

Characterization of the response of Negative Air Ions released by green tree species to temperature based on Open Top Chamber

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Research Article

Keywords: Greening tree species, Temperature, capacity indicators, Negative Air Ions, Open Top Chamber (OTC)

Posted Date: January 9th, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-5769889/v1>

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Additional Declarations: No competing interests reported.

Abstract

This study aimed to investigate the effect of environmental factors on the release of Negative Air Ions (NAI) by various green tree species. An open-top chamber (OTC) control experiment focusing on temperature was conducted using typical gardening tree species found in Beijing, including *Acer truncatum*, *Sophora japonica*, *Pinus bungeana*, and *Pinus tabuliformis*. The effect of temperature on the NAI release ability of green tree species was evaluated using five "capacity indicators": NAI release contribution (L), release coefficient (n), release rate (s), instantaneous present amount (v), and total release amount (Z). The effect of temperature on NAI release was clearly defined. When humidity and light intensity were unchanged, L , n , s , v , and Z tended to increase with the temperature gradient (25°C–35°C), and the five "capacity indicators" peaked when the temperature was 35°C. There was a significant positive correlation between the release of NAI and temperature, in the following order: *Acer truncatum* ($R^2 = 0.84$) > *Sophora japonica* ($R^2 = 0.56$) > *Pinus bungeana* ($R^2 = 0.47$) > *Pinus tabuliformis* ($R^2 = 0.37$). This study elucidates the independent effects of temperature on NAI release in various tree species and provides a scientific basis for tree species allocation, forest health management, and urban green space planning.

1. Introduction

Living in the air-conditioned environment of modern buildings for an extended period can lead to feelings of boredom, depression, dizziness, and poor mental health as well as a decline in work efficiency and health status. This phenomenon is commonly referred to as "urban office building syndrome" (Rueger et al., 1976). These symptoms are closely associated with ambient Negative Air Ions Concentrations (NAIC) in the surroundings. Higher levels of Negative Air Ions (NAI) are associated with greater benefits for the human body. Air quality is a major environmental factor that directly determines human well-being, and in some cases, survival. Therefore, NAI plays a crucial role in the urban environment. NAI can originate from various sources, such as release from the tips of green plant leaves, plant photosynthesis, and the shearing effect of water. Environmental conditions also affect the generation of NAI. An increase in temperature enhances molecular movement, leading to more intermolecular collisions and friction, higher ionization levels of oxygen molecules, and an increased release of NAI. Furthermore, temperature indirectly affects NAI production by enhancing plant photosynthesis, regulating the opening and closing of leaf stomata, and transpiration.

Air temperature is a significant environmental factor that affects NAIC. Some researchers have suggested that a temperature increase can increase the energy of air molecules, promoting molecular collision and ionization, leading to an increase in NAIC (Chen H, 2010; Deng, 2019). NAI is believed to have a brief lifespan in the air (Shao et al., 2000), typically lasting only a few minutes. Air temperature plays a crucial role in the release of NAI by plants (Ling et al., 2010). However, most studies are conducted under field conditions, making it challenging to isolate the effect of temperature on NAIC owing to the combined effects of temperature, humidity, and radiation. Existing research results on temperature and NAI lack a unified conclusion, with some studies presenting contradictory findings.

Therefore, it is necessary to analyze the influence of temperature on the concentration of negative ions in air independently.

Open-Top Chamber (OTC) technology is a semi-closed chamber made of various materials (such as plastic and glass), isolating plants in the box from the external environment to a certain extent. This setup aimed to investigate the effects of environmental changes within the chamber on the physiological and ecological processes of plants. Currently (Zhu B, Chen Y, 2020), this technology is widely used in the study of the relationship between CO₂, O₃, and other gas molecules with plants. It is considered an important means for conducting plant physiological ecology research at community and individual scales (Shang et al., 2018; Lee et al., 2021). Most existing studies rely on field observations, in which data fluctuate significantly and are influenced by numerous environmental factors, making it challenging to analyze the isolated effect of a specific environmental factor alone. Therefore, in this experiment, an open-top box control test was conducted to reduce the interference of human and environmental factors, and the independent effect of temperature on the NAI release of different tree species was analyzed. Currently, control tests are only performed in a single evaluation dimension regarding the ability of environmental factors to release NAI from plants, and it is difficult to determine the extent, manner, and process of influence. In this study, the NAI release contribution L, release coefficient n, release rate s, instantaneous present amount v, and total release amount Z were used to evaluate the effects of environmental factors on the NAI concentration from five perspectives. This study aimed to clarify the response and change thresholds of five "capacity indicators" to temperature, analyze the independent effect of temperature on NAI release by different tree species, and provide a theoretical basis for urban greenspace planning, tree species selection, and configuration.

1. Overview of the study area and research methodology

1.1 General description of the study area

The study area is located at the Institute of Forestry and Pomology, Beijing Academy of Agriculture and Forestry Sciences. It is situated at latitude 39°58 '01" N, longitude 116°13' 02" E, and has a temperate continental monsoon climate. The four seasons are distinct, with significant temperature variations in spring and abundant precipitation in summer. The temperature is pleasant in autumn, and cold and dry in winter. The average annual temperature range is 11.0°C–14.2°C, with the highest temperature reaching 35.1°C–41.9°C, and the lowest dropping to -8.7°C–11.0°C.

1.2 Materials and Methods

1.2.1 Plants materials

Evergreen needle trees (*Pinus tabuliformis* and *Pinus bungeana*) and deciduous broadleaf trees (*Sophora japonica* and *Acer truncatum*) were selected for this study. All these are recommended for

afforestation projects in Beijing. The basic growth status of these trees is presented in Table 1.

Table 1. Basic growth status of each tree species

Species	Family	Tree age/year	Plant height/cm	Diameter/cm	Crown breadth/cm × cm
<i>P. tabuliformis</i>	<i>Pinaceae</i>	2–3	65	0.78	43 × 45
<i>P. bungeana</i>	<i>Pinaceae</i>	2–3	52	0.19	30 × 25
<i>S. japonica</i>	<i>Leguminosae</i>	2–3	109	1.76	48 × 42
<i>A. truncatum</i>	<i>Sapindaceae</i> 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 determined in accordance with the Technical Specifications for the Grade of Negative Air Ions concentrations (LY/T 2586-2016) issued by the National Forestry and Grassland Administration in 2016.

1.2.3 Experiment design

According to the climatic conditions of the growing season in Beijing, the temperature gradient in the OTC was set to 25°C, 30°C, and 35°C; humidity gradients were 40%, 60%, and 80%; the light intensity gradient was 600 $\mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, 1200 $\mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and 2000 $\mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$; and the study was divided into control and experimental groups. The control group was plant-free and the experimental group was plant-filled. The tests were performed at 25°C, 30°C, and 35°C. Six basins of the same tree species were placed in the OTC, the door was closed, the temperature was adjusted to the target value, and the NAI and temperature readings were performed after 30 minutes of adaptation. At the end of the temperature gradient test, the door was opened, the air conditioner was turned off, and the next temperature gradient test was started after 10 minutes in an empty room. At the end of the temperature gradient test, the door was opened, the equipment was closed, the room was emptied for 24 hours, the next batch of tree species was replaced, and the next round of tests was conducted. At the end of the experiment, the test tree was removed, and all leaves were collected. A scanner (Epson V19) and ImageJ software were used to scan and calculate leaf area. The NAI concentration data were downloaded to a computer.

