#3

Ramirez, Angelica

LATE DIST

From: Marc Chytilo <marc@lomcsb.com>
Sent: Friday, March 6, 2020 5:07 PM
To: sbcob
Subject: public comment documents
Attachments: BHFS Steinfeld demand to Nutren 5-28-19.pdf; Dominant volatile organic compounds VOCs measured at four Cannabis growing facilities Pilot study results 9-2019.pdf; Wang et al Atmos Environ 2019 Leaf Enclosure Measurements.pdf

Clerk – attached are several documents for inclusion in the Sta Rita Valley Ag Project matter

Thank you –

Marc

* * * * *
If you believe you have received this message in error, please notify sender immediately.
* * * * *

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Brownstein Hyatt Farber Schreck

AGENDA ITEMS
ITEM #: 2
MEETING DATE: 11/7/19

May 28, 2019

Amy M. Steinfeld
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VIA E-MAIL JIM.SOARES@NUTRIEN.COM

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Nutrien Ag Solutions, Inc.
Santa Maria, CA (655)
PO Box 669
Santa Maria, CA 93456

RE: Pesticide Overspray at 1050 West Highway 246

Dear Mr. Soares:

My firm represents Sara Rotman, owner of Busy Bee's Organics, a legal and organic cannabis cultivator located on a 64-acre parcel at 1180 West Highway 246 in Buellton, California. My client is extremely concerned with your company's recent herbicide application on neighboring property located at 1050 West Highway 246.

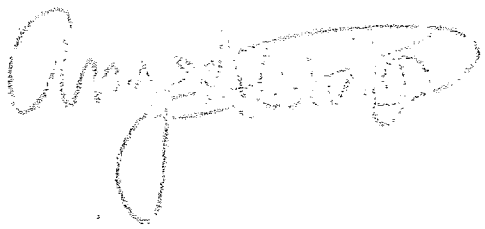
On Monday May 20, 2019, my client observed a spraying rig exiting the neighboring property, indicating that Nutrien had sprayed the property that morning. The weather that day was extremely windy, causing my client to be concerned that her cannabis plants would be contaminated by overspray or drift. California Code of Regulations section 6614(a) requires pesticide and herbicide applicators to evaluate, both prior to and during application, both the meteorological conditions and the surrounding properties to determine the likelihood of harm or damage to neighboring properties. Pesticide and herbicide application cannot be continued when there is a reasonable possibility of damage to nontarget crops or a reasonable possibility of damage to or contamination of nontarget private property. (*See* Cal. Code Regs. § 6614(b).)

My client later confirmed with you that the following products were sprayed on the property for three hours that morning: Makaze (glyphosate), Reglone (diquat), Herbimax (petroleum hydrocarbon), and Choice Weather Master (phosphate ester). These are dangerous herbicides and processing chemicals that could catastrophically damage my client's crop. California's residual pesticide, solvent and processing chemical standards for cannabis are very strict, requiring laboratory test results of less than 0.1 ppm for some residues. (Cal. Code Regs. §§ 5718, 5719.) If any chemical overspray or drift reaches my client's plants, the crop could be rendered completely useless and unmarketable, and she would be required to destroy all contaminated crops. (Cal. Code Regs. §§ 5718(d), 5719(e).)

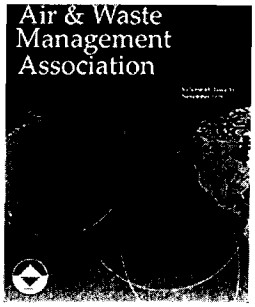
As a result, in the future, you must refrain from overspray if there is any wind or the potential for your chemicals to reach 1050 West Highway 246. In addition, I request that you provide me and my client with advanced notice each time you are scheduled to spray the property located at 1050 West Highway 246. If future spraying occurs without such notice, we will file complaints with the Santa Barbara County Agricultural Commissioner and the State Structural Pest Control Board, and pursue reimbursement for any damaged crops. (See *Jacobs Farm/Del Cabo, Inc. v. W. Farm Serv., Inc.* (2010) 190 Cal.App.4th 1502, 1511 (allowing a farmer to pursue causes of action for negligence, trespass, and nuisance against a company that had applied pesticides to a neighboring farm and subsequent pesticide drift ruined the farmer's crop of organic herbs).)

We look forward to working with your team to ensure that all crops cultivated by Busy Bee's Organics are protected from overspray.

Sincerely,



Amy M. Steinfeld



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Dominant volatile organic compounds (VOCs) measured at four *Cannabis* growing facilities: Pilot study results

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NOTEBOOK PAPER

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Dominant volatile organic compounds (VOCs) measured at four *Cannabis* growing facilities: Pilot study results

Vera Samburova[a], Mark McDaniel[a], Dave Campbell[a], Michael Wolf[b], William R. Stockwell[c], and Andrey Khlystov[a]

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ABSTRACT

In recent years, sale of recreational marijuana products has been permitted in several states and countries resulting in rapid growth of the commercial cannabis cultivation and processing industry. As previous research has shown, biogenic volatile organic compounds (BVOCs) emitted from plants can react with other urban air constituents (e.g., NOx, HO radical) and thus negatively affect regional air quality. In this pilot study, BVOC emissions from *Cannabis* plants were analyzed at four grow facilities. The concentrations of measured BVOCs inside the facilities were between 110 and 5,500 μg m^{-3}. One adult *Cannabis* plant emits hundreds of micrograms of BVOCs per day and thus can trigger the formation of tropospheric ozone (approximately 2.6 g day^{-1} $plant^{-1}$) and other toxic air pollutants. In addition, high concentrations of butane (1,080– 43,000 μg m^{-3}), another reactive VOC, were observed at the facilities equipped with *Cannabis* oil extraction stations.

Implications: High concentrations of VOCs emitted from *Cannabis* grow facilities can lead to the formation of ozone, secondary VOCs (e.g., formaldehyde and acrolein), and particulate matter. Our results highlight that further assessment of VOC emissions from *Cannabis* facilities is needed, and this assessment is one of the key factors for developing policies for optimal air pollution control.

PAPER HISTORY
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Introduction

It is well-known that vegetation is the largest source of atmospheric biogenic volatile organic compounds (BVOCs) (Atkinson and Arey 2003), contributing a significant fraction (approximately 89%) of the total atmospheric VOCs (Goldstein and Galbally 2007). Trees and other types of vegetation emit BVOCs, such as isoprene, pinenes, and terpenoid compounds (Fuentes et al. 2000). Sindelarova et al. (2014) reported that the mean total global emission of BVOCs is 760 Tg (C) $year^{-1}$, with main constituents such as isoprene (70%), monoterpenes (11%), and sesquiterpenes (2.5%). The average global isoprene emission was found to be 594 Tg $year^{-1}$, while for North America, it was 34.5 Tg $year^{-1}$. The principle reactions of BVOCs are with the hydroxyl radical (HO), ozone (O_3) and the nitrate radical (NO_3) (Fuentes et al. 2000). Since the lifetimes of major BVOCs ranges from minutes to a few hours (Atkinson and Arey 2003), they play a major role in the chemistry of the lower troposphere. For example, the lifetime of the most abundant BVOC, isoprene, is 1.4 hours with respect to its reaction with HO radical (Atkinson and Arey 2003), assuming that HO radical concentration is 2×10^6 cm^{-3}. Emitted in the air BVOCs react with HO, NO_3 and O_3 to yield products that react with nitrogen oxides and form pollutants such as ozone, formaldehyde, acetaldehyde, and acrolein (Li et al. 2016; Papiez et al. 2009; Seinfeld and Pandis 2016). Some of these pollutants are potentially hazardous compounds. Tropospheric ozone, for example, is one of the criteria air pollutants (Atkinson 2000; Logan 1985), which, in high concentrations, has harmful effects on human health (Brunekreef and Holgate 2002; Gryparis et al. 2004; Yang et al. 2003) and the environment (Chuwah et al. 2015; Dickson et al. 2001; Mills et al. 2011). Papiez et al. (2009) found that BVOCs emitted by landscaped vegetation contribute significantly to ozone growth rates in the Las Vegas region and should be considered as one of the sources of ozone air pollution. The oxidation of higher molecular weight VOCs and BVOCs produces secondary organic aerosol particles (SOA) that may be even more harmful than ozone (Claeys et al. 2004; Hoffmann et al. 1997; Katsouyanni et al. 2001).

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Color versions of one or more of the figures in the paper can be found online at www.tandfonline.com/uawm.
Supplemental data for this paper can be accessed here.

Because of the importance of atmospheric photochemical reactions, the estimation of atmospheric VOC emissions, including BVOCs, is needed where NOx emissions are high. *Cannabis* facilities are typically built in urbanized areas near automobile roads, which are known areas of high NOx concentration. These facilities can be a source of large amounts of BVOC and VOC generated during the production of *Cannabis* products. The oxidation of highly reactive BVOCs from *Cannabis* plants can lead to the formation of ozone and secondary VOCs (e.g., formaldehyde and acrolein). In recent years, the *Cannabis* market has increased drastically since the sale of recreational marijuana has been permitted in several states. At the same time, not much information on BVOC emissions from *Cannabis* is currently available. Therefore, identification of the speciated VOCs at commercial *Cannabis* facilities is needed. The goal of this pilot study is to characterize and quantitatively analyze VOC emissions at commercial *Cannabis* grow facilities and identify what future steps should be taken to evaluate their contribution to photochemical processes and production of potentially harmful compounds. In this project, 80 individual VOCs, both biogenic and anthropogenic, were measured at four different *Cannabis* producers located in California and Nevada. To our knowledge, this study is the first attempt to obtain a detailed profile and concentrations of VOCs at commercial *Cannabis* grow facilities.

Experimental

Materials and methods

To accurately identify and quantify BVOCs, a standard mixture of VOCs (Table S1) was purchased from Apel-Reimer Environmental Inc. (Broomfield, CO, USA) and a standard mixture of *Cannabis* VOCs (Table S2) was obtained from Restek (Restek Corporation, Bellefonte, PA, USA).

VOC sampling and analysis

VOC sampling canisters were cleaned prior to sampling by repeated evacuation and pressurization with humidified zero air (Airgas, Inc., Radnor, PA, USA), as described in the EPA document "Technical Assistance Document for Sampling and Analysis of Ozone Precursors" (U.S.EPA 1998, 2009) (Supplementary Material).

Canister samples were analyzed for BVOC and non-BVOC species using gas chromatography instrument coupled with mass spectrometry and flame ionization detectors (GC-MS/FID) according to EPA Method TO-15 (U.S.EPA 1999). The GC-MS/FID system includes a Lotus Consulting Ultra-Trace Toxics sample preconcentration system built into a Varian 3800 GC with FID coupled to a Varian Saturn 2000 ion trap MS. The detailed description is presented in the Supplementary Material.

Calibration of the GC-MS/FID system was conducted with a mixture that contained hydrocarbons commonly found in the air (Table S1) in the range of 0.2 to 10 ppbv. Calibration of *Cannabis* VOCs was performed using a standard mixture of terpenes (Table S2). Five point external calibrations were run prior to analysis, and one calibration check was run every 24 hours. If the response of an individual compound was more than 10% off, the system was recalibrated. Replicate analysis was conducted at least 24 hours after the initial analysis to allow re-equilibration of the compounds within the canister.

Sampling and calculation of emission rates

All the facilities where the VOC samples were collected are commercial indoor-growing *Cannabis* facilities. One facility was located in California, and another three were in the state of Nevada. Measurements in Nevada were conducted at three locations within an urban area of Reno and Sparks, while the area around the facility in California can be characterized as sub-urban/rural. At all facilities, the rooms had no access to natural light, and they were equipped with high-pressure sodium (HPS) lamps. The relative humidity inside the grow rooms was 50%–60%, and the temperature was 24–28°C. The air in the grow rooms was well mixed with fans during the sampling (Figure S1, Supplementary Material). At all tested facilities, the sampling was conducted when the plants were at their flowering grow stage and their buds had reached full maturation. The plants cultivated were a mixture of *Cannabis Sativa, Cannabis Indica*, and hybrid strains. To sample the VOCs, a Teflon sampling tube was positioned 30 cm above the *Cannabis* canopy and the other end attached to the canister medium-volume sampler. The samples were collected in different rooms: the grow room, where plants are grown under controlled conditions; the curing room, where drying and aging of the harvested buds is performed; and the purging room, where removal of any residual solvents (e.g., liquid butane) is performed from the *Cannabis* concentrate using a vacuum oven or hot water bath. The data on plant strains and other growing conditions (fertilization, soil type, etc.) were not released to us.

Table 1. Concentrations of BVOCs and non-BVOCs at four different *Cannabis* grow facilities; *facilities with extraction stations; the standard deviations were calculated based three (in some cases two) replicate canister samples collected simultaneously; grow room is a room where plants are grown under controlled conditions; curing room: where drying and aging of the harvested buds is performed in a controlled environment; purging room: where removal of any residual solvents (e.g., liquid butane) is performed from the *Cannabis* concentrate using a vacuum oven or hot water bath.

Facility name	*Total BVOCs, μg m^{-3}*	*% of the total VOCs*	*Total non-BVOCs, μg m^{-3}*	*% of the total VOCs*	*Ratio: non-BVOCs/ BVOCs*
**Facility 1.*					
Outside	0.12 ± 0.01	**1**	15 ± 1	**99**	125
Curing room	863 ± 95	**19**	3764 ± 226	**81**	4.4
Grow room	1563 ± 172	**53**	1374 ± 82	**47**	0.9
Facility 2.					
After C-scrubber	25 ± 1	**30**	59 ± 7	**70**	2.4
Grow room (light/fan: off)	5502 ± 55	**99**	51 ± 6	**1**	0.01
Grow room (light/fan: on)	634 ± 4	**90**	71 ± 9	**10**	0.11
**Facility 3.*					
Outside	N/A	-	N/A	-	-
Grow room	196 ± 4	**3**	6686 ± 152	**97**	34
Purge room	1005 ± 90	**2**	49431 ± 2482	**98**	49
Facility 4.					
Outside	N/A	-	N/A	-	-
Grow room	112 ± 55	**72**	44 ± 3	**28**	0.4
Cure room	1055 ± 517	**96**	42 ± 3	**4**	0.04

The emission rates (ERs) of target compounds produced by *Cannabis* plants were measured only at Facility 2 that had one grow room (Table 1). The ERs derived assuming the growing room has well mixed air and losses of compounds due to depositions on walls and other surfaces were not considered. In order to obtain the ERs, BVOC concentrations were measured during steady state, when exhaust fan was on, and 10 min after the exhaust fan was turned off. The increase in concentrations was used to calculate the ERs (in mg min^{-1} plant^{-1}) of each individual VOC per time unit per plant:

$$ER_i = \frac{(C_{fan\ off} - C_{fan\ on}) \times V_{room}}{t \times N_{plants}} \quad (1)$$

where: $C_{fan\ off}$ – concentration of individual BVOC (mg m^{-3}) after the exhaust fan was turned off, $C_{fan\ on}$ – concentration of individual BVOC (mg m^{-3}) before the exhaust fan was turned off, t – time while the fan was off (10 min); V_{room} – volume of the room (m^3); N_{plants} – number of plants in the room.

