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Estimation of Critical Loads of Sulfur and Nitrogen for the Korean Ecosystem

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The critical loads of sulfur and nitrogen and their exceedances by the sulfur and nitrogen deposition of 1994-1998 were mapped for South Korea for the first time with a spatial resolution of 11 km×14 km (0.125° Long.×0.125° Lat.) using the steady-state mass balance model. The Korean soil and geological maps with the map scale of 1 : 250,000 and the Korean forestry statistical yearbooks were used as basis for the estimations of weathering rate of base cations, critical alkalinity leaching, denitrification fraction and uptakes of base cation and nitrogen. Wet depositions of sulfur, nitrogen and non-sea-salt base cations were derived from measured concentrations in precipitation and precipitation rates using optimum regression equations while dry depositions of sulfur and base cations were estimated using the inferential method. However, dry deposition of nitrogen due to NO, NO_2, NH_3 and NH_4^+ species was estimated using the MM5 numerical model, a modified Regional Acid deposition Model (RADM) and the K-mean clustering technique using three consecutive days of gridded daily mean 850 hPa geopotential height fields without precipitation on the last day over South Korea for 5 years. The predominant ranges of base cation deposition, weathering and uptake were estimated to be 300～500 eq ha^{-1} yr^{-1}, 200～500 eq ha^{-1} yr^{-1} and 200～400 eq ha^{-1} yr^{-1}, respectively. Critical alkalinity leaching was mainly in the range of 1,000～2,000 eq ha^{-1} yr^{-1}. Consequently, a large percentage of the maximum critical load of sulfur was found to be in the range of 1,000～2,000 eq ha^{-1} yr^{-1}. The estimated predominant ranges of nitrogen immobilization and uptake were 120～180 eq ha^{-1} yr^{-1} and 300～400 eq ha^{-1} yr^{-1}, respectively, indicating low values of the minimum critical load of nitrogen. The maximum critical load of nitrogen was found to be relatively high (predominantly 2,000～4,000 eq ha^{-1} yr^{-1}) while the critical load of nutrient nitrogen was low (predominantly 400～800 eq ha^{-1} yr^{-1}). Exceedance of the maximum critical load of sulfur was found at 85% of the Korean ecosystems considered mainly in the southeastern part of Korea, whereas that of the critical load of nutrient nitrogen was found in the whole Korean ecosystems. This implies that Korean ecosystems are very susceptible to the combined loadings of sulfur and nitrogen.

Key Words : Exceedance, denitrification fraction, acidic loadings, Korean ecosystems, Minimum critical load of nitrogen

1. Introduction

The acid rain problem has been recognized in Europe and North America as one of the most severe threats to the environment since the end of the 1970s (Alcamo et al., 1990). As a consequence international deliberations on coordinated policies started in the 1970s.

Acidification in East Asia may be viewed as a prototype of emerging environmental problems in an area of rapid economical development during the last decades. The increase of acidifying air pollutant emissions is expected to continue for the next several years due to the accelerated use of fossil fuel burning systems planned in many Asian nations. Therefore, the environmental situation may dramatically exacerbate in future, and counter measures are required to keep the development sustainable avoiding deterious effects on ecosystems in this region.

To assess the impact of acidifying deposition on sensitive ecosystems, we should discuss the relevance of different levels of deposition. One point of reference is the critical load concept (Nilsson and Grennfelt, 1988). This concept is worthwhile to note that it focuses on chemical changes in the environment so as to link between emissions and biological ecosystems while taking into account a time-lag between a change in emissions and a change in chemical effects in the environment.

The difference between the actual deposition and the critical load is called exceedance. Such exceedance indicates areas where damage to ecosystem structure and/or function is expected but this does not tell us when these adverse effects will occur (Warfvinge and Sverdrup, 1995).

The purpose of this paper is to estimate critical loads of sulfur and nitrogen with deposition dependent sink terms by means of the steady state mass balance method (Posch et al.,1995) using national data in South Korea. Korean ecosystems under risk are to be identified by means of the exceedances of the critical loads of sulfur and nitrogen by current sulfur and nitrogen loads.

2. The steady state mass balance model

A simplified acidity balance for a homogeneous soil compartment considering the main source and sinks of sulfur and nitrogen is used to derive critical loads for sulfur and nitrogen following Posch et al. (1995).

The charge balance of the ions in the soil leachate flux (De Vries, 1992) leads to the critical load for sulfur(S) and nitrogen(N) for constant sinks:

$$\begin{aligned} CL(S+N) &= CL(S)+CL(N) \\ &= BC_{dep}-Cl_{dep}+BC_w-BC_u+N_i+N_u+N_{de}-Alk_{le(crit)} \end{aligned} \quad (1)$$

where the subscripts dep, w, u, i, de and le, respectively, stand for deposition, weathering, the net uptake by vegetations, the long-term immobilization of N in the root zone, the denitrification and the leaching. BC is the sum of base cations ($BC=Ca^{2+}+K^{+}+Mg^{2+}+Na^{+}$) and $Alk_{le(crit)}$ is the critical alkalinity leaching.

When comparing S and N depositions to $CL(S+N)$ in equation (1) the nitrogen sinks cannot compensate input sulfur acidity. We define the maximum critical load for sulfur, i.e.

$$CL_{max}(S)=BC_{dep}-Cl_{dep}+BC_w-BC_u-Alk_{le(crit)} \quad (2)$$

Eq. (2) is used to estimate the maximum critical load for sulfur in South Korea by Park and Lee (2001a).

When defining a critical load via equation (1) it is implicitly assumed that all the terms on the right-hand side do not depend on the deposition of S and/or N. However, this is usually not the case. In this study a simple model that is taking into account deposition-dependent sinks of nitrogen is employed. We assume denitrification is related to the net input of N (Posch et al., 1993) by

$$N_{de}=\begin{cases} f_{de}(N_{dep}-N_i-N_u) & if \quad N_{dep}>N_i+N_u \\ 0 & otherwise \end{cases} \quad (3)$$

where f_{de} is the denitrification fraction and N_{dep} is the deposition of nitrogen.

