Characterization of the Response of Negative Air Ions Released by Green Tree Species to Humidity Using an Open Top Chamber

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Article

Keywords: Greening tree species, Humidity, Capability indicators, Negative air ions (NAI), Open top chamber (OTC)

Posted Date: September 1st, 2025

DOI: https://doi.org/10.21203/rs.3.rs-7256798/v1

Additional Declarations: No competing interests reported.

Abstract

In order to analyze the effect of environmental factors on the release of negative air ions (NAI) by green tree species, this study conducted an open top chamber (OTC) control test in Beijing. The tree species selected were *Acer truncatum, Sophora japonica, Pinus bungeana,* and *Pinus tabuliformis.* The experiment investigated the effects of environmental factors on NAI release under different relative humidity conditions. The results of the study showed that: (1) The NAI release contribution (L), NAI release coefficient (n), NAI release rate (s), NAI instantaneous present amount (v), and total NAI release amount (Z) all showed positive responses to humidity. (2) Under constant temperature and light intensity, all five capability indicators increased with the humidity gradient (40%-80%) and reached their maximum values at 80% humidity. (3) NAI release was positively correlated with humidity, and the correlation coefficients were: *Pinus tabuliformis* (R^2 = 0.33) > *Sophora japonica* (R^2 = 0.17) > *Acer truncatum* (R^2 = 0.15) = *Pinus bungeana* (R^2 = 0.15, $p < 0.05$). (4) Under constant temperature and light intensity, the NAI release contribution (L) and NAI release coefficient (n) responded most strongly to humidity in the 40%-60% range, while the total NAI release amount (Z), NAI release rate (s), and NAI instantaneous present amount (v) responded more significantly in the 60%-80% range. *Acer truncatum* showed the strongest response in terms of NAI release contribution (L) and NAI release coefficient (n), while *Sophora japonica* exhibited the most significant response in terms of NAI release rate (s), NAI instantaneous present amount (v), and total NAI release amount (Z). This study, conducted using an OTC, clarifies the independent role of humidity on NAI released by green tree species, providing a scientific basis for forest recreation and urban green space planning.

Introduction

Extended exposure to air-conditioned environments in modern buildings often leads to boredom, depression, dizziness, poor mental condition, and reduced work efficiency and health. These symbols are collectively known as “urban office building syndrome” (Rueger et al., 1976). One contributing factor to these symptoms is the ambient negative air ions concentration (NAIC). Higher concentrations of negative air ions (NAI) are beneficial to health. This study conducted controlled experiments using an open top chamber (OTC) to investigate the independent role of humidity on the release of NAI from green tree species, which provides a scientific basis for forest recreation and urban green space planning. The molecular formulas of NAI are as follows: $O_2^-(H_2O)_n$, $(OH)^-(H_2O)_n$, and $CO_4^-(H_2O)_n$ (Luo et al., 2020). As humidity increases, more water molecules in the air ionize, releasing free electrons that attach to the water molecules, resulting in higher NAI levels (Li et al., 2013). On a macroscopic level, as air humidity increases, water molecules condense into water droplets, adsorbing airborne particles and dust, resulting in fresher air and prolonged NAI survival.

Humidity is an important environmental factor that affects the concentration of negative air ions (Shi G et al., 2021). NAI forms when water molecules combine with free charges in the air (Wu C, 2022). Given that the molecular structure of NAI usually includes water molecules such as $O_2^-(H_2O)_n$, $OH^-(H_2O)$, and

$CO_4^-(H_2O)_2$, air relative humidity generally has a significant positive correlation with NAIC (Deng, 2019). Guang Yao et al. (2021) found that when relative humidity is between 55% and 75%, an increase in air humidity leads to a rise in water molecule content. This increase allows more negatively charged ions to combine with free charges, significantly boosting NAIC. Within this humidity range, there is a positive correlation between NAI and relative humidity. Only when the water molecule content in the air reaches a certain threshold can it combine with free charges to produce NAI. Higher air humidity elevates water molecule content, facilitating air ionization. Therefore, within a certain range, higher relative humidity produces more NAI (Wang W et al., 2014). However, studies by Zhang S et al. (2011), Guo Y et al. (2013), and Yu Juan et al. (2021) indicate no significant correlation between NAIC and relative humidity. Thus, the relationship between humidity and NAIC remains inconclusive and needs to be further studied.

Open top chamber (OTC) technology uses semi-closed chambers made from materials such as plastic or glass to isolate plants from the external environment. This setup allows researchers to study the effects of environmental changes within the chamber on the physiological and ecological processes of plants. Currently, OTC technology is widely used to study the relationship between gases like CO_2 and O_3, and plants. It is considered an important tool for conducting plant phys, iological ecology research at both the community and individual scales (Shang et al., 2018; Lee et al., 2021). Most existing studies rely on field observations, which can produce highly variable data and are influenced by numerous environmental factors, making it difficult to analyze the impact of a single factor. Therefore, an OTC control test was conducted in this experiment to reduce the interference of human and environmental factors and analyze the independent effect of temperature on the release of NAI from different tree species. Current control tests typically evaluate the ability of environmental factors to influence NAI release from plants along a single dimension, which makes it difficult to determine the degree, mechanism, and process of this influence. In this study, five metrics were used to evaluate the impact of environmental factors on NAIC: the NAI release contribution (L), NAI release coefficient (n), NAI release rate (s), NAI instantaneous present amount (v), and total NAI release amount (Z). These metrics help clarify the response and change thresholds of these capability indicators to temperature, analyze the independent effect of temperature on NAI release from different tree species, and provide a theoretical basis for urban green space planning, tree species selection, and configuration.

Methodology

1.1 Overview of the study area

The study area is located at the Institute of Forestry and Pomology, Beijing Academy of Agriculture and Forestry Sciences, at latitude 39°58'01" N and longitude 116°13'02" E. The region experiences a temperate continental monsoon climate with distinct seasons. Spring has significant temperature variations, summer brings abundant precipitation, fall has pleasant temperatures, and winter is cold and dry. The average annual temperature ranges from 11.0 °C to 14.2 °C, with the highest temperatures reaching 35.1 ℃-41.9 ℃ and the lowest dropping to -8.7 ℃-11.0 ℃. The area receives an average annual precipitation of 569 mm and has an average annual relative humidity of 60%.

1.2 Materials and methods

1.2.1 Plant data

Evergreen needle trees (*Pinus tabuliformis* and *Pinus bungeana*) and deciduous broadleaf trees (*Sophora japonica* and *Acer truncatum*) were selected for this study. These species are recommended for afforestation projects in Beijing. The basic growth characteristics of these trees are detailed in Table 1.

Table 1
The basic growth status of tree species was tested

Species	Family	Tree age/year	Plant height/cm	Diameter/cm	Crown breadth/cm×cm
Pinus tabuliformis	*Pinaceae*	2–3	65	0.78	43×45
Pinus bungeana	*Pinaceae*	2–3	52	0.19	30×25
Sophora japonica	*Leguminosae*	2–3	109	1.76	48×42
Acer truncatum	*Sapindaceae Juss.*	2–3	116	1.83	65×40

1.2.2 NAI detector

The technical requirements for monitoring NAI, data processing, and evaluation methods were all conducted in accordance with the Technical Specifications for Grade of Negative Air Ion Concentration (LY/T 2586 – 2016) issued by the National Forestry and Grassland Administration in 2016. The instrument mainly measures the concentration of small particle size NAI with ion mobility ≥ 0.7 $cm^3 \cdot v^{-1} \cdot s^{-1}$. The measurement range is 0 ~ 5.0 × 10^6 $ion \cdot cm^{-3}$, with an ion concentration of ≤ 5%. The instrument collects data continuously for 30 minutes, then enters a dormant state for 5 minutes before resuming data collection.

