Global Assessment of Terrestrial Ecosystem Sensitivity to Acidic Deposition

Acidic deposition derived from sulphur and nitrogen pollution can cause many environmental problems which, until recently, were considered to be confined to Europe and North America. It is now clear that regional air pollution is a serious and growing problem in many parts of the World, particularly in certain developing countries. European and North American countries have now committed themselves to reduce total emissions of sulphur. In addition, negotiations are taking place to reduce or stabilise emissions of both nitrogen oxides and ammonia in these regions. It is anticipated that the relatively severe situation that exists in parts of these continents will improve. In many developing country regions emissions are increasing and set to rise dramatically in the next century if a 'conventional' development path is followed. Impacts associated with emissions of sulphur and nitrogen may then become more widespread and severe in some of these countries, mirroring what happened in Europe, unless steps are taken to prevent or control emissions. Such impacts include effects on human health, corrosion of materials, reductions in crop yields, eutrophication and acidification. Acidic deposition leads to acidification of sensitive terrestrial and aquatic ecosystems. Decreases in lake pH have caused huge losses of fish stocks in Europe and North America and decreases in soil pH have been implicated as a major cause of forest damage in these regions.

In aspiring to a higher standard of living developing countries have opportunities to avoid the mistakes made in Europe and North America. As an initiative to facilitate the development of action plans, strategies and policies for pollution prevention and control, the Swedish International Development Co-operation Agency (Sida) is funding a programme on Atmospheric Environment Issues in Developing Countries. The programme is co-ordinated by the Stockholm Environment Institute (SEI) and is implemented in collaboration with numerous partner organisations.

Mapping global sensitivity to acidic deposition represents one component of the Regional Air Pollution activity of the Sida-funded programme. The objective of the Sida-funded programme is to enhance the capacity of developing countries to participate locally and regionally in programmes and activities to resolve atmospheric environmental problems and to increase and facilitate the participation and involvement of developing countries in international initiatives and negotiations. One part of the programme deals with Regional Air Pollution in Developing Countries which addresses the issue of sulphur and nitrogen emissions and associated effects through a number of projects. All these projects are linked by a common theme of problem analysis, strategic action and capacity building. The specific components of the programme evolve over time, as developing countries take ownership of on-going processes of research, dialogue and policy-making.

This booklet explains the continued development of the global assessment of terrestrial ecosystem sensitivity to acidic deposition and accompanies the SEI poster of the same name. It describes the information presented on the poster in more detail and the methods implemented to derive the datasets.

The global sensitivity map represents the second version of such a map to be produced by SEI. The initial methodology (used for Version One), which combined soil, land cover and climatic data, was discussed by ecologists, soil scientists and others at three workshops held in Bangkok, Thailand; Harare, Zimbabwe; and San José, Costa Rica during 1996. The methodology used to produce the updated (Version Two) map has been revised from the initial version based on the comments received from the regional experts at these workshops. The methodology was finalised at a meeting in York in 1997 attended by Howard Cambridge (SEI), Steve Cinderby (SEI), Rafael Herrera (IVIC, Venezuela), Kevin Hicks (SEI), Johan Kuylenstierna (SEI), Frank Murray (Murdoch University, Australia) and Kim Olbrich (CSIR, South Africa). In addition, the methodology was sent to all the participants of the workshops, who generally agreed with the changed method.

The methodology for mapping global sensitivity is outlined in Section 1 of this booklet. Sensitivity maps form one component of a framework that may be used to determine risks of impacts posed by acidic deposition in different parts of the World. Such maps showing potential risks associated with sulphur and nitrogen deposition have proven useful in raising awareness concerning the threat posed by acidification and providing impetus to prevent emissions giving rise to the damage. The framework for assessing the risk posed to terrestrial ecosystems from acidifying deposition is outlined in Figure A of the poster. The framework is as follows:

- calculated emissions of sulphur are fed into atmospheric transfer models to derive sulphur depositions;
- net acidifying inputs to ecosystems are determined by estimating the neutralising effect of base cations derived from soil blown dust and subtracting this from the acidifying inputs of sulphur deposition;
- net acid inputs are compared to environmental damage thresholds, critical loads, which have been assigned to the relative sensitivity classes;
- any resulting excess of acid input highlights locations where ecosystems are at risk from acidification-related damage.

The details of each stage of this process are outlined in Section 2 of this booklet. It should be realised that both sulphur (SO_2) and nitrogen (NO_x and NH_3) emissions can ultimately give rise to acidification. In the work described here only sulphur is considered as a first stage. The inclusion of nitrogen deposition would increase the risk posed to ecosystems.