1.3 Test instrument

The experiment was conducted between April and October 2023. As shown in Figure 1, an OTC consists of three main parts: a supporting frame, chamber wall, and base. The entire structure is made of

stainless steel tubes and colorless transparent glass with a layer of electrically insulating polytetrafluoroethylene (PTFE) film pasted on the inside of the OTC chamber wall.

1.4 Capability Indicators

To further clarify the characteristics and differences in the response of NAIs to environmental factors, we examined the independent and multifactorial interactions of environmental variables affecting the release of NAI from various tree species, from different perspectives. The assessment was based on five "capacity indicators": NAI release contribution (L), release coefficient (n), release rate (s), instantaneous present amount (v), and total release amount (Z) representing a plant's ability to release NAI. As a unified and comparative evaluation criterion, controlled experiments were conducted using OTC to analyze the NAI release ability and the variations among the five indicators from the perspective of the contribution of NAI released by the plant, the ability to release NAI instantly, the rate of NAI release (quickly or slowly), the effect of the release of NAI at a certain time point, and the total amount of NAI released during a certain period.

Indicator model and parameters

(1) The NAI release contribution rate (L) refers to the percentage of the number of NAI released by plants in the total number of NAI within a certain period, that is, the contribution of plants to the total NAIC. The calculation formula is as follows.

$$\text{Release contribution rate: } L = (G_{\text{Treat}} - G_{\text{CK}}) / G_{\text{Treat}} \times 100\%. \quad \text{Eq. (1)}$$

where L is the contribution rate of plant release (%) and G_{Treat} is the mean NAIC ($\text{piece} \cdot \text{cm}^{-3}$) in the plant group. G_{CK} is the average NAIC ($\text{piece} \cdot \text{cm}^{-3}$) in the control group without plants.

(2) The NAI release coefficient (n) refers to the ratio of the number of NAI released by plants to the number of blank control groups without plants within a certain period, which is an indicator of the ability of plants to release NAI immediately. The calculation formula is as follows.

$$\text{Release coefficient: } n = (G_{\text{Treat}} - G_{\text{CK}}) / G_{\text{CK}} \quad \text{Eq.}$$

where n represents the NAI release coefficient.

(3) The NAI release rate (s) refers to the number of NAI increases per unit leaf area within a unit of time, representing the speed and intensity of NAI release by plants. The calculation formula is as follows:

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

where s is the NAI release rate ($\text{piece} \cdot \text{cm}^{-2} \cdot \text{min}^{-1}$), V is the OTC volume (cm^3), S_a is the leaf area (cm^2), and t_{survival} is the survival time of NAI in the air (min). t_{survival} was uniformly taken as 10 minutes,

according to 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 of leaf area and the number in the blank control group without plants, which is an index to determine the effect of plant release at a certain moment.

Instantaneous stock on hand: $V = (G_{\text{Treat}} - G_{\text{CK}}) \times V / S_a$ Eq. (4)

where v is the NAI instantaneous present volume ($\text{piece} \cdot \text{cm}^{-2}$) and S_a is leaf area (cm^2).

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

Total Release: $Z = (G_{\text{Treat}} - G_{\text{CK}}) \times V \times T_{\text{Total}} / (t_{\text{Survival}} \times \text{LAI} \times S_a)$ Eq.(5)

Z is the number of NAI provided by the plant per unit of leaf area during that period ($\text{piece} \cdot \text{cm}^{-2} \cdot \text{h}^{-1}$), and T_{total} is the period of time (minutes) because the negative ion monitoring test lasts for 30 minutes and the $T_{\text{presidential}}$ is equivalent to 30 minutes.

2. Results and analysis

2.1 NAI release contribution (L)

As shown in Figure 2, the relationship between the NAI release contribution (L) of each tree species and temperature was explored under different humidity and light intensity conditions. Overall, with an increase in temperature, the release contribution rate L of the four afforestation tree species exhibited an increasing trend. When the temperature was 35°C , the release contribution rate L was the highest, with a greater number of conifer species than broadleaf species.

When the humidity was 40%, the change in light intensity affected the release contribution rate L , and the release contribution rate L also increased with the increase in light intensity. When the light intensity was $600 \mu\text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, with an increase in the temperature gradient ($25^\circ\text{C} - 35^\circ\text{C}$), the release contribution rate L of broadleaf tree species was 15.46%, which was twice that of conifer species (6.75%). At a light intensity of $1200 \mu\text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, the growth rates of broad-leaved and conifer species were 7.34% and 6.18%, respectively. In contrast, when the light intensity was $2000 \mu\text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, the contribution rate of broadleaf species increased significantly (8.17%) compared with that of conifer species (3.49%).

When humidity was 60%, the release contribution rate L of broadleaf species (57.48%) increased by approximately twice that of conifer species (32.84%) with an increase in temperature under different light intensity changes. Compared with the 40% humidity condition (90.32%), the rate of increase (60.58%) was significantly lower, and the decrease in broadleaf species (26.45%) was approximately

seven times that of conifer species (3.30%). The results showed that broadleaf species were more responsive and susceptible to temperature increases.

When the humidity was 80%, an increase in temperature under different light intensity conditions resulted in a significantly higher release contribution rate L (41.15%) of broadleaf species than that of conifer species (27.96%). The rate of increase (69.11%) was significantly lower than that in the 40% humidity condition (90.32%), and the decrease rate of broadleaf species (16.33%) was four times that of conifer species (4.88%). Compared with 60% humidity, the variation in broadleaf species (10.12%) was approximately 10 times higher than that in conifer species (1.58%). Overall, the variation in broadleaf species (26.45%) was approximately four times that of conifer species (6.47%), indicating that broadleaf species had a more pronounced response to temperature increase and a higher sensitivity to temperature change than coniferous tree species.

In summary, as temperature increased, the release contribution rate L of broadleaf species (129.66%) was significantly higher than that of conifer species (90.34%).

2.2 NAI release coefficients (n)

As shown in Fig. 3, the relationship between the NAI release coefficients (n) and temperature remained consistent for each green tree species under different humidity and light intensity conditions. Overall, with increasing temperature, the NAI release coefficients (n) of all four green tree species showed an increasing trend. At 35°C, the coefficient reached its peak, and the total number of conifer species was significantly higher than that of the broadleaf species.

At 40% humidity, changes in light intensity affected the NAI release coefficient n, which increased with increasing light intensity. At a light intensity of $600 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the increase was significantly greater for broad-leaved tree species (1.68) than for coniferous species (1.02) as the temperature gradient (25°C–35 °C) increased. The conifer species increased (1.05) compared with broadleaf species (0.96) when the light intensity was $1200 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and the increase in broadleaf species (1.06) was significantly greater than that in conifer species (0.71) when the light intensity was $2000 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

At 60% humidity, the increase in the NAI release coefficient n was significantly greater for conifer species (2.61) than for road-leaved tree species (1.50) under different light intensities as the temperature increased. The increase (4.11) was significantly lower than that at 40% humidity (6.49), with broad-leaved tree species decreasing (2.21) 12 times more than conifer species (0.17).

