 1988, Warfvinge, 1992). The PROFILE model can also be used to calculate soil pH, BC:Al ratios and critical load and represents, therefore, a sophisticated and refined approach to the application of the critical loads concept. It is a steady state deterministic model and is the basis of a later dynamic model called SAFE.

Critical Load Maps of Europe

Using the types of approaches described above, maps of the critical loads of acidity to soils have been compiled for the whole of Europe. (de Vries, 1993). The picture portrayed by these maps is alarmingly bleak, even bearing in mind the inevitable over-generalization and over-aggregation of data engendered by the use of the 60 x 60 km grid EMEP squares as a unit of mapping. Thus, practically the whole of central and eastern Europe as well as much of western Europe is shown as an area of gross critical load exceedance both at the current time and into the future when emission reduction plans are taken into account. The implication is that terrestrial ecosystems dependent on the soil are being, and will continue to be, seriously damaged by acid deposition over this vast area. Soil scientists in general, and soil mineralogists in particular, should be quite properly concerned with the scientific basis for these grim scenarios, particularly when it is recalled that the fundamental driving force behind this work has been political in nature and has been concerned essentially with obtaining international agreement on the necessity to reduce substantially acidic emissions to the atmosphere. And while it is understandable that governments should wish to adopt the "precautionary principle" in environmental matters where scientific understanding may be incomplete, nevertheless, scientists ultimately have a duty to seek the truth, be objective and to remain sceptical in a healthy and positive way. It is in this spirit that some cautionary comments are now made concerning the application of the critical loads concept to the acidification of soils, particularly those aspects that relate to soil mineralogy.

Cautionary Comments

As noted above, while the evidence linking atmospheric acid deposition with acidification of surface waters and consequent damage to aquatic ecosystems is convincing, the same cannot be said of damage to terrestrial ecosystems, particularly in the context of exceedance of critical load of acidity to soils. Soil acidification is, of course, a perfectly natural process and it is difficult to quantify the extent to which this process is being accelerated by acid deposition. This has been done in relatively few cases. (for example, Falkengren-Grerup, 1987, Falkengren-Grerup et al, 1987). It has also proved to be extremely difficult to demonstrate in the field a clear connection between critical load exceedance, declining BC:Al ratios in the soil solution and biological damage resulting from this change. It would be understandable if there was a certain degree of caution in some sections of the scientific community regarding the acceptance of the European critical load exceedance maps while this relationship remains putative rather than clearly established. Furthermore, varying degrees of uncertainty attach to the different approaches that have been used for mapping and for the determination of critical loads of acidity to soils. For example, the UK critical load soil map based upon the empirical Skokloster approach corresponds rather poorly with the UK critical load map for fresh waters. (Hornung et al, 1995, Harriman et al, 1995). In addition, attempts to
relate soils belonging to the different Skokloster classes to objectively determined soil chemical properties have not met with conspicuous success and generally show that each class may encompass a wide distribution of chemical soil properties. (Dodds and Fey, 1998)

Again, with regard to the PROFILE model, a recently published critical evaluation concludes that the cumulative effect of the various uncertainties involved in calculating soil mineral weathering rates amounts to + or - 250%. (Hodson et al, 1997). It has also been found that many of the inputs to the model that most significantly affect its output, such as quantitative mineralogy, active mineral surface area, mean soil moisture content etc, are precisely those that are most difficult to determine on a routine basis. It can only be concluded that, at present, critical load applications of PROFILE are open to doubt until the implications of the various uncertainties in the model are clarified.

A recent development raises the question as to whether knowledge of the bulk properties of forest soils is necessarily relevant to the prediction of plant nutrient supply from these soils. This follows from observations that mycorrhizal fungi on roots of coniferous tree species are capable of directly dissolving silicate minerals by the excretion of metal complexing organic acids. (Jongmans et al, 1997). In these circumstances, it is the properties of the rhizosphere soil that are important, not those of the bulk soil, in supplying plant nutrients, and this a point that has so far not been taken into account in the mineral weathering elements of the critical load approach. This finding could also call into question the rationale behind the liming programmes of forest soils currently being pursued in Scandinavia.

Conclusions

Maps have been compiled showing that the critical loads of acidity to soils over large parts of Europe are currently exceeded and are therefore suffering, or will suffer in the future, serious ecological damage. The compilation of such maps to a large extent presupposes that adequate soil data are available and that there is sufficient understanding of the fundamental process that underpins this application of the critical loads concept, namely mineral weathering and the way in which this process relates to soil chemistry and plant nutrition. The validity of these assumptions is, at least, questionable and it is hoped that many of the papers contributed to this Symposium will explore the relationship between mineral weathering and soil acidity, particularly in the context of critical loads.

References


Keywords: critical loads, soil mineralogy, acid deposition soil acidification

Mots clés : charges critiques, minéralogie des sols, dépôts acides, acidification des sols