Substituting Eq. (3) into Eq. (1) assuming $CL(S)=0$, the maximum critical load for nitrogen is obtained:

$$CL_{max}(N)=CL_{min}(N)+\frac{CL_{max}(S)}{1-f_{de}} \quad (4)$$

where $CL_{min}(N)=N_i+N_u$, the minimum critical load for N.

The effect of N deposition on nutrient status of an ecosystem is assessed by the critical load for nutrient nitrogen, $CL_{nut}(N)$ that is given by

$$CL_{nut}(N)=CL_{min}(N)+\frac{N_{le(crit)}}{1-f_{de}} \quad (5)$$

where $N_{le(crit)}$ is the critical nitrogen leaching.

When considering the critical load of acidifying and nutrient nitrogen simultaneously, two possibilities arise. One is $CL_{nut}(N) \geq CL_{max}(N)$ and the other is $CL_{nut}(N) \leq CL_{max}(N)$. The first case $CL_{nut}(N)$ can be ignored so that the maximum permissible N deposition by $CL_{max}(N)$, while the second case $CL_{nut}(N)$ limits the maximum permissible N deposition.

3. Calculation of critical loads for sulfur and nitrogen in South Korea

Sulfur and nitrogen critical load calculations basically require the regional quantification of cation fluxes from deposition, weathering, vegetation uptake and leaching.

Atmospheric deposition of non-sea-salt base cation in South Korea is mapped for 1994 to 1997 using the inferential model. For the spatial distribution of the wet deposition flux of base cation, we first derive an optimum regression equation between the measured base cation concentration in precipitation, precipitation rate and air concentration of TSP using the data obtained from the 7 precipitation monitoring sites. Second the derived regression equation is applied to the data set obtained from air monitoring and meteorological observations sites to estimate the base cation concentration in precipitation at 25 sites where the precipitation chemistry is not available but both TSP and surface meteorological data are available (+ signed sites in Figure 1). With these data wet deposition of base cations in South Korea is mapped using a objective analysis technique with a weighting function that is inversely proportional to the square of distance in a spatial resolution of 11 km × 14 km (0.125° Long × 0.125° Lat.). Dry deposition is estimated using the air concentrations derived from rain chemistry, scavenging rates and deposition velocity calculated using surface meteorological data obtained from 65 sites over South Korea (Figure 1). For details see Park and Lee (2001b).

Wet and dry depositions of sulfur are estimated using routinely available meteorological data and the air monitoring data (Park et al., 2000). The method for the estimation of wet deposition of sulfur takes into account different mechanisms of precipitation formation that determines sulfate concentration in precipitation water. Four different precipitation cloud types including cold cloud, warm cloud, stratified cloud and convective cloud, according to their precipitation formations are incorporated differently to estimate sulfate concentration in precipitation water with the airborne sulfate concentration estimated by routinely available air monitored data by optimum regression equations. Two different regression equations for the estimation of airborne

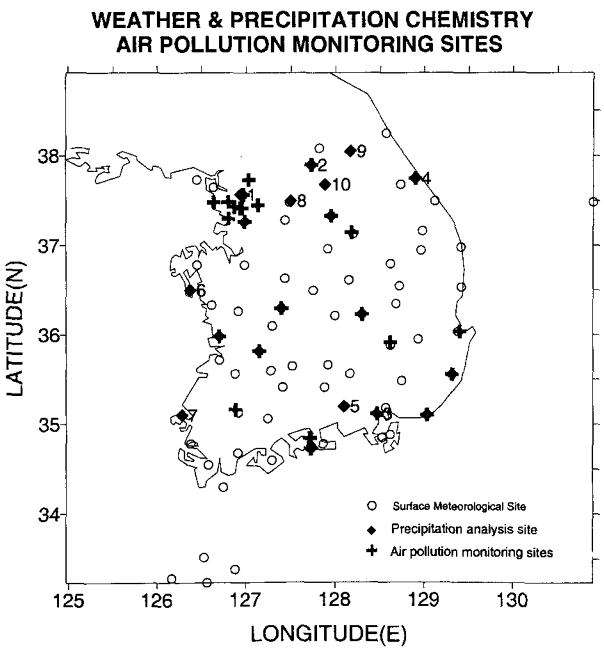

Figure 1 Locations of surface meteorological observation sites (○), air pollution monitoring sites (✚) and precipitation chemistry monitoring sites (◆) in South Korea.

sulfate concentration are developed : one is applicable in winter and the other is other seasons. Estimation of dry deposition of sulfur requires the dry deposition velocities of SO_2 and sulfate and their concentrations. The dry deposition velocity of SO_2 is estimated by inferential method. While that of sulfate is not well established so we have assumed a constant deposition velocity of 0.2 cm s^{-1} followed by the EMEP-II model (Alcamo et al., 1990)

Wet deposition of nitrogen is obtained from optimum regression equations derived with the concentrations of NO_3^- and NH_4^+ in precipitation monitored at 10 sites and the precipitation rates measure at 65 sites supplemented by the annual emission rates of NO_2 and NH_3 in a 11 km × 14 km grid scale in South Korea for 3 years from 1996 to 1998 (Park and Lee, 2002). On the other hand, dry deposition of nitrogen due to NO_2, HNO_3, NO, NO_3^-, and NH_4^+ species is estimated using a modified Regional Acid Deposition Model (RADM) and the K-mean clustering technique using three consecutive days of gridded daily mean 850 hPa geopotential height fields for the non-precipitation case on the last day over South Korea for 5 years from 1994 to 1998 (Park et al., 2001c). The MM5 numerical model is used for the simulation of the consecutive 3-day meteorological fields for each identified cluster in each season. The simulated meteorological fields are incorporated to the transport model and chemical model to estimate dry deposition of nitrogen.