At 80% humidity, the broadleaf species NAI release coefficient increased more (2.17) than that of conifer species (1.88) with increasing temperature and under different light intensity conditions. Compared with 40% humidity, the amount of change in broadleaf species (1.53) was approximately 1.6 times greater than that in conifer species (0.90). Compared with 60% humidity, the amount of change in broadleaf

species (0.68) was not significantly different from that in conifer species (0.73), indicating that broadleaf species exhibited a more pronounced response to temperature.

The NAI release coefficient exhibited the greatest increase in response to the temperature gradient under different environmental conditions for the different tree species. *A. truncatum* and *P. tabuliformis* demonstrated the highest increase (1 and 0.70, respectively) at 40% humidity and $600 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ light intensity. *S. japonica* exhibited the greatest increase (0.78) at 40% humidity and $1,200 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ light intensity. In contrast, *Pinus bungeana* exhibited the greatest increase (0.51) at 60% humidity and *Pinus bungeana* increased the most (0.51) at 60% humidity and $600 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ light intensity.

In summary, the NAI release coefficient n exhibited a significant difference between the conifer species (102.62) and broadleaf species (73.20). However, the increase was slightly higher in broadleaf species (7.38) than in conifer species (7.28). Broadleaf species demonstrated the most pronounced response to temperature at 40% humidity and $600 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ light intensity, whereas conifer species exhibited the most significant response to temperature at 60% humidity and $1200 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ light intensity.

2.3 NAI release rate (s)

As shown in Figure 4, the relationship between the NAI release rate (**s**) of each tree species and temperature differed under different humidity and light intensity conditions. Overall, with increasing temperature, the NAI release rate (**s**) exhibited an increasing trend, with the most significant increase observed at 25°C and 30°C. The NAI release rate (**s**) of the conifer species was significantly higher than that of the broadleaf species.

When humidity was 40%, the change in light intensity affected the NAI release rate (**s**) of green tree species. The NAI release rate (**s**) continued to increase with an increase in light intensity. As the temperature increased at a light intensity of $600 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the NAI release rate (**s**) of broadleaf species increased by 93%, which was twice that of conifer species (41%). When the light intensity was $1200 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the growth rate of the broad-leaved tree species (101%) was 2.4 times higher than that of the conifer species (42%). Notably, *S. japonica* exhibited the most significant increase in the growth rate, reaching 133%. At a light intensity of $2000 \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the growth rate decreased significantly. However, the growth rate of the broadleaf tree species (55%) was approximately seven times higher than that of the conifer species (8%), with *P. tabuliformis* showing the lowest growth rate of only 7%.

Under 60% humidity, with an increase in temperature and different light intensities, the NAI release rate (**s**) of broadleaf tree species (403.73%) increased by 1.8 times that of conifer species (220.77%). Compared with 40% humidity, the growth rate decreased by 64.90%, and the growth rate of conifer species (158.29%) was approximately 1.6 times higher than that of broadleaf trees (93.96%).

Under 80% humidity and different light intensities, with an increase in temperature, the NAI release rate (**s**) (318.44%) of broadleaf species increased twice as fast as that of conifer species (168.73%).

Compared with 60% humidity, the variation in broadleaf trees (85.29%) was twice that of the conifer species (42.03%). Compared with 40% humidity, the variations in the broadleaf and conifer species were very similar, at 179.25% and 200.32%, respectively. These results indicated that broadleaf trees were more sensitive to temperature changes and that the NAI release rate was easily affected by temperature.

In conclusion, with an increase in the temperature gradient, the NAI release rate (**s**) of conifer species ($1,419,900 \pm 349,600 \cdot \text{cm}^{-2} \cdot \text{min}^{-1}$) was significantly higher than that of broadleaf species ($537,900 \pm 135,500 \cdot \text{cm}^{-2} \cdot \text{min}^{-1}$). However, the NAI release rate of broadleaf species (1172.49%) was approximately twice that of the conifer species (566.57%).

The release rate of NAI in broadleaf species (1172.49%) was approximately twice that of conifer species (566.57%). Specifically, at 40% humidity and $1200 \mu\text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ light intensity, the release rate of broadleaf species exhibited the strongest response to temperature increases, with a growth rate of 101%. Conversely, at 60% and the same light intensity, conifer species demonstrated a stronger response to temperature, resulting in a 52% growth rate increase. This finding indicated that the NAI release rate of broadleaf species was more sensitive to temperature variation than that of conifer species, making them more susceptible to temperature fluctuations. Although conifer species exhibited strong adaptability to temperature changes, their NAI release ability was much higher than that of broadleaf species.

2.4 NAI instantaneous present amount (v)

As shown in Fig. 5, the relationship between the NAI instantaneous present amount (v) and temperature was explored for each tree species under different humidity and light intensity conditions. Overall, with an increase in temperature, the NAI instantaneous present amount (v) of the four greening tree species exhibited an increasing trend, peaking at 35 °C. The NAI of each greening tree species was higher than that of the other greening tree species, indicating significant differences among the greening tree species.

When the humidity was constant, the NAI instantaneous present amount (v) increased with an increase in the light intensity. When humidity was 40% and light intensity was $600 \mu\text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, with an increase in temperature, the NAI instantaneous present amount (v) growth rate of broadleaf species (186.02%) was approximately 2.2 times higher than that of conifer species (83.79%). When the light intensity was $1200 \mu\text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, the growth rate of the broadleaf species (201.54%) was much higher than that of the conifer species (83.52%). At $2000 \mu\text{m} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ light intensity, the growth rate of broadleaf species (110.13%) was approximately five times higher than that of conifer species (24.40%).

When humidity was 80%, as the temperature increased, the rate of increase in NAI instantaneous present amount (v) growth of broadleaf species (531.64%) was significantly higher than that of conifer species (293.15%) under the different light intensity conditions. Compared with 60% humidity, the decrease in growth of broadleaf species (85.29%) was twice that of conifer species (42.03%); compared with 40% humidity, the difference was very significant, with a decline of 192.22%, and the broadleaf species

reduction (179.25%) was 14 times higher than that of conifer species (12.97%). This finding indicated that the increase in light intensity and temperature leads to the inhibition of photosynthesis and a decrease in the NAI release ability of plants, with broadleaf species experiencing a more pronounced effect than conifer species.

At 35°C, the four green tree species reached the maximum value of NAI instantaneous present amount (v). Among them, *P. bungeana* had the highest value ($482,200 \cdot \text{m}^{-2}$), whereas *A. truncatume* had the lowest ($87,000 \cdot \text{m}^{-2}$).

In conclusion, with an increase in temperature, the NAI instantaneous present amount (v) ($1,419,900 \pm 101,500 \cdot \text{m}^{-2}$) of conifer species was significantly higher than that of broadleaf species ($537,900 \pm 32,100 \cdot \text{m}^{-2}$). However, the growth rate of the broadleaf species (318.44%) was significantly higher than that of the conifer species (178.74%). The results showed that the NAI release capacity of conifer species was much greater than that of broadleaf species; however, broadleaf species were more responsive and susceptible to temperature changes.

2.5 NAI total release amount (Z)

As shown in Figure 6, the correlation between the NAI total release amount Z of each tree species and temperature was explored under different humidity and light intensity conditions. Overall, with an increase in temperature, the NAI total release amount Z showed an increasing trend, with the most pronounced increase observed at temperatures of 25°C and 30°C. Between 30°C and 35°C, the increasing trend remained relatively stable, and the total release Z of the conifer species was greater than that of the broadleaf species.

