Variation Characteristics of Air Negative Ions in Different Plant Communities of Arboretums Based on Path Analysis: Postprint

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Abstract

To investigate the variation patterns and influencing factors of negative air ion concentration (NAIC) in typical plant communities within arboretums, the Hohhot Arboretum was selected as the study site. During 2022–2023, five days with clear, calm or light-wind conditions were selected per season, and environmental parameters were synchronously measured in situ from 08:00 to 18:00 across 11 distinct plant communities and control points. The study analyzed and compared NAIC variation patterns among different plant community structures and explored the environmental parameters influencing NAIC. The results indicated that: (1) NAIC in arboretum plant communities was significantly higher in spring (611–1115 $\text{ions} \cdot \text{cm}^{-3}$), summer (714–1033 $\text{ions} \cdot \text{cm}^{-3}$), and autumn (678–1120 $\text{ions} \cdot \text{cm}^{-3}$) compared to winter (202–372 $\text{ions} \cdot \text{cm}^{-3}$), though differences among communities within the same season were not significant. The diurnal variation trend of NAIC exhibited a "U"-shaped curve in spring, fluctuated in summer and autumn, and showed a pattern of initial decline followed by increase in winter, with seasonal variations in the timing of peak and trough values. (2) Air cleanliness of plant communities could achieve the highest cleanliness rating during spring, summer, and autumn, while remaining at clean to acceptable levels for most of winter. (3) The effects of environmental factors on NAIC varied seasonally, with different primary environmental factors influencing NAIC variation across seasons. Overall, fine particulate matter PM2.5 and PM1.0 represented the main factors affecting NAIC; the direct effects of particulate matter across different size fractions constituted the primary drivers of NAIC variability.

Full Text

Abstract

To investigate the variation characteristics of negative air ion concentration (NAIC) and their influencing factors in typical plant communities within an arboretum, this study examined the Hohhot Arboretum in Hohhot City, Inner Mongolia Autonomous Region, China. Field observations were conducted during five sunny and windless or breezy days in each season from 2022 to 2023 across eleven different plant communities and control sites. Environmental indicators were measured simultaneously from 08:00 to 18:00. The study analyzed and compared the diurnal variation patterns of NAIC across different plant community structures and explored the environmental factors influencing NAIC in arboretum plant communities. The results demonstrated that: (1) NAIC levels in arboretum plant communities were significantly higher during spring (611–1115 ions $\cdot$ cm^{-3}), summer (714–1033 ions $\cdot$ cm^{-3}), and autumn (678–1120 ions $\cdot$ cm^{-3}) compared to winter (202–372 ions $\cdot$ cm^{-3}), though no significant differences were observed among communities within the same season. Daily NAIC patterns exhibited seasonal variation, forming a "U-shaped" curve in spring, fluctuating in summer and autumn, and decreasing before increasing in winter, with the timing of peaks and troughs varying by season. (2) Air cleanliness of plant communities reached the cleanest level during spring, summer, and autumn, while winter showed cleanliness ranging from clean to acceptable for most observation periods. (3) The influence of environmental factors on NAIC varied by season, with $PM_{2\cdot 5}$ and $PM_{1\cdot 0}$ identified as the primary factors affecting NAIC. Variations in NAIC were mainly attributed to the direct effects of particulate matter of different sizes.

Keywords: arboretum; plant community; negative air ions; environmental factors; path analysis

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1. Materials and Methods

1.1 Study Area

Hohhot City is located in central Inner Mongolia and features a temperate continental climate with pronounced seasonal differences. The arboretum is situated in the Saihan District of Hohhot (111°42 16 E, 40°48 22 N), covering an area of 22 hm^2 in the urban center. The site exhibits significant interactions between vegetation and urban climate, with diverse tree species, stable community structure, and minimal human disturbance.

1.2 Observation Point Setup

Based on field surveys and considering plant community structure and species composition, eleven typical plant communities with good growth conditions and minimal human interference were selected as observation points within the arboretum. Each observation point was located more than 50 m from main roads, with monitoring stations established at the center. The control point was a hard-paved plaza with open space and no surrounding vegetation or tall buildings.

