Article

Seasonality in emission patterns of isoprene from two dominant tree species of Central India: Implications on terrestrial carbon emission and climate change

Tanzil Gaffar Malik, **Triratnesh Gajbhiye**, **Sudhir Kumar Pandey**
Department of Botany, Guru Ghasidas Central University, Bilaspur, 495009, C.G., India
E-mail: skpbhu@gmail.com

Received 25 June 2018; Accepted 30 July 2018; Published 1 December 2018

Abstract
A significant quantity of biogenic volatile organic compounds (BVOCs) is emitted mainly from terrestrial plants. Among them, isoprene is the most abundant, which is emitted in enormous quantities from various plant species. Their emission is temperature and light dependent. Therefore, we discuss here the variations in the emission rate of isoprene under different seasons along with environmental parameters such as temperature, CO_2, relative humidity and photosynthetic active radiation (PAR). For this purpose, isoprene emission rates from two dominant tropical tree species (*Dalbergia sissoo* and *Shorea robusta)* were measured across different seasons using a dynamic enclosure chamber. Significantly high seasonal variations in isoprene emission rates were observed in both the tree species. A clear seasonal cycle was detected with the highest emission rates in summer which decreases in winter. However, a gradual increase was again observed in rainy season. Correlation analysis revealed that isoprene emission were mainly temperature and PAR dependent. The information on emission rates of isoprene is relevant for air quality modelling studies and urban forestry programmes and terrestrial carbon loss. Moreover, their emission pattern tied with the global climate change conditions may surplus the emission rates of BVOCs in future especially in tropical regions.

Keywords isoprene; seasonal variations; average normalized emission rate; terrestrial carbon loss; climate change.

Proceedings of the International Academy of Ecology and Environmental Sciences
ISSN 2220-8860
URL: http://www.iaees.org/publications/journals/piaees/online-version.asp
RSS: http://www.iaees.org/publications/journals/piaees/rss.xml
E-mail: piaees@iaees.org
Editor-in-Chief: WenJun Zhang
Publisher: International Academy of Ecology and Environmental Sciences

1 Introduction

Isoprenoids represent a class of heterogeneous compound consisting of a wide range of reactive volatile hydrocarbons (i.e. isoprene, monoterpenes, and sesquiterpenes) which are emitted by most plant species. Among them, isoprene is one of the main isoprenoids which is emitted from many plant species (Guenther et al., 1999; Kesselmeier and Staudt, 1999), in large quantities. Terrestrial plants are the main source of isoprene.

The estimation of annual global emission of isoprene has been conducted previously (e.g., Guenther et al., 1995; Arneth et al., 2008; Dunn-Johnston et al., 2016; Dani et al., 2017), according to which the estimated value is about of 400-600 TgC yr^{-1}. Moreover, the emissions of isoprene from plants contribute significantly to the global carbon budgets and provide an idea for the estimation of carbon stock especially at forest levels (Dar and Sahu, 2018).

Isoprene emissions are largely affected by seasonal cycles of environmental conditions such as temperature, light, and water availability. However, the effect of seasonality and water availability paid a little attention. The emission of isoprene from plants is dependent on environmental factors, such as light and temperature (Guenther et al., 1991; Guenther et al., 1993; Sharkey and Singsaas, 1995; Penuelas and Llusia, 2001; Guenther et al., 2006; Grote and Niinemets, 2008; Niinemets et al., 2010). This ubiquitous trace constituent of VOC in atmosphere from plants plays an important role in atmospheric chemistry. For instance, the emission of isoprene from plants get oxidized in the atmosphere to form one of the most ubiquitous volatile compound HCHO (Palmer et al., 2003, 2006) which promotes the formation of photochemical smog (Chameides et al., 1988; Claeys et al., 2004), and secondary organic aerosols (SOAs) which plays a significant role in cloud formation and precipitation (Andreae and Crutzen, 1997; Poschl et al., 2010; Niinemets et al., 2011; Sun et al., 2012; Waked et al., 2012; Tuankrua et al., 2014). An increase in aerosol concentration may lead to an increase in cloud condensation nuclei (CCN) which ultimately affects the cloud properties (Tuankrua et al., 2014).