When the humidity was 40%, the change in light intensity affected the NAI total release amount Z. As the temperature gradient increased (25°C–35 °C), the fluctuation range of broadleaf species ($99,200\text{--}289,700 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) was much smaller than that of conifer species ($68,800\text{--}337,800 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) under different light intensity conditions.

When humidity was 60%, with an increase in temperature, the NAI total release amount Z of broadleaf and conifer species fluctuated significantly under different light intensities, ranging from $63,300$ to $253,800 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ and $25,600$ to $373,100 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, respectively. Compared with 40% humidity, the fluctuation amplitude increased ($25,600,000\text{--}431,700 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$), and the fluctuation amplitude of conifer species ($25,600,000\text{--}373,100 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) increased by approximately 2.1 times as much as that of broadleaf species ($99,200\text{--}253800 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$).

When the humidity was 80%, with an increase in temperature, the NAI total release amount Z fluctuation amplitude of conifer species ($49,500\text{--}234,400 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) was approximately 2.5 times higher than that of broadleaf species ($24,100 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) under different light intensities. Compared with 60% humidity, the

fluctuation range of conifer species ($25,600,000\text{--}373,100\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) was 2.8 times that of broadleaf species ($99,200\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). Compared with 40% humidity, the difference was most significant, and the fluctuation amplitude of conifer species ($68,000\text{--}337,80\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) was approximately 35 times higher than that of broadleaf species ($99,20\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). The results showed that with an increase in temperature, the NAI release capacity of conifer species was much higher than that of broadleaf species.

In conclusion, with the increase in temperature gradient, the fluctuation range of the NAI total release amount Z of conifer species ($343,300\text{--}1,394,300\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) was significantly higher than that of broadleaf species ($152,200\text{--}517,900\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). The NAI total release amount Z of the conifer species ($42,598,400 \pm 10,486,900\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) was 2.6 times higher than that of the broadleaf species ($16,136,100 \pm 4,0664,500\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). Notably, under conditions of 40% humidity and $1200\ \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ light intensity, the NAI total release amount Z released by broadleaf species exhibited the most significant response to temperature increase, showing a range of $217,200\text{--}506,800\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. Conversely, conifer species at 80% humidity and $1200\ \mu\text{m}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ light intensity demonstrated the strongest response to temperature increases ($828,100\text{--}127.3,900\cdot\text{m}^{-2}\cdot\text{h}^{-1}$).

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

When humidity and light intensity remained constant, the five "capability indicators" exhibited an increasing trend with increasing temperature. The response pattern to temperature was consistent across the release contribution rate L , release coefficient n , release rate s , instantaneous present amount v , and total release amount Z . These indicators showed the most significant response to temperature within the range of $25^{\circ}\text{C}\text{--}30^{\circ}\text{C}$. In this temperature range, the five "capacity indicators" exhibited the most significant increases. The response of the five "capacity indicators" to temperature varied, with the NAI total release amount Z , release rate s , and instantaneous present amount v being the most responsive to temperature, whereas release coefficient n and release contribution rate L had the weakest temperature response.

The responses of the five "ability indicators" to temperature varied among the four afforestation species. *A. truncatum* showed the most significant increase in the release contribution rate L with increasing temperature. *S. japonica* exhibited the most significant response to temperature in terms of release coefficient n , total release Z , release contribution rate L , and instantaneous present amount v .

As shown in Figure 7, the NAI released from each tree species was positively correlated with the temperature gradient. However, the correlation coefficients varied among tree species. The magnitude of the correlation between the NAI release and temperature for the four green tree species was ranked as follows: *A. truncatum* ($R^2 = 0.84$) $\gg$ *S. japonica* ($R^2 = 0.56$) $\gg$ *P. bungeana* ($R^2 = 0.47$) $\gg$ *P. tabuliformis* ($R^2 = 0.37$). The correlation with temperature was more pronounced for broadleaf species than for conifer

species, indicating that NAI released from broadleaf species is more responsive to variations in temperature and more susceptible to temperature variations.

3. Discussion

3.1 Positive response of the five "capacity indicators" to temperature

Based on the controlled conditions of temperature, humidity, and light intensity in the OTC, different green tree species exhibited varying responses to temperature changes in terms of the NAIC. Under consistent humidity and light intensity conditions, as temperature increased, the NAIC of the four tree species followed a distinct pattern. Conifer species, such as *P. tabuliformis* and *P. bungeana* exhibited higher NAIC levels compared with the broadleaf species, *A. truncatum* and *S. japonica*. The conifer species demonstrated a stronger ability to release NAI and were more sensitive to environmental change. This difference may be attributed to the significantly larger number of leaf tips in conifer species than in broadleaf species. A higher number of leaf tips in conifers provided more channels for electron release. In addition, the smaller radius of curvature of coniferous leaf blades enhances the generation of plasma for air ionization through tip discharge, as highlighted by Du et al. (2018), leading to the production of higher NAI levels.

With an increase in the temperature gradient, the NAIC of green tree species showed a trend of continuous increase. The NAIC of the four greening tree species was ranked as follows: needle *P. bungeana* > *P. tabuliformis* > *S. japonica* > *A. truncatum*. The highest NAIC value was recorded at 35 °C. The production of NAI in plants occurs through tip discharges in the canopy, branches, and leaves, as well as through the photoelectric effect of photosynthesis (Shan et al., 2015; Qi et al., 2011). Temperature plays a direct role in influencing plant enzyme activity; as the temperature increases, photosynthesis of the plants increases, leading to the release of more oxygen that combines with free electrons in the air, consequently producing a large amount of NAI. The increase in temperature also increases the speed of intermolecular movement and the possibility of intermolecular collisions, which intensifies air intermolecular friction and significantly elevates the ionization level of oxygen molecules, thereby leading to a significant increase in NAI emission (Zhu S et al., 2023). The hydraulic conductivity of conifer species was higher than that of broadleaf trees, and a positive correlation was observed between hydraulic conductivity and photosynthetic strength, which is consistent with the results of Jingshuo et al. (2021). Therefore, conifer species demonstrate a stronger ability to release NAI than broadleaf species.

3.2 Differences in the temperature response of the five "capacity indicators"

In an OTC with controlled environmental factors, under consistent levels of humidity and light intensity, the five "capacity indicators" of broadleaf species exhibited a more pronounced response to temperature variation than that of conifer species as the temperature increased. This discrepancy can be attributed to

the process by which plant leaves generate oxygen through photosynthesis, which is a reaction that involves the combination of oxygen with free electrons in the atmosphere to form NAIs. The amount of oxygen released is closely related to the number of stomata on the leaf surface, with broadleaf species typically possessing a larger leaf area and more stomata than conifer species. As temperature increases, there is a significant enhancement in leaf photosynthesis, resulting in the production of more oxygen, which indirectly enhances the concentration of negative ions in the air.

Therefore, the five "capacity indicators" of the broadleaf species responded more strongly to temperature. The leaves of conifer species have small needle-like leaves with an oil layer, which weakens transpiration and respiration. With an increase in temperature, photosynthesis is weakened. Compared with broadleaf species, conifer species exhibit slower photosynthesis, organic matter conversion, and transportation. Consequently, their development is slower and their physiological and biochemical activities are affected. This is why broadleaf species are able to release anions in response to temperature changes. This difference explains why broadleaf species release NAIs to a greater extent in response to temperature changes.