1.2.3 Experimental design

According to the climatic conditions of the growing season in Beijing, the humidity gradients were set to 40%, 60%, and 80%. The study was divided into a control group and an experimental group. The control group did not contain any plants, while the experimental group included six pots of the same tree species placed in the OTC. After closing the door and adjusting the temperature to the target value, NAI and temperature readings were taken after a 30-minute adaptation period. After the temperature gradient test was completed, the door was opened, the air conditioner was turned off, and a 10-minute empty room period was observed before replacing the tree species for the next round of testing. After completing the temperature gradient tests, the door was opened, the equipment was turned off and the room was emptied 24 hours before replacing the tree species for the next round of testing. At the end of the experiment, the test trees were removed, and all leaves were collected. The leaves were scanned using an Epson V19 scanner, and the leaf area was calculated using ImageJ software. NAI concentration data were then downloaded to a computer for analysis.

1.3 Test instrument

The experiment was conducted between April and October 2023. As illustrated in Fig. 1, an OTC consists of three main components: a supporting frame, chamber wall, and base. The entire structure is constructed from stainless steel tubes and colorless transparent glass, with a layer of electrically insulating polytetrafluoroethylene (PTFE) film applied to the inside of the OTC wall.

1.4 Capability indicators

To better understand the characteristics and differences in the response of NAIs to environmental factors, both independent and multifactorial interactions affecting NAI release from various tree species were examined. This assessment utilized five capability indicators: NAI release contribution (L), NAI release coefficient (n), NAI release rate (s), NAI instantaneous present amount (v), and total NAI release amount (Z), which represent a plant's ability to release NAI. Controlled experiments using OTC were conducted to analyze NAI release capability and variations among these indicators. The evaluation considered the overall contribution of NAI released by the plant, the ability to release NAI instantly, the rate of NAI release (whether rapid or slow), the effect of NAI release at specific time points, and the total amount of NAI released over a certain period.

1.4.1 Indicator model and parameters

(1) The NAI release contribution rate (L) measures the percentage of NAI released by plants relative to the total number of NAI in a given period. This reflects the plants' contribution to the overall NAIC. The calculation formula is as follows.

$L = (G_{Treat} - G_{CK})/G_{Treat} \times 100\%$. (1)

where L represents the plant release contribution rate (%), G_{Treat} is the mean NAIC (ions·cm^{-3}) in the plant group, and G_{CK} denotes the average NAIC (ions·cm^{-3}) in the control group without plants.

1. The NAI release coefficient (n) represents the ratio of NAI released by plants to the amount of NAI in the control group without plants over a specific period. This coefficient indicates the plants' ability to release NAI immediately. The calculation formula is as follows:

$n = (G_{Treat} - G_{CK})/G_{CK}$ (2)

where n represents the NAI release coefficient, G_{Treat} is the mean NAIC (ions·cm^{-3}) in the plant group, and G_{CK} denotes the average NAIC (ions·cm^{-3}) in the control group without plants.

(3) The NAI release rate (s) measures the increase in the number of NAI per unit leaf area over a specific time period, reflecting the speed and intensity of NAI release by plants. The calculation formula is as follows:

$$s = (G_{Treat} - G_{CK}) \times V // (t_{survival} \times S_a). \quad (3)$$

where s represents the NAI release rate (ions·cm^{-2}·min^{-1}), V denotes the OTC volume (cm^3), S_a indicates the leaf area (cm^2), and $t_{survival}$ is the survival time of NAI in the air (min). $t_{survival}$ was consistently taken as 10 minutes based on the findings of Li Shaoning et al. (2020).

(4) The NAI instantaneous present amount (v) refers to the difference between the number of NAI released by plants per unit leaf area and the number of NAI in the control group without plants. This index measures the effect of plant NAI release at a specific moment. The formula for calculating the instantaneous present amount is as follows:

$$V = (G_{Treat} - G_{CK}) \times V / S_a \quad (4)$$

where v represents the NAI instantaneous present volume (ions·cm^{-2}), V is the volume of the OTC (cm^3), and S_a is the leaf area (cm^2).

(5) The total NAI release amount (Z) refers to the total number of NAI released per unit area of the plant over a specific period. It is an indicator of the overall NAI release effect by the plant. The calculation formula is as follows:

$$Z = (G_{Treat} - G_{CK}) \times V \times T_{Total} / (t_{survival} \times LAI \times S_a) \quad (5)$$

where Z represents the total amount of NAI released by the plant per unit leaf area during the period (ions·cm^{-2}·h^{-1}), and T_{Total} denotes the duration of the monitoring period (min). Since the negative ion monitoring test lasts for 30 minutes, and T_{Total} is set to 30 minutes.

This study is not a clinical trial; therefore, Clinical trial number: not applicable.

Results

2.1 NAI release contribution (L)

Figure 2 illustrates the relationship between the NAI release contribution (L) of each tree species and humidity under different temperature and light intensity conditions. Overall, the NAI release contribution

(L) for all four tree species increased with increasing humidity, with the maximum NAI release contribution observed at 80% humidity.

At a temperature of 25 ℃, changes in light intensity impacted the NAI release contribution (L), which increased with higher light intensity. When the light intensity was 60 $μm·m^{-2}·s^{-1}$, the increases in NAI release contribution with increasing humidity (40%-80%) were relatively small for both broadleaf and conifer species, 3.64% and 2.61%, respectively. At 1200 $μm·m^{-2}·s^{-1}$, the increases were 2.71% for broadleaf species and 1.93% for conifer. At 2000 $μm·m^{-2}·s^{-1}$, the increases were similar for both broadleaf and conifer species, at 3.70% and 3%, respectively. Overall, the NAI release contribution (L) showed an increasing trend with increasing humidity, but the increase was minimal and not significant.

At a temperature of 30 ℃, the increase in the NAI release contribution (L) from broadleaf species (18.02%) was slightly greater than from conifer species (14.21%) under varying light intensity conditions. Compared to the 25 ℃ condition (35.20%), the overall increase (32.23%) at 30 ℃ was slightly lower. The reduction in NAI release contribution for broadleaf species (2.09%) was about twice that of conifer species (1%).

At a temperature of 35 ℃, under different light intensities, the NAI release contribution (L) from broadleaf species (40.68%) was significantly greater than that from conifer species (16.31%). Compared to the condition at 25 ℃, the increase for broadleaf species (18.36%) was 9.2 times that of conifer species (2%). Compared to the condition at 30 ℃, the increase of broadleaf (16.26%) was 16 times that of conifer species (1%). This indicates that broadleaf species are more sensitive to changes in humidity. The greater the humidity variation, the more significant the change in NAI release for broadleaf species.

In summary, with increasing humidity, the NAI release contribution (L) of broadleaf species (74.50%) was significantly greater than that of conifer species (45.60%). However, the total NAI release of conifer species (34.51%) was slightly greater than that of broadleaf species (32.67%). At a temperature of 35 ℃ and a light intensity of 1200 $μm·m^{-2}·s^{-1}$, broadleaf species showed the most significant increase in L, up to 19.46%, in response to rising humidity. In contrast, conifer species showed the most pronounced response at a temperature of 35 ℃ and a light intensity of 2000 $μm·m^{-2}·s^{-1}$, with an increase of 9.01%. This indicates that conifer species are more adaptable to changes in humidity compared to broadleaf species, resulting in a smaller increase in L. Consequently, conifer species have greater overall NAI release capability than broadleaf species.