Base cation weathering for various parent rock-soil type associations is estimated using the 99 legends of parent rock types in the Korean geological map with the map scale of 1 : 250,000. Mineral contents for each legend are analyzed using the data available in the literature and the sampled data at 597 sites in South Korea. Geographic Information System (GIS) is applied to estimate weathering rates in each 11 km × 14 km grid according to the Skokloster assignment (Sverdrup and Warfvinge, 1988 ; UBA, 1996). The weathering rate of the individual mineral estimated by its concentration and the mineral class is summed to get the total weathering rate. The mineral classes used in this study are given in Table 1. The Korean soil map with the map scale of 1 : 25,000 is used for the calculation of mineral compositions (Yeo and Kim, 2002).

Uptake of nitrogen and base cations are estimated based on the primary productivity of plant communities and the harvested biomass uptake obtained from the result of Shim and Park (2001). Over the long term, net uptake is equal to the removal in harvested biomass. However, the harvested biomass is about 5% of the net growth biomass in Korea because most of the trees in South Korean forest are younger than the rotation period. Therefore we consider both growth and harvest uptake as total uptake.

Using the annual average growth rate and the contents of the four elements in the various compartments the annual net growth uptake can be calculated as (e.g., De Vries et al., 1993)

$$X_u = k_{gr} \cdot \rho_{st} \, (X_{ST} + f_{br/st} \cdot X_{br}) \qquad (6)$$

where k_{gr} is the annual average growth rate (m^3 ha^{-1} yr^{-1}), ρ_{st} the density of stemwood (kg m^{-3}), X_{st} and X_{br} the content of element X(BC, N) in stems and branches (eq kg^{-1}), respectively and $f_{br/st}$ the branch to stem ratio.

Annual average growth rates in 272 provinces in South Korea are calculated using the data obtained from the statistical yearbook of forestry in Korea from 1995 to 1999. The other data obtained from the literature are shown in Table 2. Annual mean uptake by harvested biomass at 272 provinces are also calculated using timber production data in 1999 (Korea Forest Service, 2000) and the data in Table 2. The calculated growth and harvest uptake at each province is apportioned according to the forest area of the grid.

Table 1 The approximate weathering rates of mineral classes of soil material suggested at the Skokloster workshop (UBA, 1996)

Mineral class	Average mineral class content (%)				
	100	30	3	0.3	0.03
	Weathering rate keq/ha/yr				
Carbonates	25	15	10	3.0	0.3
Fast weathering	8	5	1.5	0.15	0.02
Intermediate weathering	5	3	0.3	0.03	-
Slow weathering	0.6	0.2	0.02	-	-
Very slow weathering	0.3	0.1	0.01	-	-
Inert group	0.1	0.01	-	-	-

Table 2 The density of stemwood, the branch to stem ratio($f_{br/st}$), mean concentrations of nitrogen(N) and base cations(BC) in stems and branches. The values are based on the literature.

Forest type	Stem density (kg m^{-3})	$f_{br/st}$	Mean concentration(eq kg^{-1})			
			N_{st}	N_{br}	BC_{st}	BC_{br}
Coniferous	356	0.26	0.14	0.29	0.12	0.26
Deciduous	695	0.33	0.18	0.33	0.13	0.34
Mixed forest	526	0.30	0.16	0.31	0.12	0.30

The normalized difference vegetation index data with the horizontal resolution of 1.1 km × 1.1 km measured by the Advanced Very High Resolution Radiometer (AVHRR) is used for the vegetation distribution in South Korea. The critical alkalinity leaching is calculated as (e.g., Posch et al., 1995)

$$AlK_{le(crit)} = -Al_{le(crit)} - H_{le(crit)} = -Q([Al]_{crit} + [H]_{crit}) \qquad (7)$$

where the square bracket denotes concentration (in eq m^{-3}) and Q is the precipitation runoff (m^3 ha^{-1} yr^{-1}). The relationship between [H] and [Al] is described by a gibbsite equilibrium such that (e.g., Posch et al., 1995)

$$[Al] - K_{gibb} \, [H]^3 \; or \; [H] = ([Al]/K_{gibb})^{1/3} \qquad (8)$$

where K_{gibb} is the gibbsite equilibrium constant that depends on the soil type. To obtain a critical alkalinity leaching we assume that $[Al]_{crit}$ to be 0.2 eq m^{-3} as in Hettelingh et al.(1992) and K_{gibb} to be given in UBA (1996). The precipitation run-off Q is calculated by the estimation of evapotranspiration using Linacre (1977) method with precipitation rates observed from 65 sites over South Korea for five years from 1994 to 1998 (Figure 1).

Denitrification fraction, f_{de} is calculated in a 11 km × 14 km grid scale according to the soil type and climate conditions with taking care of soil drainage conditions using the Korean soil map following De Vries et al. (1993). The soil texture classified by using the US Department of Agriculture (USDA) in each grid scale is obtained from the detailed Korean soil map with the map scale of 1 : 25,000. The value of f_{de} for each soil texture is given

Table 3 Values of denitrification fraction, f_{de} with soil textures

Soil texture	Sandy Loam	Loam	Silt Loam	Clay Loam	Silty Clay Loam	Silty Clay	Clay
f_{de}	0.2	0.4	0.5	0.6	0.6	0.7	0.7

Table 4 Rate of critical nitrogen immobilization (eq ha^{-1} yr^{-1})

Vegetation / Annual Mean temperature(C)	Coniferous	Deciduous	Mixed forest
< 10	200	180	180
10 – 12	180	140	160
12 – 14	160	120	140
> 14	140	100	120

in Table 3.

The rate of critical nitrogen immobilization, Ni is estimated using the data reported in literature (UBA, 1996) with the annual mean temperature and vegetation types in South Korea. Table 4 shows the value of immobilization of nitrogen used in this study.

For computing critical load of nutrient N, a critical nitrogen leaching has to be specified. When nitrogen appears in significant amounts in the soil solution, plant species composition on the forest or ground vegetation may change (Posch et al., 1995).

The critical N leaching can be estimated as

$$N_{le(crit)} = Q \times [N]_{crit} \quad (9)$$

where $[N]_{crit}$ is a critical N soil solution concentration. Values for $[N]_{crit}$ used in this study are 0.0143 eq m^{-3} for coniferous and 0.0215 eq m^{-3} for deciduous and mixed forests (Posch et al., 1993).