1 METHODOLOGY FOR MAPPING GLOBAL SENSITIVITY OF TERRESTRIAL ECOSYSTEMS TO ACIDIC DEPOSITION

1.1 Introduction

Global, regional and national maps showing ecosystem sensitivity to acidic deposition have been produced for a number of years. Global assessments include Troedsson and Nykvist (1973) and Rodhe *et al.* (1988) who produced maps giving a broad overview of areas sensitive to acidic deposition. Kuylenstierna *et al.* (1995) produced a map using soil buffering, land cover and climatic variables that showed sensitivity of terrestrial ecosystems to acidic deposition. This map (also produced as a poster – Version One, described in Kuylenstierna *et al.,* 1995) formed the basis of discussions held at several workshops during 1996/97 (see introduction). These involved international experts, mainly from developing countries, who were invited to critique the mapping activity and discuss changes to the methodology consistent with their regional experience. On the basis of these comments, the methodology has been changed and the new method presented here is based purely on the buffering ability of soils around the World. This has been carried out even though vegetation and climate are known to be important parameters influencing the response of terrestrial ecosystems to acidic deposition. This is primarily because global land-cover data were considered by the delegates of the validation workshops to be too coarse to yield reliable additional information. This is in contrast to available global soil data which are considered to be of relatively high quality. In addition, the influence of vegetation type on sensitivity is not easy to determine for ecosystems globally. Climate was considered important for the evaluation of sensitivity but its influence was not clear enough for inclusion in the methodology at this stage.

The rationale for using soil characteristics is as follows. The sensitivity of terrestrial ecosystems to acidic deposition is dependent upon the buffering ability of the soils and the response of the living organisms to soil acidification. Acidification will be avoided if deposition is maintained at a level that may be buffered by the soil. Consequently, the major component influencing terrestrial ecosystem sensitivity can be mapped by considering soil buffering alone. Well-buffered ecosystems are unlikely to acidify and therefore will be insensitive. Poorly buffered systems will acidify under sustained acidifying deposition which will cause impacts on organisms according to their tolerance of acidic conditions. Even the yield of tolerant species decreases upon acidification of the soil and, for this reason, acidification of the soil is the primary concern. If this is avoided, impacts on vegetation will be prevented irrespective of the tolerance of species.

The most important in-soil process that can buffer acidifying deposition is the chemical weathering of soil minerals. The weathering reaction between the minerals and hydrogen ions neutralises acidity. Minerals weather at different rates and therefore the overall buffering rate will depend on the proportion of various minerals in the soil.

Another buffering process is the exchange of cations in the soil. The number of positively charged sites on soil particles is measured by the Cation Exchange Capacity (CEC). The proportion of this filled by base cations as opposed to hydrogen or aluminium ions is called the base saturation (usually expressed as a percentage). The total amount of exchangeable bases represents the capacity of the soil to buffer by means of cation exchange.

Ulrich (1985) has described the buffering of soil in terms of buffer ranges where different reactions dominate. Well-buffered soils such as those in the carbonate buffer range have the highest weathering rate minerals - the carbonates. As buffering ability decreases soils contain a higher proportion of minerals that have lower weathering rates. Eventually cation exchange becomes a dominant buffering reaction and, when the base saturation decreases and pH reaches levels below 5, acidic deposition is buffered by the weathering of aluminium containing minerals. This gives rise to an exponential increase in aluminium ion concentrations in soil solution with inputs of acidifying deposition as pH decreases below 5. This is important as aluminium ions are toxic to plant roots (Ulrich, 1985). Other changes in the soil affect the growth of plants and soil organisms. These can be summarised as (adapted from Rorison, 1980):

- Direct effects: injury by hydrogen ions at pH < 4.2
- Direct effects due to low pH: decreases in nutrient availability to plants (phosphates, base cations, and micro-nutrients such as molybdenum); increased solubility and toxicity of aluminium, manganese, iron etc.
- Abnormal biotic factors: impaired nitrogen cycle and fixation; impaired mycorrhizal activity; increased attack by soil pathogens.

Thus, as different soils are able to buffer to different degrees depending on soil chemical and physical properties, ecosystems will have different sensitivity to acidic deposition. Soils with a high proportion of fast weathering minerals will be well buffered in the long term. Soils with a high proportion of inert minerals will have low weathering rates and be more susceptible to acidification. The buffering capacity afforded by the exchange of cations in the soil (as shown by CEC) is limited and will diminish with time but will still buffer soils over the short- to medium-term. In addition, a large CEC will dampen short-term changes in soil chemistry.

1.2 Method

The buffering ability of soils, and therefore the sensitivity of terrestrial ecosystems to acidic deposition, is based upon two parameters in the Version Two methodology presented here:

a) base saturation (BS);
b) cation exchange capacity (CEC).

Base saturation

Soils with high base saturation either have a high input rate or low loss rate of base cations. High weathering rate soils, with a high input rate of base cations to the soil exchange complex, will therefore tend to have high base saturation. Base saturation is therefore the variable used in this assessment to identify those soils that have high weathering rate. The proportion of different soil minerals would give the best approximation to weathering rates in a given soil type but this exercise has not yet been carried out for the different FAO (Food and Agriculture Organisation) soil types used in this assessment. In the absence of soil mineralogy data and other specific information, the soil buffering properties of different soil types have been assessed on the basis of base saturation which is generally measured in soil profile analyses. In addition, high base saturation indicates those soils where base cations accumulate due to soil processes other than weathering such as net upward water flux and calcification. Five categories of base saturation have been derived according to the following classes: 0-20 per cent, 20-40 per cent, 40-60 per cent, 60-80 per cent and 80-100 per cent. These have been related to different soil buffer ranges characterised by buffering mechanisms related to the weathering of different minerals and cation exchange. For example, it is assumed that soils in the range 80-100 per cent will be in the carbonate buffer range, whereas soils with 60-80 per cent will either have a low content of carbonate minerals or a high content of relatively high weathering rate minerals. Soils with a BS of 0-20 per cent will be likely to exist in the aluminium buffer range, and 20-40 per cent either within or close to the aluminium buffer range.

