

1. Introduction

The Acid Deposition Monitoring Network in East Asia (EANET) is an intergovernmental regional network established for promoting cooperation among countries in East Asia to address acid deposition problem. EANET has gained international recognition for its success in promoting regional cooperation on acid deposition monitoring in East Asia and facilitating inter-regional exchange on data measurement and assessments of the state of acid deposition. In 2021, EANET expanded its scope to address both air pollution problem and acid deposition.

The Periodic Report on the State of Acid Deposition in East Asia (PRSD), one of the most important publications of EANET, has been published four times to date. The target audience of this publication is government officials, researchers, and the general public. The objective of issuing the Periodic Report is to provide rigorous information to the international community on long-term trends and regional distribution of acid deposition and air concentration in East Asia.

Preparation of the fourth period report

The EANET published the PRSD in 2006, 2011, 2016, and 2021 based on the EANET monitoring data accumulated from 2000-2004, 2005-2009, 2010-2014, and 2015-2019, respectively. This report is the fifth periodic report, and the title has been changed to the Periodic Report on the State of Atmospheric Environment (PRSAE) as the scope of the EANET has been expanded to both air pollution problem and acid deposition. The Fifth PRSAE (PRSAE5) is based on the monitoring data from 2000 to 2024 (Twenty five years), focusing on spatial distribution, trend analysis and, possibly, impact assessment of acid deposition and air pollution in the region. The data 2020-2024 is also utilized for evaluating the current status of the environment in the EANET region, following the first, second, third and fourth periodic reports to share the results of the past five years provided by the EANET in its regular phase, as well as to evaluate scientifically the monitoring data generated.

The Twenty-Fourth Session of the Scientific Advisory Committee (SAC24) in October 2024 approved the establishment of the Drafting Committee (DC) for the PRSAE5 to prepare the implementation plan and other related works. The Twenty-Sixth Session of the Intergovernmental Meeting (IG26) in November 2024, Kuala Lumpur, Malaysia agreed to initiate the preparation of the PRSAE5 in 2025, with the process to be approved by Participating Countries by email in the first quarter of 2025. After the process of the preparation of PRSAE5 was reviewed and approved by PCs on 7 February 2025 by email, the DC for the PRSAE5 has been established. The first DC meeting for the PRSAE5 was held virtually on 24 June 2025. It was organized by the Network Center for the EANET in Niigata, Japan. The DC members from 13 participating countries of the EANET participated in the meeting. Prof. Taehyoung Lee, Hankuk University of Foreign Studies, Republic of Korea was elected as the Chairperson of the DC.

The DC developed the format and contents of the PRSAE5. The PRSAE5 consists of three parts: Part I: Regional Assessment, Part II: National Assessment, and Executive Summary. The DC also nominated the Lead Authors and Contributors to draft the report. The contents of the PRSAE5 are as follows:

- Chapter 1: Introduction
- Chapter 2: Monitoring Data Quality
- Chapter 3: Gas and Aerosol Concentration in East Asia
- Chapter 4: Wet and Dry Deposition in East Asia
- Chapter 5: Impacts on Ecosystems in East Asia
- Chapter 6: Summary and Recommendations for Future Activities

The report was prepared as a scientific assessment of the state of acid deposition and air pollution in East Asia based on the data accumulated in the EANET. A trend analysis was also implemented to

investigate the long-term variation in acid deposition using data prior to 2019 in addition to the data from 2020-2024 for this report.

EANET activities in 2000-2024

EANET was established as an important initiative for regional cooperation among the participating countries to create a common understanding of the state of acid deposition problems and provide useful inputs to policymakers at various levels.

Monitoring activities

EANET monitoring covers five environmental media, air concentration/dry deposition, wet deposition, soil/vegetation, inland aquatic environment, and catchment-scale monitoring. The monitoring activities have been conducted following a set of monitoring guidelines and technical manuals of the EANET (EANET 2010a, 2010b, 2010c, 2010d, 2010e, 2013, and 2022). Monitoring for wet and dry deposition is implemented to measure concentrations and fluxes of acidic and other substances to the ground. In addition, monitoring soil/vegetation, inland aquatic environment, and catchment are being implemented to assess adverse impacts on terrestrial and aquatic ecosystems. All the sites follow a standardized set of methodologies for site selection, sampling, and chemical analyses to ensure technical conformity within the network.

1. Air Concentration/Dry Deposition

- Monitoring Interval
 - every day to two weeks, or every hour when measured by automatic instruments
- Major Measurements
 - Gases: concentrations of ozone (O_3), sulfur dioxide (SO_2), nitrogen oxides (NO , NO_2 , and NO_x), nitric acid (HNO_3), hydrogen chloride (HCl), ammonia (NH_3), and others
 - Particulate matter ($PM_{2.5}$ and PM_{10}), and particulate components (SO_4^{2-} , NO_3^- , etc).

2. Wet Deposition

- Monitoring Interval
 - every 24 hours or every precipitation event for an urban, rural or remote site
- Major Parameters
 - Precipitation analysis: pH, electrical conductivity (EC), concentrations of sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), and other ions

3. Soil and Vegetation

- Monitoring Interval
 - once three to five years
- Major Parameters
 - Soil: pH, concentrations of exchangeable ions and effective cation exchange capacity (ECEC)
 - Vegetation (forest): survey of tree decline, and general description of a forest

4. Inland Aquatic Environment

- Monitoring Interval
 - More than four times a year
- Major Parameters
 - Inland water: pH, electrical conductivity (EC), alkalinity and cations such as ammonium (NH_4^+), and anions such as nitrate (NO_3^-)

5. Catchment

- Monitoring Interval
 - continuously (precipitation and discharge), every week to 2 weeks (chemical components)
- Major Parameters
 - Rainwater and stream water: Precipitation amount, discharge from the stream, major cations (Ca^{2+} , NH_4^+ , etc.) and anions (SO_4^{2-} , NO_3^- , etc.), estimation of total deposition (wet + dry), etc.

EANET monitoring sites are classified into two basic categories: air concentration/acid deposition monitoring sites and ecological survey sites. Air concentration/acid deposition monitoring sites are sites for collecting fundamental data on the temporal and spatial distribution of air pollution and acid deposition. They are further classified into three sub-categories: remote sites, rural sites, and urban sites for specific objectives of the monitoring. Ecological survey sites provide basic data for assessing the effects of acidification on terrestrial ecosystems. They are further classified into two sub-categories: basic survey sites and ecosystem analysis sites.

Thirteen EANET countries, namely Cambodia, China, Indonesia, Japan, Lao PDR, Malaysia, Mongolia, Myanmar, Philippines, Republic of Korea, Russia, Thailand, and Vietnam participated in air concentration and acid deposition monitoring in 2024. A total of sixty-five sites were nominated for the monitoring, including 26 urban, 19 rural, and 20 remote sites. Soil and vegetation monitoring and inland aquatic environment monitoring are conducted at 33 plots in 10 countries and 19 lakes/rivers in 11 countries. Most of the ecological monitoring sites correspond to the acid deposition monitoring sites. It is expected that the acid deposition monitoring data collected in their nearest monitoring sites will be used for the interpretation of the data on ecological monitoring in these sites.

Research activities

As one of the activities of the EANET, EANET continued to promote research activities aimed at improving scientific understanding of air pollution, acid deposition, and their ecological impacts in East Asia. These activities made use of the long-term monitoring data accumulated through EANET and promoted collaboration among researchers and institutions in the Participating Countries. Research activities are also implemented to improve capacities for monitoring methodologies, deposition estimations, the development of emission inventories, and using air quality models to assess and analyze the trend of air pollution and atmospheric depositions at all scales.

Promotion of research activities related to air pollution and acid deposition problems includes the following:

- Promotion of research studies, particularly on the applicability of various methodologies for measurement of air concentrations in East Asia;
- Promotion of studies on the effects of air pollution, acid deposition and other priority chemical species on the ecosystem;
- Promotion of studies on methodologies of application of air quality models to assess and analyze the trend of national and regional air pollution, acid deposition and related chemical species in East Asia through workshops, training courses, etc.; and
- Promotion of research on methodologies to develop emission inventories through workshops, training courses, pilot studies, preparation of reference materials, etc.

The fellowship research program was also conducted. It has been promoted since 2005, which is an effective mechanism for encouraging young researchers from across the region to participate in air pollution research activities. Joint research projects conducted by the EANET participating countries were implemented as well.

Scientific findings from the research activities are shared with the scientists from participating countries and their scientific and technical research results are published in relevant international and national journals, including in the EANET Science Bulletin and the EANET Research Portal (<https://www.eanet.asia/eanet-research-portal>).

Capacity building activities

EANET continued to strengthen the technical and institutional capacities of its Participating Countries for air quality monitoring and management. A major component of EANET's capacity-building activities was technical training for government officials, researchers, and technical staff from the Participating Countries. The EANET individual training course at the Network Center has been implemented once or twice a year from the beginning of the EANET activities. Training covered fundamental aspects of acid deposition and air quality monitoring, including sampling and

chemical analysis, operation and maintenance of monitoring equipment, data management, and quality assurance and quality control (QA/QC). During and after the COVID-19 pandemic, online training and lectures were also used for capacity-building activities. Practical training and knowledge sharing also contributed to improving the comparability and reliability of monitoring data across the EANET network.

The technical capabilities and skills of the participating countries for air concentration and acid deposition monitoring and assessment were significantly enhanced through a number of EANET activities. The Network Center dispatch technical missions annually to the participating countries to assist them in monitoring performance, laboratory operations, data management, and other procedures. Other activities to enhance the skills and knowledge of personnel included national workshops, annual expert meetings and scientific workshops on ecological impacts and other topics related to acid deposition. Numerous EANET publications (Technical Manuals and Guidelines, Data Report, Reports on QA/QC projects, Training materials, etc.) have been produced for use by technical staff, specialists and researchers involved in the EANET monitoring, data quality, and data management. All of these materials are available on the EANET website (<https://www.eanet.asia>).

Capacity-building activities also gradually expanded in response to the broader scope of EANET. In addition to conventional acid deposition monitoring, training and technical activities addressed wider air quality management issues, including PM_{2.5} and ozone, emission inventories, air quality modeling, and other emerging technical needs. EANET's capacity-building activities contributed to maintaining and improving technical expertise, strengthening monitoring and QA/QC capabilities, promoting the application of new approaches and technologies, and developing human resources for effective air quality management in East Asia.

Public awareness activities

The promotion of public awareness on air pollution and acid deposition and sharing a common understanding of atmospheric environmental issues is an important part of the EANET activities. During 2021–2024, EANET conducted a range of public awareness and outreach activities to increase understanding of air pollution issues in East Asia, disseminate the outcomes of EANET activities, and strengthen communication among policymakers, scientists, national stakeholders, and the wider public. These activities also supported the expansion of EANET's scope beyond acid deposition to address broader air quality issues.

Regional and national workshops were major components of EANET's public awareness activities. Regional Awareness Workshops provided opportunities to share scientific knowledge, monitoring results, and experiences related to air pollution and air quality management. Topics covered included particulate matter, ozone, atmospheric deposition, air quality monitoring technologies, and approaches to improving air quality management. National stakeholder workshops were also organized in several Participating Countries to introduce EANET activities and promote greater involvement of national institutions and stakeholders.

EANET increasingly used online and digital communication tools to disseminate information. The EANET website, newsletters, web stories, online workshops, and other communication materials were used to share information on EANET activities, scientific findings, and regional air pollution issues with a broader audience. By these public awareness activities, the EANET is increasing its visibility and strengthening stakeholder engagement and promoting regional cooperation for improved air quality management in East Asia.

2. Monitoring Data Quality

QA/QC

In order to create a common understanding of the state of the atmospheric environment based on EANET monitoring data, it is essential that the reliability and comparability of the monitoring data be maintained. Such reliable and comparable monitoring data are also necessary to provide a sound basis for decision-making at the local, national, and regional levels aimed at preventing or reducing adverse environmental impacts caused by atmospheric environment-related substances. Furthermore, EANET monitoring data are also required to be comparable with those from leading monitoring networks worldwide and to meet the quality standards necessary for use in data analysis and model validation by researchers and experts around the world. This requires Quality Assurance (QA) and Quality Control (QC) to be implemented appropriately and on a continuous basis.

Against this background, the EANET produced four QA/QC programs (Wet Deposition, Air Concentration, Soil and Vegetation, Inland Aquatic Environment) in 2000. Then, the Technical Manuals for Wet Deposition Monitoring, Air Concentration Monitoring, Soil and Vegetation Monitoring, and Inland Aquatic Environment Monitoring described QA/QC matters (EANET, 2010a, 2010b, 2010c, 2010d, 2010e, 2013, and 2022). The QA/QC programs are composed of several procedure types: i) siting, ii) sampling procedures and sample handling, iii) chemical analysis, and iv) QA/QC for the measurement data at each site (EANET, 2016).

Preparation of National Monitoring Plan (NMP)

National Monitoring Plan (NMP) includes information on monitoring sites, monitoring methods, monitoring frequency etc. in participating countries. The format of NMP consists of following items:

- 1) Information on established monitoring sites and their arrangement;
- 2) Measurement programs including sets of parameters and monitoring interval;
- 3) Metadata on participating laboratories for each field of monitoring activities, and;
- 4) Geoinformation on the respective monitoring sites with their scale maps.

This information is crucial for QA/QC activities in the EANET. First summarization of the NMP was prepared in November 2001. Every participating country of EANET has been required to prepare its NMP in accordance with the “Data Reporting Procedures and Formats for Acid Deposition Monitoring in East Asia”. The NMPs were prepared by participating countries after starting regular phase and have been reviewed every year with possible revision, if necessary.

Siting

EANET monitoring sites are classified into two basic categories according to types of measurement programs, namely, air concentration/acid deposition monitoring sites and ecological survey sites. Air concentration/acid deposition monitoring sites are operating bodies collecting fundamental data on air concentrations and wet acidified deposition to investigate its temporal and spatial distribution. They are classified into 3 sub-categories: remote sites, rural sites and urban sites with some differences in the objectives of the monitoring. Ecological survey sites are those that provide basic data for assessing the effects of air concentration and acidification on terrestrial ecosystems, and they are principally classified into 2 sub-categories: survey sites and ecosystem analysis sites.

Sampling and sample handling

The sampling has been carried out according to the monitoring manuals for each monitoring category. Especially for the collected wet deposition samples, dry monitoring samples using the filter pack method, and inland water samples, samples are stored in the refrigerator or added a biocide such as thymol to prevent deterioration or at least minimize possible conversion of the chemical species in the collected sample before chemical analysis. The collected soil samples are air-dried, sieved and then stored in cool and dark places before the analysis.

Chemical analysis

The major ions, hydronium ion (H^+ , as pH), ammonium ion (NH_4^+), calcium ion (Ca^{2+}), potassium ion (K^+), magnesium ion (Mg^{2+}), sodium ion (Na^+), sulfate ion (SO_4^{2-}), nitrate ion (NO_3^-), chloride ion (Cl^-) in the collected water samples are analyzed. Alkalinity as an indicator for acid neutralizing capacity is also analyzed in the inland water samples, while exchangeable cations, including Ca^{2+} , Mg^{2+} , K^+ , Na^+ , H^+ , and Al^{3+} , are analyzed in the soil samples. The operation manuals for each monitoring categories provide several acceptable analytical techniques to be applied in the laboratories of the participating countries.

QA/QC procedure prior to the data submission to the national and network center

The quality of the chemical analysis was evaluated in terms of ion balance and conductivity checks. The evaluation was quantified as R_1 and R_2 as defined below (WMO, 2004; EANET, 2010).

$$R_1 = \frac{(C - A)}{(C + A)} \times 100 (\%) \quad R_2 = \frac{(\Lambda_{obs} - \Lambda_{calc})}{(\Lambda_{obs} + \Lambda_{calc})} \times 100 (\%)$$

where the symbols are defined as below and the symbols of the ion denote their concentration on an equivalent basis, and λ is the molar conductivity of the individual ion at infinite dilution at 25°C.

$$\begin{aligned} C &= [H^+] + [NH_4^+] + [Ca^{2+}] + [K^+] + [Mg^{2+}] + [Na^+] \\ A &= [SO_4^{2-}] + [NO_3^-] + [Cl^-] \\ \Lambda &= \lambda_{H^+} [H^+] + \lambda_{NH_4^+} [NH_4^+] + \lambda_{Ca^{2+}} [Ca^{2+}] + \lambda_{K^+} [K^+] + \lambda_{Mg^{2+}} [Mg^{2+}] + \lambda_{Na^+} [Na^+] \\ &\quad + \lambda_{SO_4^{2-}} [SO_4^{2-}] + \lambda_{NO_3^-} [NO_3^-] + \lambda_{Cl^-} [Cl^-] \end{aligned}$$

The acceptable ranges for R_1 and R_2 are defined as a function of the concentration sums of the analytical suites and presented in Table 2.2.2. Λ_{obs} indicates the measured value of the electrical conductivity of the sample. When the value of either R_1 or R_2 does not meet the criteria, the samples are supposed to be a subject of reanalysis as well as more detailed examination of all analytical procedures is involved. Then, it is also recommended that some ionic species including hydrogen carbonate, HCO_3^- , or organic acids should be added to the analytical suites or the criteria should be modified as a function of pH. The acceptable ranges are encouraged to be revised in consideration of the ionic composition and concentration levels as well as the present state of arts of the analytical laboratories.

Evaluation of Inter Laboratory Comparison Projects

The Inter-Laboratory Comparison project of EANET is a well-designed world-wide approach of the round-robin test performed with a common sets of simulated water (artificial rainwater or surface water) or unified common samples in all analytical laboratories for the EANET monitoring. The purpose of this project is to evaluate the analytical systems through the evaluation of analytical accomplishments, analytical instruments and their operating condition and other relevant and appropriate practices.

Throughout the Inter-Laboratory Comparison project, the outlier data and the actual procedure in each participating laboratory have been evaluated using artificial rainwater sample for wet deposition monitoring, artificial filter sample for the dry deposition monitoring with filter pack method, actual soil sample for soil monitoring and artificial inland water sample for the inland aquatic environment monitoring.

Wet deposition

The Inter-Laboratory Comparison surveys were conducted 27 times between 1998 and 2024. During this period, 21 to 37 laboratories from 13 countries participated. The results of the analysis in the project were evaluated in terms of the exceedance of the Data Quality Objectives (DQOs) values which had been prescribed in the EANET QA/QC program as a deviation of $\pm 15\%$ from prepared value for each analytical suite. The flag "E" was put to the data that exceed DQOs by a factor of 2 ($\pm 15\% \sim \pm 30\%$), and the flag "X" to the data exceeding DQOs by a factor of over 2 ($< -30\%$ or $> 30\%$). A set of the data for each sample was evaluated with the data checking procedures. The overall

Executive Summary

percentages of flagged data, “E” and “X” respectively, are shown in Figure 2.1. The percentage of data within the DQOs increased from 75.4-78.3% (1998) to 89.6-95.0% (2024). The percentage of the flagged data, which may be related to the concentration levels of the artificial rainwater, has been generally decreasing toward the 27th attempt.