Calculation of relative ozone formation potential of emitted BVOCs

Ozone formation potentials (OFP) are widely used to estimate the potential of individual VOC to form ozone in the air. While there are differenent possible methods of estimating OFP, here we use the concept of maximum incremental reactivity (MIR) that is based on incremental reactivity (Carter 1994). Carter defines incremental reactivity (IR) as the change in the O_3 mass concentration ($\Delta[O_3]$) due to an incremental change in the mass concentration of a VOC (Δ[VOC]) for standard conditions, Equation (2).

$$IR = \frac{\Delta[O_3]}{\Delta[VOC]} \quad (2)$$

To estimate maximum incremental reactivity, a standard VOC mixture is chosen and a series of simulations are made for varying concentrations of NO_x. There will be a NO_x level where the IR values reach a maximum, the MIR point (Carter 1994; Stockwell, Geiger, and Becker 2001). At the MIR point more simulations are made with incremental variations of individual VOCs to calculate MIR values from Equation (2). Note that the MIR point is at a NO_x level where O_3 production is very limited by the available VOC. Carter with the Calibornia Air Resources board performed these calculations (Carter 1994, 2009) and they provide tables of standard MIR values for individual VOC on the California Air Resources Board website (ARB 2012).

Here, the OFP of each measured emitted BVOC was estimated by multiplying its mass emission rate by its MIR value using the following equation:

$$OFP_i = ER_i \times MIR_i \quad (3)$$

where: ER_i – mass emission rate for individual VOC (mg plant^{-1} day^{-1});

MIR – maximum incremental reactivity in mg-O_3 mg-VOC^{-1}.

The relative OFP of the measured BVOC mixture was calculated by summing the OFPs for the mixture and dividing each OFP_i to determine the percent relative OFP (%OFP).

$$\%OFP = \frac{OFP_i \times 100\%}{\sum OFP_i} \quad (4)$$

Results and discussion

Concentrations of BVOCs and nonbiogenic VOCs measured at four *Cannabis* facilities are presented in Table 1. The variation of VOC levels between facilities and rooms depends on several factors, such as the number of plants and their growing stage, the performance of ventilation systems, the size of facility rooms, and the presence of other VOC sources. Overall, VOC levels are specific for each individual facility. The highest concentration of the total BVOCs was observed at Facility 2 (5502 ± 55 μg m^{-3}), when the fan was off and BVOCs accumulation was the largest. The lowest BVOC concentration was in the grow room of Facility 4 (112 ± 55 μg m^{-3}), even though in this room the number of plants per volume of the room was the highest among grow rooms at other facilities (Table S3). The total BVOCs were also measured outside the facilities (Facilities 1 and 2). In the case of Facility 1, the concentration of the total analyzed BVOCs was thousands of times lower outside than inside (Figure 1a). Facility 2 was equipped with C-scrubbers, and the samples were collected outside of the grow room as the area was not climate controlled. Even though Facility 2 was located in a forest area, the total concentration of BVOCs was significantly higher inside the facility than outside, being 220 times higher in the grow room with fan off and 25 times higher in the same room (with fan on) than outside (Figure 1b). Analysis of individual BVOCs showed that the most abundant compounds at all four facilities are β-myrcene, D-limonene, terpinolene, α-pinene, and β-pinene. For example, in the curing room at Facility 1 (Figure 1a), the top analyzed BVOCs were β-myrcene (54% of the BVOCs, 840 ± 96 μg m^{-3}), terpinolene (20%, 312 ± 23 μg m^{-3}), and

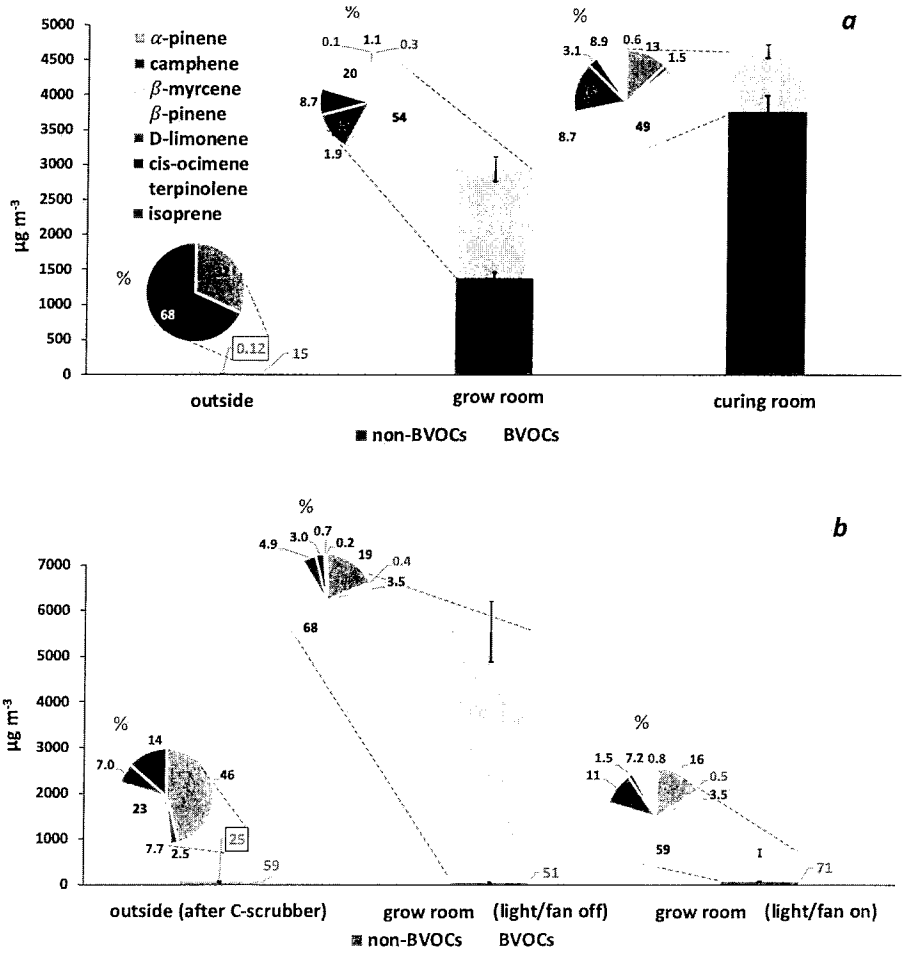

Figure 1. Biogenic (in μg m^{-3}) and non biogenic (in %) VOCs at four *Cannabis* facilities: (a) Facility 1, (b) Facility 2, (c) Facility 3, and (d) Facility 4. The standard deviations were calculated based on three (in some cases two) replicate canister samples collected simultaneously.

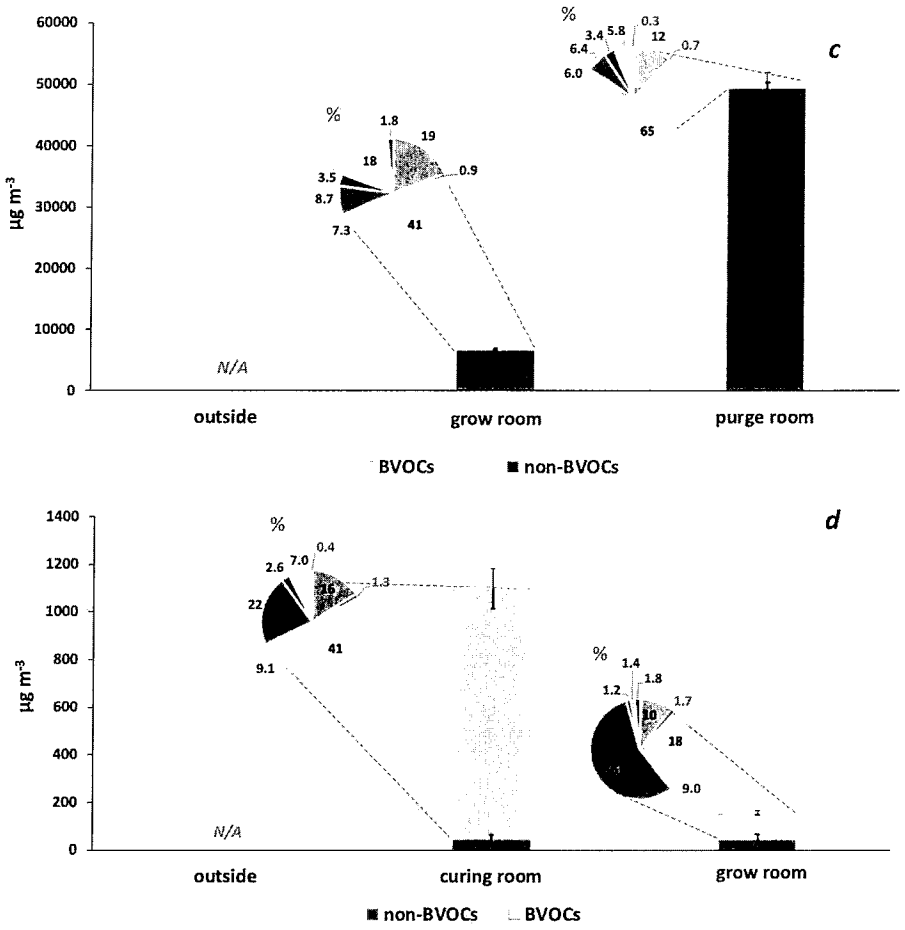

Figure 1. (Continued).

D-limonene (13%, 202 ± 12 µg m^{-3}). At the same time, the most abundant BVOCs outside of Facility 1 were isoprene (0.084 ± 0.009 µg m^{-3}) and α-pinene (0.039 ± 0.004 µg m^{-3}), being 68% and 32% of the total analyzed outside BVOCs, respectively. In comparison, the most abundant BVOCs at Facility 2 were β-pinene and α-pinene. When the fan and lights were off, the β-pinene and α-pinene concentrations were 3766 ± 452 µg m^{-3} and 1036 ± 124 µg m^{-3}, which are 68% and 19% of the total BVOCs, respectively (Figure 1b). Predictably, the BVOC levels were lower when the fan and lights were on, and the concentrations of β-pinene and α-pinene, the most abundant at Facility 2, were 377 ± 45 µg m^{-3} (59% of the total BVOCs) and 102 ± 12 µg m^{-3} (16% of the total BVOCs), respectively. For Facility 3 (Figure 1c), the most abundant BVOCs were β-myrcene (78–650 µg m^{-3}) and α-pinene (35–140 µg m^{-3}), while at Facility 4, the highest levels were observed for D-limonene (44–232 µg m^{-3}) and β-myrcene (10–432 µg m^{-3}). Isoprene is the major biogenic compound, being two-thirds of the total global BVOCs (Guenther et al. 1995; Sindelarova et al. 2014), and it is widely used as a tracer compound of biogenic emissions (Carlton, Wiedinmyer, and Kroll 2009; Kleindienst et al. 2007; Wang et al. 2013), while for *Cannabis* emissions, it is not in the top five of the analyzed BVOCs (Figure 1). Similar to our results, Wang et al. (2019) found that β-myrcene is one of the most abundant BVOCs emitted from four strains of *Cannabis* plants. However, in contrast to Wang's study, in our results, eucalyptol was not a dominating terpene at any of the tested commercial facilities.

The total concentrations of the non-BVOCs (Table 1) widely varied between the facilities with and without additional plant-processing stations. Facilities 1 and 3 were equipped with extraction stations, where low molecular weight alkanes, such as liquid butane, are used as an extraction solvent of the oil from the *Cannabis* plants. At these facilities, the total concentration of non-BVOCs in different rooms ranged from 1,290 to 52,000 µg m^{-3}. These levels of non-BVOCs were 0.9–49 times higher than BVOCs concentrations for the same rooms (Table 1). At Facilities 2 and 4, the non-BVOC concentrations ranged from 30 to 80 µg m^{-3} . BVOCs were 2.5–107 times higher than the non-BVOCs inside these facilities. Therefore, to control VOC emissions from *Cannabis* facilities, non-BVOCs must also be monitored, especially at the

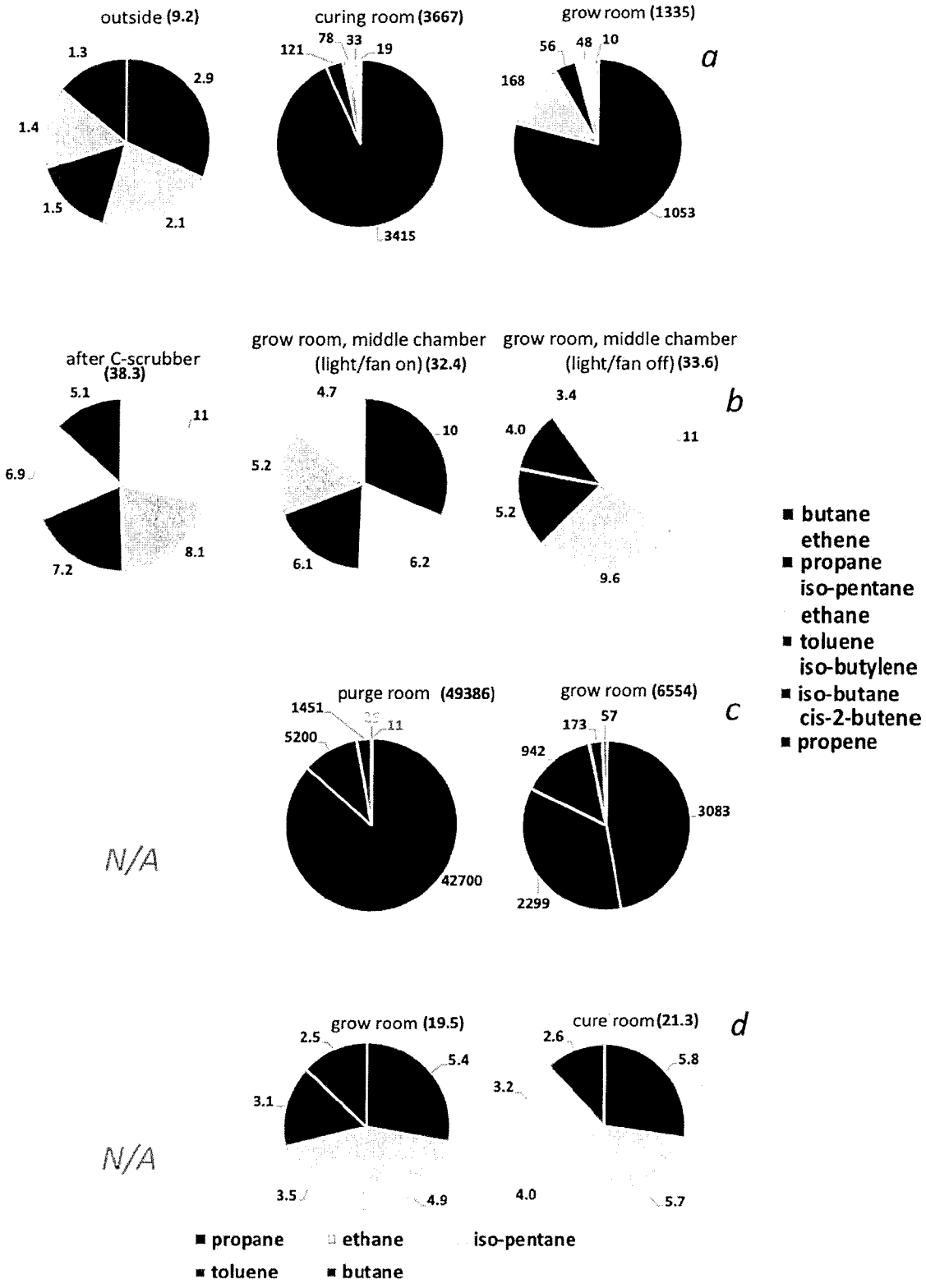

Figure 2. Top five non-BVOCs at four commercial *Cannabis* facilities: (a) Facility 1, (b) Facility 2, (c) Facility 3, (d) Facility 4; (in μg m^{-3}); total of the top five non-BVOCs are presented in brackets in bold font (units: μg m^{-3}).

facilities with additional processing of the *Cannabis* product.

