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Biogeochemical approaches to assessment of East Asian ecosystem sensitivity to acid depositon

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Abstract. We used the critical load (CL) concept to calculate ecosystem response to acid deposition in East Asia. The calculation of critical loads to assess the sensitivity of ecosystems to acidic deposition was made using a biogeochemical approach, which took into consideration both rates of biogeochemical cycling and temperature responses. On the basis of these data the soil-biogeochemical mapping has been carried out for the area of East Asia and the CL values for acid-forming compounds have been calculated using modified steady-state mass balance (SSMB) equations. In the north-eastern ecosystems of the Asian part of Russia these values of critical loads for N [CL(N)] and S [CL(S)] compounds are shown to be less than in Europe due to peculiarities of climate, soil and vegetation. The minimum values of both CL(N) and CL(S) are <50 eq/ha/yr (which occur in 8.3% and 40.5% of this area for N and S, correspondingly) and the maximum values are >300 eq/ha/yr. These values are occasionally lower than for corresponding European ecosystems. For the south-eastern ecosystems of the northern part of Thailand the minimum values are <200 eq/ha/yr and maximum values are >700 eq/ha/yr. The minimum CL values (<200 eq/ha/yr) occur in more than 75% of the studied Thai area.

Introduction

The large population of East Asia and the significant growth of both industrial and agricultural production currently ensure that large increases in SO_2 and NO_x emissions will occur with time. The consequences of these growing emissions are the enhanced acidification loading on many ecosystems. The number of ecosystems at actual and potential risk in this East Asian domain has sharply increased during recent years (Ayers et al. 1996; Park 1996).

There is agreement both nationally and internationally that long-range transboundary air pollution may span continents: pollutants are transferred from Europe to North America and Asia as well as in the opposite directions (Posch et al. 1996). Consequently, the calculation and mapping of critical loads as indicators of ecosystem sensitivity to acid deposition in regions outside of Europe are of great scientific and political interest, and some preliminary attempts have been made to calculate the acidification loading for Asia (Dianwu et al. 1994; Acid Deposition Survey 1995; Shindo et al. 1995; World Bank 1994; Kuylenstierna et al. 1995; Bashkin et al. 1995, 1996a, b, c; Bashkin 1997b; Kozlov et al. 1997).

It has been argued (Bashkin et al. 1995) that the best approach to the calculation and mapping of critical loads on ecosystems in East Asia[1] is to use various combinations of expert approaches and geoinformation systems, including different modern methods of expert modeling and environmental risk assessment. These systems can operate using databases and knowledge bases relative to the areas with great spatial data uncertainty. As a rule, the given systems include an analysis of the cycles of various elements in the key plots, a choice of algorithms describing these cycles, and corresponding interpretation of the data. This approach requires numerous cartographic data, such as vegetation, soil, geochemical and biogeochemical maps, information on pollution and buffering capacity of soil, water and atmosphere. This approach is the most appropriate for Russia as well as for other Asian countries such as China, India, Thailand where, at present, adequate information on the great spatial variability of natural and anthropogenic factors is either limited or absent (Bashkin et al. 1996a, b).

The applicability of these approaches for the assessment of acidification loading on the terrestrial ecosystems in the East Asia is made here using the examples of North-Eastern Asia (Asian part of Russia) and South-Eastern Asia (Northern part of the Thailand). In spite of the great differences in climate, soil and vegetation conditions, these regions can serve as a good test of the proposed methodology.

In this paper we assess the applicability of critical load methodology for the determination of ecosystem sensitivity to acidic deposition in East Asia using a modeling approach that incorporates rates of biogeochemical cycling.

Methods

It is well known that biogeochemical cycling is a universal feature of the biosphere, which provides its sustainability against anthropogenic loads, including acid forming compounds. Using biogeochemical principles, the

[1] For the purposes of this paper East Asia includes both East Asian and South-East Asian regions.

concept of critical loads (CL) has been developed in order to calculate the deposition levels at which effects of acidifying air pollutants start to occur. A UN/ECE (Economic Committee of Europe) working Group on Sulfur and Nitrogen Oxides has defined the critical load on an ecosystem 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' (Nilsson & Grennfelt 1988). These critical load values may be also characterized as 'the maximum input of pollutants (sulfur, nitrogen, heavy metals, POPs, etc.), which will not introduce harmful alterations in biogeochemical structure and function of ecosystems in the long-term, i.e., 50–100 years' (Bashkin 1997).

The critical load concept intended to achieve the maximum economic benefit from the reduction of pollutant emissions since it takes into account the estimates of differing sensitivity of various ecosystems to acid deposition. Thus, this concept is considered to be an alternative to the more expensive BAT (Best Available Technologies) concept (Posch et al. 1996). Critical load calculations and mapping allow the creation of ecological-economic optimization models with a corresponding assessment of minimum financial investments for achieving maximum environmental protection.