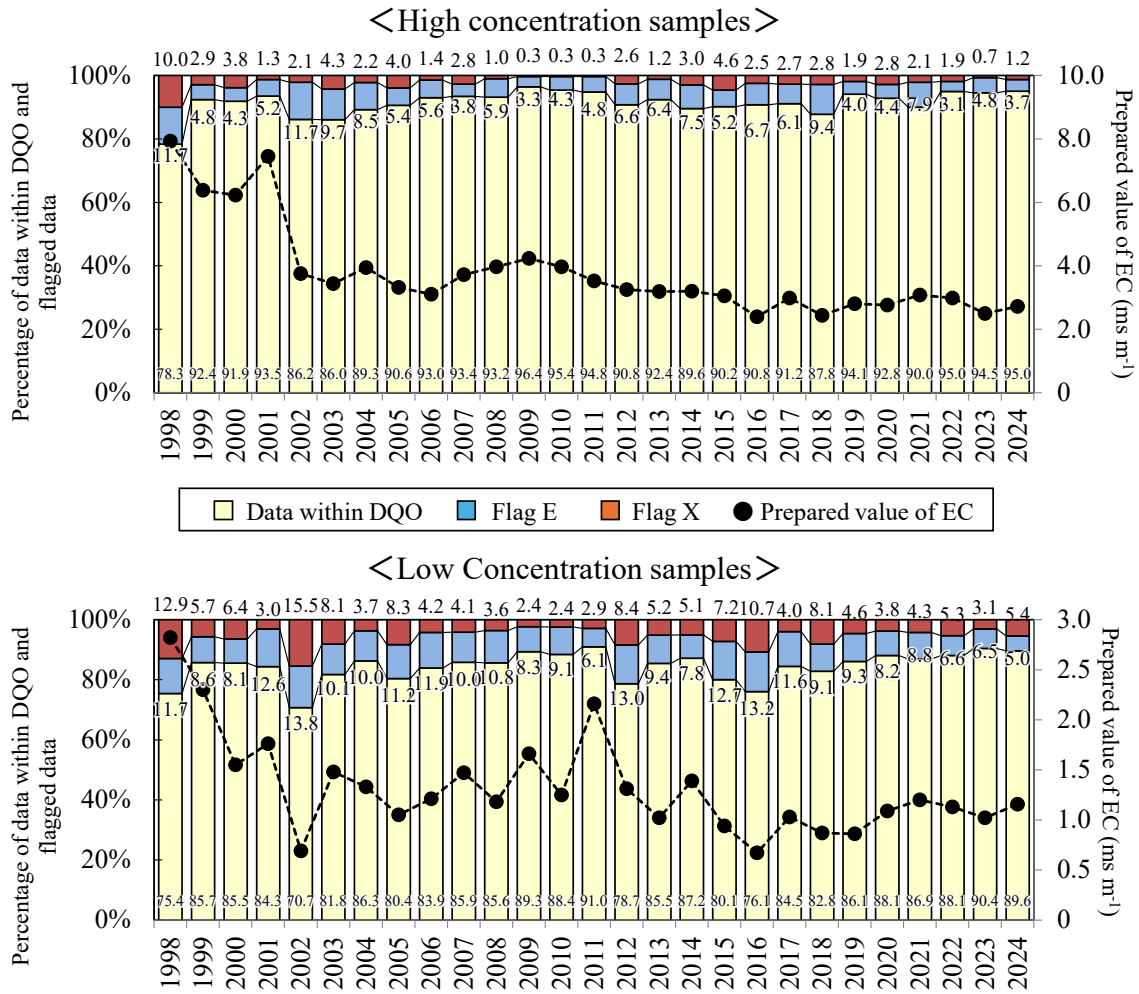


Figure 2.1. Overall comparisons of all Inter-Laboratory Comparison projects for wet deposition during 1998-2024.

Dry deposition

The Inter-Laboratory Comparison surveys on filter analysis were conducted 20 times between 2005 and 2024. The DQOs of EANET are specified that determined values are expected for fall within $\pm 15\%$ deviation from the prepared values in *Technical Manual for Air Concentration Monitoring in East Asia* (EANET, 2013). Each laboratory analyzed each sample 3 times, and these average values are evaluated based on the deviation from the corresponding prepared values. A flag E indicates that its deviation exceeds $\pm 15\%$ but not $\pm 30\%$, and a flag “X” indicates that its deviation exceeds $\pm 30\%$. The overall percentages of flagged data, “E” and “X” respectively, are shown in Figure 2.2. The percentage of data within the DQOs slightly increased from 73.2% (2005) to 75.0% (2024) for small quantity samples and decreased from 80.4% (2005) to 77.1% (2024) for large quantity samples.

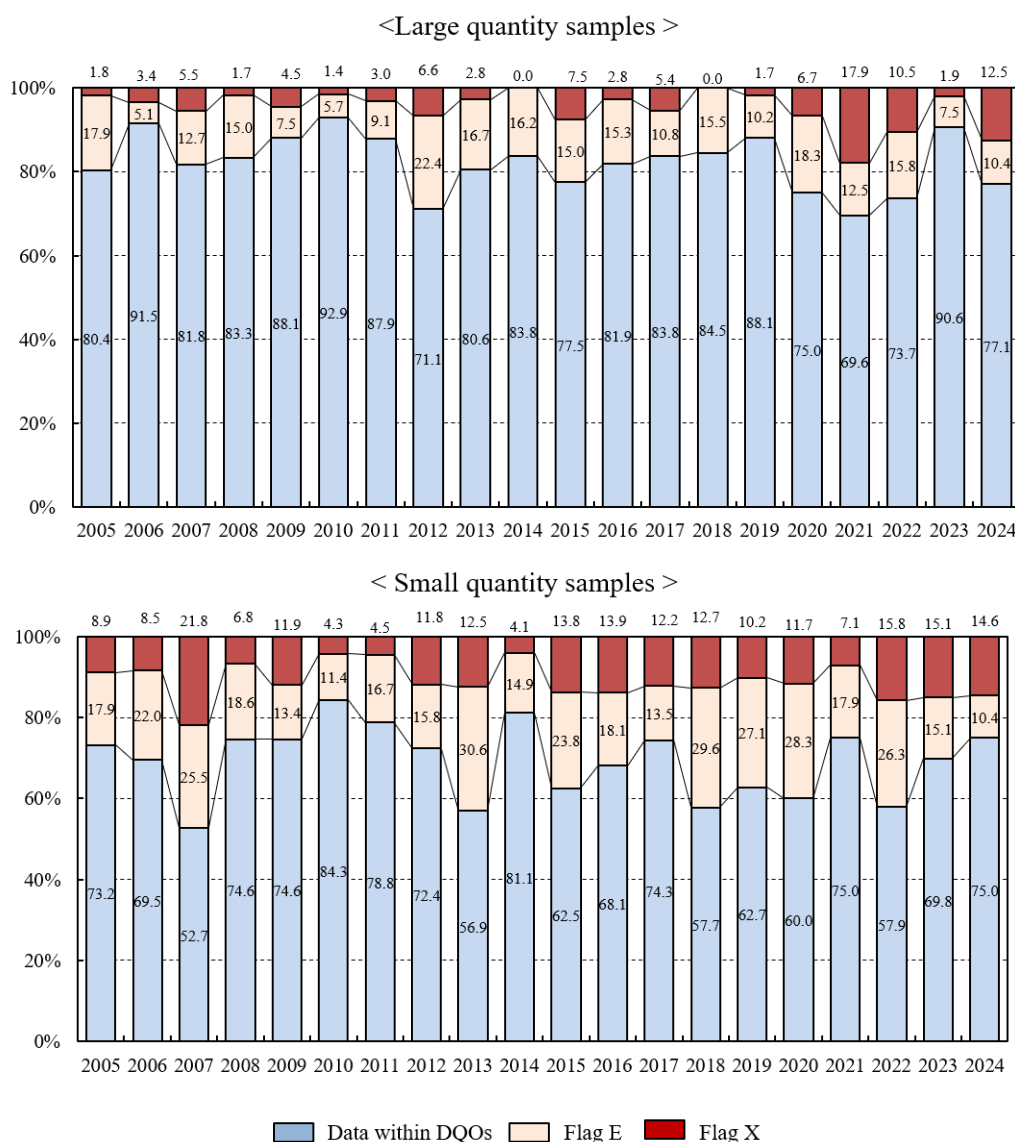


Figure 2.2. Overall comparisons of all Inter-Laboratory Comparison projects for dry deposition during 1998-2024.

Soil

The project on soil sample analysis started in 1999 as one of the activities within the QA/QC programs. Air-dried soil samples, which were prepared by the NC, were distributed to the laboratories every year except 2001. The laboratories carried out the whole procedures of the soil analysis including extraction, instrumental analysis or titration, and reporting. The laboratories analyzed each sample twice under the within-laboratory reproducibility condition (time, analysts, and/or instruments are different in a same laboratory). Moreover, triplicate analysis under the repeatability condition was carried out each time.

Each parameter is statistically evaluated according to the several procedures described in the Technical Manual. One of the procedures is detection of outliers by Cochran and Grubbs method. Evenness of within-laboratory precision (variation in each laboratory) and inter-laboratory precision (variation between participant laboratories) are verified by this method. Figure 2.3 shows the change of outlier ratio in all properties and laboratories from 2002 to 2024. The ratio is calculated by $\{(N \text{ of entire dataset}) - (N \text{ of verified dataset})\} / (N \text{ of entire dataset})$. Although the outlier ratio has decreased since the initial experiment in 2002, it has remained relatively high (10-25%) between

Executive Summary

2003 and 2024. Appropriate standard solution, extraction solution, dilution rate and calculation should be checked to reduce extremely different values considered as outliers.

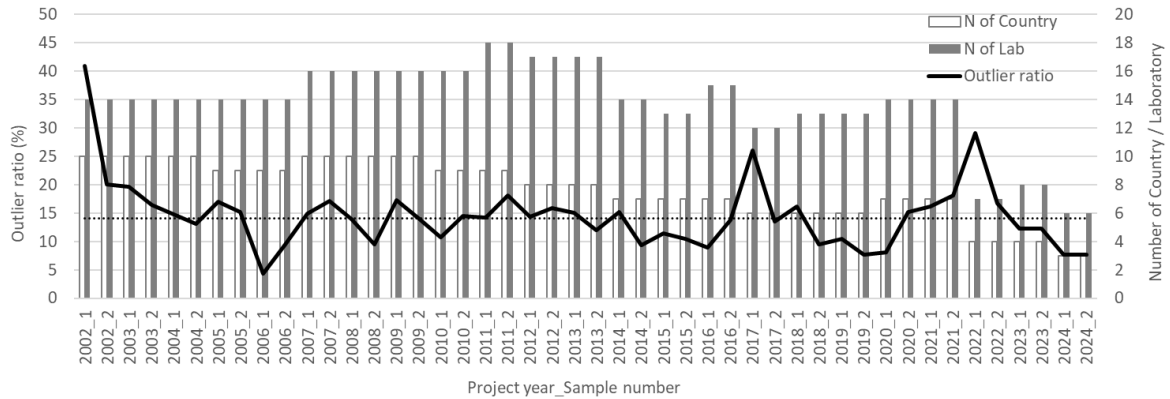


Figure 2.3. Change of the outlier ratio in all properties and laboratories from 2002 to 2024
Outlier ratio = $\{(N \text{ of entire dataset}) - (N \text{ of verified dataset})\} / (N \text{ of entire dataset})$.
The suffixes ‘_1’ and ‘_2’ denote the two types of the samples analyzed each year (e.g., 241s and 242s). The dotted line indicates the average outlier ratio from 2003 to 2023.

Inland aquatic environment

The project on inland aquatic environment sample analysis started in 2000 as one of the activities within the QA/QC programs. One artificial inland water sample, which contained all analyzed ions and was prepared by the NC, was distributed to the laboratories every year. The laboratories carried out the whole procedures of the inland water analysis including extraction, instrumental analysis or titration, and reporting. Performance at each step would be responsible for the inter-laboratory variations. The Inter-Laboratory Comparison projects of EANET have been carried out 25 times, and the results showing the percentage of flagged data and the percentage of data that satisfied the DQOs are shown in Figure 2.4. The percentage of data within DQOs showed some fluctuations in the early years, but remained at a high level in subsequent projects.

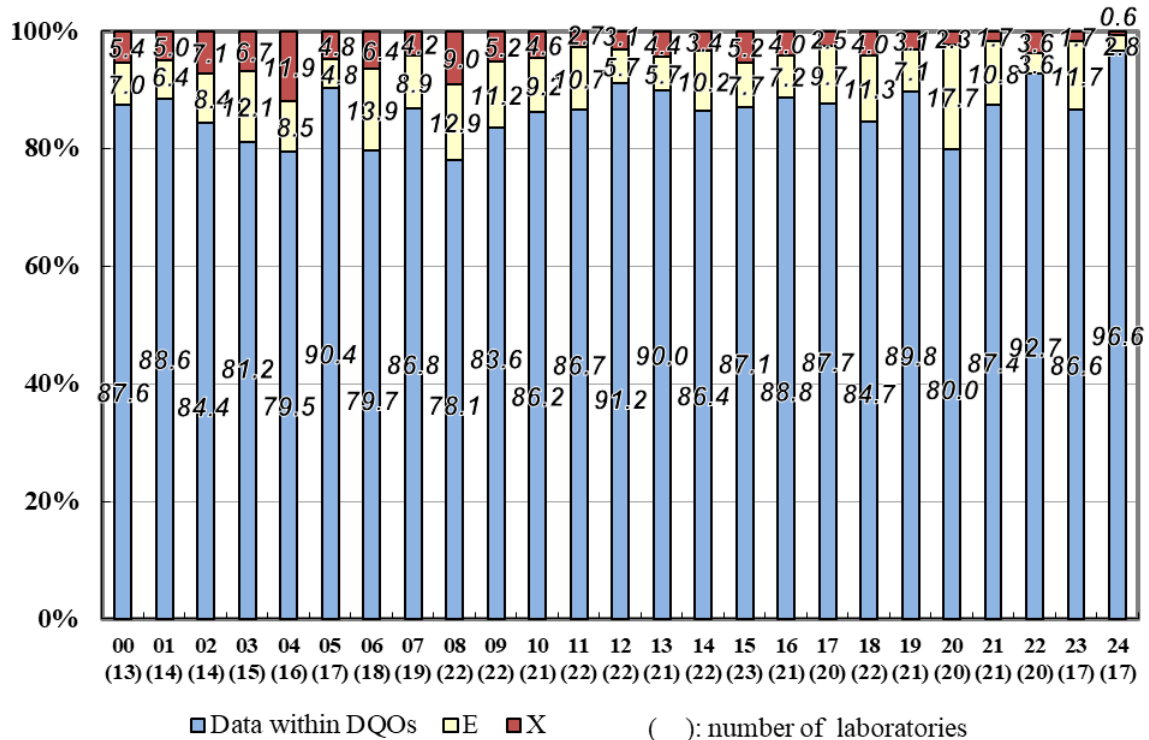


Figure 2.2. Overall comparisons of all Inter-Laboratory Comparison projects for inland aquatic environment during 1998-2024.

Evaluation of the measurements

The objectives of the QA/QC program are to obtain reliable data that can be comparable among the countries of the East Asian region, as well as with other networks by ensuring data accuracy, precision, representativeness and completeness in acid deposition monitoring. All activities of data management are directed to ensure acceptable quality assurance levels. Evaluation of the datasets from the viewpoints described below has ensured that a large proportion of the measurements, including those obtained during the early stage of the network, are of acceptable quality, while the quality of more recent datasets has further improved.

Flow for the data reporting and verification

The process related to the data reporting and verification is carried out annually. Monitoring data compiled and verified by each participating country's National Center under its QA/QC Manager are submitted to the Network Center for the EANET, where further checking and verification are conducted. Any issues identified are referred to the relevant country for confirmation and correction as appropriate. The data are then reviewed by the Verification Group, comprising external researchers and experts, as part of the quality assurance process. Based on the verified data, the Network Center prepares the Data Report, which is reviewed and adopted by the Scientific Advisory Committee and subsequently approved by the Intergovernmental Meeting before publication. The Data Report and monitoring data are available through the EANET website (<https://monitoring.eanet.asia/document/public/index>), although registration is required to access detailed monitoring data (<https://monitoring.eanet.asia/document/register/index>).

Validation of the data for wet deposition

The quality of annual wet deposition data is assessed using quality flags and QA/QC criteria. Quality flags are assigned to samples or individual measurements that do not meet defined criteria, such as those affected by insufficient sample volume or low analytical precision. As part of routine quality assurance procedures, all wet deposition samples are evaluated using ion balance (*R1*) and conductivity agreement (*R2*). Annual attainment rates for these criteria are compiled, and their long-term trends are evaluated using the Mann–Kendall trend test to identify possible improvements or deterioration in data quality. These assessments provide information for participating countries to review laboratory practices, sample handling, and analytical performance and to take appropriate actions to maintain and improve data quality.

Data completeness

Data completeness is an important data quality indicator for ensuring the reliability of monthly and annual statistics. For wet deposition monitoring, completeness is evaluated using two Data Quality Objectives (DQOs): Percent Precipitation Coverage Length (%PCL) and Percent Total Precipitation (%TP). Both indicators are required to exceed 80%. For dry deposition (air concentration) monitoring, data completeness is calculated as the proportion of valid hourly data for automatic monitoring or valid measurement days for filter pack and other manual methods. A completeness of at least 70% is required for calculating monthly and annual air concentrations and dry deposition fluxes. The attainment of these DQOs is evaluated regularly to identify data gaps and possible operational problems. Measures to improve data completeness include appropriate maintenance and replacement of monitoring equipment and installation of systems to prevent data loss caused by power failures or other equipment-related problems.

Site representativeness

The characteristics of monitoring sites are assessed to ensure appropriate interpretation and representativeness of EANET monitoring data. Air concentration and atmospheric deposition sites are classified as urban, rural, or remote based on potential pollution sources, surrounding land use, and other conditions at on-site, local, and regional scales. Relevant site information is collected through the National Monitoring Plans and is considered when analyzing monitoring data. Changes in site conditions or relocation of monitoring equipment may require reevaluation of the site

Executive Summary

classification. Ecological monitoring sites are established to assess the effects of atmospheric deposition on soil, vegetation, and inland aquatic ecosystems and are preferably located near air concentration and deposition monitoring sites. EANET also promotes greater integration of atmospheric and ecological monitoring, including catchment-scale approaches, to better evaluate relationships between atmospheric inputs and ecosystem responses.

3. Gas and Aerosol Concentration in East Asia

Monitoring Network and Data Coverage

Once the pollutants are emitted and mixed in the air, they are deposited locally and across the wide range. Since its establishment in 2000, EANET has continuously monitored atmospheric concentrations of gaseous and particulate pollutants across East Asia. Fig. 3.1 illustrates the number of gas and aerosol monitoring sites in EANET from 2000 to 2024. By 2024, air concentration measurements were conducted at 65 monitoring sites located in 13 participating countries, including urban, rural, remote, coastal, mountainous, and island environments. The monitoring network provides one of the longest and most comprehensive regional datasets available for assessing atmospheric composition and its changes over time.

The air concentration monitoring covers a wide range of gaseous and aerosol species, including SO₂, NO₂, NO_x, O₃, HNO₃, HCl, NH₃, particulate matter (PM₁₀ and PM_{2.5}), and major inorganic aerosol components such as Cl⁻, NO₃⁻, SO₄²⁻, NH₄⁺, Na⁺, K⁺, Ca²⁺ and Mg²⁺. The long-term observations collected through harmonized monitoring methodologies and rigorous quality assurance and quality control procedures provide a robust scientific basis for evaluating the status and trends of air quality in East Asia. These observations also support assessments of atmospheric deposition, wide range air pollution, ecosystem impacts in the EANET region.

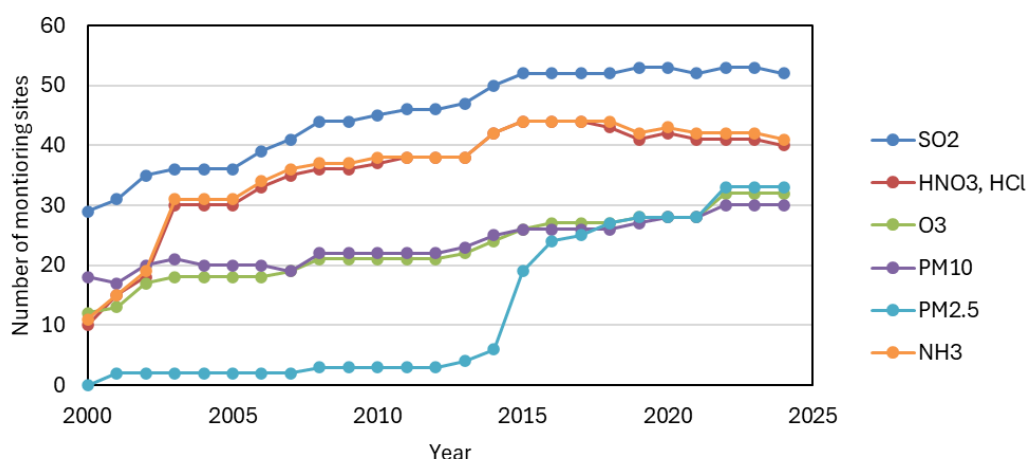


Figure 3.1. Number of gas and aerosol monitoring sites in EANET (2000-2024)

Spatial Distribution of Gaseous and Particulate Pollutants

The spatial distributions of gaseous and particulate pollutants across East Asia exhibited pronounced regional variability, reflecting differences in emission sources, economic activities, land use, meteorological conditions, and atmospheric transport processes. The long-term monitoring data collected by EANET provide valuable insights into the current status of air quality and the factors controlling atmospheric composition throughout the region (Figures 3.2-3.6).