1.3 Index Measurement

During spring, summer, autumn, and winter of 2022–2023, observation days were selected based on weather forecasts and China Environmental Monitoring Network data, excluding days with strong winds or precipitation that could affect measurements. Five observation days were chosen per season, totaling 20 days, all characterized by sunny or partly cloudy conditions with light or no wind. Observations were conducted from 08:00 to 18:00 at 2-hour intervals, synchronized across all points, at a height of 1.3–1.5 m above ground.

AIC-1000 negative air ion monitors (resolution 10 $\mathrm{ions \cdot cm^{-3}}$, range 10–1.999\$×10^{5}\$ $\mathrm{ions \cdot cm^{-3}}$) were used to measure positive and negative air ion concentrations. Kestrel 4500 weather stations monitored air temperature (resolution 0.1°C, range -29–70°C), relative humidity (resolution 0.1%, range 0–100%), average wind speed (resolution 0.1 $\mathrm{m \cdot s^{-1}}$, range 0.4–40.0 $\mathrm{m \cdot s^{-1}}$), dew point temperature (resolution 0.1°C, range -29–70°C), and atmospheric pressure (resolution 0.1 hPa, range 750–1100 hPa). All instruments were calibrated before observation to avoid errors. After stabilization, three readings were recorded at each observation point and averaged.

1.4 Evaluation Methods

Air cleanliness was evaluated using the internationally recognized Ampere air ion evaluation index based on positive and negative air ions, calculated as follows:

$$\mathrm{CI} = (\mathrm{n}^{-}/\mathrm{n}^{+}) \times (1/\mathrm{q})$$

where CI is the Ampere air ion evaluation index; n^{+} and n^{-} are positive and negative air ion concentrations ($\mathrm{ions \cdot cm^{-3}}$), respectively; q is the unipolar coefficient; and n^{-} is the negative air ion concentration. The air cleanliness grading standard is shown in .

1.5 Data Analysis

Data were organized and plotted using Origin 2021. SPSS 26.0 was employed for one-way ANOVA and Duncan's multiple comparisons to analyze differences between plant communities and control points. Pearson correlation analysis and multiple linear stepwise regression were used for path analysis and decision analysis of environmental factors. The calculation formulas were:

$$\mathrm{P} \quad = \mathrm{p} \ \times \mathrm{r}$$
$$\mathrm{Q} \ = 2 \times \mathrm{r} \quad \times \mathrm{p} \ \text{-} \ \mathrm{p}^{2}$$

where P is the indirect path coefficient of environmental factor i acting on NAIC through factor j; r is the correlation coefficient between environmental factors i and j; p and p are the direct path coefficients of factors i and j, respectively; Q is the decision coefficient of environmental factor i on NAIC; and R^2 reflects the contribution of each factor to the regression model's reliability.

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2. Results

2.1.1 Diurnal Variation Characteristics

In spring, NAIC at all observation points exhibited a "U-shaped" curve [Figure 1: see original paper], with lower values appearing at 12:00–14:00 and higher values at 08:00, 10:00, and 18:00. Observation point 3 showed higher values more frequently, while point 4 showed lower values more frequently. In summer, NAIC fluctuated [Figure 1: see original paper], with higher values occurring more frequently at 08:00, 12:00–14:00, and 18:00, and lower values at 10:00–12:00 and 16:00–18:00. Observation point 3 showed higher values more frequently, while point 4 showed lower values more frequently. In autumn, NAIC alternated irregularly [Figure 1: see original paper], with most observation points showing higher values at 10:00 and 14:00, though the timing of lower values was not consistent. Observation point 3 showed lower values more frequently, while point 4 showed higher values more frequently. In winter, most observation points showed a decreasing trend [Figure 1: see original paper], with higher values at 08:00–10:00 and lower values at 14:00–18:00. Observation point 3 showed higher values more frequently, while point 4 showed lower values more frequently.

2.1.2 Seasonal Variation Characteristics

Within the same season, mean NAIC values across different plant communities showed that observation point 3 had the highest mean in spring and summer, while point 4 had the lowest [Figure 2: see original paper]. ANOVA revealed that in spring, observation point 4's mean was significantly lower than other points; in autumn, point 3's mean was significantly lower than point 4's; while in summer and winter, differences among points were not significant.

For the same plant community across seasons, most observation points showed highest NAIC in spring or autumn, with observation point 3 highest in spring and point 4 highest in autumn [Figure 2: see original paper]. All observation points and the control showed lowest NAIC in winter. ANOVA indicated that for most observation points, NAIC in spring, summer, and autumn was not significantly different, but was significantly higher than in winter. Observation point 3's spring NAIC was significantly higher than in spring, winter, and the control's spring values. Observation point 4's winter NAIC was significantly lower than in other seasons.