Some previous studies demonstrated that the seasonal changes may have impact on isoprene emissions by influencing relative difference in environmental variables (such as temperature and light differences) which changes the emission capacities (Schurgers et al., 2011; Hantson et al., 2017). Thus, the emission of isoprene from the tropical plants in Indian sub-continent provides a general idea for predicting the seasonal effect on their emission (Singh et al., 2007; Saxena and Ghosh, 2015). Only two reports are available regarding the seasonal variations of isoprene emission from Indian tropical plant species was studied (Singh et al., 2007; Saxena and Ghosh, 2015). To our knowledge, no study have been performed to date in the present two tropical tree species (*Dalbergia sissoo* and *Shorea robusta*) of central India. Therefore, the present study of isoprene emission in relation with seasonal changes during different seasons from two selected tropical plants species are important to improve the further information of isoprene emission. In addition, we have characterized the monthly variations of isoprene emission from the same plant species. The objective of the present study was to study isoprene emission rates from two dominant plant species(*Dalbergia sissoo* and *Shorea robusta*) over four seasons in order to evaluate variation in isoprene emission rates due to the environmental factors (temperature, PAR, RH and CO_2) during distinct seasons.

2 Study Area and Methodology

2.1 Sampling

Three years old saplings of *Dalbergia sissoo* and *Shorea robusta* were obtained from a local nursery. Three saplings were used for each plant species. Each sapling was transplanted into a pot (15cm) containing soil mixed with organic manure. Samplings were watered daily and received full exposure to sunlight. All the emission measurements were conducted at the GGV campus under natural environmental conditions over a one year period (from November 2015 to October 2016). Here, there are three distinct seasons; viz. summer (from March to June), rainy (from July to October) and winter (from November to February).

Samplings were carried out by using a specific dynamic enclosure System, which were employed previously by Yassaa et al. (2010). The cuvette system was a cylindrical chamber having height 0.60m and diameter 0.35m, constructed from two acrylic rings connected with four acrylic rods and the lateral covering of

this system is covered with 50µm thick transparent Fluorinated Ethylene Propylene (FEP) Teflon foil. The upper side of the cuvette was closed with a lid whose surface was coated with FEP foil. The air inside the chamber (driven through inlet port) was mixed with Teflon coated fan fitted on the upper surface of lid and the outlet port for withdrawal of analytical samples. The cuvette enclosure was carefully fitted around the plant in order to prevent the disturbance of the emission from the plant while attaching with it. The single integrated humidity/ CO_2 probe was placed inside the chamber and the upper portion of integrated Temperature and photosynthetically active radiation (PAR) probe (Model EGM-4, PP systems, USA, Model TRP-2 PP System, USA) was also placed on the upper side of the chamber having a small hole of the same size of that probe. These parameter values were monitored concurrently and recorded in five minute intervals for one hour. Inlet and outlet airflow rates of enclosure chamber were measured by calibrated rotameter. Samplings were carried out at a flow rate of 200 mL min^{-1} for 30 min. from the enclosure on to Tenax TA carbosieve II (100 mg) solid adsorbent ((200 mg)/ obtained from Supelco Inc. Bellefonte, PA).

2.2 Analysis of BVOCs

After the sample collection, tubes were stored at 4˚C until they were analyzed. The adsorbed compounds were desorbed by using the thermal desorption system (Shimadzu, TD-20) interfaced with a gas chromatograph-FID system (GC-FID; Shimadzu, 74704, GC-2010). The desorption temperature was 240°C for 10 minutes. During sample desorption, the internal trap temperature was 35°C for 5 min, and then increased to150˚C at a rate of 5°C min^{-1} for 5min there after temperature increased at a rate of 15°C up to 250°C and maintained for 10min. The gas chromatograph was equipped with a flame ionization detector (GC-FID; Shimadzu, 74704, GC-2010) with a DB-5MS (30 m length, 0.25 mm i.d.) capillary column (Restek, US). Isoprene was determined with the help of a standard calibration plot prepared from the liquid chemical standard obtained from Sigma-Aldrich, USA. The liquid chemical standard of isoprene were prepared by serial dilution (i.e., 10, 50, 100, 200, 500 µmol L^{-1} in 1000 µmol L^{-1} of Methanol) in round flasks fitted with screw cap. The retention time and peak area detected for isoprene was used to identify and quantify the real sample. The detection limit was about below 2 pptv. The level of precision for the analytical procedure was about 5%, and recovery rate was obtained 96% approximately.