Particulate matter concentrations showed particularly large spatial gradients across East Asia. Annual mean PM₁₀ concentrations were generally highest at the site in Mongolia (> 45 µg/m³) and some Southeast Asian countries, where mineral dust emissions, biomass burning, and urban activities contribute substantially to ambient particle levels (Figure 3.1). The elevated PM₁₀ concentrations observed in Mongolia were associated with arid and semi-arid environments that are attributable to soil erosion and windblown dust generation. In contrast, Southeast Asian urban areas are affected by a combination of traffic emissions, industrial activities, open biomass burning, and secondary particle formation.

Executive Summary

The spatial distribution of PM_{2.5} was broadly similar to that of PM₁₀, although fine particles were more strongly influenced by combustion-related emissions and atmospheric chemical processes (Figure 3.2). Elevated PM_{2.5} concentrations were observed in metropolitan and industrialized regions, indicating the important contributions of fossil fuel combustion, industrial emissions, biomass burning, and secondary aerosol formation. Conversely, relatively low PM_{2.5} concentrations were recorded at remote and rural sites in Japan and other background locations ($> 10 \mu\text{g}/\text{m}^3$), demonstrating the influence of emission intensity and source proximity on regional particulate pollution levels.

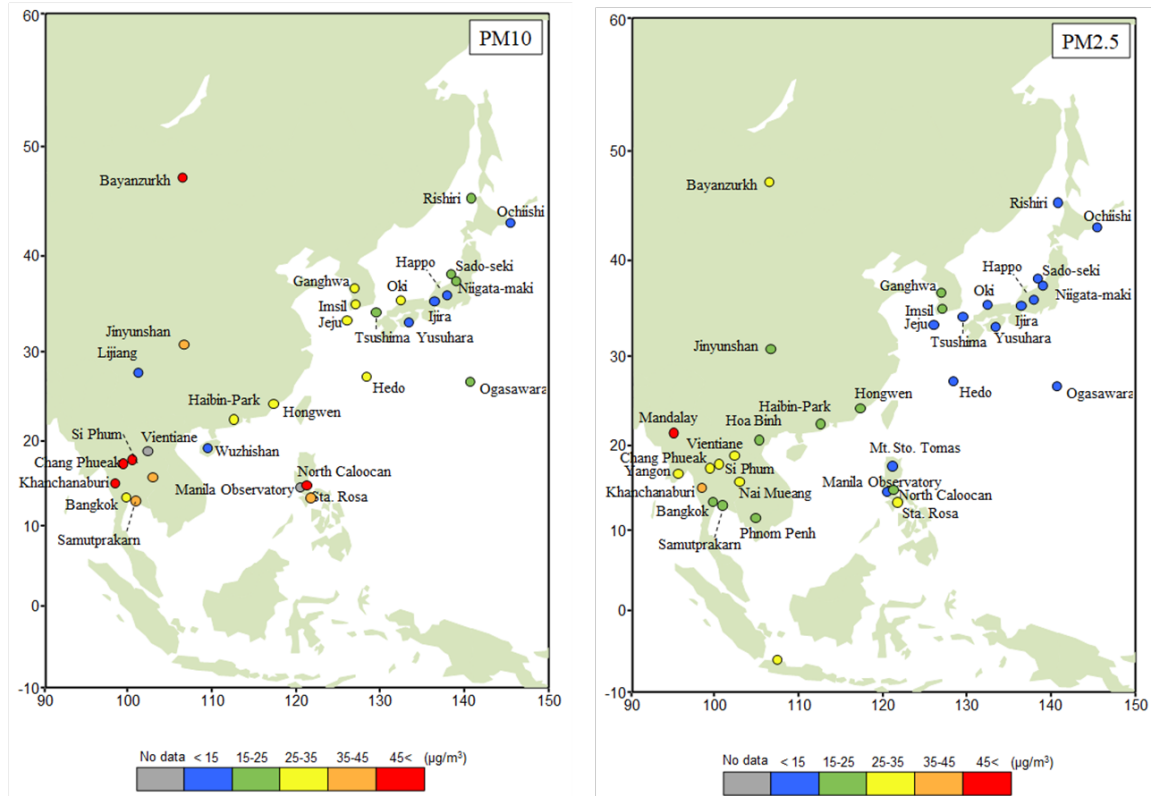


Figure 3.2 Spatial distribution map of PM₁₀ and PM_{2.5} concentrations (2020-2024)

Surface ozone (O₃) exhibited a distinctly different spatial pattern compared with particulate matter and primary gaseous pollutants (Figure 3.2). Relatively high O₃ concentrations were frequently observed at rural and remote sites rather than in densely populated urban areas. Annual mean O₃ concentrations exceeded 45 ppb at several sites, including Haibin-Park in China and Sta. Rosa in the Philippines, while concentrations of 35-45 ppb were commonly observed at remote and rural sites in Japan and the Republic of Korea. In Japan, elevated O₃ levels were recorded at sites such as Rishiri, Ochiishi, Sado-seki, Happon, and Oki, where local precursor emissions are relatively low but regional transport influences would be significant. This characteristic reflects the regional nature of O₃ pollution, which is affected by photochemical production, long-range transport, and atmospheric mixing processes. In urban environments, O₃ concentrations are often depleted through reactions with freshly emitted nitrogen oxides (NO_x), whereas in rural and remote regions O₃ can accumulate and persist over larger spatial scales. Seasonal trend analyses further indicate that O₃ concentrations tend to peak during spring at many sites in Northeast Asia, reflecting enhanced photochemical production and long range transport from source regions. These results highlight the need for coordinated regional cooperation to reduce O₃ precursor emissions and to better understand the interactions among emissions, atmospheric chemistry, and long range transport in East Asia.

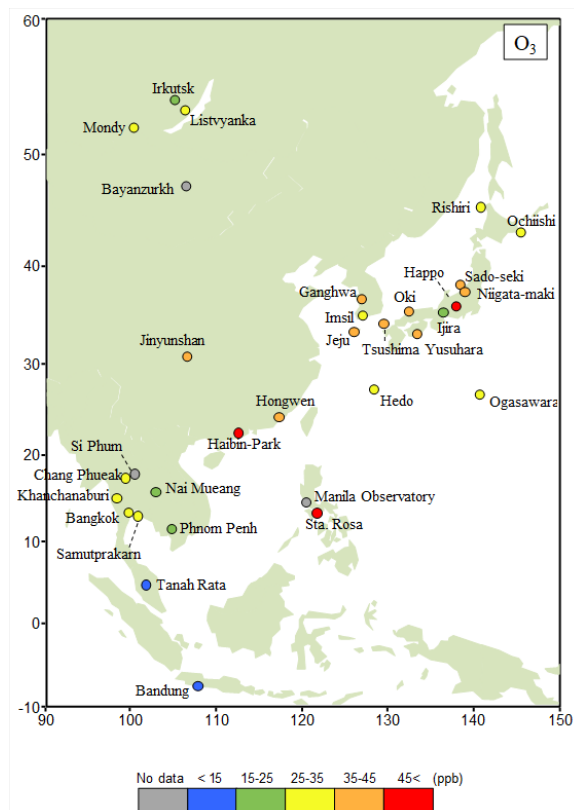


Figure 3.3 Spatial distribution map of O₃ concentration (2020-2024)

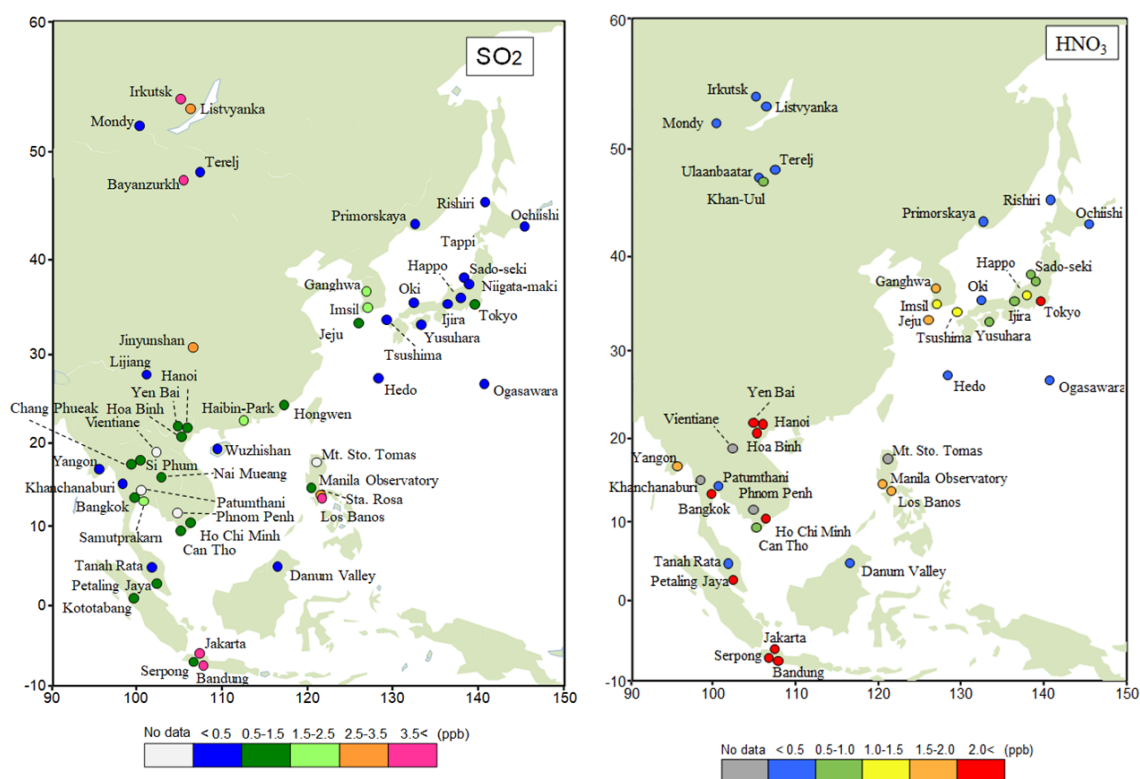


Figure 3.4 Spatial distribution map of SO₂ concentration (2020-2024)

Figure 3.5 Spatial distribution map of HNO₃ concentration (2020-2024)

The spatial distribution of SO₂ revealed generally low concentrations across much of the EANET region (Figure 3.4). Most remote and rural sites recorded annual average concentrations below 0.5 ppb, reflecting substantial reductions in sulfur emissions achieved through emission control policies and cleaner fuel use. On the other hand, relatively elevated SO₂ levels were still observed at some urban and industrial sites, particularly in regions where coal combustion and industrial activities remain important sources. The observed distribution demonstrates both the success of sulfur emission controls and the continuing influence of local anthropogenic emissions.

Reactive nitrogen species showed substantial spatial variability throughout East Asia. HNO₃ concentrations were generally higher in areas affected by intensive anthropogenic activities, reflecting the oxidation of nitrogen oxides emitted from transportation, industrial, and energy sectors (Figure 3.5). Elevated HNO₃ concentrations were also observed in regions characterized by active photochemical processes, highlighting the importance of atmospheric oxidation in determining regional nitrogen distributions.

NH₃ exhibited a different spatial distribution pattern (Figure 3.6). Higher concentrations were frequently observed in agricultural regions where livestock production and fertilizer application represent major emission sources. Unlike sulfur dioxide and oxidized nitrogen compounds, ammonia emissions are closely linked to agricultural activities and therefore often exhibit distinct geographical patterns. The observed NH₃ distributions indicate that agricultural emissions remain an important contributor to atmospheric nitrogen loading and secondary aerosol formation in many parts of East Asia.

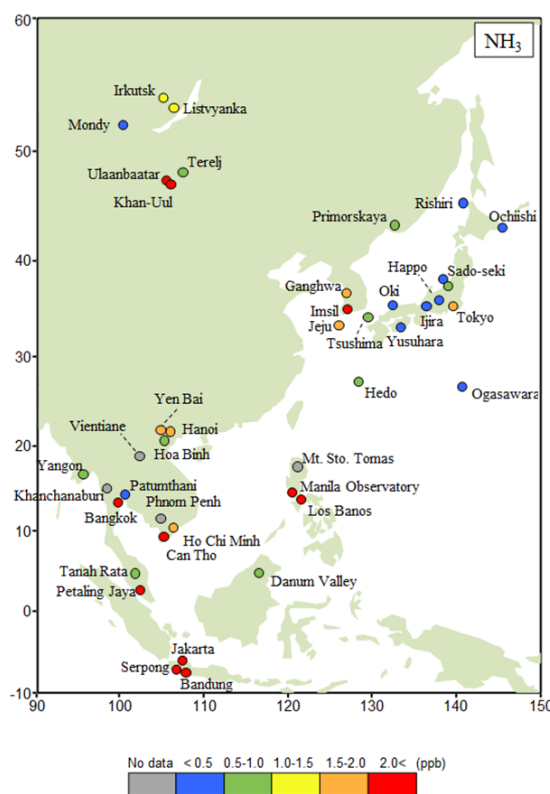


Figure 3.6 Spatial distribution map of NH₃ concentration (2020-2024)

Seasonal and Diurnal Characteristics of PM_{2.5} and O₃

The seasonal and diurnal characteristics of PM_{2.5} and O₃ provide important insights into the processes controlling air quality across East Asia. Unlike annual mean concentrations, these temporal variations reflect the combined influences of emissions, atmospheric chemistry, meteorological conditions, and long-range transport.

Monthly variations of PM_{2.5} exhibited clear regional differences (Figure 3.7). In Northeast Asia, PM_{2.5} concentrations generally increased during winter and early spring owing to enhanced combustion emissions, stagnant meteorological conditions, and reduced atmospheric boundary-layer heights. In contrast, many sites in mainland Southeast Asia showed elevated PM_{2.5} concentrations during the dry season, reflecting the influence of biomass burning and regional haze events. These seasonal patterns indicate that both anthropogenic activities and climatic conditions play important roles in determining PM_{2.5} concentrations throughout the region.

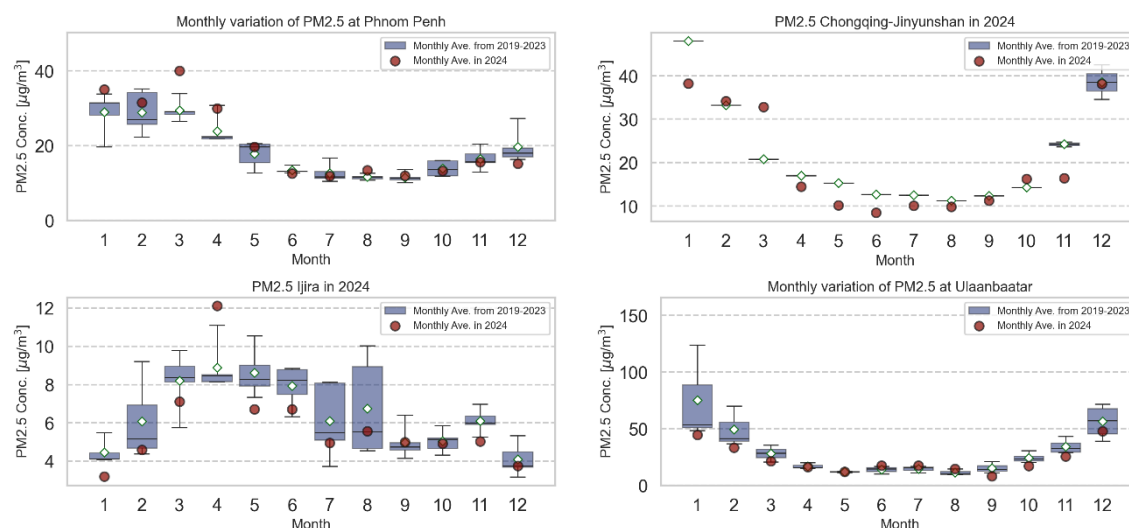


Figure 3.7 Monthly variations of PM_{2.5} concentration (2019-2023, 2024)

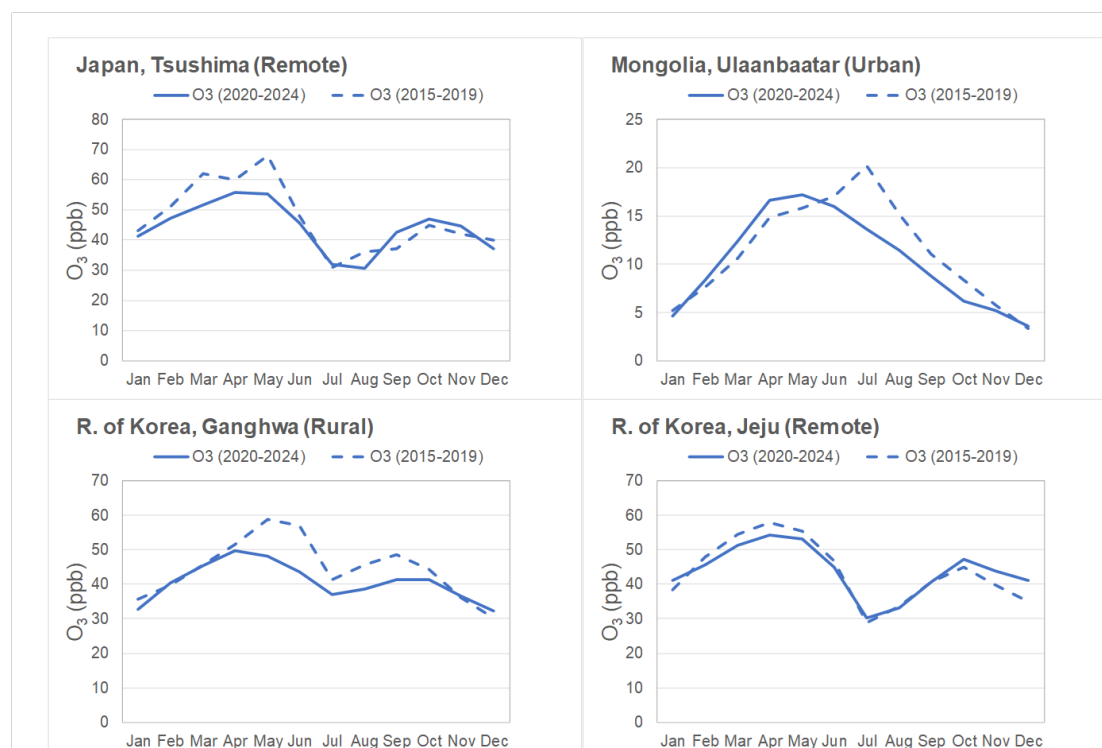


Figure 3.8 Seasonal trend of O₃ concentration (2015-2019, 2020-2024)

Executive Summary

O₃ exhibited a markedly different seasonal cycle from PM_{2.5} (Figure 3.8). At many rural and remote sites in Japan, the Republic of Korea, and China, O₃ concentrations reached their highest levels in spring. This spring maximum is consistent with enhanced photochemical production and long range transport of O₃ and its precursors across Northeast Asia. Summer concentrations remained relatively high at many sites due to strong solar radiation and active photochemistry, whereas lower concentrations were generally observed during winter when photochemical activity was limited.

Diurnal variations further highlight the contrasting behavior of PM_{2.5} and O₃ (Figure 3.9). PM_{2.5} commonly exhibited relatively modest diurnal variability compared with gaseous pollutants, suggesting that regional transport and secondary aerosol formation contribute substantially to ambient concentrations. At several urban locations, PM_{2.5} concentrations tended to be higher during nighttime and early morning hours, when atmospheric mixing was weak and pollutants accumulated near the surface.