Results and discussion

Biogeochemical approaches to assessment of ecosystem sustainability to acid deposition

Conceptual ideas

Soil and land-use databases characterizing biogeochemical cycling of S and N compounds can serve as a basis for critical load calculation and mapping (Bashkin et al. 1995). The question arises, however, as to how we can combine steady-state and dynamic approaches to avoid both exaggeration and underestimation of ecosystem sensitivity especially in the predominant north Asian areas such as the arctic and subarctic permafrost zones and in the subtropical and tropical zones where the greatest number of ecosystems occur.

We developed an approach which applies two dimensionless coefficients to weigh various parameters such as the rates of chemical weathering, nutrient uptake, nitrogen immobilization and denitrification. These parameters are widely used in models for critical load calculations (UBA 1996). First, a coefficient of biogeochemical cycling, Cb, which we have determined as a ratio of litterfall input to decomposition, is calculated to take into account the speed of circulation of various elements, including pollutants. The required

Cb values have been calculated for the all main ecosystems of East Asia based on literature devoted to an assessment of biological turnover and geochemical mapping (Bashkin et al. 1995; Bashkin 1996). Consequently, in accordance with existing data and preliminary estimations, Cb varies from >35–50 for arctic swamps with very depressed (slow) biogeochemical turnover to ≤0.1–0.2 for tropical rain forests with very intensive (fast) turnover (Table 1). Secondly, for northern areas the real duration of any processes (biochemical, microbiological, geochemical, biogeochemical) must be taken into account because they are depressed annually for 6–10 months and the influence of acid forming compounds, as well as any other pollutant, occurs during summer. A process duration term has been derived as the active temperature coefficient, Ct, which is the duration of active temperatures >5 °C relative to the total sum. This is applied as a correction to Cb values.

Characterization of soil-biogeochemical conditions in East Asia

The interest in acidic deposition has resulted in the development of intensive biogeochemical investigations of a large number of ecosystems in North America, Europe, Asia and South America (Moldan & Cherny 1994; Bashkin & Park 1998). The biogeochemical cycling concept is designed to summarize the cycling process within various components of ecosystems such as soil, surface and ground water, bottom sediments, biota and atmosphere. Ecosystem and soil maps can serve as a basis for biogeochemical mapping (Glazovskaya 1990). Combining these maps with the quantitative assessments of organic matter (OM) biological turnover, as well as climate data, gives an opportunity to calculate the values of biogeochemical cycling, Cb, and active temperature, Ct, coefficients for different ecosystems using soil-geographic mapping of East Asia.

Consequently, we will briefly describe below the main vegetation, soil, and climatic characteristics, which allowed us to calculate the Cb and Ct values for main East Asian ecosystems. On the basis of case studies and literature data (Moldan & Cherny 1994; Kennedy 1994; NIES 1996; Bashkin & Park 1998) we will also make some preliminary statements on the possible sensitivity of these ecosystems to acid deposition.

Arctic deserts and primitive tundra ecosystems. This zone occurs in the most northern part of the Asian Arctic. These ecosystems are characterized by an arctic climatic regime, related to very severe temperatures, low precipitation (50–150 mm annually) and primitive bush-like, algae and lichen vegetation. The biological OM turnover can be termed as very depressed. The predominant soil types are lithosols and regosols, and in hollows, histosols (Figure 1, Table 1).

Table 1. The values of biogeochemical cycling (Cb) and active temperature (Ct) coefficients in various soil-ecosystem geographical regions of the East Asia.

Ecosystems	Main FAO soil types	Geographical region	Index Figure 1	Cb	Ct
Arctic Deserts and Primitive Tundra	Litosols, Regosols	Eurasian	1_2	10.0	0.06
Tundra	Cryic Gleysols, Histrosols,	Eurasian	2_2	18.0	0.15
Boreal Taiga Forest	Podzols, Podsoluvisols,	North-Siberian	3_6	9.5	0.25
	Spodi-Distric, Cambisols,	Central-Siberian	3_7	9.3	0.30
	Albi-Gleyic Luvisols,	East-Siberian	3_8	7.5	0.20
	Gelic and Distric Histosols, Rendzinas and Gelic Rendzinas, Andosols,	Kamchatian-Aleutian	3_9	5.0	0.25
Taiga Meadow Steppe	Gleysols Planosols	Central-Yakutian	4_a1	10.0	0.35
Subboreal Forest	Podzols, Dystric and	East-Asian	5_a1	2.6	0.67
	Eutric Cambisols, Umbric Leptosols, Podsoluvisols	East-Chinese	5_a2	1.5	0.81
Forest Meadow Steppe	Luvic Fhaeozems,	South Siberian	6_a4	2.0	0.42
	Chernozems	Amur-Manchurian	6_a5	1.5	0.65
Steppe	Chernozems, Kashtanozems Solonetzes	Mongelean-Chinese	8_a2	0.8	0.61
Desert Steppe and Desert	Xerosols, Regosols,	Pamir-Tibetan	11_a2	0.6	0.62
	Arenosols, Yermosols,	Hindukush-Alayean	11_a5	0.4	0.86
	Solonetzes, Solonchaks	Tan-Shanean	11_a6	0.6	0.60

Table 1. Continued.