Enclosed branches were harvested at the end of the samplings to determine the dry foliage weight. The weights of leaves were measured after they were dried with an oven at 50°C for 48 hours. Using this data, dry foliage weight based emission rate was calculated.

3 Results and Discussion

3.1 Seasonal variations in isoprene emission

Dalbergia sissoo: The average normalized emission rate was ranged from 11.84±1.43 to 81.25±15.8 µg $g^{-1}h^{-1}$ (based on leaf dry weight). The maximum average normalized isoprene emission rate was found in the summer season (81.25±15.8 µg g^{-1} h^{-1}), followed by rainy (32.51±4.67 µg g^{-1} h^{-1}) and winter (11.84±1.43 µg $g^{-1}h^{-1}$) season (Fig. 1). The high summer/winter (S/W) isoprene ratio (6.86) was observed.

Shorea robusta: The average normalized emission rate was ranged from below detection limit (BDL) to 7.64±2.51 µg $g^{-1}h^{-1}$ (based on leaf dry weight). The maximum average normalized isoprene emission rate was found in the summer season (7.64±2.51 µg g^{-1} h^{-1}), followed by rainy (3.83±0.95 µg g^{-1} h^{-1}) and BDL during the winter season (Fig. 1). The high summer/winter (S/W) isoprene ratio (7.64) was observed.

There are several reports regarding the seasonal variation in isoprene emission rate (Hanson and Sharkey, 2001; Petron et al., 2001; Kuhn et al., 2004; Funk et al., 2005; Singh et al., 2007; Meeningen et al., 2017). Seasonal variations in isoprene emission capacity were also described by Kuhn et al. (2004). They studied that the high emission capacity of isoprene was found during the summer season as compared to winter.

Additionally, seasonal variations in isoprene rate have been examined in four tropical deciduous plants over a 1-year period 2002-03 (Singh et al., 2007). They noted that the maximum isoprene emission rate was occurred during the summer and minimum in the winter or spring. Recently, Saxena and Ghosh (2015) found the seasonal variations of isoprene emission rates from two plant species (*Dalbergia sissoo* and *Nerium oleander*). However, they reported that high emission rate was found in summer followed by winter and monsoon. In the present study, the emission rate was highest in summer followed by rainy and winter. This implies that factors such as temperature and PAR, relative humidity might be responsible for showing the high emission of isoprene during the summer season.

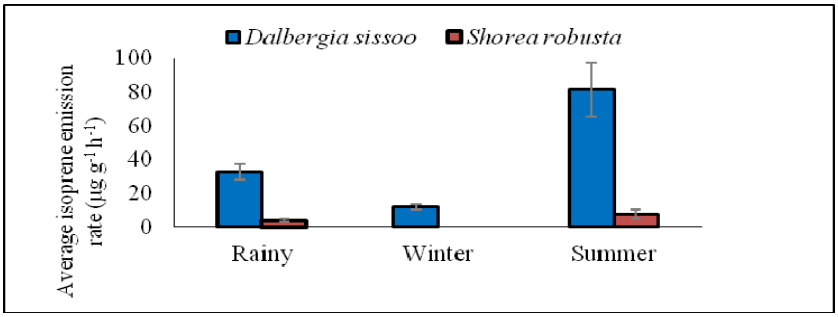

Fig. 1 Seasonal variations in average normalized isoprene emission rates (µg g^{-1} h^{-1}) from two tropical tree species.