Figure 2 presents the top five individual non-BVOCs that were detected at facilities with (Facility 1 and 3) and without (Facility 2 and 4) extraction stations. As was expected, butane was the dominant non-BVOC at the facilities where butane extraction was performed. For Facility 1, butane concentrations inside the curing and

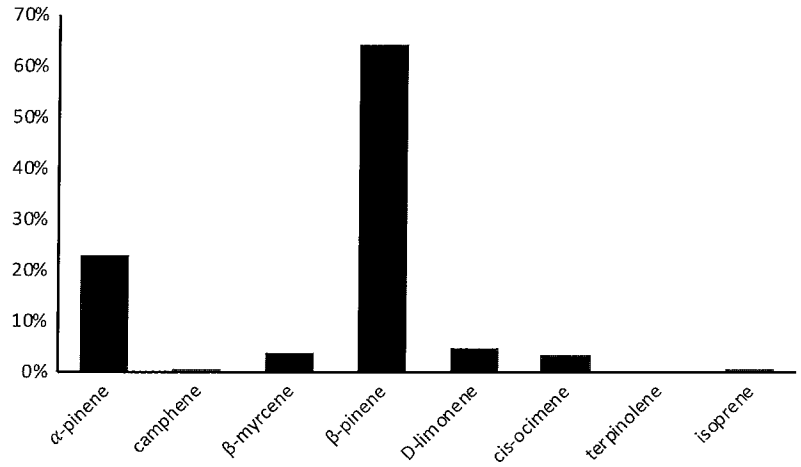

Figure 3. Relative contribution to ozone forming potential of the most abundant BVOCs at Facility 2.

grow rooms were 3,415 ± 205 (90.7% of total non-BVOCs) and 1,083 ± 43 μg m^{-3} (75.8% of total non-BVOCs), respectively, which are approximately 2,600 and 800 times more than the butane level measured outside of this facility (1.3 ± 0.4 μg m^{-3}). In the case of Facility 3, which was also equipped with an extraction station, the butane levels in its grow (3,083 ± 302 μg m^{-3}) and purge (42,723 ± 4,300 μg m^{-3}) rooms were 1.7–36 times higher than in the rooms of Facility 1, and butane was responsible for 46% and 86% of the total non-BVOCs, respectively (Figure 2). In Facilities 2 and 4, butane concentrations were low (2.5–4.3 μg m^{-3}) compared with Facilities 1 and 3, since there were no butane extraction stations there. Butane is one of the most reactive VOCs with a lifetime of 2.5 days under typical HO level atmospheric conditions (2×10^6 of HO radicals per m^{-3}) (Finlayson-Pitts and Pitts 2000). It is well-known that ozone is produced via photochemical reactions of n-butane with oxidants in the atmosphere (Andersson-Sköld, Grennfelt, and Pleijel 1992; Bowman, Pilinis, and Seinfeld 1995; Finlayson-Pitts and Pitts 1997). High concentrations of n-butane in the air can lead to high levels of harmful tropospheric ozone (Bell, Peng, and Dominici 2006; Fann et al. 2012; Kampa and Castanas 2008). Therefore, n-butane emissions from the facilities with butane extraction stations should not be ignored.

Emission rates and ozone-forming potential

To predict the potential of analyzed BVOCs for ozone formation, the ERs of target BVOCs were measured. We were able to obtain the ERs only for the BVOCs at Facility 2, and they are summarized in Table S4 (Supplementary Material). The highest ERs were observed for β-pinene (518 mg day^{-1} $plant^{-1}$), α-pinene (143 mg day^{-1} $plant^{-1}$), and D-limonene (31 mg day^{-1} $plant^{-1}$), which are 70%, 19%, and 4% of the total measured BVOCs (744 mg day^{-1} $plant^{-1}$), respectively.

Figure 3 shows the relative OFP contributions of the most abundant BVOCs collected at Facility 2. It is clear that α- and β-pinenes contributed the most to the OFP, being 87% of the total OFP for all analyzed *Cannabis* BVOCs. The OFP can significantly vary (more than two orders of magnitude) for the species with the same ER (Benjamin and Winer 1998). For example, MIR for isoprene (10.61, Supplementary Material) is three times higher than for β-pinene (3.52), but because ER for isoprene is more than 400 times lower than for β-pinene, β-pinene's contribution to ozone formation is significantly higher (146 times) than for isoprene's. However, as our results showed, BVOCs can vary among the facilities; therefore, different terpenes can be responsible for the formation of harmful compounds. Assuming that terpenes are released from Facility 2 into typical ambient conditions, α- and β-pinenes will be responsible for the formation of a maximum of approximately 2.6 g day^{-1} $plant^{-1}$ of ozone (Table S3), and plants that produce 1–10 g day^{-1} $plant^{-1}$ of ozone are considered as "medium" OFP species (Benjamin and Winer 1998).

Conclusion

The analysis of volatile terpenes at four commercial *Cannabis* facilities showed that the most abundant BVOCs at all facilities are β-myrcene, D-limonene, terpinolene, α-pinene, and β-pinene. The calculated terpenes' OFP at one of the facilities where ERs were measured demonstrated a significant contribution of α- and β-pinenes to the total OFP. These

results suggest that isoprene, which is a widely used tracer for studying chemistry and modeling of biogenic emissions, is not suitable for estimating BVOC emissions from *Cannabis* facilities and for understanding the chemical processes of *Cannabis* BVOCs in the lower troposphere. We also found that butane concentration at the facilities with cannabis oil extraction stations can be very high; thus, butane emissions from these facilities may significantly contribute to the chemistry of emitted-in-the-air VOCs, and it may lead to the formation of harmful compounds.

Since this research is a pilot study, there are several questions that need to be addressed in the future. Measuring at what rate BVOCs and other VOCs are emitted outside by *Cannabis* facilities and estimating the effect of these emissions on air quality will be important. The ERs should be measured for more than one *Cannabis* facility, and significantly more data points should be collected during these experiments. In this study, we have focused on volatile BVOCs collected with canisters, but our preliminary research showed that semivolatile biogenic organic compounds (e.g., linalool, β-caryophylene, and α-bisabolol) that can be sampled with Tenax sorbent tubes are also emitted by *Cannabis* plants in high quantities. The effects of these species on the formation of ozone, formaldehyde, and other harmful compounds have to be evaluated. Moreover, different types of plants (mainly *Cannabis sativa* and *Cannabis indica*) at different growing stages and conditions (soil type, light, fertilization, watering, ventilation, size of pots, concentration of CO_2 in grow rooms, relative humidity, temperature, etc.) may release BVOCs in various ratios (Niinemets, Loreto, and Reichstein 2004; Riedlmeier et al. 2017; Wiß et al. 2017). Knowing the ERs of BVOCs per plant, the non-BVOC concentrations in the facilities, the release of these emissions into the air, and the concentrations of NOx around the facilities can help estimate the impact of *Cannabis* grow facilities on air quality and develop optimal air pollution control strategies in the future.

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References

Andersson-Sköld, Y., P. Grennfelt, and K. Pleijel. 1992. Photochemical ozone creation potentials: a study of different concepts. *J. Air Waste Manage. Assoc.* 42 (9):1152–58. doi:10.1080/10473289.1992.10467060.

ARB. 2012. *California Air Resources Board (ARB), tables of Maximum Incremental Reactivity (MIR) values.* Sacramento, CA: California Air Resource Board.

Atkinson, R. 2000. Atmospheric chemistry of VOCs and NOx. *Atmos. Environ.* 34 (12–14):2063–101. doi:10.1016/S1352-2310(99)00460-4.

Atkinson, R., and J. Arey. 2003. Gas-phase tropospheric chemistry of biogenic volatile organic compounds: a review. *Atmos. Environ.* 37:S197–S219. doi:10.1016/S1352-2310(03)00391-1.

Bell, M. L., R. D. Peng, and F. Dominici. 2006. The exposure–response curve for ozone and risk of mortality and the adequacy of current ozone regulations. *Environ. Health Perspect.* 114 (4):532. doi:10.1289/ehp.8816.

Benjamin, M. T., and A. M. Winer. 1998. Estimating the ozone-forming potential of urban trees and shrubs. *Atmos. Environ.* 32 (1):53–68. doi:10.1016/S1352-2310(97)00176-3.

Bowman, F. M., C. Pilinis, and J. H. Seinfeld. 1995. Ozone and aerosol productivity of reactive organics. *Atmos. Environ.* 29 (5):579–89. doi:10.1016/1352-2310(94)00283-Q.

Brunekreef, B., and S. T. Holgate. 2002. Air pollution and health. *Lancet* 360 (9341):1233–42. doi:10.1016/S0140-6736(02)11274-8.

Carlton, A., C. Wiedinmyer, and J. Kroll. 2009. A review of Secondary Organic Aerosol (SOA) formation from isoprene. *Atmos. Chem. Phys.* 9 (14):4987–5005. doi:10.5194/acp-9-4987-2009.

Carter, W. P. 1994. Development of ozone reactivity scales for volatile organic compounds. *Air Waste* 44 (7):881–99. doi:10.1080/1073161X.1994.10467290.

Carter, W. P. 2009. *Updated maximum incremental reactivity scale and hydrocarbon bin reactivities for regulatory applications.* Riverside, CA: University of California, College of Engineering Center for Environmental Research and Technology.

Chuwah, C., T. van Noije, D. P. van Vuuren, E. Stehfest, and W. Hazeleger. 2015. Global impacts of surface ozone changes on crop yields and land use. *Atmos. Environ.* 106:11–23. doi:10.1016/j.atmosenv.2015.01.062.

Claeys, M., B. Graham, G. Vas, W. Wang, R. Vermeylen, V. Pashynska, J. Cafmeyer, P. Guyon, M. O. Andreae, and P. Artaxo. 2004. Formation of secondary organic aerosols through photooxidation of isoprene. *Science* 303 (5661):1173–76. doi:10.1126/science.1092805.

Dickson, R. E., M. Coleman, P. Pechter, and D. Karnosky. 2001. Growth and crown architecture of two aspen genotypes exposed to interacting ozone and carbon dioxide. *Environ. Pollut.* 115 (3):319–34.

Fann, N., A. D. Lamson, S. C. Anenberg, K. Wesson, D. Risley, and B. J. Hubbell. 2012. Estimating the national public health burden associated with exposure to ambient PM2.5 and ozone. *Risk Anal.* 32 (1):81–95. doi:10.1111/j.1539-6924.2011.01630.x.

Finlayson-Pitts, B. J., and J. N. Pitts. 1997. Tropospheric air pollution: ozone, airborne toxics, polycyclic aromatic hydrocarbons, and particles. *Science* 276 (5315):1045–51. doi:10.1126/science.276.5315.1045.

Finlayson-Pitts, B. J., and J. N. J. Pitts. 2000. *Chemistry of the upper and lower atmosphere.* San Diego, CA: Elsevier Science Publishing Co, Inc.

Fuentes, J. D., M. Lerdau, R. Atkinson, D. Baldocchi, J. Bottenheim, P. Ciccioli, B. Lamb, C. Geron, L. Gu, and A. Guenther. 2000. Biogenic hydrocarbons in the atmospheric boundary layer: a review. *Bull. Amer. Meteor. Soc.* 81 (7):1537–76. doi:10.1175/1520-0477(2000)081<1537:BHITAB>2.3.CO;2.

Goldstein, A. H., and I. E. Galbally. 2007. *Known and unexplored organic constituents in the earth's atmosphere. Environ. Sci. Technol.* 41 (5):1514-1521.

Gryparis, A., B. Forsberg, K. Katsouyanni, A. Analitis, G. Touloumi, J. Schwartz, E. Samoli, S. Medina, H. R. Anderson, and E. M. Niciu. 2004. Acute effects of ozone on mortality from the "air pollution and health: a European approach" project. *Am. J. Respir. Crit. Care Med.* 170 (10):1080–87. doi:10.1164/rccm.200403-333OC.

Guenther, A., C. N. Hewitt, D. Erickson, R. Fall, C. Geron, T. Graedel, P. Harley, L. Klinger, M. Lerdau, W. A. McKay, et al. 1995. A global-model of natural volatile organic-compound emissions. *J. Geophys. Res. Atmos.* 100 (D5):8873–92. doi:10.1029/94JD02950.

Hoffmann, T., J. R. Odum, F. Bowman, D. Collins, D. Klockow, R. C. Flagan, and J. H. Seinfeld. 1997. Formation of organic aerosols from the oxidation of biogenic hydrocarbons. *J. Atmos. Chem.* 26 (2):189–222. doi:10.1023/A:1005734301837.

Kampa, M., and E. Castanas. 2008. Human health effects of air pollution. *Environ. Pollut.* 151 (2):362–67. doi:10.1016/j.envpol.2007.06.012.

Katsouyanni, K., G. Touloumi, E. Samoli, A. Gryparis, A. Le Tertre, Y. Monopolis, G. Rossi, D. Zmirou, F. Ballester, and A. Boumghar. 2001. Confounding and effect modification in the short-term effects of ambient particles on total mortality: results from 29 European cities within the APHEA2 project. *Epidemiology* 12:521–31. doi:10.1097/00001648-200109000-00011.

