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Original Research

The Impact of Acid Deposition on China's Three Gorges Reservoir

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Abstract

In the Three Gorges Reservoir area, 78.1% of precipitation pH was measured below 5.6 by gathering 233 samples of precipitation in 2009-13. The forest ecological system in this area was threatened. In order to quantify the acid risk to the forest ecosystem, acid deposition and nutrient nitrogen critical loads in the area were estimated using simple mass balance equations based on the critical load concept. The values of acid deposition and nutrient nitrogen critical loads varied from 0 to 10.3 $keq \cdot ha^{-1} \cdot yr^{-1}$ and from 0 to 3.5 $keq \cdot ha^{-1} \cdot yr^{-1}$, respectively. Among them, acid critical loads were mostly sensitive to net nitrogen uptake and the ratio of Bc to Al. The accuracy of two parameters improved for reducing the evaluation error of critical loads. And then, exceedance of critical loads was calculated on the basis of critical loads. For the forest soil, exceedance of critical loads were predicted (0-2.1 $keq \cdot ha^{-1} \cdot yr^{-1}$). Acid critical loads were exceeded approximately 4.8% across the entire region, which affected nutrient pools in forested mineral soils. For the forest plants, 20.1% of the forests were predicted to exceed the empirical critical load. In addition, plant species diversity was significantly reduced with the increase of nitrogen deposition. This suggested that forest soil and plants have been adversely affected by acid deposition in some regions of the reservoir area. Thus, the impact of acid deposition on the forest ecosystem can provide key protection regions for the government and a basis for the implementation of emissions reduction policy.

Keywords: acid deposition, critical load, forest ecosystem, Three Gorges Reservoir area

Introduction

Previous studies have described atmospheric sulfur (S) and nitrogen (N) deposition as one of the most serious global environmental problems [1-3]. The results have seen the appearance of a number of negative effects on forest ecosystems. For example, excessive nitrogen deposition causes fallen leaves and death [4], and excessive acid deposition has contributed to acidification of soils, export of nutrient cautions, and mobilization of aluminum (Al) in soils [5, 6]. In addition, acidification of the soil is toxic to plants and other biota, and cation depletion in soils may cause a wide range of plant health problems, such as growth rate decrease and forest species composition changes [7, 8]. According to the Ministry of Environmental Protection [9], the Chinese government established compulsory targets for emission reduction. However, the National Bureau of Statistics of China [10] reported that the consumption of coal nationwide has amounted to 3.75×10^9 tons in 2013 – 3.7% more than the previous year. S and N depositions are still increasing, especially in southeast China because of growing industrial and agricultural activities [11]. In such a situation, it is necessary to assess the impact of acid deposition on the forest ecosystem to develop a reasonable emission-reduction policy.

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In general, the critical load, defined as the highest acid deposition below which significant damage does not occur, does not occur over the long-term [12] and is applied to quantify the sensitivity of ecosystems to acidification and eutrophication. The fundamental theory of the critical load presents a mass balance between sources and sink of sulphur (S) and nitrogen (N) in the forest ecosystem. If sources are larger than sinks, the ecosystem is safe. On the contrary, if sources are smaller than sinks, the ecosystem is at risk and may be damaged. Deposition in excess of the critical load is known as an indication of the long-term potential for harmful effects to ecosystems at a steady state [13].

Various approaches have been designed to assess the critical loads of ecosystems, including PROFILE, SMB (simple mass balance model), MACAL (model to assess a critical acid load), MAGIC (model of acidification of groundwater in catchment), SAFE (soil acidification in forested ecosystems), SMART (simulation model for acidification's regional trends), and so on [14-19]. Here, the SMB model is applied to estimate critical load due to its simple model structure, lower data requirements, and suitability for large-scale applications [15, 20]. This model uses static soil, vegetation, and acid deposition data to estimate critical loads and the exceedance of critical loads [21]. At present, it has been widely used in Europe, Canada, and the United States [22-24]. This paper describes acid, nutrient nitrogen critical loads, and exceedance level based on the concept of critical loads in the Three Gorges Reservoir area. The main concern is to assess the impact of acid deposition on the forest ecosystem in the area and classify the regions that should be protected to set reasonable emission-reduction policies. In addition, the sensitivities inherent in the predictions of critical loads were explored using single-parameter sensitivity analysis.

