

Project in Natural Resources Management

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ACTUAL AND CRITICAL LOAD OF ACIDIFYING SUBSTANCES IN STOCKHOLM -LANDSCAPE MANAGEMENT UNDER UNCERTAINTY

Introduction

Acidification of soil and water is a major environmental problem in industrialised regions of the world (Howells, 1990). World-wide, anthropogenic and natural emissions of acidifying substances are of the same magnitude. The anthropogenic emissions, however, are concentrated to a few heavy industrialised regions, including Europe. This is thought to be the major cause of soil and ground water acidification in these regions. However, an alternative hypothesis is that biological acidification is accelerated in those regions due to intense forestry (cf. Eriksson et al., 1992; SNV, 1993). Biological activity, weathering and runoff of base cations causes naturally maturing soils to show decreasing pH over time (Howells, 1990). Hence soil acidification is problematic to define, and its origin difficult to trace. The effects of acidification include forest dieback, soil degradation, drinking water quality deterioration and sterilisation of lake ecosystems through aluminium toxification (Berdén et al., 1987; Chadwick and Hutton, 1991; Ambio, 1992; SNV, 1993; Maxe, 1995; Staaf and Tyler, 1995).

Mitigation of acidification is necessary for redeveloping viable ecosystems, and hence for sustainable development. A usable tool for management of acidification is the critical load concept, which forms the basis for regional discussions of emission control strategies in Europe (IIASA, 1993). Critical load is a measure of soil capacity to buffer long term acid deposition through weathering of cations (Nordic Council of Ministers, 1988 and 1989). A temporary strategy for soil recovery is liming, which has been practised at least since Roman times. Long term solution can only be reached by balancing actual and critical load, unless next ice age is coming up soon.

In Södertörn south of Stockholm there are several sources of deposition of acidifying substances. The two most important local sources being the highway E4/E20 and the Igelsta coal-power plant (appendices 3 and 4). It is also a well known fact that the background deposition is high, mostly due to emissions from the countries around the Baltic sea. The relative importance of local versus regional sources, however, is not known. Further, the critical load of the soils in Botkyrka is not known. There are indications that some natural soils in the region are in a process of being acidified (Jacks, 1992).

Objective

The objective of this project is to evaluate soil acidification and identify regions where liming is necessary to maintain forest productivity. Actual and critical load of acidifying substances in natural soils shall be modelled in GIS. Regard shall be taken to both local and regional sources of acidifying substances. Generating iterative scenarios, results will be compared with field data. Uncertainty in data shall be considered when identifying acidified areas and suggesting management. After the project you shall have gained understanding about acidification processes, and factors determining soil and groundwater vulnerability to acidification. You shall

also have become aware of the origin of the acid depositions, and the relative importance of different sources. You shall have improved your skills in using GIS for modelling and scenario development. You should understand the importance of hypothesis formulation, uncertainty, and the scientific method of model calibration and validation.

Optional study subjects include evaluating the influence of biological acidification, using a combination of literature studies and GIS-modelling based on forest growth models. An alternative GIS-oriented subject is to add a study of critical load of nitrogen, including reviewing background to that specific problem. You could also try to improve the compulsory approach by including additional information on critical load (e.g. soil base cation content, sulphur deposition, proximity to forest edges filtering airborne pollution). As regional sources are well known to be larger than local, you could also choose to study the influence of different European countries on the acidification in Södertörn (using the model RAINS) and evaluate and discuss the technical and economical feasibilities of different strategies that would lead to a balance of critical and actual load. Alternatively the influence of traffic emissions in Stockholm could be evaluated.

Background

Critical load is defined as "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Nordic council of ministers, 1988). For soils critical acid load is determined by the chemical weathering rates of the minerals in the soil. The critical load is the level where weathering balances the load of hydrogen ions (i.e. where pH and cation content is maintained and not deteriorated). The critical load level hence depends primarily on the mineralogical composition of the soil (appendix 1). Other factors of importance include: precipitation, vegetation type, slope, soil texture, soil drainage, soil depth. The quantitative critical load estimate for acidifying substances in natural soils is given in appendix 1.¹

Pollutant emissions giving rise to acid rain are predominantly the oxides of sulphur and nitrogen. Sulphur dioxide (SO₂) is derived by oxidation of sulphur in the course of combustion of fossil fuels. Nitrogen oxides (NO and NO₂) are generated during the process of combustion by oxidation of the nitrogen present in air. Those oxides are further oxidised in the atmosphere at a rate of about 1-3 % per hour, influenced by temperature, humidity and catalysing agents such as manganese and iron (SNV, 1984; Howells, 1990). The oxidation demands stronger oxidation agents than O₂ (i.e. O₃, H₂O₂, OH, HO₂), and can take several different routes (SNV, 1984; Berner and Berner, 1987; Howells, 1990). Volatilisation of ammonia (NH₃), mainly from dung fertilisers, is another source of acidification. Ammonia will act as a base when dissolved in rainwater, however on deposition it will be oxidised to nitrate and hence also contribute to the acidification (Howells, 1990). Ammonia is not transported as far in the atmosphere as sulphur dioxide and nitrogen oxides, and will hence have a more local effect (in the vicinity of intense live-stock agricultural areas).