Ecosystems	Main FAO soil types	Geographical region	Index Figure 1	Cb	Ct
Savanna and Tropical Forest	Livi-Plinticic Ferrasols, Luvisols, Vertisols, Subtropical Rendzinas, Ferralitic Cambisols, Nitosols, Arenosols, Ferralitic Arenosols,	South-Asian	12_a1	0.3	1.00
Subtropical and Tropical Wet Forest	Subtropical Solonchaks, Ferrasols, Eutric Subtropical Histosols, Gleyic Subtropical Podzols, Plinthic Gleysols, Nitosols	South-East-Asian	13_a1	0.2	1.00
		Himalayan	13_a2	0.4	0.80
		Malaysian	13_a3	0.1	1.00

Tundra ecosystems. These ecosystems are characterized by low temperature, a short but very intensive period of active temperatures (the mean values of Ct is equal to 0.15), wide distribution of permafrost, low precipitation, low biological and microbiological activity and low rate of chemical weathering. The mean Cb values are equal to 18 (15–50), which correspond to a very depressed type of biogeochemical cycling. However, the long winter period enhances the accumulation of various pollutants in snow cover, which intensifies their influence on different components of ecosystems during the short summer period.

Boreal Taiga forest ecosystems. These coniferous forests are characterized by a low organic matter turnover (depressed type of biogeochemical cycling); the Cb values vary from 5.0 to 9.5. Under cold climate conditions the additional stress of acidic deposition to the exposed plants may tend to make the vegetation in the taiga forest ecosystems more sensitive to the changes caused by acidification (Glazovskaya 1990; Kennedy 1994; Kuylenstierna 1995).

Taiga meadow steppe ecosystems. Under the long severe winter period and hot, dry short summer, the biological turnover is depressed in these ecosystems; mean Cb is equal to 10 (Figure 1, Table 1).

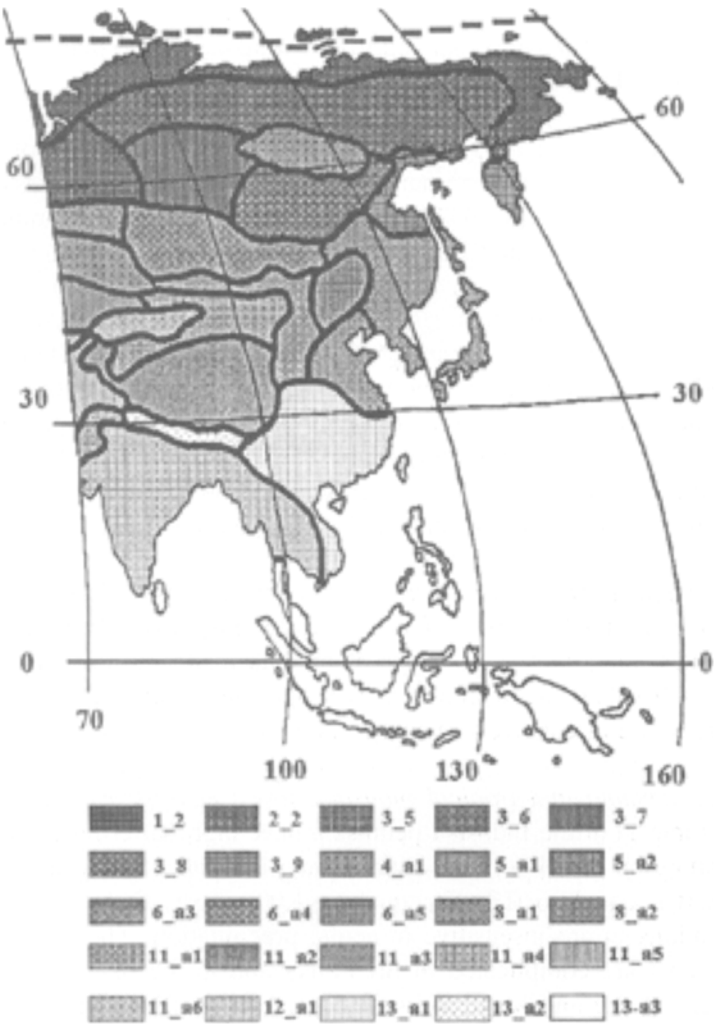

Figure 1. Map of soil-biogeochemical regions in East Asia. Key to legend is presented in Table 1.

Subboreal forest ecosystems. These ecosystems are in a monsoon climate and are characterized by a moderate rate of organic matter turnover with mean values of Cb equal to 2.5 and Ct equal to 0.67. Such moderate rates are favorable to soil acidification with deposition input of sulfur and nitrogen acid forming compounds (NIES 1996; Bashkin & Park 1998). This process can be especially enhanced in ecosystems with predominantly vitric andosols where high porosity favors rapid chemical and biogeochemical weathering with allophane-kaolinite formation processes. The abundance of free iron and aluminum oxides under acid soil reactions, reinforced by acidic deposition leads to a release of Al^{3+} ions and toxic influence on the fine roots of trees (Izuta & Totsuka 1996).

Forest meadow steppe ecosystems. The biogeochemical cycling of elements in these ecosystems can be characterized as moderate in depressions and as semi-intensive in high mountain forest ecosystems with cambisols, the average Cb is equal 2 and Ct equal to 0.42.

