DERIVING CRITICAL LOADS FOR ASIA

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Abstract. Critical loads have been computed and mapped in Southeast Asia, comprising China, Korea, Japan, The Philippines, Indo-China, Indonesia and the Indian subcontinent. The methodology involved the Steady-State Mass Balance (SSMB) method, originally developed for Europe. In contrast to Europe, where critical loads were computed for forest soils and surface waters, in Asia critical loads for 31 different vegetation types have been computed. Critical chemical limits as well as soil stability criteria were derived for each of these vegetation types, which include both natural and managed ecosystems. Results show that low critical loads in Asia occur in Bangladesh, Indo-China, Indonesia and the southern part of China. Uncertainties of the results are mainly due to uncertainties in base cation deposition. The critical loads are part of the impact module of the Asian version of the Regional Air pollution INformation and Simulation model (RAINS-Asia), a model used to assess abatement strategies for sulfur emissions which are rapidly increasing in this part of the world. The difference in the level of detail between European and Asian critical load maps enables different applications. In Europe, critical loads for sulphur were used in comparison to actual sulphur deposition with the aim of decreasing the excess of sulphur deposition over critical loads through optimal emission abatement. In Asia in general and China in particular the geographical distribution of critical loads of sensitive ecosystems, with some emphasis on crops, is likely to be used as a basis for future emission (re-)allocation.

Key words: acid deposition, air pollution impacts, critical loads, integrated modeling, ecosystem sensitivity.

1. Introduction

Due to high economic growth, emissions of SO₂ in Asia are rapidly increasing from about 34 Mt in 1990 to about 110 Mt by 2020 when no control measures are taken (Foell *et al.*, 1995). Historical data in Europe provide evidence of the relationship between soil and surface water acidification and increasing emissions, transport and deposition of sulfate. Therefore, it is appropriate to investigate the risk of damage due to acidification in Asia (see also Rodhe and Herrera, 1988; Zhao and Xiong, 1988; Zongwei and Kyunfeng, 1991; Xue and Schnoor, 1994). A Regional Air pollution, INformation and Simulation model for Asia (RAINS-Asia) has been developed to assess the relationship between the energy system, sulfur emissions, long-range dispersion and environmental impacts. The impact module of RAINS-Asia (Hettelingh *et al.*, 1995a) is used to provide information on the probability of damage from acid deposition exceeding critical loads for emission reduction alternatives (Foell *et al.*, 1995). The critical load concept has been used in negotiations of the reduction of sulfur emissions in Europe (Hettelingh *et al.*, 1995b) with the aim of decreasing the excess of sulfur deposition over critical loads through cost-optimal emission abatement. The derivation of critical loads in Asia, which is described in this paper, was improved in comparison to the European application, e.g. by including significantly more vegetation types. This improved resolution may also enable the use of critical loads as a basis for future emission (re-)allocation.

2. Computation and Mapping of Critical Loads in Asia

Critical loads were computed for Asian ecosystems by means of the Steady-State Mass Balance (SSMB) method. This method was applied in conjunction with the semi-quantitative method of relative sensitivity (Kuylensstierna and Chadwick, 1989) in order to compare the areas with stock-at-risk. The application of the method of relative sensitivity to Asia is described elsewhere (Cinderby *et al.*, 1995). This paper focusses on the quantitative assessment of critical loads in Asia using the SSMB method.

2.1 THE STEADY-STATE MASS BALANCE METHOD

The SSMB method is extensively described elsewhere (Downing *et al.*, 1993; Sverdrup and de Vries, 1994). In Europe critical loads were computed with the SSMB method mainly for forest soils and surface waters. For Asia an improvement to the European exercise was made by including 31 ecosystems in the critical load assessment. The computation of critical loads is based on plant response criteria and soil stability criteria. A critical molar ratio of the concentrations of base cations to aluminum in soil solution, $(BC/Al)_{crit}$ for each plant species is used as indicator of plant response. Using these critical BC/Al ratios in the SSMB method it is possible to compute maximum allowable acidifying deposition, i.e. the critical load:

$$CL = ANC_w + \left(1.5 \frac{x_{Ca+Mg+K} ANC_w + BC_d - BC_u}{(BC/Al)_{crit} K_{gibb}} \right)^{1/3} Q^{2/3} + 1.5 \frac{x_{Ca+Mg+K} ANC_w + BC_d - BC_u}{(BC/Al)_{crit}} \quad (1)$$

where ANC_w is the alkalinity produced by weathering, $ANC_{l,crit}$ is the critical alkalinity leaching, K_{gibb} the gibbsite solubility constant, Q is the runoff, BC_d the base cation deposition, BC_u the base cation uptake and $x_{Ca+Mg+K}$ the fraction of weathering as Ca, Mg and K. The soil stability criterion is introduced to avoid that acid deposition leads to Al leaching in excess of Al produced by weathering and other processes, e.g. in high precipitation areas. The critical load for acidity based on the soil stability criterion is computed by:

$$CL = 3ANC_w + \left(2 \frac{ANC_w}{K_{gibb}} \right)^{1/3} Q^{2/3} \quad (2)$$

Critical loads for each ecosystem are computed by taking the minimum of equations (1) and (2).

2.2 DATA AND MAPPING

Several different types of response expressions, using the BC/Al ratio as explanatory variable, can be derived from assuming an antagonism between base cations and Al through different types of ion exchange at the roots. The response equation can be made specific for (a) particular species, and (b) a particular ion exchange mechanism, i.e. Vanselow, Gapon or Gaines-Thomas (Sverdrup and Warfvinge, 1993). An example of relationships

between root growth reduction and BC/Al ratios in soil solution is given in Fig.1 for five tree species. Critical values for BC/Al as thresholds for root growth reduction have been established for many plant species by Sverdrup and Warfvinge (1993). An overview of the ecosystems for which critical loads have been computed is provided in Table 1.