Two principal mechanisms are responsible for removal of the atmospheric content of substances - wet and dry deposition. As oxidised substances are more soluble, dry deposition dominate in the near-field, with increasing wet-deposition down-wind (Howells, 1990).

¹ Hint: Mineralogical composition of different bed rocks can be found in Loberg, B (1980); Geologi, or any other basic book in geology.

Wet deposition is fairly easy to measure and thus well known. Figures of deposition is published annually in Sweden within the national environmental control net (PMK) (Granat, 1991) - appendix 5. The rate of dry deposition is calculated from a "deposition velocity" and atmospheric concentration of gases. The deposition velocity is a very rough estimate and varies for different gases, as well as for different kinds of surfaces (cf. appendix 2). In general dry deposition is higher in coniferous forests, and at forest edges (cf. Wiman et al., 1990).

Note that biological acidification, mentioned above, is an alternative hypothesis explaining soil and ground water acidification (Ambio, 1992; SNV, 1993).

Uncertainty and risk

The information on which we base our decision making is clearly not perfect. There are several sources of uncertainty. Measurement errors occur in all digital data layers. With quantitative data, the normal expression of measurement error is the degree to which measurements will vary from the true value. This is expressed as the root-mean-square-error (RMSE) or standard deviation for data with normally distributed random errors:

$$RMSE = \sqrt{\frac{\sum (x_i - t)^2}{n}}$$

where:

x_i = a measurement

t = true value

n = number of measurements

For instance, measurements of pH in soil is not totally accurate (appendix 2). Measurement (and model) errors can be managed by recognising and accepting a defined level of risk (Fig. 1). If there is some a priori knowledge (evidence) available, this knowledge can be used for estimating the likelihood of a hypothesis being true. Measuring soil pH is more accurate in clayey and silty soils, and this knowledge can be used in order to decrease uncertainty. This is done using Bayes' Theorem which states:

$$p(h|e) = \frac{p(e|h)p(h)}{\sum_i p(e|h_i)p(h_i)}$$

where:

$p(h|e)$ = the probability of the hypothesis being true given the evidence

$p(e|h)$ = the probability of finding that evidence given the hypothesis being true

$p(h)$ = the probability of the hypothesis being true regardless of the evidence

h_i = the set of hypothesis under consideration

A second type of error is *human conceptual error*. The threshold for defining an acidified lake for instance, varies between pH 5.0 to 5.4. The definition is thus not precise. This kind of uncertainty can be handled by fuzzy set theory (fig. 1).