Steppe ecosystems. The main characteristic features of these ecosystems are related to the continental climate and low precipitation, precipitation: potential (and actual) evapotranspiration (P:PE). P:PE ranges between 0.6–0.3. In accordance with the given climatic conditions, the soils of steppe ecosystems (chernozems, kashtanozems, solonetzes) are characterized by the presence of a few buffer layers, such as humus, carbonate, and gypsum that makes them insensitive to actual and potential acidic precipitation.

Desert-steppe and desert ecosystems. The main soil types of these ecosystems are characterizing by high buffering capacity, high pH values, low ratio of P:PE. Thus, in spite of rapid rates of organic matter turnover and nutrient cycling, Cb values are in limits of 0.3–0.6, these soils and corresponding ecosystems are insensitive to actual and potential acidification.

Xerofitic savanna and tropical monsoon forest ecosystems. The main soil types (Table 1) of the Indostan peninsula have high buffering capacity, high base saturation and low P:PE ratio. Thus, in spite of very intensive OM cycling (Cb equal to 0.3; Ct equal to 1.00) most of the soil/ecosystem combinations in are insensitive to acidic precipitation. These biogeochemical features are complicated in Sri Lanka and in the plain and low plain areas of Mekong and Menam river basins. These subregions are characterized by a monsoon climate with wet summers (1200–1300 mm) and dry winter periods. In the eastern part of the Mekong-Manam geographical subregion the ecosystems with nitosols and rhodic ferrasols are characterized by very intensive biological turnover and a very high buffering capacity. These ecosystems might have low sensitivity to acidic input (Glazovskaya 1990). In contrast, luvi-plinthic and xantic ferrasols, subtropical albi-gleyic luvisols with plinthite are widespread in the depositional low plains of river deltas. The combination of these moisture conditions with very intensive OM cycling (Cb equal to 0.3) leads to the formation of ecosystems which are very sensitive to actual and potential acidic deposition potentiating the release of free Al^{3+} in the soil-water system.

Sub-tropical and tropical wet forest ecosystems. The main characteristic features of these ecosystems are the very old soil parent materials which are transformed by very intensive geochemical weathering leading to the destruction of all primary minerals excepted quartz and the accumulation of new formed minerals such as kaolinite, hematite, gibbsite, hydrogillite. The predominant soils are ferrasols characterized by very low buffering capacity, abundance of free Al^{3+} and Fe^{3+}, acid reaction with soil depth, very intensive biogeochemical cycling of all elements and especially nutrients such as N, P, K, S, Ca, and Mg. The combination of these features with a monsoon and equatorial climate leads undoubtedly to a shift in the original equilibrium towards acidification under the increasing input of acid forming sulfur and nitrogen compounds.

South-east Asian geographical region

The region occurs in the northern part of tropical wet forest ecosystem zone and is predominantly characterized by acric ferrasols. Biogeochemical cycling is very intensive (mean Cb is equal to 0.2) but there are definite differences between hilly plains and low mountains up to 400–500 m a.s.l. (above sea level) and middle elevation mountains (up to 1000 m a.s.l.) where the humus biogeochemical barrier is present in the profiles of podzolized ferrasols.

Himalayan geographical region

This region is situated in the eastern part of Tibet and the Chino-Tibetan mountains. Biogeochemical cycling is very complex with vertical geochemical catenas of different soils, such as evergreen broad leaf forests on mountainous acric ferrasols (1400–2000 m a.s.l.), evergreen and deciduous forests on transitive ferrasol-cambisol soils (2000–2700 m a.s.l.), mixed coniferous/deciduous forest on cambisols (2500–2800 m a.s.l.), dark coniferous forest on histosols, gleysols and cambisols (2700–3000 m a.s.l.) and mountainous meadows on mountainous fhaeozems (3000–3200 m a.s.l.). The soil-ecosystem sequences are connected to climate differences and accompanied by rates of OM cycling progressing from very rapid in the lowest parts ($Cb < 0.2$) to moderate in the highest ecosystems ($Cb > 0.5$). The mean values of the biogeochemical cycling coefficients are equal to 0.4 and the active temperature coefficient to 0.8.

Malaysian geographical region

This region is situated in the Malaysian peninsula, and the islands of the Indonesia and New Guinea. The predominant ecosystems are Wet Equatorial Tropical Forest with ferrasols. In accordance with the very intensive biogeochemical cycling ($Cb < 0.1$) and natural acid features of the soils, all components of ecosystems are very sensitive to actual and potential acidic deposition (Bashkin & Park 1998).

This general assessment of biogeochemical turnover in various East Asian ecosystems is complicated by the uncertainty of the data used to calculate the values of organic matter turnover and corresponding coefficients of biogeochemical cycling of nutrients as well as active temperature coefficients. However, the application of data shown in Table 1 and Figure 1 allows us to take into account the general features of studied ecosystems and carry out more detailed parameterization of various inputs used in critical load calculation models. Furthermore, the calculation and mapping of critical loads allow the developing broad-scale quantitative assessment of East Asian ecosystem sensitivity to acid deposition.