2.2 NAI release coefficients (n)

Figure 3 shows the relationship between the NAI release coefficients (n) and humidity for the four green tree species under different temperatures and light intensity conditions. Overall, the NAI release coefficients (n) exhibited an increasing trend with rising humidity, reaching a maximum of 80% humidity.

At a temperature of 25 ℃, changes in light intensity affected the NAI release coefficients (n), which increased with higher light intensity. At a light intensity of 600 $μm·m^{-2}·s^{-1}$, the increase for conifer species (0.36) was slightly larger than that for broadleaf species (0.35). At 1200 μm·m^{-2}·s^{-1}, the increases for conifer and broadleaf species were very close, at 0.33 and 0.31, respectively. At 2000 μm·m^{-2}·s^{-1}, the increase for conifer species (0.60) was significantly larger than for broadleaf species (0.36).

At a temperature of 30°C, the increase in the NAI release coefficients (n) was greater for broadleaf species (1.53) than for conifer species (1.26) under varying light intensities. Compared to the condition at 25°C, the NAI release coefficient increased by 0.4 for broadleaf species and decreased by 0.02 for conifer species.

At a temperature of 35 ℃, the increase in NAI release coefficients (n) was significantly larger in broadleaf species (2.35) compared to conifer species (0.95) under different light intensities. This represents a 2.5 times greater increase for broadleaf species. Compared to the condition at 30 ℃, the overall increase was 0.51, with broadleaf species increasing by 0.82, and conifer species showing a decrease of 0.31. Compared to the condition at 25 ℃, the change was more significant, with an overall increase of 0.88, where broadleaf species increased by 1.22 and conifer species decreased by 0.33. This suggests that the NAI release coefficients (n) were influenced by the interaction of temperature and humidity, with broadleaf species being more susceptible to these environmental effects.

In summary, the total NAI release coefficients (n) were significantly larger for conifer species (98.26) compared to broadleaf species (85.71). However, the increase in NAI release coefficients was significantly higher for broadleaf species (5) than for conifer species (3.49). At a temperature of 35 ℃ and a light intensity of 1200 μm·m^{-2}·s^{-1}, broadleaf species showed the strongest response to humidity, with an increase of up to 1.08. Conversely, conifer species showed the most pronounced response at a temperature of 25°C and a light intensity of 2000 μm·m^{-2}·s^{-1}, with an increase of 0.60. This indicates that conifer species have a greater overall capability for releasing NAI, while broadleaf species are more sensitive to changes in humidity.

2.3 NAI release rate (s)

As shown in Fig. 4, the NAI release rate (s) for each three species exhibited an increasing trend with rising humidity under different temperatures and light intensity conditions. However, the rate and magnitude of this increase varied. Overall, the NAI release rate **(s)** for each tree species increased most significantly at 60% and 80% humidity, with conifer species showing a considerably higher increase than broadleaf species.

At a temperature of 25 ℃, the NAI release rate **(s)** increased with increasing light intensity. At a light intensity of 600 μm·m^{-2}·s^{-1}, the increase rate was greater for broadleaf species (33%) compared to conifer species (25%) as the humidity range increased (40%-80%). At 1200 μm·m^{-2}·s^{-1}, the increase rates were 33% for broadleaf and 25% for conifer species. At 2000 μm·m^{-2}·s^{-1}, the increase rate for broadleaf species (38%) was twice that of conifer species (19%).

At a temperature of 30 °C, the NAI release rate **(s)** increased more in broadleaf species (146.11%) than in conifer species (122.74%) under different light intensities. Compared to the conditions at 25 °C, the overall increase was 14.15%. However, the increase rate decreased in both broadleaf and conifer species by 16.37% and 18.19%, respectively.

At a temperature of 35 °C, the NAI release rate **(s)** increased significantly more in broadleaf species (153.49%) compared to conifer species (118.50%) under varying light intensities. However, compared to the 30 °C condition, the release rate decreased significantly by 82.08%, with broadleaf species showing a reduction of 77.84%, which is 18 times greater than the 4.24% reduction in conifer species. Compared to the 25 °C condition, the NAI release rate decreased by 67.93%, with broadleaf species experiencing a reduction of 94.21%, approximately 4 times greater than the 22.43% reduction in conifer species.

In summary, the NAI release rate **(s)** for conifer species (5,548,800 ± 136,500 $cm^{-2}\cdot min^{-1}$) was approximately 3.9 times higher than for broadleaf species (1,424,400 ± 349,600 $cm^{-2}\cdot min^{-1}$) as humidity increased. The release rate of broadleaf species (515%) was significantly higher than that of conifer species (382%). Broadleaf species responded most strongly to increasing humidity at a temperature of 25 °C and a light intensity of 2000 $\mu m\cdot m^{-2}\cdot s^{-1}$, with a growth rate of up to 49%. Conifer species showed the most significant response to increasing humidity at a temperature of 25 °C and a light intensity of 1200 $\mu m\cdot m^{-2}\cdot s^{-1}$, with a growth rate of 39%. Overall, the NAI release rate **(s)** response to humidity was much greater in broadleaf species than in conifer species, indicating that conifer species are more adaptable to humidity changes, resulting in a smaller release rate compared to broadleaf species, which respond more strongly to humidity changes and thus exhibit a much greater release rate.

2.4 NAI instantaneous present amount (v)

As shown in Fig. 5, the relationship between the NAI instantaneous present amount (v) and humidity was explored for each tree species under different temperatures and light intensities. Overall, as humidity increased, the NAI instantaneous present amount (v) for all four tree species showed an increasing trend, reaching its maximum value at 80% humidity.

At a temperature of 25°C, the NAI instantaneous present amount (v) increased with increasing light intensity. When the light intensity was 600 $\mu m\cdot m^{-2}\cdot s^{-1}$, the increase for broadleaf species (65.97%) was significantly greater than that for conifer species (49.01%) as humidity increased. At 1,200 $\mu m\cdot m^{-2}\cdot s^{-1}$, the increase for broadleaf species (66.28%) was slightly higher than for conifer species (53.51%). At 2000 $\mu m\cdot m^{-2}\cdot s^{-1}$, the increase for broadleaf species (76.35%) was about twice as high as for conifer species (38.42%).

At a temperature of 30°C, the increase in the NAI instantaneous present amount (v) for broadleaf species (192.23%) was significantly greater than for conifer species (122.74%). The overall rate of increase decreased by 34.57% compared to the 25°C condition, with decreases observed in both broadleaf species (16.37%) and conifer species (18.19%).

At a temperature of 35°C, the growth rates of the NAI instantaneous present amount (v) for broadleaf species and conifer species were close, at 114.39% and 118.50%, respectively. Compared to the 30 °C condition, the growth rate significantly decreased by 82.08%, with the reduction in broadleaf species (77.84%) being up to 18 times greater than that of conifer species (4.24%). When compared to the condition at 35 °C, the growth rate was reduced by 116.64%, with the reduction in broadleaf species (94.21%) being about 4 times greater than that of conifer species (22.43%). This indicates that under the interaction of temperature and humidity, the NAI instantaneous present amount (v) gradually decreased, with broadleaf species being more susceptible to these changes compared to conifer species.