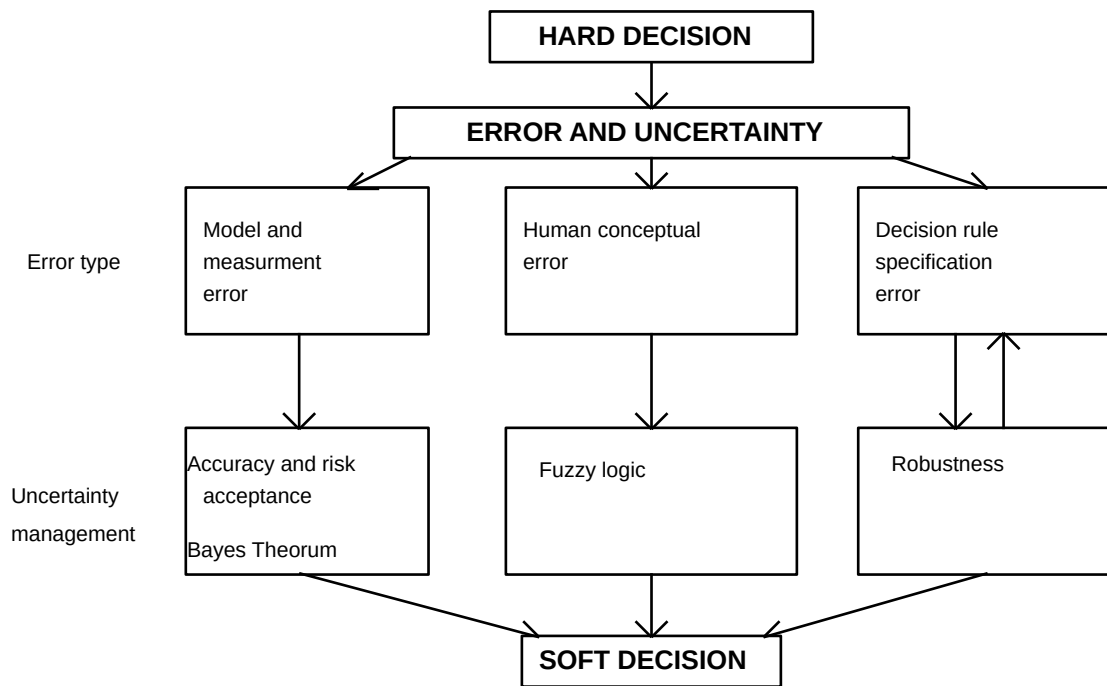


Fig. 1. Uncertainty and risk in decision making; different types of errors, and management of uncertainty.

Specification error in decision rules is a third kind of error. As maturing soils get more acid, a soil with a low pH might be naturally acid. Liming such a soil might change natural ecosystem development, and would not be desired in a nature reserve for instance. Decision rules might also be very sensitive to small changes in some criteria. One way to handle errors in decision rules is to validate the robustness by applying an iterative procedure (fig. 1).

Incorporating risk and uncertainty in the decision making is sometimes referred to as going from a hard to a soft decision (fig. 1).

Compulsory task

Your task is to identify areas in need of mitigation action (e.g. liming) in the Stockholm SV area using GIS. You shall model actual and critical load of acidifying substances. Critical load evaluation should be based on the concept set forth in appendix 1 (Nordic Council of Ministers, 1988). Actual load should be calculated with two models, one for local and one for regional sources. The local contribution from the Igelsta power plant and E4/E20 highway must be computed using a simple model for spreading of local air-pollution (Frennemo, 1983). In appendix 3 you find information about the model (IMPAIR), together with the necessary background information about Igelsta power plant and E4/E20. Also in appendix 3 you find a wind-rose showing the wind pattern over the area of interest. As dry-deposition (which dominate in the close vicinity of an emitting source) is governed by vegetation, the actual deposition is preferably generated in IDRISI (see appendix 2).

The regional, European background, contribution of nitrogen and sulphur is calculated with RAINS (Regional Acidification and INformation Simulation), a model developed at IIASA (International Institute for Applied System Analysis) (Alcamo et al., 1987; IIASA, 1993), appendix 4. One problem with RAINS is that national emissions are calculated as point sources from the geographical centre of each country. However, industrial and traffic concentrations

around Stockholm biases Swedish emissions of both nitrogen and sulphur oxides towards the Stockholm region.

The ratio of actual to critical load shall be compared with the field data on soil pH collected previous years in the Environmental Data course. Use simple regression to represent the relation between ratio and soil pH. Evaluate the result, and try to improve the correlation by iteratively changing the scenario for actual load, or determination of critical load (or both). Use the regression model to create an image that shows soil pH for the whole study area. This image will be validated against an independent set of field measurements. Then you shall take uncertainty in defining a threshold for acidified soils and pH measurements into account, and identify areas in need of liming. Finally, if you are aiming at a higher grade, one optional subtask should be included.

Optional subtasks

To receive a higher grade you must solve an additional task. No detailed instructions are given for the subtasks so you are free to develop the project within certain frames. You are offered 6 alternatives:

- How could the regional depositions be decreased (the figures derived from RAINS). Different scenarios in RAINS should be modelled followed by an analysis and evaluation of economical and technical feasibility (available in the RAINS model). Discuss how different actions to decrease pollution can be realised. Should the energy consumption be lowered, energy sources altered, etc.? Implementation could be discussed e.g. from a game perspective (cf. Mäler, 1991).
- Forest edges are highly exposed to dry deposition; they filter the pollution. A second subtask deals with the problem of defining forest edges in a GIS environment and to find a way to integrate the effects of the edges into the project. How are the results affected by this new factor?
- In recent research, the causes of acidification are discussed. Forestry management itself causes acidification, due to the hydrogen ion exchange in the growing phase of the tree and forestry biomass withdrawal. The third optional subtask is to do a literature study on biological acidification and try to implement a GIS-model of forest growth and compare model results with pH and evaluate model predictability.
- The hillslope flow path of water largely affects acidification (e.g. Norrström, 1995), especially the division in recharge and discharge areas is important. Use literature to evaluate the importance of small scale topography for acidification, and try to implement this in your modelling (use the program *updrain*, found under P:\DOS\IDRISI\UPDRAIN\, that works against IDRISI format). Evaluate the results.
- Emissions from traffic and other sources in Stockholm most likely affect acid rain in Södertörn. The amount of emissions and its potential impact on acidification in Södertörn is one optional subtask.
- You can choose to construct a critical load model for nitrogen depositions. This subtask also includes a literature review on nitrogen critical load and its origin.

