Investigating the Ecological Effects of Acid Deposition on Forest Flora in the Huangshan Region: A Policy-Oriented Analysis

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Abstract. Acid rain is a severe, long-term environmental problem that has harmed the forest ecosystem around the world, so new scientific management is needed to protect these trees. According to the acid rain monitoring data in the Huangshan area from 2008 to 2025, it was found that the frequency of acid rain shows a pattern of "initial increase, followed by fluctuation and decline", and there is a certain delayed response relationship between it and the annual average pH value of precipitation. Although the "Two Control Zones" policy and the "Air Pollution Prevention and Control Action Plan" have reduced the frequency of acid rain, it is still erratic due to regional pollution transport. This paper takes the critical load concept from the Gothenburg Protocol and the US experience of active remediation through lime addition in watersheds as its foundation, proposes a policy system from source prevention to ecological restoration, and offers a scientific reference for vegetation protection and adaptive management of acid deposition in the Huangshan World Natural Heritage Site.

Keywords: Acid rain; Acid deposition; Forest ecosystem; Vegetation dynamics; Huangshan; Adaptive management.

1. Introduction

Acid rain is a global problem, affecting various parts of the world to varying degrees. Its environmental impact is slow and continuous. Acid rain not only corrodes buildings and harms human health but also has a huge and far-reaching impact on aquatic and terrestrial ecosystems. Among them, acid rain is most harmful to forest ecosystems. This harm is not only manifested in the direct corrosion of plant leaves, canopies, and even roots by acid rain [1], but also in the deterioration of the internal state of plants, such as disrupting plant homeostasis and reducing leaf chlorophyll content [2, 3], ultimately leading to slowed plant growth or even death.

China is one of the areas most severely damaged by acid rain after Europe and North America [4]. Given the problems of regional and severe air pollution, a number of control measures have been introduced in China. Although the frequency of acid rain in China has decreased in recent years, the problem has not been solved, and pollutants and acid radicals (SO_4^{2-}, NO_3^-) that cause acid rain are still rising [4, 5]. Recently, the mean pH of the rainfall in southern China has generally been below 4.6, and some extreme cases have dropped as low as 3.6 [4].

The three stages of acid rain control in China are approximately as follows: The first stage was from the 1980s to the mid-1990s. With the development of industrialisation and increased consumption of coal, sulphur dioxide emissions rose from about 15 million tonnes in 1980 to approximately 24 million tonnes by 1995, and the area affected by acid rain exceeded one million square kilometres; it is now one of the top three regions with acid rain in the world. The second period is from the 1990s to 2005. China started issuing regional pollution control policies. In 1998, the State Environmental Protection Administration issued the "Delineation Scheme for Acid Rain Control Zones and Sulfur Dioxide Pollution Control Zones" and designated areas severely polluted by acid rain and sulphur dioxide as "Two Control Zones" [6, 7]. Although policy intervention reduced the speed of decline, the rapid development of heavy industry still resulted in sulphur dioxide emissions of 25.49 million tons in 2005, and acid rain remained serious. The third stage is from 2006 to the present. After China joined the WTO and increased environmental awareness, the 11th Five-Year

Plan set a mandatory goal of reducing sulphur dioxide emissions by 10%. Emissions reached a high of 25.88 million tons in 2006 and have been falling steadily since. Subsequently, the joint prevention and control strategy has been strengthened in an all-around manner: In 2010, the State Council issued the "Guiding Opinions on Promoting Joint Prevention and Control of Air Pollution and Improving Regional Air Quality" [6]; in 2012, the "12th Five-Year Plan for Air Pollution Prevention and Control in Key Regions" designated 13 key regions, including Wuhan and its surrounding urban clusters, as areas with complex pollution [8, 9]; and the revised "Air Pollution Prevention and Control Law" in 2015 established a special chapter on joint prevention and control systems [6, 10]. Under the continuous support of policies, the proportion of acid rain areas across the country has fallen from about 40% in 2005 to 4.8% in 2020, and the average annual pH of precipitation has exceeded 5.6, thus achieving good results in acid rain control.