Critical load values of acid forming compounds on ecosystems of East Asia

North-Eastern Asia

The critical load calculations for North-Eastern Asia have been made on the basis of the following data: the inventory of soil types and subtypes, scale 1:5,000,000; biogeochemical regionalization of terrestrial ecosystems, scale 1:4,000,000; annual biomass uptake, scale 1:8,000,000; geology, scale 1:5,000,000; forest data, scale 1:5,000,000; precipitation data and evapotranspiration data, scale $1^\circ \times 1^\circ$ LoLa; sulfur and nitrogen deposition, scale 150 $\times$ 150 km Asian EMEP grid cell. The sources of these data have been shown earlier (Bashkin et al. 1995, 1996a, 1997b).

The calculations of wet and dry sulfur and nitrogen deposition in the North-Eastern part of Asia were made on the basis of meteodata and emissions for 1991 (Galperin et al. 1994).

Using biogeochemical approaches and corresponding mapping, the critical load values for acid forming N and S compounds were calculated running simplified steady state mass-balance (SSMB) model in accordance with the following algorithm (Bashkin et al. 1995, 1996a).

Critical loads of nitrogen

Critical loads of nitrogen were calculated as

$$CL(N) = *Nu + *Ni + *Nde + *Nl_{(crit)},$$

where $*$ means that each of the terms refers to the values at the total (wet and dry) atmospheric deposition at a site. Nu, Ni, Nde and $Nl_{(crit)}$ are acceptable nitrogen uptake, soil immobilization, denitrification and leaching, correspondingly.

Acceptable atmospheric nitrogen uptake ($*Nu$) was given as

$$*Nu = Nupt - Nu,$$

where Nupt = annual accumulation of nitrogen in biomass and Nu = annual uptake of N from the soil (without accounting for deposition N input).

Nupt was calculated accounting for the coefficients of biogeochemical turnover (Table 1). Annual Nu from the soil was calculated on the basis of nitrogen mineralization capacity (NMC) of the soil, which was determined experimentally or calculated using regression equations (Bashkin et al. 1997). So,

$$Nu = (NMC - Ni - Nde)Ct,$$

where

$$Ni = 0.15NMC, \text{ if } C : N < 10 \; Ni = 0.25NMC, \text{ if } 10 < C : N < 14,$$

$$Ni = 0.30NMC, \text{ if } 14 < C : N < 20 \; Ni = 0.35NMC, \text{ if } C : N > 20,$$

$$Nde = 0.145NMC + 6.447, \text{ if } NMC > 60kg/ha/yr,$$

$$Nde = 0.145NMC + 0.900, \text{ if } NMC < 10kg/ha/yr,$$

$$Nde = 0.145NMC + 2.605, \text{ if } 10 < NMC > 60kg/ha/yr.$$

Acceptable immobilization of atmospheric deposition N (*Ni) was found as

$$*Ni = [(0.20NH_4 + 0.10NO_3)/Cb]Ct, \text{ if } C : N < 10,$$

$$*Ni = [(0.30NH_4 + 0.20NO_3)/Cb]Ct, \text{ if } 10 < C : N < 14,$$

$$*Ni = [(0.35NH_4 + 0.25NO_3)/Cb]Ct, \text{ if } 14 < C : N < 20,$$

$$*Ni = [(0.40NH_4 + 0.30NO_3)/Cb]Ct, \text{ if } C : N > 20,$$

where NH_4, $NO_3 - NO_x$ and NH_x wet and dry deposition, respectively.

Acceptable denitrification from atmospheric deposition N (*Nde) was found as

$$*Nde = (Nde/NMC)NtdCt,$$

where Nde/NMC – denitrification fraction, which depends on many features of the soils and is calculated on the basis of experimental data and Ntd – total (wet and dry) N deposition.

Finally, acceptable critical leaching of atmospheric nitrogen ($*Nl_{(crit)}$) was given as

$$*Nl_{(crit)} = QC_{Ncrit},$$

where Q = annual surplus of precipitation (runoff) and C_{Ncrit} = acceptable nitrogen concentration in surface water (ranging from 0.5 to 1.0 mg/L N in dependence upon the standards set in the studied regions).

Critical loads of sulfur

Since for the majority of ecosystems in North-Eastern Asia the ratio of precipitation to potential (and actual) evapotranspiration (P:PE) is to ≤ 1.00 or slightly exceeds 1.00 (except for ecosystems with some cambisols, histosols and andosols), the values of runoff can be neglected in the calculation of critical loads of acidity, CL(Ac), and thus CL(Ac) was calculated as

$$CL(Ac) = (BCwCt)/Cb,$$

where BCw = weathering of base cations.

The application of the biogeochemical coefficient Cb is connected to the intensity of various elements cycling in ecosystems that accompanied with different manifestation of proton formation (for example, nitrogen and sulfur cycles). The use of the active temperature coefficient Ct is related to an accounting of the duration of different processes that are influencing chemical weathering.

Critical loads of sulfur were calculated as

$$CL(S) = SfCL(Ac),$$

where Sf = sulfur fraction of the total sum of sulfur and nitrogen deposition.