You are welcome to discuss the topics, and please inform us on your choice before starting. The optional subjects will be central topics of the final oral NRM-seminar.

The project must be reported in a scientifically correct written article. Your subtask should be presented as an interwoven part in the article. The article should be written in times roman, size 12, with double spacing and margins on all sides of 2.5 cm. It should contain the following:

Title	
Abstract	
Key words	
Introduction	Why did you start?
Material and methods	How did you do it?
Results	What answer did you get?
Discussion	What does it mean?
References	Written as in this instruction!

The following maps shall be included in the report:

- Summation of total actual load
- Calculation of critical load
- Evaluation of actual versus critical load
- Model prediction of soil pH
- Identification of acidified areas in need of liming

References

- Alcamo, J., Amann, M., Hettelingh, J.-P., Holmberg, L.H., Kämäri, L., Kauppi, P., Kornai, G. and Mäkelä, A. 1987. Acidification in Europe: A simulation model for evaluating control strategies. *Ambio*, 16: 232-244.
- Ambio*, Vol. 92, No. 2, 1992. Special issue on acidification.
- Berdén, M., S.I. Nilsson, K. Rodén and G. Tyler, 1987. Soil acidification. Extent, causes and consequences. An evaluation of literature information and current research. SNV Report 3292. Swedish Environmental Protection Agency, Solna.
- Berner, E.K. and Berner, R.A. 1987. The global water cycle. *Geochemistry and environment*. Prentice-Hall, Englewood Cliffs. 397 p.
- Chadwick, M.J. and Hutton, M. (Eds), 1991. Acid depositions in Europe. Environmental effects, control strategies and policy options. Stockholm Environmental Institute. 376 p.
- Eliassen, A. and Saltbones, J. 1983. Modelling of long-range transport of sulphur over Europe: a two year model run and some model experiments. *Atmos. Environ.*, 17: 1457-1473.
- Eriksson, E., E. Karlton and J.E. Lundmark, 1992. Acidification of forest soils in Sweden, *Ambio* 92(2): 150-154.
- Frennemo, 1983. Spridning av luftföroreningar. Enkel spridningsmodell för programmerbar räknedosa. Miljövard. Göteborgs Universitet. 32 p.
- Granat, L., 1991. Luft- och nederbördskemiska stationsnätet inom PMK. Rapport från verksamheten 1990. Naturvårdsverket Rapport 3942. Solna. 65 p.
- IIASA, 1993. Options. Winter issue.
- Jacks, G., 1992. Acidification of soil and water below the highest shoreline on Södertörn, central eastern Sweden. *Sveriges Geologiska Undersökningar, Ser. Ca 81*, pp 145-148.
- Howells, G.H. 1990. Acid rain and acid waters. Ellis Horwood, Chichester, UK. 216 p.
- Maxe, L. (Ed), 1995. Effects of acidification on groundwater in Sweden. Swedish Environmental Protection Agency, Report 4388.

- Mäler, K.-G., 1991. The acid rain game. In H. Folmer and E. van Ierland (Eds), Valuation methods and policy making in environmental economic, Elsevier, Amsterdam, pp 231-252.
- Nordic Council of Ministers, 1988. Critical loads for sulphur and nitrogen. Miljörapport 1988:15.
- Nordic Council of Ministers, 1989. Acid precipitation. Literature review. Miljörapport 1989:4.
- Norrström, A.-C., 1995. Chemistry at groundwater/surface water interfaces. Royal Inst. of Technology, Div. of Land and Water Resources. Dissertation.
- Skyllberg, U. 1993. Acid-base properties of humus layers in northern coniferous forests. Swedish University of Agricultural Sciences. Department of Forest Ecology. Umeå. Dissertation.
- SNV (Swedish Environmental Protection Agency), 1981. Försurning av mark och vatten. Monitor. SNV, Solna, 175 pp.
- SNV, 1984. Långväga transport av luftföroreningar. Monitor. SNV, Solna. 134 pp.
- SNV, 1993. Försurning och kalkning av svenska vatten. Monitor. 144 pp. (Also in English).
- Staaf, H. and G. Tyler, (Eds), 1995. Effects of acid deposition and tropospheric ozone on forest ecosystems in Sweden. Ecological Bulletins, No 44, Copenhagen.
- Wiman, B.L.B., M.U. Unsworth, S.E. Lindberg, B. Bergkvist, R. Jaenicke and H.-C. Hansson., 1990. Perspectives on aerosol deposition to natural surfaces: Interaction between aerosol residence times, removal processes, the biosphere and global environmental change. J. Aerosol Sci., 21: 313- 338.