Most of the research and policy proposals at present are macro-level and focus on urban areas. This paper will conduct physicochemical tests on how acid rain affects the vegetation of mountains (particularly pine trees in the Huangshan area) and evaluate the effect of current policies. At present, there are no particular research reports or papers published on this subject. Therefore, the present paper will present a review of the literature and propose policy recommendations.

2. Current Status of Acid Rain Impacts on Huangshan Vegetation

As a renowned geopark, the Huangshan region has experienced an increase in acid rain frequency in recent years, threatening its geological and ecological environment. Studies [4] show that the average acid rain frequency in the Huangshan area reached 62.5% between July 2014 and March 2016. The main acid-causing ions in the precipitation were SO_4^{2-} and NO_3^-, with weighted average concentrations of 61.2 $\mu eq \cdot L^{-1}$ and 43.1 $\mu eq \cdot L^{-1}$, respectively. The average equivalent concentration ratio of SO_4^{2-}/NO_3^- was 1.7, indicating that the acid rain type is a sulfuric acid-nitric acid mixed type, mainly composed of sulfuric acid, but the impact of nitrogen oxides (NOx) emissions from vehicle exhaust is becoming increasingly significant. Seasonally, the pH value of precipitation in autumn and winter is lower than that in spring and summer, which is consistent with the seasonal distribution characteristics of acid rain in southern China [4]. Although the concentrations of most ions in Huangshan's precipitation are lower than those in surrounding cities in the Yangtze River Delta, they are higher than background values in clean areas (such as Waliguan Mountain), indicating that Huangshan's precipitation has been polluted to some extent [4]. Comprehensive analysis using methods such as isotope tracing determined that vehicle exhaust emissions are the primary source of acidic ions in the precipitation of the study area [4]. Increasingly frequent acid rain poses a significant threat to the geological and ecological environment of the Huangshan area. Acid deposition causes soil acidification; thus, toxic aluminium ions are released in the soil, and essential plant cations such as Ca^{2+} and Mg^{2+} are leached out, damaging the function of plant roots and nutrient uptake. Prolonged exposure to acid rain directly damages the protective waxy layer of the leaves on plants, inhibits photosynthesis, reduces the plant's defence capability against pests, diseases and severe weather such as frost [2].

3. Analysis of Acid Rain Distribution Characteristics and Vegetation Response

3.1. Distribution of Acid Rain in Huangshan Area

Figure 1 is the temporal variation feature plot of acid rain frequency and the annual average pH of precipitation in the Huangshan area from 2008 to 2025. The general trend of the annual mean pH values for precipitation in the study period was a fluctuation, and most of these values fell in the range of 4.7-5.4; the median was around 5.1, and they generally remained in the weakly acidic range. The smallest value was about 2009 (approximately 4.7), and the largest value was around 2024 (approximately 5.4). The upper and lower quartiles were approximately Q1≈4.95 and Q3≈5.20; thus, most of the years had a pH value in a relatively narrow range and were not widely dispersed.

According to the trend in time series data, the average pH values of the years have been slowly rising. From 2008 to 2012, it was at a relatively low level; then, from 2013 to 2016, it increased slightly; in 2017, there was a small decline; finally, from 2018 to 2024, it rose steadily to a high point and then slightly decreased in 2025. Therefore, it can be seen that the degree of acidification of precipitation in this area has been decreasing gradually over a long period, but interannual variations are still relatively prominent.