4. Results

Figure 2 shows the spatial distribution of mean annual total deposition of non-sea-salt base cations ($Ca^{2+}+Mg^{2+}+K^{+}$) in a 11 km × 14 km grid scale over South Korea. The annual mean total deposition is about 420 eq ha^{-1} yr^{-1} with the predominant range of 400 to 600 eq ha^{-1} yr^{-1} (Park and Lee, 2001b).

The spatial pattern of the weathering rate of base cations over South Korea is given in Figure 3. The weathering rates range widely from 50 to 23,000 eq ha^{-1} yr^{-1}. However, more than 70% of the weathering rates fall within 500 eq ha^{-1} yr^{-1}. Very high values of the weathering rate occurring in the central eastern part of South Korea are associated with the carbonate mineral.

Figure 4 shows the spatial distributions of the forest coverage (%) and uptake of base cations in a 11 km × 14 km grid scale (Shim and Park, 2001). The forest includes coniferous, deciduous and mixed forest that occupy about 22%, 15% and 16% of the whole area of South Korea, respectively. The annual total uptake of base cations by growing and harvested biomass is about 312 eq ha^{-1} yr^{-1} with the predominant range of 200 to 400 eq ha^{-1} yr^{-1} (Figure 4b).

The spatial distributions of the annual mean run-off estimated using the observed meteorological data at 65 sites (Figure 1) from 1994 to 1998 and critical alkalinity leaching over South Korea are given in Figure 5. The lowest run-off of less than 200 mm yr^{-1} occurs in the southeastern part of Korea, whereas the maximum of more than 800 mm yr^{-1} occurs in the northeastern part of Korea where high mountains are located (Figure 5a). The lowest values of critical alkalinity leaching occur in the southeastern part of Korea in accordance with the region of the lowest run-off. More than 80% of the area analyzed has critical alkalinity leaching values less than 1,500 eq ha^{-1} yr^{-1} while values larger than 1,500

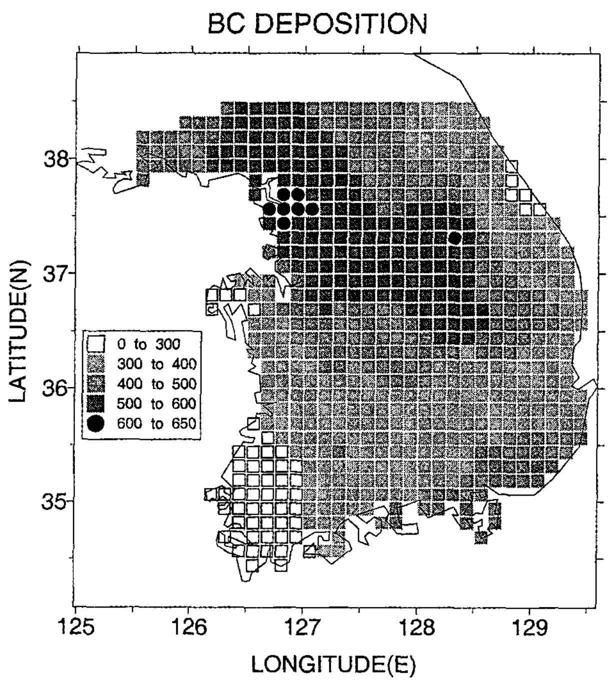

Figure 2 Spatial distribution of annual total deposition of non-sea-salt base cations (eq ha^{-1} yr^{-1}) in a 11 km × 14 km grid scale over South Korea.

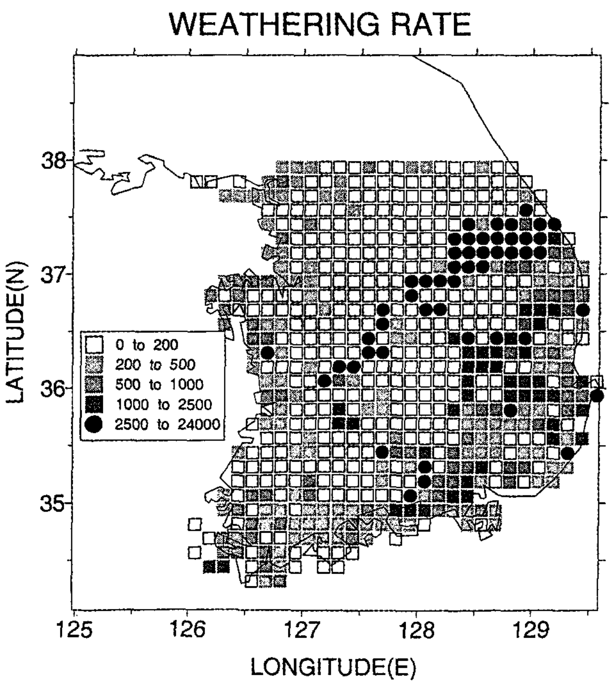

Figure 3 Spatial distribution of weathering rate (eq ha^{-1} yr^{-1}).

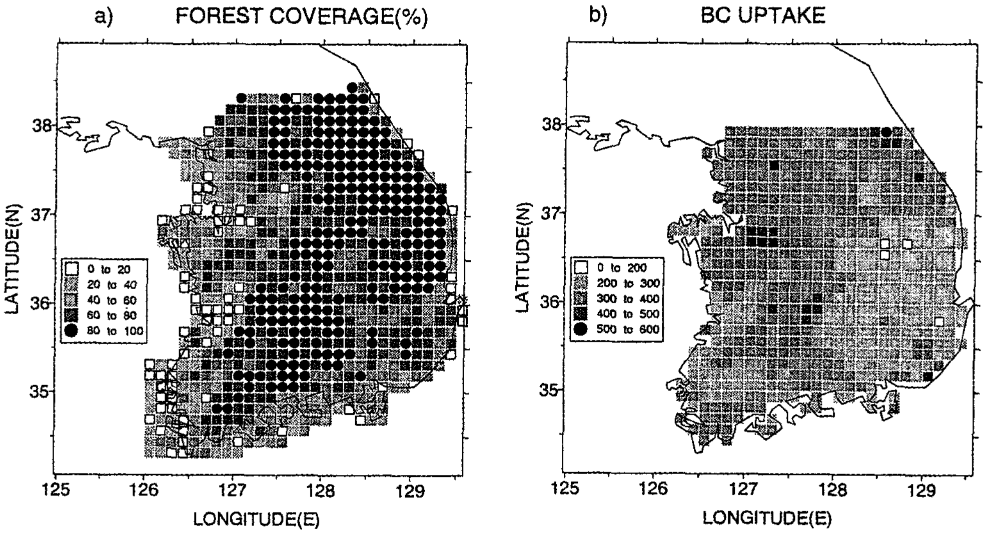

Figure 4 Spatial distributions of a) forest coverage(%) and (b) base cation uptake (eq ha^{-1} yr^{-1}).