Appendix 1

Critical load - acidification

The ideas of critical load for sulphur and nitrogen is gaining acceptance. For soils this concept assumes that the critical acid load is determined by the chemical weathering rates of minerals in the soil. The critical load thus is the level where weathering balances the load of hydrogen ions (i.e. where pH and cation content is maintained and not deteriorated). The critical load mainly depends on mineralogical and petrological conditions in the soil, table 1 (Nordic Council of Ministers, 1988). In addition to mineralogy, also several other factors influence catchment sensitivity to acidic deposition, table 2.

Table 1. Critical load for forest soils (0-50 cm) in relation to mineralogical and petrological conditions

Class	Minerals	Parent rock	sulphur g/m ²
1	Quarts K-feldspar	Granite Quartzite	<0.3
2	Muscovite Plagioclase Biotite(<5%)	Granite Gneiss	
3	Biotite Amphibolite(<5%)	Granodiorite Greywacke Schist Gabbro	0.8-1.6
4	Pyroxene Epidote Amphibolite(<5%)	Gabbro Basalt	1.6-3.2
5	Carbonates	Limestone Marl	> 3.2

Table 2 Conditions influencing critical load to forest soil

Factor	Decreasing critical load value	Increasing critical load value
Precipitation	high	low
Vegetation	coniferous	deciduous
Elevation/slope	high	low
Soil texture	coarse-sandy	fine
Soil drainage	free	confined
Soil/till depth	shallow	thick
Soil sulphate adsorption capacity	low	high
Base cation deposition	low	high

Critical load - nitrogen

Nitrogen is an essential macro nutrient, and also often the limiting substance for growth. However, high depositions of nitrogen might cause soil saturation of nitrogen, leading to high leakage of both nitrogen and other nutrients. The critical load for nitrogen in this respect is mostly determined by vegetation productivity. Higher productivity means a higher capacity to absorb the deposited nitrogen (Table 3).

Table 3 Critical Nitrogen loads for ecosystems varying in productivity ($\text{kg N ha}^{-1}\text{y}^{-1}$)

Ecosystem	Critical load
Deciduous forests**	5-20*
Coniferous forests**	3-15*
Dwarf shrub vegetation	3-5***
Grassland	3-10***
Raised bog	3-5***

* in mature forests the critical load may approach 0

** declining systems should approach 0

*** without major removal of N by management

Considering a critical nitrate concentration for groundwater of 50 mg l^{-1} (EEC standard) and a precipitation surplus varying between 100 and 400 mm yr^{-1} leads to critical loads of up to 10 to $40 \text{ kg N ha}^{-1} \text{ yr}^{-1}$.

Appendix 2

Some help in front of the computer

First an important remark. It is very important to keep track of units in this project. A good idea is to write comments in your batch files. In the project directory there are some batch files which you can use as a help during the project. None of the files are complete however, you have to fill in the missing syntax if you want to use them.

Start the project by login, go to G:\KURSER\AOM\1B1636 and type *acid_p*. A batch is run that creates the directory h:\acid under your user containing all the starting files. Note that if you repeat this command later you can loose all the information you have created. Write *connect* to open the path to IDRISI.

Calculation of isoareas of atmospheric content (local sources) [actual.bat]

You have two local sources of emissions to take into account, the Igelsta power plant and E4/E20. From the IMPAIR model (appendix 3) you shall have atmospheric content of nitrogen and sulphur from those sources as annual mean concentrations in the canopy at different distances.

The image containing the Igelsta power plant is called <igelsta> and the image containing E4/E20 is called <roads>. As Södertörn (the studied area) is rather hilly, obviously some slopes will be exposed to emissions whereas others are shadowed. An analysis of the Igelsta power plant has shown that its chimney is high enough to overshadow the hilliness. However the traffic emissions will deposit more on slopes directed towards the highway than from. Thus the next step is to classify the landscape into slopes facing towards and away from E4/E20. Slopes facing the highway (+/- 45°) should get double concentration value (x2), slopes turned away (+/- 45°) only half the value (x0.5), and intermediate slopes and flat areas keep the original value (x1). Run the program *surface* using the image <dtm> and *reclass* the result. Combine the aspect information with the model results from IMPAIR.