In summary, the NAI instantaneous present amount (v) for conifer species (263,800 ± 29,300 m^{-2}) was about 2.6 times that of broadleaf species (102,700 ± 31,100 m^{-2}). However, the rate of growth for broadleaf species (515.22%) was much higher than that for conifer species (382.18%). The greatest growth rate for the NAI instantaneous present amount (v) in broadleaf species (73.61%) occurred at a temperature of 30 °C and a light intensity of 600 $\mu m \cdot m^{-2} \cdot s^{-1}$. For conifer species, the highest growth rate (53.51%) was observed at a temperature of 25 °C and a light intensity of 1200 $\mu m \cdot m^{-2} \cdot s^{-1}$. The response of the NAI instantaneous present amount (v) to the 60%-80% humidity range was significantly greater than that to the 40%-60% humidity range.

2.5 Total NAI release amount (Z)

Figure 6 illustrates the effect of humidity on the total NAI release amount (Z) under different temperatures and light intensity conditions. Overall, the total NAI release amount (Z) increased with rising humidity, peaking at 80% humidity. Notably, conifer species had a higher total release amount compared to broadleaf species.

At a temperature of 25°C, as light intensity increased, the total NAI release amount (Z) also rose. At a light intensity of 600 $\mu m \cdot m^{-2} \cdot s^{-1}$, the range of fluctuation in total NAI release amount (Z) was significantly larger in broadleaf species (72,800 – 161,600 $m^{-2} \cdot h^{-1}$) compared to conifer species (214,000-241,200 $m^{-2} \cdot h^{-1}$). When light intensity increased to 1,200 $\mu m \cdot m^{-2} \cdot s^{-1}$, the fluctuation range in broadleaf species (84,600 – 184,600 $m^{-2} \cdot h^{-1}$) was about twice that of conifer species (246,200–297,800 $m^{-2} \cdot h^{-1}$). At 2000 $\mu m \cdot m^{-2} \cdot s^{-1}$, the fluctuation range in broadleaf species (84,600 – 184,600 $m^{-2} \cdot h^{-1}$) was about twice that of conifer species (246,200–297,800 $m^{-2} \cdot h^{-1}$). At 2000 $\mu m \cdot m^{-2} \cdot s^{-1}$, the fluctuation range in broadleaf species (105,200 – 23,200 $m^{-2} \cdot h^{-1}$) was approximately eight times greater than that in conifer species (226,600 – 244,400 $m^{-2} \cdot h^{-1}$).

At a temperature of 30 °C, the range of fluctuation in the total NAI release amount (Z) was greater for conifer species (199,600 – 395,400 $m^{-2} \cdot h^{-1}$) compared to broadleaf species (113,600 – 276,800 $m^{-2} \cdot h^{-1}$). This fluctuation increased by 116,000 $m^{-2} \cdot h^{-1}$ relative to the 25 °C condition. Additionally, the total NAI release amount for conifer species (11,200,000 $m^{-2} \cdot h^{-1}$) was about 28 times higher than that for broadleaf species (3,938 $\cdot m^{-2} \cdot h^{-1}$).

At a temperature of 35 ℃, the fluctuation range of the total NAI release amount (Z) was approximately twice as large for conifer species (16.8–44.6 million $m^{-2}·h^{-1}$) compared to broadleaf species (75.4–20.8 million $m^{-2}·h^{-1}$) under different light intensities. Compared to the 30 ℃ condition, the fluctuation range increased by 40,400,000 $m^{-2}·h^{-1}$ for conifer species and decreased by 37,800,000 $m^{-2}·h^{-1}$ for broadleaf species. Compared to the 25 ℃ condition, the fluctuation range increased by 160,000 $m^{-2}·h^{-1}$, with an increase of 19,400,000 $m^{-2}·h^{-1}$ for conifer species and a decrease of 33,800,000 $m^{-2}·h^{-1}$ for broadleaf species.

In summary, the fluctuation in the total NAI release amount (Z) with increasing humidity was greater for broadleaf species (168,200–446,000 $m^{-2}·h^{-1}$) compared to conifer species (75,400 – 276,800 $m^{-2}·h^{-1}$). However, the total NAI release amount (Z) for conifer species (85,464,000 ± 20,973,800 $m^{-2}·h^{-1}$) was significantly higher than for broadleaf species (33,268,600 ± 8,129,000 $m^{-2}·h^{-1}$). Broadleaf species exhibited the most significant response to humidity at a temperature of 30°C and a light intensity of 600 $μm·m^{-2}·s^{-1}$, with fluctuations ranging from 600,000 to 876,600 $m^{-2}·h^{-1}$. Conversely, conifer species showed the strongest response to humidity at a temperature of 35°C and a light intensity of 1,200 $μm·m^{-2}·s^{-1}$ (2,342,600-2,788,600 $m^{-2}·h^{-1}$). This indicates that while conifer species were more capable of releasing NAI, they were less affected by changes in humidity compared to broadleaf species, which demonstrated greater fluctuations and were more sensitive to humidity changes.

2.6 Response degree of the five capability indicators to humidity, consistency, and difference in the process

As humidity increased, all five capability indicators showed an increasing trend, though their responses varied in both magnitude and pattern. The total NAI release amount (Z), NAI release rate **(s)**, and NAI instantaneous present amount (v) showed the greatest sensitivity to changes in humidity. The NAI release coefficients (n) followed, with the NAI release contribution (L) exhibiting the weakest response. Within the 40%-60% humidity range, the NAI release contribution (L) and the NAI release coefficients (n) responded most significantly, reaching their maximum values as humidity increased. In contrast, the total NAI release amount (Z), NAI release rate **(s)**, and NAI instantaneous present amount (v) showed a more significant response within the 60%-80% humidity range. The increase in these indicators was most significant in this higher humidity range compared to the other gradients.

The response of the five capability indicators to humidity varied among the four tree species. As humidity increased, *Acer truncatum* exhibited the most significant changes in the NAI release contribution (L) and the NAI release coefficients (n). In contrast, *Sophora japonica* showed the most pronounced response in terms of the total NAI release amount (Z), NAI release rate **(s)**, and NAI instantaneous present amount (v).

As shown in Fig. 7, the NAI release for all four tree species showed a positive correlation with increasing humidity, though the strength of the correlation varied. The correlation coefficients for the NAIC with humidity for each tree species were as follows: *Pinus tabuliformis* (R^2 = 0.33) > *Sophora japonica* (R^2 =

0.17) > *Acer truncatum* (R^2 = 0.15) = *Pinus bungeana* (R^2 = 0.15). The correlation between the NAIC of *Pinus tabuliformis* and humidity was greater compared to the other species, suggesting that *Pinus tabuliformis* NAI release shows greater sensitivity to humidity changes and is more affected by humidity fluctuations.

