



## Volatile organic compounds from vegetation in southern Yunnan Province, China: Emission rates and some potential regional implications

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### Abstract

Little information is currently available regarding emissions of biogenic volatile organic compounds (BVOCs) in southern Asia. To address the need for BVOC emission estimates in regional atmospheric chemistry simulations, 95 common plant species were screened for emissions of BVOC in and near the Xishuangbanna Tropical Biological Gardens in southern Yunnan Province, Peoples' Republic of China in February 2003. In situ measurements with leaf cuvettes and branch bag enclosures were used in combination with portable gas chromatography, flame ionization, photoionization, and mass spectral detection to identify and quantify BVOC emissions. Forty-four of the species examined emitted isoprene at rates exceeding  $20 \mu\text{g C g}^{-1}$  (leaf dry weight)  $\text{h}^{-1}$ . An emphasis was placed on the genus *Ficus*, which is important in the region and occupies a wide range of ecological niches. Several species in the footprint of a nearby flux tower were also examined. Several palm species and an abundant fern (*Cyclosorus parasiticus*) emitted substantial amounts of isoprene, and probably accounted for observed daytime mean isoprene fluxes from the understory of a *Hevea brasiliensis* plantation of  $1.0$  and  $0.15 \text{ mg C m}^{-2} \text{ h}^{-1}$  during the wet and dry seasons, respectively. These measurements verify that both the forest floor and canopy in this region can be sources of isoprene. Monoterpene emissions exceeded  $1.0 \mu\text{g-C g}^{-1}$  (leaf dry weight)  $\text{h}^{-1}$  from only 4 of 38 species surveyed, including some *Ficus* species and *H. brasiliensis*. However most of the trees of the latter species were sparsely foliated due to dry season senescence, and emission factors are approximately an order of magnitude lower than those reported during the wet season. BVOC emission rates and physiology of many species are impacted by reduced moisture availability, especially *Mangifera indica*. South Asia is a region undergoing rapid landuse change and forest plantation establishment, with large increases in area of high BVOC-emitting species in the genera *Bambusa*, *Elaeis*, *Eucalyptus*, *Hevea*, *Pinus*, and *Populus* (among others). This could result in profound changes in atmospheric chemistry in these regions, for instance, terpene emissions from *H. brasiliensis* could increase wet season biogenic organic aerosol burdens by approximately a factor of 2 in the Xishuangbanna region. Increases in plantation area

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established with high isoprene emitting species, (e.g. *Bambusa* spp. and *Eucalyptus* spp.) are also projected for China and other parts of Southeast Asia in the near future. Thus, landcover change in South Asian landscapes is usually associated with large increases in BVOC flux with the potential to alter the atmospheric chemical composition and air quality over this rapidly developing region.

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## 1. Introduction

Biogenic volatile organic compound (BVOC) emission from vegetation is the world's largest known source of non-methane volatile organic compounds (NMVOCs). The importance of BVOC is enhanced by high reactivity with ozone ( $O_3$ ), hydroxyl radical (OH), and nitrate radical ( $NO_3$ ) compared to other abundant atmospheric NMVOCs, consequently BVOCs play key roles in the tropospheric chemistry of  $O_3$  and particle formation, and in the atmospheric chemistry and physics associated with climate change. Modeling (Guenther et al., 1995) and limited measurement (Guenther et al., 1999, 1996; Kesselmeier et al., 2000; Geron et al., 2002; Greenberg et al., 2004) studies in the tropical Americas and Africa have suggested that at least 50% of the global annual BVOC flux is from tropical ecosystems, due to vast expanses ( $0.5\text{--}1.0 \times 10^9$  ha) of evergreen vegetation and warm climate throughout the year (Guenther et al., 1995). However, very little is known of emissions from tropical Asia. Historically, this region was extensively forested, but is now intensely cultivated and features rapid landscape changes. Species-level BVOC emission rate measurements made under carefully controlled environmental conditions are needed to develop emission models for this region in order to assess the atmospheric and ecological impacts of these changes. Here we present BVOC emissions measured at leaf and branch scales from 95 plant species including some of the most abundant in Southwestern China. Isoprene, monoterpenes, and acetone were measured at the Xishuangbanna Tropical Biological Gardens in southern Yunnan Province, Peoples' Republic of China.

