

Article

Seasonal Dynamics and Composition of Biogenic Volatile Organic Compounds in Different Forests

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Abstract

Understanding seasonal patterns of forest biogenic volatile organic compounds (BVOCs) is essential for clarifying their ecological functions and potential health benefits. In this study, BVOC samples were collected from ten representative forest stands in Caoyutang Forest Park across four seasons using adsorption tube sampling coupled with thermal desorption–gas chromatography/mass spectrometry (TD-GC/MS). Pronounced spatial and temporal variations in BVOC composition and relative abundance were observed among different forest stands. The number of detected BVOCs varied considerably among seasons, following the order autumn > winter > spring > summer, while relative BVOC abundance was highest in autumn and lowest in spring. *Thujopsis dolabrata* stands showed relatively high BVOC relative abundance in spring, whereas several mixed forest stands exhibited greater compound richness and relative abundance during autumn. Seasonal shifts in dominant BVOC groups differed among forest stands, with esters becoming prominent in *Cunninghamia lanceolata*–*Hydrangea* mixed stands during summer, while aromatic hydrocarbons and alkanes dominated many stands during winter. Across all samples, alkanes and esters represented major compound classes, whereas aromatic hydrocarbons, aldehydes, and esters contributed substantially to relative abundance. A total of 10 terpenoid compounds were identified, with camphene representing one of the major components, and a higher relative abundance of terpenoids was observed in *Abies firma* stands. Principal component analysis indicated distinct compositional patterns among *Cunninghamia lanceolata*-dominated mixed stands, highlighting the influence of associated tree species and stand structure on BVOC profiles. This study elucidates spatial and seasonal BVOC patterns of BVOC composition in relation to forest structure, providing a scientific basis for planning forest therapy bases and selecting therapeutic plant species in landscape design.

Keywords: biogenic volatile organic compounds (BVOCs); forest stand structure; seasonal variation; terpenoids; forest therapy; Caoyutang Forest Park

Academic Editor: Chunjian Zhao

Received: 17 May 2026

Revised: 23 July 2026

Accepted: 29 July 2026

Published: 3 August 2026

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1. Introduction

Forest therapy has received increasing attention as a nature-based approach that integrates forest environments with human health promotion. Forest ecosystems contribute

to environmental regulation by improving air quality, moderating microclimatic conditions, and releasing biogenic volatile organic compounds (BVOCs), which represent an important group of secondary metabolites involved in plant–environment interactions and may contribute to the potential health benefits of forest environments [1]. BVOCs are low-molecular-weight organic compounds released by plants during physiological processes and in response to environmental stress, including terpenoids and oxygenated volatile organic compounds (OVOCs), such as esters, ketones, aldehydes, and alcohols [2,3]. Previous studies have shown that different BVOC groups perform distinct ecological and biological functions. Terpenoids, particularly monoterpenes such as α -pinene and linalool, exhibit antioxidant, anti-inflammatory, and neurophysiological activities that may contribute to the health benefits associated with forest environments [4–6]. Esters are often characterized by pleasant odors and have been reported to exhibit relaxation-related and antimicrobial effects [7,8]. Aldehydes show bactericidal effects [9], while ketones and alcohols display sedative, antimicrobial, and neuroregulatory potential [10,11]. Therefore, forest BVOCs are considered an important chemical component, potentially contributing to the ecological functions and health-related perceptions of forest environments.

Different forest types exhibit distinct BVOC compositions and relative abundance profiles due to variations in species composition, physiological traits, and stand structure [12]. For example, Scots pine forests have been reported to contain substantially higher atmospheric terpenoid concentrations than European beech forests, whereas English oak and European beech display contrasting emission profiles of isoprene, monoterpenes, and green leaf volatiles. Moreover, downy birch emits a chemically diverse mixture of monoterpenes, sesquiterpenes, and oxygenated VOCs, further highlighting the species dependence of BVOC emissions [13–15]. In addition, the stand structure further regulates the production and release of BVOCs by influencing canopy layers, canopy closure, and the forest microenvironment [16]. Mixed forests, characterized by higher plant diversity and more complex community structures, may therefore exhibit greater chemical diversity of BVOCs due to the combined contributions of multiple plant species [17].

Seasonal variations in BVOC composition have been widely observed. Studies by Tarvainen et al. and Hakola et al. showed that monoterpene concentrations generally increase during warm periods, with summer often representing the period of maximum abundance, whereas a wider variety of oxygenated volatile organic compounds are released during the spring budding and active growth period [18,19]. Meanwhile, environmental factors, including air humidity, atmospheric CO₂ concentration, and wind speed, influence BVOC production, release, atmospheric transport, and accumulation processes in forest ecosystems [20–22]. These environmental factors interact with vegetation characteristics to influence the temporal and spatial variation patterns of BVOC composition in forest ecosystems.

Existing research has primarily focused on the relationships between BVOCs and environmental factors [23], emission characteristics from a few typical forest types [24,25], and BVOC profiles of individual forest parks over specific time scales [26]. Research comparing seasonal variations in BVOC composition among different stand structures within the same region remains limited. This knowledge gap is particularly relevant for subtropical forests, where mixed stands typically contain diverse plant communities and complex canopy structures, resulting in heterogeneous microclimatic conditions that may influence BVOC composition.

Caoyutang Forest Park, located in Zhejiang Province, China, contains extensive forest coverage and diverse mixed coniferous–broadleaf forest stands. Differences in tree species composition, community structure, and microenvironmental conditions among these stands provide an ideal natural setting for comparing BVOC composition and seasonal dynamics among forest stands with contrasting species compositions and structural characteristics.

Based on existing research, this study proposes the following scientific hypotheses:

- (1) Forest stands with different species compositions and structures would exhibit distinct BVOC profiles due to species-specific contributions and stand-level interactions.
- (2) BVOC composition would show seasonal succession patterns regulated by vegetation phenology, environmental conditions, and compound-specific release mechanisms, with seasonal responses varying among forest stands.

Therefore, this study selected Caoyutang Forest Park in Jingning County, Zhejiang Province, China, as its research subject to conduct a systematic comparative analysis of forest environmental volatile compounds across different stand structures on both spatial and temporal scales, thereby providing a theoretical basis and practical reference for the construction of forest wellness bases, the implementation of wellness activities, and the selection of wellness plants.