Cation exchange capacity

The sensitivity of a soil having a given base saturation will be modified by the CEC. If there is a very large CEC then this will have the effect of dampening any fluctuations in pH from a given acid load. In the long term the total content of base cations held on the exchange complex (Total Exchangeable Bases, or TEB) which represents a combination of base saturation and CECs will be related to the ability of a soil to buffer acidic inputs by the process of cation exchange. Buffering by cation exchange can only occur for a finite period of time. Obviously, if the CEC, and by implication the TEB, is high then the buffering by cation exchange may be considerable. Ecosystems with high CEC soils would then be considered to have a lowered sensitivity compared to soils with moderate CEC. In areas with very low CEC and TEB, episodic inputs of acidity may cause larger fluctuations in pH, even where weathering rates are reasonably high. Therefore, such areas might be considered to have slightly higher sensitivity. CEC has been used as a parameter for the estimation of soil sensitivity to acidic deposition by a number of authors (McFee, 1980; Lucas and Cowell, 1984). They proposed three categories of CEC for mapping purposes and in this assessment the categories of Lucas and Cowell have been used: <10, 10-25 and >25 meq/100g soil.

Soil buffering ability

The base saturation and cation exchange capacity were combined to give a ranking of soil buffering ability as shown in Table 1.1. Essentially soils with moderate CEC are ranked 1-5 to show increasing buffering ability according to base saturation categories. For low CEC soils the buffering ranking is one class lower than for moderate CEC soils. Naturally, being already at the lowest rank, 1 cannot decrease any further. Conversely, soils with high CEC have been ranked one class higher than those with moderate CEC. Soils in the carbonate buffer range are assigned the highest buffer ability regardless of CEC. This represents the simplest method for the combination of CEC and BS, even though the progression of buffering is not linear and there is no *a priori* reason why the class should be exactly one higher or one lower depending on CEC. The success of this classification should be reviewed as experts apply it to their particular situation.

1.3 Application of the Method to Soil Maps

Several issues have to be tackled when applying the method to spatially referenced soil data. The soil depth under consideration has to be decided. This has been related in this case to rooting depth as it is chemical changes in the rooting zone that will most affect vegetation. CEC and BS data must then be calculated for the chosen soil depths and sensitivity values determined for each soil type that can be represented as a map.

Table 1.1 The table used to allocate soil types to relative sensitivity classes (1-5) according to mean BS and CEC calculated over depth d (either 50 or 100 cm soil depth)

		Base Saturation % (mean over depth d)				
		0-20	**20-40**	**40-60**	**60-80**	**80-100**
CEC (meq/100g)	**<10**	1	1	2	3	5
	10-25	1	2	3	4	5
	>25	2	3	4	5	5

Note: The data for the BS and CEC were derived for the rooting zone of different soil types from the ISRIC soil database (ISRIC, 1995) and then incorporated into the FAO database (see Annex I). The rooting zone is considered to be within the top 50-100cm of the soil for the majority of roots for most vegetation types (Jackson *et al.,* 1996).

Soil maps often depict soil assemblages rather than soil types. Therefore, BS and CEC data need to be assigned to soil types and a statistic chosen to represent the sensitivity of the soil assemblage on the soil map. There are therefore three stages in the application of the method to soil maps:

i. choose soil depth for the assessment of sensitivity;
ii. assign BS and CEC data to soil types over this depth;
iii. represent the combined sensitivity of the soil assemblage using some statistic.

Soil depth

Rooting depths vary with plant form and species and the conditions in which they are grown. It is therefore difficult to assign a soil depth to different vegetation types on different soils in different climates. For this reason a simple approach has been taken. From global assessments of root distributions of different biomes covering the World (Jackson *et al*., 1996) it can be seen that many species have more than 90 per cent of root biomass in the top 50 cm of soil; the top 100 cm of soil typically account for more than 90 per cent of root biomass for most vegetation types of the World. Therefore, the analysis here using the FAO Soil Map of the World has considered average properties over both of these soil depths.

Assigning BS and CEC data to soil types

There are several different classification systems for soil types (e.g. United States Department of Agriculture (USDA) and FAO). Soil types are described according to typical characteristics, often related to end use requirements. These may or may not be related to physico-chemical characteristics such as BS and CEC. However, there are data available for a large number of soil profiles representing soil types that have been used here to assign typical BS and CEC data to soil types. This assessment uses the FAO classification system (FAO, 1995) and the ISRIC database (ISRIC, 1995) was used to obtain profile information of soils shown on the FAO map. CEC and BS information were weighted by depth and density to obtain mean values for two depths - 50 and 100 cm. The mean values were then used to calculate the sensitivity class using the decision rules described in Table 1.1 (see Appendix I). This exercise was more successful for some soil types than others dependent on: (i) the amount of data for each soil type; (ii) whether soil taxonomy is related to the BS and CEC characteristics. Where the calculated sensitivity class differed between the 50 cm and 100 cm profiles the minimum value calculated was assigned to that soil type.

