Postprint: Variation Patterns of PM2.5 Concentration and Leaf Adsorption Amount in Pinus tabuliformis Forests at Different Altitudes in the Western Hills of Beijing

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Abstract

This study investigated Pinus tabuliformis plantations across different altitude gradients in Beijing's Western Mountains, analyzing variations in PM2.5 concentration and leaf PM2.5 adsorption capacity, and employing electron microscopy to observe leaf surface micromorphological characteristics at different altitudes to elucidate differences in PM2.5 adsorption. The results demonstrated that PM2.5 mass concentration decreased progressively with increasing altitude. The diurnal variation of PM2.5 mass concentration in Pinus tabuliformis forests at all altitudes exhibited a typical bimodal pattern, with peak values occurring at 7:00 and 19:00, and the minimum value appearing around 13:00-15:00. On a monthly basis, the maximum PM2.5 mass concentration occurred in February (winter), while the minimum value was observed in August. The annual mean PM2.5 mass concentration in Pinus tabuliformis forests at different altitudes was 84 m ((102.28±18.44) g/m3) > 110 m ((94.18±18.34) g/m3) > 160 m ((81.53±19.23) g/m3) > 230 m ((75.39±15.71) g/m3). With increasing altitude, the PM2.5 adsorption capacity per unit leaf area gradually decreased, declining by 23.25% for every 50 m increase in altitude, while the PM2.5 adsorption capacity per hectare decreased by 26.43%. The annual mean PM2.5 adsorption capacity per hectare in Pinus tabuliformis forests at different altitudes was 84 m ((8.61±1.08) kg/hm2) > 110 m ((7.30±0.94) kg/hm2) > 160 m ((6.35±0.99) kg/hm2) > 230 m ((4.34±1.14) kg/hm2). The leaf surfaces of Pinus tabuliformis at low altitudes were relatively rough, with substantial particulate matter accumulating inside and around stomata, which was morphologically more favorable for PM2.5 adsorption; the opposite pattern was observed at high altitudes. Air quality at high altitudes was superior to that at low altitudes, while plants at low altitudes adsorbed more particulate matter

than those at high altitudes. These findings can provide data support for urban afforestation and forest-based atmospheric purification.

Full Text

Preamble

Variations in PM2.5 Concentration and Leaf Adsorption Capacity of *Pinus tabuliformis* Forests at Different Altitudes in Beijing' s Xishan Mountains

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Abstract

This study investigated PM2.5 concentration dynamics and leaf adsorption capacity in artificial *Pinus tabuliformis* forests across different altitude gradients in Beijing' s Xishan Mountains. Leaf surface micro-morphological characteristics at various altitudes were observed using electron microscopy to interpret differences in PM2.5 adsorption. The results revealed that PM2.5 concentration decreased with increasing altitude. Diurnal variations in PM2.5 concentration exhibited a typical bimodal curve across all altitudes, with peaks occurring at 7:00 and 19:00, and minimum concentrations detected between 13:00–15:00. Seasonally, the highest PM2.5 concentrations occurred in winter (February), while the lowest appeared in summer (August). The annual mean PM2.5 concentration across altitudes showed a decreasing trend: 84 m ((102.28±18.44) g/m^3) > 110 m ((94.18±18.34) g/m^3) > 160 m ((81.53±19.23) g/m^3) > 230 m ((75.39±15.71) g/m^3). PM2.5 adsorption per unit leaf area also decreased with altitude, reducing by 23.25% for every 50 m increase in elevation. The annual mean PM2.5 adsorption per hectare across altitudes was: 84 m ((8.61±1.08) kg/hm^2) > 110 m ((7.30±0.94) kg/hm^2) > 160 m ((6.35±0.99) kg/hm^2) > 230 m ((4.34±1.14) kg/hm^2), decreasing by 26.43% per 50 m altitude increase. Low-altitude pine needles exhibited rougher leaf surfaces with numerous particles aggregated inside and around stomata, making them morphologically more conducive to PM2.5 adsorption, whereas high-altitude needles showed opposite characteristics. Air quality was superior at higher altitudes, while plants at lower altitudes adsorbed more particulate matter. These findings provide data support for urban afforestation and atmospheric purification using forests.

