Short communication

Monoterpene emissions from needles of hybrid larch F1 \( (Larix gmelinii\ var. japonica \times Larix kaempferi) \) grown under elevated carbon dioxide and ozone

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**Highlights**

- Saplings of hybrid larch F1 were grown under elevated CO\(_2\) and O\(_3\).
- The rate of total monoterpene emission was significantly decreased by elevated CO\(_2\).
- However, elevated O\(_3\) had no effect on the total monoterpene emission rate.
- Relative abundances of highly reactive monoterpenes were smaller under elevated O\(_3\).
- The higher reactivity with O\(_3\) may mitigate oxidative damage in needles of the larch.

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**Abstract**

We measured monoterpene emissions from needles of hybrid larch F1 \( (Larix gmelinii\ var. japonica \times Larix kaempferi) \) to evaluate the response of monoterpene emission rates and their composition to elevated CO\(_2\) (600 \(\mu\text{mol mol}^{-1}\)) and O\(_3\) (60 nmol mol\(^{-1}\)) conditions. The dominant monoterpenes were \(\alpha\)-pinene and \(\beta\)-pinene. The emission rate of total monoterpenes significantly decreased under elevated CO\(_2\) conditions \((P < 0.05)\). The ratio of carbon emission in the form of monoterpenes to photosynthetically fixed carbon also significantly decreased under elevated CO\(_2\) conditions. By contrast, elevated O\(_3\) did not significantly affect the emission rate of total monoterpenes. The ratios of \(\alpha\)-pinene/\(\beta\)-pinene, limonene/\(\beta\)-pinene, and myrcene/\(\beta\)-pinene were all significantly decreased by O\(_3\) exposure \((P < 0.05)\). High reactivity of \(\alpha\)-pinene, limonene, and myrcene when combining with O\(_3\) may be able to mitigate oxidative damage inside the larch needles. No significant combined effects of elevated CO\(_2\) and O\(_3\) on individual or total monoterpene emissions were detected.

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1. Introduction

Biogenic volatile organic compounds (BVOCs), such as isoprene and monoterpenes, are emitted from many forest ecosystems. Current global BVOC emissions are estimated to be approximately 1000 Tg year\(^{-1}\) \((\text{Guenther et al., 2012})\), which represent nearly 90% of the total volatile organic compound emissions from anthropogenic and biogenic sources \((\text{Boucher et al., 2013})\). Monoterpenes are important in atmospheric chemistry and climate, owing to their high reactivity with the OH radical and ozone \((O_3)\) \((\text{Atkinson and Arey, 2003})\). They are closely associated with secondary organic aerosol (SOA) formation \((\text{Mochizuki et al., 2015})\). This SOA forms cloud condensation nuclei (CCN), which contribute to positive or negative radiative forcing \((\text{Kanakidou et al., 2005; Boucher et al., 2013})\), and therefore affect global climate change. Monoterpenes also contribute to the formation of photochemical oxidants such as O\(_3\). The photochemical oxidants not only have an effect on human health \((\text{Ebi and McGregor, 2008})\) and plants \((\text{Karnoskey et al., 2005})\) but also have a positive effect on global warming \((\text{Boucher et al., 2013})\). In addition, monoterpene emission from forest ecosystems is an important component of the carbon budget in the atmosphere. Previous studies have shown that the ratio of carbon...
emitted as terpenoids to that fixed by photosynthesis at the leaf level is a few percentage that may increase during stressful conditions (Kesselmeier et al., 1997; Tani and Kawawata, 2008).

The Larix species are widely spread in boreal forests of the northeastern Eurasian continent. Major Larix species including Larix sibirica (Ruuskainen et al., 2007), Larix cajanderi (Kajos et al., 2013), and Larix kaempferi (Mochizuki et al., 2014) have been reported as monoterpene emitters with storage organs (Chirardo et al., 2010). A hybrid larch F1 (crossing Larix gmelinii var. japonica x Larix kaempferi) has been developed for high resistance to biological stressors and toughness against harsh natural conditions, such as wind and snow damage (when compared with L. kaempferi) (Koike et al., 2004). In addition, this hybrid has a high growth rate driven by high CO2 fixation rates (Koike et al., 2012; Watanabe et al., 2013), and it is thus considered an important species for afforestation in the boreal areas of northern Japan and the Eurasian continent.