Methods

Site Description

The study area (Fig. 1) in Three Gorges, China (28º10'-32º13' N and 105º17'-110º11' E) [25] encompasses 20 counties of Hubei province and Chongqing municipalities. The catchment area is approximately 58,000 km^2. Long-term mean annual air temperature is about 18.2ºC across the area [26]. Average annual precipitation is 1,172 mm, and the rainy season is concentrated in May to September [26]. The main soil types are purple (47.8%), limestone (34.1%), and yellow (16.3%) earth [25]. The main vegetation types include clod-warm coniferous forests, warm coniferous forests, broad-leaved forest, bamboo forest, shrubs, and shrub grassland, and they occupy 46.4% of the area (about 26,867 km^2) [27].

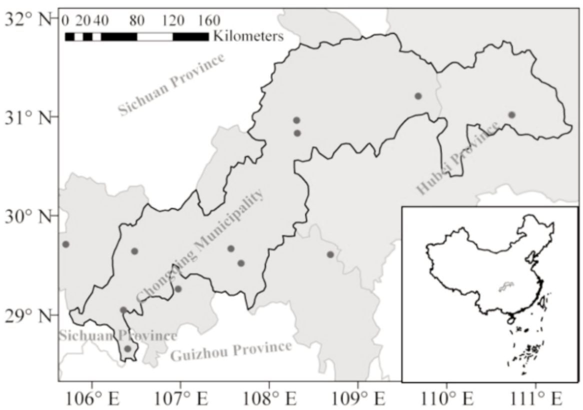

Fig. 1. The study area is located in the Three Gorges reservoir area of Hubei and Chongqing provinces. The grey circles represent the monitoring sites. The exact position is shown in the inset.

Modeling Approach

Data Sources

Atmospheric deposition data involving base cation (BC), SO_2^-, NH_4^+, NO_3^- and Cl^- deposition flux in wet deposition were obtained from previous research results [28-32]. Thus the total ion deposition was estimated by multiplying the wet deposition with a dry deposition factor [33]. Soil weathering rates (8ºC), net-based cation, net nitrogen uptake, net nitrogen immobilization, nitrate loss by denitrification, critical nitrogen leaching flux, and coefficient of gibbsite equilibrium were collected by Xie et al. [33]. Here, weathering rates were calibrated with actual soil temperature at 40 cm soil depth [34]. Soil and vegetation types as well as soil temperature at 40 cm depth were obtained from the China Meteorological Administration and Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences. Runoff was obtained from the Chongqing Water Resources Bulletin and Hubei Water Resources Bulletin [35]. Vegetation coverage was estimated by Geospatial data cloud. Plant species diversity was assessed by Xiao et al. [27]. Molar Bc:Al ratio of 10 was set to protect long-term nutrient pools in forest soil [36].

Model Setting

Critical loads for forest soil were estimated using SMB [15]. The model was based on the mass balance equation for soil solutions [37]. Detailed calculations are given by Eqs. (1)-(2) [38, 39]:

$$CL_{(S+N)} = BC_{dep} + BC_W - Cl_{dep} - BC_u + N_i + N_u + N_{de} - AN_{Cle(crit)} \quad (1)$$

$$CL_{nut}(N) = N_i + N_u + N_{de} + N_{le,crit} \quad (2)$$

...where $ANC_{le(crit)}$ was calculated using the critical aluminum concentration method (Eq. 3):

$$ANC_{le(crit)} = Q^{\frac{2}{3}} \times (1.5 \times \frac{BC_{dep} + BC_W - BC_u}{K_{gibb} \times (\frac{BC}{Al})_{crit}})^{\frac{1}{3}} + 1.5 \times \frac{BC_{dep} + BC_W - BC_u}{(\frac{BC}{Al})_{crit}} \quad (3)$$

$$BC_w = BC_{w0} \cdot Exp\left(\frac{3600}{281} - \frac{3600}{273+t}\right) \quad (4)$$

The basic input parameters are described in Table 1.

Sensitivity Analysis

To determine the key components to predictions of critical load, *SSA* was applied based on the rates of change in model output caused by changes in the values of a single parameter [20, 40]. The *SSA* principle was to change one parameter at a time by a given percentage and estimate *CL* for each parameter set, thereby estimating the sensitivity of *CL* to the parameters. Therefore, we set change range to reduce or increase by 10%, 20%, and 30% (which was labeled as x%). The specific equation is as follow:

$$SSA = \frac{CL_{x\%} - CL_{100\%}}{CL_{100\%}} \quad (5)$$

The spatial analysis model is based on spatial data and conducts a set of sequence and interaction of spatial analysis operation commands between raw data and derived data, thereby establishing the space conceptual model. In this study, the model builder module in GIS was applied to build the model and conduct batch data processing.