Keywords: varying altitude; *Pinus tabuliformis* forest; PM2.5 concentration; PM2.5 adsorption capacity; leaf surface morphology

1. Introduction

Rapid socioeconomic development, accelerating urbanization, and rising energy consumption have made particulate matter the primary pollutant in China' s urban atmosphere, with fine particulate matter (PM2.5) receiving widespread attention. PM2.5 not only reduces atmospheric visibility but also increases mortality and respiratory disease incidence. As China' s capital, Beijing has experienced severe air quality challenges with urbanization. In 2014, Beijing' s annual mean PM2.5 concentration reached 83.2 g/m^3, exceeding national secondary standards by 137.71%, indicating a substantial gap from the environmental requirements of an international metropolis.

Numerous studies have demonstrated that vegetation effectively purifies airborne particulates, particularly in absorbing atmospheric pollutants and improving air quality. Trees can directly remove particles from the atmosphere, with most particles intercepted on plant surfaces. Research on urban vegetation' s particulate retention capacity has become a hot topic, with scholars investigating dust retention per unit leaf area, per unit leaf weight, and annual dust retention across different species. For instance, studies in Huizhou' s built-up area found that *Ficus altissima* and *Bauhinia blakeana* had leaf area-based dust retention of 0.98 and 0.75 g/m^2, respectively. In the West Midlands, increasing forest cover from 4% to 8% reduced PM10 concentrations by 0.7%-1.4%. Beijing' s Mentougou natural vegetation could achieve annual dust retention of 39.47×10 t.

As Beijing' s socioeconomic development and urban expansion continue, ecotourism has become increasingly important for urban residents. Beijing's Xishan Mountains represent a critical area for hiking, photography, and other recreational activities. Air quality in recreational forests is a decisive factor for evaluating forest ecotourism suitability. While previous research has focused on spatiotemporal variations, source analysis, and hazard assessment of atmospheric particulates, studies on air particulates in urban recreational forests remain scattered and discontinuous. No comprehensive, continuous studies have reported on spatiotemporal changes in forest interior air particulate concentrations and particulate adsorption capacity across different altitudes. This study examines PM2.5 concentration and leaf adsorption in *Pinus tabuliformis* forests at four altitude gradients in Beijing' s Xishan National Forest Park, exploring vertical variation trends and elucidating forests' environmental air purification functions to provide scientific evidence for forest ecological construction and environmental protection.

2. Study Area Overview

Beijing Xishan National Forest Park, located in the western suburbs of Beijing on Xiaoxishan, covers 5,970 hm^2 based on the Beijing Xishan Experimental Forest Farm. The park' s forest coverage rate ranges from 43% to 79%, with 48.39% of days classified as polluted. While air quality is relatively better than downtown Beijing, the overall air quality remains suboptimal. The regional climate is warm temperate with monsoon-influenced continental characteristics, receiving 634.2 mm annual precipitation. The zonal vegetation is warm temperate deciduous broad-leaved forest, with rich flora and fauna resources totaling 517 plant species. Dominant tree species include *Pinus tabuliformis*, *Pinus bungeana*, and *Populus* spp., with major shrubs including *Forsythia suspensa* and *Jasminum nudiflorum*.

3. Tree Species Selection

Pinus tabuliformis is a primary landscaping tree species in northern China, extensively planted in Xishan National Forest Park. Its leaf surfaces contain abundant oil secretions and exhibit high roughness, enabling substantial particulate adsorption. This study selected *Pinus tabuliformis* plantations with similar stand ages across different altitudes. Based on field conditions and altitude variations, four elevation gradients were established at 84 m, 110 m, 160 m, and 230 m. Statistical analysis of basic parameters across these altitudes showed normal distribution (skewness: -0.35, kurtosis: 0.83). Basic stand information is presented in Table 1.

Basic information of *Pinus tabuliformis* forests at different altitudes

4. Leaf Collection Methods

Before leaf collection, entire individual trees were cleaned using a sprayer. Leaves were collected monthly, with functional leaves sampled from upper, lower, eastern, western, southern, and northern canopy positions, avoiding rainy days (sampling postponed until after rainfall). Collected leaves were sealed in paper bags and transported to the laboratory for processing. PM2.5 concentrations in air at 1.5 m height were measured using a handheld dust monitor (Dustmate) from 5:00 to 19:00, with synchronous observations at all four altitude gradients. Each observation was replicated three times.