2. Materials and Methods

2.1. Study Area

Caoyutang Forest Park (27°54′13″–27°55′30″ N, 119°39′33″–119°42′12″ E) is located in Jingning She Autonomous County, Zhejiang Province, approximately 20 km southeast of the county seat. The park covers an altitude range of 850–1500 m (average 1150 m), with the highest peak, Mount Chimu, reaching 1519.1 m. Forest coverage exceeds 96.8%. The region experiences a mid-subtropical maritime monsoon climate, with a recorded maximum temperature of 31 °C and an annual average temperature of 12.80 °C. The park features a favorable microclimate, dominated by tree species such as *Thujopsis dolabrata*, *Pseudolarix amabilis*, *Pinus hwangshanensis*, *Cunninghamia lanceolata*, and *Abies firma*. The area is characterized by high elevation, a cool climate, and rich natural and cultural landscapes.

Ten representative forest stands, including *Sassafras tzumu* + *C. lanceolata* + *Liquidambar formosana* + *Camellia oleifera* mixed stand (SCLC01), *L. formosana* + *C. lanceolata* + *Taxus wallichiana* var. *mairei* + *Lithocarpus hancei* mixed stand (LCTL02), *C. lanceolata* + *Hydrangea chinensis* + *Hydrangea vinicolor* + *Actinidia eriantha* mixed stand (CHHA03), *Cryptomeria fortunei* + *C. lanceolata* + *Schima superba* + *Prunus buergeriana* mixed stand (CCSP04), *C. lanceolata* + *Prunus schneideriana* + *Hydrangea paniculata* + *Indocalamus tessellatus* mixed stand (CPHI05), *C. lanceolata* + *S. superba* + *Eurya hebeclados* + *L. glauca* mixed stand (CSEL06), *Castanopsis eyre* + *P. hwangshanensis* + *Lithocarpus glaber* + *Quercus glauca* mixed stand (CPLQ07), pure *Abies firma* stand (ABFI08), *Litsea coreana* Levl. var. *sinensis* + *P. hwangshanensis* + *L. glauca* + *Raphiolepis indica* mixed stand (LPLR09), and pure *Thujopsis dolabrata* (THDO10) stand. Plot details are summarized in Figure 1 and Table 1. Plant details are in Table S1.

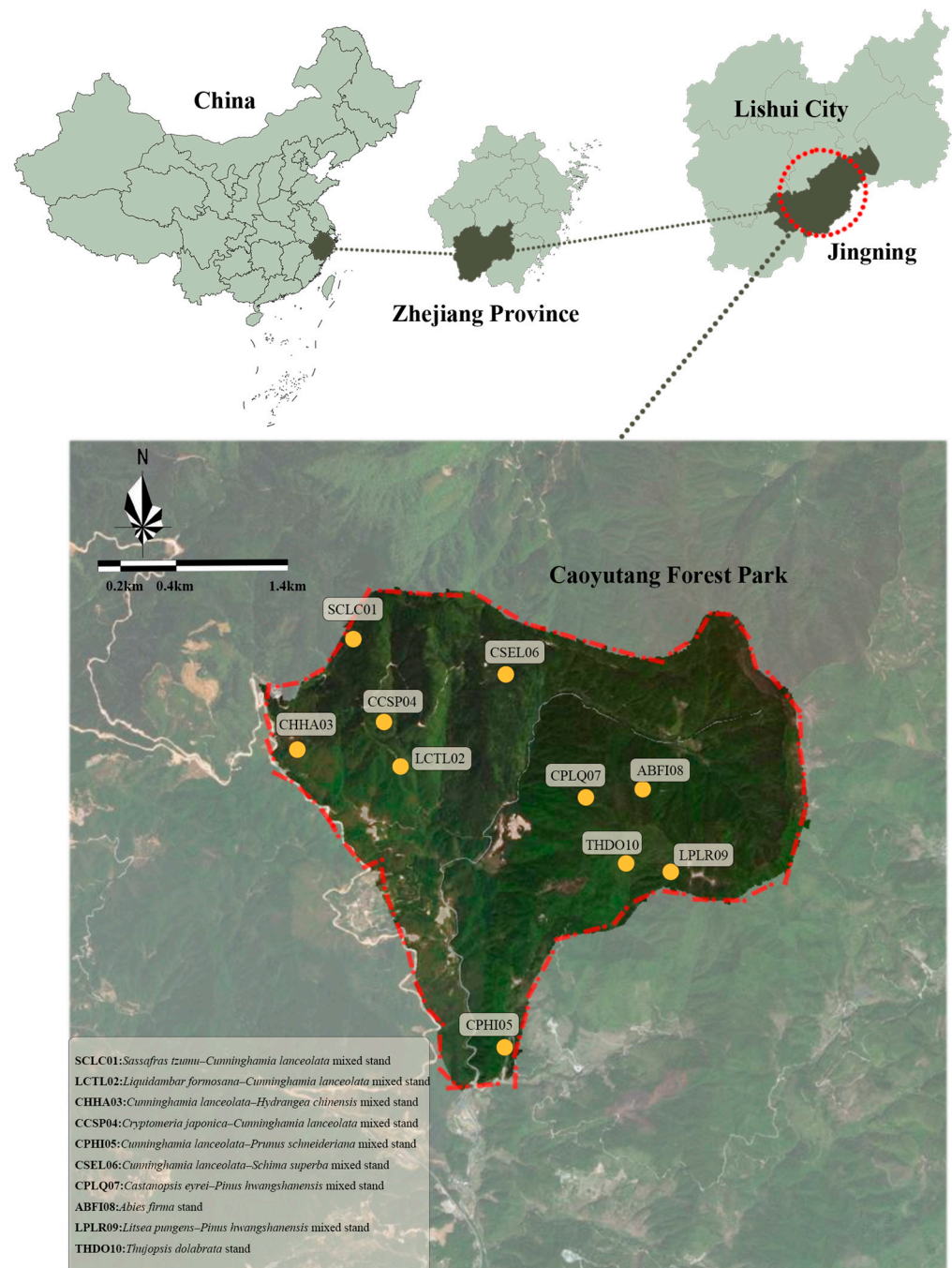


Figure 1. Location of the experimental forest area at Caoyutang Forest Park.

Table 1. Basic characteristics of the sample forest stands.