You should now have three images showing isoareas of atmospheric content of:

- nitrogen oxides from the highway
- nitrogen oxides from Igelsta
- sulphur oxides from Igelsta

Calculation of deposition [actual.bat]

Deposition consists of two components, dry and wet deposition. Wet deposition is normally measured directly, whereas dry deposition is calculated. The rate of dry deposition is normally assumed to be linearly dependent on concentration. To relate atmospheric concentration (mg*m⁻³) to deposition the necessary proportionality constant is usually given in cm/s ("deposition velocity"). Deposition varies significantly during day and night and different seasons.

Deposition is higher when stomata is open, and also higher in coniferous forests in comparison with deciduous (Wiman et al., 1990). However, transformations and deposition of different airborne substances to different vegetation and terrain is non-linear, and any deposition velocity hence likely to be in error (*ibid.*). Having noted this, the following values can be used as rough estimates for deposition velocity (Nordic Council of Ministers, 1988; Howells, 1990):

Table 1 Deposition velocities for different substances and land cover (cm/s)

Substance	Grassland	Deciduous forest	Coniferous forest
SO ₂	0.1-1.0	0.2-1.5	0.3-2
H ₂ SO ₄	0.1-0.5	0.2-1	0.2-2
HNO ₃	2-4	2-5	3-6
NO ₂	0.1-0.8	0.2-1.5	0.3-2
NO ₃	0.1-0.5	0.1-0.8	0.2-1
NH ₃	2-10	5-20	5-25

The higher deposition velocity of ammonia reflects the fact that it is transported much shorter distances, and hence has a more local influence than the other substances.

As we are close to the local sources we can assume that dry deposition is far more important and thus exclude wet deposition as negligible. Use *reclass* or *assign* (*idrsign* if in command line mode) and the image <landuse> to define areas of different vegetation with respect to deposition velocity. Use *overlay* to generate the actual deposition combining atmospheric concentration and deposition velocity (carefully note the different units, here the advantage of batchfile is obvious). You have to do different species of sulphur and nitrogen separately (as they have different deposition velocities).

Convert the different deposition images into one (use *overlay*), giving the total deposition of acidifying agents expressed in one unit (elementary sulphur recommended - appendix 1). You must use relation between masses, molecular weights and molecular ratios to do the conversions. Time to think! And be careful with your units and categories! Now it is also time to add the regional deposition (i.e. the figures you derived from RAINS, appendix 4). Assume that this deposition is equally large over the whole area (which is correct since it is mostly wet, and precipitation is equally distributed). Before adding the figures, convert them to the same (single) unit that you used for the total local deposition, and then use *scalar*.

In the file ACTUAL.BAT you will find some help for calculating actual load.

Calculation of critical load [critfac.bat]

The critical load concept that we use here is only applicable for forests and unmanaged grasslands. Water, farmland and exploited areas should not be included. Thus mask them as nodata using *reclass* (or read the appendix through and exclude them using *mce*).

The capacity of the soil to withstand acidification (i.e. the critical load) is governed by several factors, with mineralogical composition as the single most important. All factors of importance are listed in appendix 1. To find out mineralogical composition, look at the <bedrock> image. Then you know in what span you can find critical load (appendix 1). Assume that the mineralogical composition is similar over the whole area (mixed together by the movement of the ice). Of the more important factors determining where in the span you will end up (appendix 1) three are available in the data set:

- Vegetation (through <landuse>)
- Slope (through <dtm>)
- Soil texture (through <geology>)

Annual precipitation in the region is approximately 600 mm. Knowing this you should also be able to take rainfall into account. Start by assuming that each of those four factors (vegetation, slope, soil and precipitation) have the same relative importance. One way to get a result is to reclass the 3 raster-files above according to the ideas in appendix 1, with an equally great span (i.e. all reclassified into 5 or 10 classes for instance) (Table 2).

Table 2. Suggestion for a 5 class solution of factors determining critical load

Class	1	2	3	4	5
Vegetation	Coniferous	Grassland	Mixed forest	Deciduous	Hard-wood
Slope	>20	16-20	11-15	6-10	0-5
Soil texture	rock outcrop	sand/gravel	coarse till	fine till/silt	clay
Rainfall (mm/yr)	>1200	800-1000	600-800	400-600	<400

The best way to combine the four factors is by using *mce*, an IDRISI module for multi criteria evaluation. With *mce* you can apply different weights to the factors, and thus easily create several scenarios. (In *mce* you can also exclude areas by defining them as constraints, which is a way to mask out water, agriculture and built up areas.) Alternatively you can also use *overlay* to calculate an average of those 4 factors for each cell in your selected area. Then *stretch* your result into the original span set by the mineralogical composition. The resulting map should show critical load in your selected area. Note that the unit of the image must be the same as for the image of actual load (elementary sulphur recommended).