This approach has been used in calculations of critical loads in Europe (Posch et al. 1993; Bashkin et al. 1997) as well as for various ecosystems in developing countries (Kuylenstierna et al. 1995).

Values of BCw were calculated on the basis of FAO soil nomenclature, soil parent material and soil texture (De Vries et al. 1993), and calculated values of Cb and Ct were applied. The root zone was assumed to be equal to 0.5 m. (For more details see Manual on Methodologies and Criteria for Mapping Critical Levels and Loads, UBA 1996.)

Exceedances of critical loads

The values of exceedances were calculated as follows:

$$Ex(N) = Ntd - CL(N),$$

$$Ex(S) = Std - CL(S),$$

where Ex(N), EX(S) are the amounts by which the inputs of nitrogen and sulfur compounds exceed the calculated critical loads, and Ntd, Std are nitrogen and sulfur deposition.

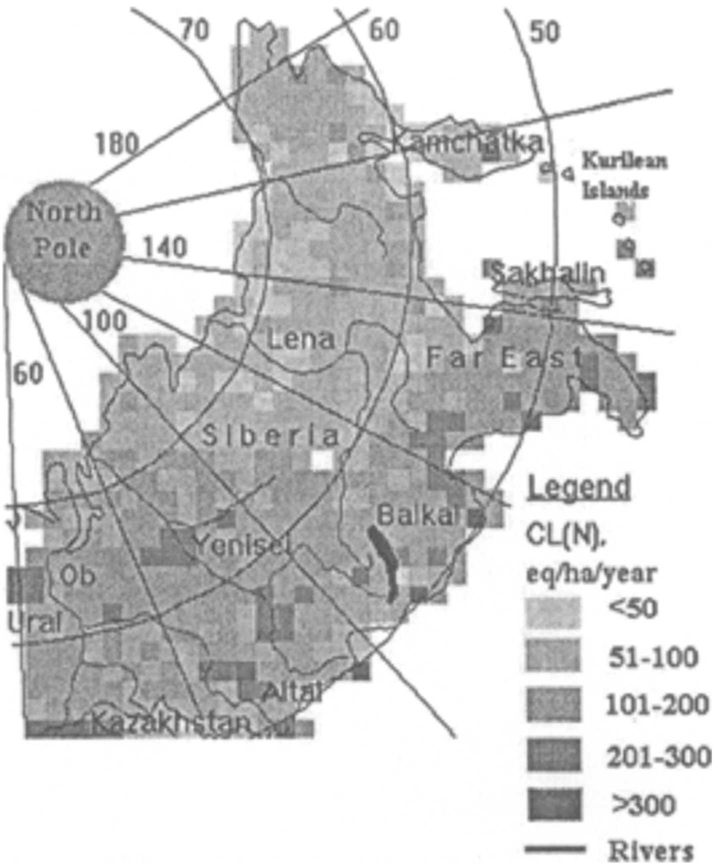

Figure 2. Critical loads of nitrogen on the ecosystems in North-Eastern Asia (Asian part of Russia).

On the basis of the modified and simplified SSMB equations, the critical loads for nutrient and acidifying nitrogen as well as for sulfur and acidity were calculated for various terrestrial ecosystems of North-Eastern Asia. Due to the large dimensions of the area, all calculation and mapping procedures were carried out using a geoinformation system combined with elements of a simplified expert-modeling system (Bashkin et al. 1996a, b). Initial information consisted of geological, vegetation, and soil mapping. For every elemental structural unit (taxon) the main links of biogeochemical cycles of N and S and base cations weathering (BCw) have been characterized quantitatively on a basis of available case studies and literature sources. The grid cells were $1° \times 0.5°$.