To study the effect of environmental parameters (Temperature, PAR, RH and CO_2) on isoprene emission rates of both the plant species (*Dalbergia sissoo* and *Shorea robusta*), a correlation analysis was conducted between isoprene emission rates *vs.* TEM, PAR RH and CO_2. During the summer season, a very positive and significant correlation were observed between ISOP and TEM (r = 0.91), PAR and ISOP (r = 0.96), PAR and TEM (r = 0.92) at 0.001 level, RH *vs.* ISOP (r = 0.66), RH *vs.* PAR (r = 0.70) at 0.01 level (Table 1 (a)). During the rainy season, there were significant positive correlations between pairs of isoprene (ISOP) *vs.*TEM (r = 0.75), ISOP *vs.* PAR (r = 0.74), PAR *vs.*TEM (r = 0.79) at 0.01 level. However, its significant level is different compared to summer season (Table 1 (b)). Whileas, in case of winter season, the correlation between isoprene emissions (ISOP) *vs.* environmental parameters (TEM, PAR, RH and CO_2) were not significant (Table 1 (c)). Thus, in summer season temperature, PAR, RH plays an important role for controlling the isoprene emission rates. During the rainy season, TEM and PAR are responsible for controlling the isoprene emission rate. Moreover, in winter the low emission rate was found, it is because of the low temperature and light intensity. However, CO_2 have no role for isoprene emission in all the seasons.

Table 1 Correlation analysis of isoprene emission with environmental parameters (PAR, TEM, CO_2 and RH) of *Dalbergia sissoo*

(a) Summer

	ISOP	TEM	PAR	CO_2	RH
ISOP	1.00				
TEM	0.91**	1.00			
PAR	0.96**	0.92**	1.00		
CO_2	0.35	0.17	0.35	1.00	
RH	0.66*	0.57	0.70*	0.42	1.00

*Correlation is significant at 0.01 level (one-tailed)
**Correlation is significant at 0.001 level (one-tailed)

(b) Rainy

	ISOP	TEM	PAR	CO_2	RH
ISOP	1.00				
TEM	0.75*	1.00			
PAR	0.74*	0.79*	1.00		
CO_2	0.18	-0.15	-0.14	1.00	
RH	0.22	-0.04	0.22	0.44	1.00

*Correlation is significant at 0.01 level (one-tailed)
**Correlation is significant at 0.001 level (one-tailed)

(c) Winter

	ISOP	TEM	PAR	CO_2	RH
ISOP	1.00				
TEM	0.11	1.00			
PAR	0.21	0.41	1.00		
CO_2	0.21	-0.17	-0.06	1.00	
RH	-0.14	0.10	0.07	-0.31	1.00

*Correlation is significant at 0.01 level (one-tailed)

**Correlation is significant at 0.001 level (one-tailed)

Table 2 Correlation analysis of isoprene emission with environmental parameters (PAR, TEM, CO_2 and RH) of *Shorea robusta*

(a) Summer

	ISOP	TEM	PAR	CO_2	RH
ISOP	1.00				
TEM	0.97**	1.00			
PAR	0.73*	0.75*	1.00		
CO_2	-0.16	-0.10	-0.07	1.00	
RH	0.48	0.44	0.54	-0.33	1.00

*Correlation is significant at 0.01 level (one-tailed)

**Correlation is significant at 0.001 level (one-tailed)

(b) Rainy

	ISOP	TEM	PAR	CO_2	RH
ISOP	1.00				
TEM	0.70*	1.00			
PAR	0.93**	0.80**	1.00		
CO_2	-0.15	0.14	-0.04	1.00	
RH	0.38	0.59	0.40	-0.15	1.00

*Correlation is significant at 0.01 level (one-tailed)

**Correlation is significant at 0.001 level (one-tailed)

For instance, in case of *Shorea robusta*, a relatively strong and significant correlations were observed in summer between the pairs of ISOP *vs.* TEM (r = 0.97), at 0.001 level, ISOP *vs.* PAR (r = 0.73), PAR *vs.*TEM (r =0.75) at 0.01 level However, RH and CO_2 shows no significant correlations with the isoprene emission. (Table 2 (a)).This implies that temperature and PAR are the main environmental factors for controlling the emission of isoprene during the summer season. In rainy season, similar trends were observed. However, the significant levels were different as shown in Table 2 (b).