Since industrial revolution, the global atmospheric [CO2] has been continuously increased year by year, and this trend will continue in the future (Boucher et al., 2013). In the Asian region, the atmospheric [O3] also has been increasing, largely due to enhanced economic growth and transboundary air pollution (Akimoto, 2003). Rosenstiel et al. (2003) demonstrated that elevated [CO2] decreased isoprene emission rate and isoprene substrate DMAPP (dimethylallyl diphosphate) content of a deciduous broadleaved tree, Populus deltoides. The decreased isoprene emission rate under elevated [CO2] seemed to result from competition for photosynthetic metabolism (Rosenstiel et al., 2003). As for monoterpene, the emission rate of an evergreen broadleaved tree, Quercus ilex, decreased under elevated [CO2] due to a reduction in monoterpene synthase activity (Loreto et al., 2001). On the other hand, elevated [CO2] has been reported to have no effect on monoterpene emissions from the conifer tree, Pinus sylvestris (Raisanen et al., 2008) and the deciduous broadleaved tree, Betula pendula (Vuorinen et al., 2005). Thus, inconsistent results have been reported for the CO2 effect, regardless of whether the studied plants have specialized monoterpene storage organs or not (Niinemets et al., 2010).

There are fewer reports on the effects of elevated [O3] on monoterpene emission than those on isoprene emission (Vickers et al., 2009). Monoterpene emission from trees is increased (Loreto et al., 2004; Li et al., 2009), or not significantly affected (Hartikainen et al., 2012), by elevated [O3], meaning that the effect is different for different plant species. No consistent mechanisms have been reported so far.

Calfapietra et al. (2008) reported that the isoprene emission rate of an O3-sensitive clone of P. tremuloides was lower than that of an O3-tolerant P. tremuloides clone. They suggest that higher O3 uptake rate by the O3-sensitive clone may lead to higher frequency of the reaction between isoprene and O3 in the leaves, resulting in a lower isoprene emission rate. Many monoterpene species are several times more reactive with O3 than isoprene. As the reactivity of individual monoterpene species with O3 are different, the relative abundance of monoterpene inside leaves may vary with the reaction occurring inside the leaves. This might alter monoterpene composition in the emissions, but no reports on this have been published.

Thus, the effects of elevated CO2, O3, or both in combination, on the monoterpene production and emission of trees seem to differ among plant species; no consistent mechanisms explaining these differences have been reported so far. For larch species, there have been no reports investigating monoterpene emissions and composition under elevated CO2 and O3 conditions. To estimate the effect of monoterpene emitted from larch species on the atmospheric chemistry of the northeastern Eurasian continent in the present and foreseeable future, it is necessary to investigate how emissions and composition of monoterpene emitted form larch species vary against climate change.

In the present study, to understand the long-term effects of elevated CO2, O3, or both in combination, on the composition of and rates of monoterpene emissions from the hybrid larch F1, we measured monoterpene emissions of F1 trees kept for two growing seasons under elevated CO2 and O3 separately, and also under elevated CO2 and O3 in combination, using open-top growth chambers.

2. Materials and methods

2.1. Elevated CO2 and O3 experiments in open-top chambers

12 open-top chambers (OTC) (1.2 m long, 1.2 m wide, 2.2 m height) were built in the experimental nursery of the Field Science Center for the Northern Biosphere of Hokkaido University (43° 07’ N, 141° 38’ E; 15 m a.s.l.). Four saplings of 2-yr-old hybrid larch F1 (Larix gmelinii var. japonica × Larix kaempferi) were planted in the ground in each of 12 OTCs, in July 2011, in well-homogenized brown forest soil. Four experimental treatments were set-up for the control (ambient CO2: approximately 380 nmol mol−1; ambient O3: <6 nmol mol−1), elevated CO2 conditions (target: 600 µmol mol−1), elevated O3 conditions (target: 60 nmol mol−1), and elevated CO2 and O3 conditions (target CO2: 600 µmol mol−1; target O3: 60 nmol mol−1). Three OTCs were used as replicates for each treatment. Fumigation of the elevated [CO2], [O3], and [CO2 × O3] treatments was performed from 11 July to 30 September 2011, and from 16 May to 20 October 2012 (total 270 days), during the daytime (spanning two growing seasons). Monthly average CO2 concentrations in elevated [CO2] and elevated [CO2 × O3] treatments ranged from 570 to 640 µmol mol−1 and from 593 to 624 µmol mol−1, respectively, during the exposure period. The monthly average O3 concentration in elevated [O3] treatment ranged from 51 to 81 nmol mol−1 during the exposure period, except in August 2012 (27 nmol mol−1), in which anomalies of the fumigation system occurred. Under elevated [CO2 × O3] treatment O3 concentration ranged from 45 to 63 nmol mol−1 during the exposure period. Air temperature and PPFD in OTCs were not measured. Monthly average air temperature and monthly cumulative PPFD in the experimental site were recorded and ranged from 13 to 23 °C and from 213 to 381 mol m−2 month−1, respectively, during the exposure period. Snow accumulation (maximum snow depth: ~76 cm) was recorded from 16 November 2011 to 11 April 2012. Further details of the experimental design were described previously (Wang et al., 2015).