Table 1. Input parameters used in the SMB model.

Parameter	Unit	Description
BC_{dep}	$keq \cdot ha^{-1} \cdot yr^{-1}$	Total deposition of base cation (Ca+Mg+Na+K)
Cl_{dep}		Total deposition of Cl
BC_{W0}		Weathering of base cation
BC_u		Vegetative uptake of base cation
N_{de}		Net denitrification rate
N_i		Net nitrogen immobilization rate in the soil
N_u		Net nitrogen uptake (harvesting removal)
$ANC_{le(crit)}$		Critical leaching acid neutralization capacity
$N_{le,crit}$		Critical N leaching flux
Q	$m^3 \cdot ha^{-1} \cdot yr^{-1}$	Annual runoff
K_{gibb}	$m^6 \cdot eq^{-2}$	Gibbsite equilibrium constant
t	ºC	Soil temperature
$(BC/Al)_{crit}$	-	Critical base cation to Al

Results

Acid Deposition Critical Loads

The critical loads for acid deposition ($CL_{(S+N)}$) and nitrogen deposition ($CL_{nut}(N)$) differed greatly across Three Gorges, showing high spatial variation (Fig. 2).

$CL_{(S+N)}$ showed high spatial variation in the area (Fig. 2a). Values of $CL_{(S+N)}$ varied between 0 and 10.3 $keq \cdot ha^{-1} \cdot yr^{-1}$, mainly concentrated in the range of 3.0-5.0 $keq \cdot ha^{-1} \cdot yr^{-1}$. Furthermore, the higher values for $CL_{(S+N)}$ above 5.0 $keq \cdot ha^{-1} \cdot yr^{-1}$ were found in the upstream and downstream reaches of the area owing to the high base cation deposition and the high forest coverage rate. In contrast, the lower critical loads below 1.0 $keq \cdot ha^{-1} \cdot yr^{-1}$ focused on the upstream part of the area with low base cation deposition and forest coverage rate.

Compared with $CL_{(S+N)}$, $CL_{nut}(N)$ and their spatial variation were lower than $CL_{(S+N)}$. $CL_{nut}(N)$ were set to protect against the adverse effects of nitrogen deposition on receptors such as plants [41]. The values varied between 0 and 3.5 $keq \cdot ha^{-1} \cdot yr^{-1}$, mainly concentrated in the range of 1.0-3.0 $keq \cdot ha^{-1} \cdot yr^{-1}$ (Fig. 2b). In comparison with the same serious acid rain area of the Pearl River Delta in China ($CL_{nut}(N)$, it was mainly concentrated in the range of 0.5-1.0 $keq \cdot ha^{-1} \cdot yr^{-1}$), and there were higher values of $CL_{nut}(N)$ [37]. This implied that plants tolerated higher nitrogen deposition in the area than the Pearl River Delta.