2.2.1 Temporal Air Cleanliness Evaluation

In spring, observation points and the control showed cleanest air cleanliness levels from 08:00–12:00 and 14:00–18:00, with more periods of CI$ $1.00. From 14:00–16:00, air cleanliness was clean to polluted, while other times showed cleanest levels [Figure 3: see original paper]. In summer, observation points 3 and 4 showed moderate cleanliness from 08:00–10:00, with other points at cleanest level. The control showed acceptable cleanliness from 08:00–10:00 and moderate from 14:00–16:00 [Figure 3: see original paper]. In autumn, observation point 4 showed acceptable cleanliness at 08:00, with other points at cleanest level. The control showed clean cleanliness at 08:00 and acceptable at 18:00 [Figure 3: see original paper]. In winter, observation point 4 showed polluted cleanliness at 08:00, with other points at cleanest level. The control showed clean cleanliness [Figure 3: see original paper].

2.2.2 Seasonal Air Cleanliness Evaluation

Within the same season, air cleanliness across different plant communities showed that in spring and autumn, all observation points and the control achieved cleanest levels, with observation point 3 significantly higher than other seasons. In summer, air cleanliness ranged from cleanest to clean levels, with observation point 3 at clean level and the control at acceptable level. In winter, air cleanliness ranged from cleanest to acceptable levels, with observation point 4 at polluted level .

For the same plant community across seasons, most observation points and the control showed highest air cleanliness in spring and lowest in autumn. Observation point 3 had highest cleanliness in spring, while the control had lowest in summer. ANOVA showed that observation point 3's spring cleanliness was significantly higher than summer and winter, while point 4's winter cleanliness was significantly lower than other seasons.

2.3.1 Correlation Analysis

As shown in , environmental factors significantly affecting NAIC in arboretum plant communities varied by season: spring showed inhalable particulate matter (PM_{10}), fine particulate matter ($PM_{2\cdot5}$), respirable particulate matter ($PM_{1\cdot0}$), and air temperature; summer showed total suspended particulate matter (TSP), $PM_{2\cdot5}$, $PM_{1\cdot0}$, and air positive ions; autumn showed $PM_{2\cdot5}$, $PM_{1\cdot0}$, and relative humidity; winter showed air temperature and dew point temperature. $PM_{2\cdot5}$ and $PM_{1\cdot0}$ showed significant effects across all seasons, indicating they are primary factors affecting NAIC in different structured plant communities, while other factors had effects but were not significant.

2.3.2 Path Analysis and Decision Analysis

Stepwise regression analysis excluded minor factors, with remaining factors' path and decision analysis results shown in . The analysis revealed that NAIC variation was directly and indirectly affected by different environmental factors across seasons. In spring, $PM_{1\cdot 0}$ had the largest direct effect, while $PM_{2\cdot 5}$ had the largest indirect effect; summer showed $PM_{2\cdot 5}$ with the largest direct effect and $PM_{1\cdot 0}$ with the largest indirect effect; autumn showed $PM_{1\cdot 0}$ with the largest direct effect and $PM_{2\cdot 5}$ with the largest indirect effect; winter and the annual mean showed $PM_{2\cdot 5}$ with the largest direct effect and $PM_{1\cdot 0}$ with the largest indirect effect.

Based on contributions to regression model reliability (R^2), the main factors affecting NAIC variation were: spring—$PM_{1\cdot 0}$ and $PM_{2\cdot 5}$; summer—$PM_{2\cdot 5}$; autumn—$PM_{1\cdot 0}$; winter and annual mean—$PM_{2\cdot 5}$. Decision coefficients reflect the comprehensive determining ability of each variable on the result, used to identify main decision variables' promoting and limiting effects. Results showed NAIC variation in spring was mainly limited by $PM_{1\cdot 0}$, indicating spring and autumn were primarily affected by large particulate matter, while other seasons were affected by small particulate matter.

