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Effects of Green Environment Exposure on Stress-Related Human Skin Gas Emissions

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Article

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Abstract

Urban living is associated with multiple environmental and psychosocial stressors, and urban greening has been promoted as a nature-based approach to improve health and well-being. However, the effects of green space exposure on dermal emissions of human skin gases, which may reflect physiological responses to stress, remain poorly understood. In this study, a randomized crossover design was used to investigate changes in skin gas emissions following stress and subsequent recovery. Thirteen healthy participants underwent standardized stress induction, followed by a 1-h rest period in either a green space within Ikuta Ryokuchi Park, Japan or an indoor meeting room. Skin gases were collected from the forearm using passive flux samplers, and dermal emission fluxes of stress-related compounds (ammonia and allyl mercaptan) and plant-derived monoterpenes (α-pinene, β-pinene, and limonene) were quantified. Resting in the green space significantly reduced dermal emissions of ammonia and allyl mercaptan, while increasing monoterpene levels. These results suggest that green space exposure modulates skin gas profiles in association with stress reduction, potentially influenced by inhaled monoterpenes. Skin gas analysis may provide a non-invasive approach for assessing physiological responses to environmental exposure.

Introduction

Stress is an increasing public health concern that is closely related to adverse mental health outcomes. Urban living is linked to a wide range of environmental and psychosocial stressors, including high population density, chronic exposure to traffic noise and air pollution, and elevated ambient temperatures due to the urban heat island effect, all of which contribute to sustained physiological stress responses [1,2]. In addition, psychosocial pressures such as time constraints, occupational demands, and reduced social cohesion may further exacerbate stress levels [3]. Importantly, limited access to natural environments in urban settings has been identified as a key factor underlying stress [4], and consequently, urban greening has been increasingly emphasized as a “nature-based solution” to promote health and well-being [5–8].

A growing body of empirical evidence supports the notion that exposure to green environments helps individuals cope with everyday stress and plays a key role in mitigating the risk of adverse mental health outcomes. For example, visits to green spaces (e.g., parks, woodlands, and urban forests) are known to enhance positive emotions such as life satisfaction, happiness, and self-esteem, while reducing negative emotions such as depression and anxiety [9–11]. In addition to these subjective assessments, the restorative effects of green environment exposure have also been demonstrated through measurements of conventional physiological markers, including salivary cortisol level [7,12], heart rate variability [12–15], blood pressure [15], and skin conductance [15,16]. However, little is known about how exposure to green environments influences dermal emissions of human skin gases, which may reflect physiological responses to stress.

Human skin gas, which significantly contributes to body odour, comprises a complex mixture of inorganic and organic volatile compounds. Although the complete profile of skin gases remains incompletely characterized, over 800 distinct compounds have been identified to date [17,18]. These gases are released via three primary emission pathways: surface chemical reactions, sweat gland excretion, and transdermal diffusion from the bloodstream [17,18]. Ammonia is a typical skin-emitted gas, and its sharp odour is a well-known contributor to body odour. When produced endogenously through metabolic processes, ammonia is carried in the bloodstream and released either through the skin or via sweat secretion [19,20]. Because dermal ammonia emissions are known to increase under psychological stress and/or physical exertion [19–21], the resulting body odour is often described as “fatigue odour” [19]. Although the formation mechanism is still unclear, volatile sulphur compounds (VSCs), such as allyl mercaptan and dimethyl trisulfide, were detected from the skin of subjects experiencing acute tension or anxiety, and suggested that these compounds are responsible for “onion-like odour” associated with psychological stress [22].

Based on these backgrounds, this study aimed to elucidate the effects of exposure to a green environment on stress-induced changes in skin gas emissions using a randomized crossover design. Participants were exposed to a stress condition in a meeting room, followed by recovery periods either in an outdoor green space or in the same room. The primary outcomes were stress-related skin gases, namely ammonia and allyl mercaptan. Meanwhile, since exogenous volatile compounds inhaled through respiration can also be emitted from the skin via the transdermal blood route, aromatic monoterpenes such as α-pinene, β-pinene, and limonene, which are derived from trees in green spaces [23, 24], were targeted as secondary outcomes. To our knowledge, this is the first study to apply skin gas analysis as a physiological marker in a crossover study of green environment exposure.

Results

Changes in dermal emissions of ammonia and allyl mercaptan

To facilitate interpretation of the results, a brief overview of the study design is provided here. Randomized crossover experiments were conducted in spring and autumn using healthy volunteers (*n* = 6 and 7, respectively). Participants were first exposed to a stress-induction protocol, followed by a 1-h rest period either in a green space consisted of a tree-lined outdoor environment within Ikuta Ryokuchi Park or in an indoor meeting room (control condition). Each participant experienced both conditions in a crossover manner with counterbalanced order. Skin gas samples were collected during both the stress-induction and post-stress rest periods (Figure 1).