Other data, i.e. climate, soil, geology and vegetation data, and their geographical distribution, required to compute and map critical loads have been derived from a variety of sources which are summarized in Cinderby *et al.* (1995). The uncertainty of the critical load estimates is largely due to the uncertainties of base cation weathering and base cation deposition estimates which require further verification.

In order to be able to compare sulfur depositions, which are computed by the RAINS-Asia model on a raster of $1^\circ \times 1^\circ$ grid cells, with critical loads the original polygon map of critical load has to be converted to the same raster. Each grid cell contains several critical loads reflecting the variety of ecosystems and their areas. A cumulative distribution of these critical loads is derived for each grid cell allowing the computation of a p th percentile (protecting $100-p$ percent of the ecosystem area) for comparison with the deposition in that grid cell (see Hettelingh *et al.*, 1995a).

TABLE 1

Values used for the calculation of critical loads with the SSMB method in Asia (see Hettelingh *et al.*, 1995a; some vegetation types of a total of 31 have been lumped for convenience).

Vegetation type	$(BC/Al)_{crit}$	Root depth (m)	$\log_{10} K_{gibb}$	BC_u (eq ha ⁻¹ yr ⁻¹)
Polar or rock desert	6	0.1	8.1	0
Tundra	2	0.2	8.1	0
Cool semi-desert/ scrub	2	0.3	8.1	0
Montane cool scrub/grass	2	0.3	8.1	0
Cool scrub/grassland	2	0.3	8.1	0
Main + southern taiga	1	0.5	8.5	250
Coniferous forest	1.5	0.5	8.5	250
Mixed forest	1	0.8	8.5	250
Temperate broadleaf forest	0.6	0.8	8.5	250
Interrupted temperate woods	1	0.5	8.5	100
Dry/highland woods	2	0.5	8.5	100
Mediterranean woodland	1	0.5	8.5	100
Interrupted tropical woods	2	0.5	8.1	0
Subtropical dry forest	2	0.5	8.5	100
Subtropical wet forest	1	0.2	8.1	0
Tropical dry forest	1	0.5	8.5	100
Tropical wet forest	0.6	0.2	8.1	0
Tropical savanna	10	0.5	8.5	100
General farmland	10	0.3	8.3	0
Coastal wetland	10	0.5	8.5	0
Hot scrub/grassland	10	0.3	8.3	50
Succulents/thorn dry woods	10	0.3	8.3	50
Semi-arid forest	10	0.5	8.3	50
Non-polar rocky vegetation	10	0.2	8.5	0
Sand and semi desert	10	0.5	8.5	0

Fig.1. The relationship between root growth reduction and BC/Al ratios for five tree species growing in China. For example, a root growth reduction of less than 20% occurs for $BC/Al > 1$ (Sverdrup and Warfvinge, 1993).

3. Results

Fig.2 shows the map of critical loads for acidity in Asia. Low critical loads (i.e. below $500 \text{ eq ha}^{-1}\text{yr}^{-1}$) are found in south-eastern Asia, parts of the Himalayan range and the Tibetan plateau and in parts of the boreal forest in northern China. Other areas with low critical loads (high sensitivity) include the rain forest strip in south-western India.

These results do not imply that soils are acidified yet. Fig.2 illustrates that some areas with low critical loads are subject to a higher risk of acidification than other areas. The map provides indications of where continued excess of critical loads may, in some areas earlier than in others, ultimately exhaust the buffering capacity of the soils. Areas with an increased risk of growth reduction, yield loss or dieback can thus be located. The dry regions in most of India and north-western China show relatively high critical loads (exceeding $2000 \text{ eq ha}^{-1}\text{yr}^{-1}$). The 25th percentile critical load, i.e. protecting 75% of the ecosystems in each grid cell against sulfur based acidification has been chosen as basis for comparison with sulfur deposition. The reason of choosing the 25th percentile is that the resolution of the vegetation data, used as basic map in the SSMB method, does not allow reliable estimates of ecosystem protection when lower percentiles are chosen. Fig.3 shows the 25th percentile critical load map of acidity for every $1^\circ \times 1^\circ$ grid cell covering Asia.

4. Concluding Remarks

A first critical load map for Asia has been derived by applying the Steady-State Mass Balance method to 31 vegetation types, taking into account information on soil types and climatic and meteorological conditions which are specific to the Asian region. The map of critical loads presented in this paper (a) enables large scale assessments of areas at risk due to long-range dispersion of acidifying pollutants, and (b) may assist in decisions on emission (re-)allocations. However, the calculation of critical loads for much of Asia with its highly varying environmental conditions and ecosystems is a considerable effort.

Fig.2. Critical loads in Asia computed with the Steady-State Mass Balance Method.

Fig.3. The 25-percentile critical load, protecting 75% of the ecosystems in each $1^\circ \times 1^\circ$ grid cell in Asia.

They encompasses tropical rain forest to near desert conditions and mangroves to areas of taiga: there is an associated range of soil types and a wide range of cropping systems and land use. Therefore, extensive validation procedures are required to improve the assessment of risk of damage on local scales. Further work is also required to include other causes of risk of damage in addition to deposition. Atmospheric concentrations of SO_2 , NO_x , and O_3 have been shown to cause direct damage to natural ecosystems and crops, as well as having health effects in large urban areas. In fact in many parts of Asia the concern for urban air quality is increasing and air concentrations of SO_2 may already reach hazardous levels.

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