Kleindienst, T. E., M. Jaoui, M. Lewandowski, J. H. Offenberg, C. W. Lewis, P. V. Bhave, and E. O. Edney. 2007. Estimates of the contributions of biogenic and anthropogenic hydrocarbons to secondary organic aerosol at a southeastern US location. *Atmos. Environ.* 41 (37):8288–300. doi:10.1016/j.atmosenv.2007.06.045.

Li, Y., M. C. Barth, G. Chen, E. G. Patton, S. W. Kim, A. Wisthaler, T. Mikoviny, A. Fried, R. Clark, and A. L. Steiner. 2016. Large-eddy simulation of biogenic VOC chemistry during the DISCOVER-AQ 2011 campaign. *J. Geophys. Res. Atmos.* 121 (13):8083–105. doi:10.1002/2016JD024942.

Logan, J. A. 1985. Tropospheric ozone - Seasonal behavior, trends, and anthropogenic influence. *J. Geophys. Res. Atmos.* 90 (ND6):10463–82. doi:10.1029/JD090iD06p10463.

Mills, G., F. Hayes, D. Simpson, L. Emberson, D. Norris, H. Harmens, and P. Büker. 2011. Evidence of widespread effects of ozone on crops and (semi-) natural vegetation in Europe (1990–2006) in relation to AOT40-and flux-based risk maps. *Glob. Chang. Biol.* 17 (1):592–613. doi:10.1111/j.1365-2486.2010.02217.x.

Niinemets, Ü., F. Loreto, and M. Reichstein. 2004. Physiological and physicochemical controls on foliar volatile organic compound emissions. *Trends Plant Sci.* 9 (4):180–86. doi:10.1016/j.tplants.2004.02.006.

Papiez, M. R., M. J. Potosnak, W. S. Goliff, A. B. Guenther, S. N. Matsunaga, and W. R. Stockwell. 2009. The impacts of reactive terpene emissions from plants on air quality in Las Vegas, Nevada. *Atmos. Environ.* 43 (27):4109–23. doi:10.1016/j.atmosenv.2009.05.048.

Riedlmeier, M., A. Ghirardo, M. Wenig, C. Knappe, K. Koch, E. Georgii, S. Dey, J. E. Parker, J.-P. Schnitzler, and A. C. Vlot. 2017. Monoterpenes support systemic acquired resistance within and between plants. *Plant Cell* 29 (6):1440–59. doi:10.1105/tpc.16.00898.

Seinfeld, J. H., and S. N. Pandis. 2016. *Atmospheric chemistry and physics: from air pollution to climate change.* Hoboken, NJ: John Wiley & Sons.

Sindelarova, K., C. Granier, I. Bouarar, A. Guenther, S. Tilmes, T. Stavrakou, J.-F. Müller, U. Kuhn, P. Stefani, and W. Knorr. 2014. Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years. *Atmos. Chem. Phys.* 14 (17):9317–41. doi:10.5194/acp-14-9317-2014.

Stockwell, W. R., H. Geiger, and K. H. Becker. 2001. Estimation of incremental reactivities for multiple day scenarios: an application to ethane and dimethyoxymethane. *Atmos. Environ.* 35 (5):929–39. doi:10.1016/S1352-2310(00)00354-X.

U.S.EPA. 1998. EPA/600-R-98/161. Technical assistance document for sampling and analysis of ozone precursors. NC, USA: U.S. Environmental Protection Agency.

U.S.EPA. 1999. Method TO-15. Determination of Volatile Organic Compounds (VOCs) in air collected in specially-prepared canisters and analyzed by Gas Chromatography/Mass Spectrometry (GC/MS)-Second Edition. EPA/625/R-96/010b, January. Cincinnati, OH: U. S. Environmental Protection Agency.

U.S.EPA. 2009. Technical assistance document for the national air toxics trends stations program. http://www.epa.gov/ttnamti1/files/ambient/airtox/nattsTADRevision2_508Compliant.pdf.

Wang, C.-T., C. Wiedinmyer, K. Ashworth, P. C. Harley, J. Ortega, and W. Vizuete. 2019. Leaf enclosure measurements for determining volatile organic compound

emission capacity from Cannabis spp. *Atmos. Environ.* 199:80–87. doi:10.1016/j.atmosenv.2018.10.049.

Wang, J.-L., C. Chew, C.-Y. Chang, W.-C. Liao, S.-C.-C. Lung, W.-N. Chen, P.-J. Lee, P.-H. Lin, and -C.-C. Chang. 2013. Biogenic isoprene in subtropical urban settings and implications for air quality. *Atmos. Environ.* 79:369–79. doi:10.1016/j.atmosenv.2013.06.055.

Wiß, F., A. Ghirardo, J. P. Schnitzler, C. Nendel, J. Augustin, M. Hoffmann, and R. Grote. 2017. Net ecosystem fluxes and composition of biogenic volatile organic compounds over a maize field–interaction of meteorology and phenological stages. *Gcb Bioenergy* 9 (11):1627–43. doi:10.1111/gcbb.12454.

Yang, Q., Y. Chen, Y. Shi, R. T. Burnett, K. M. McGrail, and D. Krewski. 2003. Association between ozone and respiratory admissions among children and the elderly in Vancouver, Canada. *Inhal. Toxicol.* 15 (13):1297–308. doi:10.1080/08958370390241768.

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Leaf enclosure measurements for determining volatile organic compound emission capacity from *Cannabis spp.*

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ABSTRACT

The legal commercialization of Cannabis for recreational and medical use in certain US states has effectively created a new and nearly unregulated cultivation industry. Within the city limits of Denver, Colorado, there are now more than 600 registered *Cannabis spp.* cultivation facilities (CCFs) for recreational and medical uses, each containing thousands of plants. Ambient measurements collected inside growing operations pre-legalization have found concentrations as high as 50–100 ppbv of terpenes; a group of highly reactive biogenic volatile organic compounds (BVOCs) and known precursors for the formation of ozone and particulate matter (PM). Due to its illicit nature there has been insufficient experimental data produced to determine *Cannabis spp.* emission rates. This study used, for the first time, an enclosure chamber and live *Cannabis spp.* plants during a 90-day growing period consisting of four different strains of *Cannabis spp.*: Critical Mass, Lemon Wheel, Elephant Purple, and Rockstar Kush. These measurements enabled characterization of terpenes and estimates of emission capacity (EC, $\mu gC\ g^{-1}\ hr^{-1}$) at standard conditions. During peak growth, the percentages of individual BVOC emissions were dominated by β-myrcene (18–60%), eucalyptol (17–38%), and d-limonene (3–10%) for all strains. Our results showed large variability in the rate and composition of terpene emissions across different strains. For the Critical Mass and Lemon Wheel, the dominant terpenoid was eucalyptol (32% and 38%), and it was β-myrcene (60% and 45%) for the Elephant Purple and Rockstar Kush. Critical Mass produced the highest terpene emission capacity ($8.7\ \mu gC\ g^{-1}\ hr^{-1}$) and Rockstar Kush the lowest ($4.9\ \mu gC\ g^{-1}\ hr^{-1}$). With 600 CCFs in Denver, and assuming 10,000 plants per CCF, an emission capacity of $8.7\ \mu gC\ g^{-1}\ hr^{-1}$ would more than double the existing rate of BVOC emissions to 520 metric ton $year^{-1}$. Using Maximum Incremental Reactivity (MIR) values the total ozone formation potential from all these emitted species could produce 2100 metric tons $year^{-1}$ of ozone, and based on published secondary organic aerosols yields 131 metric tons $year^{-1}$ of PM. It is likely that the ECs calculated here are lower than those achieved in CCFs where growing conditions are optimized for rapid growth and higher biomass yields. Further studies including a greater number of the 620 available *Cannabis spp.* strains and a wider range of treatments are needed to generate a representative dataset. Such a dataset could then better enable assessments of the potential impacts of this new industry on indoor and regional air quality.

1. Introduction

The use of *Cannabis spp.* and its various products have long been controversial, with opponents of the relaxation of restrictions pointing to studies linking long-term use to mental health problems (WHO, 2016), and advocates arguing that it provides many therapeutic benefits (Ashton, 2001; Madras and World Health Organisation, 2015). Supporters of the decriminalization and legalization of *Cannabis spp.* liken current regulations to the early 20th Century United States prohibition laws, suggesting that many of the detrimental societal impacts of *Cannabis spp.* production, sale, and use are directly associated with its illegality. This argument is beginning to hold sway and, for the first time, in 2014, the United Nation Global Commission on Drug Policy (UNGCDP) called for legalization with regulation (UNGCDP, 2014). The UN Office on Drugs and Crime reports over 180 million users worldwide (UNODC, 2016), and the cultivation and use of *Cannabis spp.* for

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medical purposes is already legal or decriminalized in more than 40 countries around the world. The UNGCDP argues that regulation of the recreational use of *Cannabis spp.* would bring transparency at all stages of the supply chain, reducing associated criminal activity and trafficking, ensuring drug safety and allowing monitoring of environmental impacts. Furthermore, legalization of the recreational use of *Cannabis spp.* offers an opportunity for increased fiscal revenue: in the US state of Colorado, tax revenue from sales of *Cannabis spp.* for recreational use in 2014 (the first year of legal commercial sales) amounted to over $76 million (UNODC, 2016). Many US states have followed Colorado's lead, a trend that is expected to spread to many countries around the world.

Cannabis spp. are native to the Indian sub-continent and require warm temperatures and high light intensity to achieve good yields. Optimal growing conditions for commercial varieties are typically around 30 °C, 1000–1500 $\mu mol\ m^{-2}\ s^{-1}$ of photosynthetically active radiation (PAR; depending on growth stage) and, in an outdoor environment, 22.7 L of water per day per plant (Green, 2009; Mills, 2012; Bauer et al., 2015). Although *Cannabis spp.* can be grown outdoors in many regions of the world, all large-scale commercial cultivation in Denver, Colorado occurs indoors or in greenhouses. This enables year-round operations, ensures security, and allows for the precise control of the growing environment to maximize yields. At indoor commercial facilities, such as those found in Denver, plants receive light 24 h per day during the initial growth stages. Since *Cannabis spp.* are photoperiod sensitive (i.e. only flowering when the length of daylight shortens), once sufficient leafy biomass accumulation has occurred, the lighting regime in these facilities is altered to induce budding. In most cases, a 12-h on, 12-h off pattern is used, but this can vary to as little as 8 h on over a 24-h period. Typically, the flower buds are enriched in the active ingredients Tetrahydrocannabinol (THC) and Cannabidiol (CBD) in comparison to foliage, and in most varieties, other plant tissues (stems, branches, roots) contain negligible amounts of these compounds. The average yield of saleable biomass from commercial strains of *Cannabis spp.* is around 1 kg per plant (Green, 2009; Jankauskiene and Gruzdeviene, 2015), and the approximate time to harvest is 2–3 months, permitting ~5 crop cycles per year (Green, 2009).

The production of *Cannabis spp.* in indoor facilities has been the focus of studies quantifying the environmental impacts of energy and water use (Mills, 2012). Considerably less is known about the potential impacts of this industry on indoor and outdoor air quality due to BVOCs emitted directly from the plants themselves. *Cannabis spp.* plant tissues, such as leaves and buds, are known to contain many BVOCs. Previous studies of dried plant material (Turner et al., 1980; Rice and Koziel, 2015) and oil extracts from buds (Ross and ElSohly, 1996) have identified high concentrations of monoterpenes ($C_{10}H_{16}$), other terpenoid compounds (e.g. eucalyptol; $C_{10}H_{18}O$), sesquiterpenes ($C_{15}H_{24}$), and methanol that is associated with plant growth and cell expansion. Other studies have focused on identifying characteristic odor profiles to facilitate detection of illicit *Cannabis spp.* products or chromatographic signatures to detect smuggled drugs (Hillig, 2004; Fischedick et al., 2010; Rice and Koziel, 2015). Measurements of BVOC concentrations in headspace and (illicit) grow rooms have detected and identified many hundreds of BVOCs, often in very low concentrations, of which mono- and sesquiterpenes are dominant. These species include: α-pinene, β-pinene, β-myrcene, limonene, hashishene, caryophyllene, and humulene (Martyny et al., 2013; Marchini et al., 2014). Hood et al. (Hood et al., 1973) analysed the air above *Cannabis spp.* plants and found that the monoterpenes α-pinene, β-pinene, β-myrcene and d-limonene accounted for over 85% of the detected VOCs emitted, with acetone and methanol contributing a further 10%. Marchini et al. (2014) reported the composition of headspace, but not the concentration of each species. Martyny et al. (2013) reported total monoterpene (consisting of α-pinene, β-pinene, β-myrcene and d-limonene) concentrations of 50–100 ppbv in the grow rooms of illicit cultivation facilities, suggesting high emissions from growing *Cannabis spp.*. Due to *Cannabis spp.* status as an illegal Schedule 1 drug by the U.S. Drug Enforcement Agency (USD.E.A., 2017), there are no known systematic studies to characterize and specifically quantify the volatile emissions during the growing and budding process. Based on previous studies, however, the *Cannabis spp.* plants have the potential to emit VOCs into the facility in which they are grown, and also into the atmosphere.

Emissions of VOCs in urban areas have the potential to contribute to ozone production (Fehsenfeld et al., 1992; Pierce et al., 1998; Ryerson et al., 2001) and the formation of secondary organic aerosol (SOA) (Kanakidou et al., 2005; Lee et al., 2006). Once VOCs are released into the urban atmosphere, they can react with the hydroxyl (OH) radical, nitrate (NO_3) radical, and ozone (O_3) (Hites and Turner, 2009; Braure et al., 2014). These initial oxidation reactions lead to further atmospheric processing, which can ultimately lead to the formation of ozone and SOA. In Denver, for example, where there are > 600 *Cannabis spp.* cultivation facilities releasing BVOCs, the magnitude of these emissions has the potential to impact local and regional air quality, depending to some extent on the precise mix of compounds emitted. To understand the effect of BVOC emissions from these facilities on atmospheric chemistry and composition, it is necessary to identify and quantify the sources.

The goal of this study was to estimate the emission capacity (EC, $\mu gC\ g^{-1}\ hr^{-1}$) range and terpene emission composition of cannabis plants. There is sparse BVOC data available from enclosure techniques, and thus these studies provide new data on the quantification of emissions of BVOCs from live commercially-available strains of *Cannabis spp.* at different phenological stages in their lifecycle.

2. Methods

Air samples were collected from *Cannabis spp.* using plant enclosures onto solid adsorbent cartridges. These cartridges were later analysed using gas chromatography with mass spectrometry and flame ionization detection (GC-MS/FID) to identify individual BVOC compounds and quantify emission rates. The plants were purchased by volunteers and were handled, housed, and sampled in a private off-site location. After the experiments, those plants were disposed of and composted locally. We did not have access to laboratory facilities or a growth room with a controlled environment. Thus, these experiments should be viewed as field measurements.