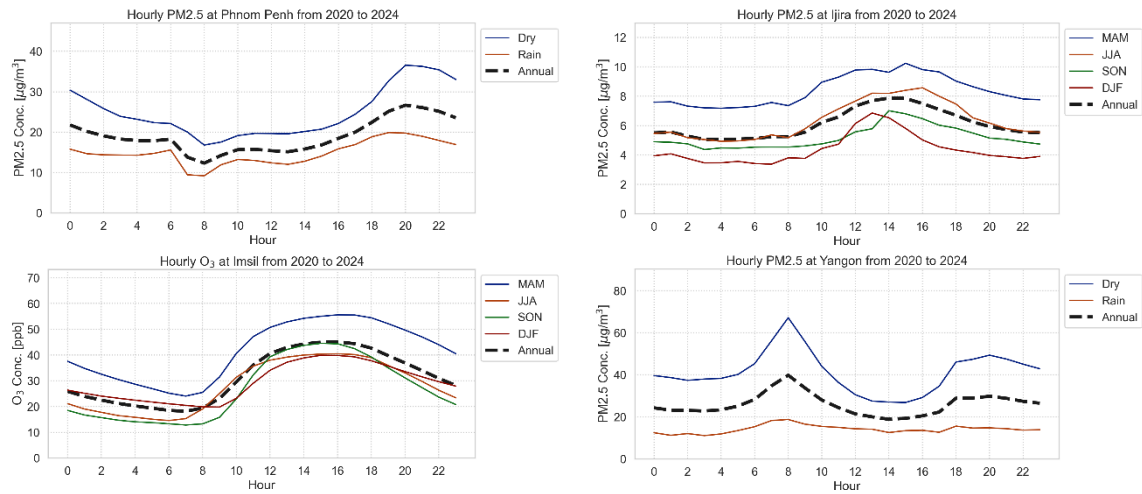


Figure 3.9 Diurnal variations of PM_{2.5} concentration for each season (2020-2024)

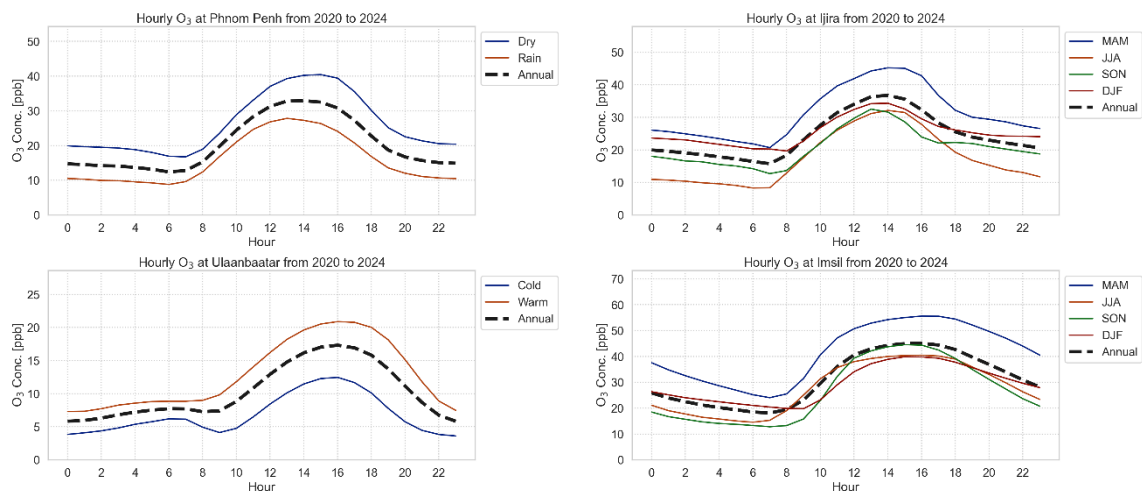


Figure 3.10 Diurnal variation of O₃ concentrations at respective EANET sites in each season (2020-2024)

O₃ showed a characteristic diurnal cycle throughout the EANET region (Figure 3.10). Concentrations typically increased after sunrise as photochemical production intensified, reached maximum levels during the afternoon, and subsequently decreased after sunset. Nighttime O₃ reduction was associated with cessation of photochemical production, surface deposition, and reactions with

nitrogen oxides. The consistency of this pattern among monitoring sites demonstrates the dominant influence of solar radiation and photochemical processes on surface O₃ concentrations.

These seasonal and diurnal characteristics emphasize that PM_{2.5} and O₃ are controlled by different physical and chemical mechanisms. Whereas PM_{2.5} is influenced by emissions, secondary aerosol formation, and accumulation processes, O₃ is strongly controlled by photochemical reactions and regional-scale atmospheric transport.

Maximum Daily 8-hour Average Ozone (MDA8 O₃)

To assess elevated O₃ exposure more effectively, Maximum Daily 8-hour Average (MDA8) O₃ concentrations were evaluated in addition to annual mean concentrations. MDA8 O₃ is widely used for air-quality assessment because it represents sustained daytime exposure to high O₃ levels and is therefore more relevant to human health and vegetation impacts. The analysis revealed substantial spatial variability in MDA8 O₃ concentrations across East Asia (Figure 3.11). Elevated MDA8 O₃ values were observed not only at urban sites but also at many rural and remote locations, indicating the regional nature of O₃ pollution. This contrasts with primary pollutants such as NO₂ and PM_{2.5}, whose highest concentrations are generally found near major emission sources.

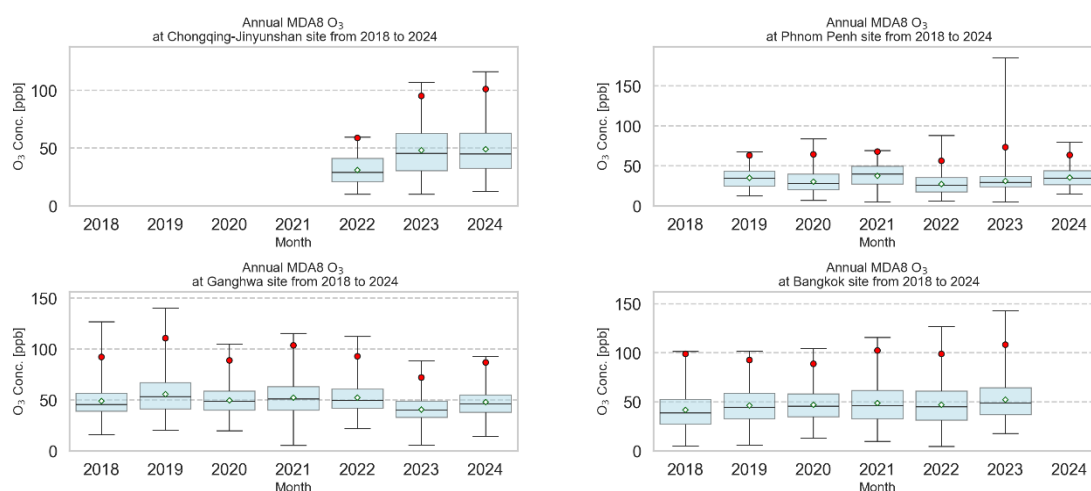


Figure 3.11 Annual Trend of MDA8 O₃ Concentration at respective EANET sites (2018-2024)

Seasonal analyses of MDA8 O₃ showed that exceedances occurred most frequently during spring and early summer, particularly at sites in Northeast Asia. These periods coincide with enhanced photochemical activity and efficient long-range transport of O₃ and precursor species. Consequently, elevated MDA8 O₃ concentrations were often observed even in areas distant from major urban or industrial emission sources. The widespread occurrence of high MDA8 O₃ concentrations highlights the complexity of O₃ management in East Asia. While long-term observations indicate substantial reductions in sulfur dioxide, nitrogen oxides, and particulate matter concentrations, O₃ continues to exhibit regionally variable behavior. This reflects the nonlinear relationship between O₃ formation, precursor emissions, and meteorological conditions.

Long-term Changes in Gas and Aerosol Concentrations

Long-term observations conducted under EANET provide a unique opportunity to evaluate how atmospheric composition has changed across East Asia over the past two decades. To quantify these changes, Mann-Kendall trend analyses were applied to the monitoring data for major gaseous and particulate pollutants. The trend analysis results demonstrate substantial improvements in regional air quality while also highlighting several emerging challenges.

Executive Summary

Particulate matter concentrations showed predominantly decreasing trends throughout the EANET region. For both PM₁₀ and PM_{2.5} (Table 3.1), the number of monitoring sites exhibiting significant decreasing trends was considerably larger than the number showing increasing trends. These reductions were observed at urban, rural, and remote sites and likely reflect the combined effects of stricter emission regulations, improved combustion technologies, cleaner fuels, and enhanced industrial controls implemented in many East Asian countries. The decreasing trends observed for PM_{2.5} are particularly important because fine particles are strongly associated with human health impacts and atmospheric visibility degradation.

Table 3.1 Annual trends of PM_{2.5} concentrations at respective EANET sites (2000-2024)

$\mu\text{g m}^{-3} \text{ year}^{-1}$						$\mu\text{g m}^{-3} \text{ year}^{-1}$					
Country	Site	N	Z-score	Sen's slope	Trend	Country	Site	N	Z-score	Sen's slope	Trend
Cambodia	Phnom Penh	8	0.38	0.33	No trend	Mongolia	Ulaanbaatar	5	N/A	N/A	N/A
China	Jinyunshan	3	N/A	N/A	N/A		Bayanzurkh	11	-3.05	-3.33	Dec.
	Hongwen	3	N/A	N/A	N/A	Myanmar	Yangon	7	0.76	0.50	No trend
	Haibin-Park	3	N/A	N/A	N/A		Mandalay	6	N/A	N/A	N/A
Indonesia	Jakarta	4	N/A	N/A	N/A	Philippines	Manila Observatory	7	-2.70	-1.50	Dec.
Japan	Rishiri	24	-3.82	-0.08	Dec.		North Caloocan	2	N/A	N/A	N/A
	Ochiishi	17	-4.36	-0.46	Dec.		Sta. Rosa	3	N/A	N/A	N/A
	Tappi	4	N/A	N/A	N/A		Mt. Sto. Tomas	4	N/A	N/A	N/A
	Sadoseki	10	-2.84	-0.43	Dec.	Republic of Korea	Ganghwa	9	-2.54	-1.00	Dec.
	Happo	10	-1.70	-0.25	No trend		Jeju	9	-2.00	-0.63	No trend
	Ijira	10	-2.91	-0.50	Dec.		Imsil	6	N/A	N/A	N/A
	Oki	23	-3.41	-0.25	Dec.	Thailand	Bangkok	10	-2.29	-0.88	Dec.
	Banryu	4	N/A	N/A	N/A		Samutprakarn	9	-0.64	-0.24	Dec.
	Yuahara	10	-3.11	-0.33	Dec.		Khanchanaburi	8	1.00	1.30	No trend
	Hedo	10	-2.35	-0.33	Dec.		ChangPhueak	9	0.32	0.25	No trend
	Ogasawara	10	-2.24	0.00	No trend		Si Phum	12	-2.15	-0.82	Dec.
	Niigata-maki	5	N/A	N/A	N/A		Nai Mueang	6	N/A	N/A	N/A
	Tsushima	6	N/A	N/A	N/A	Vietnam	Hoa Binh	9	-3.14	-2.42	Dec.
Lao PDR	Vientiane	7	0.15	1.00	No trend						

Table 3.2 Annual trends of O₃ concentrations at respective EANET sites (2000-2024)

ppb year ⁻¹						ppb year ⁻¹					
Country	Site	N	Z-score	Sen's slope	Trend	Country	Site	N	Z-score	Sen's slope	Trend
Cambodia	Phnom Penh	6	N/A	N/A	N/A	Mongolia	Ulaanbaatar	0	N/A	N/A	N/A
Indonesia	Bandung	8	-2.14	-0.67	Dec.		Bayanzurkh	11	-2.19	-0.25	Dec.
Japan	Rishiri	25	-3.77	-0.38	Dec.	Philippines	Manila Observatory	2	N/A	N/A	N/A
	Ochiishi	17	-1.50	-0.26	No trend		Sta. Rosa	2	N/A	N/A	N/A
	Tappi	17	-1.37	-0.45	No trend	Republic of Korea	Ganghwa	23	0.75	0.07	No trend
	Sado-seki	25	-3.03	-0.33	Dec.		Jeju	23	3.11	0.37	Inc.
	Happo	24	-4.31	-0.50	Dec.		Imsil	23	1.93	0.13	No trend
	Ijira	24	-0.55	-0.10	No trend	Russia	Mondy	19	-1.55	-0.33	No trend
	Oki	25	0.52	0.00	No trend		Listvyanka	7	-0.46	-0.68	No trend
	Banryu	19	-3.46	-0.21	Dec.		Irkutsk	6	N/A	N/A	N/A
	Yusuhara	24	0.80	0.09	No trend	Thailand	Bangkok	16	3.99	1.00	Inc.
	Hedo	24	-3.10	-0.33	Dec.		Samutprakarn	22	4.64	0.75	Inc.
	Ogasawara	25	1.69	0.33	No trend		Khanchanaburi	21	3.03	0.69	Inc.
	Niigata-maki	6	N/A	N/A	N/A		ChangPhueak	20	3.33	0.61	Inc.
	Tsushima	5	N/A	N/A	N/A		Si Phum	2	N/A	N/A	N/A
Malaysia	Tanah Rata	1	N/A	N/A	N/A		Nai Mueang	15	1.88	0.33	No trend

The trend patterns for O₃ differed markedly from those of primary pollutants. Unlike particulate matter, O₃ showed both increasing and decreasing trends depending on location (Table 3.2). Although decreasing trends were detected at some monitoring sites, increasing trends were also observed, particularly at urban sites in parts of Southeast Asia. These contrasting responses reflect the complex interactions among precursor emissions, atmospheric chemistry, meteorological conditions, and long-range transport processes. The results indicate that O₃ remains a challenging regional air-pollution issue despite the substantial reductions achieved for many primary pollutants.

Table 3.3 Annual trends of NH₃ concentration at respective EANET sites (2000-2024)

ppb year ⁻¹						ppb year ⁻¹					
Country	Site	N	Z-score	Sen's slope	Trend	Country	Site	N	Z-score	Sen's slope	Trend
Cambodia	Phnom Penh	8	-2.35	-0.96	Dec.	Mongolia	Ulaanbaatar	16	-1.04	-0.11	No trend
China	Hongwen	7	0.60	0.20	No trend		<i>Khan-Uul</i>	3	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>
Indonesia	Jakarta	9	-0.73	-0.76	No trend		Tereji	18	0.57	0.01	No trend
	Serpong	22	0.23	0.04	No trend	Myanmar	Yangon	14	-3.56	-0.87	Dec.
	Bandung FP	9	1.89	0.27	No trend	Philippines	Manila Observatory	16	1.58	0.13	No trend
Japan	Rishiri	23	4.03	0.01	Inc.		Los Baños	12	0.34	0.06	No trend
	Ochiishi	17	-1.71	0.00	No trend		Mt. Sto. Tomas	10	1.25	0.13	No trend
	Tappi	16	-0.48	0.00	No trend	Republic of Korea	Ganghwa	19	-2.88	-0.27	Dec.
	Sado-seki	21	2.95	0.01	Inc.		Jeju	17	0.49	0.03	No trend
	Happo	22	2.59	0.01	Inc.		Imsil	20	0.62	0.05	No trend
	Ijira	22	-4.16	-0.02	Inc.	Russia	Mondy	24	1.43	0.02	No trend
	Oki	23	-0.30	0.00	No trend		Listvyanka	25	2.48	0.08	Inc.
	Banryu	16	-2.83	-0.03	Dec.		Irkutsk	25	1.29	0.04	No trend
	Yusuhara	22	0.79	0.00	No trend		Primorskaya	23	-2.81	-0.14	Dec.
	Hedo	21	1.38	0.01	No trend	Thailand	Bangkok	20	-1.07	-0.12	No trend
	Ogasawara	22	0.19	0.00	No trend		Pathumthani	9	-0.31	-0.11	No trend
	Tokyo	18	-4.14	-0.10	Dec.		Khanchanaburi	17	0.78	0.08	No trend
	<i>Niigata-maki</i>	5	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>		Mae Hia	19	-1.30	-0.07	No trend
	<i>Tsushima</i>	5	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>		Sakaerat	14	2.91	0.21	Inc.
Lao PDR	<i>Vientiane</i>	3	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>	Vietnam	Hanoi	25	-2.97	-0.13	Dec.
Malaysia	Petaling Jaya	21	-0.15	-0.01	No trend		Hoa Binh	25	-3.98	-0.11	Dec.
	Tanah Rata	23	2.87	0.05	Inc.		Can Tho	11	2.26	0.27	Inc.
	Danum Valley	18	1.33	0.02	No trend		Ho Chi Minh	11	-0.94	-0.07	No trend
							Yen Bai	10	0.00	0.00	No trend

Reactive nitrogen compounds exhibited similarly complex behavior. HNO₃ concentrations generally showed decreasing tendencies at many monitoring sites, consistent with reductions in oxidized nitrogen emissions. However, NH₃ exhibited a more mixed pattern, with both increasing and decreasing trends identified across the network (Table 3.3). The occurrence of increasing NH₃ concentrations at some sites suggests that agricultural emissions remain an important source of reactive nitrogen in East Asia. Because ammonia contributes to the formation of ammonium sulfate and ammonium nitrate aerosols, continued NH₃ emissions may limit future reductions in secondary particulate matter.

Overall, the Mann–Kendall trend analysis clearly demonstrates that air quality has improved substantially across East Asia during the past two decades. The predominance of decreasing trends for PM_{2.5} shows the effectiveness of regional emission-control policies. At the same time, the mixed trends observed for O₃ and NH₃ indicate that photochemical pollution and reactive nitrogen compounds remain important environmental challenges. These results underscore the value of long-term monitoring and highlight the need for continued regional cooperation to address emerging air-quality issues in East Asia.

4. Wet and Dry Deposition in East Asia

Under the EANET framework, there are currently 57 wet deposition monitoring sites and 51 dry deposition monitoring sites located in 13 EANET member countries. In accordance with EANET criteria, the monitoring sites are categorized into three types: urban, rural, and remote. Sampling techniques, sample storage and analysis, data processing, and QA/QC procedures of all monitoring sites and laboratories participating in EANET are conducted according to EANET's guidelines and manuals (EANET, 2010a, 2010b, 2013, and 2022). Dry deposition was estimated using the inferential method described in the Technical Manual for Dry Deposition Flux Estimation in East Asia (EANET, 2010b). The details of each process can be found in the main text.

Sulfur deposition

Table 4.1 shows trends in wet deposition of non-sea-salt sulfate (nss-SO_4^{2-}) assessed by the Mann–Kendall test and Figure 4.1 presents the trends in wet deposition of nss-SO_4^{2-} at EANET sites in 2000–2024. The long-term temporal variations of nss-SO_4^{2-} wet deposition across Asia reflect the profound impacts of regional atmospheric sulfur dioxide (SO_2) mitigation. Northeast Asia shows coherent and statistically significant decreasing trends, particularly in China and Japan, consistent with substantial reductions in SO_2 emissions. Declines at Japanese remote and background sites also indicate reduced transboundary acid deposition from the Asian continent. In contrast, Southeast Asia shows more heterogeneous and often non-significant trends, likely reflecting differences in precipitation regimes and emission controls. Urban sites generally exhibit higher deposition fluxes and greater variability, while rural and remote sites show smoother trends that more clearly reflect regional-scale atmospheric changes.

Figure 4.2 shows the spatial distributions of the five-year mean wet deposition of nss-SO_4^{2-} for the periods 2000–2004, 2010–2014, and 2020–2024.

For 2000–2004, the highest five-year mean values were observed at Shizhan (China, urban: $64.8 \text{ kg S ha}^{-1} \text{ yr}^{-1}$), followed by Jinyunshan (China, rural: $38.4 \text{ kg S ha}^{-1} \text{ yr}^{-1}$), Jakarta (Indonesia, urban: $24.4 \text{ kg S ha}^{-1} \text{ yr}^{-1}$), and Jiwozi (China, remote: $23.7 \text{ kg S ha}^{-1} \text{ yr}^{-1}$). During this period, substantial wet deposition of sulfur was widely observed, particularly in China and Indonesia, and this phenomenon was evident not only at urban sites but also at rural and remote sites.

For 2010–2014, the highest values were recorded at Haifu (China, urban: $37.1 \text{ kg S ha}^{-1} \text{ yr}^{-1}$), Jinyunshan ($36.6 \text{ kg S ha}^{-1} \text{ yr}^{-1}$), Petaling Jaya (Malaysia, urban: $21.6 \text{ kg S ha}^{-1} \text{ yr}^{-1}$), and Bandung (Indonesia, urban: $20.2 \text{ kg S ha}^{-1} \text{ yr}^{-1}$). Although an overall decreasing trend was observed compared to 2000–2004, widespread wet deposition of sulfur persisted, particularly in China, Malaysia, and Indonesia.