2.2. Leaf cuvette method

To collect monoterpene from sapling needles, we fabricated a monoterpene sampling system using a portable photosynthesis measurement system (LI-6400XT, Li-Cor Inc., USA) equipped with a conifer cuvette (6400-05, Li-Cor Inc, USA) (Fig. 1) made from transparent acrylic resin. Because the conifer cuvette has a cylinder-shaped structure (diameter: 5 cm, height: 7 cm), it can enclose a 5-cm length shoot. For monoterpene sampling, the outlet air from the conifer cuvette was split into two lines using PFA tubing and Teflon T-junction, one line for monoterpene sampling and the other for CO2 and H2O analyzer (LI-6400XT with a built-in infrared gas analyzer (IRGA)). Monoterpene were collected in stainless-steel adsorbent tubes (ø1/4 inch × 3.5 inch) filled with 200 mg Tenax TA (GL Science, Japan) and 100 mg Carbopack (Supelco, USA) for 10 min at a constant flow rate of 200 ml min−1 using a portable pump (MP-30, Shibata Inc., Japan). We previously confirmed that measurements of net photosynthetic rates and
other parameters were not influenced by the decreased flow rate (from 400 μmol s\(^{-1}\) to 251 μmol s\(^{-1}\)) supplied to the infrared gas analyzer (Tani and Kawawata, 2008).

In a preliminary experiment, we measured monoterpenes emissions from three individual Larix kaempferi saplings using the leaf cuvette method to determine the time required for stabilizing the monoterpenes emission rate after enclosing leaves. Monoterpenes sampling was initiated at 30 min after enclosing leaves and continued for 10 min. This sampling was conducted every 30 min using different sampling tubes until 2 h later. Air was purified by passing through activated charcoal before to be sent to the conifer cuvette to illuminate the sapling leaves. The photosynthetic photon flux density (PPFD), temperature, relative humidity, and [CO₂] were 800 μmol m\(^{-2}\) s\(^{-1}\), 25 °C, 55%, and 400 μmol mol\(^{-1}\), respectively.

To investigate the effects of elevated CO₂, O₃, and their combination on monoterpenes emissions from hybrid larch F₁, we conducted simultaneous measurements of monoterpenes emission rate (E), and net photosynthetic rate (A) using the leaf cuvette method during 12–15 September 2012. Gas sampling was conducted at least 60 min after leaf enclosure. Temperature, PPFD, and purified airflow rate were 25 °C, 800 μmol m\(^{-2}\) s\(^{-1}\), and 400 μmol s\(^{-1}\), respectively. Relative humidity in conifer cuvette was not controlled (range: 50%–70%). The [CO₂] in the conifer cuvette was maintained at 380 μmol mol\(^{-1}\) for the control and elevated [O₃] treatments, and at 600 μmol mol\(^{-1}\) for elevated [CO₂] and [CO₂ × O₃] treatments. O₃ was removed from the supplied air by activated charcoal. We also supplied MnO₂ filters upstream of the adsorbent tubes (Calogirou et al., 1996) to avoid degradation of monoterpenes on the adsorbents. Six individual saplings per treatment were measured using three shoots per individual. Single data regarding individuals were the average of three shoots and data of treatment were the average of six saplings.