Figure 2 shows the changes in dermal emission flux of ammonia under the different rest conditions.

Although the field experiment was conducted in both spring and autumn, a consistent decrease in dermal ammonia emission during the post-stress period was observed in the experimental group that rested in the green space, whereas no marked change was observed in the control group that remained

in the meeting room. In addition, no differences in dermal ammonia emission were observed between the experimental and control groups during the stress-induction period, suggesting that potential order effects were minimized by the crossover design. Therefore, data from both trials were combined for further analysis (*n* = 13).

As shown in Figure 2c), in the experimental group, the dermal emission flux of ammonia significantly decreased from $1.8 \times 10^2 \pm 2.0 \times 10^2$ ng cm^{-2} h^{-1} during the stress-induction period to 60 ± 41 ng cm^{-2} h^{-1} during the rest period in the green space (paired t-test, $p = 0.035$), corresponding to an approximate reduction of 67%. In contrast, no significant change was observed in the control group, with values of $1.5 \times 10^2 \pm 1.2 \times 10^2$ ng cm^{-2} h^{-1} during the stress-induction period and $1.3 \times 10^2 \pm 1.2 \times 10^2$ ng cm^{-2} h^{-1} during the rest period in the meeting room.

Similar trends were observed for allyl mercaptan. As shown in Figure 3, in the experimental group, the combined dermal emission flux significantly decreased from 5.1 ± 4.5 ng cm^{-2} h^{-1} during the stress-induction period to 1.2 ± 1.3 ng cm^{-2} h^{-1} during the rest period in the green space (paired t-test, p= 0.0046), corresponding to an approximate 76% reduction. In contrast, the control group showed a slight, non-significant decrease from 3.6 ± 5.1 to 2.4 ± 2.0 ng cm^{-2} h^{-1} ($p = 0.055$). These results indicate that use of the green space significantly reduced dermal emissions of stress-related skin gases.

Changes in dermal emissions of monoterpenes

Meanwhile, cutaneous emissions of α-pinene, β-pinene, and limonene were detected in participants. These biogenic VOCs are present in the ambient air of Kawasaki City, and relatively higher levels were observed in Ikuta Ryokuchi Park [25,26]. These monoterpenes are rapidly absorbed via inhalation through the lungs, distributed through the bloodstream [27,28], and subsequently released from the skin surface prior to hepatic metabolism [17,18]. Increased dermal emissions of these compounds were consistently observed in the experimental group, whereas no notable changes were observed in the control group in either season. Therefore, data from both trials were again combined (*n* = 13), as shown in Figure. 4.

The dermal emission fluxes of monoterpenes followed the order α-pinene > limonene > β-pinene across all periods. Significant increases were observed during the rest period in the green space (paired t-test: $p = 0.017$ for α-pinene, $p = 0.031$ for β-pinene, and $p = 0.035$ for limonene), whereas no significant differences were observed in the control group. Overall, these findings indicate that spending one hour in the green space reduced the dermal emission of stress-related malodorous compounds while increasing the emission of green aroma compounds. Although olfactory evaluation of body odour was not conducted in this study, the observed changes in skin gas composition may contribute to improvements in body odour.

Discussion

This study demonstrated that exposure to a green environment modulates stress-related changes in dermal emissions of skin gases under a randomized crossover design. The crossover design enabled

within-subject comparisons, minimizing inter-individual variability and enhancing sensitivity to environmental effects, thereby strengthening causal interpretation. Compared with recovery in the indoor meeting room, recovery in the green space of Ikuta Ryokuchi Park was associated with altered emission patterns of stress-related skin gases, suggesting that environmental context exerts measurable physiological effects on stress responses.

These findings are consistent with previous studies showing that exposure to green environments promotes parasympathetic activation and suppresses sympathetic nervous activity [13,14]. Such autonomic shifts may influence metabolic processes, sweat gland activity, vasodilation and vasoconstriction, skin surface chemistry, and other physiological processes, thereby affecting the emission of skin gases. Ammonia emission from the skin is known to reflect a heart rate variation induced by psychological stress, and tends to increase under sympathetic dominance and decrease under parasympathetic dominance [20]. Thus, the observed reduction in cutaneous ammonia emission likely reflected a shift toward parasympathetic predominance induced by the green exposure.