4.1 PM2.5 Adsorption Calculation

PM2.5 adsorption capacity was determined using an aerosol regeneration apparatus (QRJIZFSQ-II), an instrument developed by our research group. Based on wind erosion principles, leaves were placed in the apparatus chamber for destaticization and other treatments. The device resuspended particles from leaf surfaces to form aerosols, whose PM2.5 mass concentration was measured to calculate leaf surface PM2.5 content. Leaf area was determined using a leaf area scanner and software. PM2.5 adsorption per unit leaf area (M) and per hectare (Q) were calculated as:

$M = m/S$
$Q = M \times LAI \times 10$

where M is PM2.5 adsorption per unit leaf area (g/cm^2), m is PM2.5 mass from leaves placed in the apparatus (g), S is total leaf area in the apparatus chamber (cm^2), LAI is leaf area index, and 10 is a unit conversion coefficient. The aerosol regeneration method has been well-validated and recognized in academic circles.

5. Leaf Surface Micro-morphological Structure

Fresh leaves were immediately sealed in plastic to prevent compression or trichome damage. Small cubes (~1 cm^2) were cut from fresh leaves on both sides of the midrib, fixed in 2.5% glutaraldehyde solution, rinsed with phosphate buffer, dehydrated using gradient ethanol (70%, 80%, 90%, 95%), and sputter-coated for observation with an FEI Quanta-200 environmental scanning electron microscope. Suitable magnification ratios were selected for photography.

6. Results and Analysis

6.1 Diurnal Variation of PM2.5 Concentration

Overall, monthly PM2.5 concentrations showed similar diurnal variation trends across altitudes. PM2.5 concentrations were higher at low and medium altitudes than at high altitudes, displaying a typical bimodal pattern. All altitude gradients exhibited consistent diurnal trends, with concentrations gradually increasing from 5:00, peaking around 7:00, then decreasing to daily minima between 13:00–15:00, followed by a second peak around 19:00 (Figure 1).

[Figure 1: see original paper] Diurnal variation of PM2.5 concentration at different altitudes for *Pinus tabuliformis*

Monthly analysis revealed that February showed relatively 平缓 variation trends across altitudes, while other months exhibited more pronounced fluctuations. Peak PM2.5 concentrations exceeded 100 g/m^3 in winter months but remained below this threshold in summer months.

6.2 Annual Variation of PM2.5 Concentration

Daily mean PM2.5 concentrations varied significantly by month and altitude (Figure 2). At 84 m, concentrations ranged from 44.20 g/m^3 (August) to 105.88 g/m^3 (February); at 110 m, from 51.57 g/m^3 (August) to 98.50 g/m^3 (February); at 160 m, from 46.83 g/m^3 (August) to 80.66 g/m^3 (February); and at 230 m, from 42.83 g/m^3 (August) to 79.16 g/m^3 (February). High-concentration months were February, March, April, October, November, and December, while low-concentration months were June, July, August, and September.

[Figure 2: see original paper] Annual variation of PM2.5 concentration at different altitudes for *Pinus tabuliformis*

Annual mean PM2.5 concentrations decreased with altitude: 84 m ((102.28±18.44) g/m^3) > 110 m ((94.18±18.34) g/m^3) > 160 m ((81.53±19.23) g/m^3) > 230 m ((75.39±15.71) g/m^3). PM2.5 concentration decreased by

10.75% for every 50 m increase in altitude, indicating higher pollution levels at lower elevations.

6.3 Leaf PM2.5 Adsorption Capacity

PM2.5 adsorption per unit leaf area was highest at low altitudes and lowest at high altitudes (Figure 3). The annual mean adsorption values were: 84 m ((2.52 ± 0.78) g/cm²) > 110 m ((2.14 ± 0.74) g/cm²) > 160 m ((1.93 ± 0.69) g/cm²) > 230 m ((1.37 ± 0.84) g/cm²). High adsorption months were February, March, April, October, November, and December; low adsorption months were June, July, August, and September. Adsorption per unit leaf area decreased by 23.25% for every 50 m increase in altitude.

[Figure 3: see original paper] PM2.5 adsorption amount per unit leaf area for *Pinus tabuliformis* at different altitudes

PM2.5 adsorption per hectare also decreased with altitude: 84 m ((8.61 ± 1.08) kg/hm²) > 110 m ((7.30 ± 0.94) kg/hm²) > 160 m ((6.35 ± 0.99) kg/hm²) > 230 m ((4.34 ± 1.14) kg/hm²), declining by 26.43% per 50 m altitude increase (Figure 4).