The ISRIC database is based on the revised FAO 1990 soil map legend. Unfortunately, the mapped data are based on an earlier legend from 1974. This meant the transformation of 1990 soil types into their corresponding 1974 classes. Where more than one 1990 soil type corresponded to a 1974 soil the mean sensitivity class calculated from the range of 1990 classes was assigned (see Appendix II). A number of checks were carried out as part of this transformation process. Where the mean value of the 1990 classes for a 1974 soil differed from the modal value for the dataset the soil was examined in more detail. Additional texts were consulted and an expert decision taken on which class to assign to each soil type. The same process was carried out for soils that contained no profile data in the ISRIC database.

Statistical representation of sensitivity of soil assemblages

The Soil Map of the World produced by FAO (FAO, 1995) is a map of soil assemblages, with information on the percentage cover of a number of soil types in each assemblage. A statistic therefore has to be used that represents the data for the different soil types in the assemblage and can be used to represent that assemblage on the map. Many statistics can be used including any stated percentile (the soil type that represents the nth percentage of an assemblage ranked in order of sensitivity class), to a mean or mode. In order to choose one statistic to represent all assemblages, a number of maps were produced:

- maps showing the buffering class of the most sensitive soil type in an assemblage;
- maps showing the buffering class of the soil type dominating the assemblage (the modal soil type);
- maps showing the area-weighted mean indicator value.

A process of calibration was carried out at a meeting of all the main authors held in York, UK, comparing the global sensitivity maps with sensitivity and critical load maps from Europe, North America, Australia, Japan and China. The best match between the global and national maps was found with the mean value. It was therefore decided to represent sensitivity using mean buffering ability for each assemblage. The result of this process is the global sensitivity map shown on the poster.

Details of the calibration

The sensitivity map is consistent with previous global approaches and has been compared to the following regional and national investigations of sensitivity of terrestrial ecosystems to acidic deposition. To a large extent the method reproduces the pattern and degree of sensitivity in the UK, Scandinavia and other countries in Europe (Kuylenstierna and Chadwick, 1989; Hornung and Skeffington, 1992; Downing *et al.*, 1993; Posch *et al.*, 1995). There is also good agreement with the sensitivity distribution in Canada (Environment Canada, 1987) and a surface water alkalinity map for the US (Omernik, 1982 - alkalinity of waters is highly correlated with soil and geological properties). In other countries the distribution mirrors work carried out in China (Zhao *et* *al*., 1994), the base status of soils according to the Soil Map of China (Academia Sinica, 1986) and the sensitivity maps for Japan (Wada *et al*., 1983) and Australia (Chartres *et al*., 1996). In relation to other regional work the distribution is broadly similar to the critical loads map from the RAINS-Asia activity (Hettelingh *et al*., 1995). This process of calibration can increase confidence in such a global evaluation, particularly in the prediction of sensitivity in regions that have not been studied intensively.

2 GLOBAL RISK ESTIMATION

The sensitivity map represents one part of the framework to estimate risks of acidification by acidic deposition. Risk of impact is determined by relating acidic deposition to the sensitivity of ecosystems on which it falls. In order to carry out such risk estimation a number of other components are required:

- rate of deposition
- neutralising input of base cations
- quantification of ecosystem sensitivity.

The rate of deposition could be estimated using monitoring but, in order to determine risks over a large area, the outputs of atmospheric transfer models may be used. Wind-blown soil dust is used for the neutralising input of base cations since this is one of the major sources on a global scale. In order to compare the net acidic deposition to the sensitivity map, critical loads represent a very useful tool (these represent environmental thresholds to damage from acidification).

Data fed into atmospheric transfer models may represent past, current or projected future emissions and hence the models may be used to estimate various risk scenarios.

These different aspects are explained in the following sections and the overall framework for risk estimation is described in Figure A of the poster.

2.1 Emissions of Sulphur

Current emissions

The need for consistent emission inventories for all regions of the globe prompted the formation of the Global Emission Inventory Activity (GEIA) under the auspices of the International Global Atmospheric Chemistry (IGAC) project, itself part of the International Geosphere Biosphere Project (IGBP). The GEIA sulphur emission inventory was produced, firstly, by creating a gridded, 1 by 1 degree, inventory for the globe on the basis of economic data for sulphur-emitting activities, emission factors and information on sulphur recovery and emission controls. Secondly, in areas where more detailed emission inventories have been compiled, the basic inventory was replaced with the more detailed, locally generated data (Graedel *et al*., 1995). Finally, major point sources were added. The resulting map of anthropogenic emissions of sulphur for 1985 is described in Benkovitz *et al*. (1996). These data have been supplied on a 5 by 5 degree grid by Rodhe (*pers. comm*., 1998). The map is show in Figure B of the poster.