For 2020–2024, the highest values were found at Hanoi (Vietnam, urban: $36.2 \text{ kg S ha}^{-1} \text{ yr}^{-1}$), Serpong (Indonesia, rural: $23.3 \text{ kg S ha}^{-1} \text{ yr}^{-1}$), Ho Chi Minh (Vietnam, urban: $19.1 \text{ kg S ha}^{-1} \text{ yr}^{-1}$), and Yen Bai (Vietnam, rural: $18.8 \text{ kg S ha}^{-1} \text{ yr}^{-1}$). A further decreasing trend was observed compared to 2010–2014, in particular, all sites in China, previously considered major sources, showed values below $10.0 \text{ kg S ha}^{-1} \text{ yr}^{-1}$. However, the hotspot of sulfur wet deposition shifted from China to Vietnam, where pronounced deposition was observed not only in urban areas but also in rural areas, similar to the pattern observed in the early 2000s.

In Indonesia, wet deposition at Jakarta showed a decreasing trend over these 25 years, whereas Serpong exhibited an increasing trend, with deposition level exceeding $20.0 \text{ kg S ha}^{-1} \text{ yr}^{-1}$ during the 2020–2024 period. In contrast, at high-latitude sites in Mongolia and Russia (e.g., Khan-Uul, Terelj, Mondy, Irkutsk, and Listvyanka), wet deposition remained consistently low, with values below $5.0 \text{ kg S ha}^{-1} \text{ yr}^{-1}$ regardless of the period, indicating stable and low sulfur deposition levels.

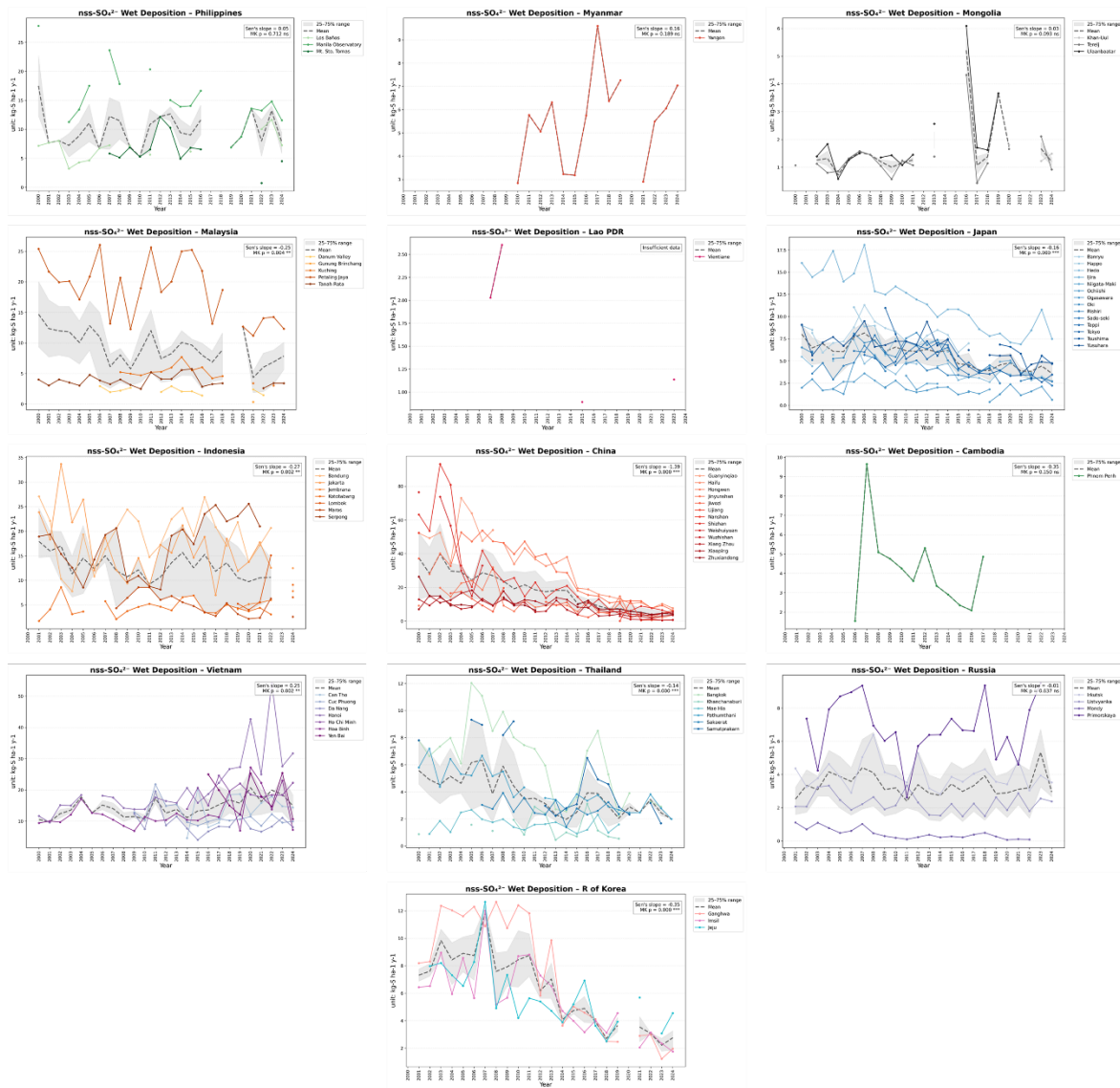


Figure 4.1. Trends in wet deposition of nss-SO₄²⁻ deposition at EANET sites (2000–2024)

Executive Summary

Table 4.1. Trends in wet deposition of nss-SO₄²⁻ (2000–2024) assessed by the Mann–Kendall test.

unit: kg S ha ⁻¹ y ⁻¹											
Country	Site	N	Z-score	Sen's slope	Trend	Country	Site	N	Z-score	Sen's slope	Trend
Cambodia	Phnom Penh	12	-0.92	-0.31	No trend	Lao PDR	<i>Vientiane</i>	4	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>
China	Haifu	17	-4.65	-2.36	Dec.	Malaysia	Danum Valley	11	-1.40	-0.07	No trend
	Hongwen	24	-3.89	-0.69	Dec.		<i>Gunung Brinchang</i>	1	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>
	Jinyunshan	24	-4.84	-2.24	Dec.		Kuching	13	-1.04	-0.11	No trend
	Jiwozi	20	-3.21	-0.85	Dec.		Petaling Jaya	24	-2.31	-0.37	Dec.
	<i>Lijiang</i>	6	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>		Tanah Rata	22	0.00	0.00	No trend
	Shizhan	25	-5.54	-1.90	Dec.	Mongolia	<i>Khan-Uul</i>	3	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>
	<i>Wuzhishan</i>	6	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>		Terelj	18	1.19	0.03	No trend
	Xiang Zhou	25	-3.57	-0.33	Dec.	Myanmar	Yangon	14	1.31	0.14	No trend
	Xiaoping	25	-3.81	-0.57	Dec.	Philippines	Los Baños	14	0.55	0.20	No trend
Zhuxiandong	20	-4.19	-0.54	Dec.		Manila Observatory	17	-1.85	-0.49	No trend	
Indonesia	Bandung	22	0.58	0.09	No trend		Mt. Sto. Tomas	12	-0.48	-0.11	No trend
	Jakarta	23	-2.01	-0.39	Dec.	R of Korea	Ganghwa	23	-4.12	-0.54	Dec.
	<i>Jembrana</i>	5	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>		Imsil	23	-3.86	-0.25	Dec.
	Kototabang	22	1.16	0.07	No trend		Jeju	21	-0.69	-0.06	No trend
	<i>Lombok</i>	5	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>	Russia	Irkutsk	24	-0.87	-0.02	No trend
	Maros	16	-2.75	-0.37	Dec.		Listvyanka	24	-0.57	-0.01	No trend
Japan	Serpong	21	2.45	0.47	Inc.		Mondy	22	-3.72	-0.03	Dec.
	Happo	16	-3.38	-0.44	Dec.		Primorskaya	22	0.00	-0.01	No trend
	Hedo	18	-1.36	-0.20	No trend	Thailand	Bangkok	23	-3.01	-0.28	Dec.
	Ijira	25	-5.30	-0.40	Dec.		Khanchanaburi	14	-0.88	-0.04	No trend
	<i>Niigata-Maki</i>	4	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>		Pathumthani	24	-4.84	-0.18	Dec.
	Ochiishi	13	-0.92	-0.13	No trend		Samutprakarn	16	-2.66	-0.49	Dec.
	Ogasawara	22	-1.24	-0.11	No trend	Vietnam	Can Tho	11	0.47	0.81	No trend
	Oki	19	-0.70	-0.09	No trend		Cuc Phuong	16	-0.95	-0.11	No trend
	Rishiri	22	-2.09	-0.12	Dec.		Da Nang	16	-0.14	-0.03	No trend
	Sado-seki	15	-1.78	-0.40	No trend		Hanoi	24	4.34	0.85	Inc.
	Tokyo	17	-4.24	-0.34	Dec.		Ho Chi Minh	11	0.31	0.26	No trend
	<i>Tsushima</i>	6	<i>N/A</i>	<i>N/A</i>	<i>N/A</i>		Hoa Binh	25	1.38	0.12	No trend
	Yusuhara	23	-3.59	-0.16	Dec.		Yen Bai	9	-0.73	-0.87	No trend

Notes: A site was classified as *Increasing (Inc.)* when its Z-score exceeded ± 1.96 and the Sen's slope was positive, or *Decreasing (Dec.)* when the slope was negative. If the Z-score fell within ± 1.96 , the site was categorized as *No trend*. Sites with sample sizes of six or fewer observations were not included in the Mann–Kendall analysis.

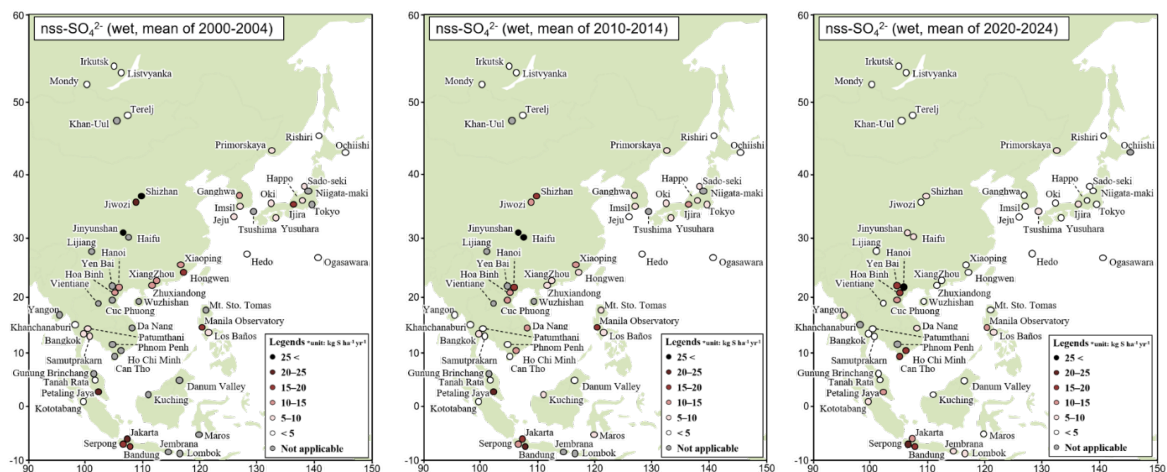


Figure 4.2. Spatial distributions of the mean wet deposition of nss-SO₄²⁻ for the period 2000–2004 (left), 2010–2014 (center), and 2020–2024 (right).

Nitrogen deposition

Table 4.2 shows trends in wet deposition of nitrate (NO_3^-) assessed by the Mann–Kendall test and Figure 4.3 presents the trends in wet deposition of NO_3^- at EANET sites in 2000–2024. Wet deposition of nitrate NO_3^- shows more complex and less pronounced trends than nss-SO_4^{2-} across Asia. Northeast Asia generally exhibits shallow, non-significant, or slightly decreasing trends, reflecting the complex influence of nitrogen oxides (NO_x) emission controls, traffic, and regional transport. Southeast Asia shows greater interannual variability, with possible increases at some urban sites associated with growing traffic and biomass burning. Urban sites generally show higher NO_3^- deposition and greater variability than remote background sites.

Table 4.3 shows trends in wet deposition of ammonium (NH_4^+) assessed by the Mann–Kendall test and Figure 4.4 presents the trends in wet deposition of NH_4^+ at EANET sites in 2000–2024. NH_4^+ deposition, largely associated with agricultural NH_3 emissions, shows substantial spatial and temporal variability. Trends in Northeast Asia are generally stable to slightly decreasing, while Southeast Asia exhibits pronounced seasonal fluctuations and localized increases associated with agricultural activities. Unlike industrial pollutants, relatively high NH_4^+ deposition can occur at rural and agricultural sites, reflecting the influence of fertilizer application and livestock emissions.

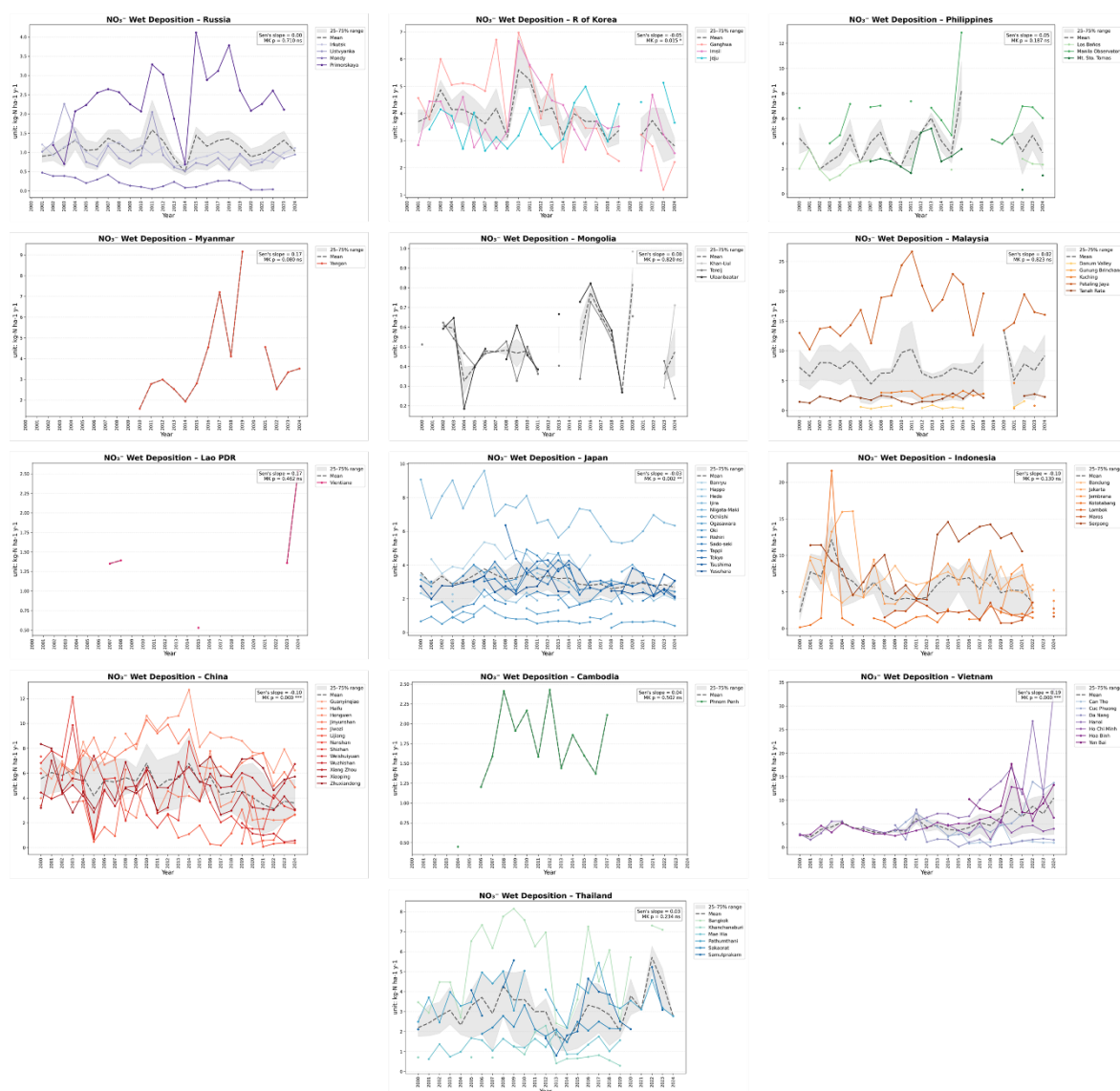


Figure 4.3. Trends in wet deposition of NO_3^- deposition at EANET sites (2000–2024)

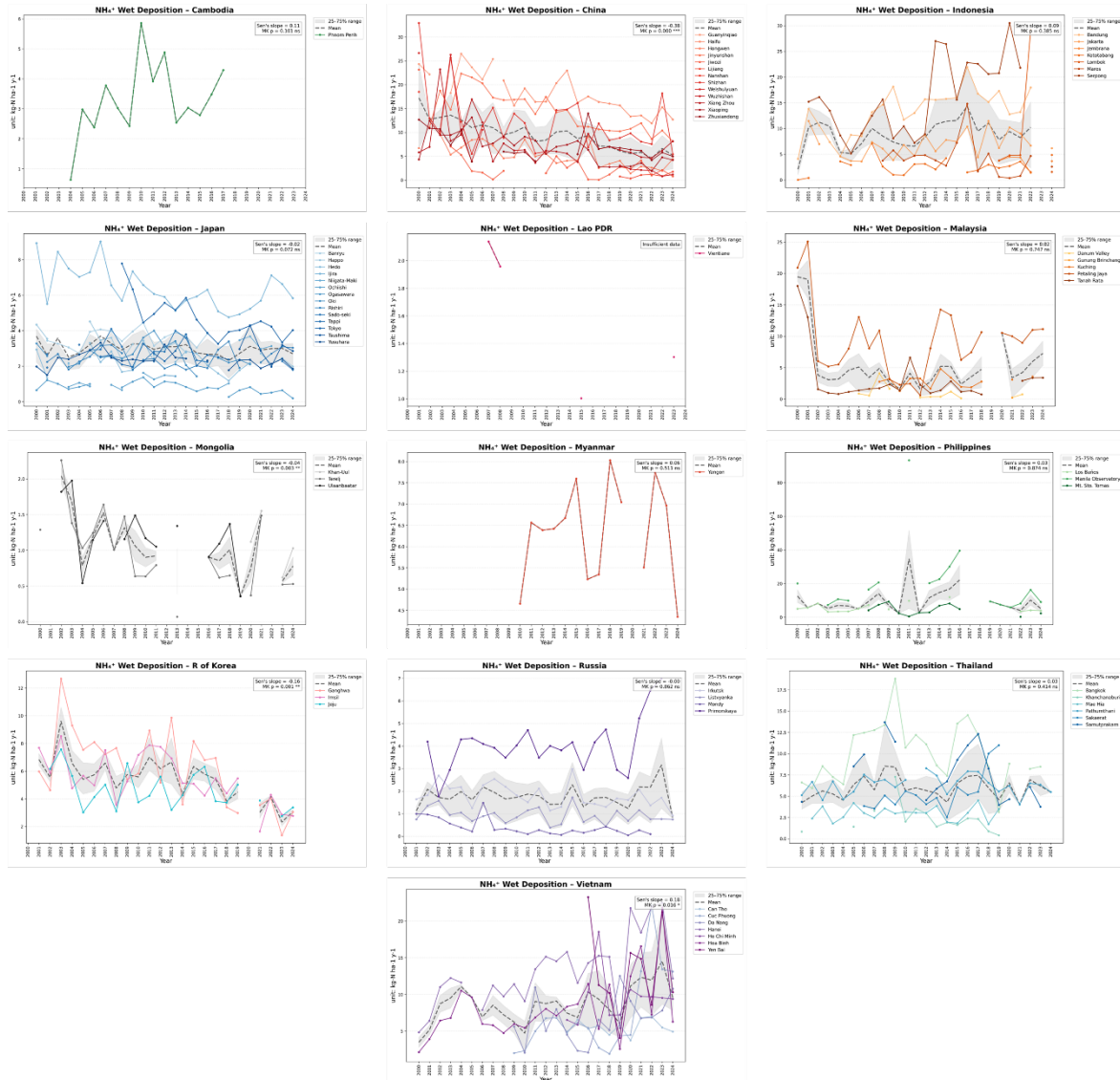


Figure 4.4. Trends in wet deposition of NH_4^+ deposition at EANET sites (2000–2024)

The spatial distribution of five-year mean NO_3^- and NH_4^+ wet deposition shows substantial regional differences and temporal shifts across Asia (Figure 4.5). NH_4^+ deposition generally exceeded NO_3^- at most sites throughout 2000–2024. During 2000–2004, high nitrogen deposition was observed in China, Malaysia, and Indonesia, at both urban and rural sites. In 2010–2014, several hotspots persisted or intensified, with exceptionally high deposition at Manila Observatory.