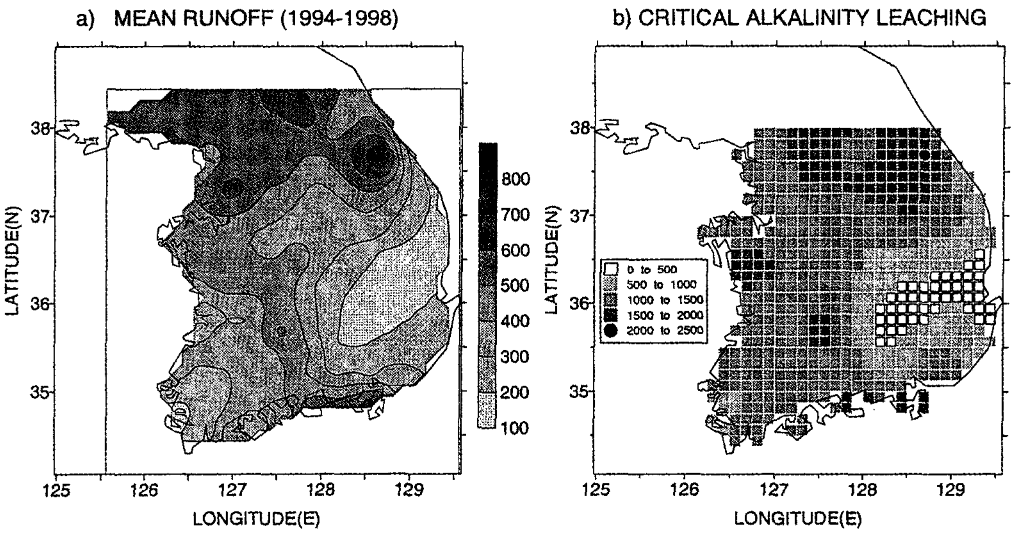

Figure 5 Spatial distributions of annual mean total (a) runoff (mm) and (b) critical alkalinity leaching (eq ha^{-1} yr^{-1}) in South Korea.

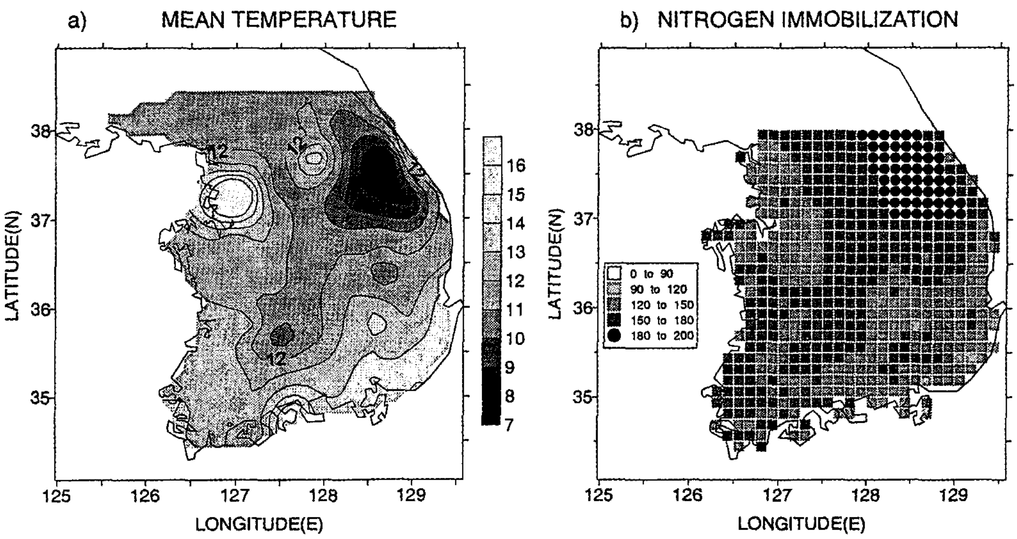

Figure 6 Spatial distributions of (a) annual mean temperature(℃) averaged for 5 years and (b) annual total nitrogen immobilization(eq ha^{-1} yr^{-1}).

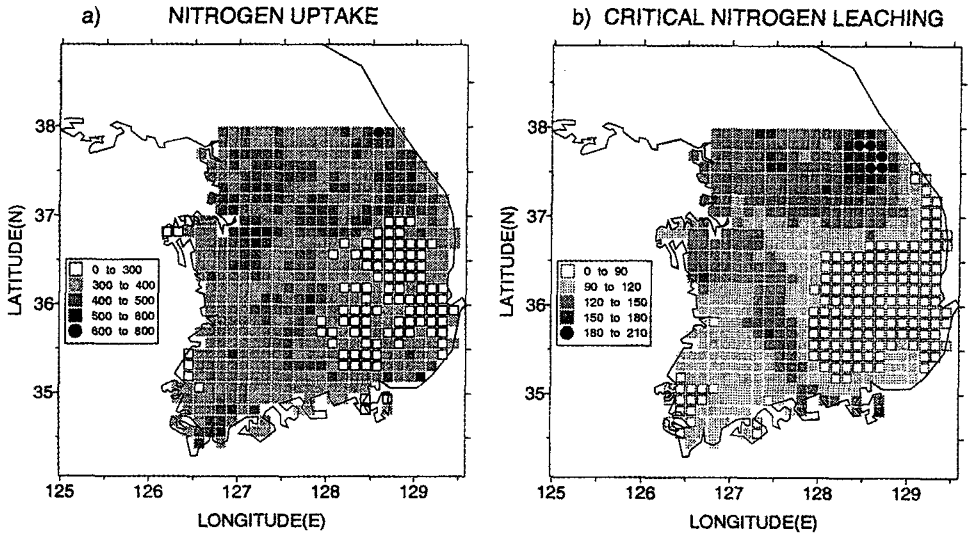

Figure 7 Spatial distributions of (a) nitrogen uptake(eq ha^{-1} yr^{-1}) and (b) critical nitrogen leaching(eq ha^{-1} yr^{-1}).