2.3. Gas chromatograph mass spectrometry

Monoterpenes were identified and quantified using a gas chromatography mass spectrometer (GC-MS) (QP5050A, Shimadzu, Japan) equipped with a thermal desorption system (Turbo Matrix ATD, Perkin Elmer Instruments, USA). Sampled monoterpenes in the adsorbent tube were thermally desorbed at 280 °C and cryofocused into a Tenax TA-filled glass tube at –20 °C. Monoterpenes were then injected into a capillary column by a fast-heating glass tube and separated using an SPB-5 capillary column (60 m × 25 mm, 1 μm film thickness, Supelco, USA). For quantitative analysis, linear calibration lines were obtained using individual monoterpenes standards diluted with methanol (10 nmol ml\(^{-1}\)). Different amounts (1, 2, and 4 μl) of the monoterpenes standard solutions were spiked into the different adsorbent tubes in a stream of purified helium (100 ml min\(^{-1}\) for 5 min) and samples were analyzed by GC-MS. Details of these analytical methods were described previously (Mochizuki et al., 2014).

2.4. Monoterpene emission rate

The monoterpene emission rate, E (μg g\(_m\)DW h\(^{-1}\)), was calculated as follows:

\[
E = \frac{C_r \times V_m}{DW}
\]  

where \(C_r\) is the monoterpenes mixing ratio in the cuvette (μg mol\(^{-1}\)), \(V_m\) is the flow rate (mol h\(^{-1}\)), DW is dry leaf weight (g). The enclosed leaves were harvested after gas sampling and dried at 80 °C for 72 h to determine their dry weights.

2.5. Estimate of canopy-level of carbon ratio

In order to upscale the leaf-level carbon ratio (carbon emitted as monoterpenes to that fixed by net photosynthetic rate) to the canopy-level carbon ratio (ratio of carbon emitted as monoterpenes fluxes to net ecosystem exchange of CO₂ (NEE)), we assumed the leaf-level carbon ratio is the same as the ratio of carbon emitted as monoterpenes fluxes (M\(_{carbon}\)) to gross primary production (GPP). The canopy-level carbon ratio is calculated from

\[
\text{Canopy-level carbon ratio} = \frac{M_{carbon}}{\text{NEE}} = \frac{M_{carbon}}{(GPP \times 0.20)}
\]

The ratio of NEE to GPP is estimated to be around 0.20 using the data of the annual NEE and GPP in Larix forests (Hirata et al., 2007; Takahashi et al., 2015).
3. Results and discussion

3.1. Steady state during conifer cuvette measurement

As a preliminary experiment, time courses of monoterpene emission rates and net photosynthetic rates of L. kaempferi saplings were measured after a branch of the sapling was enclosed with a conifer cuvette. Monoterpene emission rates decreased within 60 min and then eventually leveled off, while net photosynthetic rate reached a steady state within 60 min (Fig. 2a). Temperature and relative humidity in conifer cuvette also reached a steady state within 60 min (Fig. 2b). Similar results were obtained for all the three measurements using different saplings. Therefore, monoterpene sampling and measurement of the net photosynthetic rate were initiated at least 60 min after leaf enclosure.

Adsorption of BVOCs onto chamber inner walls may occur, depending on their material composition (Ortega and Helming, 2008). We used the conifer leaf cuvette made from acrylic resin. Although adsorption of monoterpenes onto the acrylic surface may have occurred, the adsorption seemed to reach an equilibrium under constant temperature and relative humidity, 60 min after leaf enclosure (Fig. 2a), and therefore the loss of monoterpenes onto the cuvette wall was likely negligible.

3.2. Monoterpene emission from hybrid larch F1

Table 1 summarizes the individual and total monoterpene emission rates of hybrid larch F1 under elevated [CO2], [O3], and [CO2 × O3]. Nine monoterpene compounds—α-pinene, camphene, sabinene, myrcene, β-pinene, 3-carene, limonene, β-phellandrene, and bornyl acetate—were identified as being emitted from the hybrid larch F1 grown in OTCs. In all four treatments, however, α-pinene and β-pinene were dominant. The major monoterpene species emitted from Larix cajanderi grown in Russia is 3-carene, followed by α-pinene (Kajos et al., 2013). The dominant monoterpene species emitted from Larix sibirica in Finland is sabinene (Ruuskanen et al., 2007). Major monoterpene species differ between Larix species. In addition, a difference in the relative abundance of monoterpenes in individual trees (e.g., relative standard deviation of ~10% for α-pinene) was observed in this study; this was likely caused by the different chemotypes of individual trees (Bäck et al., 2012).