4. Conclusion

(1) Consistency in temperature response across the five "capability indicators"

Under conditions of consistent humidity and light intensity, the NAI release contribution L , release coefficient n , release rate s , instantaneous present amount v , and total release amount Z all showed a positive response to temperature. That is, with an increase in temperature, the five "capability indicators" exhibited an increasing trend. When the temperature reached 35°C, the NAI release capacity of green tree species was the strongest, and the release capacity of the conifer species was greater than that of broadleaf species. These five "capacity indicators" can serve as a good evaluation of plants' ability to release NAIs. Urban plant configurations, parks, residential areas, and other recreational areas should consider planting more coniferous species.

(2) Temperature was positively correlated with NAI release from green tree species.

As the temperature gradient increased, the NAI release and temperature showed highly significant positive correlations. However, the magnitude of the correlations varied: *A. truncatum* ($R^2 = 0.84$) $\gg$ *S. japonica* ($R^2 = 0.56$) $\gg$ *P. bungeana* ($R^2 = 0.47$) $\gg$ *P. tabuliformis* ($R^2 = 0.37$).

Declarations

Funding

This work was supported by National Natural Science Foundation of China (32171844), the Funding Projects of National Forestry and Grassland Administration (2023132047).

Author Contribution

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, M.C. and X.L.; methodology, X.L.; software, X.L.; validation, X.X., N.Z. and S.L.; formal analysis, X.L.; investigation, M.C.; resources, S.L.; data curation, M.C. and X.L.; writing—original draft preparation, M.C.; writing—review and editing, X.X.; visualization, X.L.; supervision, X.X.; project administration, S.L.; funding acquisition, S.L. and S.L. All authors have read and agreed to the published version of the manuscript.”