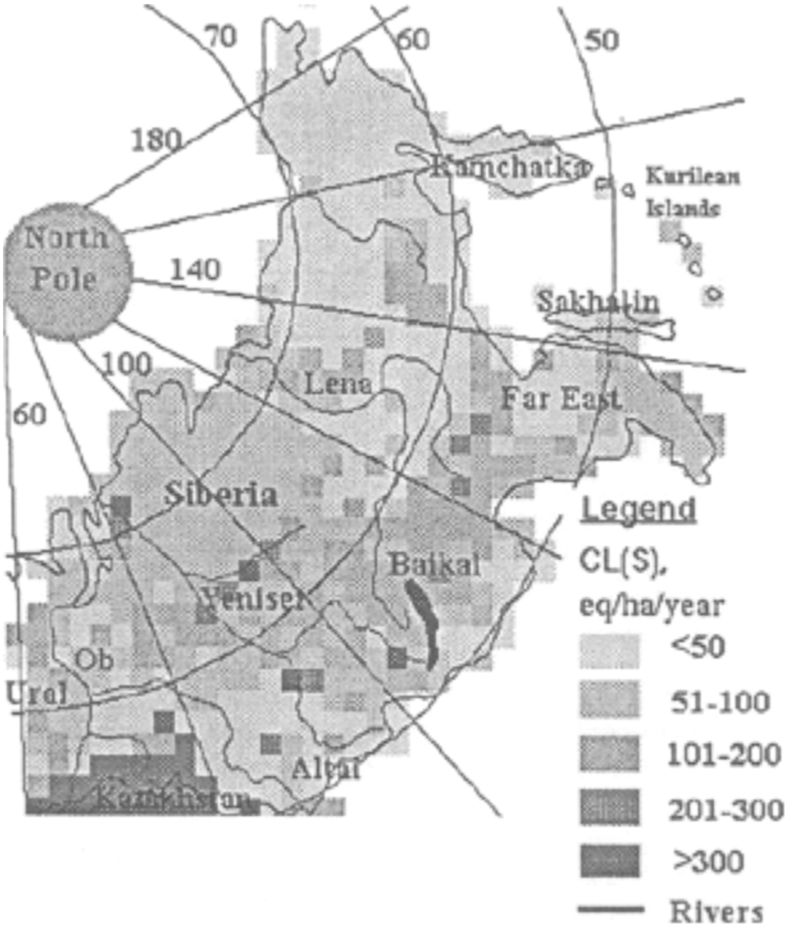

Figure 3. Critical loads of sulfur on the ecosystems in North-Eastern Asia (Asian part of Russia).

For the northern and north-eastern areas of Asia, we calculated that the minimum values of critical loads of nitrogen, CL(N), of <50 eq/ha/yr occur for arctic and subarctic ecosystems (Figure 2). Values of CL(N) in the range of 50–100 eq/ha/yr are typical for the majority of ecosystems in the permafrost area. Therefore, these ecosystems are very sensitive to excessive deposition of nitrogen. Maximum values of CL(N), >300 eq/ha/yr, are noted for ecosystems with chernozemic and chernozem-like soils of the southern regions of Siberia and the Far East. Exceedances of CL(N) are shown mainly in the Ural mountains, in the boundary regions with Kazakhstan, in the lower parts of Enisei river drainage area and in the Far East (Bashkin

Table 2. Distribution of critical load values of sulfur, nitrogen and their exceedances for the North-Eastern Asian ecosystems.

Values range, eq/ha/yr.	Percentage of area under different critical load values		Percentage of area under different exceedance values	
	For nitrogen	For sulfur	For nitrogen	For sulfur
<50	8.3	40.5	88.0	72.7
50–100	40.8	32.4	6.9	14.3
101–200	41.3	18.2	3.9	8.3
201–300	8.0	1.5	1.1	2.6
>300	1.6	7.4	0.1	2.1

et al. 1996a). The minimum values of sulfur critical loads, CL(S), as well as acidity, are shown predominantly in the northern part of East Siberia and in the Kamchatka peninsula (Figure 3). In the area between the Enisei and Ob rivers these values are shown to increase up to 50–100 eq/ha/yr and the maximum values (>300 eq/ha/yr) are shown for ecosystems having neutral and alkaline soils. The corresponding exceedances are indicated for many regions of north-eastern Asia with maximum values for the Altai mountains, for boundary regions within Kazakhstan, in the lower stretches of the Enisei river, and in the Far East, Sakhalin and South-Kurilean islands due to both local and transboundary pollution.

At current rate of atmospheric deposition 88.0% and 72.7% of ecosystems in North-Eastern Asia have no or small (<50 eq/ha/yr) exceedances of CL(N) and CL(S), respectively (Table 2). However, atmospheric deposition in excess of calculated critical loads of N and S are exceeded for 10% and 20%, respectively, of the studied ecosystems in this region.

A comparison of these critical load values with those calculated for corresponding ecosystems in Europe (Bashkin 1997a) reveals lower values in the Asian areas. This can be explained by the more prolonged winter period causing an accumulation of pollutants in the snow layer and their influence on biogeochemical cycling of nutrients during the short spring and summer period. The values of Ct are within the limits of 0.15–0.57 for the majority of North-Eastern Asian ecosystems, whereas in the European part of Russia, for example, the corresponding values are 0.25–0.87. This points to the shorter but very active periods of biogeochemical turnover in almost all of North-Eastern Asian ecosystems accelerating the effects of the acidification loading on the ecosystems.