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3. Discussion

This study found that different plant communities showed highest NAIC in spring and summer, lowest in winter, with non-significant differences among the four seasons, likely related to leaf fall and reduced photosynthesis in winter. Even coniferous trees retaining some needles had reduced physiological activity due to low temperatures, resulting in lower winter NAIC. Some studies found NAIC highest in summer and autumn, followed by spring, and lowest in winter, partially consistent with our results. This may be because our spring observations coincided with peak leaf expansion and strong physiological activity, producing more biogenic volatile organic compounds (BVOCs) that promote air ionization. The ability to produce NAIC is species-dependent, with some research suggesting conifers produce higher NAIC than broadleaf trees due to weak photosynthesis and needle tip discharge effects. However, our study found the broadleaf shrub-grass community of *Syringa oblata* had the highest NAIC in summer, possibly because broadleaf species have poorer water retention, faster water loss during transpiration, and higher air humidity, which is more conducive to NAIC generation. Winter NAIC was higher in coniferous communities like *Pinus sylvestris*, likely due to minimal leaf area change.

We found that shrub-grass coniferous forests and coniferous-broadleaf forests with arbor-shrub-grass structure had lower NAIC than other communities, possibly related to species composition and community structure. Some researchers suggest complex communities produce more NAIC than simple ones, but our results showed arbor-shrub-grass coniferous-broadleaf forests had lower NAIC, possibly due to high density, overlapping branches, poor light penetration, and ventilation, hindering photoelectric effect and NAIC transport. Individual observation points showed deviations from overall patterns, likely due to varying traffic, pedestrian flow, and activity patterns.

Our study identified air particulate matter as the main factor affecting NAIC, with $PM_{2\cdot5}$ and $PM_{1\cdot0}$ directly and indirectly influencing NAIC across seasons. Compared with urban parks in the same region, the arboretum showed higher air cleanliness, likely due to rich plant species, stable communities, and minimal human disturbance. Except in spring, $PM_{1\cdot0}$'s indirect effects through other factors exceeded its direct effects, possibly because smaller particles are more reactive to environmental changes. We found $PM_{1\cdot0}$ and $PM_{2\cdot5}$ were extremely significantly positively correlated with NAIC in spring, while most studies report negative correlations between particulate matter and NAIC. This may be because observations were conducted on windless days, limiting particulate transport, and increased humidity both promotes NAIC generation and facilitates particulate accumulation, leading to concurrent concentration changes.

Meteorological factors showed seasonal and regional differences in affecting NAIC. Air temperature correlated with NAIC in spring and summer but not other seasons. Temperature increases accelerate near-ground airflow, enhancing vertical and horizontal air movement and reducing NAIC. Relative humidity and dew point temperature significantly affected NAIC in autumn and winter, possibly because high humidity reduces solar radiation and plant physiological activity. In winter, increased humidity caused particulate settling and water molecules combining with electrons to form more NAIC. Wind speed and atmospheric pressure showed non-significant effects, likely due to stable weather conditions during observation days.

4. Conclusions

1. Daily NAIC variation in arboretum plant communities showed a "U-shaped" curve in spring, fluctuating patterns in summer and autumn, and a decreasing trend in winter, with seasonal differences in peak and trough timing. Seasonal mean NAIC was highest in spring and summer, lowest in winter, with non-significant differences among seasons. Spring and autumn showed non-significant differences among most plant communities, but significantly higher NAIC than winter.

2. Air cleanliness in spring, summer, and autumn reached the cleanest level, while winter ranged from cleanest to acceptable. Spring and autumn showed the cleanest air, with observation point 3 significantly higher than other seasons. Summer and winter showed non-significant differences among observation points.

3. Correlation analysis revealed that environmental factors significantly affecting NAIC varied by season: spring—PM_{10}, $PM_{2\cdot5}$, $PM_{1\cdot0}$, and air temperature; summer—TSP, $PM_{2\cdot5}$, $PM_{1\cdot0}$, and air positive ions; autumn—$PM_{2\cdot5}$, $PM_{1\cdot0}$, and relative humidity; winter—air temperature and dew

point temperature. $PM_{2\cdot5}$ and $PM_{1\cdot0}$ significantly affected NAIC across all seasons.

4. Path and decision analysis showed that particulate matter of different sizes was the main factor affecting NAIC in arboretum plant communities. $PM_{2\cdot5}$ primarily influenced NAIC through direct effects, while $PM_{1\cdot0}$ had substantial indirect effects. Spring and autumn were mainly affected by large particulate matter, while other seasons were affected by small particulate matter.

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