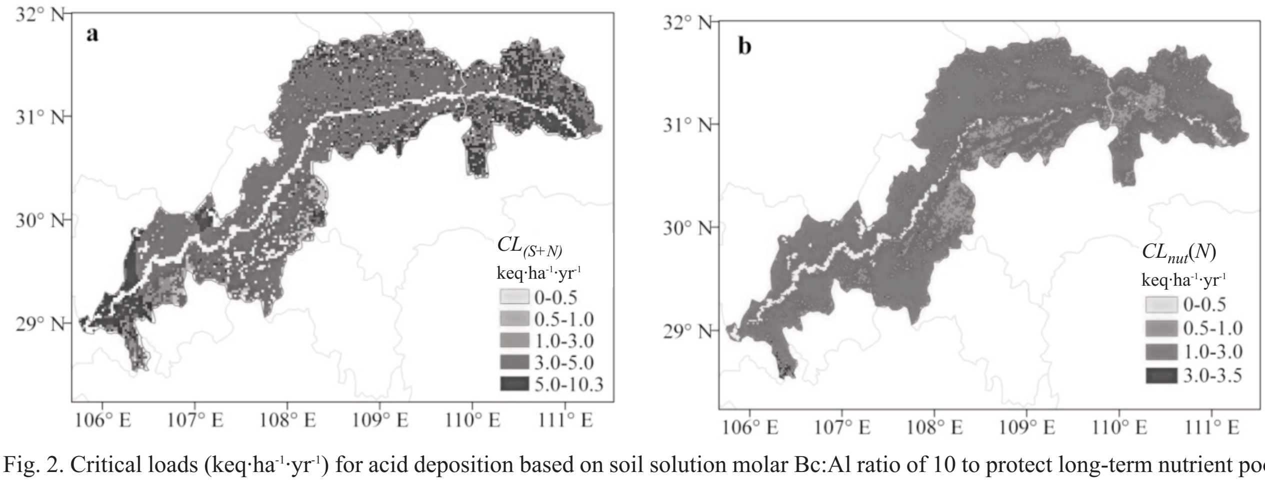

Fig. 2. Critical loads ($keq \cdot ha^{-1} \cdot yr^{-1}$) for acid deposition based on soil solution molar Bc:Al ratio of 10 to protect long-term nutrient pools in forest soil (a) and nitrogen deposition (b).

However, the lowest $CL_{nut}(N)$ were mainly distributed in the middle and upper reaches of Three Gorges, with low net immobilization, net uptake of nitrogen, and critical nitrogen leaching flux. As well as the Pearl River Delta, the distribution areas of the highest critical load (>3.0 keq·ha^{-1}·yr^{-1}) were very few, and only in the upstream region of Three Gorges [37].

Critical Load Exceedance

Critical loads for acid deposition exceeded approximately 4.8% of the entire region based on the criterion (molar Bc:Al ratio of 10), which affected nutrient pools in forested mineral soils (Fig. 3a). The values varied between 0 keq·ha^{-1}·yr^{-1} and 2.1 keq·ha^{-1}·yr^{-1}. This suggests that the areas with critical load exceedance remained a risk that was to harm nutrient pools in forested mineral soils. High-risk areas were mainly distributed in the upper middle Three Gorges area because of the value of $CL_{(S+N)}$ in this region under 3 keq·ha^{-1}·yr^{-1}. Nevertheless, Critical loads for nutrient nitrogen were exceeded in approximately 29.0% of the entire region (Fig. 3b). The values varied between 0 keq·ha^{-1}·yr^{-1} and 0.3 keq·ha^{-1}·yr^{-1}. High $CL_{nut}(N)$ areas were mainly concentrated in the upstream area with high nitrogen deposition, low plant growth rates, and low wood harvest. To compare with sulphur, most of the nitrogen deposition was usually reserved in the forest ecosystem because nitrogen was much more affected by biological processes [42]. Therefore, low plant growth rates resulted in low net uptake of nitrogen, thus leading to critical load exceedance.

Impacts of Acid Deposition on Forest Ecosystem

Soil Quality

Acid deposition caused soil acidification that characterized soil base ions leaching and soil quality decline [43]. Moreover, soil quality was greatly relevant with a molar base cation to aluminium (Bc:Al) ratio, which was used to assess the impact of acid deposition on soil quality [36]. Therefore, this study selected soil solution molar Bc:Al ratio of 10 as an indicator to protect long-term nutrient pools in forest soil in the area [44]. As stated above, 4.8% of the areas exceeded $CL_{(S+N)}$ based on the critical molar Bc:Al ratio of 10. High exceedance critical load areas were mainly concentrated in the upper middle Three Gorges area (Fig. 3a). Unlike places such as Canada, where exceedance was mainly affected by transboundary air pollution, the areas were primarily influenced by serious local air pollution [44, 45]. Although the amount of S and N in anthropogenic emissions presents a decreasing trend by emission-reduction policy [46], exceedance of critical loads is predicted (0-2.1 keq·ha^{-1}·yr^{-1}).

Plant Growth

Numerous studies have shown that moderate nitrogen deposition meets the demand for nitrogen in plants and improves the nutritional status of plants, promoting plant growth [47, 48]. However, excess nitrogen will cause nutritional imbalance trees and inhibit plant growth [48]. Therefore, it is critical to determine an empirical critical load of nitrogen deposition. In Europe, empirical critical load was usually set between 3 and 20 kgN·ha^{-1}·yr^{-1} [44, 49, 50]. Nonetheless, in recent years nitrogen deposition in China has been significantly higher than in Europe [51]. Moreover, Fang et al. [52] found that the biomass decreased in the amount of nitrogen deposition over 50 kgN·ha^{-1}·yr^{-1} in masson pine-dominated forest by simulating nitrogen deposition. Consequently, this study selected 50 kgN·ha^{-1}·yr^{-1} as an empirical critical load of the forest ecosystem.