2.1. Cultivation

Four *Cannabis spp.* strains, commonly found in CCFs in Colorado, were studied: "Rockstar Kush" (RK), "Elephant Purple" (EP), "Lemon Wheel (LW)", and "Critical Mass" (CM). Twelve plants (3 from each strain) were grown under monitored conditions over a period of 14 weeks during the summer of 2016. The plants were bought on July 8, 2016 and transplanted to 1 US gallon (3.8 L) pots on July 15, 2016, at which time one additional pot (used as a control) was filled with identical soil. The soil used was a general use potting soil suitable for most plants. The plants were placed on trays and allowed to acclimate to the growing environment. The plants were kept well-irrigated with water being added to the trays every 2–3 days. In a growing facility growing lights are kept on for 24 h a day. Thus, three 15 W LED growing lamps were positioned 1 m above the top of the pots and the growing plants received 500–900 $\mu mol\ m^{-2}\ s^{-1}$ of light continuously for 24 h (dependent on the distances between the leaf and growth light). The temperature of the growth room was not controlled and ranged between 15 and 30 °C, which is typical for local ambient conditions during summer in Denver. All plants received the same treatment and were regularly rotated to minimize edge effects and to ensure, as much as possible, that all plants experienced the same light and temperature environment.

2.2. Plant enclosure sampling

A standard plant enclosure sampling method was applied to measure BVOC emission rates (Tholl et al., 2006; Ortega and Helmig, 2008; Ortega et al., 2008). Air samples were collected from whole-plant enclosures for one specimen of each of the four strains and the blank pot after 12, 30, 46, and 96 days of growth since July 8, 2016. The same sampling routine was followed on each occasion. The pot containing the largest and tallest plant from each strain was selected and placed carefully in a 5 US gallon (19 L) PFA Teflon pail liner (Welch Fluorocarbon, Dover, NH, USA). The plants were handled as gently as possible to minimize emissions due to disturbance (Ortega and Helmig, 2008; Ortega et al., 2008). Ambient air was pumped through Teflon tubing (25.4 mm O.D.), first through an activated charcoal filter to remove O_3 and VOCs, and then into the enclosure system. This enclosure system was designed to act as a continuous stirred-tank reactor (CSTR) with a constant flow rate of 2.4–2.7 L min^{-1}. A thermocouple was fed into the air space, and the bag was then clamped tightly around the pot until the bag inflated, indicating positive pressure within the enclosure. Since the measurements were done indoors, a 90 W growth lamp was positioned above the Teflon bag, delivering 650–900 μmol m^{-2} s^{-1} (PAR) at the plant top as measured by a quantum sensor (Li-COR model 190-R, Lincoln, Nebraska). Air flowed continuously through the enclosure for 30 min prior to sampling, allowing time for several exchanges of air and for the VOC concentrations to reach a steady-state. After 30 min, BVOC sampling commenced. During sampling, two stainless steel adsorbent cartridges, each containing ~400 mg of Tenax TA and Carbograph 5TD in series (Markes International, Llantrisant, UK), were connected in parallel to the Teflon line exiting the enclosure. Air exiting the enclosure was pulled at a known flow rate (between 220 and 250 ml min^{-1}) through each cartridge for 30 min, resulting in a sample collection on each cartridge of between 6.5 and 7.5 L. Terpene concentrations measured in these samples therefore represented an average over that 30-min collection period, during which time flow rate, irradiance, and air temperature were maintained at a relatively constant value.

Following sampling, each cartridge was securely capped at both ends and refrigerated prior to analysis. After 46 and 96 days of growth, the sampled plants were harvested and dried at room temperature for over one week. At the end of the drying time, leaves and buds were removed from each plant, and weighed to obtain the dry weight mass (Mdry (g)) for each strain. Of the original 12 plants, the 10 healthiest ones by visual inspection were chosen for sampling. The emission rates were therefore normalized using leaves from the plants that were weighed in the 46- and 96-day growth periods. Details of the leaf enclosure measurements are presented in Table 1. In addition to the enclosure measurements of the four *Cannabis spp.* strains, air samples were taken from the pot containing only soil and from an otherwise empty enclosure bag to act as controls. For these controls, the soil was moistened, and the Teflon bag was placed around the pot in the same way that the plants were treated.

Enclosure carbon dioxide (CO_2) concentrations are important for the calculation of photosynthesis rates. Further, is important to keep CO_2 concentrations similar to ambient conditions so that BVOC emission rates are not inadvertently affected. These measurements of CO_2 concentrations, however, were not available during this study. In the study to keep concentrations similar to ambient we developed a protocol that set the input air flow rate of 2.4–2.7 L min^{-1} resulting in a high chamber air exchange rate of 8.2 hr^{-1}. Using this exchange rate we calculated the reduction in CO2 by assuming: photosynthesis rates of 10 μmol m^{-2} s^{-1}, ambient input CO_2 concentration of 400 ppm, active leaf area of 0.015 m^2 per plant. The estimated reduction in steady-state CO_2 concentrations were approximately 300 ppm or a reduction of 100 ppm. There amount of reduction is within the normal range of plant enclosure experiments. Therefore, we assume that this did not have an adverse impact on BVOC emission rates.

2.3. Analysis method and instrument (GCMS & GCFID)

Samples were thermally desorbed from the cartridges and analysed using a Gas Chromatograph (GC) (Agilent Technologies, model 7890 A) coupled to both a flame ionization detector (FID) and a mass spectrometer (MS) (model 5975C), following published protocols (Harley et al., 2014). Thermal desorption (TD) was achieved by heating the adsorbent cartridges to 275 °C in a UNITY TD (model UNITY, Markes International, Llantrisant, UK), followed by focusing the analyses on to a small cryotrap, and then heating this final trap as the analytes were injected on to the column. Helium was used as the carrier gas in the capillary column (RESTEK Rtx-5 model 10224, 30 m, 0.32 mm, ID, 0.25 μm film thickness). The GC oven temperature cycle started at 35 °C and was held at that temperature for 1 min, subsequently increasing 10 °C per minute up to 260 °C for each cartridge. The peak area associated with *m/z* 93, the dominant monoterpene ion fragment, of each terpenoid was quantified by GC-MS. To account for changes in MS sensitivity, 2 ml of an internal standard, decahydronaphthalene (DHN), was sampled on to each adsorbent cartridge during the analysis. The measured terpenoid signals were normalized by dividing the *m/z* 93 mass fragment by the *m/z* 95 fragment of DHN. Additional calibrations were performed by loading sorbent tubes with 100 standard cm^3 of a gas-phase standard containing 335 ppb of isoprene and 215 ppb of the monoterpene camphene. Two to four of these standard samples were run on the GC-MS and GC-FID for each batch of enclosure samples. The resulting signals were used to calculate a GC-FID response factor and a GC-MS sensitivity, which in turn were used to calculate gas-phase concentrations and emission rates.

The National Institute of Standards and Technology (NIST) database was used to identify individual monoterpenes from the GC-MS peaks by their mass fragmentation patterns using electron impact ionization. The

Table 1
Summary of leaf enclosure sampling conditions including flow rates, leaf area (when measured), and dry leaf weight.

	Strain	Air temp, in enclosure (°C)	PAR (μmol m^{-2} s^{-1})	Flow rate in (L min^{-1})	Sampling flow rate (L min^{-1})	Sampling time (min)	Estimated leaf area (m^2)	Dry Leaf weight (g)
30 days growth	Critical Mass	23.9	650	2.37	0.24 & 0.254	30	0.015	N/A
	Lemon Wheel	23.9	650	2.37	0.24 & 0.254	30	0.0093	N/A
	Elephant Purple	23.4	650	2.37	0.24 & 0.254	30	0.0047	N/A
	Rockstar Kush	22.5	650	2.37	0.24 & 0.254	30	0.0073	N/A
	Soil	22	650	2.37	0.24 & 0.254	30	N/A	N/A
46 days growth	Critical Mass	27	900	2.7	0.253 & 0.257	30	N/A	0.985
	Lemon Wheel	28	900	2.7	0.253 & 0.257	30	N/A	0.592
	Elephant Purple	26	900	2.7	0.253 & 0.257	30	N/A	N/A
	Rockstar Kush	26.5	900	2.7	0.253 & 0.257	30	N/A	0.444
	Soil	26	900	2.7	0.253 & 0.257	30	N/A	N/A

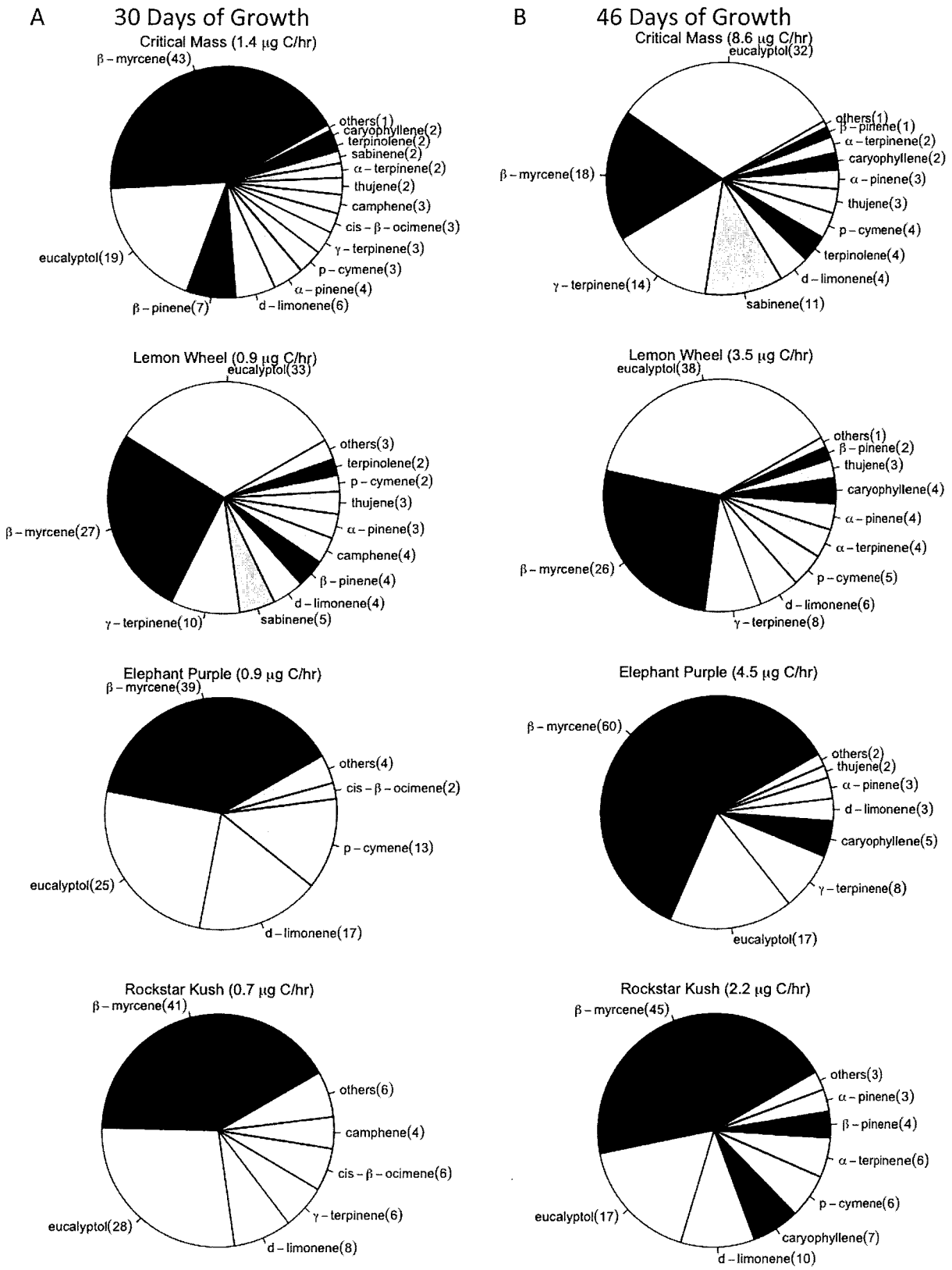


Fig. 1. Total terpene emission rate per plant ($\mu g\ C\ hr^{-1}$) and composition of emissions for (A) 30-day, and (B) 46-day growth periods from four strains of *Cannabis spp.*: Critical Mass, Lemon wheel, Elephant Purple, and Rockstar Kush. Numbers in parentheses represent the percentage of total emissions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

preliminary calculations of VOC concentrations based on GC-MS peak areas were cross-checked against the GC-FID. FID peaks of the DHN internal standard were used to ensure consistency and flag instrument drift. The measurement limitations of GC-FID and GC-MS are calculated using the blank sample. For the terpene compounds, the detection limits (DL) are three standard deviations of blank values. The average VOC concentrations from the two cartridges drawn from each enclosed plant, typically calculated by the GC-FID, was used due to its stability and linearity. In the case that there was a co-elution effect and the FID signal was lower than the FID detection limits, the GC-MS results were used. The DL of terpene by GC-MS is 0.004 μg C hr^{-1}. If the results were lower than the limits a Non-Detection symbol (ND) is shown. All of the emission rate calculated from the FID and MS signal are included in the supplemental document as Table S1A and Table S1B. Other details about the analysis, such as retention time of each terpene species and fragment percentage of ion *m/z* 93 are also included in the supplemental document shown in Table S2.

2.4. Calculation of emission capacity

The EC and its algorithms were standardized in Guenther et al. (1993) and are based entirely on temperature and incident light energy. Our study follows these best practices, which have been applied to several studies (Funk et al., 2003; Ortega and Helmig, 2008; Ortega et al., 2008; Sakulyanontvittaya et al., 2008). While this is the standard practice in derivation of EC for atmospheric chemistry-climate modelling, there is evidence to suggest that monoterpene emissions from many plant species represent a combination of direct and stored emissions (Staudt et al., 1997; Kesselmeier and Staudt, 1999; Niinemets et al., 2004). As monoterpenes share a common synthesis pathway with isoprene, direct emissions of certain monoterpenes are dependent on light as well as temperature (Kesselmeier and Staudt, 1999; Lichtenthaler, 1999). In absence of direct evidence, such as that provided by light-dark transition experiments, the light-independent (Tingey et al., 1980; Guenther et al., 1991) and light-dependent algorithms (Guenther et al., 1993; Guenther, 1997; Staudt et al., 1997) were both therefore calculated for the potential EC of all terpenoid emissions.

Based on the concentration of each VOC calculated by GC-MS/FID and the air sampling flow rate, a rate of emission, F_i (μgC g^{-1} h^{-1}), for each VOC species i was calculated using Equation (1) (Ortega and Helmig, 2008):

$$F_i = \frac{Q|C_{iout} - C_{iempty}|}{M_{dry}} \quad (1)$$

where C_{iout} is the concentration of VOC species i (μgC mol^{-1}) in air exiting the enclosure containing a *Cannabis spp.* plant, C_{iempty} is the concentration of VOC species i (μgC mol^{-1}) in air exiting the enclosure containing only the empty pot with soil and water, M_{dry} is the dry mass of leaves (g), and Q is the flow rate of air into the enclosure system (about 5.44 mol h^{-1}). Calculated values of F_i therefore represent emission rates at measured temperatures and PAR.