Discussion

3.1 Positive response of the five capability indicators to humidity

In the OTC with controlled temperature and light intensity, the NAIC for tree species increases with humidity, peaking at 80% humidity. With the increase in humidity, water vapor condenses into water droplets that capture airborne particles, improving atmospheric cleanliness and prolonging the lifespan of NAI. This results in a decrease in the rate of NAIC and a tendency for it to stabilize with higher humidity. In addition, increased humidity enhances particle coagulation, prompting smaller particles to clump together and form larger particles. This reduces the mobility of the particles, further minimizing NAI loss and leading to a stabilization in the plant's impact as humidity continues to rise. According to the theory from the Union Commission on Climate and Environmental Change (UCCEC) of the International Union of Geodesy and Geography (IUGG), the molecular formulas for NAI are $O_2^-(H_2O)_n$, $(OH)^-(H_2O)_n$, and $CO_4^-(H_2O)_n$ (Luo et al., 2020). As humidity increases, the concentration of H_2O molecules in the air increases, making it more likely for free electrons released through ionization to bond with water molecules, resulting in a higher production of NAI (Li et al., 2019). This increased humidity leads to a greater release of NAI from green tree species. The increased presence of hydrated ions contributes significantly to the increase in NAI, and higher humidity levels enhance the stability of NAIC due to the increased concentration of water molecules in the air (Smirnov, 1992). From a macroscopic point of view, increased humidity causes water molecules to condense into droplets, which adsorb airborne particles and dust, resulting in cleaner and extending the lifespan of NAI.

As air humidity increases, the temperature decreases, evaporation weakens, and soil relative humidity increases. The increase in soil humidity affects various physiological activities of plant roots, such as respiration, water uptake and utilization, and nutrient absorption. Additionally, increased humidity promotes the opening of stomata in green tree species (Dueñas C et al., 1997), leading to an increase in the release of NAI.

3.2 Differences in the humidity response of the five capability indicators

In the OTC with controlled temperature, humidity, and light intensity, the NAI release of the four tree species increased with humidity in the following order: *Pinus tabuliformis* > *Pinus bungeana* > *Acer truncatum* > *Sophora japonica*. Conifer species were more sensitive to humidity increase than broadleaf species, with the NAIC reaching its maximum at 80% humidity. As humidity increased, plant leaf transpiration weakened, stomata opened, photosynthesis was enhanced, and more oxygen was released to combine with free electrons in the air, which resulted in more NAI, consistent with the findings of Miao et al. (2018).

Broadleaf species have a larger leaf area than conifer species, and dust adherence on leaf surfaces can prevent stomata from opening, reducing photosynthesis. This may explain why broadleaf species have a weaker NAI release capability compared to conifer species.

Conclusion

(1) Consistency in humidity response across the five capability indicators

Under constant temperature and light intensity, the NAI release contribution (L), NAI release coefficients (n), NAI release rate **(s)**, NAI instantaneous present amount (v), and total release NAI amount (Z) all showed positive responses to increasing humidity. The five capability indicators also increased with humidity, with conifer species being more responsive than broadleaf species. This indicates that conifer species have a stronger ability to release NAI compared to broadleaf species. The correlation between NAIC and humidity varied among the four species: *Pinus tabuliformis* showed the strongest correlation with humidity ($R^2 = 0.33$), while other conifer and broadleaf species exhibited weaker but significant correlations ($p < 0.05$)

(2) Consistency of the five capability indicators with the NAIC

Under constant temperature and light intensity, the NAI release contribution (L), NAI release rate **(s)**, NAI release coefficients (n), NAI instantaneous present amount (v), and total NAI release amount (Z) all showed an increasing trend as humidity and NAIC increased.

(3) Differences in the response of the five capability indicators to humidity

The total NAI release amount (Z), NAI release rate **(s)**, and NAI instantaneous present amount (v) showed the strongest response to humidity, followed by the NAI release coefficients (n), with the NAI release contribution (L) responding the least. The NAI release coefficients (n), and NAI release contribution (L) were more significantly affected by humidity in the range of 40%-60%, whereas the total NAI release amount (Z), NAI release rate **(s)**, and NAI instantaneous present amount (v) responded more significantly in the range of 60%-80%. Among the species, *Acer truncatum* showed the most significant response in terms of NAI release coefficients (n) and the NAI release contribution (L), while *Sophora japonica* exhibited the strongest response in terms of total NAI release amount (Z), NAI release rate **(s)**, and NAI instantaneous present amount (v).

（4）Limitations of the experiment

The tested humidity range is relatively narrow (40%-80%), the study only focuses on 4 tree species, and there are unmeasured factors (such as soil moisture dynamics) that may affect negative ion release.

Declarations

Data availability：

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Funding

This work was supported by National Natural Science Foundation of China （32071834）

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Figures

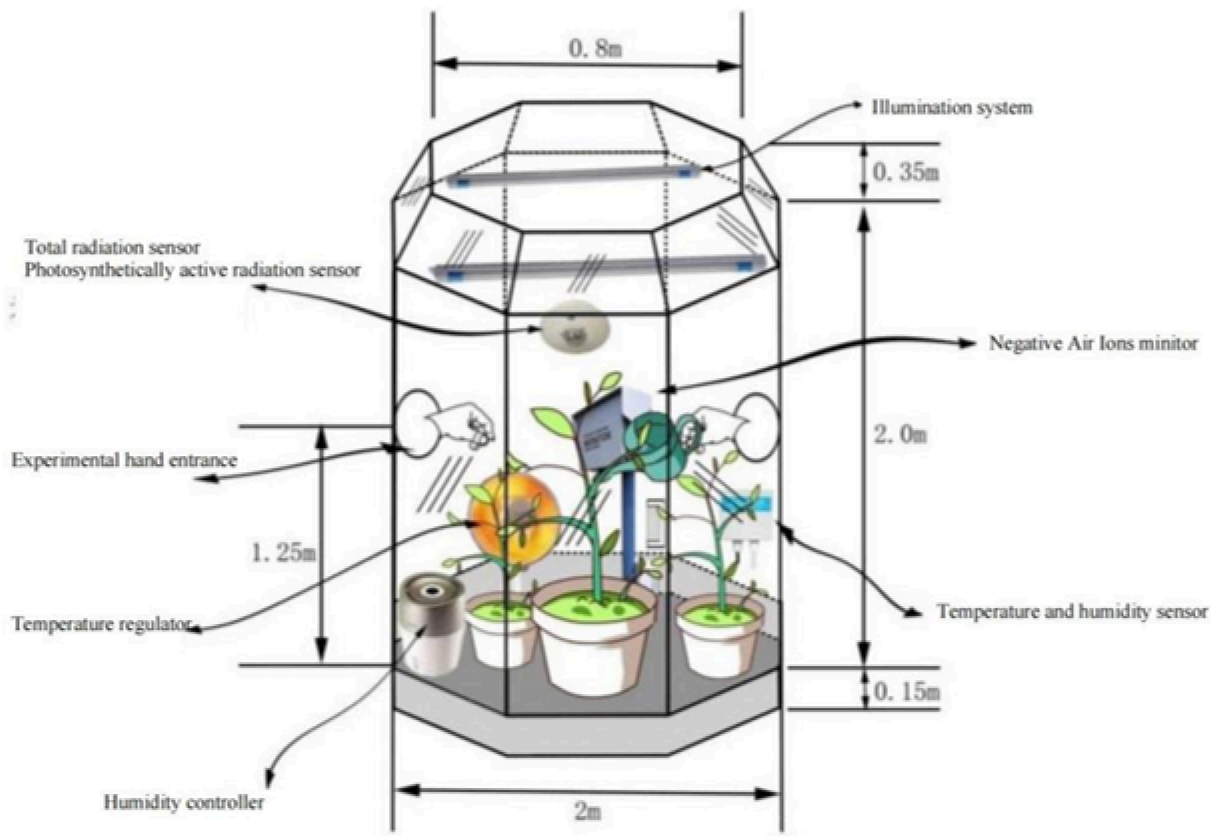

Figure 1

OTC schematic diagram.