Although the stress-related emission mechanism of allyl mercaptan has not been fully elucidated, allicin —derived from Allium species such as garlic, onions, and Chinese chives—is known to serve as its precursor [29,30]. Allicin is unstable and rapidly decomposes *in vivo* to form VSCs such as diallyl disulfide and allyl mercaptan. Allyl mercaptan is subsequently metabolized to allyl methyl sulfide in the liver via thiol S-methyl transferase [30,31]. Therefore, exposure to the green environment may have enhanced the metabolic clearance of allyl mercaptan.

The stress-reducing effects associated with green space utilization are likely mediated by a combination of environmental factors, including visual, auditory, olfactory, and air quality components [14]. Among these, plant-derived monoterpenes such as α-pinene and limonene may play a key role, as they are known to be absorbed into the body during walking in green spaces and have been reported to enhance parasympathetic activity and reduce heart rate [12–15]. Figure 5 illustrates the relationships between dermal emission fluxes of (a) ammonia and (b) allyl mercaptan and the summed emission fluxes of α-pinene, β-pinene, and limonene. A marked decrease in cutaneous emissions of ammonia and allyl mercaptan was observed with increasing dermal emission of monoterpenes. This suggests that dermal monoterpene emissions serve as an indicator of uptake of inhaled monoterpenes, and that higher levels may relieve stress, possibly by promoting parasympathetic dominance, thereby suppressing the dermal emission of ammonia.

Despite the major strengths of this study, several limitations should be acknowledged. A key issue in this field is the intensity and duration of exposure to green environments. Although this study was conducted in a large green space, access to such environments is often limited in urban settings, and further validation across diverse green spaces is required. In addition, the exposure duration was set at one hour; however, securing such time may be difficult for urban workers, highlighting the need to evaluate the effects of shorter exposure durations. These findings provide further support for the integration of environmental exposure assessment with physiological monitoring techniques.

Conclusion

This study aimed to elucidate the effects of exposure to a green environment on stress-induced changes in human skin gas emissions using a randomized crossover design. The results showed that spending one hour in Ikuta Ryokuchi Park reduced the dermal emissions of stress-related malodorous compounds while increasing the emission of green aroma monoterpenes. These findings highlight the potential of skin gas analysis as a non-invasive indicator of stress modulation and environmental exposure. This study provides novel insights into the benefits of utilizing green space for stress reduction by integrating environmental exposure with skin gas analysis.

Methods

Participants and Study Design

This study was conducted at Ikuta Ryokuchi Park, a large urban green space (1.79 km^2) located in Kawasaki City, Japan. The park comprises a semi-natural woodland environment interspersed with open spaces and walking paths, providing a representative example of urban green infrastructure within a metropolitan area. The terrain is characterized by gentle slopes and forested areas that support recreational activities such as walking and passive rest. Randomized crossover tests were carried out on May 11, 2023 (spring) and November 21, 2024 (autumn) by recruiting 6 healthy volunteers (3 males and 3 females aged 40–59 years) in spring and 7 volunteers (2 males and 5 females aged 20–59 years) in autumn.

The test schedule is presented in Fig. 1, and the experimental setup is shown in Fig. 6. During a brief instruction in a meeting room at Ikuta Ryokuchi Park, participants were randomly assigned to two groups (A and B): Group A underwent the experimental condition in the morning and the control condition in the afternoon, whereas Group B underwent the control condition in the morning and the experimental condition in the afternoon. First, all participants were exposed to a stressful situation in the meeting room for one hour (stress-induction period in the meeting room), which involved delivering a short speech followed by group discussions. Subsequently, participants in Group A spent one hour in a designated green space within the park characterized by a tree-lined path and surrounding woodland vegetation (Fig. 6a)), with minimal exposure to traffic noise and urban disturbances (post-stress rest period in the green space), whereas participants in Group B remained in the meeting room for one hour without any tasks (post-stress rest period in the meeting room). After lunch, all participants were again exposed to a stressful situation in the meeting room for one hour involving a speech contest in spring and a debate in autumn (stress-induction period in the meeting room). Thereafter, participants in Group B spent one hour in the green space (post-stress rest period in the green space), while participants in Group A remained in the meeting room (post-stress rest period in the meeting room). Human skin gas samplings were conducted during the stress-induction and rest periods (Fig. 6b)).

During the rest periods, participants' activities were not strictly controlled, except that behaviours likely to induce sweating outdoors were restricted. In addition, as visual exposure to greenery from indoors has been reported to reduce stress [8], the windows and doors of the meeting room were kept closed and blinds were drawn to prevent any view of the outside environment. The indoor temperature was maintained at 18–19°C using an air conditioner. Outdoor temperatures ranged from 15 to 21°C in spring and from 14 to 16°C in autumn. Regarding lunch, dietary intake was standardized to two rice balls (so-called onigiris) and a salad, primarily consisting of carbohydrates, because protein intake may increase dermal ammonia emissions [20]. Water and tea were allowed ad libitum throughout the study period.