According to the above investigation, the occurrence frequency of acid rain in the Huangshan area is relatively high and changes significantly; generally, it is between 35% and 95%, with a median value of approximately 70%, and there has been a large-scale fluctuation over time. Based on the summary of the five main data points, the lowest frequency of acid rain occurred around 2017 (approximately 35%), and the highest was in 2016 (about 95%); most other years had frequencies in the middle to upper ranges. Analysis of the annual change patterns shows that the general trend is "increase followed by fluctuation and decline": The frequency was relatively high from 2008 to 2016, reached a peak in 2016, dropped sharply in 2017, rose somewhat from 2018 to 2020, and then fluctuated and adjusted. A further increase took place in 2024, and then it fell in 2025. In terms of a time series, the frequency of acid rain and the annual mean pH are not in phase and show a considerable lag. For example, after a change in the frequency of acid rain in certain years, the pH response will appear in about 1-2 years (e.g., the frequency of acid rain reached a high level in 2016, but the pH dropped sharply in 2017, showing a lag response of about 1 year). Therefore, the changes in regional acid deposition are likely due to a combination of meteorological factors, pollutant accumulation and environmental buffering processes, and exhibit a certain delayed-response characteristic. In general, there is a large year-to-year fluctuation in the degree of acid rain occurrence in the study area, and the process of long-term change is not uniform but shows clear stages of fluctuation.

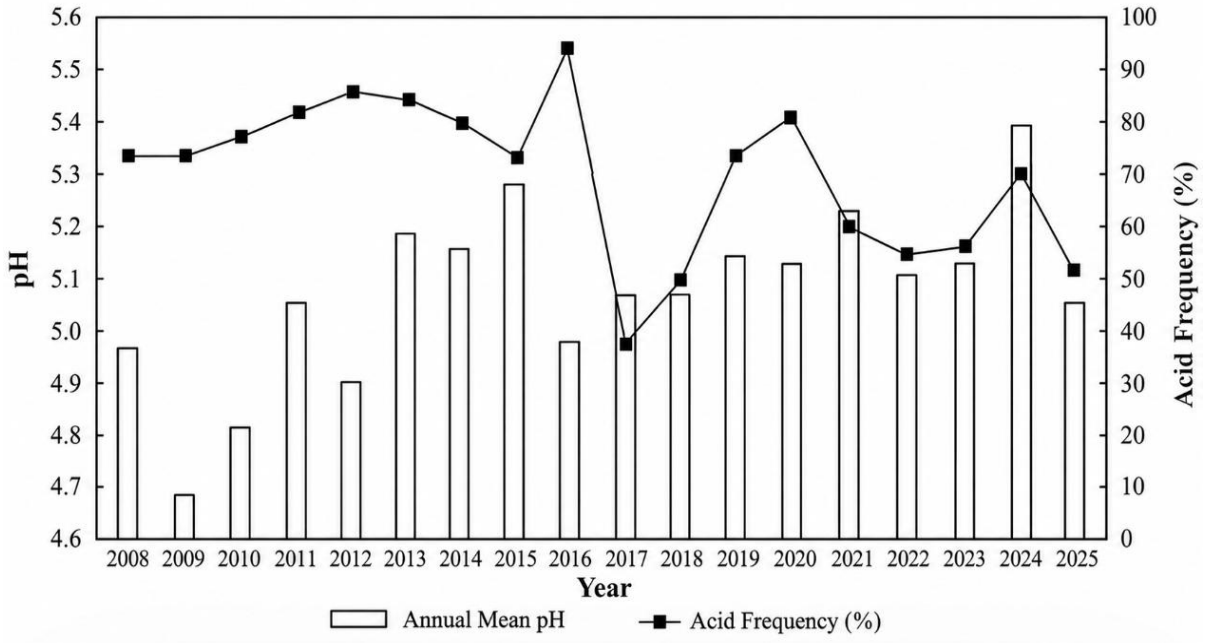


Figure 1. Trends in acid rain frequency and annual average pH value (2008-2025)

3.2. The Impact of the "Two-Control Zone" Environmental Management Policy on Acid Rain Pollution

The changes in acid rain in the Huangshan area from 2008 to 2025 generally showed a trend of "improvement followed by fluctuation and stabilization," indicating that China's atmospheric environmental governance policies at different stages had a significant impact on acid rain pollution control. As shown in the figure, the pH of precipitation generally increased from 2008 to 2015, and the acidity of acid rain gradually decreased. This was mainly due to the influence of the "Two Control