Plot	Area (hm ²)	Slope (°)	Altitude (m)	Aspect	Avg. Height (m)	Avg. DBH (cm)	Canopy Density (Decimal)	Canopy Coverage (%)	Tree Species	Dominant Tree Species
SCLC01	1.09	22	1158	South	21.6	18.2	0.9	78	3~7	<i>Sassafras tzumu</i> , <i>Cunninghamia lanceolata</i>
LCTL02	1.89	20	1137	South	20.3	17.4	0.8	75	2~6	<i>L. formosana</i> , <i>Cunninghamia lanceolata</i>
CHHA03	2.36	7	1166	South	19.2	25.7	0.7	70	2~8	<i>Cunninghamia lanceolata</i> , <i>Hydrangea chinensis</i>
CCSP04	2.12	16	1164	South	17.7	22.6	0.7	71	2~7	<i>Cryptomeria fortunei</i> , <i>Cunninghamia lanceolata</i>

CPHI05	2.51	21	1160	South	16.9	16.7	0.8	68	4~7	<i>Cunninghamia lanceolata</i> , <i>Prunus schneideriana</i>
CSEL06	1.67	20	1188	South	17.3	17.5	0.9	82	3~6	<i>Cunninghamia lanceolata</i> , <i>S.</i> <i>superba</i> , <i>Eurya hebeclados</i>
CPLQ07	2.45	18	1190	South	14.7	15.5	0.8	80	4~7	<i>Castanopsis eyre</i> , <i>P.</i> <i>hwangshanensis</i>
ABFI08	2.43	17	1246	South	22.4	27.3	0.6	20	4~6.5	<i>Abies firma</i>
LPLR09	1.33	23	1249	South	14.3	13.7	0.8	85	3~5	<i>Litsea coreana</i> Levl. var. <i>sinensis</i> , <i>P. hwangshanensis</i>

2.2. Instrumentation

BVOC sampling: FCC-1500H sampling instrument (Yancheng Tianyue Instrument Co., Ltd., Yancheng, China).

BVOC analysis: TurboMatrix 350 thermal desorber (PerkinElmer, Shelton, CT, USA) coupled with an Agilent 7890B GC/7000D MS system (Agilent Technologies, Santa Clara, CA, USA).

Temperature and humidity monitoring: HTC-1 portable meter (Lishui Jiujiu Medical Equipment Co., Ltd., Lishui, China).

2.3. Methods

2.3.1. Sample Collection

BVOC sampling was conducted in September and December 2023 and in March and June 2024 during consecutive sunny days under calm or light wind conditions. To minimize the influence of short-term meteorological variation, all forest stands within each season were sampled over two consecutive days under comparable weather conditions. Field sampling was performed daily between 09:00 and 15:00, with an effective air sampling duration of 5 h (weather details in Tables S2–S5).

Within each forest stand, three sampling sub-sites were established at the vertices of a 10 m equilateral triangle centered within the stand. Air samples from the three sub-sites were sequentially collected using the same adsorption tube, with identical sampling duration and air volume for each sub-site (approximately 40 L per sub-site). These subsamples were combined into one composite sample representing the stand-level BVOC composition. Due to equipment limitations, one representative composite sample was collected for each forest stand in each season; therefore, the forest stand was considered the observational unit in subsequent analyses.

Samples were collected using pre-conditioned TC ATD PerkinElmer adsorption tubes connected to a portable air sampling pump. The inlet of each adsorption tube was positioned 1.5 m above the ground. Air was drawn through the adsorption tubes at a flow rate of 0.4 L min⁻¹ for 5 h, yielding a total sampled air volume of 120 L per sample. After sampling, the adsorption tubes were immediately sealed with brass caps, stored at 4 °C, and transported to the laboratory. All samples were analyzed within one week of collection. These procedures were implemented to minimize potential contamination and analyte loss during sample handling and storage.

2.3.2. BVOC Analysis

BVOCs were analyzed using thermal desorption–gas chromatography/mass spectrometry (TD-GC/MS).

Thermal desorption conditions: dry purging for 1 min at 50 mL·min⁻¹; tube desorption at 260 °C for 10 min at 50 mL·min⁻¹; trap held at −5 °C and then heated at 40 °C·s⁻¹ to 280 °C (5 min desorption); transfer line at 200 °C; inlet and outlet split flows at 10 mL·min⁻¹.

GC conditions: DB-624 capillary column (30 m × 0.25 mm × 1.40 µm); helium carrier gas at constant flow (1.0 mL·min⁻¹); oven program: 40 °C (hold 1 min), 3 °C·min⁻¹ to 100 °C, 10 °C·min⁻¹ to 250 °C (hold 10 min).

MS conditions: electron impact ionization (70 eV); ion source temperature 230 °C; interface temperature 280 °C; quadrupole temperature 150 °C; mass scan range *m/z* 45–500 in full-scan mode.

2.4. Data Processing

BVOCs were identified by matching mass spectra against the NIST 2020 and Wiley spectral libraries, supplemented by manual interpretation and reference to published mass spectral data. The relative abundance (%) of each compound was calculated using the peak area normalization method based on the total ion chromatogram (TIC) and expressed as the percentage of its peak area relative to the total peak area of all detected compounds.

3. Results

3.1. General BVOC Profiles Across Seasons

Total ion chromatograms (TICs) of BVOCs from the ten stands across four seasons are shown in Figures S1–S4. The number of chromatographic peaks varied considerably among stands and seasons, indicating distinct BVOC compositions.

3.2. Seasonal and Spatial Variations in BVOC Composition

3.2.1. Spring

The total relative abundance of BVOCs ranged from 5.32% to 76.35% among forest stands in spring (Figure 2A). The *T. dolabrata* stand (THDO10) and *L. pungens*–*P. hwangshanensis* mixed stand (LPLR09) showed the highest relative abundances, whereas the *C. lanceolata*–*H. chinensis* mixed stand (CHHA03) and *C. japonica*–*C. lanceolata* mixed stand (CCSP04) showed the lowest values. The number of detected BVOCs ranged from 4 to 35 and generally followed the same pattern as total relative BVOC abundance. BVOC composition differed among forest stands. Aromatic hydrocarbons were the major compound class in the *S. tsumu*–*C. lanceolata* mixed stand (SCLC01), *A. firma* stand (ABFI08), *L. pungens*–*P. hwangshanensis* mixed stand (LPLR09), and *T. dolabrata* stand (THDO10), while alkanes contributed relatively larger proportions in the *T. dolabrata* stand (THDO10), *L. formosana*–*C. lanceolata* mixed stand (LCTL02), *C. lanceolata*–*S. superba* mixed stand (CSEL06), *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07), and *L. pungens*–*P. hwangshanensis* mixed stand (LPLR09). Terpenoids, esters, ketones, and aldehydes, respectively, reached higher relative abundances in the *T. dolabrata* stand (THDO10), *C. lanceolata*–*S. superba* mixed stand (CSEL06), *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07), *L. formosana*–*C. lanceolata* mixed stand (LCTL02), and *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05). Overall, the spring BVOC profiles differed among forest stands, with the highest total relative abundance being approximately 14-fold greater than the lowest.