Skin gas sampling and analysis

Human skin gases were collected from the forearms of participants using two co-located passive flux samplers (PFSs) designed for ammonia and volatile organic compounds (VOCs), enabling simultaneous sampling. The device structure, sampling principles, and analytical procedures of each PFS have been described in detail elsewhere[17, 32–34]. Briefly, the PFS consisted of a sampler body, a trapping medium, and stoppers. The PFS was gently affixed to the skin surface of the participant's forearm using medical tape for one hour to create a headspace. Through the open face of the sampler, skin gases emanating from the skin surface diffused toward the trapping medium within the headspace, where the gas molecules were collected. Cellulose filter paper (No. 51A, 32 mm diameter, Advantec, Tokyo, Japan) impregnated with a solution of 2% phosphoric acid and 1% glycerol in methanol was used for trapping ammonia. For VOCs, a disk-type medium composed of monolithic silica embedded with activated carbon particles (MonoTrap® SG DCC 18, GL Sciences, Tokyo, Japan) was used to trap compounds such as allyl mercaptan, α-pinene, β-pinene, and limonene. After sampling, the PFSs were transported to Tokai University for chemical analysis following previous studies[32,33]. All reagents were purchased from FUJIFILM Wako Pure Chemical Corporation (Osaka, Japan).

Ammonia was determined by ion chromatography (IC) after extraction with 8.0 mL of Milli-Q water under mild shaking (150 rpm) for 2.0 h. The IC system consisted of an LC-20AD pump, a conductivity detector (CDD-10Avp), a column oven (CTO-10Avp), an autosampler (SIL-10Ai), and a system controller (CBM-20Avp) (Shimadzu Corporation, Kyoto, Japan). Ten microliters of sample extracts, blank extracts, and calibration standards were injected into an IC YS-G guard column (4.6 mm × 10 mm, Shodex, Tokyo, Japan) and an IC YS-50 separation column (4.6 mm × 150 mm, Shodex, Japan). The eluent consisted of 3.0 mM phosphoric acid/acetonitrile (9:1, v/v) at a flow rate of 1.0 mL min^{-1} under isocratic conditions. The column oven temperature was maintained at 313 K. Calibration standards (0.20, 0.50, 2.0, and 5.0 mg L^{-1} NH_4^+ in Milli-Q water) were prepared from ammonium sulfate, yielding a linear calibration curve ($R^2 > 0.99$).

Trapped VOCs were analysed by gas chromatography–mass spectrometry (GC–MS) after elution with 0.50 mL of carbon disulfide using ultrasonic extraction for 30 min. The analysis was performed using a gas chromatograph (model 7890B, Agilent Technologies, Santa Clara, CA, USA) coupled to a mass

selective detector (JMS-Q1050GC MkII, JEOL, Tokyo, Japan). One microliter of each sample extract, blank extract, and calibration standard was injected with a split ratio of 35:1 into a DB-IMS capillary column (30 m × 0.25 mm I.D. × 0.25 μm film thickness, Agilent Technologies, Santa Clara, CA, USA) and a DB-35MS capillary column (30 m × 0.25 mm I.D. × 0.25 μm film thickness, Agilent Technologies, Santa Clara, CA, USA). The carrier gas was G1-grade helium (Taiyo Nippon Sanso, Tokyo, Japan) at a flow rate of 1.0 mL min^{-1}. The injector temperature was maintained at 280°C. The oven temperature program was as follows: held at 50°C for 8 min, ramped at 6°C min^{-1} to 120°C, then ramped at 20°C min^{-1} to 300°C and held for 2 min. Data were acquired in real-time using selected ion monitoring (SIM) mode. Calibration curves were constructed using mixed standard solutions at concentrations of 0, 0.50, 1.0, and 2.5 μg mL^{-1}. Excellent linearity was observed, with coefficients of determination (R^2) exceeding 0.99.

The dermal emission flux of the target skin gases, E (ng cm^{-2} h^{-1}) was obtained by

$$E = \frac{W}{S' t} \quad (1)$$

where W is a collection amount of each skin gas (ng), S' is an effective cross-section of the trapping media (5.26 cm^2 for ammonia, 0.594 cm^2 for VOCs) and t is a sampling duration (1.0 h). The limit of detection (LOD) for ammonia was defined as three times the standard deviation of multiple blank samplers and was calculated as 11 ng cm^{-2} h^{-1} for a 1-hour sampling duration. LODs for VOCs were determined based on a signal-to-noise ratio (S/N) of 3 using peak areas from mixed standard solutions and Eq. (1). The resulting LODs were 0.014 ng cm^{-2} h^{-1} for allyl mercaptan, 0.031 ng cm^{-2} h^{-1} for α-pinene, 0.011 ng cm^{-2} h^{-1} for β-pinene, and 0.070 ng cm^{-2} h^{-1} for limonene. Because the dermal emission fluxes were very low, only values above the LOD were considered, while those below the LOD were treated as zero.