Emission scenarios

In order to assess the potential effects of future emissions the Intergovernmental

Panel on Climate Change (IPCC) emission scenario estimates have been used to indicate anthropogenic sulphur emissions for 2050. The IPCC base case scenario, IS92a, referred to as 'business-as-usual', has been used in the assessment. This scenario makes the following assumptions:

Population	**Economic Growth**	**Energy Supplies**	**Other**	**CFCs**
11.3B by 2100	2.9% - 1990-2025	12,000 EJ fossil oil 13,000 EJ natural gas	Enacted controls on SO_x, NO_x and VOCs	Partial compliance with Montreal Protocol.
	2.3% - 1990-2100	Solar falls to 0.75/kWh 191 EJ biofuels at $70/barrel	Developing countries reduce by mid 21C	Gradual phase-out by 2075

The scenario represents the consensus opinion on current development pathways. It incorporates mid-range population and economic projections that have received widespread acceptance. The levels of sulphate aerosol in transient emissions are subject to rates of fossil fuel use and a minor level of industrial adaptation. The scenario disaggregates the emissions to five geographical regions. Assumptions have been made that the distribution of emissions within each of these regions will remain constant and only the levels will increase. The total anthropogenic emission in 2050 is assumed to be 153 Tg.S.yr^{-1}.

The emissions resulting from this scenario have been assigned to a 5 by 5 degree grid by Rodhe (*pers. comm.*, 1998). They have been distributed based on increases from the GEIA emissions for 1985. This map is shown in Figure C of the poster.

2.2 Transfer and Deposition of Sulphur

The three-dimensional MOGUNTIA tracer transport model (Zimmerman, 1987) was used to simulate the global distribution of sulphur compounds from both natural and anthropogenic sources. This model has a horizontal resolution of 10 by 10 degrees and a vertical resolution of ten layers in the troposphere. The meteorological input is based on observed monthly averages.

GEIA sulphur emissions in 1985 were used as input to the MOGUNTIA model (as detailed above) and in 2050 regional sulphur emission estimates from the IPCC IS92a scenario were modified for use in the model. The model was run for 1985 (Figure D of the poster) and 2050 (Figure E of the poster) by MISU (Department of Meteorology, Stockholm University) in Sweden (Rodhe *et al.*, 1995).

Global modelling of this nature indicates the broad patterns rather than a detailed analysis of distribution of deposition within a country. However, the model captures the main features of the deposition fields when a comparison is made to observations. Discrepancies between the observations and the models cannot be used entirely to fine-tune the results generated due to the scale of the modelling (Rodhe *et al.*, 1995).

2.3 Base Cation Deposition

In many regions of the world there is a substantial transfer and deposition of soil particles mainly emitted from dry areas. This soil dust is mainly alkaline in nature and therefore inputs buffering cations into soils where it is deposited.

Only soil blown dust has been considered in this assessment. Base cation particles emitted from industrial sources are not included at this stage of the assessment.

The global emission, transfer and deposition of soil dust have been modelled by Tegen and Fung (1995). The source areas of wind-blown dust are mainly located in the arid areas of the World, which often have calcareous soils. When wind exceeds threshold speeds soil particles become airborne with the smallest particles potentially transported over large distances.

In order to assess the input of base cations present in wind-blown dust estimates of the average calcium content of the soil have been derived. The calcium content of soils has been assumed here to vary from between 3 and 20 per cent (FAO-UNESCO, 1977; Gomes and Gillette, 1993; Avila *et al.,* 1996). From an initial calibration between modelled base cation deposition with measured wet base cation deposition rates at a limited number of monitoring sites the figure of 20 per cent achieved the best fit. Using this 20 per cent calcium content with the dust deposition rates of Tegen and Fung (1995) the global distribution of base cation deposition was modelled and is shown in Figure F of the poster. It should be noted that considerable uncertainty exists in both the global modelling of soil dust deposition and the estimates of calcium content of this dust.

2.4 Critical Loads

Critical loads are quantitative acidic deposition rates which represent thresholds to damage caused by acidification. Different definitions of critical loads have been given (Nilsson, 1986; Nilsson and Grennfelt, 1988). These initially focussed purely on the buffering rate of soils and subsequently included the tolerance of different plant species to acidic conditions. In this study critical loads are defined as being equivalent to the buffering rate of soils and are therefore highly correlated to the relative classes of sensitivity which have been mapped. For example, low weathering rate values are typical of the most sensitive areas on the map and, conversely, the least sensitive areas have high weathering rates and the highest critical load. The sensitivity map becomes particularly useful when critical load values are assigned to it in order that it may be compared to deposition estimates or measurements. There is obviously a degree of uncertainty in carrying out such an exercise, as more data on these threshold values are required for ecosystems and soils typical of developing countries. Assuming critical loads derived for well studied areas will be applicable to ecosystems with the same sensitivity that are less well studied, damage thresholds may be assigned to areas through a process of calibration. Data for critical loads from Europe and North America and also estimates for weathering rates have been used in this exercise (Eldar and Brydges, 1983; Nilsson and Grennfelt, 1988; Bain *et al*., 1995a, 1995b; Hall *et al*., 1995; Langan *et al*., 1995a, 1995b; Xie *et al*., 1995). From such a process preliminary critical loads have been assigned to the sensitivity map as shown in Table 2.1.

Table 2.1 Preliminary critical loads for use with the global sensitivity map

Sensitivity class	Critical load ($meq\ m^{-2}\ yr^{-1}$)
1 most sensitive	25
2	50
3	100
4	200
5 insensitive	>200 (no critical load)

2.5 Acidification Risks at Global and Regional Scales

The framework for risk estimation shown in Figure A has been used with the sulphur and base cation deposition estimates and the sensitivity maps described above. The base cation deposition has been subtracted from the acidic inputs associated with sulphur deposition to derive net acidic load. The net acid input map is then compared with critical load values assigned to the sensitivity map. Any excess of acidifying deposition above the ecosystem buffering rate will lead to acidification of the soil causing impacts on plant growth through decreased nutrient availability and the effects of toxic ions on roots (see introduction). The exact nature of the impacts at a given site are unpredictable; however, it is possible to state that, based on experience in Europe, crop and forest yields may decline and biodiversity change within areas predicted to be at risk from acidification.