During 2020–2024, high nitrogen deposition remained evident in China, Malaysia, and Indonesia, while new hotspots emerged in Vietnam. Notably, elevated deposition occurred not only at urban sites but also at rural and remote sites in Vietnam, indicating a geographical shift in nitrogen deposition hotspots similar to that observed for sulfur wet deposition. In contrast, high-latitude sites in Mongolia and Russia consistently showed low and stable nitrogen deposition, with combined NO_3^- and NH_4^+ deposition below $5 \text{ kg N ha}^{-1} \text{ yr}^{-1}$.



Figure 4.5. Spatial distributions of the mean wet deposition of NO_3^- (upper) and NH_4^+ (bottom) for the periods 2000–2004 (left), 2010–2014 (center), and 2020–2024 (right).

Total (wet + dry) nitrogen deposition during 2015–2024 was estimated at limited sites where filter-pack monitoring data were available (Indonesia, Japan, Russia, Thailand, Vietnam). The total nitrogen deposition was determined from the sum of wet deposition of NO_3^- and NH_4^+ and dry deposition of HNO_3 , NH_3 , particulate NO_3^- , and particulate NH_4^+ . Oxidized nitrogen was defined as the sum of wet deposition of NO_3^- and dry deposition of HNO_3 and particulate NO_3^- , whereas reduced nitrogen deposition was defined as the sum of wet deposition of NH_4^+ and dry deposition of NH_3 and particulate NH_4^+ .

Figure 4.6 shows the spatial distributions of the ten-year mean total nitrogen deposition and the spatial distribution of the ratio of reduced nitrogen deposition to total nitrogen deposition (% reduced N) during the period 2015–2024. Nitrogen deposition levels were relatively high in Southeast Asia. Total nitrogen deposition exceeding $30 \text{ kg N ha}^{-1} \text{yr}^{-1}$ was observed at Serpong and Bandung (Indonesia) and at Hanoi and Yen Bai (Vietnam). In contrast, low nitrogen deposition levels (less than $5 \text{ kg N ha}^{-1} \text{yr}^{-1}$) were observed at Mondy, Irkutsk, and Listvyanka (Russia), which are located in the interior of the continent, and at Ogasawara (Japan), which is located in the remote Pacific Ocean. At sites where total nitrogen deposition could not be estimated, relatively high wet deposition of NH_4^+ was observed at several sites in the southern part of the region (Figure 4.4.3). Therefore, total nitrogen deposition at these sites may also be relatively high. At most sites across East Asia, the % reduced N exceeded 50%. Even at sites with low total nitrogen deposition, such as Mondy, Irkutsk, Listvyanka, and Ogasawara, the % reduced N was high. These indicate that reduced nitrogen accounted for a large proportion of total nitrogen deposition across East Asia.

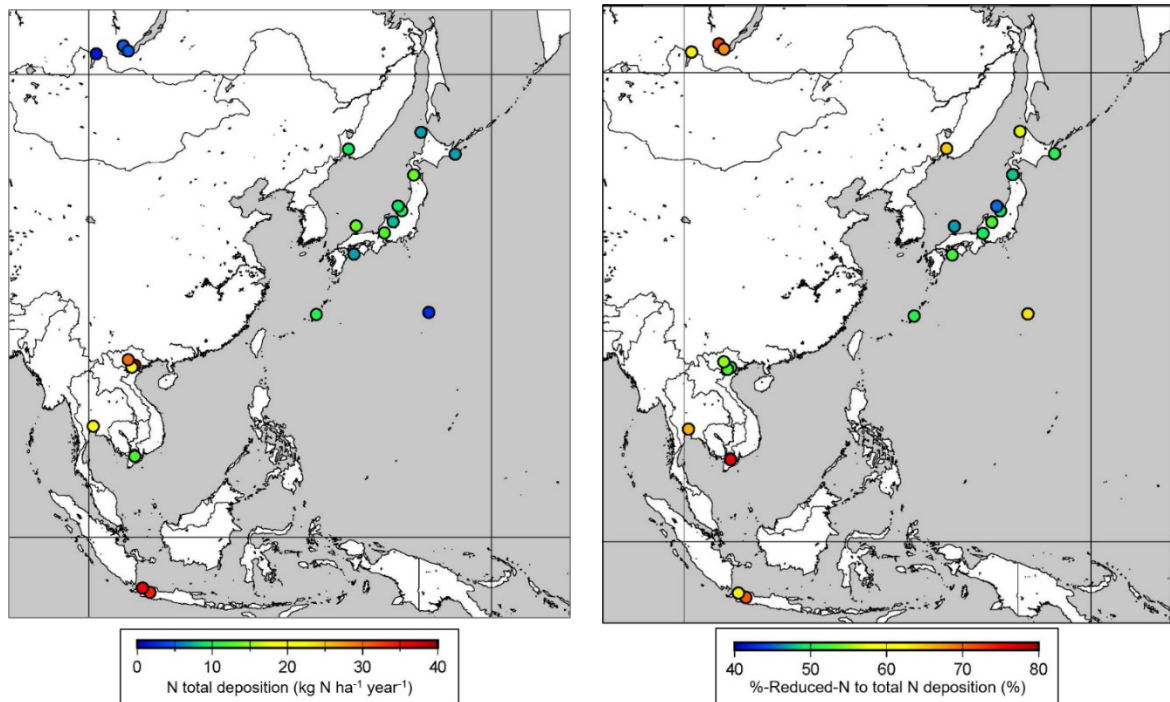


Figure 4.6. Spatial distributions of the mean total nitrogen deposition (left) and the ratio of reduced nitrogen deposition to total nitrogen deposition (right) for the periods 2015–2024

Table 4.2. Trends in wet deposition NO_3^- (2000–2024) assessed by the Mann–Kendall test.

						unit: kg N ha ⁻¹ y ⁻¹					
Country	Site	N	Z-score	Sen's slope	Trend	Country	Site	N	Z-score	Sen's slope	Trend
Cambodia	Phnom Penh	13	0.67	0.04	No trend	Lao PDR	<i>Vientiane</i>	5	N/A	N/A	N/A
China	Haifu	17	-2.92	-0.22	Dec.	Malaysia	Danum Valley	11	0.47	0.03	No trend
	Hongwen	24	-3.10	-0.20	Dec.		<i>Gunung Brinchang</i>	1	N/A	N/A	N/A
	Jinyunshan	24	-0.82	-0.05	No trend		Kuching	13	-0.43	-0.04	No trend
	Jiwozi	20	-1.20	-0.07	No trend		Petaling Jaya	24	1.71	0.25	No trend
	<i>Lijiang</i>	6	N/A	N/A	N/A		Tanah Rata	22	1.80	0.04	No trend
	Shizhan	25	-2.45	-0.19	Dec.	Mongolia	<i>Khan-Uul</i>	3	N/A	N/A	N/A
	<i>Wuzhishan</i>	6	N/A	N/A	N/A		Terelj	19	-0.56	0.00	No trend
	Xiang Zhou	25	1.89	0.06	No trend	Myanmar	Yangon	14	1.75	0.17	No trend
	Xiaoping	25	-2.64	-0.12	Dec.	Philippines	Los Baños	14	0.77	0.04	No trend
Zhuxiandong	20	0.75	0.07	No trend		Manila Observatory	17	-0.12	0.00	No trend	
Indonesia	Bandung	23	0.53	0.04	No trend		Mt. Sto. Tomas	12	-0.34	-0.06	No trend
	Jakarta	23	-0.85	-0.09	No trend	R of Korea	Ganghwa	23	-3.38	-0.15	Dec.
	<i>Jembrana</i>	5	N/A	N/A	N/A		Imsil	23	-1.16	-0.03	No trend
	Kototabang	22	2.37	0.06	Inc.		Jeju	21	1.78	0.04	No trend
	<i>Lombok</i>	5	N/A	N/A	N/A	Russia	Irkutsk	24	-2.41	-0.02	Dec.
	Maros	16	-1.04	-0.06	No trend		Listvyanka	24	-1.31	-0.01	No trend
	Serpong	21	1.72	0.22	No trend		Mondy	22	-3.38	-0.02	Dec.
Japan	Happo	16	-2.30	-0.09	Dec.		Primorskaya	22	1.41	0.04	No trend
	Hedo	18	-1.06	-0.01	No trend	Thailand	Bangkok	23	0.58	0.06	No trend
	Ijira	25	-3.53	-0.11	Dec.		Khanchanaburi	14	-1.09	-0.01	No trend
	<i>Niigata-Maki</i>	4	N/A	N/A	N/A		Pathumthani	24	-0.02	0.00	No trend
	Ochiishi	13	-0.43	-0.01	No trend		Samutprakarn	16	0.41	0.05	No trend
	Ogasawara	22	-2.31	-0.01	Dec.	Vietnam	Can Tho	11	-0.62	-0.04	No trend
	Okii	19	-0.56	-0.01	No trend		Cuc Phuong	16	1.94	0.44	No trend
	Rishiri	22	2.54	0.04	Inc.		Da Nang	16	-0.86	-0.02	No trend
	Sado-seki	15	-0.69	-0.04	No trend		Hanoi	24	5.18	0.58	Inc.
	Tokyo	17	-2.92	-0.14	Dec.		Ho Chi Minh	11	0.00	-0.02	No trend
	<i>Tsushima</i>	6	N/A	N/A	N/A		Hoa Binh	25	4.32	0.20	Inc.
	Yusuhara	23	-2.38	-0.02	Dec.		Yen Bai	9	0.00	0.05	No trend

Notes: A site was classified as *Increasing (Inc.)* when its Z-score exceeded ± 1.96 and the Sen's slope was positive, or *Decreasing (Dec.)* when the slope was negative. If the Z-score fell within ± 1.96 , the site was categorized as *No trend*. Sites with sample sizes of six or fewer observations were not included in the Mann–Kendall analysis.

Table 4.3. Trends in wet deposition NH_4^+ (2000–2024) assessed by the Mann–Kendall test.

unit: $\text{kg N ha}^{-1} \text{ y}^{-1}$

Country	Site	N	Z-score	Sen's slope	Trend	Country	Site	N	Z-score	Sen's slope	Trend
Cambodia	Phnom Penh	14	1.64	0.11	No trend	Lao PDR	Vientiane	4	N/A	N/A	N/A
China	Haifu	17	-3.25	-0.40	Dec.	Malaysia	Danum Valley	11	-1.25	-0.06	No trend
	Hongwen	24	-3.65	-0.24	Dec.		Gunung Brinchang	1	N/A	N/A	N/A
	Jinyunshan	24	-4.34	-0.52	Dec.		Kuching	13	0.92	0.03	No trend
	Jiwozi	20	-1.78	-0.17	No trend		Petaling Jaya	24	0.57	0.09	No trend
	Lijiang	6	N/A	N/A	N/A		Tanah Rata	22	0.39	0.02	No trend
	Shizhan	25	-1.70	-0.25	No trend	Mongolia	Khan-Uul	4	N/A	N/A	N/A
	Wuzhishan	6	N/A	N/A	N/A		Terelj	19	-2.94	-0.06	Dec.
	Xiang Zhou	25	-1.75	-0.11	No trend	Myanmar	Yangon	14	0.66	0.06	No trend
	Xiaoping	25	-3.90	-0.33	Dec.	Philippines	Los Baños	14	0.33	0.03	No trend
	Zhuxiandong	20	-2.17	-0.24	Dec.		Manila Observatory	17	-0.54	-0.15	No trend
Indonesia	Bandung	23	3.38	0.41	Inc.		Mt. Sto. Tomas	12	-0.62	-0.18	No trend
	Jakarta	22	1.24	0.12	No trend	R of Korea	Ganghwa	23	-3.01	-0.28	Dec.
	Jembrana	5	N/A	N/A	N/A		Imsil	23	-2.96	-0.17	Dec.
	Kototabang	20	1.14	0.08	No trend		Jeju	21	-1.54	-0.09	No trend
	Lombok	5	N/A	N/A	N/A	Russia	Irkutsk	24	-1.86	-0.03	No trend
	Maros	16	-1.31	-0.23	No trend		Listvyanka	24	-0.97	-0.01	No trend
	Serpong	21	2.26	0.72	Inc.		Mondy	22	-3.16	-0.03	Dec.
Japan	Happo	16	-2.75	-0.11	Dec.		Primorskaya	22	1.24	0.06	No trend
	Hedo	18	-1.14	-0.04	No trend	Thailand	Bangkok	23	0.32	0.03	No trend
	Ijira	25	-2.69	-0.10	Dec.		Khanchanaburi	14	-0.99	-0.11	No trend
	Niigata-Maki	4	N/A	N/A	N/A		Pathumthani	24	0.02	0.00	No trend
	Ochiishi	12	0.07	0.01	No trend		Samutprakarn	16	-1.04	-0.19	No trend
	Ogasawara	22	-2.82	-0.03	Dec.	Vietnam	Can Tho	11	0.31	0.04	No trend
	Okie	19	-0.91	-0.02	No trend		Cuc Phuong	16	1.85	0.64	No trend
	Rishiri	22	0.56	0.01	No trend		Da Nang	16	1.67	0.30	No trend
	Sado-seki	15	-1.39	-0.06	No trend		Hanoi	24	3.75	0.55	Inc.
	Tokyo	17	-2.76	-0.15	Dec.		Ho Chi Minh	11	0.47	0.16	No trend
	Tsushima	6	N/A	N/A	N/A		Hoa Binh	25	2.50	0.29	Inc.
	Yusuhara	23	-1.32	-0.01	No trend		Yen Bai	9	-0.31	-0.35	No trend

Notes: A site was classified as *Increasing (Inc.)* when its Z-score exceeded ± 1.96 and the Sen's slope was positive, or *Decreasing (Dec.)* when the slope was negative. If the Z-score fell within ± 1.96 , the site was categorized as *No trend*. Sites with sample sizes of six or fewer observations were not included in the Mann–Kendall analysis.

Precipitation chemistry

Long-term observations across EANET sites show substantial regional differences in precipitation amount, pH, ionic composition, and acid-neutralizing capacity. At about half of the sites, measured cations and anions are well balanced, while cation excess at other sites likely reflects unmeasured anions such as bicarbonate, fluoride, and organic acids. Overall, the major dissolved components are considered to be adequately characterized.

Precipitation chemistry is strongly governed by the balance between acidic components ($\text{nss-SO}_4^{2-} + \text{NO}_3^-$) and neutralizing components ($\text{NH}_4^+ + \text{nss-Ca}^{2+}$). Figure 4.7 illustrates the correlation between potential atmospheric acidity ($\text{pAi} = -\log_{10}(\text{nss-SO}_4^{2-} + \text{NO}_3^-)$) and measured precipitation pH across EANET sites, alongside the relationship between $\text{nss-SO}_4^{2-} + \text{NO}_3^-$ and $\text{NH}_4^+ + \text{nss-Ca}^{2+}$. In China, abundant ammonia and crustal dust provide strong neutralization even where acidic component concentrations are high. Japanese sites show relatively stable acid-base balance, together with reduced acidic precursor inputs over time. In contrast, some Southeast Asian sites exhibit more limited neutralization capacity, making precipitation acidity more sensitive to seasonal variations in emissions and meteorological conditions. Consequently, sites where acidic components exceed neutralizing components may experience episodes of highly acidic precipitation on monthly or daily timescales.

Executive Summary

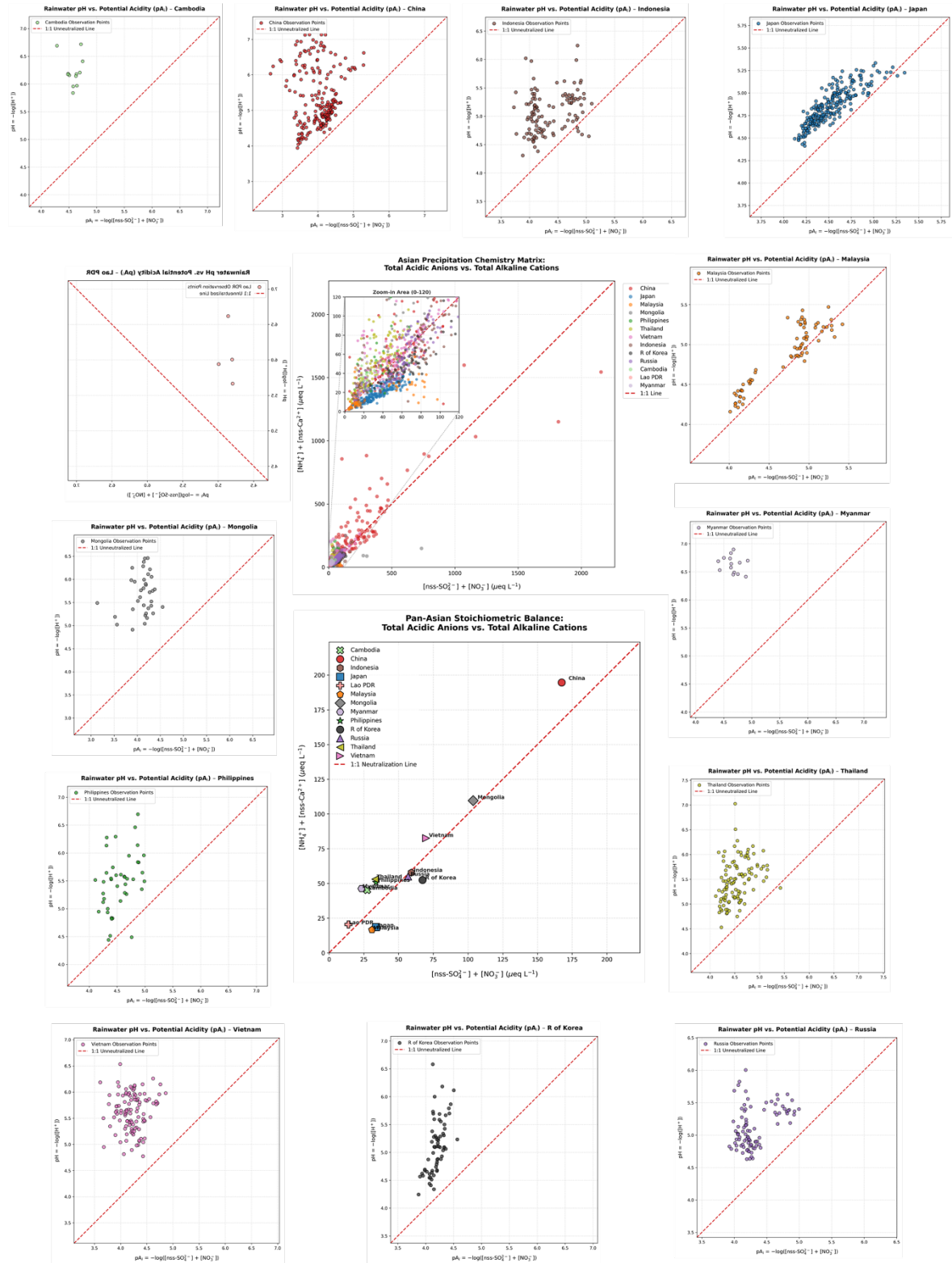


Figure 4.7. Relationship between annual mean precipitation pH and input acidity ($pA_i = -\log_{10} (nss-SO_4^{2-} + NO_3^-)$) in EANET sites (2000-2024).