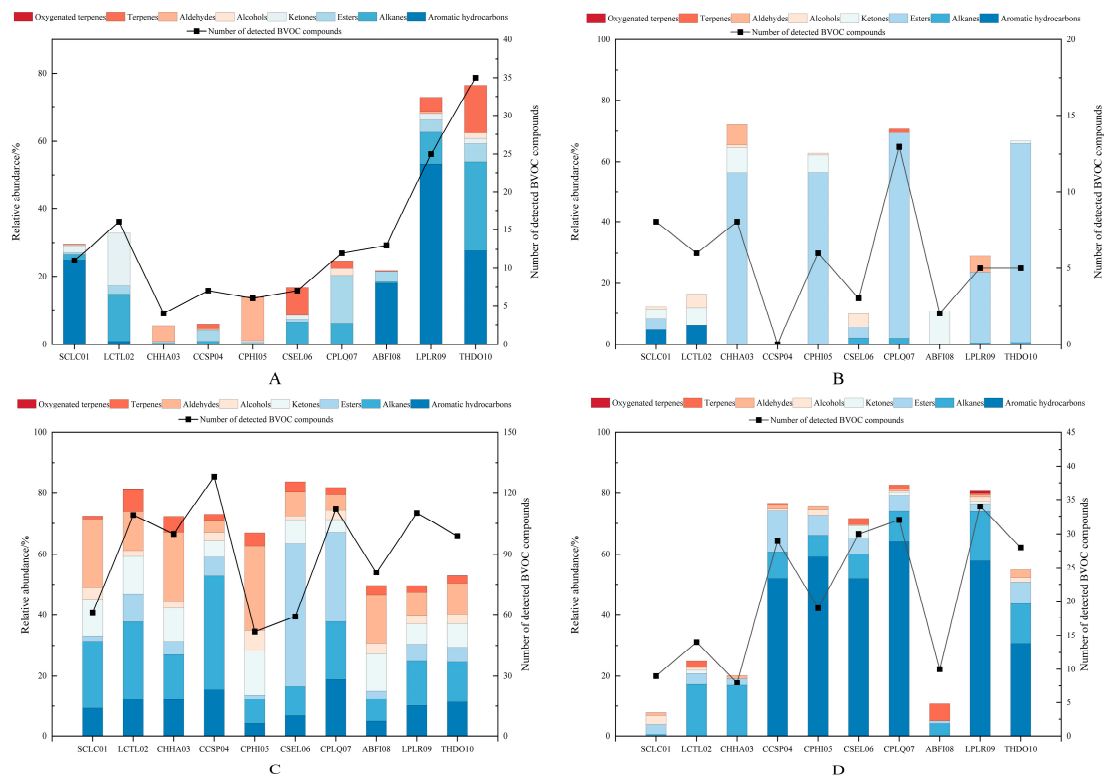


Figure 2. Relative abundance of volatile organic compounds released and number of detected BVOCs in 10 forest stands in all four seasons. Notes: (A) = spring; (B) = summer; (C) = autumn; (D) = winter.

3.2.2. Summer

Across forest stands, the total relative abundance of BVOCs ranged from 0% to 72.06% in summer (Figure 2B). The *C. lanceolata*–*H. chinensis* mixed stand (CHHA03) (72.06%), *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07) (70.70%), *T. dolabrata* stand (THDO10) (66.76%), and *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05) (62.79%) showed the highest relative abundances, whereas the remaining stands were all below 30%. The number of detected BVOCs ranged from 2 to 13. The *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07) contained the greatest number of compounds (13), followed by the *S. tsumu*–*C. lanceolata* mixed stand (SCLC01) (8), while fewer than eight compounds were detected in the remaining stands. Compared with spring, fewer BVOCs were detected across most forest stands. BVOC composition also differed among forest stands. Esters were the major compound class in the *C. lanceolata*–*H. chinensis* mixed stand (CHHA03), *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05), *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07), and *T. dolabrata* stand (THDO10), accounting for more than 55% of the detected BVOC relative abundance. Aldehydes had a relatively high proportion in the *L. pungens*–*P. hwangshanensis* mixed stand (LPLR09), whereas ketones accounted for a higher proportion in the *C. lanceolata*–*H. chinensis* mixed stand (CHHA03) and *A. firma* stand (ABFI08), and terpenoids were detected only in the *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07). Overall, the summer BVOC profiles were characterized by fewer detected compounds and a greater contribution of esters than in spring.

3.2.3. Autumn

Across forest stands, the total relative abundance of BVOCs ranged from 49.62% to 83.70% in autumn (Figure 2C). The *C. lanceolata*–*S. superba* mixed stand (CSEL06) (83.70%), *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07) (81.83%), and *L. formosana*–*C. lanceolata* mixed stand (LCTL02) (81.29%) showed the highest relative abundances. The number of

detected BVOCs ranged from 52 to 128, with the highest numbers detected in the *C. japonica*–*C. lanceolata* mixed stand (CCSP04) (128) and *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07) (112). Compared with the other seasons, autumn had the greatest number of detected BVOCs across forest stands. In terms of chemical composition, aldehydes dominated in the *S. tsumu*–*C. lanceolata* mixed stand (SCLC01), *C. lanceolata*–*H. chinensis* mixed stand (CHHA03), *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05), and *A. firma* stand (ABFI08), whereas esters showed a relatively large proportion in the *C. lanceolata*–*S. superba* mixed stand (CSEL06) and *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07). Ketones also accounted for a relatively high proportion (14.63%) in the *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05). Alcohols and terpenoids were detected in all forest stands, although their relative abundances remained below 10%. Overall, autumn BVOC profiles were characterized by relatively high compound richness and diverse chemical composition among forest stands.

3.2.4. Winter

Across forest stands, the total relative abundance of BVOCs ranged from 7.95% to 82.63% in winter (Figure 2D). The *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07) (82.63%), *L. pungens*–*P. hwangshanensis* mixed stand (LPLR09) (80.71%), *C. japonica*–*C. lanceolata* mixed stand (CCSP04) (76.58%), *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05) (75.55%), and *C. lanceolata*–*S. superba* mixed stand (CSEL06) (71.52%) showed the highest relative abundances, whereas the *S. tsumu*–*C. lanceolata* mixed stand (SCLC01) and *A. firma* stand (ABFI08) showed the lowest values. The number of BVOCs ranged from 8 to 34, with the greatest numbers detected in the *L. pungens*–*P. hwangshanensis* mixed stand (LPLR09) (34) and *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07) (32). In terms of chemical composition, aromatic hydrocarbons and alkanes represented the dominant compound groups in most forest stands. Esters accounted for a relatively large proportion in the *S. tsumu*–*C. lanceolata* mixed stand (SCLC01) (3.41%), terpenoids showed their highest relative abundance in the *A. firma* stand (ABFI08) (5.70%), and ketones accounted for a relatively high proportion in the *C. lanceolata*–*S. superba* mixed stand (CSEL06). Overall, winter BVOC profiles were dominated by aromatic hydrocarbons and alkanes across most forest stands, whereas the remaining compound classes generally contributed relatively small proportions.