Figure H on the poster shows that in 1985, according to this analysis, the highest risk is centred over Europe and North America. The areas shown to be at risk in southern Scandinavia have indeed suffered an enormous degree of lake acidification and in central Europe forest damage has been particularly severe in areas where the critical load exceedance is shown to be highest. The 1985 map also highlights areas where acidification-related damage is beginning to have environmental impacts. These areas include parts of China, the Republic of Korea, Vietnam, Indonesia and Laos. There appears to be no appreciable risk in Africa or Latin America except for a few isolated areas and even here the excess over the critical load is low.

Figure I on the poster shows that in 2050 using the IPCC IS92a sulphur emission scenario the picture has changed with a greatly increased risk of acidification in developing countries. In north-east Asia, the highest projection of exceedance is found in China, the Republic of Korea and Japan. In south Asia high-risk areas are found in parts of India, Nepal and Bhutan. Risks of acidification are predicted for every South-East Asian country with some areas showing considerable risk. In Africa by 2050, risk areas appear in Zambia, Zaire, Zimbabwe and parts of South Africa. In Latin America, large areas of Brazil, Mexico, Peru and Colombia are predicted to be at risk under this scenario.

It must be stressed that these predictions represent a global overview based on low resolution 10 by 10 degree sulphur deposition maps. The maps can only give a broad indication of the areas at risk from acidification damage; more detailed local and regional information should be used for more in-depth assessments of the risks posed by sulphur and nitrogen deposition. In addition, this map does not indicate the full risk associated with sulphur and nitrogen emissions that include, for example, impacts of gaseous pollutants on crops, even on well-buffered soils. These impacts and others are also being considered in other parts of the Sida-funded programme.

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Appendices

Appendix I: Mean CEC and base saturation for two rooting depths with sensitivity classes allocated

	Top 50cm			Top 100 cm			Sensitivity Class Assigned	
FAO 90	CEC per 100g	Base Saturation	Sensitivity Class	CEC per 100g	Base Saturation	Sensitivity Class	Class Difference	Class Assigned
ACf	3.3	32.0	1	3.4	28.1	1		1
ACg	8.0	25.4	1	8.1	24.5	1		1
ACh	10.6	32.8	2	10.6	33.2	2		2
ACp	4.4	27.2	1	4.3	26.0	1		1
ACu	17.4	29.9	2	16.7	32.6	2		2
ALf	7.5	17.7	1	7.6	14.4	1		1
ALg	8.0	36.9	1	8.0	42.9	2	Difference	1
ALh	6.5	32.0	1	6.4	32.2	1		1
ALj	8.0	57.0	2	8.0	44.5	2		2
ALp	5.5	20.7	1	5.5	13.1	1		1
ALu	8.0	30.4	1	8.0	23.1	1		1
ANg	9.5	20.3	1	10.1	19.6	1		1
ANh	17.0	57.4	3	15.8	53.5	3		3
ANm	29.4	73.6	5	30.1	71.9	5		5
ANu	16.5	30.5	2	16.7	32.6	2		2
ANz	20.4	44.7	3	20.4	45.3	3		3
ARa	2.0	59.7	2	2.0	63.4	3	Difference	2
ARb	3.0	45.4	2	3.0	45.5	2		2
ARc	3.2	91.9	5	3.2	94.0	5		5
ARg	3.2	98.0	5	3.2	98.9	5		5
ARh	6.7	94.1	5	6.6	95.6	5		5
ARl	3.2	78.5	3	3.2	76.4	3		3
ARo	2.2	45.7	2	2.2	49.8	2		2
ATc	23.6	92.8	5	22.5	95.6	5		5
ATu	8.0	65.5	3	8.0	57.5	2	Difference	2
CHh	51.5	100.0	5	55.9	100.0	5		5
CHk	17.6	80.7	5	17.6	78.5	4	Difference	4
CLh	12.7	91.5	5	12.7	92.2	5		5
CLl	12.7	95.1	5	12.7	95.9	5		5
CLp	12.7	96.0	5	12.7	93.1	5		5
CMc	21.6	98.3	5	21.9	98.5	5		5
CMd	12.1	24.0	2	12.1	20.8	2		2
CMe	19.2	86.4	5	19.8	88.1	5		5
CMg	15.6	46.3	3	14.9	44.3	3		3
CMo	7.5	28.8	1	7.4	26.1	1		1
CMu	12.9	31.1	2	12.9	29.5	2		2
CMv	41.1	85.7	5	41.1	83.6	5		5
CMx	23.3	89.2	5	26.7	91.4	5		5
FLc	15.8	96.8	5	15.8	95.7	5		5
FLd	33.2	51.6	4	33.2	49.5	4		4
FLe	10.3	89.0	5	10.1	88.2	5		5
FLm	27.8	72.3	5	27.8	76.1	5		5
FLs	27.8	47.0	4	27.8	47.0	4		4
FLt	24.7	84.1	5	25.0	86.9	5		5
FLu	30.5	54.5	4	30.5	47.5	4		4
FRg	2.5	24.1	1	2.9	25.8	1		1
FRh	6.2	36.9	1	6.2	37.3	1		1
FRp	5.0	53.2	2	5.2	42.2	2		2
FRr	4.4	36.3	1	4.4	34.7	1		1
FRu	7.8	12.8	1	7.6	12.9	1		1
FRx	3.1	25.2	1	2.9	24.7	1		1
GLd	19.9	40.9	3	20.0	46.5	3		3
GLe	22.3	92.4	5	22.9	93.1	5		5
GLi	6.2	92.4	5	6.2	92.2	5		5
GLm	17.6	95.7	5	17.6	96.1	5		5
GLt	31.3	100.0	5	29.3	94.1	5		5