Total monoterpene emission rate decreased by 36% in response to elevated [CO2] when compared with the control (P < 0.05). The emission rates of α-pinene and β-phellandrene were significantly lower under elevated [CO2] than under control conditions (α-pinene: P < 0.05, β-phellandrene: P < 0.01). Total monoterpene emission rate under elevated [O3] did not differ significantly than that under the control. Considering the specific compounds, only β-pinene under elevated [O3] had a significantly higher emission rate than the control (P < 0.05). Significant combined effects of elevated [CO2 × O3] on individual and total monoterpene emissions were not detected.

The total monoterpene emission rate of hybrid larch F1 (2.98–5.58 μg gDW h–1) was comparable to the emission rates at 25 °C, calculated from basal emission rates (at 30 °C), reported for Larix cajanderi grown in Russia (0.3–12 μg gDW h–1) (Kajos et al., 2013), and for Larix sibirica grown in Finland (3.2–13 μg gDW h–1) (Ruuskanen et al., 2007). Total monoterpene emission rate of the hybrid larch F1 was in the intermediate range compared with the rates of the other trees (Kesselmeier and Staudt, 1999).

3.3. Effect of elevated [CO2] on monoterpene emission

No effects of elevated [CO2] on total monoterpene emission rate were observed for the evergreen coniferous, Pinus sylvestris (700 μmol mol–1 throughout 5 year) (Raisanen et al., 2008) and deciduous broadleaved tree, Betula pendula clones (double of ambient [CO2] for two growing seasons) (Vuurinen et al., 2005). However, Loreto et al. (2001) reported that total monoterpene emission from an evergreen broadleaved tree, Quercus ilex decreased under elevated CO2 (700 μmol mol–1 for three years) and this reduction was significantly correlated with monoterpene synthase activity. We found that a high [CO2] also had a negative effect on total monoterpene emissions from saplings of the hybrid larch F1. However, it is unclear in this study whether the decrease in the monoterpene emissions is associated with a decrease in the monoterpene synthase activity.

As for net photosynthetic rate, no single effects of elevated [CO2] and [O3], and no combined effect of [CO2 × O3] were observed.
To investigate changes in monoterpene composition to O3 exposure, we calculated the ratio of the emission rate of each monoterpene to that of β-pinene, which is least reactive and has the longest lifetime among the major monoterpenes emitted from the hybrid larch F1 (Table 2). The ratios of α-pinene/β-pinene (P < 0.01), limonene/β-pinene (P < 0.05), and myrcene/β-pinene (P < 0.05) were all significantly lower under elevated [O3] than under control (Table 2), suggesting that the relative abundance of the highly reactive monoterpenes α-pinene, limonene, and myrcene were smaller under elevated O3. This is caused by the significantly higher emission rate of β-pinene under elevated [O3] than under the control (Table 1), despite no significant differences in the emission rates of the other monoterpenes between treatments.

Generally, the uptake of O3 inside a leaf leads to the production of reactive oxygen species (ROS) such as a singlet oxygen (1O2), a superoxide (O2·−), a hydrogen peroxide (H2O2), and hydroxyl radicals (OH) (Langebartels et al., 2002; Dizengremel et al., 2012). To remove excess ROS from a leaf, the plant may rely upon a variety of antioxidant compounds and enzymes (Apel and Hirt, 2004). Recently, Jardine et al. (2012) reported that isoprene oxidation products such as methyl vinyl ketone and methacrolein were directly emitted from oxidative-stressed leaves, suggesting that isoprene oxidation occurs in leaves to remove ROS. Hewitt et al. (1990) and Vickers et al. (2009) reported that monoterpenes might act as antioxidant compounds against O3 to protect plant leaves. This suggests that the high reactivity of monoterpenes plays an important role in scavenging O3 and excess ROS from leaves; this may explain why lower relative abundances of the more highly reactive monoterpenes were observed under elevated [O3] in our experiment. Our results suggest either that β-pinene synthesis is only enhanced by high [O3], or that synthesis of most monoterpenes is enhanced by elevated O3 but the highly reactive monoterpenes including α-pinene and limonene are decomposed within leaves by O3.