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Figures

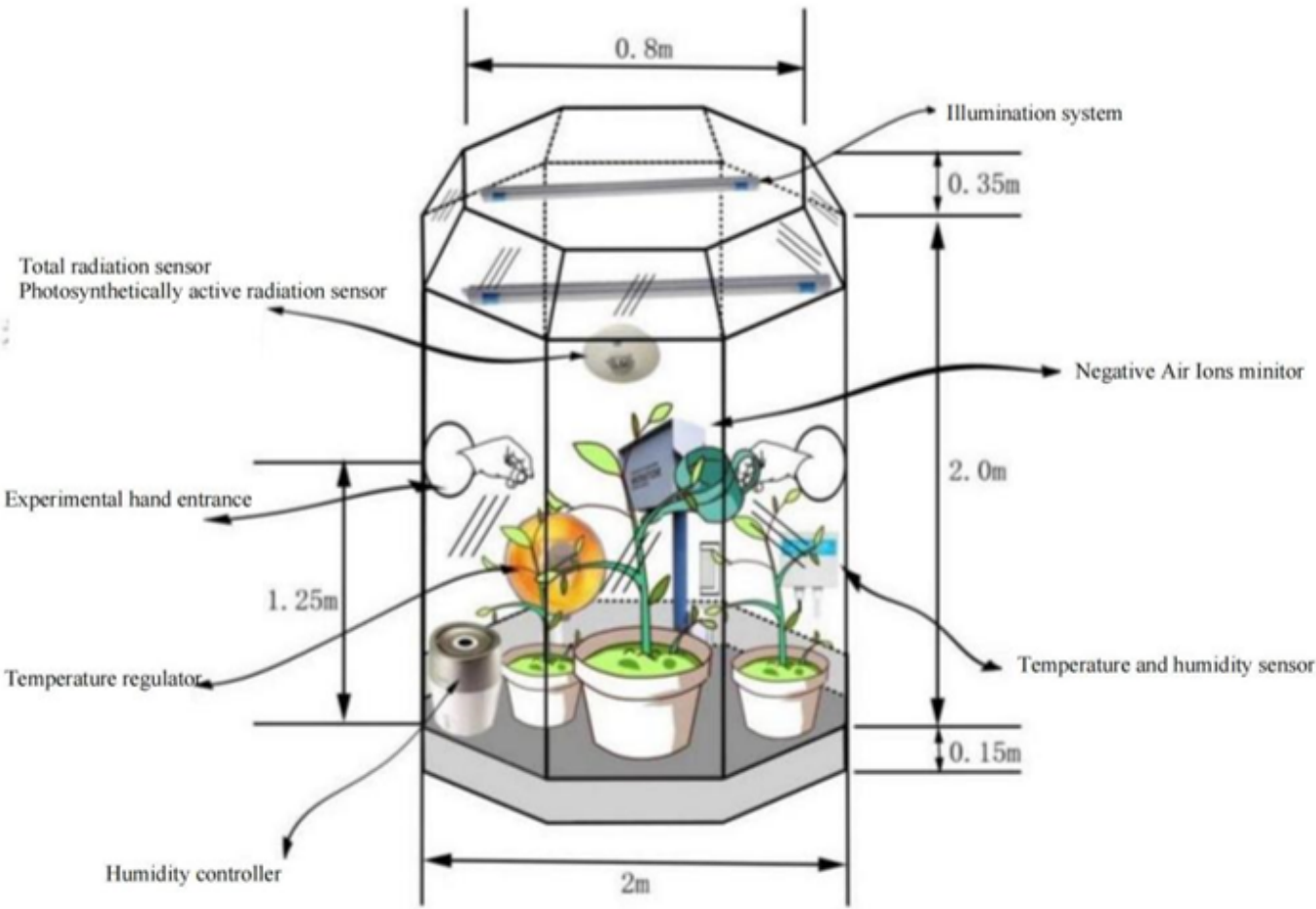


Figure 1

OTC schematic diagram

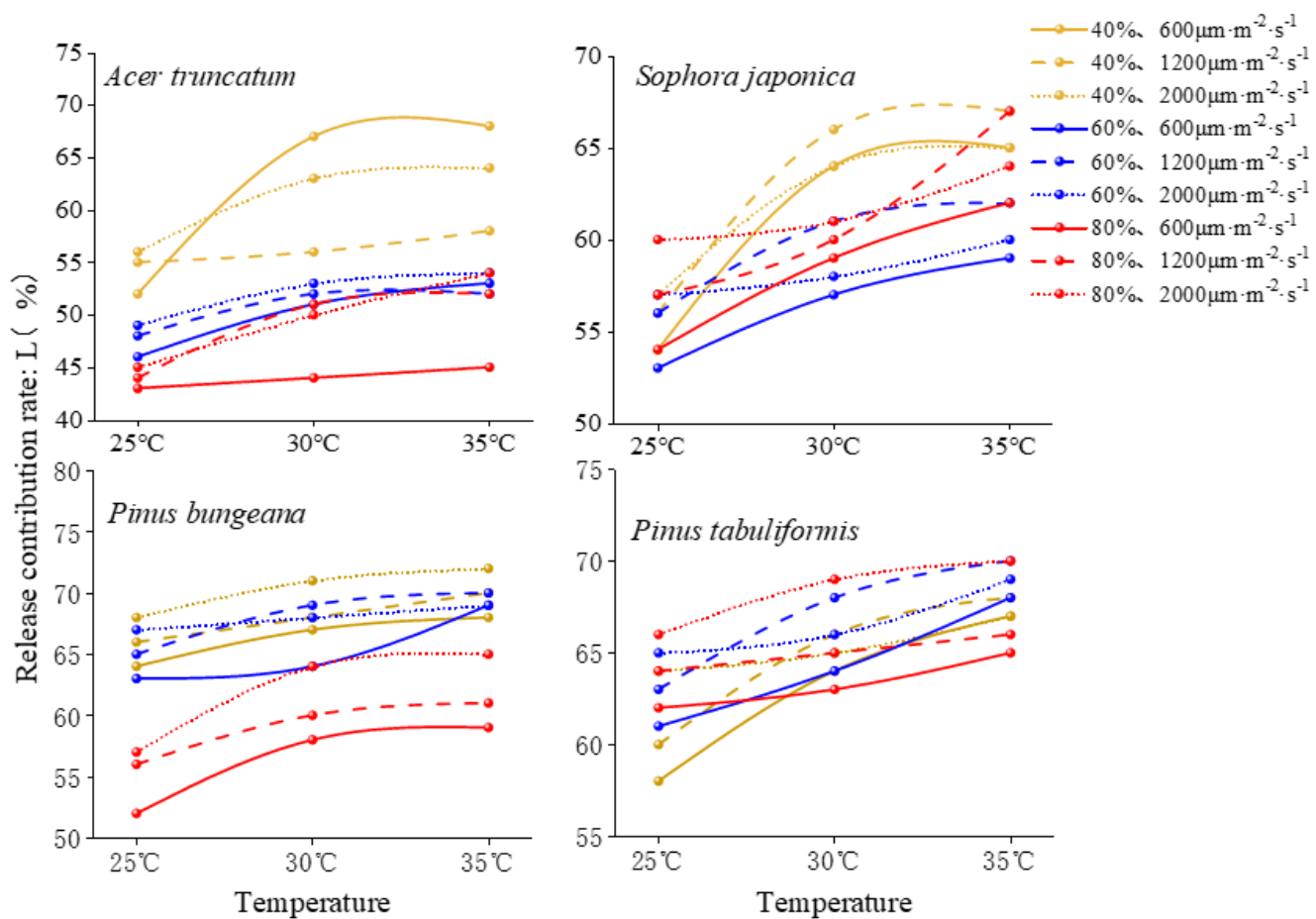


Figure 2

Contribution of plant NAI release under different environmental conditions

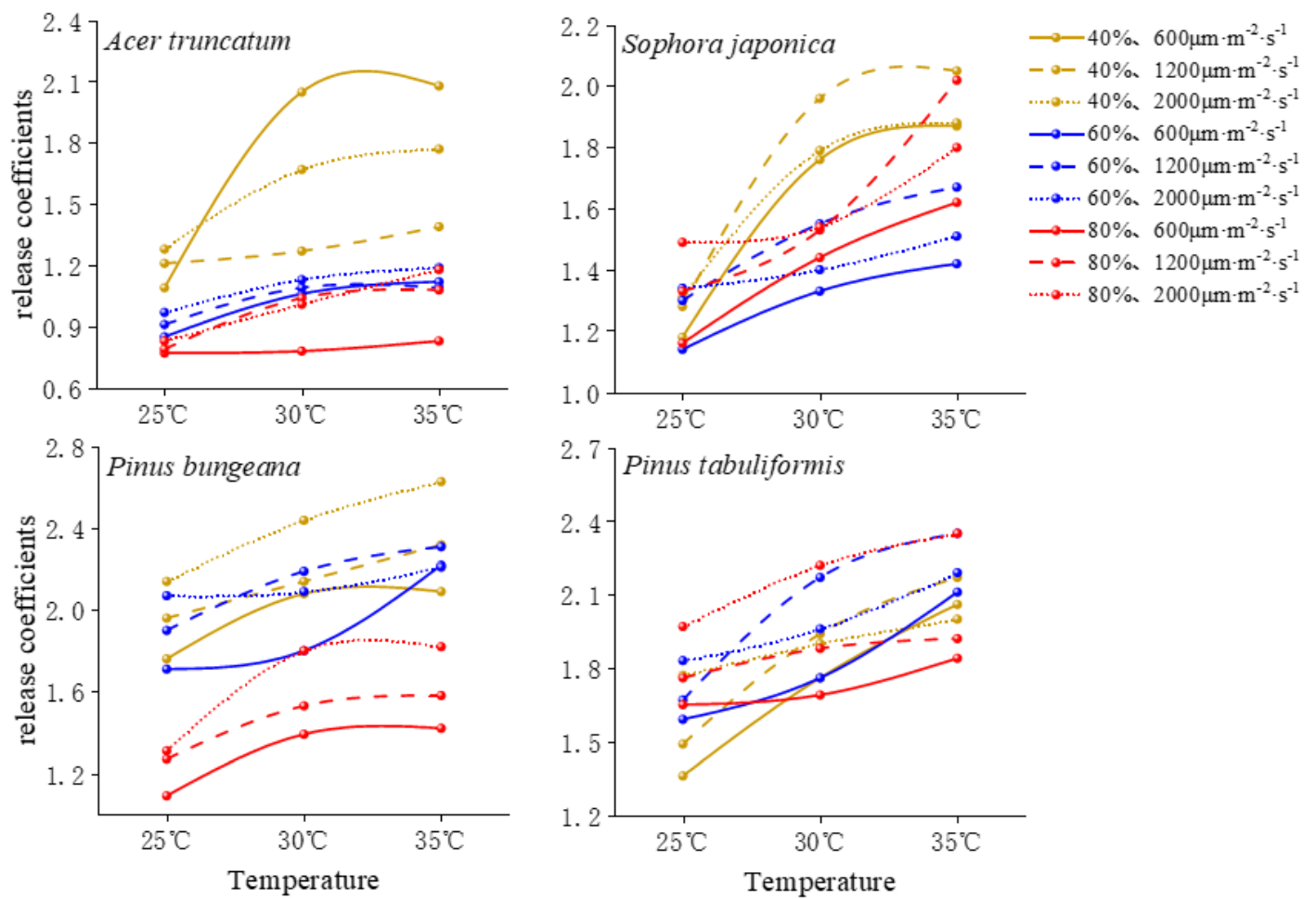