Statistical Analysis

Statistical analyses were conducted using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA). Differences in dermal emission fluxes between stress-induced period and post-stress rest period were analysed using the paired t-test. Unless indicated otherwise, statistical significance was set at $p < 0.05$.

Declarations

Ethics approval and consent to participate

This study was conducted as an observational study in accordance with the principles of the Declaration of Helsinki. The study protocol was approved by the Institutional Review Board of the Shonan Campus, Tokai University (approval numbers: 23005 and 24042). Written informed consent was obtained from all participants prior to enrolment in the study.

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Author contribution

Conceptualization, K.T. and Y.S.; methodology, J. K., K.T., M.M. and Y.S.; investigation, J. K., K.T., M.M. and Y.S.; formal analysis, J. K., K.T., and Y.S.; data curation, J.K. and M.M.; validation, Y.S.; resources, K.T. and Y.S.; writing—original draft preparation, J.K. and Y.S.; writing—review and editing, K.T.; project administration, K.T. and Y.S. All authors have read and agreed to the published version of the manuscript.

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Competing Interests

The authors declare no competing interests.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Figures

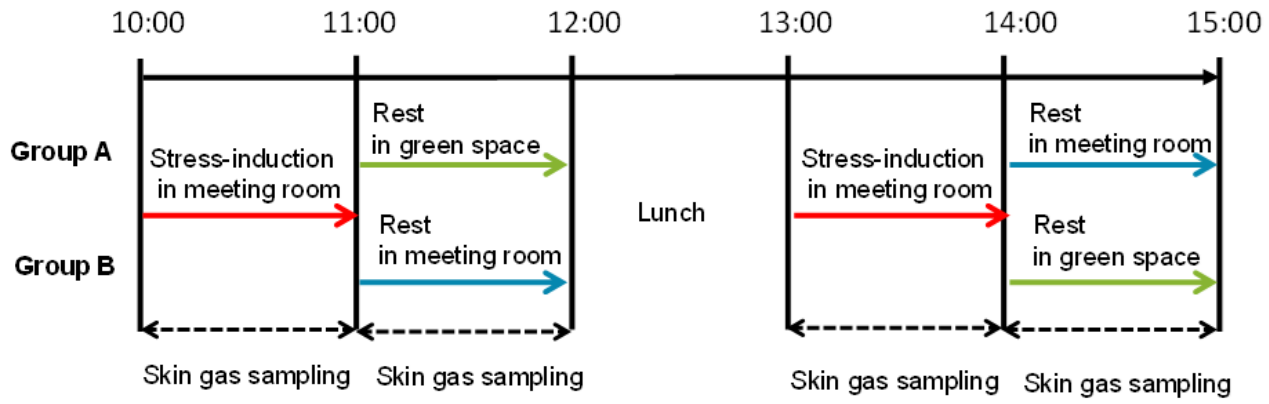


Figure 1

Overview of the study design. Participants underwent a randomized crossover protocol consisting of a stress-induction period followed by a 1-h rest period in either a green space or an indoor meeting room (control condition). Each participant experienced both conditions in a counterbalanced order (Group A: green space first; Group B: control first). Skin gas sampling was conducted during both the stress-induction and post-stress rest periods.