Zones" policy implemented in 1998 and the "Eleventh Five-Year Plan" policy. The "Two Control Zones" policy designated the Yangtze River Delta region as a key acid rain control area and strengthened the control of emissions from coal combustion, power generation, and high-polluting industries. Subsequently, during the "Eleventh Five-Year Plan" period, the country promoted large-scale desulfurization of flue gas from thermal power plants, eliminated small thermal power plants, and controlled the use of high-sulfur coal, resulting in a significant decrease in SO_2 emissions, thereby reducing the formation of sulfuric acid rain. The "Air Pollution Prevention and Control Action Plan" implemented in 2013 further strengthened air pollution control in the Yangtze River Delta region. Therefore, the improvement in acid rain in the Huangshan area was most significant from 2013 to 2016, with the precipitation pH reaching its highest value in 2016. However, the sudden drop in pH in 2017 indicated a temporary rebound in acid rain pollution, which may be related to increased industrial activity, regional pollution transport, and unfavorable meteorological conditions such as stable weather. Because Huangshan is located in the Yangtze River Delta region, it is easily affected by SO_2 and NOx emissions from surrounding industrial cities. When pollutant dispersion conditions are poor, acidic substances undergo stronger wet deposition during rainfall, leading to a decrease in pH. After 2018, with the implementation of the "Three-Year Action Plan for Winning the Battle Against Air Pollution," industrial ultra-low emission transformation, coal consumption control, and the promotion of clean energy were further strengthened, and the acid rain situation in Huangshan improved again, with pH recovering and stabilizing. Overall, the trend shown in the figure indicates that China's long-term SO_2 emission reduction and air pollution control policies have effectively alleviated acid rain pollution in Huangshan. However, due to the influence of regional pollution transport and meteorological conditions, the acid rain problem still exhibits certain fluctuations and long-term characteristics.

3.3. Current Status of Vegetation Community Distribution in Huangshan and the Impact of Acid Rain on Local Vegetation

Based on the initial baseline survey of a 10.24 hm^2 forest dynamic monitoring plot in Huangshan, a total of 89,307 independent individuals of woody plants with a diameter at breast height (DBH) ≥ 1 cm were recorded, belonging to 153 species in 97 genera and 46 families [11]. Among them, the dominant species *Castanopsis eyrei* had an importance value as high as 26.25%, and the sum of the importance values of Fagaceae and Ericaceae exceeded 50% of the total community, indicating that the overall community structure was relatively stable. A 2023 study further divided the plot into three communities dominated by *Castanopsis eyrei*. Community classification was mainly influenced by altitude, with niche processes and dispersal processes jointly dominating community building [12]. However, the macroscopic stability of the community structure does not equate to the absence of acid rain influence. Long-term acid deposition continuously accelerates the leaching of soil basic ions (Ca^{2+}, Mg^{2+}) and activates toxic aluminum ions, and the cumulative stress on different species is no longer negligible. Regarding *Pinus taiwanensis*, although long-term population monitoring data is lacking in Huangshan, studies in the neighboring Daiyun Mountain area, using DCCA ordination, revealed that soil pH is a key environmental factor influencing the community pattern of *Pinus taiwanensis*, particularly significant at altitudes of 1400–1600 m [13]. In the Ericaceae family, *Rhododendron ovatum* has an importance value of 7.60% in low-altitude evergreen broad-leaved forests, and its population is relatively stable [11]. The related species, *Rhododendron anhweiense*, is only distributed in high-altitude areas at elevations of 1000–1600 m, with individual local populations consisting of only about 200–300 individuals [7]. This narrow distribution makes it more sensitive to environmental stresses such as acid deposition. as shown in Figure 2.