The emission capacity (ε_i) for VOC i was calculated following Guenther et al. (1995):

$$\varepsilon_i = F_i/\gamma \quad (2)$$

where ε_i is the emission capacity at T_S = 30 °C (μgC g^{-1} h^{-1}), Fi is the emission rate of the VOC i (μgC g (dry matter)$^{-1}$ h^{-1}) calculated using Equation (1), and γ is a dimensionless activity factor which corrects for temperature and light conditions. In equation (3), γ is defined for temperature and independent of light.

$$\gamma = exp[\beta(T - T_S)] \quad (3)$$

where β is an empirical coefficient (in K^{-1}) taken as β = 0.09 for all monoterpenes, eucalyptol, and sesquiterpenes (Guenther et al., 1991; Ortega and Helmig, 2008; Ortega et al., 2008).

In equation (4), the γ is a factor with a light dependent condition (Guenther et al., 1993; Guenther, 1997; Staudt et al., 1997).

$$\gamma = \left[\frac{\alpha C_{L1} L}{\sqrt{1 + \alpha^2 L^2}}\right]\left[\frac{exp\left(\frac{C_{T1}(T - T_S)}{RT_S T}\right)}{C_{T3} + exp\left(\frac{C_{T2}(T - T_M)}{RT_S T}\right)}\right] \quad (4)$$

where L is the photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}), R is the ideal gas constant (8.314 J.$K^{-1}$$mol^{-1}$). α (=0.0027), C_{L1} (=1.066), C_{T1} (=95,000 J mol^{-1}), C_{T2} (=230,000 J mol^{-1}), C_{T3} (=0.961) and T_M (=41 °C) are empirical coefficients.

3. Results

The terpene emission rates per plant (μgC h^{-1}) and the percentage composition of the different emitted terpenes were calculated at 30 and 46 days of growth for all four *Cannabis spp.* strains with and without a light dependency. When a light-dependency was applied to plants at 46 days of growth, we estimated an increase of 5–10% in the emission rate. Given the high level of uncertainty in our rate estimate, the lower values without a light dependency are described in the following results. All estimates using a light dependency can be found in table S1A and S1B. Fig. 1 shows the measured composition and estimated terpene emission rates. These values are not normalized by leaf weight since the foliage was kept intact until 46 days of growth. β-myrcene and eucalyptol are the most abundant BVOC species at these two growth stages in all four strains, although the composition of terpene emissions varies among the growth stages and strains (Fig. 1). In each strain, the whole-plant emission increased as the plants grew bigger, which is to be expected due to the increased amount of foliage between 30 and 46 days. Critical Mass had the highest emission rate at both 30- and 46-day growth stages with 1.4 μgC h^{-1} and 8.6 μgC h^{-1} per plant. The terpenoid composition of Critical Mass emissions also changed across the different growth stages, at 30 days of growth the terpenoids with the highest emission rates were β-myrcene (43%), and eucalyptol (19%). Sixteen days later the largest emitted species were eucalyptol (32%), β-myrcene (18%) and γ-terpinene (14%). For Lemon Wheel, eucalyptol (33%, 38%) and β-myrcene (27%, 26%) were the dominant emissions. For Elephant Purple and Rockstar Kush the highest emissions were from β-myrcene (39% and 41%), eucalyptol (25% and 28%), and d-limonene (17% and 8%) at 30 days. At 46 days Elephant Purple and Rockstar Kush had increases in γ-terpinene (8%) and caryophyllene (5% and 7%) emissions.

After 46 days of growth, the ECs of three different strains were calculated at 30 °C and normalized by dry leaf weight (Fig. 2A). These were calculated using GC-FID data unless there was a co-elution effect and the GC-MS signal was used as shown in Table S1. Dry leaf mass was not measured for Elephant Purple, hence EC could not be calculated for this strain. The highest total terpene EC (including monoterpenes, eucalyptol and caryophyllene) was 8.7 ± 0.7 μgC g^{-1} hr^{-1} for the Critical Mass strain, of which 5.7 ± 0.5 μgC g^{-1} hr^{-1} (66%) was monoterpenes, 2.8 ± 0.19 μgC g^{-1} hr^{-1} (32%) was eucalyptol, and 0.2 ± 0.01 μgC g^{-1} hr^{-1} (2%) was caryophyllene. Total terpene EC for Lemon Wheel and Rockstar Kush were 5.9 μgC g^{-1} hr^{-1} and 4.9 μgC g^{-1} hr^{-1}. For Lemon Wheel, eucalyptol contributed 2.2 μgC g^{-1} hr^{-1} (38%) and monoterpenes 3.5 μgC g^{-1} hr^{-1} (59%); whereas for Rockstar Kush, the contributions were 0.8 μgC g^{-1} hr^{-1} (17%) and 3.7 μgC g^{-1} hr^{-1} (76%). The complete emission capacities of all terpene species, based using both the GC-FID and GC-MS data, are shown for all strains in Figure S1.

The emission variations of each terpene species among the three different *Cannabis spp.* strains after 46 days of growth are illustrated in Fig. 2B, which shows the mean for each species and ranges displayed as standard deviations. The primary emissions from *Cannabis spp.* are monoterpenes (ranging between 3.1 and 5.5 μgC g^{-1} hr^{-1}) and eucalyptol (1.0–3.0 μgC g^{-1} hr^{-1}). The absolute value and range of caryophyllene emission capacities are much smaller at 0.18–0.3 μgC g^{-1}

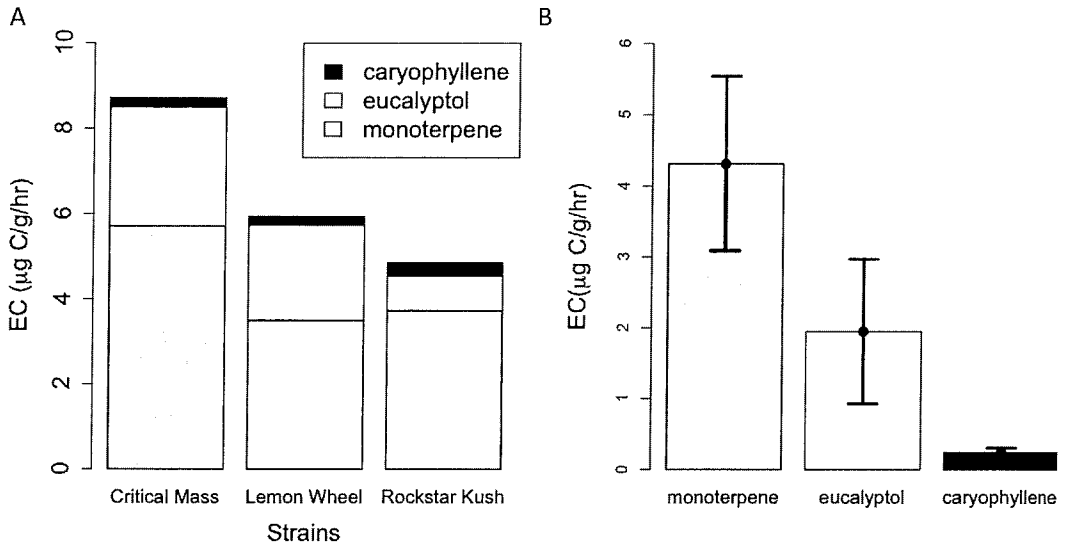


Fig. 2. Calculated emission capacities (ECs, $\mu gC\ g^{-1}\ hr^{-1}$) derived from measurements after 46 days of growth normalized by dry leaf weight (g) and a standard temperature of 30 °C for (A) Critical Mass, Lemon Wheel, and Rockstar Kush strains of *Cannabis spp.*, and the variation of EC for (B) total monoterpenes, eucalyptol and caryophyllene among the three strains. No EC for the Elephant Purple strain was estimated due to lack of dry leaf mass data. Eucalyptol is a cyclic ether with a terpenoid structure ($C_{10}H_{18}O$), the monoterpene structure is $C_{10}H_{16}$, and caryophyllene is $C_{15}H_{24}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

hr^{-1}.

To understand the potential impact of these emissions on air quality, the Ozone Formation Potential (OFP) in µg ozone per gram dry weight of *Cannabis spp.* per hour of each terpene was calculated as shown in Equation (5) (Ou et al., 2015):

$$OFP = Emission\ capacity\ (\mu g/g/hr) \times MIR\ (ozone(g)/VOC(g)) \quad (5)$$

where MIR is the Maximum Incremental Reactivity (CARB, 2010) defined as the maximum number of grams of ozone produced per gram of reactant VOC. For this study, if a specific MIR is not available, the reported average monoterpene MIR (4.04 ozone(g)/VOC(g)) was applied to calculate OFPs. A surrogate MIR for a C15 alkene was used for caryophyllene, due to it having the same carbon number and being a similar alkene species.

Fig. 3A shows the OFP estimated for the individual terpenes emitted from three *Cannabis spp.* strains (Critical Mass, Lemon Wheel, and Rockstar Kush). The total OFP rate of Critical Mass is 41 $\mu g\ g^{-1}\ hr^{-1}$, Lemon Wheel is 27 $\mu g\ g^{-1}\ hr^{-1}$ and Rockstar Kush is 22 $\mu g\ g^{-1}\ hr^{-1}$. For Critical Mass and Lemon Wheel, the eucalyptol and β-myrcene species make up 50% of the total OFP rate. The OFPs of Critical Mass for eucalyptol and β-myrcene are 12.8 $\mu g\ g^{-1}\ hr^{-1}$ and 7.3 $\mu g\ g^{-1}\ hr^{-1}$. The OFPs of Lemon Wheel for eucalyptol and β-myrcene are 10.2 $\mu g\ g^{-1}\ hr^{-1}$ and 7.1 $\mu g\ g^{-1}\ hr^{-1}$. Rockstar Kush has a higher β-myrcene OFP rate, which is 9.7 $\mu g\ g^{-1}\ hr^{-1}$, and eucalyptol is 3.7 $\mu g\ g^{-1}\ h^{-1}$.

Fig. 3B shows the SOA formation potentials (SFPs) based on the (SOA) yield (Lee et al., 2006; Iinuma et al., 2009; Fry et al., 2014; Slade et al., 2017) of individual terpenes as calculate from Equation (6).

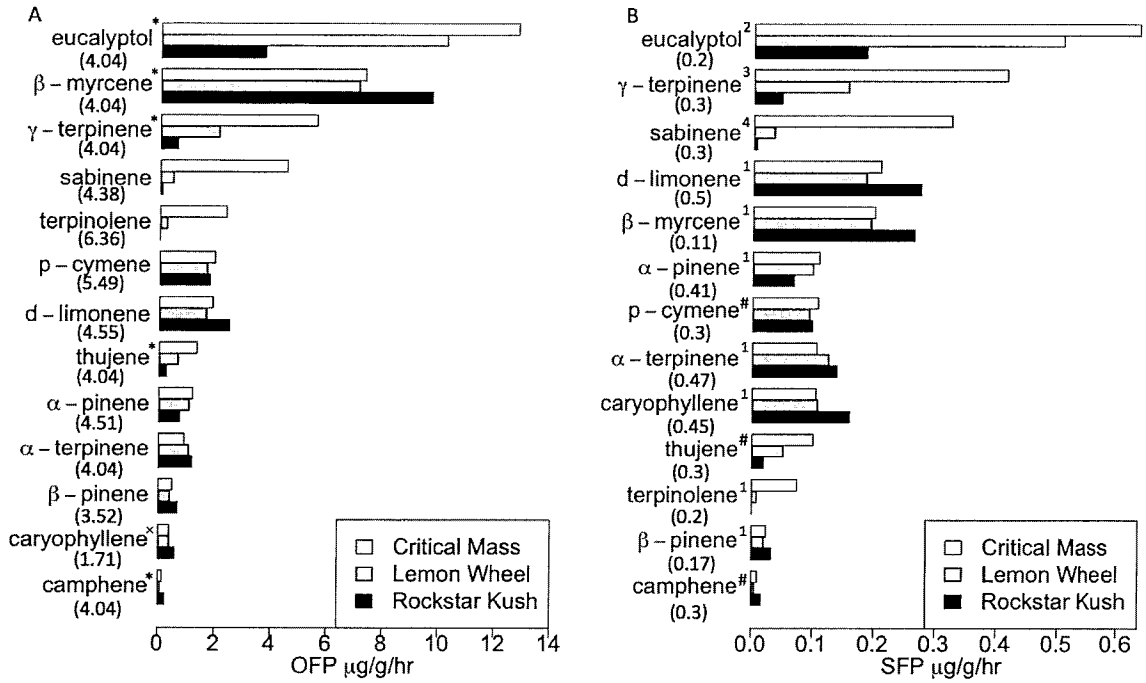
$$SFP = Emission\ capacity\ (\mu g/g/hr) \times SOA\ Yield \quad (6)$$

Fig. 3B estimated the SOA formation potential from the terpene species emitted from Critical Mass, Lemon Wheel and Rockstar Kush after 46 days of growth. For compounds without a published SOA yield (marked: #), we assumed an SOA yield 0.3. The total SFP of Critical Mass is about 2.4 $\mu g\ g^{-1}\ hr^{-1}$; with eucalyptol generating 0.63 $\mu g\ g^{-1}\ hr^{-1}$ of SOA, and γ-terpinene 0.4 $\mu g\ g^{-1}\ hr^{-1}$ of SOA. For Lemon Wheel, the total SFP is 1.6 $\mu g\ g^{-1}\ hr^{-1}$, with eucalyptol contributing 0.51 $\mu g\ g^{-1}\ hr^{-1}$, β-myrcene is 0.19 $\mu g\ g^{-1}\ hr^{-1}$ and d-limonene is 0.19 $\mu g\ g^{-1}\ hr^{-1}$. For Rockstar Kush, the total SFP is 1.3 $\mu g\ g^{-1}\ hr^{-1}$, with 0.26 $\mu g\ g^{-1}\ hr^{-1}$ from β-myrcene, and 0.27 $\mu g\ g^{-1}\ hr^{-1}$ from d-limonene. Eucalyptol, γ-terpinene, and d-limonene have the largest SOA yields, but emissions were low for the strains tested here. The complete numbers of OFP and SFP of all terpenes for all strains are in supplemental table S4.