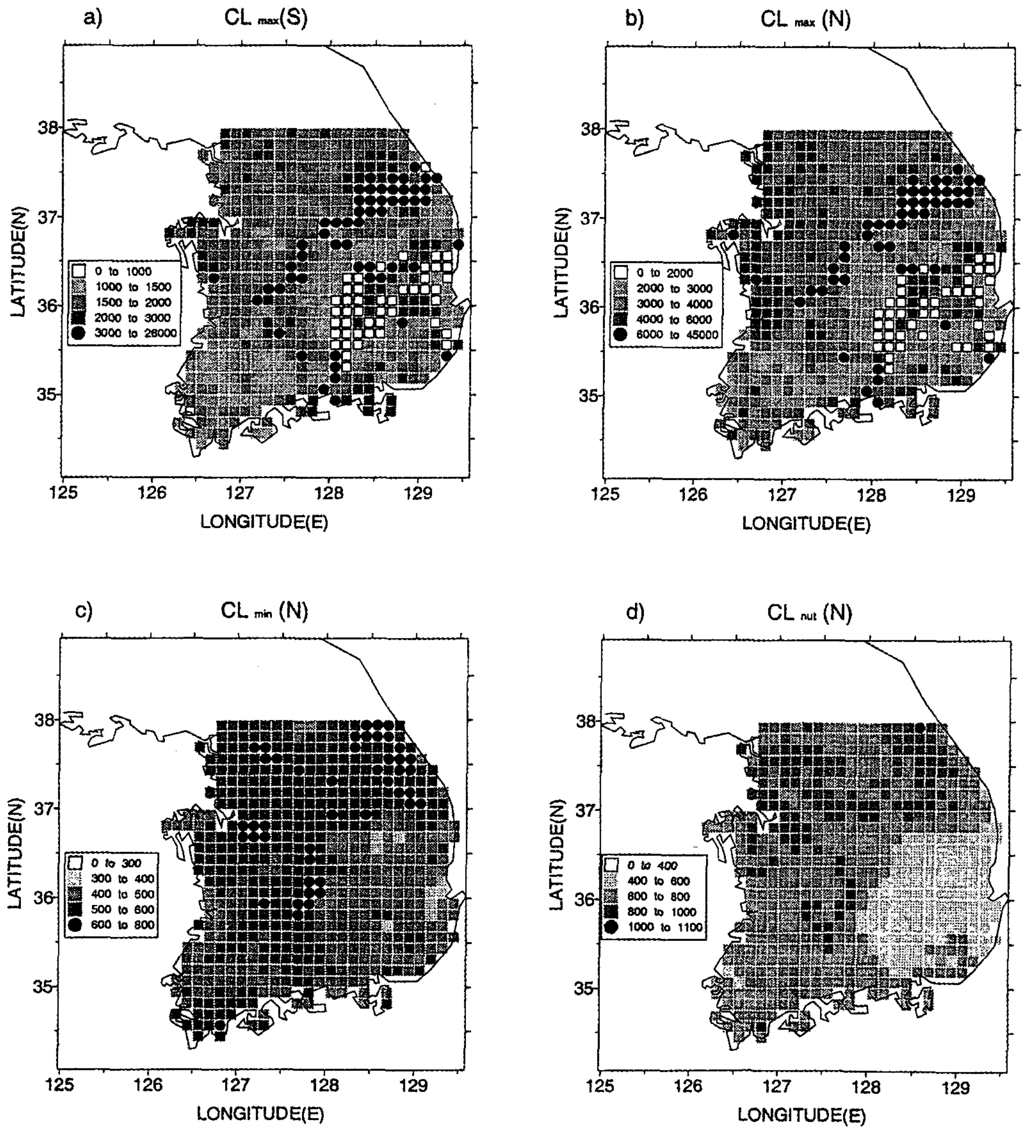

Figure 8 Spatial distributions of the maximum critical loads of (a) sulfur and (b) nitrogen, (c) the minimum critical load of nitrogen and (d) the critical load of nutrient nitrogen in a 11 km × 14 km grid scale. All units are given in eq ha^{-1} yr^{-1}.

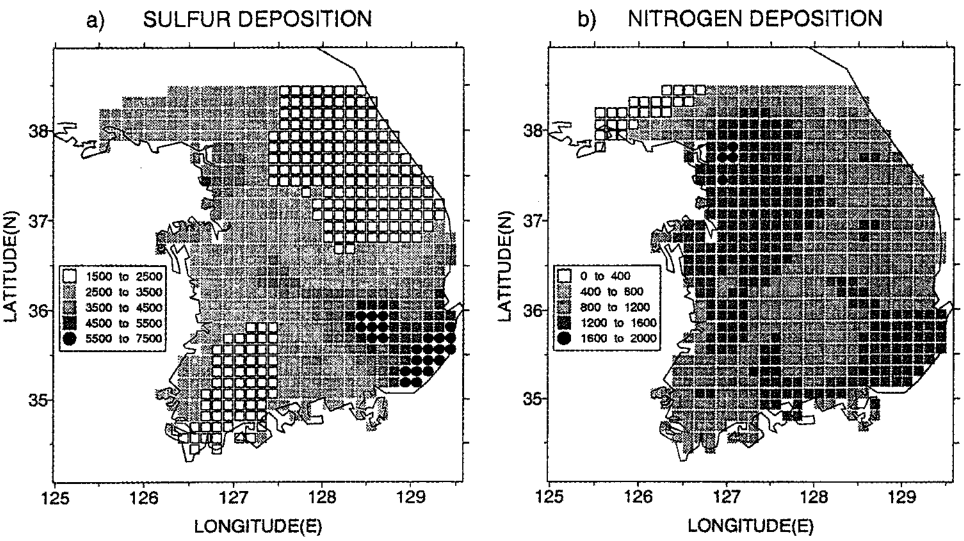

Figure 9 Mean annual total deposition of (a) sulfur (eq $ha^{-1} yr^{-1}$) and (b) nitrogen (eq $ha^{-1} yr^{-1}$).