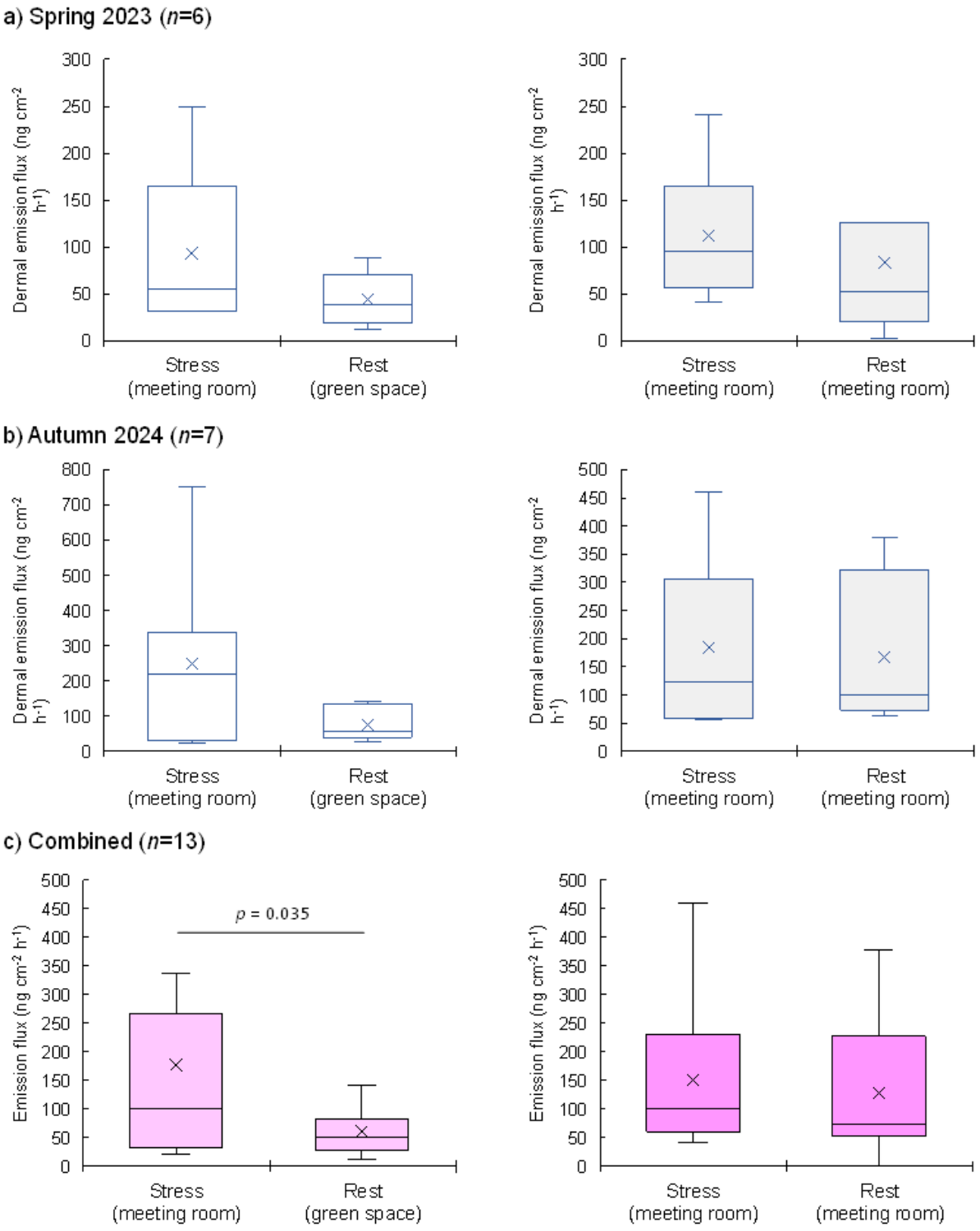


Figure 2

Changes in the dermal emission flux of ammonia across different periods. Data are shown for (a) spring 2023, (b) autumn 2024, and (c) the combined dataset (*n*=13).

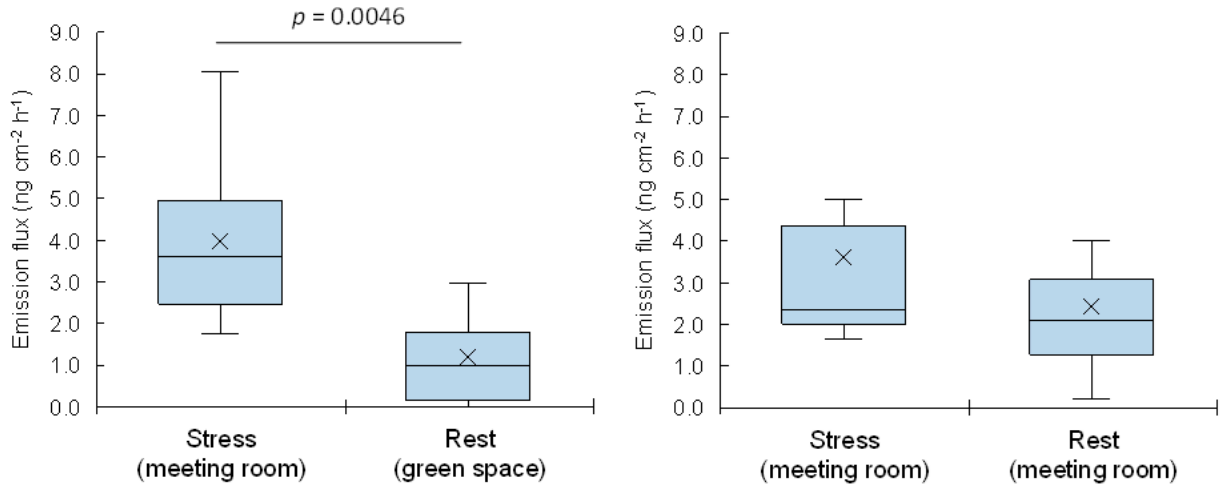


Figure 3

Changes in the dermal emission flux of allyl mercaptan across different periods. Data are shown for the combined dataset of spring 2023 and autumn 2024 (*n*=13).