There are sufficient reports regarding the impact of temperature and light on isoprene emission rate on short-term basis from plant species (Guenther et al., 1991; Sharkey et al., 1996; Funk et al., 2005; Guenther et al., 2006). Long-term responses of isoprene emission to temperature and light during the diurnal, weakly, and seasonal measurements were also well defined (Sharkey et al., 1999; Geron et al., 2000; Hanson and Sharkey, 2001; Petron et al., 2001; Singh et al., 2007). Moreover, some researchers also suggested that CO_2 plays an important role for isoprene emission (Scholefield et al., 2004; Monson et al., 2007). For instance, recent study showed that plants were grown under elevated CO_2 can result in high isoprene emission (Sun et al., 2012). However, in the present study there is no indication about the effect on isoprene emission due to CO_2 concentration. On the other hand, the leaves are present at different phenological stages in different seasons from these plants which can led to difference in emission rates leaf (Guenther et al., 1997; Petron et al., 2001; Singh et al., 2007). However, the present study does not consider the age difference (phenological stages). The two plants show different responses with environmental variables during different seasons, which may lead to different emission rates. Moreover, the different experimental approaches suggest that the plant species have same emission significance as per BVOCs emissions were taken into account across the seasons. However, we have observed that the isoprene emission rates from both the plant species (*Dalbergia sissoo* and *Shorea robusta*) during the entire period (three seasons) on the basis of temperature were varied significantly. The previous studies also revealed that the isoprene emission rate were temperature dependent (Guenther et al., 1991; Sharkey et al., 1996; Funk et al., 2005). The emission of isoprene rate influences while increasing the

temperature and light because of the activation of synthesizing enzyme (isoprene synthase enzyme) (Wolfertz et al., 2003). Their activation energy became low on increasing the temperature (temperature sensitive enzyme) described by Schnitzler et al. (1997).

3.2 Monthly variations in average isoprene emission rate

Average isoprene emission rates from both the plants varied monthly with a maximum in summer months and a minimum in winter months (Table 3). The maximum emission rate (normalized emission rate at 30˚C) of *Dalbergia sissoo* was 115.16±36.18 µg g^{-1} h^{-1} in the month of June. Whileas their minimum emission rate (normalized emission rate at 30˚C) was found 3.25±1.72 µg g^{-1} h^{-1} in the month of February. In addition, the emission rate increased sharply after March and decreased rapidly (drastically) in August. During the other periods (September-February), the monthly emission rate variations were varied roughly. In case of *Shorea robusta*, the highest average emission rate was found in May9.8±6.25 µg g^{-1} h^{-1}. In February the minimum emission rate was 1.5±0.56 µg g^{-1} h^{-1}. The emission was below detection limit (BDL) during the month of November, December and January. During the other months, the emission rate varied considerably. The normalized emission rates in May were over 9 times higher than those in December. These results indicate that the monthly emission rate variations depends on the climatic variables such as temperature, light intensity, as other studies were also documented (Kempf et al., 1996; Lerdau et al., 1997; Kuhn et al., 2002; Palmer et al., 2006) relative humidity, carbon dioxide concentrations and other environmental parameters. However, temperature and light intensity (PAR) are the main players that change the emission rate of isoprene, respectively. Guenther et al. (2006) also reported that the isoprene emissions were varied in a plant species through several factors such as leaf age, light intensity and other meteorological factors. The latter one is the important factor that determines the emission rate of isoprene because their synthesis is influenced by temperature (Sharkey and Yeh, 2001).