4. Discussion and conclusion

This study presents the first enclosure measurements of VOC emission rates from four commercial *Cannabis spp.* strains. This is a limited data set given the number of available strains and possible growing conditions. These measurements do, however, offer a good first step of demonstrating the potential impacts of emission from this new industry and provide constraints over possible ranges of emission rates. The results show that the magnitude of the emission rates from *Cannabis spp.*, and the composition of the terpenes emitted, vary by strain and growing stage. These emitted terpenes also differ from other biogenic emissions from plant species normally found in Colorado. For example, the abundance of *Pinus spp.* in the region results in α-pinene and β-pinene being the dominant terpene emissions with comparable amounts of 2-methyl-3-buten-2-ol (Harley et al., 1998). Terpene emissions from all our *Cannabis spp.* strains had eucalyptol and *β*-myrcene as the highest emitted species. Ross et al. (Ross and ElSohly, 1996) also found that fresh buds of *Cannabis spp.* plants were about 67% β-myrcene. Similar to our results, Fischedick et al., (2010) (Fischedick et al., 2010) found that terpenes extracted from buds had different compositions across 11 strains. In six of these strains the dominant terpene was also β-myrcene (> 35%).

It is important to note that for large-scale *Cannabis spp.* cultivation facilities the growth conditions are optimized. This includes elevating CO_2 concentrations to 1500 ppm in growing rooms, carefully managing water use, elevating light to > 1000 $\mu mol\ m^{-2}\ s^{-1}$ (PAR), and maintaining temperatures greater than 30 °C. Further, these growers routinely use pesticides and fertilizer to optimize plant growth (Mills, 2012; Bauer et al., 2015; Ashworth and Vizuete, 2017). In these experiments plants were not grown at these ideal conditions, and thus the emissions measured here should be seen as a conservative estimate of the total amount of VOCs emitted from commercial facilities. Further, this study was also limited in the number strains that were analysed. Four strains of *Cannabis spp.* were measured in this study, however, there are a



* Used monoterpene MIR = 4.04
× Used 15C-alkene MIR = 1.71
compounds without a published SOA yield, assumed to be 0.3

Fig. 3. For the Critical Mass, Lemon Wheel, and Rockstar Kush strains, after 46 days of growth, the (A) The Ozone Formation Potential (OFP) rate estimated using the Maximum Incremental Reactivity (MIR) ratio (CARB, 2010) and (B) estimated SOA Formation Potential (SFP) based on published SOA yields [[1](Lee et al., 2006), [2](Iinuma et al., 2009), [3](Slade et al., 2017), and [4](Fry et al., 2014)].

reported 620 *Cannabis spp.* strains planted in Denver cultivation facilities (Leafly, 2018). Those strains in CCF could change over time based on both consumer demand and other market factors. To constrain such uncertainties, further studies are required with a greater number of strains, a wider range of treatments focusing on light and temperature dependencies, controlled growing environments, and data that includes rates of venting to the atmosphere. As far as possible, conditions should reflect current industry practices so that a representative dataset of *Cannabis spp.* emission capacities could be built for the whole lifecycle of *Cannabis spp.* Such a dataset would enable authorities to assess the potential impacts of this new industry on regional air quality and if necessary determine mitigation strategies.

According to the Colorado Department of Revenue (CDOR, 2017), there were more than 1400 CCFs in Colorado in 2017, with over 600 in the Denver metro area. If these emissions from these cultivations are released into the ambient atmosphere they have the potential to impact local ozone and particulate matter (PM). For example, if each of the 600 facilities in Denver contained the permitted 10,000 plants (CDOR, 2017), with an assumed biomass of 1 kg/plant (Green, 2009; Jankauskiene and Gruzdeviene, 2015), and all emissions were released into the atmosphere, a EC of 8.7 $\mu gC\ g^{-1}\ hr^{-1}$ emission capacity would result in the annual total terpene emission of 520 metric ton $year^{-1}$. This emission rate is more than twice that of the 250 metric ton $year^{-1}$ of total biogenic VOC emissions for Denver as estimated by the Western Air Quality Study (WAQS, 2017) for Colorado's 2008 regulatory air quality model simulations (RAQC, 2016). Using MIR values shown in Fig. 3 these BVOC emissions could produce 2100 metric ton $year^{-1}$ of ozone, and using the yields shown in Fig. 3 produce 131 metric ton $year^{-1}$ of PM. Given the location of the VOCs emitted from *Cannabis spp.* from facilities in downtown Denver near major urban anthropogenic sources, there is the potential for the emissions from the commercial cultivation of *Cannabis spp.* to impact regional concentrations of ozone and PM. Additional work is needed to assess these potential air quality impacts in air quality model evaluations of not only Colorado, but in other states where the commercial cultivation and sale of *Cannabis spp.* has been legalized.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2018.10.049.

References

Ashton, C.H., 2001. Pharmacology and effects of cannabis: a brief review. Br. J. Psychiatry 178, 101–106. https://doi.org/10.1192/bjp.178.2.101.
Ashworth, K., Vizuete, W., 2017. High time to assess the environmental impacts of cannabis cultivation. Environ. Sci. Technol. 51 (5), 2531–2533. https://doi.org/10.

1021/acs.est.6b06343.
Bauer, S., Olson, J., Cockrill, A., van Hattem, M., Miller, L., Tauzer, M., Leppig, G., 2015. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. PloS One 10 (3), 25. https://doi.org/10.1371/journal.pone.0120016.
Braure, T., Bedjanian, Y., Romanias, M.N., Morin, J., Riffault, V., Tomas, A., Coddeville, P., 2014. Experimental study of the reactions of limonene with OH and OD radicals: kinetics and products. J. Phys. Chem. 118 (40), 9482–9490. https://doi.org/10.1021/jp507180g.
CARB, California Air Resources Board, 2010. FINAL regulation order tables of maximum incremental reactivity (MIR) values. Retrieved from. https://www.arb.ca.gov/consprod/regs/2012/4mirtable50411.pdf.
CDOR, Colorado Department of Revenue, 2017. Licensees - marijuana enforcement division. Retrieved from. https://www.colorado.gov/pacific/enforcement/licensees-marijuana-enforcement-division.
D. E. A. US Department of Justice, 2017. Drugs of Abuse- a DEA Resource Guide.
Fehsenfeld, F., Calvert, J., Fall, R., Goldan, P., Guenther, A.B., Hewitt, C.N., Zimmerman, P., 1992. Emissions of volatile organic compounds from vegetation and the implications for atmospheric chemistry. Global Biogeochem. Cycles 6 (4), 389–430. https://doi.org/10.1029/91gb02965.
Fischedick, J.T., Hazekamp, A., Erkelens, T., Choi, Y.H., Verpoorte, R., 2010. Metabolic fingerprinting of Cannabis sativa L, cannabinoids and terpenoids for chemotaxonomic and drug standardization purposes. Phytochemistry 71 (17–18), 2058–2073. https://doi.org/10.1016/j.phytochem.2010.10.001.
Fry, J.L., Draper, D.C., Barsanti, K.C., Smith, J.N., Ortega, J., Winkler, P.M., ... Lee, L., 2014. Secondary organic aerosol formation and organic nitrate yield from NO3 oxidation of biogenic hydrocarbons. Environ. Sci. Technol. 48 (20), 11944–11953. https://doi.org/10.1021/es502204x.
Funk, J.L., Jones, C.G., Baker, C.J., Fuller, H.M., Giardina, C.P., Lerdau, M.T., 2003. Diurnal variation in the basal emission rate of isoprene. Ecol. Appl. 13 (1), 269–278. https://doi.org/10.1890/1051-0761(2003)013[0269:dvitbe]2.0.co;2.
Green, G., 2009. Cannabis Grow Bible: the Definitive Guide to Growing Marijuana for Recreational and Medical Use.
Guenther, A., 1997. Seasonal and spatial variations in natural volatile organic compound emissions. Ecol. Appl. 7 (1), 34–45. https://doi.org/10.2307/2269405.
Guenther, A., Hewitt, C.N., Erickson, D., Fall, R., Geron, C., Graedel, T., Zimmerman, P., 1995. A global-model of natural volatile organic-compound emissions. J. Geophys. Res.-Atmos. 100 (D5), 8873–8892. https://doi.org/10.1029/94jd02950.
Guenther, A., Monson, R.K., Fall, R., 1991. Isoprene and monoterpene emission rate variability - Observations with Eucalyptus and emission rate algorithm development. Journal of Geophysical Research-Atmospheres 96 (D6), 10799–10808. https://doi.org/10.1029/91jd00960.
Guenther, A., Zimmerman, P.R., Harley, P.C., Monson, R.K., Fall, R., 1993. Isoprene and monoterpene emission rate variability - model evaluations and sensitivity analyses. Journal of Geophysical Research-Atmospheres 98 (D7), 12609–12617. https://doi.org/10.1029/93jd00527.
Harley, P., Fridd-Stroud, V., Greenberg, J., Guenther, A., Vasconcellos, P., 1998. Emission of 2-methyl-3-buten-2-ol by pines: a potentially large natural source of reactive carbon to the atmosphere. Journal of Geophysical Research-Atmospheres 103 (D19), 25479–25486. https://doi.org/10.1029/98jd00820.
Harley, P., Eller, A., Guenther, A., Monson, R.K., 2014. Observations and models of emissions of volatile terpenoid compounds from needles of ponderosa pine trees growing in situ: control by light, temperature and stomatal conductance. Oecologia 176 (1), 35–55. https://doi.org/10.1007/s00442-014-3008-5.
Hillig, K.W., 2004. A chemotaxonomic analysis of terpenoid variation in Cannabis. Biochem. Syst. Ecol. 32 (10), 875–891. https://doi.org/10.1016/j.bse.2004.04.004.
Hites, R.A., Turner, A.M., 2009. Rate constants for the gas-phase beta-myrcene plus OH and isoprene plus OH reactions as a function of temperature. Int. J. Chem. Kinet. 41 (6), 407–413. https://doi.org/10.1002/kin.20413.
Hood, L.V.S., Dames, M.E., Barry, G.T., 1973. Headspace volatiles of marijuana. Nature 242, 402–403.
Iinuma, Y., Boge, O., Keywood, M., Gnauk, T., Herrmann, H., 2009. Diaterebic acid acetate and diaterpenylic acid acetate: atmospheric tracers for secondary organic aerosol formation from 1,8-cineole oxidation. Environ. Sci. Technol. 43 (2), 280–285. https://doi.org/10.1021/es802141v.
Jankauskiene, Z., Gruzdeviene, E., 2015. Screening of industrial hemp (cannabis sativa L.) cultivars for biomass yielding capacities in Lithuania. J. Nat. Fibers 12 (4), 368–377. https://doi.org/10.1080/15440478.2014.929556.
Kanakidou, M., Seinfeld, J.H., Pandis, S.N., Barnes, I., Dentener, F.J., Facchini, M.C., Wilson, J., 2005. Organic aerosol and global climate modelling: a review. Atmos. Chem. Phys. 5, 1053–1123.
Kesselmeier, J., Staudt, M., 1999. Biogenic volatile organic compounds (VOC): an overview on emission, physiology and ecology. J. Atmos. Chem. 33 (1), 23–88. https://doi.org/10.1023/a:1006127516791.
Leafly, 2018. Cannabis Strain Explorer. Retrieved from. https://www.leafly.com/explore/sort-alpha.
Lee, A., Goldstein, A.H., Keywood, M.D., Gao, S., Varutbangkul, V., Bahreini, R., Seinfeld, J.H., 2006. Gas-phase products and secondary aerosol yields from the ozonolysis of ten different terpenes. Journal of Geophysical Research-Atmospheres 111 (D7), 18. https://doi.org/10.1029/2005jd006437.
Lichtenthaler, H.K., 1999. The 1-deoxy-D-xylulose-5-phosphate pathway of isoprenoid biosynthesis in plants. Annu. Rev. Plant Physiol. Plant Mol. Biol. 50, 47–65. https://doi.org/10.1146/annurev.arplant.50.1.47.
Madras, B.K., World Health Organisation, 2015. Update of cannabis and its medical use. Retrieved from. http://www.who.int/medicines/access/controlled-substances/6_2_cannabis_update.pdf.
Marchini, M., Charvoz, C., Dujourdy, L., Baldovini, N., Filippi, J.J., 2014. Multidimensional analysis of cannabis volatile constituents: identification of 5,5-dimethyl-1-vinylbicyclo 2.1.1 hexane as a volatile marker of hashish, the resin of Cannabis sativa L. J. Chromatogr. A 1370, 200–215. https://doi.org/10.1016/j.chroma.2014.10.045.
Martyny, J.W., Serrano, K.A., Schaeffer, J.W., Van Dyke, M.V., 2013. Potential exposures associated with indoor marijuana growing operations. J. Occup. Environ. Hyg. 10 (11), 622–639. https://doi.org/10.1080/15459624.2013.831986.
Mills, E., 2012. The carbon footprint of indoor Cannabis production. Energy Pol. 46, 58–67. https://doi.org/10.1016/j.enpol.2012.03.023.
Niinemets, U., Loreto, F., Reichstein, M., 2004. Physiological and physicochemical controls on foliar volatile organic compound emissions. Trends Plant Sci. 9 (4), 180–186. https://doi.org/10.1016/j.tplants.2004.02.006.
Ortega, J., Helmig, D., 2008. Approaches for quantifying reactive and low-volatility biogenic organic compound emissions by vegetation enclosure techniques - Part A. Chemosphere 72 (3), 343–364. https://doi.org/10.1016/j.chemosphere.2007.11.020.
Ortega, J., Helmig, D., Daly, R.W., Tanner, D.M., Guenther, A.B., Herrick, J.D., 2008. Approaches for quantifying reactive and low-volatility biogenic organic compound emissions by vegetation enclosure techniques - Part B: Applications. Chemosphere 72 (3), 365–380. https://doi.org/10.1016/j.chemosphere.2008.02.054.
Ou, J., Zheng, J., Li, R., Huang, X., Zhong, Z., Zhong, L., Lin, H., 2015. Speciated OVOC and VOC emission inventories and their implications for reactivity-based ozone control strategy in the Pearl River Delta region, China. Sci. Total Environ. 530–531, 393–402. https://doi.org/10.1016/j.scitotenv.2015.05.062.
Pierce, T., Geron, C., Bender, L., Dennis, R., Tonnesen, G., Guenther, A., 1998. Influence of increased isoprene emissions on regional ozone modeling. Journal of Geophysical Research-Atmospheres 103 (D19), 25611–25629. https://doi.org/10.1029/98jd01804.
RAQC, Reginal Air Quality Council, 2016. State implementation plan for the 2008 8-hour ozone nationa ambient air quality standard. Retrieved from. https://raqc.egnyte.com/dl/q5zyuX9QC1/FinalModerateOzoneSIP_2016-11-29.pdf_.
Rice, S., Koziel, J.A., 2015. Characterizing the smell of marijuana by odor impact of volatile compounds: an application of simultaneous chemical and sensory analysis. PloS One 10 (12), 17. https://doi.org/10.1371/journal.pone.0144160.
Ross, S.A., ElSohly, M.A., 1996. The volatile oil composition of fresh and air-dried buds of Cannabis sativa. J. Nat. Prod. 59 (1), 49–51. https://doi.org/10.1021/np960004a.
Ryerson, T.B., Trainer, M., Holloway, J.S., Parrish, D.D., Huey, L.G., Sueper, D.T., Fehsenfeld, F.C., 2001. Observations of ozone formation in power plant plumes and implications for ozone control strategies. Science 292 (5517), 719–723. https://doi.org/10.1126/science.1058113.
Sakulyanontvittaya, T., Duhl, T., Wiedinmyer, C., Helmig, D., Matsunaga, S., Potosnak, M., Guenther, A., 2008. Monoterpene and sesquiterpene emission estimates for the United States. Environ. Sci. Technol. 42 (5), 1623–1629. https://doi.org/10.1021/es702274e.
Slade, Jonathan H., de Perre, Chloé, Lee, Linda, Shepson, Paul B., 2017. Nitrate radical oxidation of gamma-terpinene: hydroxy nitrate, total organic nitrate, and secondary organic aerosol yields. Atmos. Chem. Phys. 17 (14), 8635–8650. https://doi.org/10.5194/acp-17-8635-2017.
Staudt, M., Bertin, N., Hansen, U., Seufert, G., Ciccioli, P., Foster, P., Fugit, J.L., 1997. Seasonal and diurnal patterns of monoterpene emissions from Pinus pinea (L.) under field conditions. Atmos. Environ. 31, 145–156. https://doi.org/10.1016/s1352-2310(97)00081-2.
Tholl, D., Boland, W., Hansel, A., Loreto, F., Rose, U.S.R., Schnitzler, J.P., 2006. Practical approaches to plant volatile analysis. Plant J. 45 (4), 540–560. https://doi.org/10.1111/j.1365-313X.2005.02612.x.
Tingey, D.T., Manning, M., Grothaus, L.C., Burns, W.F., 1980. Influence of light and temperature on monoterpene emission rates from slash pine. Plant Physiol. 65 (5), 797–801. https://doi.org/10.1104/pp.65.5.797.
Turner, C.E., Elsohly, M.A., Boeren, E.G., 1980. Constituents of cannabis-sativa l .17. A review of the natural constituents. J. Nat. Prod. 43 (2), 169–234. https://doi.org/10.1021/np50008a001.
UNGCDP, United Nations Global Commission on Drug Policy, 2014. Taking Control: Pathways to Drug Policies that Work. Retrieved from. https://www.globalcommissionondrugs.org/wp-content/uploads/2016/03/GCDP_2014_taking-control_EN.pdf.
UNODC, United Nations Office on Drugs and Crime, 2016. World Drug Report 2016. Retrieved from. https://www.unodc.org/doc/wdr2016/WORLD_DRUG_REPORT_2016_web.pdf.
WAQS, Western Air Quality Study, 2017. IWDW-WAQS wiki. Retrieved from. http://vibe.cira.colostate.edu/wiki.
WHO. World Health Organisation, 2016. The health and social effects of nonmedical cannabis use (ISBN 978 92 4 151024 0). Retrieved from. http://www.who.int/substance_abuse/publications/msbcannabis.pdf.