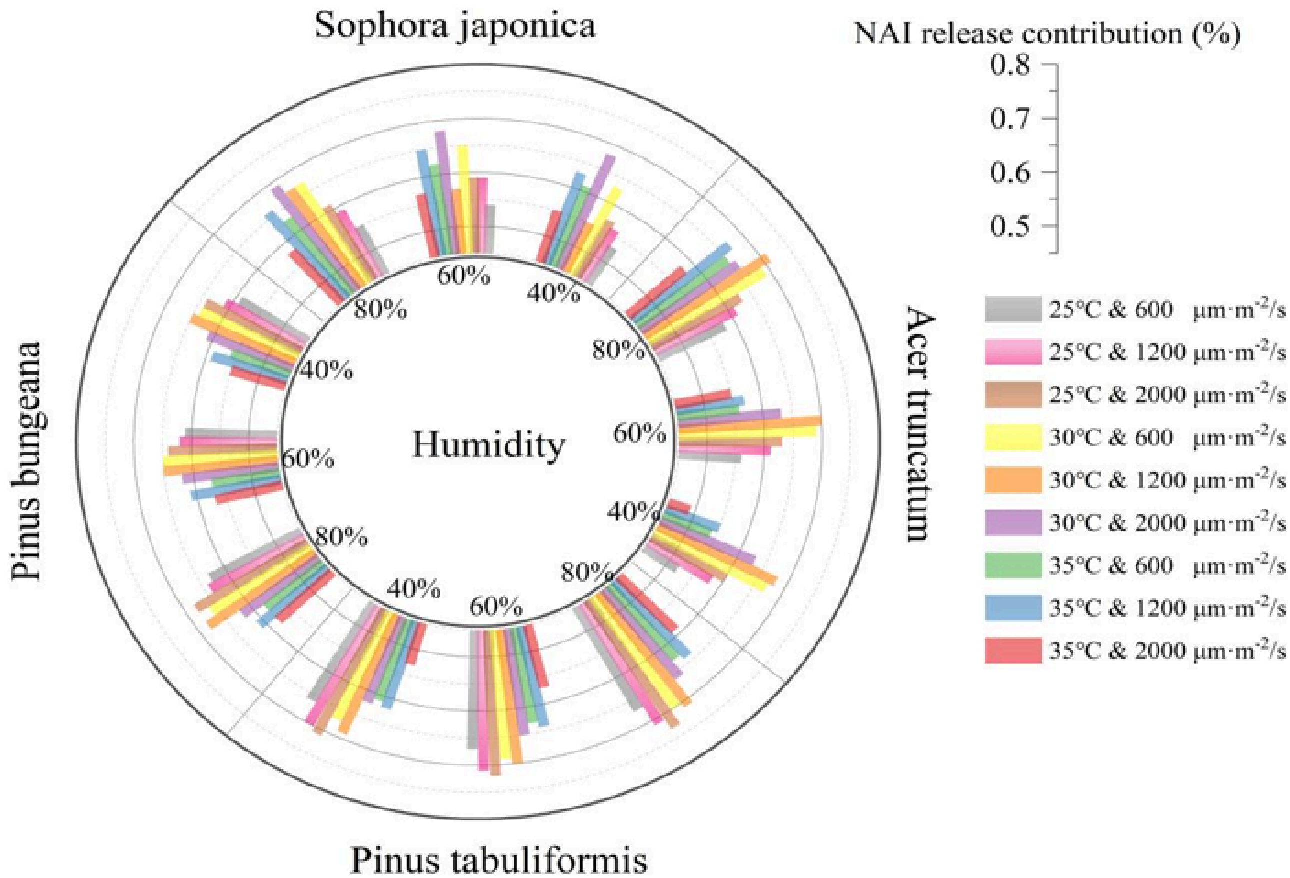

Figure 2

Contribution of NAI release from green tree species under different environmental conditions.

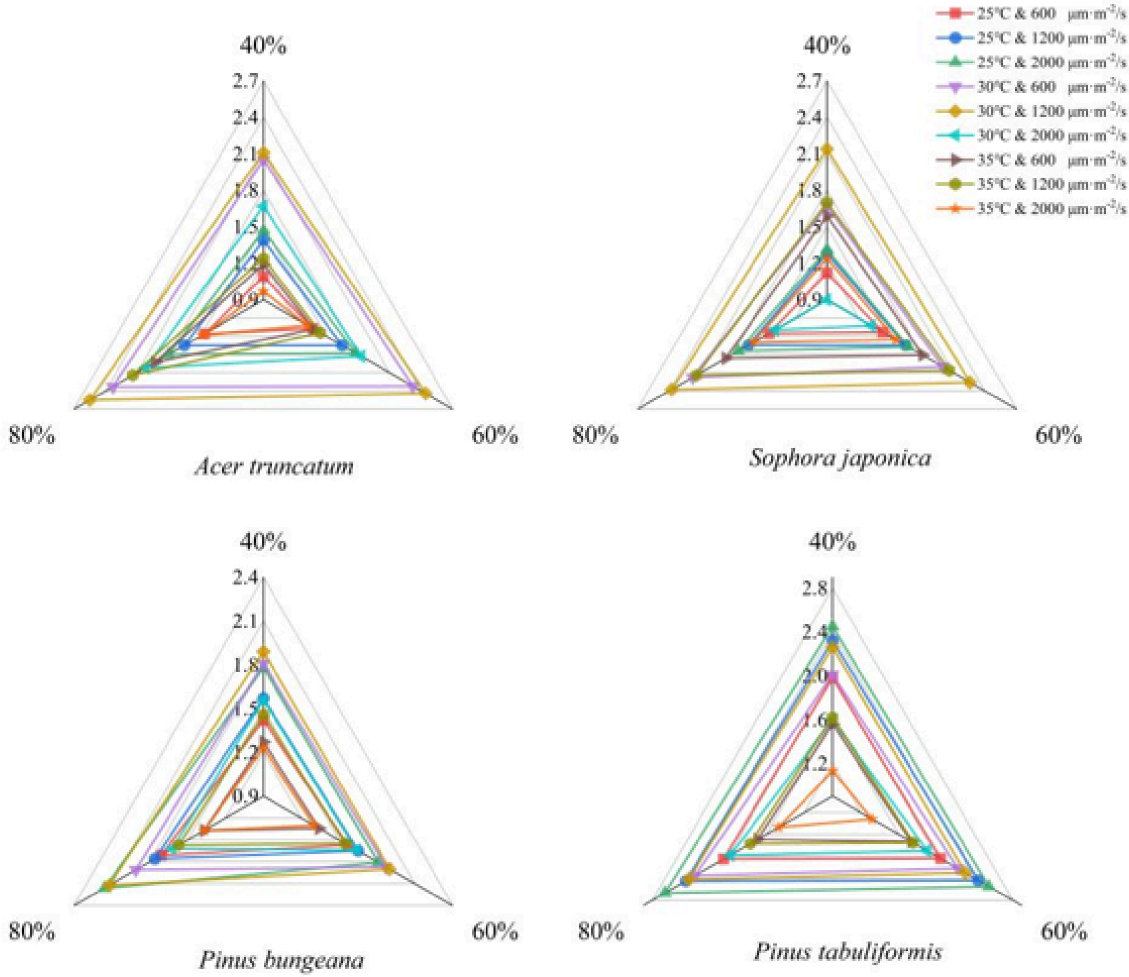

Figure 3

NAI release coefficients of green tree species at different environmental conditions