In the file CRITFAC.BAT you find help to construct the input images for MCE. It is not possible to run the *mce* module from command line however, why this has to be done outside the batchfile.

Compare actual versus critical load [ratio.bat]

See to that you have the same units in your actual and critical load images. Divide the actual load with critical load. Use RATIO.BAT as help if you want.

Evaluate your model results against field data [ratio.bat] [check.bat]

The image <soilph> contains field data of pH. Simply create a comparison of field data and the ratio actual/critical using *regress*. Evaluate the relationship (and its strength) using simple regression. The ratio actual/critical should be the independent variable and soil pH the dependent. Make sure that only cells with digitised pH values are included, and that pH values within excluded areas are **not** used. Iteratively try to improve model performance by restating either the critical load parameters (i.e. their relative importance) or the actual load scenario or by including some new factor². Evaluate your result. You can do this heuristic by checking the values of the original files determining critical load (<dtm>, <landuse> and <geology>) for the pixels that contained field data. Change the variables determining critical load, or the scenario for actual load in order to create a new ratio of actual/critical load. You can also find some other factors, distance to edges and/or intense agricultural areas for instance (see main text). Also check your deposition figures against the maps in appendix 5. Note that Swedish emissions are concentrated in the Stockholm region, which may cause higher deposition (20-30 % - SNV, 1981) than given by RAINS. In the file RATIO.BAT you will find some hints.

² It is better to find a regression formula that spread the pH values in the model run at least 2 units (say from 5 to 7), since this will make the evaluation of uncertainty more interesting.

Continue the iterations until you have calibrated your model to an acceptable significance. Then use the derived regression formula (*scalar*) to generate a final map of pH in the soil for your whole area. When you have done this you shall validate your model. This will be done by using an independent set of field measurements of soil pH. *Regress* will be used for determining model accuracy. You must ask the teachers for the independent image on soil pH. In the file CHECK.BAT you will find some help for these calculations.

Identify liming areas considering uncertainty [probab.bat]

The last step in the compulsory part is to identify areas where management to mitigate soil acidification is needed. In order to do this you must have an idea about the threshold level for acidified soils and information on uncertainty in the ground truth values of pH. The soil pH image that you have created is rather deterministic and does not account for the (random) error in measurements etc. (Model errors are dependent on several factors, obviously including the soil pH measurements; we will only deal with measurement errors). An accommodation of uncertainty replaces the hard decision deterministic boundaries with ones that are soft.

Error in soil pH can be regarded as random, and of two origins. The largest error is due to spatial fluctuations at a pixel scale, and the fact that measurements are based on single samples. The variation of pH and cation is, to a large extent a small scale phenomenon (Skylberg, 1993). 12 to 15 samples would be required to reach a 95 % confidence level with limits of +/- 2 % deviation from the mean in the upper soil horizon. 2 samples would give approximately +/- 10 % in the upper soil, and +/- 5 % in the B/C horizon (i.e. at the depth our samples were taken). The standard deviation of the estimate of our measurements (root-mean-square error, RMSE) is hence estimated to be +/-0.5 pH units. The second error comes from the laboratory analysis, which has a RMSE of approximately 0.2 pH units.

Taking these uncertainties into consideration you shall identify areas that need liming. Liming is called for when pH gets below 4.5 to 5.0. What final level to choose you must decide yourself. You could use *fuzzy* to handle this uncertainty, but it is not compulsory.

Start by defining the error in your soil pH image (the one you created from the model) in *document*. Then run *pclass* to evaluate the probability that pH is below the threshold value chosen (the threshold value is given as input in *pclass*). With this map produced by *pclass*, for example, a data value of 0.40 indicates that the data cell has a 40 % chance of having a pH higher or lower (dependent on how you parameterised *pclass*) than the level chosen. Now that we have the probability map, the task of the decision maker is reduced to making a soft decision rule subject to an acceptance of some level of risk. Select level of risk by using *reclass*. Choose a second level of risk and compare the two levels of risk by using *crossstab*.

One way to decrease the uncertainty is to check the consistency of soil pH in different soil types (i.e. comparing geology with soil pH and model results). If in some soil types pH predictions are much better you can use Bayes' Theorem to include this a priori knowledge. The a priori knowledge is then combined with the unknown probability. The module for including the a priori knowledge in IDRISI is called *bayes*.