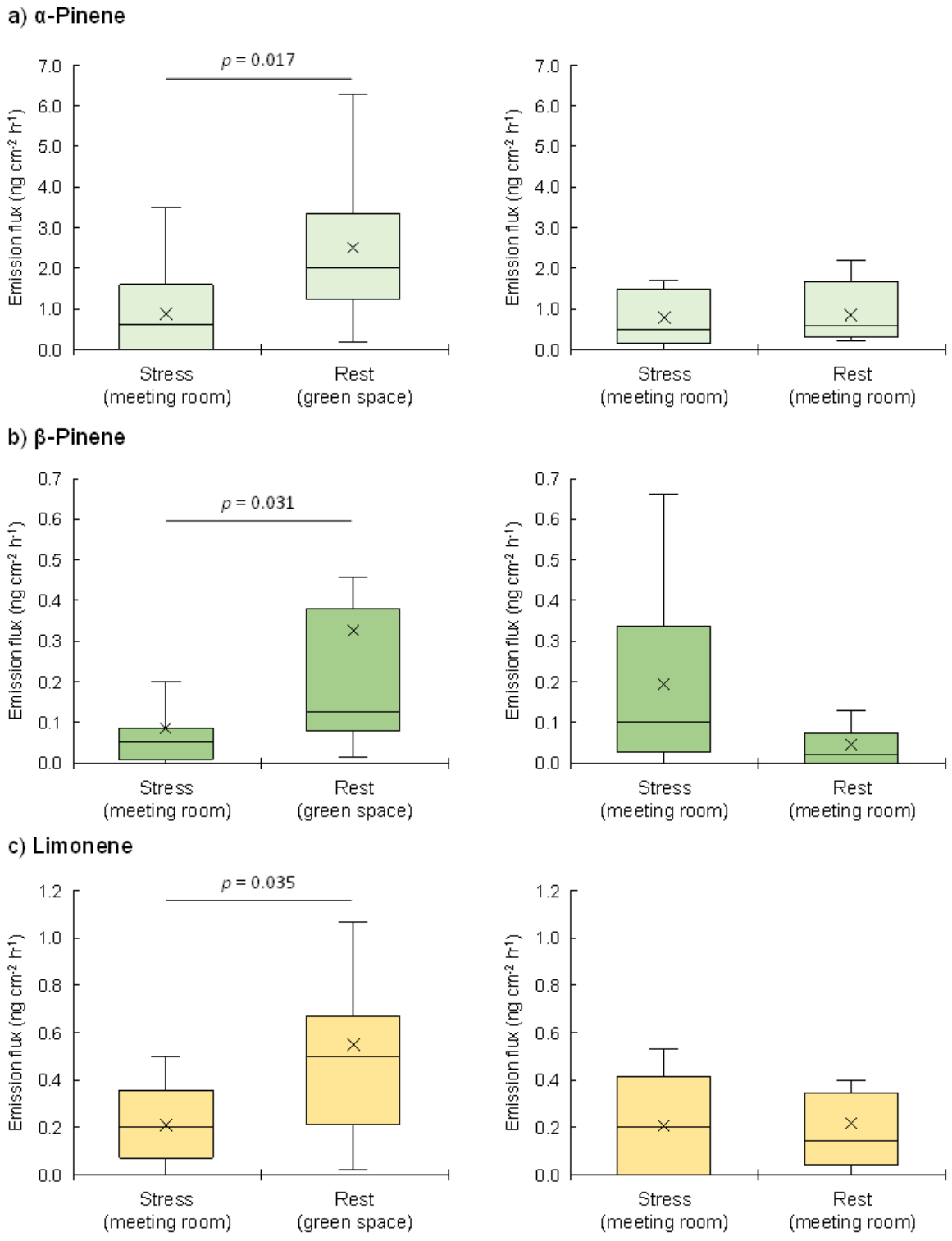


Figure 4

Changes in the dermal emission fluxes of α-pinene, β-pinene, and limonene across different periods. Data are shown for the combined dataset of spring 2023 and autumn 2024 (*n*=13).