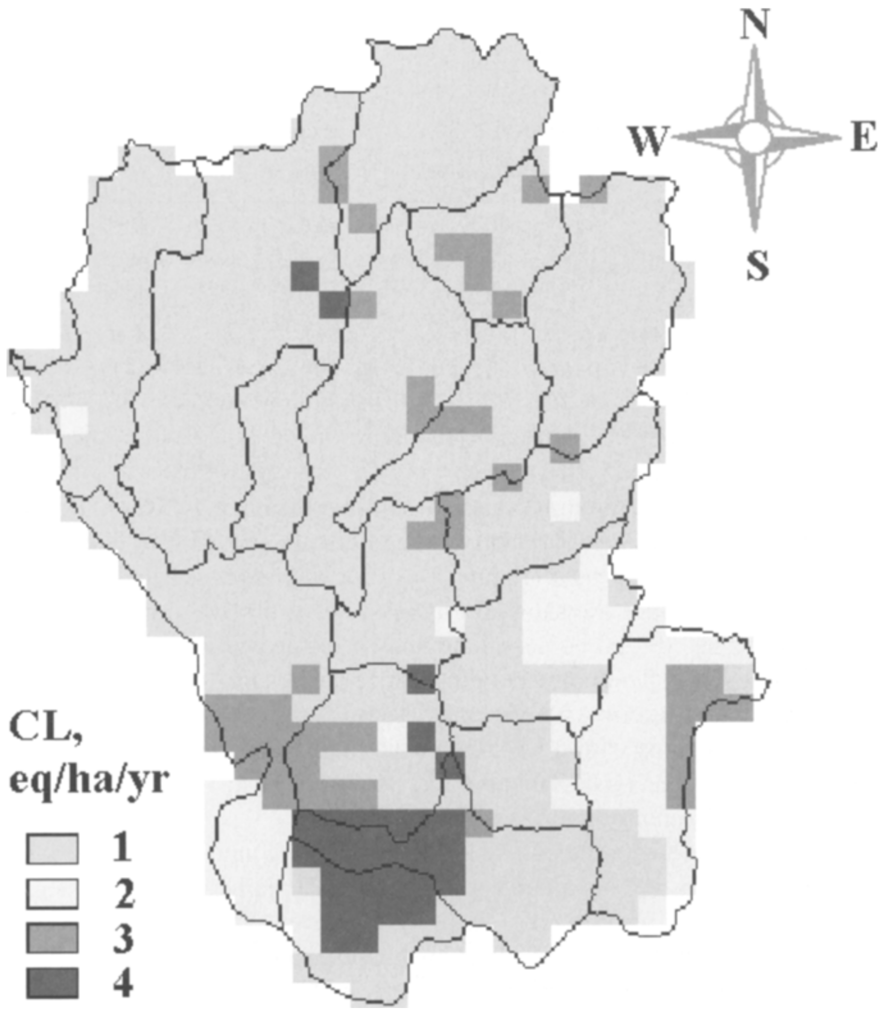

Figure 4. Critical loads of acidity on the ecosystems in South-Eastern Asia (the Northern Thailand). (A) Derived from moisture regime data; (B) Derived from soil types data; for legend description see text.

South-Eastern Asia

The principles carried out by Hettelingh et al. (1995) were also applied during the development of a corresponding algorithm for the calculation of critical loads of acidity in Northern Thailand. The general algorithm description is not different from that applied for the previous calculations of critical loads of acidity on Asian ecosystems in RAIN-ASIA project (World Bank 1994), where only acidity loading was calculated without separating S and N inputs. In our paper, the biogeochemical soil/ecosystem mapping, more detailed soil and land use types with more tine resolution scale were applied in order to recalculate the CL(Ac) values. Furthermore, during the subdivision of the study area into elemental structural units (taxones) the soil-biogeochemical characteristics of each ecosystem were taken into account (Bashkin & Park 1998).

The critical load values for acidity are shown in Figure 4. The map legend includes: 1 – <200, 2 – 200–400, 3 – 400–700 and 4 – >700 eq/ha/yr. The spatial distribution of these values corresponds very closely to soil mapping and partly to land use mapping of the area of Northern Thailand. One can see that the calculated CLs across most of the studied area are low and the sensitivity of the majority of ecosystems to acidification loading is very high. To assess the influence of present deposition on the ecosystems of Northern Thailand, the RAIN-ASIA model run values was used (World Bank 1994). The studied area experiences modest exceedances, usually between 375 and 750 eq/ha/yr, although this level of excess deposition is three to six times greater than the calculated CL values. As a result of both the high sensitivity of ecosystems and level of exceedances across Northern Thailand, more than 75% of the ecosystems across about 50% of this territory is at significant risk from acid deposition.

Although it is difficult to validate these data due to the lack of comprehensive experimental data sets, the high sensitivity of tropical forest and mountain ecosystems to acid loading estimated on a basis of these critical load models is clear.

Conclusions

(1) Ecosystem sensitivity to acidic deposition has been assessed for East Asia using a biogeochemical approach to critical load calculations and mapping. The corresponding values of biogeochemical and active temperature coefficients are presented for ecosystems of the area under study in order to take into account the prolonged winter (north-eastern part) and very active summer (south-eastern part) periods in these ecosystems.

(2) The values of critical loads for acid forming N and S compounds in the north-eastern part of Asia are shown to be less than in Europe due to many peculiarities of the climate and biogeochemical cycling of elements. The minimum values both CL(N) and CL(S) are <50 eq/ha/yr and the maximum values >300 eq/ha/yr, at least 2–3 times less than the corresponding European ecosystems.

(3) The calculated critical load values across most of the area of Northern Thailand are low and the sensitivity of the majority of ecosystems to

acidification loading is very high. As a result of both the high sensitivity of ecosystems and level of exceedances across Northern Thailand, more than 75% of the ecosystems across about 50% of this territory is at significant risk from acid deposition.

(4) The critical loads values for the East Asia territory provide a useful tool for the assessment of current and future acidification loading on the various ecosystems. However, more detailed calculation and mapping research will have to be conducted.

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