We have such a priori knowledge concerning the accuracy of measuring pH in different soils (but not about model accuracy). The standard error is smaller in more fine textured soils. Hence we can use Bayes' Theorem to include this smaller error, and decrease the uncertainty in our model. The following table give a more detailed accuracy level (complement to error) of soil pH measurements:

clay	0.7
silt	0.6
sand	0.5
gravel	0.4
fine till	0.6
coarse till	0.5

Create an image (use *assign* or *idrsign*) with categories accordingly, and use it as a priori knowledge running *bayes*. Compare the areas identified in need of liming before and after having applied a priori knowledge. Use the same level of risk and compare by using *crosstab*. Include the result in the report. Finally suggest areas that should be managed, include the size of these areas. Defend your choice of risk level. You may find the file `PROBAB.BAT` useful.

Choose an optional task.

Appendix 3

Some help using the IMPAIR model

The program "IMPAIR" is a simple model for spreading of local air pollution. *IMPAIR* outputs a raster map layer where the cell values represent atmospheric pollution content at ground.

IMPAIR is supported by MS-DOS and is adapted to IDRISI format.

The model assumes a normally distributed (gaussian) spreading of air-pollution along a trajectory, and is applicable for distance between 100 and 10 000 m from the source. It is started by writing IMPAIR at the DOS prompt.

IMPAIR can be used for point or line (e.g. roads) sources of emissions. As georeferenced input the model needs an image identifying the source, and a digital terrain model. Model output will cover the same region and resolution as the terrain model. Data for the emission volume, smoke stack elevation, and atmospheric conditions are given interactively at model initiation.

Try to use the information available in the windrose plot when parameterising the model atmospheric conditions. And then use it to adjust the result (e.g. increase if in main wind direction, or the other way around). The windrose plot might be difficult to interpret, but at least try before asking.

The result from running the local model is given in concentrations equivalent to the unit given for the emission (e.g. mg/s gives mg/m^3).

E4/E20

The number of vehicles passing on E4/E20 (between Hallunda and Salem) is approximately 50000/day, of which 7 % is heavy traffic (pers. comm. Mats Hagström, Vägverket). Emissions of SO_x is negligible, whereas NO_x emissions are dependent on speed. For an average velocity of 90 km/h NO_x emissions from light vehicles can be set to 1.4 g/km and for heavy vehicles to 12.5 g/km (Vägverkets publikation 1989:16B). Use those figures as to calculate input for the model.

Igelsta power plant

Most of the necessary information about Igelsta can be found in the article below. However, some additional information is needed. The chimney is built on ground situated 10 m.a.s.l. The internal diameter of the chimney can be set to 5 meters, and the velocity of the emissions to 2 m/s. With this information you have all the necessary input data to run IMPAIR. Run the program for both sulphur and nitrogen emissions.

Appendix 4

Instructions for using the RAINS model

The RAINS model is more or less self instructive, there is no manual except the help function in the program. To start the program you go to the directory G:\KURSER\AOM\1B1636\NRM\RAINS and write RAINS after the DOS-prompt. RAINS consists of several subroutines and data-bases. There are data-bases for energy use and energy future in all European countries, you can display those by choosing "1" in the main menu. As you see there are different scenarios available. You can also create your own scenario here. There are several option how to create your own scenario. This is outside the project, but you are welcome to try.

From a defined scenario RAINS uses an atmospheric transportation and deposition model to calculate mean annual concentrations and deposition for a selected region or point in Europe. The model for transport, transformation and deposition of sulphur and nitrogen is based on the EMEP-model (Eliassen and Saltbones, 1983), and uses a 150x150 km² grid resolution. This part is reached under "2" in the main menu. There are several options for how you want to display your results. What we are most interested in are mean annual deposition rates. Choose the option "deposition at a specific location due to a group of countries". The specific location is naturally Sweden. Longitude is in the Stockholm region 18 and latitude 59 (approximately). It is enough to give one figure for nitrogen and one for sulphur. Be careful noting what molecular form nitrogen and sulphur really are expressed in (i.e. atomic or as molecules). If nothing is said, figures represent atomic (elementary) units.

The entries 3 to 5 in the main menu are not necessary to use in this project, however you can try them as well.

Note that RAINS generate total deposition whereas the maps in appendix 5 show only wet deposition. Can you think of a way to increase the resolution of the RAINS model by using the information available in your dataset? The problem is the separation of dry and wet deposition (don't do this part, just think about it).