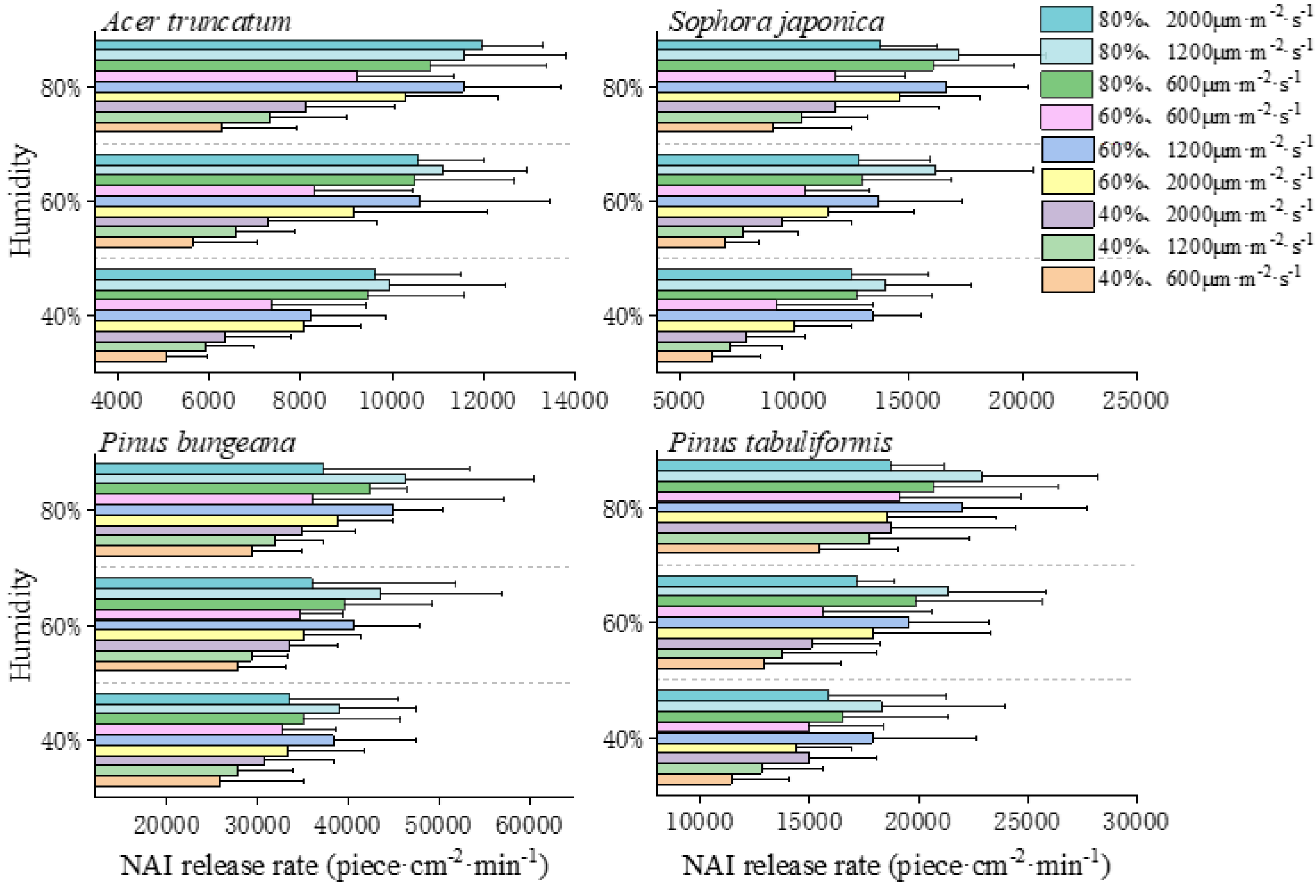

Figure 4

NAI release rate of green tree species under different environmental conditions

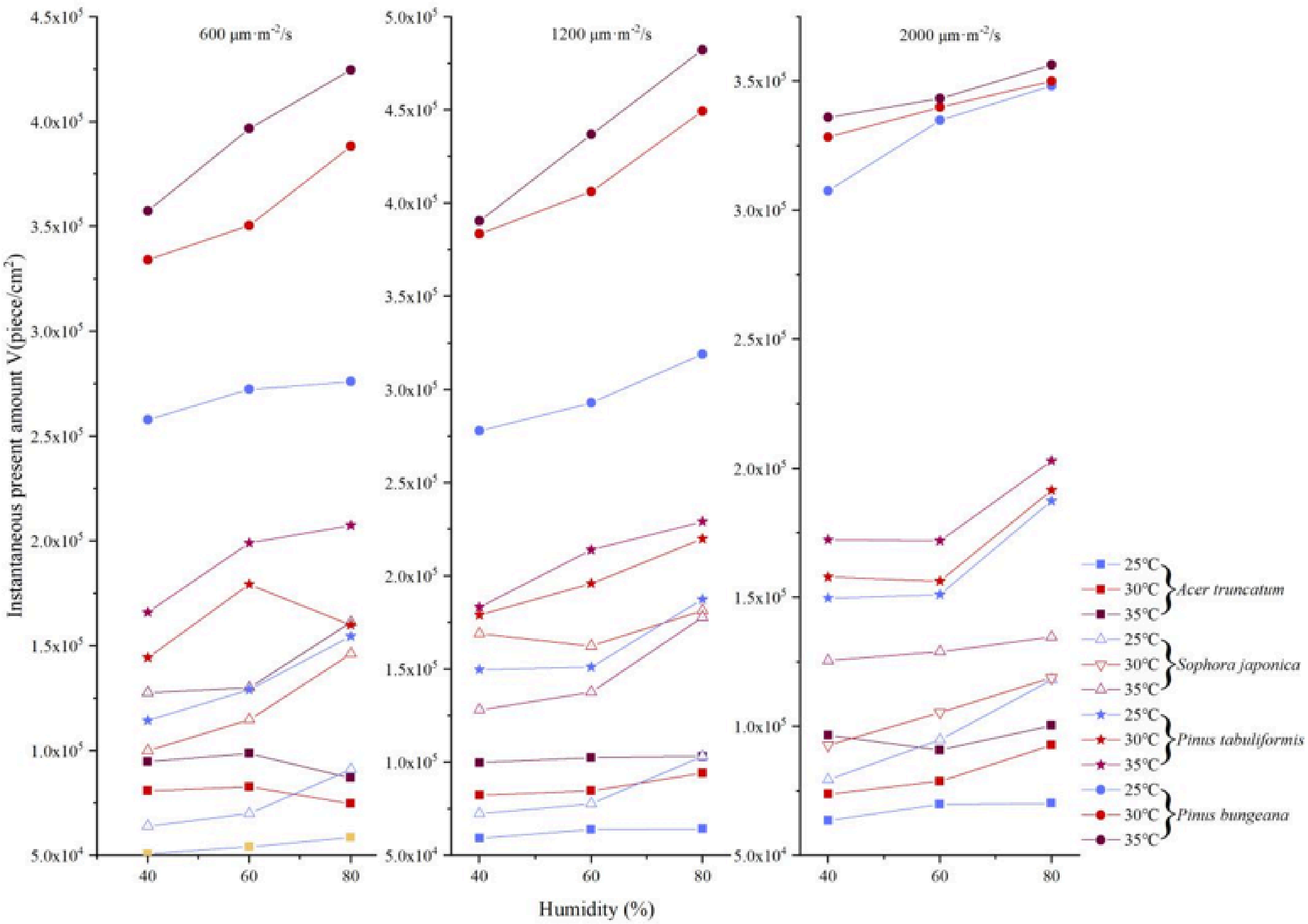

Figure 5

Instantaneous NAI extant of green tree species under different environmental conditions