Forestry area was estimated at 26,867 km^2 (46.4% of the Three Gorges Reservoir area) [27]. Under total N deposition, 20.1% of the forests were predicted to exceed the empirical critical load for nutrient nitrogen (50 kgN·ha^{-1}·yr^{-1}) (Fig. 4). In addition, the vegetation cumulative frequency curve showed a slow tendency and the vegetation coverage

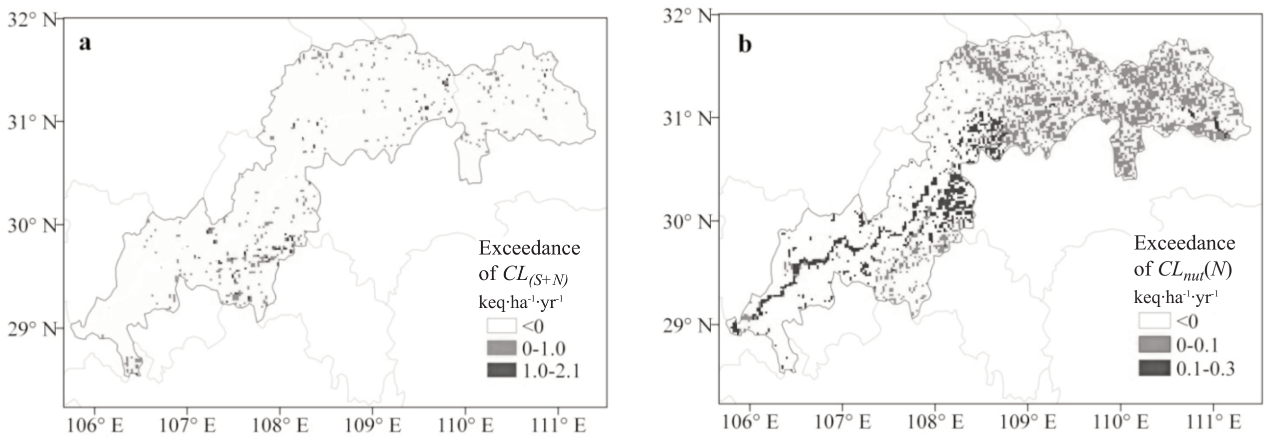

Fig. 3. Critical load exceedance areas (keq·ha^{-1}·yr^{-1}) for acid deposition based on soil solution molar Bc:Al ratio of 10 to protect long-term nutrient pools in forest soil (a) and nutrient nitrogen deposition (b). The white portion represents critical loads not being exceeded in the Three Gorges Reservoir area.

decreased in the region above the critical load, indicating that forest vegetation may be adversely affected when nitrogen deposition is greater than the empirical critical load.

Plant Species Diversity

Plant species diversity was expressed as the Shannon-Wiener index, which was an aggregative indicator combining species richness and uniformity [53]. According to the Shannon-Wiener index figure against nitrogen deposition (Fig. 5), Shannon-Wiener was reduced with the increase of nitrogen deposition. Moreover, Shannon-Wiener was correlated with nitrogen deposition based on Spearman rank correlation analysis ($R^2 = 0.531$, $p<0.05$). This showed a potential loss of plant species diversity when nitrogen deposition increased. This was consistent with the results of the effect of deposition on plant diversity [54, 55].

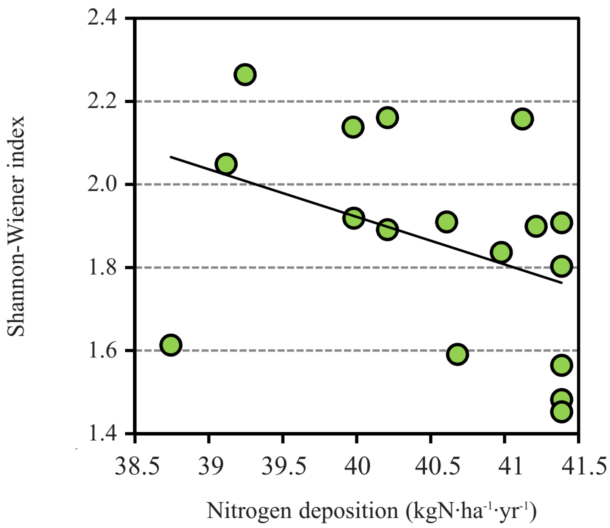

Fig. 5. Map of Shannon-Wiener index against nitrogen deposition. The slash expresses the trend line.