3.2.5. Seasonal Variation in BVOCs Shared Among Forest Stands

No BVOCs were common to all forest stands in spring, summer, or winter (Figure 3). In autumn, six compounds were shared across all ten forest stands. Among these compounds, benzaldehyde and nonanal showed the highest cumulative relative abundances (59.21% and 16.24%, respectively). Both compounds belong to oxygenated BVOCs and have been widely reported as products of plant secondary metabolism and lipid oxidation processes, suggesting that these compounds may represent common components of the autumn BVOC background across mixed forest stands.

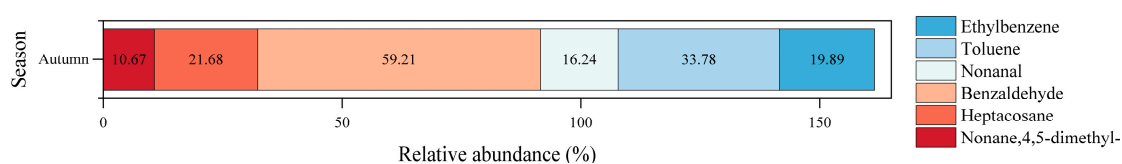


Figure 3. Cumulative relative abundance of compounds in ten forest stands during autumn.

3.3. Seasonal Dynamics Within Stands

Venn analysis revealed no shared BVOs across all four seasons in any stand (Figure 4). Season-specific BVOs accounted for 81%–95% of total detected compounds, with the highest numbers in the *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07) (130) and *C. japonica*–*C. lanceolata* mixed stand (CCSP04) (121).

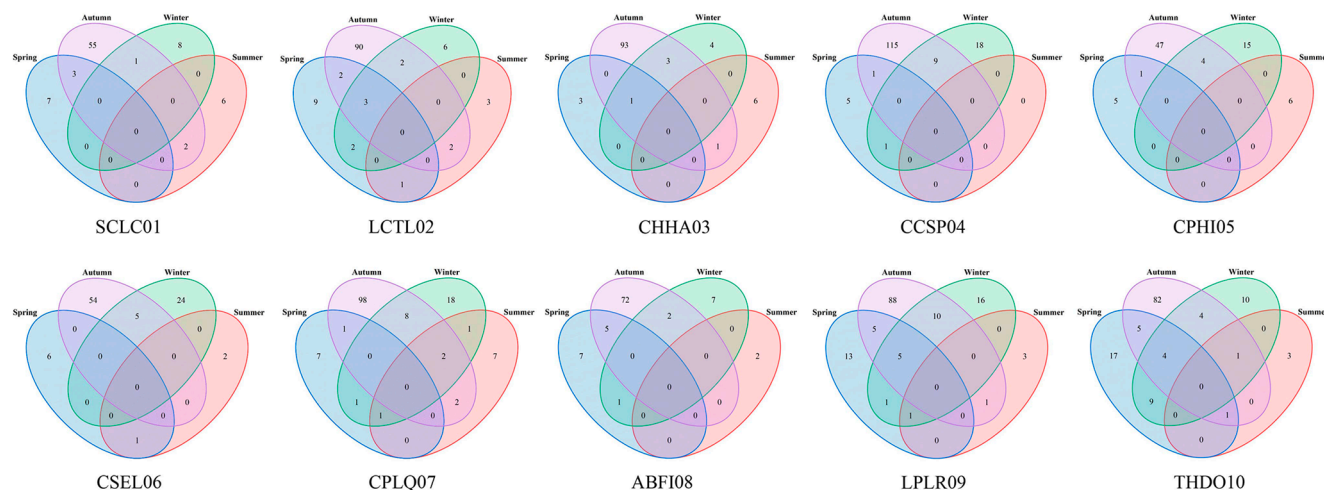


Figure 4. Number of BVOs released by 10 forest stands across the four seasons.

Seasonal changes in BVOC relative abundance and chemical composition differed among the ten forest stands (Figure 5). Six stands showed their highest total relative abundances in autumn, and five reached their highest values in winter. Overall, autumn and winter were the seasons with relatively high BVOC relative abundance in most forest stands.

The major BVOC classes also changed across seasons. Aromatic hydrocarbons, alkanes, and aldehydes were the major compound classes in spring. During summer, esters became the major compound class in the *C. lanceolata*–*H. chinensis* mixed stand (CHHA03), *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05), *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07), and *T. dolabrata* stand (THDO10). Several tentatively identified ester compounds, including heptyl tetraphenylacetate and 2-oxo-bicyclo [3.2.2] nona-3,6-dien-1-yl benzoate, accounted for a considerable proportion of the ester fraction. In autumn, aldehydes, alkanes, and esters were the major compound classes in different forest stands. During winter, aromatic hydrocarbons dominated in *C. japonica*–*C. lanceolata* mixed stand (CCSP04), *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05), *C. lanceolata*–*S. superba* mixed stand (CSEL06), *C. eyrei*–*P. hwangshanensis* mixed stand (CPLQ07), and *L. pungens*–*P. hwangshanensis* mixed stand (LPLR09), whereas alkanes or aldehydes remained predominant in the remaining forest stands.

Seasonal changes in dominant BVOC classes also differed among forest stands. The *C. lanceolata*–*H. chinensis* mixed stand (CHHA03), *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05), and *T. dolabrata* stand (THDO10) showed clear seasonal shifts, with the dominant compound classes changing from aromatic hydrocarbons or alkanes in spring to esters in summer, followed by aldehydes, alkanes, or aromatic hydrocarbons in autumn and winter. In contrast, the *L. formosana*–*C. lanceolata* mixed stand (LCTL02) and *A. firma* stand (ABFI08) showed relatively similar BVOC profiles throughout the year, with aldehydes, alkanes, and aromatic hydrocarbons remaining the major compound classes across seasons.