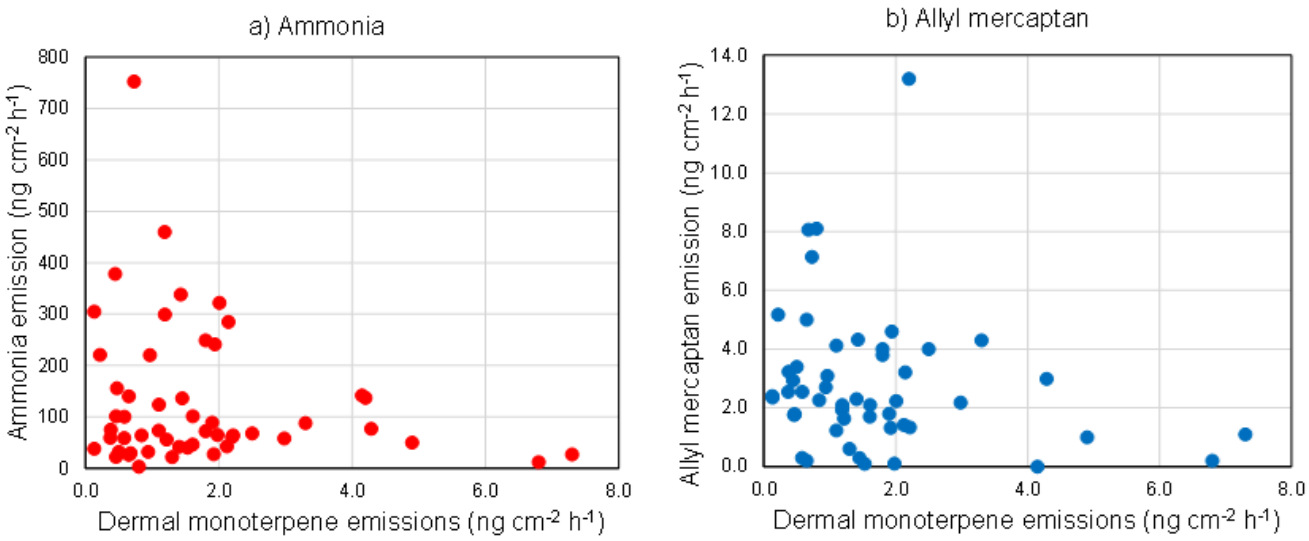


Figure 5

Relationships between dermal emission fluxes of (a) ammonia and (b) allyl mercaptan and the summed emission fluxes of α-pinene, β-pinene, and limonene. Plots were shown using all data (*n*=52).

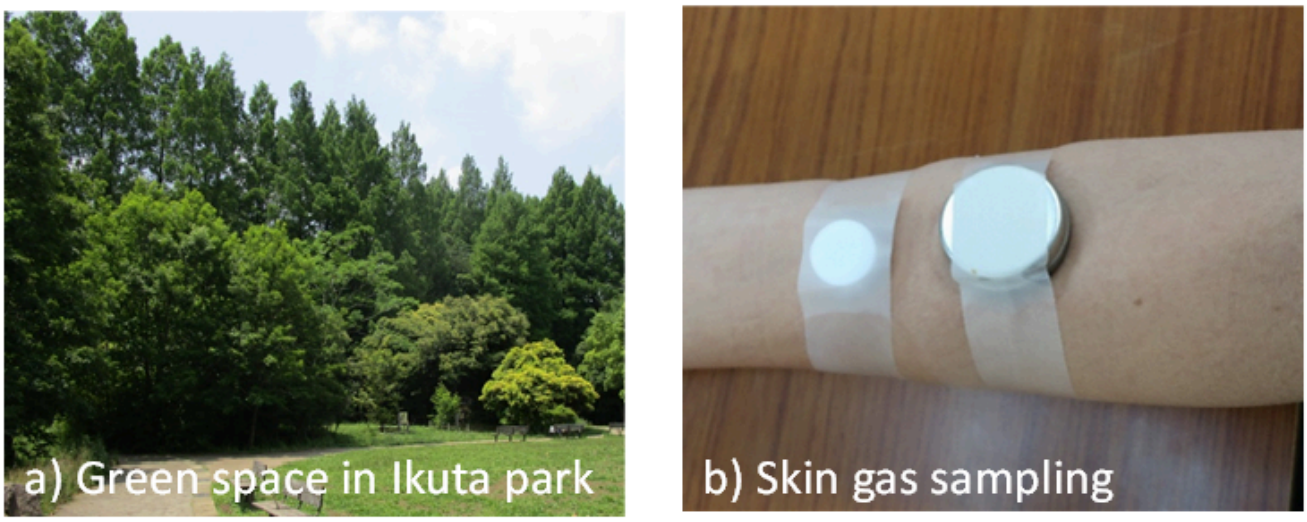


Figure 6

Experimental setups. a) a typical green space within the park and b) Simultaneous sampling of ammonia and VOCs by the passive flux samples.