Discussion

Acid Deposition

The critical load was exceeded in parts of the Three Gorges Reservoir area, partly because of higher acid deposition in the regions. The range of acid deposition was from 104.03 to 131.67 kg·ha^{-1}·yr^{-1}, in which sulfur deposition accounted for 60-70%. Relatively speaking, sulphur deposition in the region was still less than the Pearl River Delta (about 108.5 kg·ha^{-1}·yr^{-1}) [37]. However, the area showed serious acid rain, with 78.1% of precipitation pH below 5.6 after gathering 233 samples of precipitation in 2009-13.

High acid deposition in the area was mainly attributed to three reasons. Firstly, the source of the acid deposition differed from some regions such as Canada affected by the monsoon. Due to the special geographical position (in the Sichuan Basin, which is one of four basins in China [44]), this area was not influenced by monsoon. It goes against pollutant transport/diffusion into the distance, causing serious local pollution. Secondly, the areas have many old industrial zones. Enterprises mostly belong to high-consumption industries that burn coal such as metallurgy, the chemical industry, pharmacy, building materials, and electricity, resulting in a large quantity of pollutant discharge. Moreover, rapid urbanization causes dust from building and demolition, and exhaust emissions increase [45].

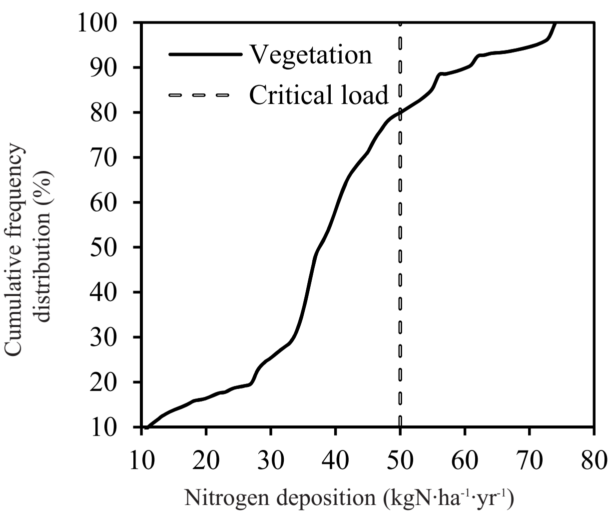

Fig. 4. Cumulative frequency distribution of vegetation against nitrogen deposition in Three Gorges Reservoir area. The dashed vertical line indicates the empirical critical load of 50 kgN·ha^{-1}·y^{r-1} effects on plant diversity.

Effects of Acid Deposition on Forest Ecosystems

The results of this large-scale survey suggest that the effects of acid deposition on forest ecosystems are observed across the entire region. Analysis shows that soil, plant growth, and plant diversity have been severely affected by acid deposition in sensitive regions – implying that soil and plants are sensitive to acid deposition.

According to the MEP, the Chinese government has established compulsory targets to reduce SO_2 emissions by 10% during 2005-10, and a further 8% by 2015. In addition, national NO_x emissions should be reduced by 10% by 2015 [9]. However, as can be seen from Fig. 3a, high acid deposition resulted in the exceedance of critical loads in parts of the Three Gorges area. This will cause increased depletion of base saturation of soils and increased aluminum and hydrogen concentrations in the soil solution. Additionally, it disturbs the nutrient status of soils by inducing strong changes in the availability of essential elements [56]. Therefore, people's awareness of environmental protection should be raised while the mandatory policy is implemented to reduce air pollution in several ways.

Moreover, in this study the vegetation cumulative frequency curve presents a slowing trend and the cumulative amount decreases when the nitrogen deposition is greater than 50 kgN·ha^{-1}·yr^{-1}. The result is consistent with those found by Liu et al. [57], who conducted an investigation and research of masson pines in the South Mountain of Three Gorges Reservoir area, where they found that manganese and cobalt of leaves were significantly reduced, while aluminum content of leaves increased to three times the normal level. As a result, he believed that the main cause of masson pine decay was soil acidification due to acid deposition, resulting in the precipitation and loss of nutrients and directly affecting plant growth.