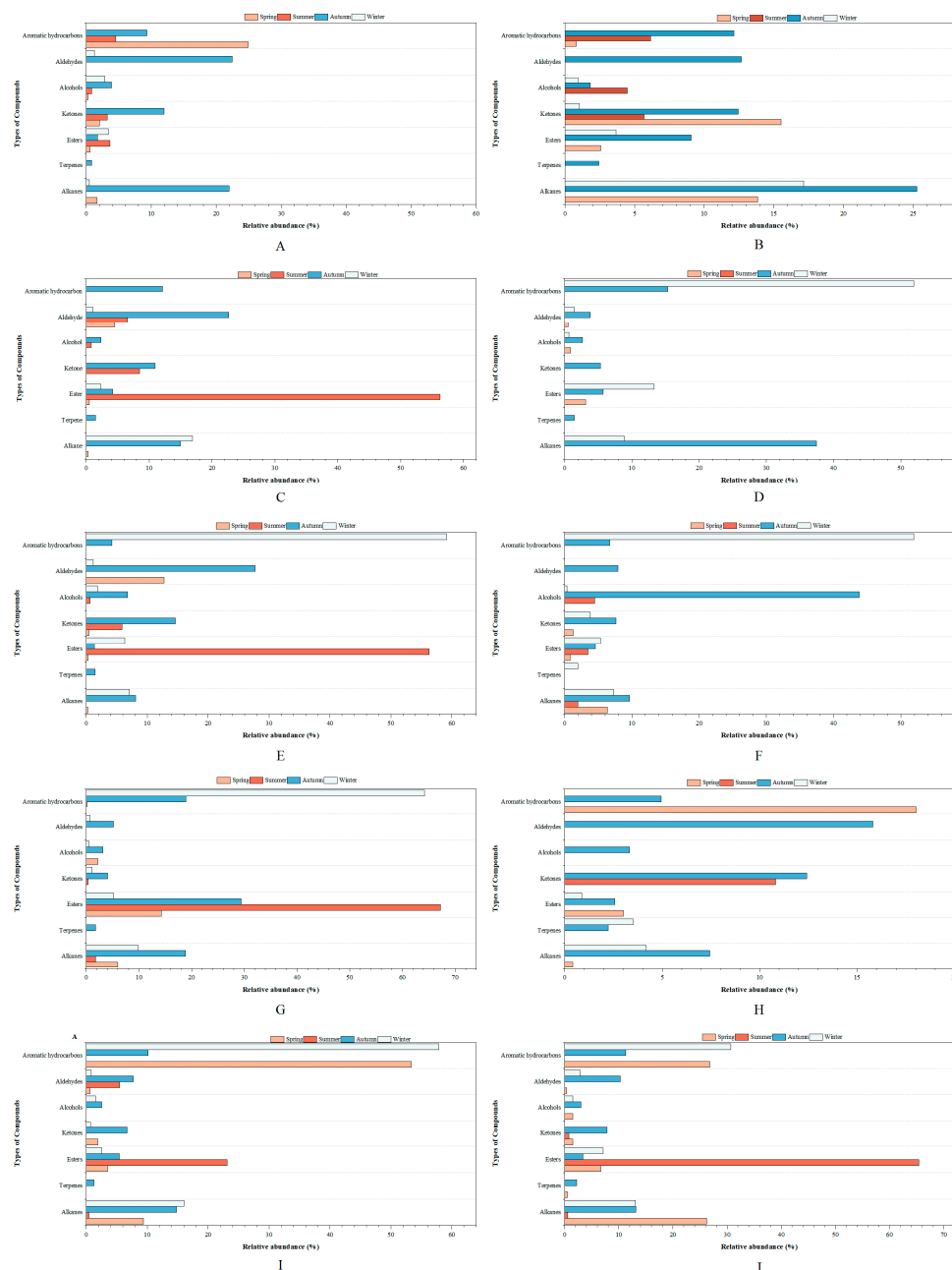


Figure 5. Relative abundance of BVOCs released by 10 forest stands throughout the four seasons. Notes: (A) = SCLC01; (B) = LCTL02; (C) = CHHA03; (D) = CCSP04; (E) = CPHI05; (F) = CSEL06; (G) = CPLQ07; (H) = ABFI08; (I) = LPLR09; (J) = THDO10.

3.4. Terpenoid Characteristics

A total of 10 terpenoid compounds were detected across the investigated forest stands (Table 2). Overall, terpenoid profiles were characterized by the dominance of a few high-relative-abundance compounds accompanied by multiple low-relative-abundance components; among these, the *A. firma* stand (ABFI08) (5.75%) and *T. dolabrata* stand (THDO10) (2.72%) had the highest total terpenoid abundance.

Table 2. The relative total abundance of terpenoid compounds released in the four seasons.

No.	Compounds	For- mula	Relative Abundance (%)									
			SCLC01	LCTL02	CHHA0 3	CCSP04	CPHI05	CSEL06	CPLQ07	ABFI08	LPLR09	THDO1 0
1	Camphene	C ¹⁰ H ¹⁶		0.51	0.30				0.23	3.68	0.62	0.67
2	3-Carene	C ¹⁰ H ¹⁶	0.45									
3	o-Cymene	C ¹⁰ H ¹⁴	0.39		0.65	0.17	1.09	1.95	0.56		1.09	0.49
4	p-Cymene	C ¹⁰ H ¹⁴		1.23			0.18			0.70		0.18
5	Longifolene	C ¹⁵ H ²⁴		0.71					0.83	1.37		1.00
6	γ-Terpinene	C ¹⁰ H ¹⁶			0.13							
7	D-Limonene	C ¹⁰ H ¹⁶				0.60			0.15			
8	β-Ocimene	C ¹⁰ H ¹⁶					0.17					
9	Alpha-phel- landrene	C ¹⁰ H ¹⁶			0.36	0.12						0.07
10	Isosativene	C ¹⁵ H ²⁴										0.31
	Total		0.84	2.45	1.44	0.89	1.44	1.95	1.77	5.75	1.71	2.72

Several terpenoid compounds, including camphene, o-cymene, p-cymene, and longifolene, were detected across multiple forest stands. Among these, o-cymene was the most widely distributed, while camphene exhibited significantly higher levels in the *A. firma* stand (ABFI08). In contrast, γ-terpinene, D-limonene, β-ocimene, α-phellandrene, and isosativene occurred at relatively low abundances and were detected only in a limited number of forest stands.

3.5. BVOC Composition Patterns in *Cunninghamia Lanceolata*-Dominated Mixed Stands

Principal component analysis (PCA) was performed to evaluate differences in BVOC composition among six *Cunninghamia lanceolata*-dominated forest stands across four seasons (Figure 6). The first two principal components explained 69.1%, 68.4%, 72.1%, and 76.7% of the variance in the standardized BVOC relative abundance matrix for spring, summer, autumn, and winter, respectively. The PCA results showed clear separation among the six *Cunninghamia lanceolata*-dominated forest types in the ordination space across seasons, indicating distinct BVOC composition profiles despite their shared dominant tree species.