[Figure 4: see original paper] PM2.5 adsorption amount per hectare for *Pinus tabuliformis* at different altitudes

6.4 Leaf Surface Micro-morphological Characteristics

Significant differences in leaf surface morphology were observed across altitudes (Figure 5). Low-altitude pine needles (84 m, 110 m) showed: - High surface roughness with abundant particles - Indistinct surface textures - Numerous oil secretions and dense stomata with small apertures - Heavy particle accumulation inside and around stomata

Mid-altitude needles (160 m) exhibited: - Moderate particle quantities - Smaller surface roughness with clear textures - Fewer particles inside and around stomata - Reduced oil secretions

High-altitude needles (230 m) displayed: - Minimal particle quantities - Smoother surfaces with lower roughness - Dense, clear textures and wrinkles - Larger stomatal density and apertures with fewer surrounding particles

7. Discussion

7.1 Spatiotemporal Variation of PM2.5 Concentration Across Altitudes

The bimodal diurnal pattern, with peaks at 7:00 and 19:00 and minima at 13:00-15:00, aligns with atmospheric dynamics and human activity patterns. Morning and evening periods feature lower temperatures, weaker atmospheric convection, and reduced pollutant dispersion. These times coincide with rush hour traffic, increasing emissions. During 11:00–15:00, rising temperatures enhance atmospheric turbulence and vertical mixing, diluting PM2.5 concentrations. Afternoon peaks in atmospheric pressure and air circulation further reduce particulate retention. This pattern corroborates findings from Wang Yuerong' s study on PM2.5 reduction by Beijing' s roadside vegetation and Wang Zhanshan' s research on Beijing' s PM2.5 distribution.

Seasonally, winter (February) showed highest concentrations due to coal combustion emissions, low temperatures hindering dispersion, and stable atmospheric conditions promoting accumulation. Spring dust storms from northwest and southeast winds further elevated PM2.5. Conversely, summer' s high temperatures, abundant rainfall, and vigorous plant growth enhanced atmospheric convection and particulate capture, reducing concentrations. These seasonal trends are consistent with studies by Wang Yongying in Harbin and Wang Cheng in Beijing' s Xishan recreational forests.

Altitude effects were pronounced: PM2.5 concentration decreased by 10.75% per 50 m elevation gain. Higher altitudes experience cooler temperatures, weaker convection, and reduced particulate mobility, while PM2.5' s mass causes gradual settling and accumulation at lower elevations. Temperature differences of ~0.6°C per 100 m create pressure gradients that influence particulate distribution, resulting in higher concentrations at low altitudes.

7.2 Altitudinal Variation in Leaf PM2.5 Adsorption

Leaf surface characteristics critically influence particulate adsorption capacity. Stomatal density, aperture size, surface roughness, and oil layers directly affect PM2.5 capture. Species with grooved surfaces or dense trichomes exhibit stronger dust retention. This study demonstrates decreasing adsorption with altitude: 23.25% reduction per 50 m for unit leaf area and 26.43% for hectare-scale adsorption.

Low-altitude needles' higher roughness, oil secretions, and surface irregularities increase contact area with particulates, enhancing adsorption. High-altitude needles' smoother surfaces and reduced surface features limit particulate capture. Sabin et al. reported that rough leaves with 绒毛, mucus, or oil layers have stronger adsorption capacities. The presence of surface depressions and protrusions at low elevations creates favorable micro-environments for particle interception, while high-altitude needles' smoother morphology reduces adsorption efficiency.

8. Conclusion

1. PM2.5 concentration decreased with increasing altitude in *Pinus tabuliformis* forests. Diurnal variation showed a typical bimodal curve with peaks at 7:00 and 19:00, and minima at 13:00–15:00.
2. Seasonally, PM2.5 concentrations peaked in winter (February) and reached

minima in summer (August). Annual mean concentrations decreased with altitude: 84 m > 110 m > 160 m > 230 m.

3. PM2.5 adsorption per unit leaf area and per hectare decreased with altitude, reducing by 23.25% and 26.43%, respectively, for every 50 m elevation increase.
4. Low-altitude pine needles exhibited rougher surfaces with dense stomata and abundant oil secretions, creating morphological advantages for PM2.5 adsorption compared to high-altitude needles.
5. Air quality was superior at higher altitudes, while low-altitude vegetation demonstrated greater particulate adsorption capacity. These results provide scientific support for urban afforestation planning and atmospheric purification strategies.

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Note: Figure translations are in progress. See original paper for figures.