Table 3 Monthly variations of average isoprene emission rates [average normalized isoprene emission rate (µg$g^{-1}h^{-1}$)] from *Dalbergia sissoo** and *Shorea robusta*** species

Month	N	MT	PAR (µmol.$m^{-2}s^{-1}$)	RH (%)	CO_2 (ppm)	ANIER (µg g^{-1} h^{-1})*	ANIER(µg g^{-1} h^{-1})**
November	3	30	978	52.17	397	19.32±7.64	BDL
December	3	27.1	489	53.65	399	16.52±5.42	BDL
January	4	24.2	469	68.3	403	8.31±3.1	BDL
February	4	31.6	654	59.7	372	3.25±1.72	1.5±0.56
March	5	33.6	2070	60.65	384	60.21±23.84	10.8±3.61
April	4	37.8	2457	61.1	419	70±32.71	17.37±7.95
May	3	42.4	2317	63.5	401	85.65±31.91	19.8±6.25
June	3	39	2589	67.6	394	115.16±36.18	13.8±4.51
July	3	31.4	2064	85.6	371	79.47±25.98	6.42±1.25
August	4	29.5	1962	87.5	368	52±16.35	5.96±2.36
September	3	31.7	1566	79.95	374	48.86±13.73	6.47±2.72
October	5	32.2	1048	69.15	365	42.45±11.55	3.71±1.12

N: No. of samples; MT: Mean Temperature; PAR: Photosynthetically Active Radiation; RH: Relative Humidity; ANIER: Average Normalized Isoprene Emission Rate; BDL: Below Detection Limit

There is only one report discussing the seasonality or monthly of average isoprene emission rate (normalized at 30 ˚C) on the tropical plants of India (Singh et al., 2007). They carried out their study in other tropical plants across four distinct seasons. They found the high emissions during the summer and spring

months and low emission during the winter months. We also found high emission rate in summer and low in winter. In addition, in winter months (especially in January and February) the low temperature was responsible for the low emission of isoprene.

4 Conclusions

A distinct seasonal as well as monthly variation in isoprene emission was observed from both the tropical plant species. The emission rates of isoprene were the highest during the summer, followed by rainy and winter seasons of both the species. However, *Shorea robusta* had their low emission as compared to *Dalbergia sissoo* during all the seasons, respectively. On the other hand, the correlations between isoprene emission rates *vs.* environmental parameters (temperature, PAR, RH and CO_2) were found different of both the plant species during all the seasons. The significant correlations were found between the pairs of isoprene emission *vs.*TEM and PAR. This indicated that isoprene emission from both plants is highly temperature and light dependent. Thus, the seasonal as well as monthly variations could affect the isoprene emissions, and indirectly changes the environmental carbon balance and deteriorating the air quality especially in rainy and summer months. Moreover, *Dalbergia sissoo* plant is a high isoprene emitter so they are not suitable for planting purposes especially in urban areas. The understanding on effects of important environmental variables such as light and temperature on plant's isoprene emissions facilitates the simulation of monthly and seasonal changes in BVOC emissions from central India (especially AABR) and improving the global inventory. BVOCs emission may represent a considerable loss of photosynthetically fixed carbon. As such, they can exert a profound influence on the global carbon budget of terrestrial ecosystems.

Acknowledgement

This work was supported by Department of Science and Technology (DST), Government of India, New Delhi, (Ref No.: SB/YS/LS-277/2013).

References

Andreae MO, Crutzen PJ. 1997. Atmospheric aerosols: Biogeochemical sources and role in atmospheric chemistry. Science, 276 (5315): 1052-1058

Arneth A, Monson RK, Schurgers G, et al. 2008. Why are estimates of global terrestrial isoprene emissions so similar (and why is this not so for monoterpenes)? Atmospheric Chemistry and Physics, 8: 4605-4620

Chameides WL, Lindsay RW, Richardson J, et al. 1988. The role of biogenic hydrocarbons in urban photochemical smog: Atlanta as a case study. Science, 241(4872): 1473-1475

Claeys M, Wang W, Ion AC, et al. 2004. Formation of secondary organic aerosols from isoprene and its gas-phase oxidation products through reaction with hydrogen peroxide. Atmospheric Environment, 38(25): 4093-4098