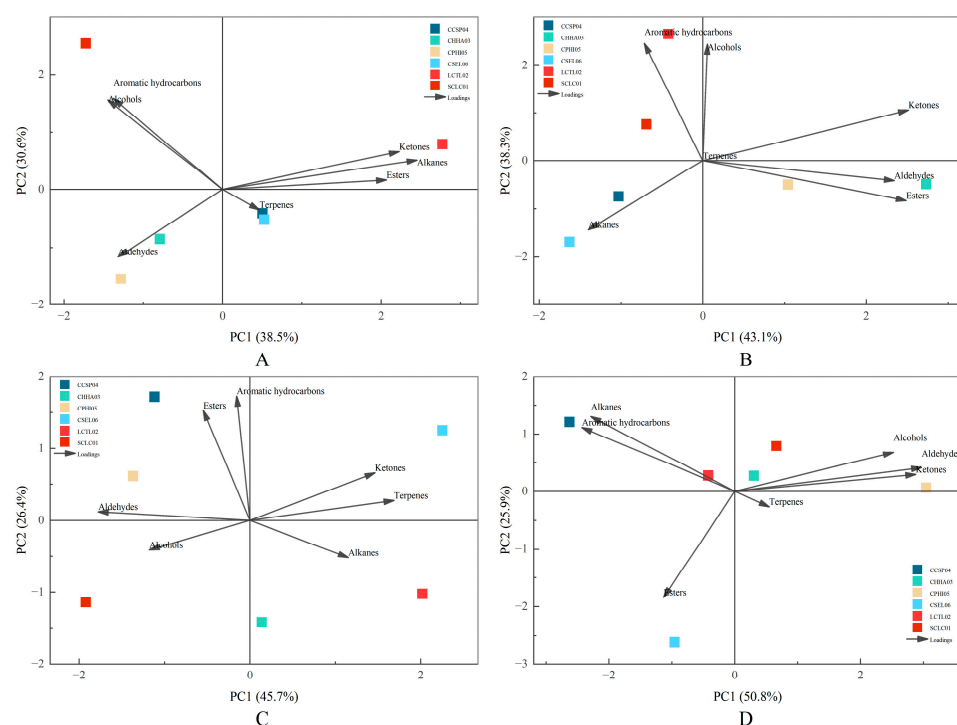


Figure 6. PCA biplots of BVOC composition in six *Cunninghamia lanceolata*-dominated forest stands across the four seasons. Notes: (A) spring; (B) summer; (C) autumn; (D) winter. Arrows represent the loading vectors of different BVOC classes, and points represent the six forest stands.

The *S. tzumu*–*C. lanceolata* mixed stand (SCLC01) remained separated from other forest stands along the positive direction of PC2 in most seasons, suggesting differences in BVOC composition profiles. *L. formosana*–*C. lanceolata* mixed stand (LCTL02) was consistently positioned near the positive direction of PC1 across multiple seasons and showed strong associations with ketones, esters, and alkanes, indicating relatively consistent positioning in relation to these compound groups across seasons. The *C. lanceolata*–*P. schneideriana* mixed stand (CPHI05) and *C. lanceolata*–*S. superba* mixed stand (CSEL06) exhibited close spatial positions in several seasons, suggesting similar BVOC composition patterns.

The PCA loading plots further demonstrated that different BVOC groups contributed differently to the separation of forest stands. Based on the loading values (Table S6), ketones, esters, and alkanes showed relatively high positive contributions to PC1, whereas alcohols, aromatic hydrocarbons, and aldehydes contributed more strongly to PC2 or the negative direction of PC1. These patterns suggest that the separation of forest stands was associated with the combined contribution of multiple BVOC classes rather than a single compound group.

3.6. Spatial Distribution of BVOCs Across Seasons

Heat map analysis based on relative abundance revealed clear spatial and seasonal patterns (Figure S5). Spring and autumn exhibited higher BVOC richness and differentiation among stands. Summer releases were less diverse. Both stand type and season jointly influenced BVOC composition, resulting in distinct spatiotemporal distribution patterns.

4. Discussion

4.1. Effects of Forest Stand Composition on BVOC Spatial Variation

Under different seasonal conditions, BVOC composition and relative abundance exhibited clear spatial heterogeneity among different forest stands. Among the investigated forest stands, the *T. dolabrata* stand (THDO10) showed relatively high BVOC relative

abundance during spring. This pattern is consistent with previous phytochemical studies showing that *Thujopsis dolabrata* contains abundant terpenoids, including α -pinene, sabinene, and other mono- and sesquiterpenes stored in resin-rich tissues [27–29]. These species-specific chemical characteristics may contribute to the relatively high proportion of terpene-related compounds detected in this stand. In contrast, forest stands containing *Pinus hwangshanensis*, particularly the *C. eyrei*–*P. hwangshanensis* (CPLQ07) and *L. pungens*–*P. hwangshanensis* (LPLR09) mixed stands, maintained relatively high BVOC relative abundance and compound richness during autumn and winter. Previous studies have shown that pine species possess well-developed resin ducts that store terpenoid-rich oleoresins, allowing volatile compounds to remain detectable even under relatively low-temperature conditions [30,31].

Mixed forest stands generally exhibited more diverse BVOC profiles than single-species stands, particularly during autumn. This observation agrees with previous studies showing that coniferous and broadleaf species often contribute different groups of volatile compounds, increasing the compositional diversity of stand-level BVOCs [32,33]. However, several studies have also suggested that greater species richness does not necessarily result in higher BVOC diversity or emissions [34]. Instead, BVOC composition is more strongly influenced by tree species identity [35], stand composition [36], and interactions among coexisting species [37]. The spatial variation observed in this study therefore likely reflects the combined influence of dominant tree species and stand composition rather than species diversity alone.

4.2. Seasonal Dynamics of BVOCs Within Stands

Seasonal changes in BVOC composition were observed within individual forest stands, although the seasonal trajectories differed among stands. Overall, autumn and winter were associated with relatively higher BVOC relative abundance, whereas summer was characterized by lower compound richness and compositional shifts in several forest stands. Similar seasonal variability has been reported in previous studies, suggesting that BVOC composition is regulated by the combined effects of plant phenology and environmental conditions rather than by temperature alone [38,39].

A notable feature of the present study was the relatively high contribution of esters in several forest stands during summer. This pattern differs from observations in many coniferous forests, where monoterpenes typically dominate the summer BVOC profile [40]. Elevated temperature generally promotes terpene biosynthesis and volatilization from storage tissues, resulting in increased monoterpene abundance during the growing season [41]. However, unlike many coniferous forests where monoterpenes dominate summer BVOC profiles [42], several forest stands in the present study showed relatively high proportions of esters. This pattern may be associated with the flowering phenology of *Hydrangea* species rather than temperature alone. Floral esters are synthesized through alcohol acyltransferase-mediated esterification pathways and play important roles in pollinator attraction and reproductive signaling [43,44]. Because *Hydrangea* species flower mainly from May to July [45], enhanced floral volatile production may explain the increased contribution of esters observed during summer [46].

The autumn maximum observed in this subtropical forest differs from the summer-dominated BVOC patterns commonly reported in temperate forests [47], likely owing to differences in regional climate and plant physiological responses. In subtropical monsoon forests, prolonged summer heat, high humidity, and reduced solar radiation may constrain photosynthetic carbon assimilation and light-dependent BVOC production, whereas improved radiation conditions after the monsoon favor BVOC accumulation and release in autumn [48]. Accordingly, aldehydes and ketones accounted for relatively large

proportions in many forest stands during autumn, consistent with leaf senescence and membrane lipid degradation [49].