Figure 3

Plant NAI release coefficients under different environmental conditions

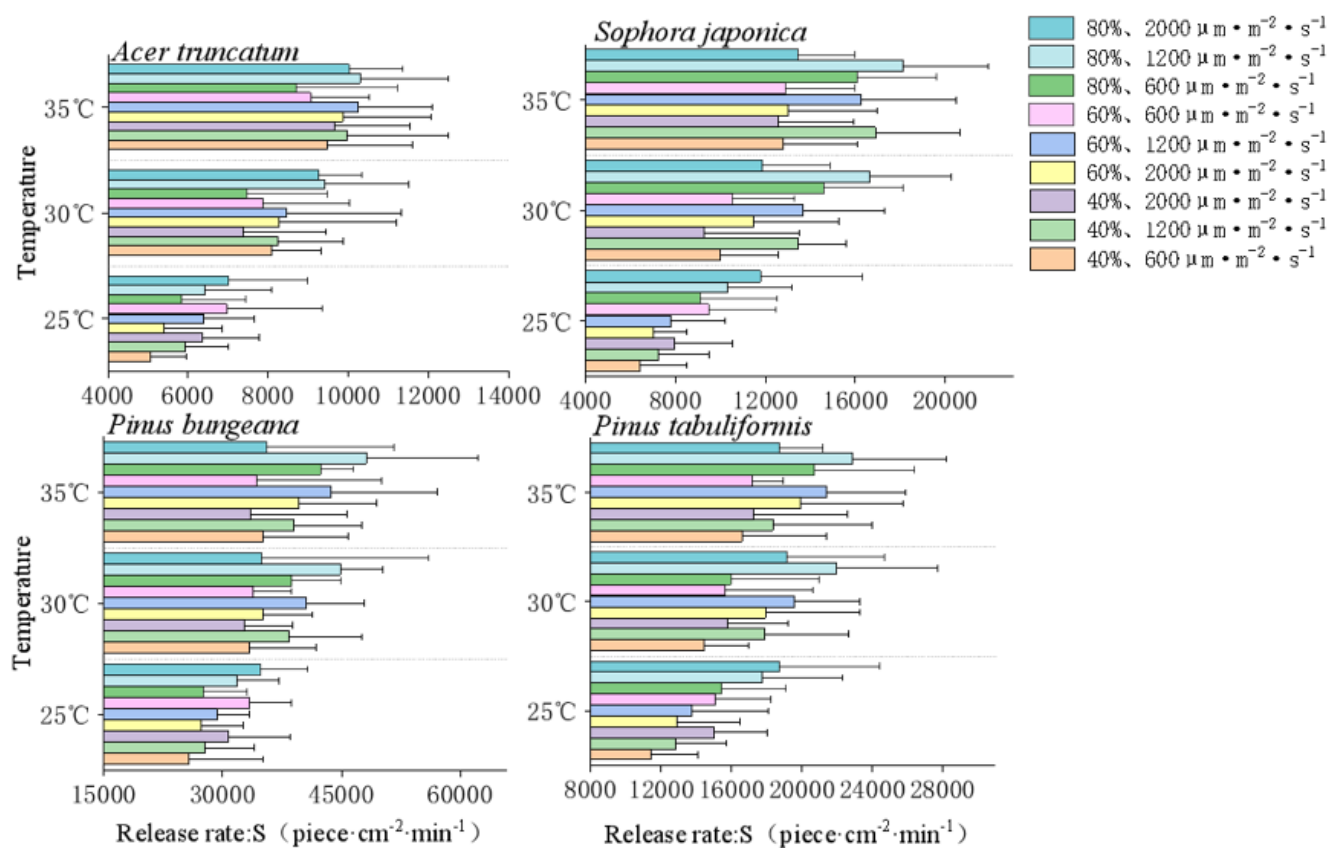


Figure 4

Plant NAI release rates under different environmental conditions

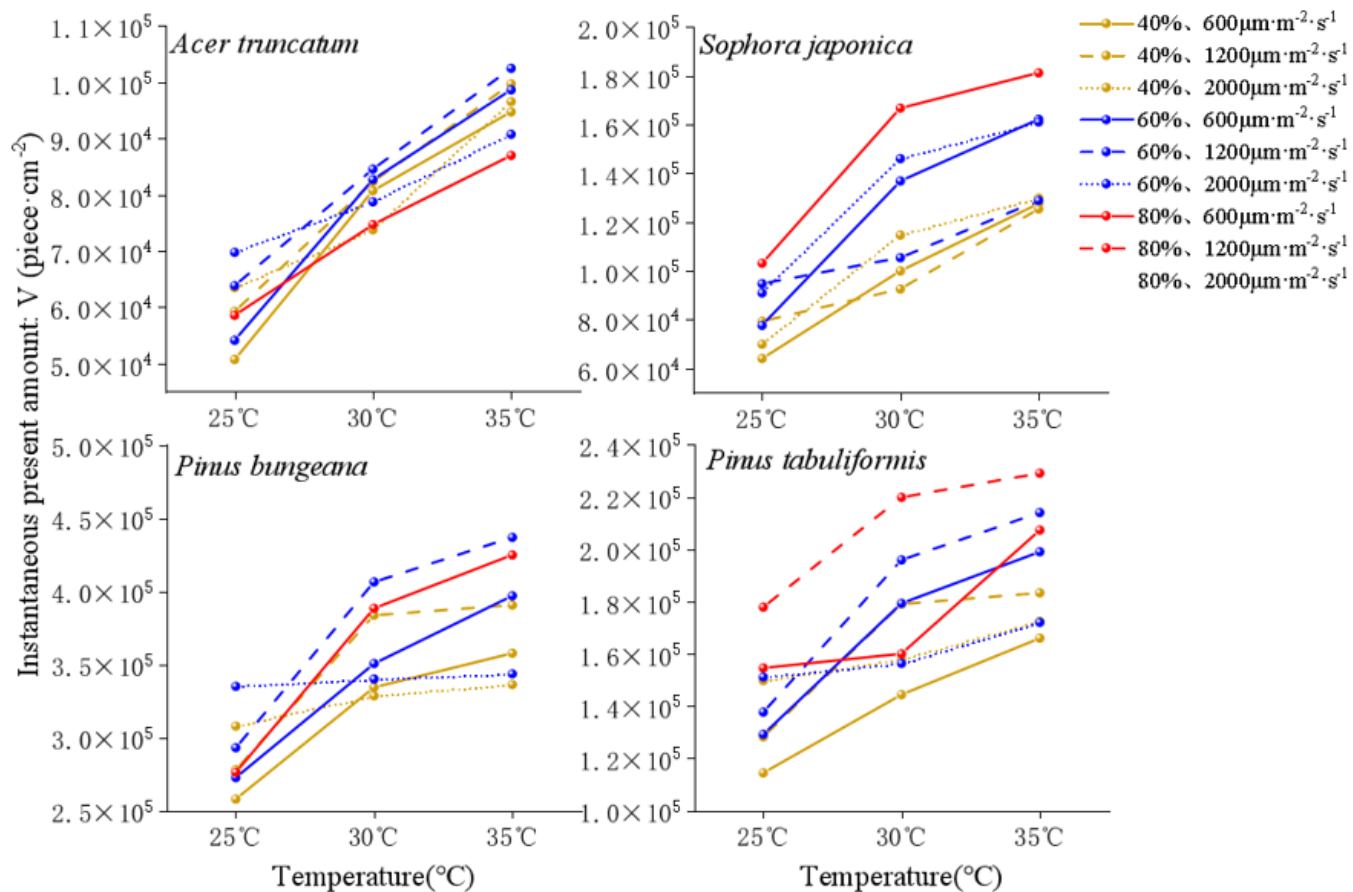


Figure 5

Plant NAI transients under different environmental conditions