Dani KGS, Silva Benavides AM, Michelozzi M, et al. 2017. Relationship between isoprene emission and photosynthesis in diatoms, and its implications for global marine isoprene estimates. Marine Chemistry, 189: 17-24

Dar DA, Sahu P. 2018. Assessment of biomass and carbon stock in temperate forests of Northern Kashmir Himalaya, India. Proceedings of the International Academy of Ecology and Environmental Sciences, 2018, 8(2): 139-150

Dunn-Johnston KA, Kreuzwieser J, Hirabayashi S, et al. 2016. Isoprene Emission Factors for Subtropical Street Trees for Regional Air Quality Modeling. Journal of Environmental Quality, 45: 234-243

Funk JL, Jones CG, Gray DW, et al. 2005. Variation in isoprene emission from *Quercus rubra*: sources, causes, and consequences for estimating fluxes. Journal of Geophysical Research: Atmospheres, 110(D4): D04301

Geron C, Guenther A, Sharkey T, et al. 2000. Temporal variability in basal isoprene emission factor. Tree Physiology, 20: 799-805

Guenther AB, Monson RK, 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

Guenther AB, Zimmerman PR, Harley PC, et al. 1993. Isoprene and monoterpene emission rate variability: model evaluations and sensitivity analyses. Journal of Geophysical Research: Atmospheres, 98(D7): 12609-12617

Guenther A, Hewitt CN, Erickson D, et al. 1995. A global model of natural volatile organic compound emissions. Journal of Geophysical Research: Atmospheres, 100(D5): 8873-8892

Guenther A, 1997. Seasonal and spatial variations in natural volatile organic compound emissions. Ecological applications, 7(1): 34-45

Guenther A, Baugh B, Brasseur G, et al. 1999. Isoprene emission estimates and uncertainties for the Central African EXPRESSO study domain. Journal of Geophysical Research: Atmospheres, 104(D23): 30625-30639

Guenther CC, 2006. Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). Atmospheric Chemistry and Physics, 6: 3181

Grote R, Niinemets U. 2008. Modeling volatile isoprenoid emissions–a story with split ends. Plant Biology, 9: 42-59

Hanson DT, Sharkey TD, 2001. Rate of acclimation of the capacity for isoprene emission in response to light and temperature. Plant, Cell & Environment, 24(9): 937-946

Hantson S, Knorr W, Schurgers G, et al. 2017. Isoprene and monoterpene emissions under changing climate, vegetation, CO2 and land use. Atmospheric Environment, 155: 35-45

Kempf K, Allwine E, Westberg H, et al. 1996. Hydrocarbon emissions from spruce species using environmental chamber and branch enclosure methods. Atmospheric Environment, 30(9): 1381-1389

Kesselmeier J, Staudt M, 1999. Biogenic volatile organic compounds (VOC): an overview on emission, physiology and ecology. Journal of atmospheric chemistry, 33(1): 23-88

Kuhn U, Rottenberger S, Biesenthal T, et al. 2002. Isoprene and monoterpene emissions of Amazonian tree species during the wet season: Direct and indirect investigations on controlling environmental functions. Journal of Geophysical Research: Atmospheres, 107(D20)

Kuhn U, Rottenberger S, Biesenthal T, et al. 2004. Seasonal differences in isoprene and light-dependent monoterpene emission by Amazonian tree species. Global Change Biology, 10(5): 663-682

Meeningen YV, Wang M, Karlsson T, et al. 2017. Isoprenoid emission variation of Norway spruce across a European latitudinal transect. Atmospheric Environment, 170: 45-57

Monson RK, Trahan N, Rosenstiel TN, et al. 2007. Isoprene emission from terrestrial ecosystems in response to global change: minding the gap between models and observations. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 365(1856): 1677-1695

Niinemets U, Monson RK, Arneth A, et al. 2010. The leaf-level emission factor of volatile isoprenoids: caveats, model algorithms, response shapes and scaling. Biogeosciences, 7(6): 1809