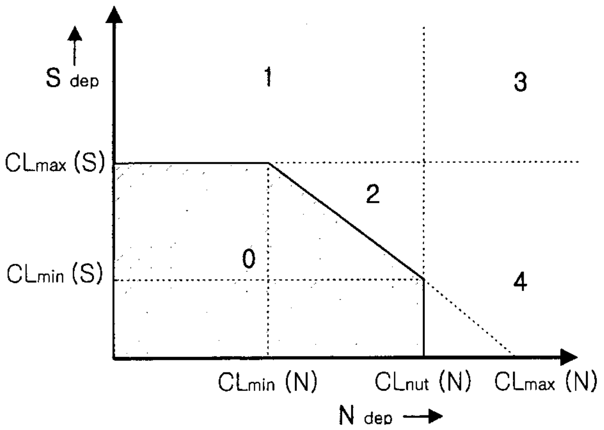

Figure 10 Relationship between sulfur and nitrogen deposition and the critical loads of sulfur and nitrogen and the critical load of nutrient nitrogen for the case of $CL_{nut}(N) < CL_{max}(N)$. The five cases of exceedance are indicated. 0 ; No exceedance, 1 ; mandatory S reductions, 2 ; N or S reductions, 3 ; mandatory N and S reductions and 4 ; mandatory N reductions.

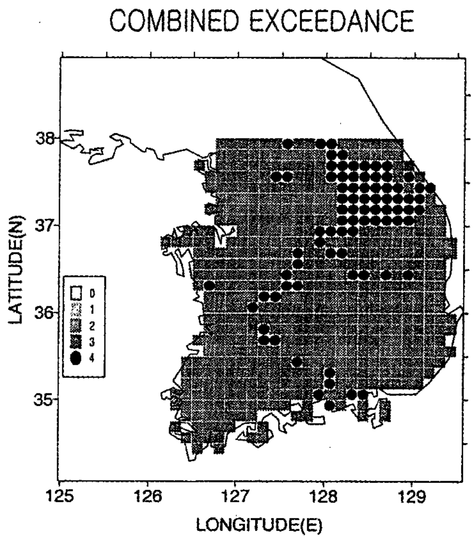

Figure 11 Spatial distributions of the exceedances of the combind critical loads of sulfur and nutrient nitrogen in terms of regions classified in Figure 10.

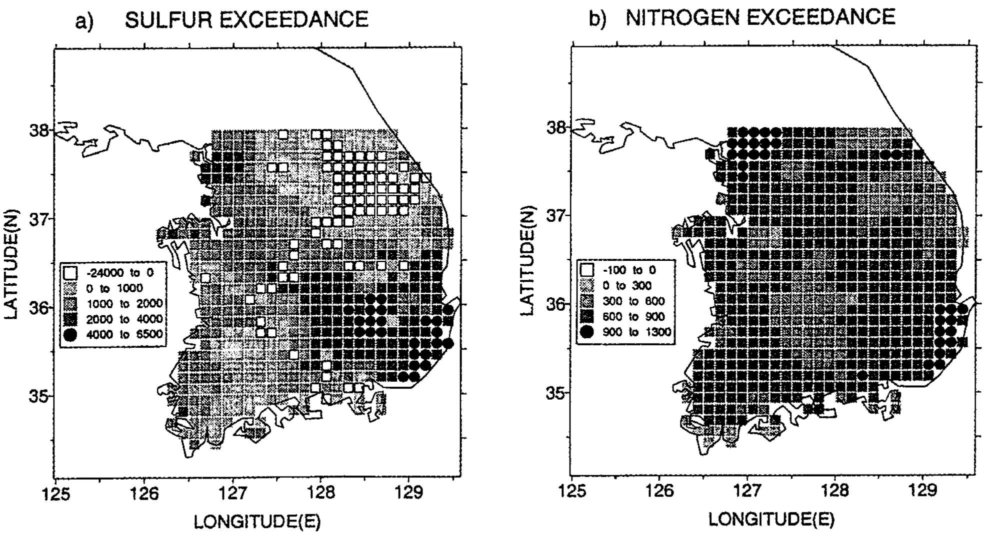

Figure 12 Spatial distributions of exceedances (eq $ha^{-1} yr^{-1}$) of (a) the maximum critical load of sulfur and (b) the critical load of nutrient nitrogen.

eq $ha^{-1} yr^{-1}$ are only found at 17% of the analysis domain (Figure 5b).

The spatial distributions of annual mean temperature averaged for the years 1994 to 1998 at 65 sites and the estimated nitrogen immobilization are given in Figs. 6a and 6b, respectively. The relatively low temperature occurs along the mountain ranges that extend from north to south along the east coastline and from the central eastern coast to the southwestern coastline in South Korea (Figure 6a). The spatial distribution pattern of the annual mean nitrogen immobilization (Figure 6b) is quite similar to that of temperature (Figure 6a) with high values in the low temperature regions. The annual mean nitrogen immobilization ranges from 114 eq $ha^{-1} yr^{-1}$ to 197 eq $ha^{-1} yr^{-1}$ with the annual mean of 158 eq $ha^{-1} yr^{-1}$ over South Korea (Figure 6b).