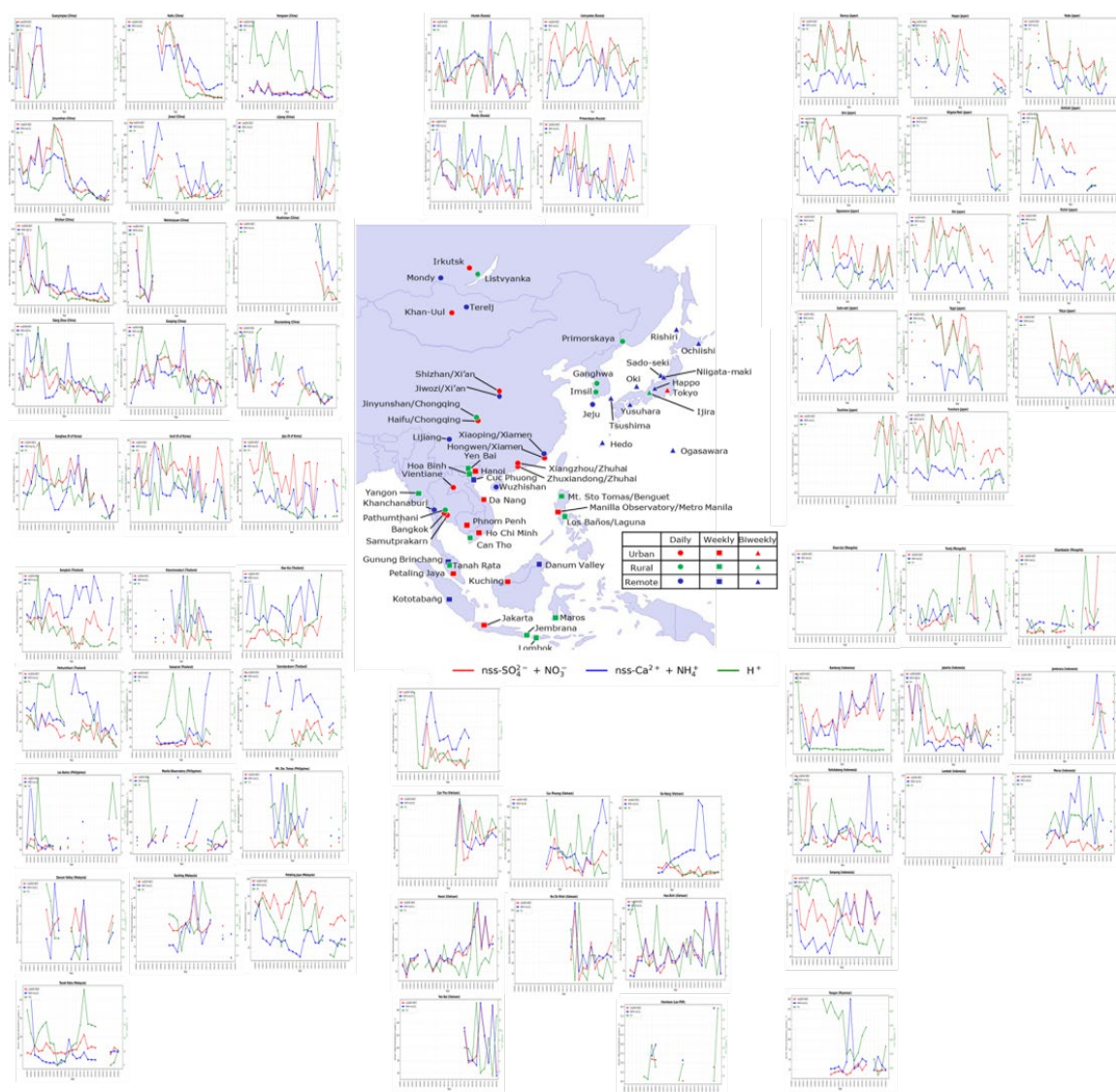


Figure 4.8. Long term trends of precipitation acidity (H^+) and concentrations of acids ($nss-SO_4^{2-}+NO_3^-$) and bases ($nss-Ca^{2+}+NH_4^+$) that acidified or neutralized precipitation in selected EANET sites (2000-2024). * Figures of remote and rural sites are hatched.

Figure 4.8 illustrates the 25-year secular changes in $nss-SO_4^{2-} + NO_3^-$, $NH_4^+ + nss-Ca^{2+}$, and H^+ concentrations across representative EANET sites. Precipitation acidity has generally decreased across Northeast Asia over the past 25 years. Acidic components declined markedly in China and Japan, consistent with reductions in sulfur and nitrogen emissions, while neutralizing components remained substantial or relatively stable, resulting in lower H^+ concentrations. In contrast, Southeast Asia shows greater interannual variability and less consistent long-term trends, reflecting the combined influences of urbanization, vehicle emissions, biomass burning, agricultural activities, and monsoon dynamics. Urban sites generally show higher acid concentrations and greater variability, whereas rural and remote sites exhibit smoother regional-scale trends. Overall, precipitation acidity reflects the changing balance between acidifying and neutralizing components, with clearer improvements in Northeast Asia and more variable conditions in Southeast Asia.

Relationship between long-term emission trends and wet deposition

SO_2 and NO_x emissions in Northeast Asian countries declined, whereas those in Southeast Asian countries generally increased. Compared with SO_2 and NO_x emissions, NH_3 emissions showed flat or slightly increasing trends over the two decades in all Asian countries (Guizzardi et al., 2025).

Such long-term variations in anthropogenic emissions would affect ambient concentrations of air pollutants and, consequently, deposition.

For wet deposition, oxidized nitrogen showed decreasing trends at many sites in Northeast Asia, whereas significant increasing trends were observed at several sites in Southeast Asia. The decreasing trends in nss-SO_4^{2-} and NO_3^- wet deposition observed at many sites in Northeast Asia are consistent with the decreasing trends in SO_2 and NO_x emissions in China, Japan, and the Republic of Korea, respectively. Similarly, the increasing trends in nss-SO_4^{2-} and NO_3^- wet deposition observed at some sites in Indonesia and Vietnam are consistent with the increasing trends in SO_2 and NO_x emissions in these countries, respectively. In most EANET countries, NH_3 emissions have recently become comparable to NO_x emissions. This is consistent with the finding that the proportion of reduced nitrogen deposition exceeded 50% at many sites across East Asia (Figure 4.6).

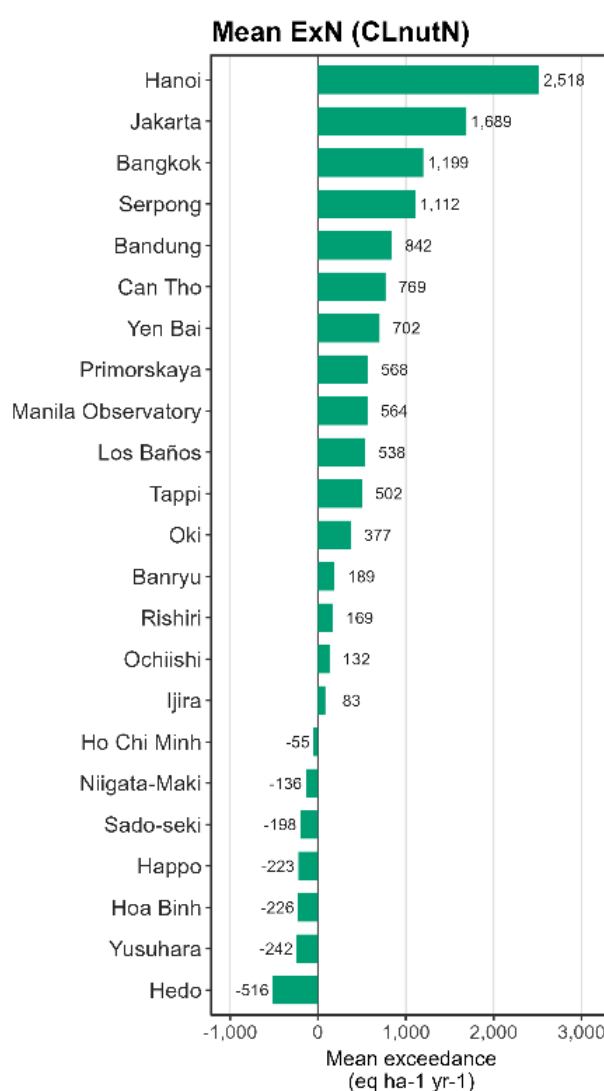


Figure 4.8. Critical load exceedances of total N deposition for inland-water eutrophication based on the data from 2015 to 2024

Critical load analysis

To assess the potential ecological risks of atmospheric deposition across East Asia, exceedances of critical load for inland-water eutrophication was estimated at EANET monitoring sites using the critical load map developed by Yamashita et al. (2022). Critical loads provide a quantitative indicator

of the long-term risk of ecosystem eutrophication. An acceptable NO_3^- -N concentration of 0.3 mg N L^{-1} in leaching water at the lower edge of the soil was adopted.

The analysis used data from 2015 onward at 27 sites in Japan, Viet Nam, Russia, Indonesia, the Philippines, and Thailand, where both wet and dry N deposition data were available. As a result, the critical load for eutrophication exceeded 20 of the 27 sites. Large exceedances were found around major urban areas in Southeast Asia, particularly in Viet Nam and Indonesia. At Hanoi, the exceedance increased with increasing N deposition (Figure. 4.8).

Because surface-water NO_3^- -N concentrations in these regions are also influenced by agricultural and domestic wastewater, the exceedance should not be interpreted directly as the risk of water-quality deterioration caused by atmospheric deposition. Nevertheless, in nearby forest ecosystems with limited direct N inputs from these sources, elevated N deposition may still increase the potential for N leaching, particularly following disturbances that reduce plant N uptake. Continued monitoring is therefore warranted.

5. Impacts on Ecosystems in East Asia

Forest ecosystems deliver a wide range of essential ecological services, including the provision of natural resources, groundwater recharge, carbon sequestration, and disaster prevention. However, prolonged atmospheric deposition of acidifying substances and associated chemical compounds has the potential to disrupt ecosystem functions and reduce the resilience of forest environments. In many EANET participating countries, emissions of major air pollutants have begun to decline. Nevertheless, experiences from Europe and North America indicate that the recovery of forest ecosystems from acidification has not progressed as expected, and ecological impacts have persisted even after substantial reductions in SO₂ and NO_x emissions.

Monitoring methodology

Monitoring on soil, forest vegetation, inland aquatic environment, and forest catchments has been implemented in accordance with the following technical manuals and guideline:

- Technical Manual for Soil and Vegetation Monitoring in East Asia (EANET, 2000c)
- Technical Manual for Inland Aquatic Environment Monitoring in East Asia–2010 (EANET, 2010d)
- Guideline for Catchment-scale Monitoring in East Asia (EANET, 2010e)

Soil chemical properties

Soil monitoring has been conducted at 33 sites in 10 countries, including a pre-survey carried out in 1999. To elucidate which factor is most important in controlling soil chemical properties among the three factors --- soil type, forest type, and mean annual precipitation--- PLS-R (partial least squares regression) analysis was performed. The results showed that soil type was the dominant factor controlling variations in Na⁺, Al³⁺, and H⁺ (Table 5.1). Forest type was the dominant factor for Ca²⁺, Mg²⁺, and K⁺, while mean annual precipitation was the dominant factor for pH(H₂O), pH(KCl), Ca²⁺, Mg²⁺, and Na⁺. Soil is formed from the accumulation and decomposition of forest litter, as well as the weathering products of bedrock. The annual photosynthetic rate of the forest, which determines litter production, depends on the amount of annual precipitation. Annual precipitation reflects not only water supply and leaching, but also the average temperature. Therefore, these results suggest that soil formation processes, forest composition, and climatic conditions, as represented by mean annual precipitation, influence soil chemical properties.

Table 5.1 Results of PLS-R: VIP* for soil chemical properties

	pH(H ₂ O)	pH(KCl)	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	Al ³⁺	H ⁺
- Soil type	0.62	0.83	0.93	0.54	0.39	1.22	1.18	1.51
- Forest type	0.46	0.73	1.00	1.04	1.44	0.71	0.92	0.81
- Mean annual precipitation	1.55	1.34	1.07	1.27	0.87	1.00	0.88	0.27

*, VIP (variable importance for projection) means the strength of each explaining variable.

To examine the relationships between soil chemical properties and atmospheric deposition, a regression analysis was conducted between soil pH(H₂O) and the wet deposition of pH, nss-SO₄²⁻, nss-Ca²⁺, NH₄⁺ and NO₃⁻ (Table 5.2). A positive (+) correlation indicates that soil pH(H₂O) follows the fluctuations in wet deposition; that is, an increase in the wet deposition of a specific constituent is accompanied by an increase in soil pH(H₂O).

Theoretically, increase in nss-SO₄²⁻, NH₄⁺, and NO₃⁻ – which act as acidifying substances in the soil – should lead to a decrease in soil pH(H₂O). However, the sign of the correlation varied between positive and negative among sites, suggesting that the soil's response to wet deposition is not uniform. The results suggested that soil responses do not necessarily parallel the trends in atmospheric deposition. Given the diverse distribution of soil characteristics among EANET sites, the reaction processes likely vary by site.

Table 5.2 Slope of correlation between soil pH(H₂O) and items of wet deposition

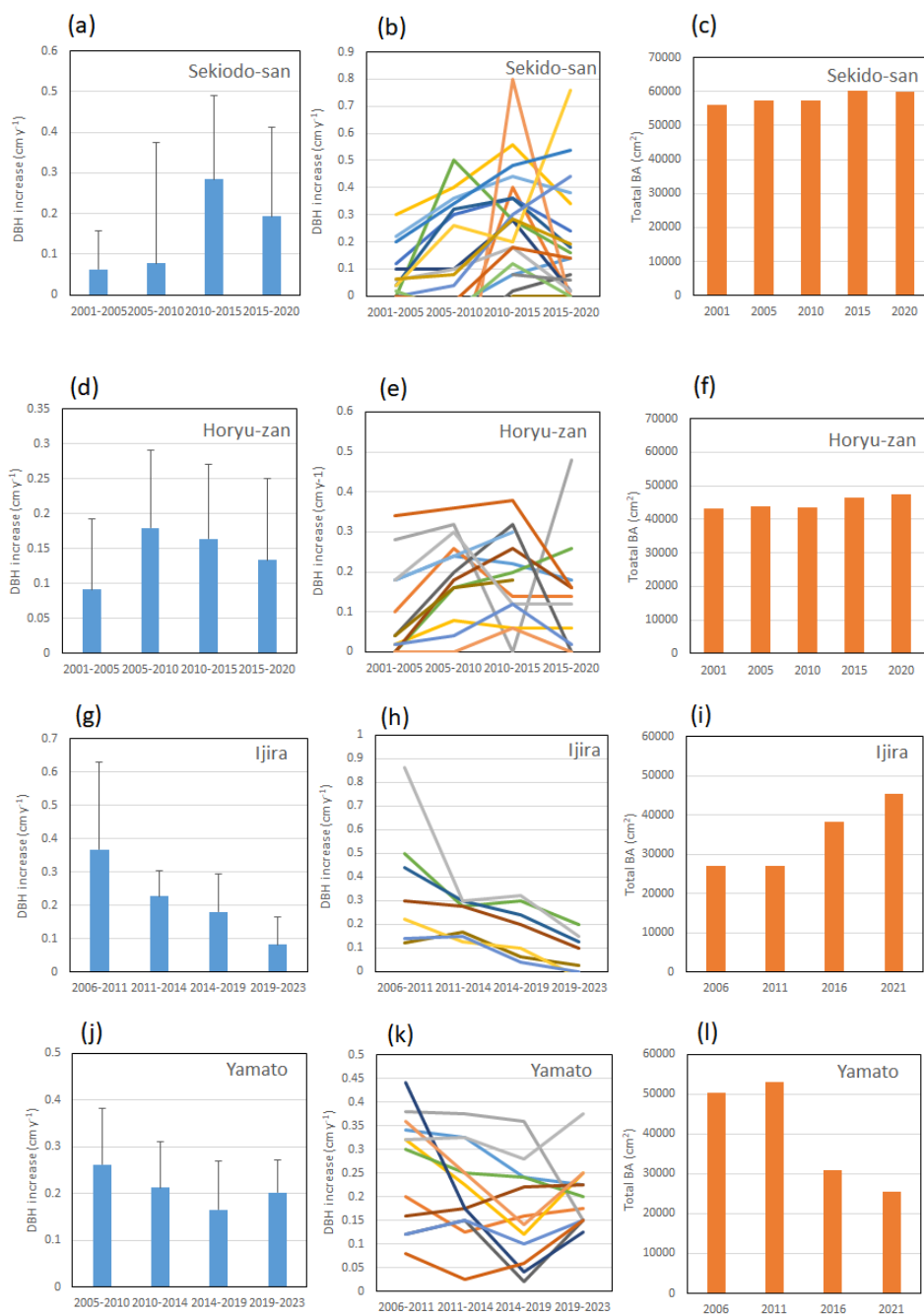
Country	Site code	pH	nss-SO ₄ ²⁻	nss-Ca ²⁺	NH ₄ ⁺	NO ₃ ⁻
China	CNS004	+	ns	+	ns	+
	CNS007	—	+	+	+	+
	CNS009	+	—	—	—	—
	CNS011	+	—	—	—	ns
Indonesia	IDS002	—	ns	ns	—	—
Japan	JPS005	ns	ns	ns	ns	ns
	JPS105	—	+	+	+	+
	JPS006	+	—	—	—	—
	JPS106	+	—	+	—	—
Malaysia	MYS001	+	—	ns	—	+
	MYS101	ns	ns	ns	ns	ns
Mongolia	MNS001	+	+	+	+	—
	MNS002	+	ns	ns	ns	—
Philippines	PHS002	ns	—	—	—	—
	PHS102	—	+	—	+	—
	PHS001	—	+	+	—	—
R. of Korea	KRS003	+	+	—	+	—
Russia	RUS003	+	+	+	+	+
	RUS002	ns	ns	ns	ns	ns
	RUS004	+	—	—	—	—
Thailand	THS004	+	ns	—	ns	ns
	THS104	+	—	—	ns	ns

+, —, and ns represent significant-positive, significant-negative and not significant correlations, respectively.

Forest vegetation

Vegetation monitoring has been conducted at 29 sites in 9 countries since 2000. However, there is a large variation in the content and frequency of surveys among sites. Regarding vegetation monitoring, it was assumed that comprehensive forest survey (General description of forest; GDF), tree decline survey (Observation of tree decline; OTD), and understory vegetation survey would be conducted periodically. However, the only sites that have been surveyed more than once since 2015 are those in China and Japan, namely, two plots at Jinyunshan (CNS004), Dabagou (CNS007), Xiaoping (CNS009), Sekido-san (JPS005), and Horyu-zan (JPS105). Because two sites in Japan were newly registered as EANET sites in 2019, data from Japanese national monitoring conducted before their registration are also included.

Tree growth and stand biomass were affected by multiple factors, including atmospheric deposition, climate, stand age, species composition, competition, and human disturbance. Fig. 5.1 shows that temporal changes in DBH increase and total trunk cross-sectional area at breast height (BA) differed greatly among stands and among individual trees, indicating that forest responses were not uniform. Although reduced transboundary air pollution may have contributed to increased growth at some Japanese sites, its effects were difficult to separate from those of climate, density effects, logging, thinning, and typhoons. Differences among species and stand structures, such as those observed in mixed or plantation forests, also appeared to influence growth patterns. These results indicate that long-term monitoring of identified individual trees is essential for quantitatively evaluating the effects of air pollution on forest ecosystems.