Niinemets Ü, Kuhn U, Harley PC, et al. 2011. Estimations of isoprenoid emission capacity from enclosure studies: measurements, data processing, quality and standardized measurement protocols. Biogeosciences, 8: 2209-2246

Palmer PI, Jacob DJ, Fiore AM, et al. 2003. Mapping isoprene emissions over North America using formaldehyde column observations from space. Journal of Geophysical Research: Atmospheres, 108(D6)

Palmer PI, Abbot DS, Fu TM, et al. 2006. Quantifying the seasonal and interannual variability of North American isoprene emissions using satellite observations of the formaldehyde column. Journal of Geophysical Research: Atmospheres, 111(D12)

Penuelas J, Llusia J, 2001. The complexity of factors driving volatile organic compound emissions by plants. Biologia Plantarum, 44(4): 481-487

Petron G, Harley P, Greenberg J, et al. 2001. Seasonal temperature variations influence isoprene emission. Geophysical Research Letters, 28(9): 1707-1710

Poschl U, Martin ST, Sinha B, et al. 2010. Rainforest aerosols as biogenic nuclei of clouds and precipitation in the Amazon. Science, 329(5998): 1513-1516

Saxena P, Ghosh C, 2015. Seasonal variations isoprene emissions from tropical roadside plant species and their possible role in deteoriating air quality. Environmental Skeptics and Critics, 4(2): 67-80

Schnitzler JP, Lehning A, Steinbrecher R, 1997. Seasonal pattern of isoprene synthase activity in Quercus robur leaves and its significance for modeling isoprene emission rates. Plant Biology, 110(3): 240-243

Scholefield PA, Doick KJ, Herbert BMJ, et al. 2004. Impact of rising CO_2 on emissions of volatile organic compounds: isoprene emission from *phragmites australis* growing at elevated CO_2 in a natural carbon dioxide spring. Plant, Cell and Environment, 27: 393-401

Schurgers G, Arneth A, Hickler T, 2011. Effect of climate-driven changes in species composition on regional emission capacities of biogenic compounds. Journal of Geophysical Research Atmospheres, 116(D22)

Sharkey TD, Singsaas EL, 1995. Why plants emit isoprene. Nature, 374(6525): 769-769

Sharkey TD, Singsaas EL, Vanderveer PJ, et al. 1996. Field measurements of isoprene emission from trees in response to temperature and light. Tree Physiology, 16(7): 649-654

Sharkey TD, Singsaas EL, Lerdau MT, et al. 1999. Weather effects on isoprene emission capacity and applications in emissions algorithms. Ecological Applications, 9(4): 1132-1137

Sharkey TD, Yeh S, 2001. Isoprene emission from plants. Annual Review of Plant Biology, 52(1): 407-436

Singh AP, Varshney CK, Singh UK, 2007. Seasonal variations in isoprene emission from tropical deciduous tree species. Environmental monitoring and assessment, 131(1-3): 231-235

Tuankrua V, Tongdeenog P, Tangtham N, et al. 2014. Assessment of aerosol-cloud-rainfall interactions in Northern Thailand. Proceedings of the International Academy of Ecology and Environmental Sciences, 4(4): 134-147

Sun Z, Niinemets Ü, Hüve K, et al. 2012. Enhanced isoprene emission capacity and altered light responsiveness in aspen grown under elevated atmospheric CO_2 concentration. Global Change Biology, 18(11): 3423-3440

Waked A, Afif C, Seigneur C, 2012. An atmospheric emission inventory of anthropogenic and biogenic sources for Lebanon. Atmospheric Environment, 50: 88-96

Wolfertz M, Sharkey TD, Boland W, et al. 2003. Biochemical regulation of isoprene emission. Plant, Cell & Environment, 26(8): 1357-1364

Yassaa N, Custer T, Song W, et al. 2010. Quantitative and enantioselective analysis of monoterpenes from plant chambers and in ambient air using SPME. Atmospheric Measurement Techniques, 3(6): 1615-1627