### Table 1

<table>
<thead>
<tr>
<th>Monoterpene emission rate, net photosynthetic rate, and the carbon ratio of hybrid larch F1 tree saplings under control and elevated [CO2], [O3], and [CO2 × O3] conditions.</th>
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<tr>
<td></td>
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<tr>
<td>α-Pinene (μg gDW h−1)</td>
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<tr>
<td>Camphene</td>
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<tr>
<td>Sabine</td>
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<tr>
<td>Myrcene</td>
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<td>β-Pinene</td>
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<tr>
<td>L-3-Carene</td>
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<tr>
<td>Limonene</td>
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<tr>
<td>β-Phellandrene</td>
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<tr>
<td>Bornyl acetate</td>
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<tr>
<td>Total monoterpenes</td>
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<tr>
<td>Net photosynthetic rate, A (mg C gDW h−1)</td>
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<tr>
<td>Carbon ratio (%)</td>
</tr>
</tbody>
</table>

Data are shown mean ± standard deviation (n = 4–6).
Carbon ratio means the ratio of carbon emitted as monoterpenes to that fixed by net photosynthesis.
Significant differences according to two-way ANOVA are indicated with asterisks (*: P < 0.05, **: P < 0.01, degrees of freedom = 1).

### Table 2

| Concentration ratio of each monoterpene to β-pinene under control and elevated [CO2], [O3], and [CO2 × O3] conditions. | Lifetime (h) |
| --- |
| Control | Elevated CO2 | Elevated O3 | Elevated CO2 × O3 | β-Pinene | β-Phellandrene | Sabine | α-Pinene | Limonene | Myrcene |
| 3-Carene/β-Pinene | 1.62 ± 2.04 | 0.67 ± 0.58 | 0.61 ± 0.36 | 0.66 ± 0.55 | 0.52 ± 0.21 | 0.23 ± 0.13 | 0.29 ± 0.23 |
| β-Phellandrene/β-Pinene | 1.08 ± 0.88 | 0.52 ± 0.24 | 0.66 ± 0.10 | 0.52 ± 0.21 | 0.23 ± 0.13 | 0.29 ± 0.23 |
| Sabine/β-Pinene | 0.17 ± 0.12 | 0.09 ± 0.06 | 0.11 ± 0.08 | 0.08 ± 0.03 | 0.20 ± 0.03 | 0.20 ± 0.03 |
| α-Pinene/β-Pinene | 2.61 ± 0.78 | 1.60 ± 0.46** | 1.32 ± 0.23** | 1.22 ± 0.20* | 1.22 ± 0.20* | 1.22 ± 0.20* |
| Limonene/β-Pinene | 0.51 ± 0.33 | 0.40 ± 0.28 | 0.25 ± 0.08* | 0.26 ± 0.10 | 0.26 ± 0.10 | 0.26 ± 0.10 |
| Myrcene/β-Pinene | 0.54 ± 0.71 | 0.63 ± 0.26 | 0.40 ± 0.09 | 0.44 ± 0.25 | 0.44 ± 0.25 | 0.44 ± 0.25 |

Data are shown mean ± standard deviation (n = 6).
Significant differences according to two-way ANOVA are indicated with asterisks (*: P < 0.05, **: P < 0.01, degrees of freedom = 1).
4. Conclusion

We measured monoterpene emission in hybrid larch F1 (Larix gmelinii var. japonica × L. kaempferi) saplings exposed for two growing seasons to elevated [CO₂], [O₃] and [CO₂ × O₃] conditions. The compound α-pinene and β-pinene were the dominant monoterpene emissions. Total monoterpene emission from hybrid larch F1 was significantly decreased by elevated [CO₂] (P < 0.05). The ratio of carbon emitted as monoterpene to net photosynthesis (i.e. carbon ratio) was significantly decreased, which indicated that a high [CO₂] reduced re-emission of carbon from hybrid larch F1. No effects of O₃ exposure were observed on total monoterpene emission. However, the ratios α-pinene/β-pinene, limonene/β-pinene, and myrcene/β-pinene were significantly decreased (P < 0.05) by O₃ exposure. Hence, a higher reactivity of α-pinene, limonene, and myrcene with O₃ may be able to mitigate the oxidative damage of leaf against O₃. No combined effects of elevated CO₂ and O₃ on individual and total monoterpene emissions were observed.

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References