During winter, aromatic hydrocarbons accounted for a relatively larger proportion of the detected volatile compounds. Because this study evaluated relative abundance rather than absolute concentrations, this pattern should not be interpreted as enhanced winter emissions of aromatic hydrocarbons. Instead, it most likely reflects the marked seasonal decline in plant-derived terpenoids and oxygenated BVOCs [50], together with possible contributions from regional background air or other non-biogenic sources [51]. Nevertheless, terpene-related compounds remained detectable in several conifer-dominated stands, probably because stored terpenoids can continue to volatilize from resin ducts even when photosynthetic activity and de novo terpene biosynthesis are greatly reduced during winter [52,53]. These observations suggest that seasonal BVOC dynamics are jointly shaped by seasonal environmental conditions and stand characteristics.

4.3. Patterns and Drivers of Terpenoids

Terpenoids, particularly monoterpenes such as camphene and o-cymene, are among the major bioactive BVOCs emitted by forest vegetation and have been reported to exhibit anti-inflammatory, antioxidant, and neuroactive activities that may contribute to the health benefits associated with forest exposure [54]. Their seasonal release patterns varied among stands: *T. dolabrata* stand (THDO10) peaked in spring, consistent with its high terpene synthesis potential due to its genetic characteristics [55]; *A. firma* stand (ABFI08) peaked in winter, suggesting storage-driven release [56]; other stands showed autumn or spring peaks, aligning with some temperate forest studies [57,58] but contrasting with summer peaks reported elsewhere [59], possibly due to local microclimatic factors such as reduced solar radiation during the monsoon season [60]. Overall, the relative abundance of terpenoids was generally low across the investigated stands, indicating that species composition and local environmental conditions may constrain terpene emissions in this subtropical forest ecosystem.

4.4. BVOC Characteristics in Chinese Fir-Dominated Mixed Stands

Although *Cunninghamia lanceolata* was the dominant tree species in all six forest stands, PCA revealed distinct differences in BVOC composition among stands across seasons. This finding suggests that the presence of the same dominant species does not necessarily result in similar BVOC profiles. Similar observations have been reported in mixed forest ecosystems, where tree species identity and associated species composition exert a stronger influence on BVOC composition than the dominant canopy species alone [61]. Different companion species contribute distinct groups of volatile compounds through species-specific metabolic pathways, resulting in characteristic stand-level BVOC profiles [62].

Among the six mixed stands, the clear separation of the *S. tsumu*–*C. lanceolata* mixed stand (SCLC01) suggests that this stand possessed a relatively distinct BVOC composition. Previous studies have shown that broadleaf and coniferous tree species differ in their BVOC composition because of species-specific secondary metabolic pathways and emission capacities, with broadleaf species often contributing a wider range of oxygenated BVOCs to mixed forest stands [63]. By contrast, the relatively close distribution of the *C. lanceolata*–*P. schneideriana* (CPHI05) and *C. lanceolata*–*S. superba* (CSEL06) mixed stands suggests that these forest stands shared more similar BVOC composition, possibly because of comparable functional traits and chemical characteristics of the associated tree species.

The PCA loading patterns indicate that stand differentiation reflected the combined contribution of multiple BVOC classes rather than any single characteristic compound.

This observation is consistent with previous studies showing that forest BVOC composition represents an integrated volatile blend generated by multiple compound classes emitted from coexisting plant species, rather than by individual marker compounds alone [64].

5. Conclusions

This study demonstrated pronounced spatial and seasonal variation in BVOC composition and relative abundance among ten representative forest stands in Caoyutang Forest Park. Forest stand characteristics and seasonal environmental conditions jointly influenced BVOC composition, resulting in distinct stand-specific volatile profiles throughout the year. Autumn exhibited the greatest BVOC richness across most forest stands, whereas the relative abundance of specific compound classes varied markedly among seasons.

Among the investigated stands, the *Thujopsis dolabrata* stand (THDO10) exhibited relatively high terpenoid abundance during spring, while the *Abies firma* stand (ABFI08) showed the highest relative terpenoid abundance during winter. The mixed conifer–broadleaf stands containing *Hydrangea* species displayed relatively high proportions of esters during summer, whereas autumn was characterized by greater BVOC richness and chemical diversity across many mixed stands. These seasonal characteristics suggest that forest therapy activities could be scheduled according to stand-specific BVOC profiles, with spring and winter emphasizing terpenoid-rich coniferous stands and summer or autumn utilizing mixed forests with higher oxygenated BVOC diversity.

The results demonstrate that differences in tree species composition and forest stand characteristics are associated with variations in BVOC profiles, even among forests with the same dominant tree species. These findings provide ecological insights into seasonal BVOC dynamics and highlight the importance of considering vegetation composition and seasonal characteristics in the evaluation and management of forest wellness environments.

This study was based on relative abundance data rather than quantitative BVOC emission flux measurements, and the limited spatial replication within stands may constrain the interpretation of small-scale variability. Future studies should integrate long-term monitoring, quantitative emission measurements, environmental factors, and human physiological assessments to further clarify the ecological and health-related implications of forest BVOCs.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/f17080914/s1>. Figures S1. Total ion chromatograms of volatile components in different forest stands of the grass carp pond in spring; Figures S2. Total ion chromatograms of volatile components in different forest stands of the grass carp pond in summer; Figures S3. Total ion chromatograms of volatile components in different forest stands of the grass carp pond in autumn; Figures S4. Total ion chromatograms of volatile components in different forest stands of the grass carp pond in winter; Figure S5. Spatial distribution characteristics of BVOC composition in different forest regions across seasons; Table S1. Overview of plot plants; Tables S2–S5. Weather data for Caoyutang Forest Park; Table S6. PCA loading values of BVOC classes across seasons.

Author Contributions: Conceptualization, L.L. and Y.L.; methodology, L.P., Q.L., and H.L.; formal analysis, L.P. and J.Y.; investigation, L.P., Q.L., H.L., and J.Y.; writing—original draft preparation, L.P.; writing—review and editing, L.L. and Y.L.; supervision, L.L.; funding acquisition, L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Zhejiang Province, grant number LGN22C160007, and the Lishui Key Research and Development Program, grant number 2020ZDYF06.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request.

Acknowledgments: This work was supported by the Natural Science Foundation of Zhejiang Province (Grant No. LGN22C160007) and the Lishui Key Research and Development Program (Grant No. 2020ZDYF06).

Conflicts of Interest: The authors declare no conflicts of interest.

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