Appendix I (continued)

	Top 50cm			Top 100 cm			Sensitivity Class Assigned	
FAO 90	**CEC per 100g**	**Base Saturation**	**Sensitivity Class**	**CEC per 100g**	**Base Saturation**	**Sensitivity Class**	**Class Difference**	**Class Assigned**
GLu	17.0	38.4	2	17.0	51.7	3	Difference	2
GRh	15.5	95.1	5	17.0	87.2	5		5
GYh	34.7	89.2	5	37.7	86.2	5		5
GYk	6.2	100.0	5	6.2	91.0	5		5
GYl	6.2	98.1	5	6.2	99.1	5		5
GYp	6.2	72.5	3	6.2	74.8	3		3
HSs	103.8	36.6	3	103.8	45.2	4	Difference	3
KSh	18.4	100.0	5	18.4	100.0	5		5
KSk	45.0	81.0	5	48.0	82.5	5		5
LPd	31.5	45.7	4	31.5	45.7	4		4
LPe	31.5	97.3	5	31.5	97.3	5		5
LPk	0.0	0.0	1	0.0	0.0	1		1
LVa	11.6	73.1	4	11.9	74.0	4		4
LVf	6.2	66.6	3	6.2	72.2	3		3
LVg	15.7	75.7	4	15.7	77.9	4		4
LVh	11.4	87.4	5	11.4	88.2	5		5
LVj	24.8	84.5	5	24.6	86.8	5		5
LVk	12.8	97.2	5	12.8	98.3	5		5
LVv	36.2	97.2	5	37.0	98.4	5		5
LVx	16.2	85.1	5	16.0	85.5	5		5
LX	13.7	47.9	3	13.7	71.5	4	Difference	3
LXf	10.0	76.4	3	10.0	72.6	3		3
LXh	10.4	72.5	4	10.0	74.8	3	Difference	3
LXj	17.4	100.0	5	19.9	100.0	5		5
LXp	13.7	54.0	3	13.7	58.4	3		3
NTh	11.0	70.0	4	11.0	72.3	4		4
NTr	10.5	69.0	4	10.0	74.6	4		4
NTu	10.8	33.3	2	10.6	35.2	2		2
PDd	19.1	73.5	4	19.1	67.6	4		4
PDe	11.8	77.7	4	11.8	66.9	4		4
PHc	43.7	98.0	5	42.5	97.9	5		5
PHg	17.1	83.1	5	17.1	89.0	5		5
PHh	19.9	87.0	5	19.8	88.0	5		5
PHj	15.8	87.1	5	15.8	92.7	5		5
PHl	16.4	88.6	5	16.2	88.9	5		5
PLe	12.2	70.1	4	13.0	78.5	4		4
PLm	30.2	90.2	5	30.2	93.3	5		5
PTa	16.4	25.8	2	16.4	17.7	1	Difference	1
PTd	16.4	41.3	3	16.4	31.2	2	Difference	2
PTe	6.4	64.9	4	16.4	63.2	4		4
PTu	3.2	17.5	1	2.8	11.0	1		1
PZb	13.5	31.2	2	13.5	35.6	2		2
PZc	10.3	8.8	1	10.3	8.1	1		1
PZg	4.0	5.6	1	4.9	6.5	1		1
PZh	13.2	15.4	1	12.7	30.8	2	Difference	1
RGc	19.0	91.9	5	19.2	92.7	5		5
RGd	4.1	30.7	1	4.2	38.9	1		1
RGe	7.4	80.1	5	6.9	81.0	5		5
SCg	20.5	100.0	5	20.5	100.0	5		5
SCk	41.4	100.0	5	43.9	100.0	5		5
SCn	42.6	100.0	5	36.3	100.0	5		5
SCy	21.8	100.0	5	21.8	100.0	5		5
SNg	17.5	95.3	5	17.5	96.2	5		5
SNh	18.9	95.7	5	19.0	96.3	5		5
SNj	30.9	91.2	5	31.3	93.3	5		5
SNk	19.4	99.9	5	19.4	99.6	5		5
SNy	19.4	97.9	5	19.4	97.9	5		5
VRd	51.7	73.6	5	51.7	58.4	4	Difference	4
VRe	52.5	96.9	5	52.5	96.7	5		5
VRk	52.4	98.0	5	53.0	98.3	5		5