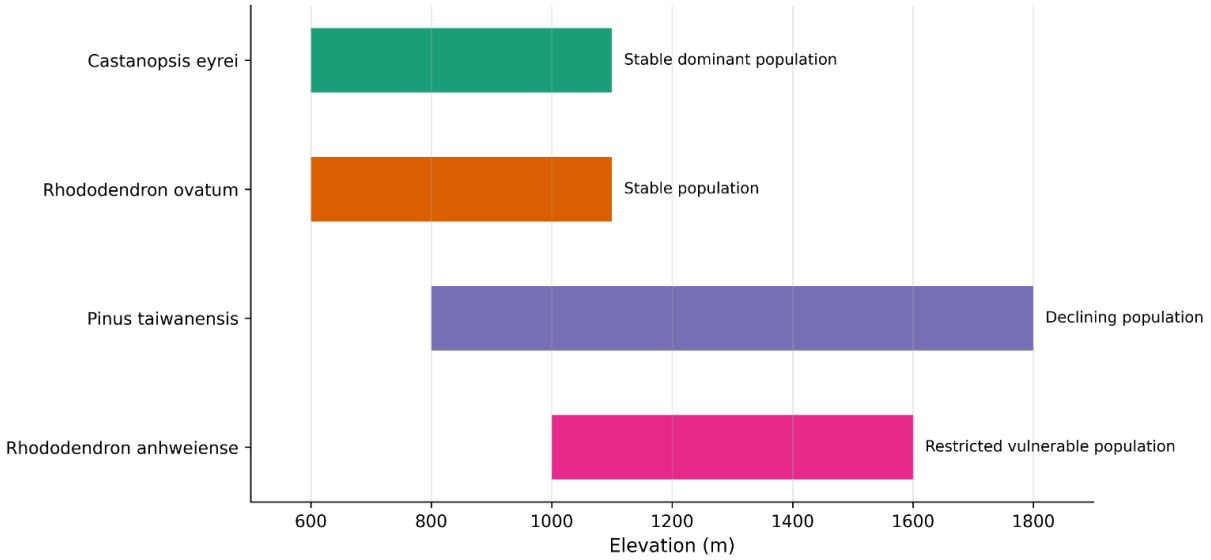


Figure 2. Altitudinal distribution of major dominant plant species in Huangshan.

4. Assessment of Governance Standards and Policy Proposals for Ecological Restoration

4.1. Policy Proposals Regarding the Lag in Ecological Restoration and the Assessment of Standards for Acid Deposition Remediation

Despite the implementation of proactive air pollution control policies globally and the significant environmental improvements achieved, research indicates that ecosystem recovery, particularly vegetation restoration, often exhibits a significant lag and irreversibility, making a complete return to pre-disturbed conditions difficult. For example, Zhou et al. [14] found that while the US Clean Air Act and subsequent amendments significantly reduced sulfur dioxide and nitrogen oxide emissions, leading to a recovery in the acid-neutralizing capacity of lakes in the Adirondack region and an increase in fish and zooplankton species richness, even under conditions of complete elimination of anthropogenic acid deposition, significant losses of exchangeable basic ions (such as calcium and magnesium) in the soils of some sensitive lakes meant that the lake water's acid-neutralizing capacity could not recover to pre-industrial levels, and the soil chemistry upon which vegetation communities depended was also difficult to restore. Therefore, future ecological management efforts in China need to be mindful that while sound policies can bring valuable positive impacts, complete vegetation restoration is not guaranteed. Thus, in terms of pollutant control, policy direction should shift from "methods for treating pollutants after pollution" to "how to prevent acid rain by adjusting industrial structure and reducing pollutant emissions."