Plant growth not only was affected by the acid deposition, but also plant species diversity was affected. For example, the mortality rate of spruce and fir significantly increased after six years nitrogen treatment (nitrogen application: 16-31 kgN·ha^{-1}·yr^{-1}) in southeastern Vermont, United States, leading to a decline in the entire forest [54]. In addition, eight years of nitrogen deposition experiments in Millbrook, New York, also showed that high nitrogen deposition (50-100 kgN·ha^{-1}·yr^{-1}) significantly increased the mortality rate of oak [55]. Due to high nitrogen deposition, plant species diversity has also decreased with the increase of acid deposition in the Three Gorges area. De Vries et al. said this was mainly because of excessive nitrogen deposition that led to the leaves wax, cuticle, and stoma being damaged and causing fallen leaves [4]. Secondly, excessive nitrogen deposition harmed root growth, and then it was not conducive to the absorption of nutrients [47]. After that, excessive nitrogen deposition led to nutritional imbalances in plants [54]. In the end, excessive nitrogen deposition reduced the plant tolerance to environmental stress and increased its sensitivity to pests, freezing, and drought [58, 59].

Although nitrogen deposition did not reach 50 kgN·ha^{-1}·yr^{-1} in Three Gorges, and compared with Guangdong province with serious acid rain, the Shannon-Wiener index was basically higher than in Guangzhou (<1.6) [60]. We should be vigilant and establish reasonable reduction policies to protect plant species diversity in the Three Gorges Reservoir area. This is mainly because most forest species compositions were changed when nitrogen deposition rates were up to 10-20 kg·ha^{-1}·yr^{-1} [61].

In conclusion, the emission-reduction policy cannot only consider the impact of deposition on the soil or the plants to protect the forest ecological system – it should be a combination of both, thereby formulating reasonable emission-reduction policies. Taken together, the critical loads exceedance of both mainly concentrated in the middle and upper reaches of Three Gorges (Fig. 6). Compared with non-sensitive areas, the region has significantly more than the critical load. Therefore, it should focus on protecting against forest ecosystems suffering further damage.

Sensitivity Analysis

The sensitivity analysis is applied as a method in identifying the relative importance of key parameters. Sensitivity analyses of critical load have been carried out by estimating the model response as the parameters. The most influential parameters were net nitrogen uptake (N_u) and the ratio of Bc to Al (Bc:Al) (Fig. 7). The others had little effect on the evaluation of critical load — especially gibbsite equilibrium constant (K_{gibb}), annual runoff (Q), and temperature (t). For N_u and Bc:Al, they determined growth rate, stem wood density in stems, and nutrient pool, respectively, thereby causing proportional changes because they were used in multiplicity in CL and $ANC_{le(crit)}$ models.

The contribution of N_u and Bc:Al to assess acid critical loads reached 37.0% and 33.3%, respectively. The contribution rate of these two parameters accounted for 70% of the total contribution. Therefore, these two parameters were ensured accuracy in order to reduce the error in the evaluation of critical loads.

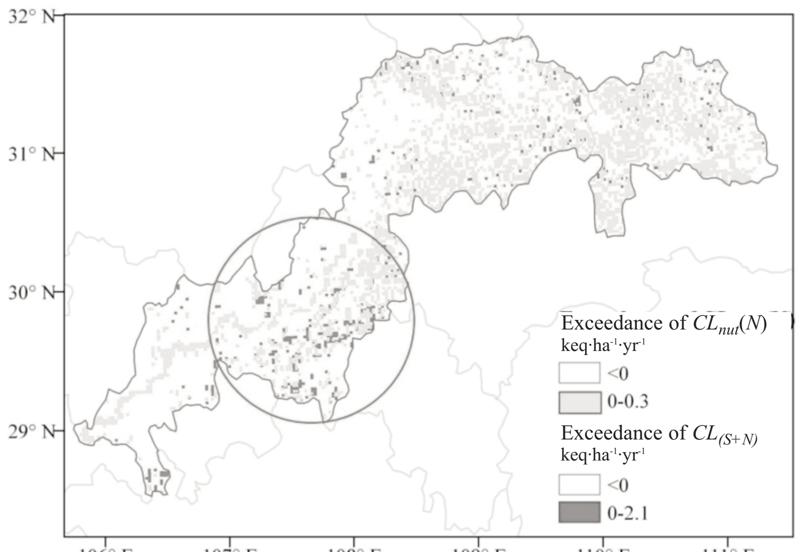

Fig. 6. Map of combination between the exceedance of acid critical loads and the exceedance of nutrient nitrogen critical loads. It is the key protection and prevention area in the grey circle.