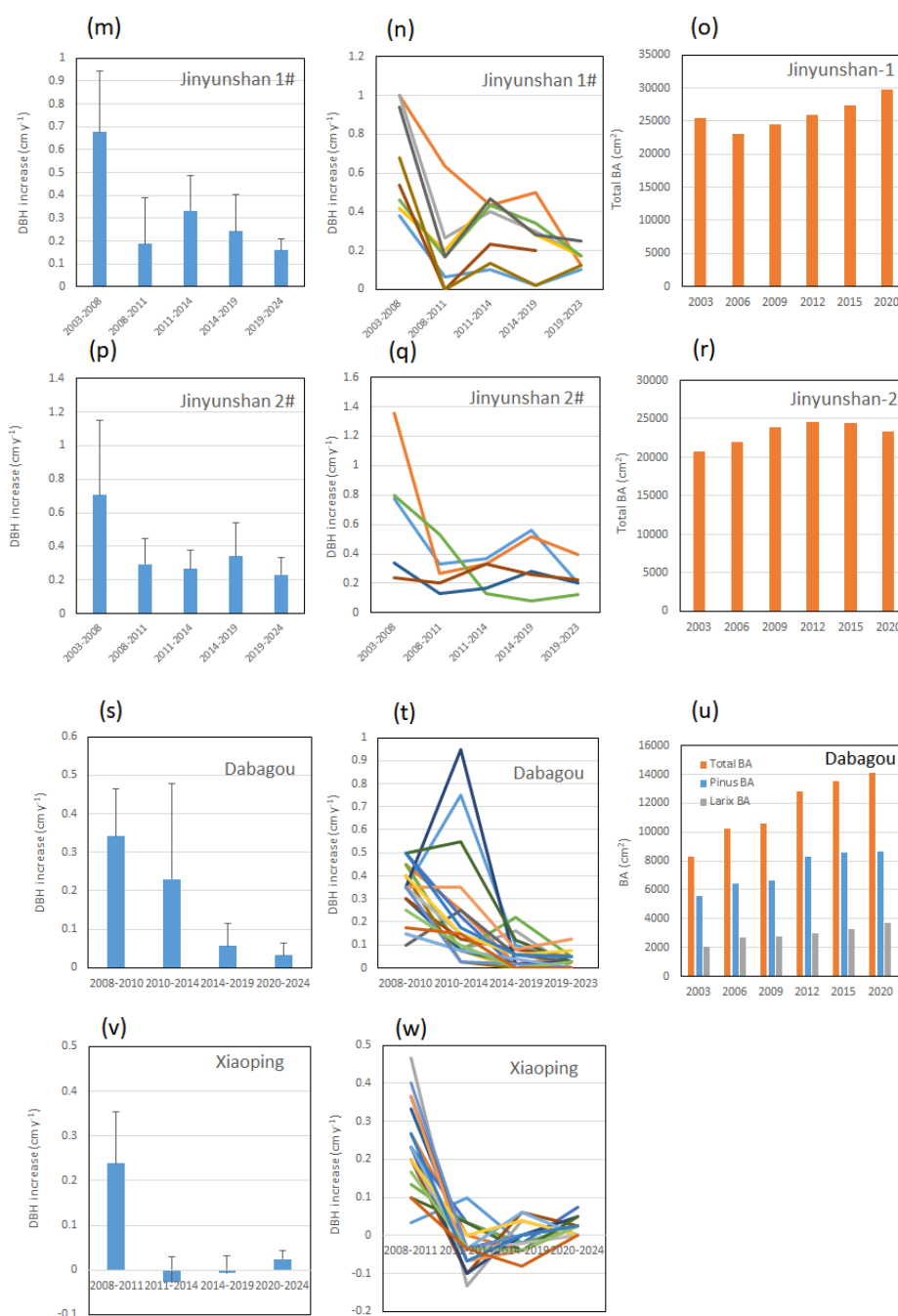


Fig. 5.1 Average annual increase in DBH (left column) of OTD, DBH increase for each individual tree of OTD (middle column), and changes in total BA for each year at each GDF survey (right column). Vertical lines indicate standard deviation. In the graphs showing the OTDs in the middle row (b, e, h, k, n, q, t, w), each colored line represents a different individual.

Inland water chemistry

Monitoring on the inland aquatic environment has been conducted at 17 sites in 9 countries. The seasonal Mann–Kendall trend analyses at the 17 sites (Table 5.3) indicate that long-term patterns varied widely among sites, reflecting site-specific processes rather than a consistent regional pattern. However, changes potentially related to acidification were observed at some sites. A decreasing trend in pH was found at Mo1, while increasing trends in NO_3^- concentrations were detected at C4 and V1. In contrast, alkalinity increased at C1 and T1-2, and both pH and alkalinity increased at C2. In addition, decreasing trends in SO_4^{2-} concentrations were observed at C4 and J1. These findings

Executive Summary

indicate that, although site-specific processes dominate the long-term patterns, some sites have shown distinct changes in the most recent period.

Several sites showed corresponding changes between atmospheric deposition and inland water chemistry when inland water data were compared with the atmospheric deposition data calculated in Chapter 4. At C1, C3, C4, and J1, sulfur- and/or nitrogen-related parameters showed decreasing trends recently in both inland water chemistry and atmospheric deposition. However, the other sites showed only partial or no correspondence to changing atmospheric deposition. Overall, responses of inland water chemistry to atmospheric deposition were highly site-specific and were influenced not only by atmospheric inputs but also by catchment characteristics, hydrological conditions, and biogeochemical processes.

Table 5.3 Results of seasonal Mann–Kendall trend analysis for inland water of the EANET sites for the data until 2019 and until 2024.

Site name		Duration		pH	EC	Alkalinity	SO ₄ ²⁻	NO ₃ ⁻	Cl ⁻	NH ₄ ⁺	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺
Jinyunshan Lake	C1	2001-	2019	-0.70	2.22	4.17	0.40	2.63	-1.20	-2.64	0.06	1.32	3.16	-0.21
			2024	0.40	-0.73	4.79	-3.02	1.22	-4.32	-2.95	-2.44	0.72	0.01	-1.85
Xiaoping Dam	C2	2001-	2019	0.08	0.67	5.14	0.86	-0.71	-2.23	-0.82	-2.80	3.22	5.65	0.00
			2024	3.37	1.33	5.23	-0.44	-1.56	-2.72	-2.16	-1.70	4.10	5.70	-0.56
Jiwozi River	C3	2001-	2019	-1.69	-1.03	6.68	-2.30	0.61	-1.92	1.56	-0.68	1.55	-2.31	-0.38
			2024	-1.40	-4.63	6.01	-6.10	1.41	-3.35	2.17	-2.61	-1.09	-4.86	-3.61
Zhuxiandong Stream	C4	2004-	2019	-3.09	2.62	2.92	-5.45	4.17	-3.74	-3.42	0.52	0.71	0.21	1.58
			2024	-2.15	0.13	0.75	-7.35	4.74	-2.36	-5.97	2.11	0.35	-2.40	-0.96
Ijira Lake	J1	2000-	2019	1.51	-5.02	0.22	-1.98	-6.32	-7.05	-6.22	-5.28	-3.38	-4.11	-5.26
			2024	1.53	-6.42	0.80	-3.78	-8.14	-8.61	-6.78	-6.11	-3.76	-4.24	-6.33
Futago Lake oike	J3-1	2019-	2019											
			2024	0.83	1.10	2.01	-3.22	1.64	1.61		2.08	0.04	0.68	1.10
Futago Lake meike	J3-2	2019-	2019											
			2024	-1.21	-3.22	-0.73	-4.63	-2.05	0.646		0.833	-2.52	-2.62	-3.43
Nam Houm Lake	L1	2009-	2019	1.06	-1.33	-1.91	2.04	-1.66	-2.58					
			2024	-1.10	1.10	0.57	0.00	-0.93	-0.34	0.00	2.33	0.00	0.36	-0.54
Baru river	Ma3	2022-	2019											
			2024	-1.44	-2.92	-3.45	-2.62	1.71	1.25	2.16	-0.19	-2.62	-3.75	-3.30
Terelj river	Mo1	2002-	2019	-2.87	0.02	1.42	4.43	-1.46	-1.89	0.60	-1.50	-0.64	-1.00	-1.96
			2024	-4.05	-2.28	2.20	2.07	-3.28	-1.34	2.13	-1.03	0.15	-0.33	-1.93
Pandin Lake	P1	2004-	2019	-0.29	0.66	0.09	3.27	-1.72	0.46	0.05	0.74	-3.64	3.68	-0.28
			2024	0.91	0.69	-0.08	6.77	-3.81	0.43	-1.08	1.26	-3.46	2.08	2.03
Ambulalakaw Lake	P2	2005-	2019	1.01	1.17	-0.82	-2.05	-1.80	-0.02	-0.32	2.55	1.00	-0.12	0.91
			2024	1.90	4.59	-1.22	-2.23	-2.13	1.63	-0.77	-0.57	0.38	0.37	0.33
Pereemnaya River	R1	2004-	2019	-0.09	1.74	-1.64	3.96	-1.49	-1.31	-5.46	0.52	-1.67	3.78	-1.76
			2024	0.38	2.41	-1.73	4.57	-1.13	-3.38	-6.59	0.50	-0.93	4.38	-1.24
Komarovka River	R2	2005-	2019	-4.60	0.47	-2.32	3.20	5.70	0.33	0.68	3.12	3.74	1.33	-1.84
			2024	-2.89	-1.23	1.29	-0.67	0.85	0.36	-0.10	6.50	7.25	3.23	-1.45
Vachiralongkorn Dam 1	T1-1	2000-	2019	0.46	0.84	2.33	0.48	1.14	2.21	2.11	3.70	1.35	3.06	2.11
			2024	0.98	2.75	2.70	0.79	1.52	4.42	2.05	4.55	1.39	4.55	2.24
Vachiralongkorn Dam2	T1-2	2000-	2019	2.66	0.43	4.49	0.91	2.49	1.78	1.71	2.47	0.34	3.46	1.11
			2024	2.62	3.33	5.33	1.43	2.95	4.24	0.79	3.52	0.83	5.09	2.80
Hoa Binh Reservoir	V1	2000-	2019	-0.31	-1.49	-4.14	-0.04	3.66	2.49	-4.17	3.14	0.75	-2.48	-2.15
			2024	-0.50	-2.63	-4.96	-2.79	5.02	1.77	-1.47	2.48	3.55	-1.17	-6.14

p < 0.05	-	+
p < 0.01	-	+
p < 0.001	-	+

Note : Value shows Z score, which indicates the increasing trend with positive values or the decreasing trend with negative values. Color shows significant levels.

Catchment-scale analysis

Catchment-scale analyses of four forested catchments in three countries, namely, the Lake Ijira catchment (IJR), the La Mesa Watershed (LMW), the Komarovka River catchment (KMR), and the Pereemnaya River catchment (PRN), revealed that stream water chemistry did not always respond immediately to changes in atmospheric deposition. At IJR, which had previously been acidified and

N-saturated, stream water SO_4^{2-} and DIN concentrations, mostly NO_3^- , decreased in association with declining atmospheric deposition, suggesting ongoing recovery processes, as shown in changes in N leaching (Fig. 5.2). High DIN concentrations tended to occur in forested catchments where N deposition was comparable to or exceeded the empirical thresholds for N. However, at other sites, no clear relationship with atmospheric deposition was observed during the observation period. Other factors, such as meteorological and hydrological conditions, appeared to influence S and N leaching processes. At LMW, atmospheric deposition is still increasing; therefore, possible delayed responses of the forest ecosystem should be carefully monitored.

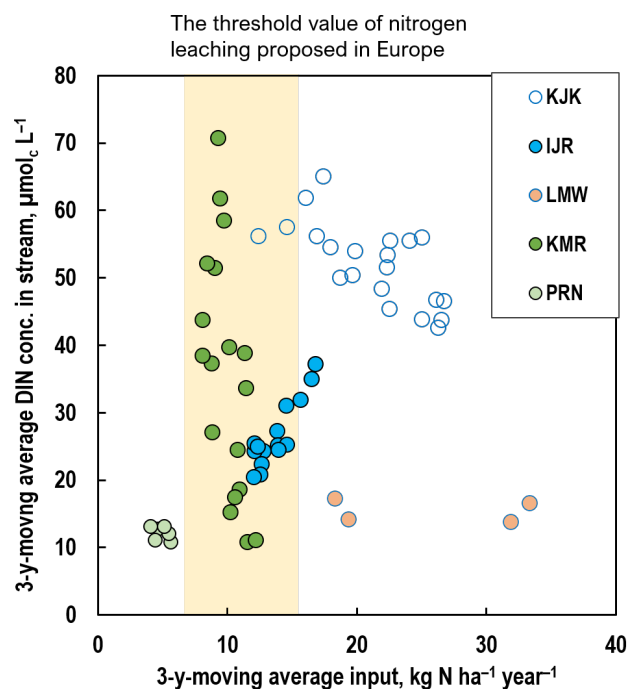


Fig. 5.2 Relationship between atmospheric nitrogen (N) inputs and leaching of dissolved inorganic nitrogen (DIN) to stream water at EANET catchment sites. Three-year moving averages of total N deposition (wet and dry) and stream-water DIN concentrations are shown. The yellow band indicates the range of threshold value for leaching proposed in Europe (7 – 15 kg N ha⁻¹ year⁻¹). KJK, Kajikawa catchment site, surveyed by the EANET project until 2025 (modified from Sase et al. 2021).

Summary of impacts on ecosystems in East Asia

Overall, ecosystem responses were not always consistent with changes in atmospheric deposition, indicating strong influences of meteorological, hydrological, geological, and internal biogeochemical processes at individual monitoring sites. At the same time, relationships between atmospheric deposition and ecosystem responses were observed at several sites, and atmospheric deposition is still increasing at some sites.

Ecosystem responses to atmospheric deposition vary considerably among regions, vegetation types, water bodies, and catchments, making it difficult to assess impacts solely from N and S deposition levels. Rising CO₂ concentrations, increasing temperatures, and changing precipitation patterns may also directly and indirectly influence these responses. Continued monitoring of atmospheric deposition and ecosystems is therefore needed to evaluate delayed recovery, acidification, and changes in N retention under broader environmental change.

6. Summary and Recommendations for Future Activities

Summary: Overview of state of atmospheric environment in East Asia

East Asia is a global hotspot not only for air pollution but also for atmospheric deposition, particularly reactive nitrogen. These pollutants and atmospheric deposition have significant impacts on human health and ecosystems. Against this backdrop, effective management of the atmospheric environment in East Asia through science-based, data-driven policymaking has become an increasingly important societal and policy priority.

EANET has conducted long-term monitoring of air concentrations, atmospheric deposition, and ecosystem responses across East Asia since 2000. Over more than two decades, these activities have generated consistent and comparable datasets through established Quality Assurance and Quality Control (QA/QC) procedures. The QA/QC system has basically remained unchanged since 2000 and includes standardized procedures for siting, sampling and sample handling, chemical analysis, and data evaluation. Inter-Laboratory Comparison projects and multi-level data verification have further supported the reliability and comparability of EANET data.

The long-term EANET observations provide an important basis for assessing the status and trends of the atmospheric environment in East Asia. As of 2024, EANET operated 54 air concentration monitoring sites across participating countries. The assessment indicates that air pollution has improved in some parts of East Asia, while important regional and local challenges remain. PM_{2.5} concentrations have decreased at many long-term sites in Japan, the Republic of Korea, Mongolia, Thailand, and Vietnam, partly reflecting reductions in emissions in China and associated decreases in long-range transport. SO₂ and NO_x concentrations have also decreased substantially at Chinese sites. These results indicate the effectiveness of emission reduction measures in reducing particulate and acidic air pollution in Northeast Asia and their regional benefits.

In contrast, surface O₃ shows an emerging regional air quality concern. While springtime O₃ has decreased at some remote sites in Japan, likely reflecting reduced long-range transport from China, significant increases have been observed at urban sites in Thailand. This suggests increasing photochemical ozone production associated with NO_x and VOC emissions. Biomass burning in Southeast Asia and coal combustion in Mongolia also remain important sources of particulate matter. These findings indicate that the major characteristics of air pollution are changing across East Asia, from predominantly sulfur-related pollution toward more complex pollution involving PM_{2.5}, O₃, and their precursors.

The assessment of atmospheric deposition also indicates a changing regional environmental situation. Wet deposition of sulfur has generally decreased, particularly in Northeast Asia, consistent with reductions in SO₂ emissions. In contrast, nitrogen deposition shows more complex spatial patterns, and reduced nitrogen is now the dominant form of nitrogen deposition at most sites. High nitrogen deposition and exceedance of critical loads at many assessed sites indicate potential risks of nitrogen accumulation and eutrophication, particularly in parts of Southeast Asia. These findings highlight the growing importance of NH₃ and reactive nitrogen management.

EANET ecological monitoring has provided further evidence on the environmental consequences of atmospheric deposition. Although relationships between changes in atmospheric deposition and soil, forest, and inland-water responses have been observed at some sites, ecosystem responses are not uniform and are strongly influenced by meteorological, hydrological, geological, and biogeochemical processes. Continuing changes in climate may further modify these responses. Continued integrated monitoring is therefore essential for assessing both delayed ecosystem responses and emerging environmental risks.

Overall, the EANET assessment demonstrates that the atmospheric environment in East Asia has improved in some respects, particularly with regard to sulfur pollution and PM_{2.5} in several areas,

but new and persistent challenges remain, including surface O₃, reactive nitrogen, NH₃ emissions, biomass burning, and ecosystem impacts. The long-term EANET monitoring network provides a unique scientific basis for identifying these regional changes, evaluating the effectiveness of emission control measures, and supporting evidence-based environmental policy. Future priorities should include maintaining and strengthening long-term monitoring; expanding PM_{2.5}, O₃, precursor, and reactive nitrogen observations; improving assessment of total deposition; promoting source apportionment and integrated modeling; and strengthening QA/QC, data harmonization, and regional collaboration.

Recommendations for Future Activities

Based on the findings of this Assessment Report, it is important that EANET's activities over the next five years continue to follow the direction set out in the current Medium-Term Plan (MTP), with a focus on supporting atmospheric environment management in the region. In particular, EANET should strengthen monitoring and data analysis for ozone and PM_{2.5}, improve understanding of their current status based on scientific evidence, and generate policy-relevant outputs that can support data-driven, decision-making in participating countries.

Furthermore, the emphasis should be placed on the three strategic perspectives identified in the current MTP: sustainable monitoring, nitrogen cycle and management, and impacts of meteorological conditions on air pollution.

For sustainable monitoring, (1) priority should be given to the integrated use of low-cost sensors, satellite observations, and existing monitoring networks; (2) improving understanding of the spatiotemporal characteristics of air pollution through the integration of observational data, chemical transport models, and emission inventories; (3) promoting the application of AI technologies to support these activities; (4) strengthening technical capacity across all participating countries; (5) enhancing the sustainability of the EANET monitoring system; and (6) strengthening collaboration with other international initiatives.

For nitrogen cycle and management, priority should be given to (1) establishing quantitative, long-term, continuous, and region-wide monitoring of atmospheric deposition of reactive nitrogen; utilizing satellite observations of nitrogen dioxide (NO₂) and ammonia (NH₃) to regional monitoring; and (2) integrating diverse observational datasets with atmospheric models to produce region-wide maps of reactive nitrogen deposition across East Asia.

For understanding the impacts of meteorological conditions on air pollution, priority should be given to (1) conducting long-term and continuous monitoring of meteorological conditions, air pollutant concentrations, and atmospheric deposition in order to detect the impacts of meteorological variability; (2) applying atmospheric models and AI-based analytical approaches to distinguish the effects of meteorological changes on the processes governing atmospheric pollutants, including anthropogenic and natural emissions, atmospheric transport, chemical transformation, and deposition; and (3) predicting future changes in air pollutant concentrations and atmospheric deposition under changing meteorological conditions.

7. References

- EANET. 2010a. Technical Manual for Wet Deposition Monitoring in East Asia -2010.
<https://www.eanet.asia/wp-content/uploads/2019/04/techwet.pdf>
- EANET. 2010b. Technical Manual for Dry Deposition Flux Estimation in East Asia.
<https://www.eanet.asia/wp-content/uploads/2019/04/techdry.pdf>
- EANET. 2000c. Technical documents for soil and vegetation monitoring in East Asia.
- EANET 2010d. Technical Manual for Inland Aquatic Environment Monitoring in East Asia -2010.
- EANET. 2010e Guideline for Catchment-scale Monitoring in East Asia.
https://www.eanet.asia/wp-content/uploads/2019/04/catchment_guideline.pdf

- EANET. 2013 Technical Manual for Air Concentration Monitoring in East Asia.
- EANET. 2022. Technical Manual for Air Concentration Monitoring in East Asia (Second Edition).
<https://www.eanet.asia/wp-content/uploads/2026/02/Technical-Manual-for-Air-Concentration-Monitoring-2022.pdf>
- Guizzardi, D., Crippa, M., Butler, T., Keating, T., Wu, R., Kaminski, J., Kuenen, J., Kurokawa, J., Chatani, S., Morikawa, T., Pouliot, G., Racine, J., Moran, M. D., Klimont, Z., Manseau, P. M., Mashayekhi, R., Henderson, B. H., Smith, S. J., Hoesly, R., Muntean, M., Banja, M., Schaaf, E., Pagani, F., Woo, J.-H., Kim, J., Pisoni, E., Zhang, J., Niemi, D., Sassi, M., Duhamel, A., Ansari, T., Foley, K., Geng, G., Chen, Y., Zhang, Q. 2025. The HTAP_v3.2 emission mosaic: merging regional and global monthly emissions (2000–2020) to support air quality modelling and policies. *Earth System Science Data*, 17, 5915–5950.
- Yamashita, N., Sase, H., & Kurokawa, J. 2022. Assessing critical loads and exceedances for acidification and eutrophication in the forests of East and Southeast Asia: A comparison with EANET monitoring data. *Science of the Total Environment*, 158054.