Appendix II: FAO 1974 soil types and sensitivity classes

Soil Code	Soil Type	Class
A	Acrisols	1
Af	Ferric Acrisol	1
Ag	Gleyic Acrisol	1
*Ah	Humic Acrisol	1
*Ao	Orthic Acrisol	1
Ap	Plinthic Acrisol	1
B	Cambisols	5
Bc	Chromic Cambisol	5
Bd	Dystric Cambisol	1
Be	Eutric Cambisol	5
Bf	Ferralic Cambisol	1
*Bg	Gleyic Cambisol	3
Bh	Humic Cambisol	2
Bk	Calcic Cambisol	5
Bv	Vertic Cambisol	5
*Bx	Gelic Cambisol	5
C	Chernozems	5
Cg	Glossic Chernozem	5
Ch	Haplic Chernozem	5
Ck	Calcic Chernozem	5
Cl	Luvic Chernozem	5
D	Podzoluvisols	4
*Dd	Dystric Podzoluvisol	2
De	Eutric Podzoluvisol	4
Dg	Gleyic Podzoluvisol	4
*E	Rendzinas	5
F	Ferralsols	1
Fa	Acric Ferralsol	1
*Fh	Humic Ferralsol	1
Fo	Orthic Ferralsol	1
Fp	Plinthic Ferralsol	1
*Fr	Rhodic Ferralsol	1
Fx	Xanthic Ferralsol	1
G	Gleysols	4
*Gc	Calcaric Gleysol	5
Gd	Dystric Gleysol	3
Ge	Eutric Gleysol	5
Gh	Humic Gleysol	2
Gm	Mollic Gleysol	5
*Gp	Plinthic Gleysol	1
*Gx	Gelic Gleysol	3
H	Phaeozems	5
Hc	Calcaric Phaeozem	5
Hg	Gleyic Phaeozem	5
Hh	Haplic Phaeozem	5
Hl	Luvic Phaeozem	5
I	Lithosols	0
J	Fluvisols	4
Jc	Calcaric Fluvisol	5
Jd	Dystric Fluvisol	4
Je	Eutric Fluvisol	5
*Jt	Thionic Fluvisol	4
K	Kastanozems	5
Kh	Haplic Kastanozem	5
*Kk	Calcic Kastanozem	5
Kl	Luvic Kastanozem	5
L	Luvisols	4
La	Albic Luvisol	4
*Lc	Chromic Luvisol	5
*Lf	Ferric Luvisol	1
Lg	Gleyic Luvisol	4
Lk	Calcic Luvisol	5
Lo	Orthic Luvisol	5
Lp	Plinthic Luvisol	1
Lv	Vertic Luvisol	5
M	Greyzems	5
*Mg	Gleyic Greyzem	5
Mo	Orthic Greyzem	5
N	Nitosols	3
Nd	Dystric Nitosol	1
*Ne	Eutric Nitosol	4
Nh	Humic Nitosol	2
O	Histosols	3
*Od	Dystric Histosol	2
Oe	Eutric Histosol	3
Ox	Gelic Histosol	3
P	Podzols	1
*Pf	Ferric Podzol	1
Pg	Gleyic Podzol	1
Ph	Humic Podzol	1
Pl	Leptic Podzol	2
Po	Orthic Podzol	1
Pp	Placic Podzol	1
Q	Arenosols	3
Qa	Albic Arenosol	2
Qc	Cambic Arenosol	5
Qf	Ferralic Arenosol	2
*Ql	Luvic Arenosol	3
R	Regosols	4
Rc	Calcaric Regosol	5
Rd	Dystric Regosol	1
Re	Eutric Regosol	5
*Rx	Gelic Regosol	2
S	Solonetzes	5
Sg	Gleyic Solonetz	5
*Sm	Mollic Solonetz	5
So	Orthic Solonetz	5
T	Andosols	3
Th	Humic Andosol	2
Tm	Mollic Andosol	5
To	Ochric Andosol	3
*Tv	Vitric Andosol	1
*U	Rankers	1
V	Vertisols	5
Vc	Chromic Vertisol	5
Vp	Pellic Vertisol	5
W	Planosols	5
*Wd	Dystric Planosol	3
We	Eutric Planosol	4
*Wh	Humic Planosol	3
Wm	Mollic Planosol	5
Ws	Solodic Planosol	5
*Wx	Gelic Planosol	1
*X	Xerosols	5
*Xh	Haplic Xerosol	5
*Xk	Calcic Xerosol	5
Xl	Luvic Xerosol	4
Xy	Gypsic Xerosol	5
Y	Yermosols	5
Yh	Haplic Yermosol	5
*Yk	Calcic Yermosol	5
Yl	Luvic Yermosol	5
*Yt	Takyric Yermosol	5
*Yy	Gypsic Yermosol	5
Z	Solonchaks	5
Zg	Gleyic Solonchak	5
*Zm	Mollic Solonchak	5
Zo	Orthic Solonchak	5
Zt	Takyric Solonchak	5

Note: In general, the mean value of the sensitivity classes from the corresponding FAO 1990 soil types (calculated using the ISRIC database as described in Section 1.3) has been assigned to the 1974 classes. Where little or no data existed in the ISRIC database expert decisions on the appropriate class were made based upon additional texts and reference to existing sensitivity and critical load maps. Such cases have been highlighted with an asterisk.

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