Figure 7a shows the spatial distribution of total nitrogen uptake including the growing and harvested biomass of Korean forests. The annual mean nitrogen uptake is about 370 eq $ha^{-1} yr^{-1}$, of which 95% is contributed by the forest growings. The predominant range of nitrogen uptake is 300∼400 eq $ha^{-1} yr^{-1}$ (Shim and Park, 2001). The estimated critical nitrogen leaching is displayed in Figure 7b. The spatial distribution pattern quite resembles that of runoff in Figure 5a with relative large values in the high runoff regions. The annual mean critical nitrogen leaching is 100 eq $ha^{-1} yr^{-1}$ with the predominant range of 90∼150 eq $ha^{-1} yr^{-1}$.

The maximum critical load for sulfur (Figure 8a) is low (< 1,000 eq $ha^{-1} yr^{-1}$) in the southeastern part of Korea, while high critical loads are seen in the northeastern part of Korea. More than 42% of Korean ecosystems considered have maximum critical load of sulfur between 1,500 eq $ha^{-1} yr^{-1}$ and 2,000 eq $ha^{-1} yr^{-1}$.

The maximum critical load for nitrogen (Figure 8b) is relatively high with the predominant range of 2,000∼4,000 eq $ha^{-1} yr^{-1}$. High maximum critical load of nitrogen(> 6,000 eq $ha^{-1} yr^{-1}$) is found in the northeastern part of Korea, while low critical loads are found in the southeastern part of Korea.

The sum of nitrogen immobilization in Figure 6b and nitrogen uptake in Figure 7b yields the minimum nitrogen critical load, $CL_{min}(N)$ and is displayed in Figure 8c. Areas of high minimum nitrogen critical load are found in the northeastern part of Korea. The annual mean minimum nitrogen critical load is 515 eq $ha^{-1} yr^{-1}$ with the predominant range of 400∼600 eq $ha^{-1} yr^{-1}$.

The critical load of nutrient nitrogen (Figure 8d) is low (< 400 eq $ha^{-1} yr^{-1}$) in the southeastern part of Korea, while high critical loads are seen in the northeastern and the northwestern parts of Korea. More than 75% of the analysis domain considered have the critical load of nutrient nitrogen between 400 eq $ha^{-1} yr^{-1}$ and 800 eq $ha^{-1} yr^{-1}$ with the annual mean of 700 eq $ha^{-1} yr^{-1}$.

The spatial distribution patterns of annual mean total sulfur deposition estimated by Park et al. (2000) and that of nitrogen deposition by Park and Lee (2002) averaged for the years 1994 to 1997 are shown in Figure 9. High sulfur deposition occurs in the southeastern and the central western parts of Korea while low deposition of sulfur occurs in the central eastern part of Korea (Figure 9a), whereas high nitrogen deposition occurs in the central western and the southeastern parts of Korea. The former is largely attributed to wet deposition of nitrogen while the latter is mainly attributed to dry deposition of nitrogen (Figure 9b).

The permissible depositions of acidifying nitrogen and sulfur are given in Figure 10 for the case of $CL_{nut}(N) < CL_{max}(N)$. Exceedance of the combined critical loads of sulfur and nitrogen determined by the regions in Figure 10 is displayed in Figure 11. Present depositions of sulfur and nitrogen fall in the regions 3 and 4 that occupy more than 85% and 14% of the domain considered, respectively. This suggests that the present deposition levels of sulfur and nitrogen exceed the critical loads of sulfur and nutrient nitrogen for all domain considered. Consequently, counter measures are prerequite to maintain Korean ecosystem sustainability

Even though about 14% of analysis areas do not exceed the maximum critical load of sulfur in the northeastern part of Korea (Figure 12a) in accordance with the location where large values of weathering rate occur due to carbonate minerals, nitrogen deposition exceeds the critical load of nutrient nitrogen in the whole South Korean territory (Figure 12b). Areas of high exceedance of the maximum critical load of sulfur(≥2,000 eq $ha^{-1} yr^{-1}$) are found in the southeastern part of Korea (Figure 12a), whereas area of high exceedance of the critical load of nutrient nitrogen (≥700 eq $ha^{-1} yr^{-1}$) are found in the northwestern and the southeastern parts of Korea (Figure 12b), where the ecosystems are likely affected adversely by present sulfur and nitrogen depositions. In fact, some decay of forests are reported in the Southeastern part of South Korea.

5. Conclusions

Estimated base cation deposition (predominantly 300∼500 eq $ha^{-1} yr^{-1}$), weathering rate (predominantly less than 500 eq $ha^{-1} yr^{-1}$) except for the small areas located by carbonate minerals, uptake (mainly 200∼400 eq $ha^{-1} yr^{-1}$) are found to be relatively low, while relatively high values of critical alkalinity leaching (predominantly 1,000∼2,000 eq $ha^{-1} yr^{-1}$) due to relatively high precipitation runoff are found in South Korea. Consequently, a large percentage of the maximum critical load of sulfur(more than 70%) is in the range of 1,000∼2,000 eq $ha^{-1} yr^{-1}$ as reported in Park and Lee (2001a).

The estimated nitrogen immobilization (mainly 120∼180 eq $ha^{-1} yr^{-1}$) and uptake (predominantly 300∼400 eq $ha^{-1} yr^{-1}$) are found to be low. Therefore, the minimum critical load of nitrogen is relatively low with the predominant range of 400∼600 eq $ha^{-1} yr^{-1}$. The critical load of nutrient nitrogen is also found to be relatively low with more than 75% of the analysis domain belonging to the range of 400∼800 eq $ha^{-1} yr^{-1}$. The exceedance of the combined critical loads of sulfur and nutrient nitrogen indicates that the Korean ecosystems are under the influence of high stress due to present depositions of sulfur and nitrogen especially in the southeastern part of Korea, suggesting emission reductions of acidic precursors being needed for the Korean ecosystem sustainability.

Areas with no exceedance of the maximum critical load of sulfur are found in the northeastern part of Korea but the nitrogen deposition in these areas exceeds the critical load of nutrient nitrogen. Therefore areas with no exceedance of the combined critical loads of sulfur and nutrient nitrogen are not found in South Korea.

In this study we have made every effort to estimate more accurately each parameter that is related to the evaluation of critical loads of sulfur and nitrogen using available national data. However, some parameters including the weathering rate of carbonate mineral and soil type dependency of the denitrification fraction should be studied in more detail.

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