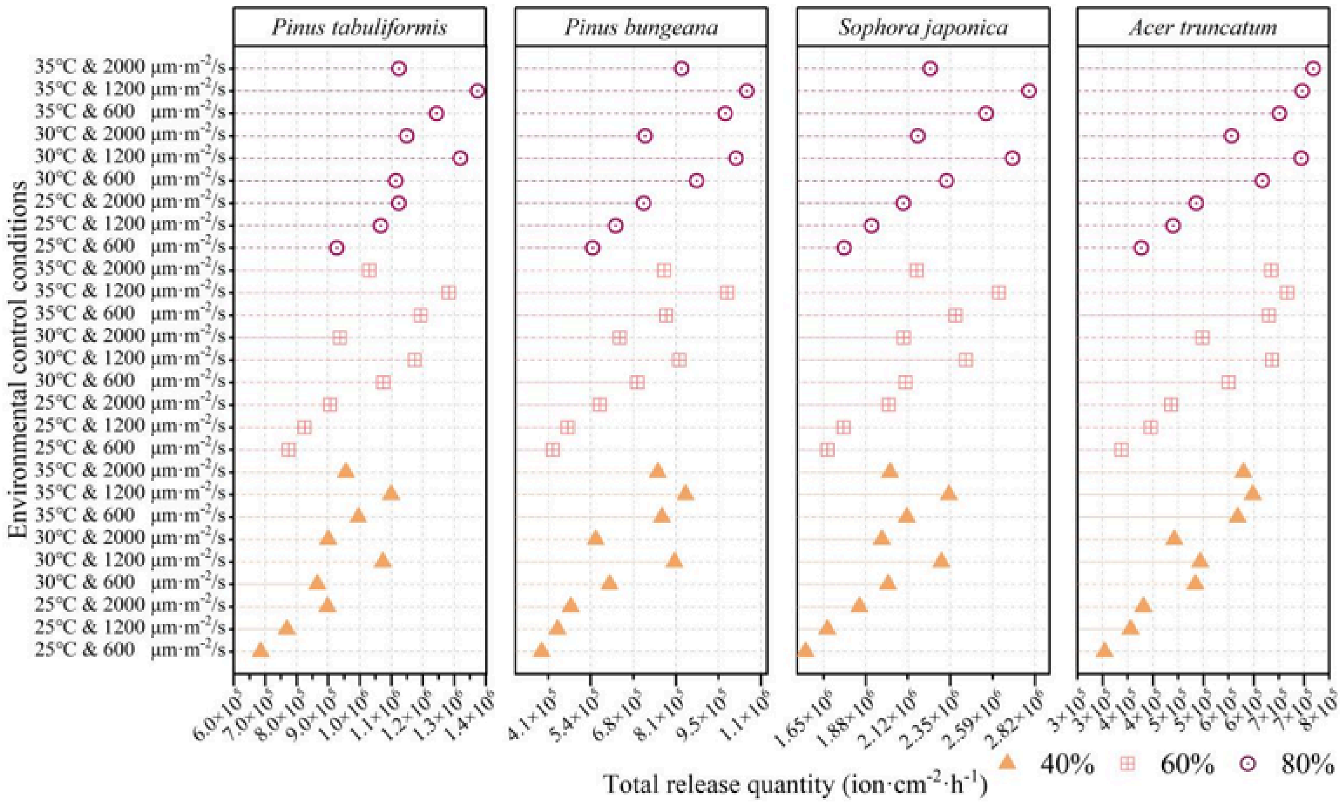

Figure 6

Total NAI released from green tree species under different environmental conditions

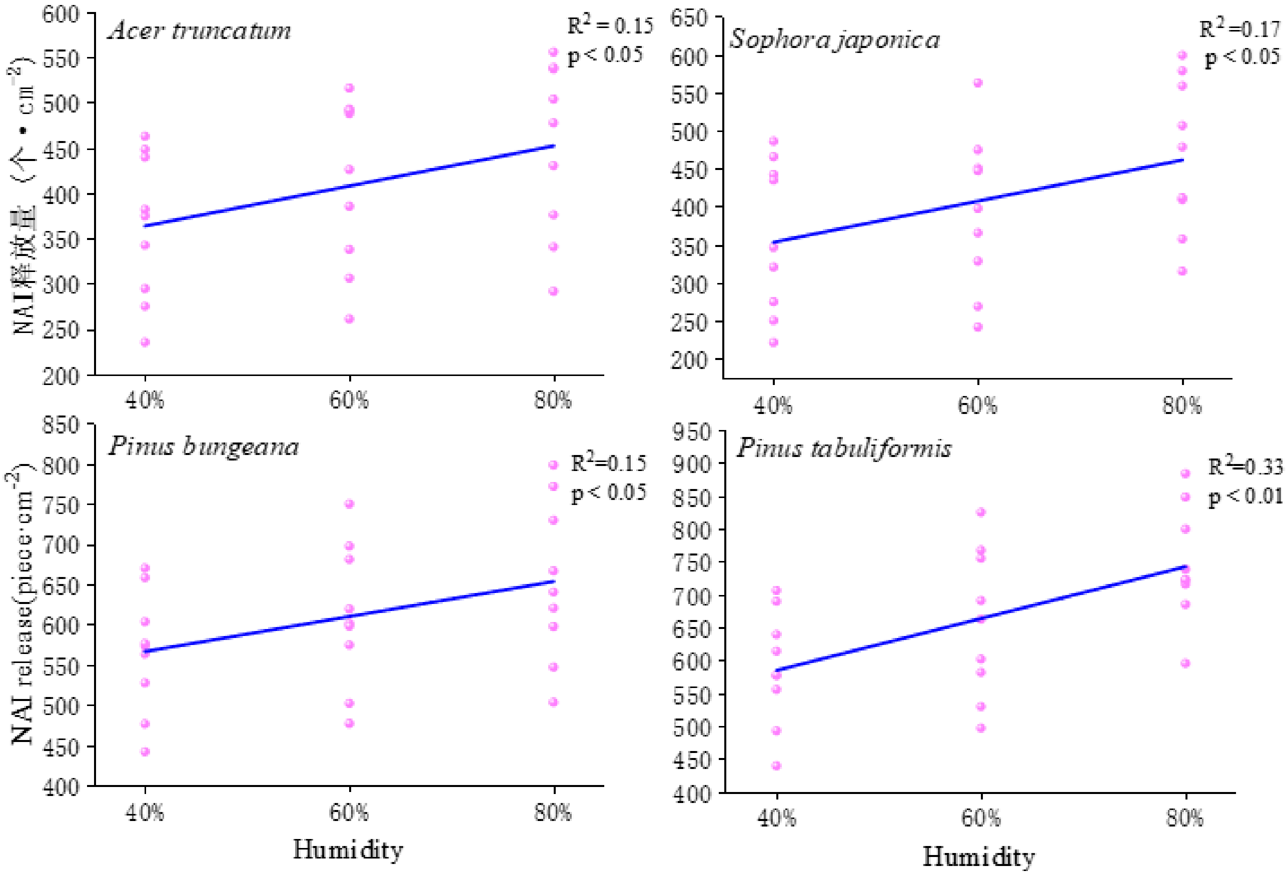

Figure 7

Correlation analysis between NAI release and humidity for different tree species

Supplementary Files

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