The Gothenburg Protocol, within the framework of the United Nations Economic Commission for Europe, addresses acid deposition, eutrophication, and near-surface ozone by comprehensively reducing four pollutants: sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds (VOCs). It establishes differentiated national emission reduction commitments based on different countries' critical loads and is complemented by best feasible technical standards and a regular review mechanism, thereby achieving coordinated control of multiple pollutants and ecological demand-oriented target management [15]. This policy also has important implications for the Huangshan region: First, a critical load approach should be introduced to scientifically assess the acid deposition tolerance thresholds of sensitive vegetation such as Huangshan pine and rhododendron, as well as the soil, and based on this, regional sulfur dioxide and nitrogen oxide reduction targets specific to the Huangshan region should be set. Second, technical specifications and dynamic assessment systems should be established, and governance requirements should be incorporated into local ecological and environmental regulations. Finally, cross-regional joint prevention and control must be strengthened,

and irreversible ecological damage such as soil calcium loss caused by historical acidification must be acknowledged, with proactive restoration measures such as soil improvement and species restoration being implemented.

4.2. Policy Proposals for Ecological Restoration Following Acid Rain Pollution

In the area of ecological restoration, policies for acid rain ecological restoration have been proactively implemented in acid-sensitive mountainous areas, such as the Appalachian Mountains in the United States, to repair damage to the ecosystem and achieve good results [14]. The typical case is the watershed lime addition strategy. The scientific basis for this method is that, due to extended acid deposition, calcium, magnesium and other essential base cations have been leached from the soils of the mountains and toxic aluminium ions have been released. Even at a low level of atmospheric deposition, the natural recovery of the soil chemical environment will take several decades or longer and thus restrict the progress of vegetation recovery. Therefore, in cooperation with the state government, the Environmental Protection Agency has introduced large-scale limestone powder addition in the most severely acidified sub-watersheds. High-purity limestone powder is uniformly distributed in the forest catchment area by helicopter or hand-application to reduce soil acidity, increase the supply of basic cations, and lower phytotoxicity caused by aluminium; thus, suitable soil conditions are created for root system repair and the regeneration of native trees. This policy can also provide some reference points for the Huangshan area: when the cumulative impact of long-term acid rain deposition has led to severe local soil acidification, and sensitive tree species (such as Huangshan pine) show symptoms of nutrient deficiency or difficulties in seedling regeneration, relying solely on regional emission reduction may not be sufficient for ecological restoration in a short amount of time. In light of the above, pilot studies on lime addition could be conducted in specific small watersheds with severe acid rain, and their effects on the survival rate of Huangshan pine seedlings, soil chemical properties and surface water quality would be examined. This would provide a local scientific basis for determining whether to add proactive restoration to the toolkit of ecological protection in Huangshan.

5. Conclusion

From 2008 to 2025, the median frequency of acid rain in the Huangshan area is estimated to be approximately 70%, with the annual average pH value of precipitation fluctuating between 4.7 and 5.4. The overall trend is characterized by “first deterioration, then fluctuation and improvement,” with a lag of about one year between acid rain frequency and the annual average pH value. Policies such as the “Two Control Zones” and the “Air Pollution Prevention and Control Action Plan” have effectively promoted improvements in acid rain, but due to the combined influence of regional pollution transport and meteorological conditions, the acid rain problem remains volatile and long-term. In terms of vegetation, the Huangshan forest community is dominated by *Castanopsis eyrei* (importance value 26.25%), with the combined importance values of Fagaceae and Ericaceae accounting for more than half of the community. The overall structure is relatively stable, but the high-altitude Huangshan pine population is significantly affected by soil pH, showing a declining trend with an increase in older individuals and insufficient regeneration. The narrowly distributed Huangshan rhododendron is more sensitive to acid deposition. This paper is the first to systematically integrate long-term acid rain monitoring data and forest community baseline data in Huangshan, revealing the potential risks to sensitive species under macro-stability of the community and proposing a policy framework that emphasizes both source prevention and ecological restoration. Due to insufficient long-term monitoring data for high-altitude species, future research should strengthen in-situ collaborative observation and promote critical load assessment and acidified soil remediation pilot projects to evaluate the impact of limestone addition on the restoration of acid rain-polluted vegetation.

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