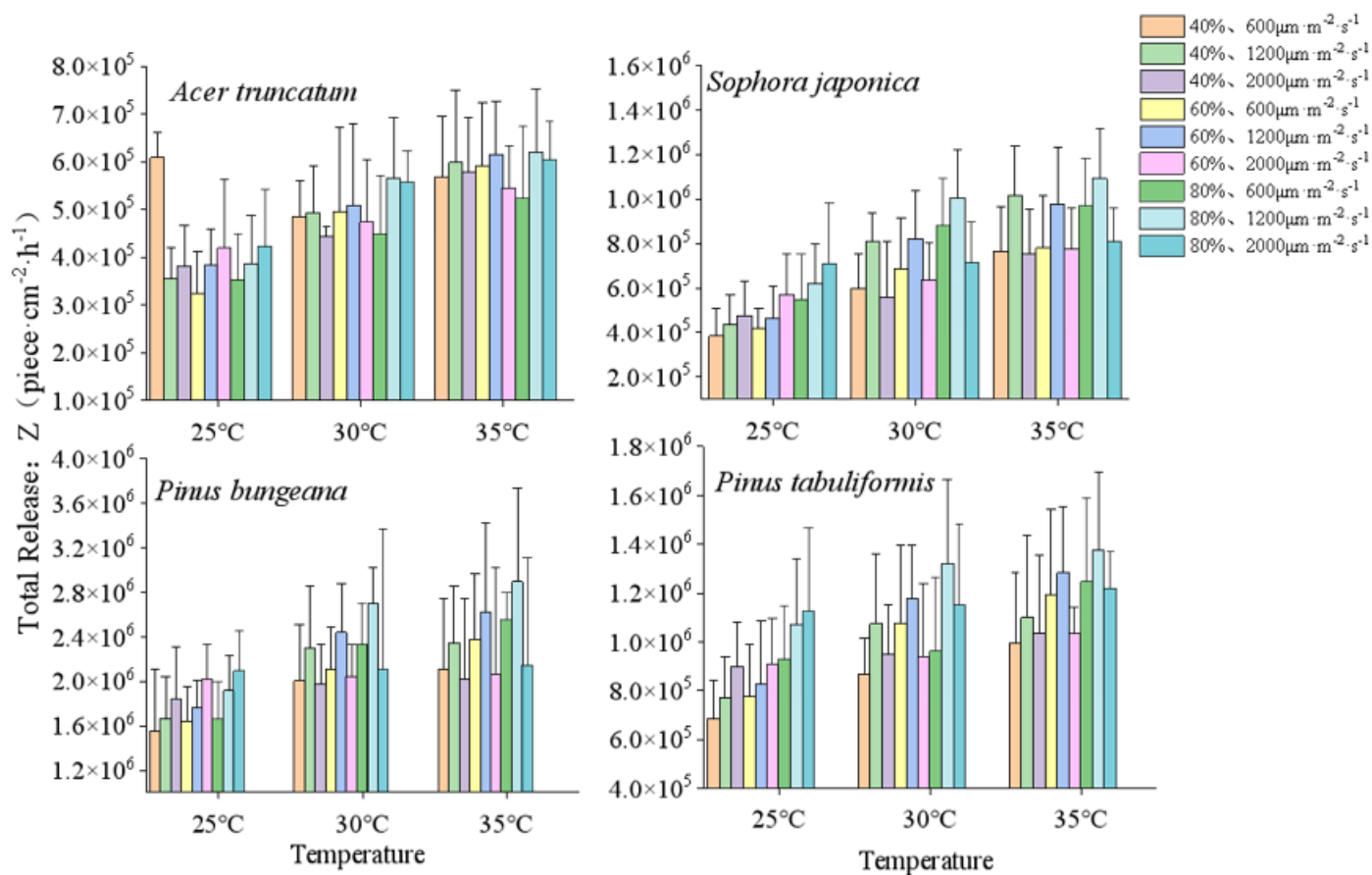


Figure 6

Total amount of NAI released from plants under different environmental conditions

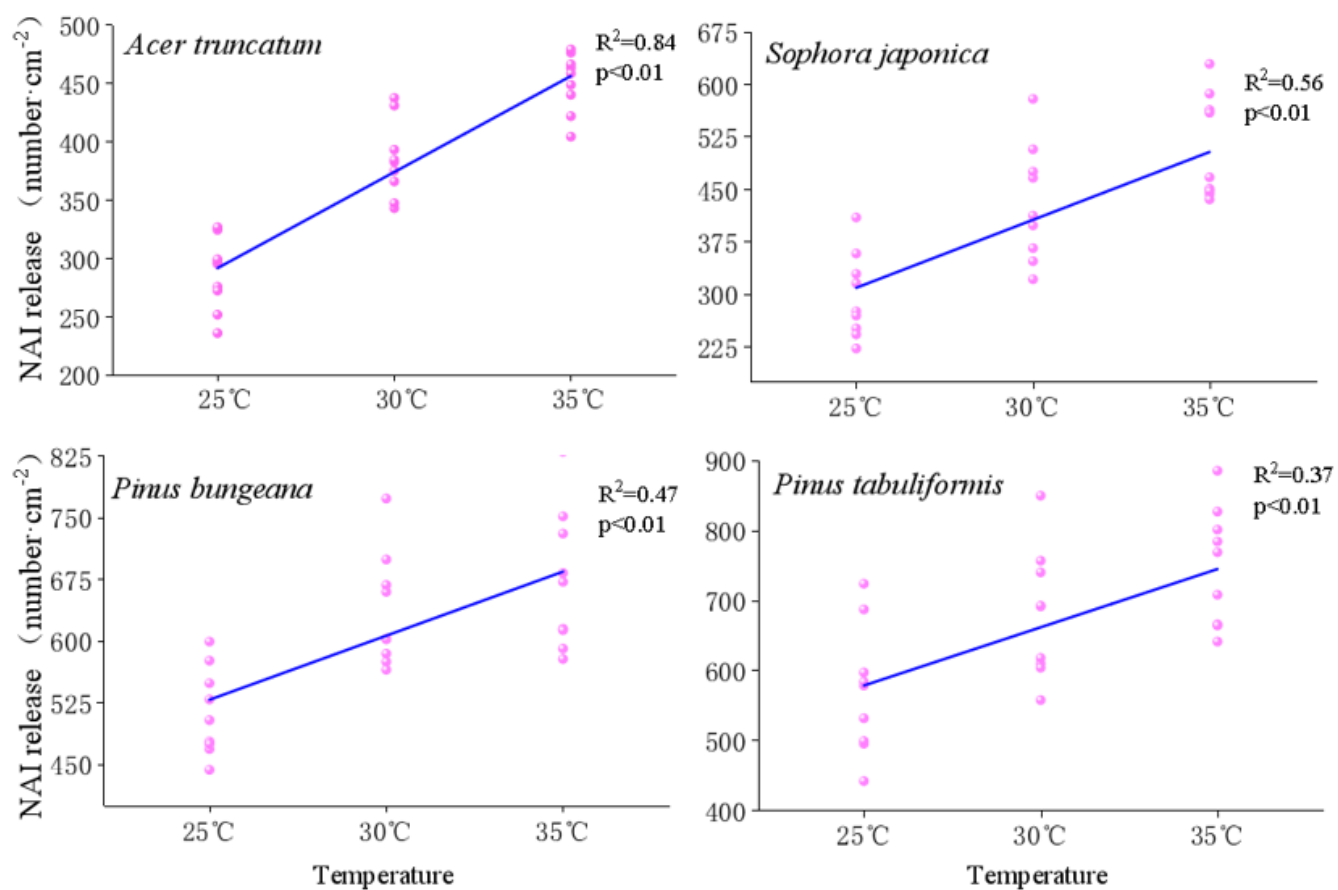


Figure 7

Correlation analysis between NAI release and temperature for different tree species