Supplementary Material

Table S1. The estimated VOC emission rate per plant (μgC h^{-1}) based on data from the Gas Chromatograph coupled to a flame ionization detector (GC-FID) and mass spectrometer (GC-MS) (A) without a light dependency and (B) with a light dependency. The bold font indicates the data used to estimate emission capacity (EC). When possible the GC-FID data was selected due to its stability and linearity. If there was a co-elution effect, or if the GC-FID signal was lower than the detection limits, then the GC-MS results were used.

A

	Strains	Terpene	thujene	alpha-pinene	camphene	sabinene	beta-pinene	beta-myrcene	alpha-phellandrene	alpha-terpinene	p-cymene	d-limonene	cis-beta-ocimene	gamma-terpinene	terpinolene	caryophyllene	eucalyptol
30 days of growth	Critical Mass	FID (µg C / h)	**0.033**	**0.060**	**0.037**	**0.024**	**0.096**	**0.592**	-	-	**0.048**	**0.077**	**0.039**	**0.044**	ND	**0.021**	**0.258**
		MS (µg C / h)	0.050	0.060	0.015	0.027	0.029	0.467	**0.012**	**0.028**	-	0.112	0.049	0.071	**0.021**	-	-
	Lemon Wheel	FID (µg C / h)	**0.029**	**0.031**	**0.034**	-	-	**0.243**	ND	-	**0.021**	**0.040**	ND	**0.088**	ND	ND	**0.300**
		MS (µg C / h)	0.039	0.028	0.007	**0.046**	**0.036**	0.073	ND	**0.014**	-	0.058	**0.012**	0.079	**0.021**	-	-
	Elephant Purple	FID (µg C / h)	ND	ND	ND	ND	ND	**0.364**	ND	ND	**0.120**	**0.162**	ND	ND	ND	ND	**0.237**
		MS (µg C / h)	**0.008**	**0.008**	ND	ND	ND	0.116	ND	ND	-	0.025	**0.021**	**0.019**	ND	-	-
	Rockstar Kush	FID (µg C / h)	**0.013**	**0.009**	**0.031**	ND	ND	**0.291**	ND	ND	**0.018**	**0.057**	ND	ND	ND	ND	**0.195**
		MS (µg C / h)	0.010	0.007	0.017	ND	ND	0.164	ND	ND	-	0.046	**0.042**	**0.043**	ND	-	-
	Blank pot with soil	FID (µg C / h)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		MS (µg C / h)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
46 days of growth	Critical Mass	FID (µg C / h)	**0.291**	**0.232**	-	**0.939**	-	**1.573**	-	**0.195**	**0.312**	**0.363**	ND	**1.203**	**0.324**	**0.202**	**2.751**
		MS (µg C / h)	0.318	0.278	**0.028**	0.260	**0.123**	1.164	**0.055**	0.132	-	0.237	ND	0.452	0.127	-	-
	Lemon Wheel	FID (µg C / h)	**0.090**	**0.126**	-	**0.062**	-	**0.917**	-	**0.139**	**0.163**	**0.194**	ND	**0.271**	ND	**0.125**	**1.324**
		MS (µg C / h)	0.084	0.127	**0.009**	0.060	**0.063**	0.264	**0.019**	0.043	-	0.162	ND	0.150	**0.022**	-	-
	Elephant Purple	FID (µg C / h)	**0.076**	**0.131**	ND	ND	-	**2.663**	-	-	**0.028**	**0.136**	ND	**0.356**	ND	**0.222**	**0.759**
		MS (µg C / h)	0.066	0.109	ND	**0.010**	**0.060**	1.592	**0.016**	**0.024**	-	0.199	ND	0.138	ND	-	-
	Rockstar Kush	FID (µg C / h)	**0.026**	**0.065**	-	ND	-	**0.942**	ND	**0.116**	**0.128**	**0.215**	ND	-	ND	**0.139**	**0.362**
		MS (µg C / h)	0.013	0.063	**0.022**	**0.007**	**0.076**	0.585	ND	0.024	-	0.162	ND	**0.060**	ND	-	-
	Blank pot with soil	FID (µg C / h)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		MS (µg C / h)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

B

	Strains	Terpene	thujene	alpha-pinene	camphene	sabinene	beta-pinene	beta-myrcene	alpha-phellandrene	alpha-terpinene	p-cymene	d-limonene	cis-beta-ocimene	gamma-terpinene	terpinolene	caryophyllene	eucalyptol
30 days of growth	Critical Mass	FID (µg C / h)	**0.043**	**0.077**	**0.047**	**0.031**	**0.124**	**0.760**	-	-	**0.062**	**0.099**	**0.050**	**0.057**	ND	**0.028**	**0.331**
		MS (µg C / h)	0.032	0.039	0.010	0.017	0.019	0.299	**0.008**	**0.018**	-	0.072	0.031	0.046	**0.013**	-	-
	Lemon Wheel	FID (µg C / h)	**0.037**	**0.040**	**0.043**	-	-	**0.311**	ND	-	**0.028**	**0.051**	ND	**0.113**	ND	ND	**0.385**
		MS (µg C / h)	0.025	0.018	0.005	**0.029**	**0.023**	0.047	ND	**0.009**	-	0.037	**0.008**	0.051	**0.013**	-	-
	Elephant Purple	FID (µg C / h)	ND	ND	ND	ND	ND	**0.476**	ND	ND	**0.157**	**0.211**	ND	ND	ND	ND	**0.310**
		MS (µg C / h)	**0.005**	**0.005**	ND	ND	ND	0.076	ND	ND	-	0.016	**0.013**	**0.012**	ND	-	-
	Rockstar Kush	FID (µg C / h)	**0.016**	**0.017**	**0.042**	ND	ND	**0.395**	ND	ND	**0.024**	**0.077**	ND	ND	ND	ND	**0.263**
		MS (µg C / h)	0.007	0.005	0.012	ND	ND	0.111	ND	ND	-	0.031	**0.028**	**0.029**	ND	-	-
	Blank pot with soil	FID (µg C / h)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		MS (µg C / h)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
46 days of growth	Critical Mass	FID (µg C / h)	**0.314**	**0.250**	-	**1.015**	-	**1.699**	-	0.211	**0.337**	**0.392**	ND	**1.299**	**0.350**	**0.218**	**2.893**
		MS (µg C / h)	0.343	0.300	**0.030**	0.281	**0.133**	1.257	**0.060**	0.143	-	0.256	ND	0.488	0.121	-	-
	Lemon Wheel	FID (µg C / h)	**0.094**	**0.132**	-	**0.065**	-	**0.961**	-	**0.146**	**0.171**	**0.203**	ND	**0.283**	ND	**0.135**	**1.387**
		MS (µg C / h)	0.088	0.133	**0.009**	0.063	**0.066**	0.276	**0.020**	0.045	-	0.169	ND	0.157	**0.023**	-	-
	Elephant Purple	FID (µg C / h)	**0.085**	**0.146**	ND	ND	-	**2.974**	-	-	**0.031**	**0.152**	ND	**0.398**	ND	**0.248**	**0.847**
		MS (µg C / h)	0.074	0.122	ND	**0.011**	**0.066**	1.778	**0.018**	**0.027**	-	0.222	ND	0.155	ND	-	-
	Rockstar Kush	FID (µg C / h)	**0.028**	**0.071**	-	ND	-	**1.034**	ND	**0.127**	**0.141**	**0.237**	ND	-	ND	**0.153**	**0.397**
		MS (µg C / h)	0.014	0.069	**0.024**	**0.008**	**0.084**	0.642	ND	ND	-	0.178	ND	**0.066**	ND	-	-
	Blank pot with soil	FID (µg C / h)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		MS (µg C / h)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table S2. The retention time and fragment used for Gas Chromatograph with mass spectrometer (GC-MS)

Terpene	Retention time (min)	fragment used for quantitation	m/z 93 fragment(%)
thujene	8.4	93	28.6
alpha-pinene	8.56	93	26.3
camphene	8.89	93	18.8
sabinene	9.3	93	26.6
beta-pinene	9.43	93	25.5
beta-myrcene	9.54	93	23.7
alpha-phellandrene	9.93	93	32.1
alpha-terpinene	10.13	93	15.4
p-cymene	10.28	119	-
d-limonene	10.39	93	12
cis-beta-ocimene	10.56	93	22.4
gamma-terpinene	10.87	93	20
terpinolene	11.38	121	14.5
caryophyllene	16.9	93	-
eucalyptol	10.5	93	-

Table S3. The terpene emission composition for four different strains

		emission rate (μg C / h)	thujene	alpha-pinene	camphene	sabinene	beta-pinene	beta-myrcene	alpha-phellandrene	alpha-terpinene	p-cymene	d-limonene	cis-beta-ocimene	gamma-terpinene	terpinolene	caryophyllene	eucalyptol
30 days of growth	Critical Mass	1.392	2.4%	4.3%	2.6%	1.7%	6.9%	42.6%	0.9%	2.0%	3.4%	5.5%	2.8%	3.2%	1.5%	1.5%	18.5%
	Lemon Wheel	0.913	3.1%	3.4%	3.7%	5.0%	3.9%	26.6%	0.0%	1.5%	2.3%	4.4%	1.3%	9.7%	2.3%	0.0%	32.8%
	Elephant Purple	0.942	0.9%	0.8%	0.0%	0.0%	0.4%	38.6%	0.0%	0.0%	12.8%	17.2%	2.2%	2.0%	0.0%	0.0%	25.1%
	Rockstar Kush	0.703	1.8%	1.3%	4.4%	0.0%	0.5%	41.5%	0.0%	0.0%	2.6%	8.1%	5.9%	6.2%	0.0%	0.0%	27.7%
40 days of growth	Critical Mass	8.589	3.4%	2.7%	0.3%	10.9%	1.4%	18.3%	0.6%	2.3%	3.6%	4.2%	0.0%	14.0%	3.8%	2.4%	32.0%
	Lemon Wheel	3.521	2.6%	3.6%	0.3%	1.7%	1.8%	26.0%	0.5%	3.9%	4.6%	5.5%	0.0%	7.7%	0.6%	3.6%	37.6%
	Elephant Purple	4.480	1.7%	2.9%	0.0%	0.2%	1.3%	59.4%	0.4%	0.5%	0.6%	3.0%	0.0%	8.0%	0.0%	5.0%	16.9%
	Rockstar Kush	2.157	1.2%	3.0%	1.0%	0.3%	3.5%	43.7%	0.0%	5.4%	6.0%	10.0%	0.0%	2.8%	0.0%	6.4%	16.8%

Table S4. The estimated Ozone Formation Potential (OFP) and SOA Formation Potential (SFP) for all observed terpenes.

OFP (μg/g/h)	thujene	alpha-pinene	camphene	sabinene	beta-pinene	beta-myrcene	alpha-terpinene	p-cymene	d-limonene	gamma-terpinene	terpinolene	caryophyllene	eucalyptol
Critical Mass	1.4	1.2	0.1	4.5	0.5	7.3	0.9	2.0	1.9	5.6	2.4	0.4	12.8
Lemon Wheel	0.7	1.1	0.1	0.5	0.4	7.1	1.1	1.7	1.7	2.1	0.3	0.4	10.2
Rockstar Kush	0.3	0.7	0.2	0.1	0.7	9.7	1.2	1.8	2.5	0.6	0.0	0.6	3.7
SFP (μg/g/h)													
Critical Mass	0.10	0.11	0.01	0.32	0.02	0.20	0.11	0.11	0.21	0.42	0.07	0.10	0.63
Lemon Wheel	0.05	0.10	0.01	0.03	0.02	0.19	0.13	0.09	0.19	0.16	0.01	0.11	0.51
Rockstar Kush	0.02	0.07	0.02	0.01	0.03	0.26	0.14	0.10	0.27	0.05	0.00	0.16	0.18

Figure S1. The emission capacities for all measured terpene compounds among the three *Canabis sp*. strains.