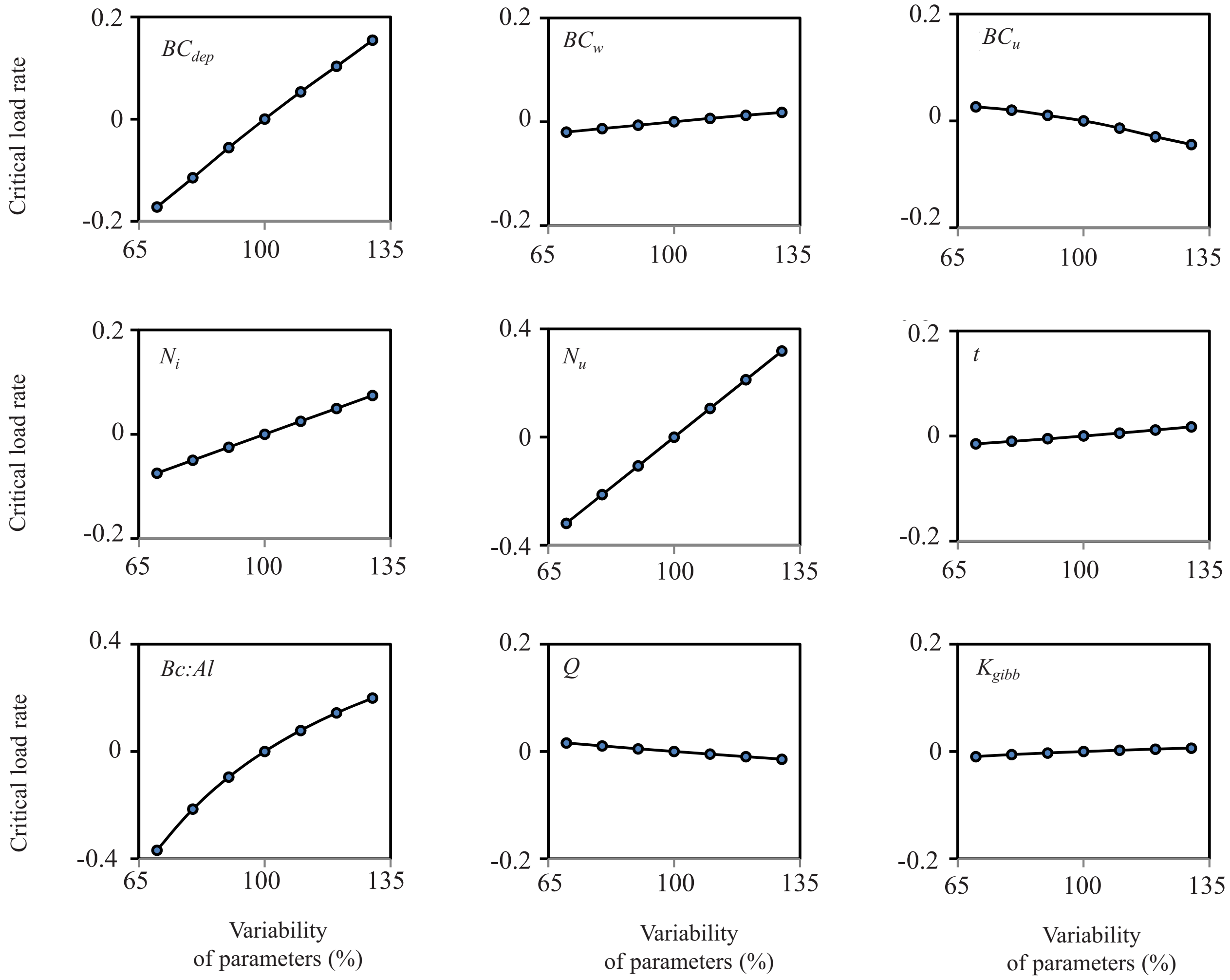

Fig. 7. Sensitivity of the key components based on the ninth simulation analysis.

Conclusions

Critical loads are mapped to provide an efficient scientific approach as a criterion for the acid deposition that can be tolerated by the forest ecosystem. The approach may help to provide an appropriate emission-reduction policy by the linking of critical load exceedance to the ecosystem impacts. This study suggests that the critical loads are exceeded in parts of Three Gorges Reservoir area and the forest ecosystem, including soil and plants suffering from the harm of acid deposition – especially in the middle and upper reaches of the Three Gorges area. Thus, at the same time of emission-reduction policies setting, the region should focus on protection against further damage to forest ecosystems. Moreover, N_u and Bc:Al ensured accuracy in order to reduce errors in the evaluation of critical loads.

Acknowledgements

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