## 2. Methods

Measurements were conducted at the Xishuangbanna Tropical Biological Gardens (XTBG,

$21^\circ55.60'N$ ,  $101^\circ15.94'E$ , 570 m above sea level) in the Yunnan Province near the Laotian border. Average temperature is  $20.9^\circ C$ , and annual mean rainfall is approximately 128 cm, over 80% of this falls during the May–October wet season. Leaf-level measurements were taken after dissipation of morning fog between approximately 11:00 AM and 5:00 PM from 21 February to 8 March 2003. Klinger et al. (2002) performed BVOC enclosure measurements in this region during the latter part (August through early October) of the wet season.

### 2.1. Leaf measurements

Species in the families *Palmae* (palms), *Moraceae* (especially *Ficus* or fig species) were abundant at XTBG. Plantations of *Camellia sinensis* (tea), *Citrus maxima* (grapefruit), *Elaeis guineensis* (oil palm), *Hevea brasiliensis* (rubber), and *Mangifera indica* (mango) are important commercially and are common features on the landscape. We performed gas exchange measurements on sunlit leaves of these and other species for BVOC emission determination. All leaf and branch emission measurements were made on mature, fully expanded leaves or branches with primarily healthy mature foliage. However, the drought-deciduous nature of some plant species impacted BVOC emission at XTBG during this study.

Leaf gas exchange was monitored with Li-Cor Li-6400 (Li-Cor, Inc., Lincoln, NE) and ADC (Lcpro, ADC Bioscientific Ltd., UK) gas exchange measurement systems (GEMS) with red/blue light sources. These systems measure water vapor ( $H_2O$ ) and carbon dioxide ( $CO_2$ ) exchange from leaf surfaces with infrared gas analyzers (IRGAs) and allow control of photosynthetic photon flux density (PPFD), leaf and air temperature, humidity,  $CO_2$  concentration, and air flow over 6 and  $6.25\text{ cm}^2$  leaf area, respectively, enclosed in the cuvettes. These systems were used to perform leaf-level BVOC emission screening of plant species under precisely

controlled conditions. They also allowed us to perform light and temperature response experiments and to monitor physiology during the course of measurements. Ambient purge air was drawn by the gas exchange system 2–3 m from the leaves being measured. This air was passed through 1–2-l plastic mixing vessels at a flow rate of  $300 \mu\text{mol s}^{-1}$  (resulting in a mixing time of ca. 5 min.) to help stabilize ambient concentrations of isoprene,  $\text{H}_2\text{O}$ , and  $\text{CO}_2$  entering the GEMS. The ADC system was fitted with a charcoal filter on the inlet line to scrub ambient hydrocarbons and  $\text{O}_3$  from the ambient purge air.

Three-way Teflon valves were installed on the Li-6400 to direct cuvette exhaust air to either (1) the Li-6400 reference and sample analyzers (for IRGA matching purposes), (2) Teflon bags for GC-FID analysis within a few hours at XTBG, (3) 850 ml electropolished steel canisters for GC/MS/FID analysis at Oregon Graduate Institute (OGI), (4) adsorbent cartridges (200 mg Tenax TA and 100 mg Carbotrap in 1/4" o.d. silco-steel tube) for thermal desorption and GC/MS/FID analysis at the University of Lancaster (LAN) or the National Center for Atmospheric Research (NCAR) or (5) a Photovac Voyager portable gas chromatograph (GC) with a photoionization detector (PID, Perkin-Elmer, Norwalk, CT). Calibration, sampling, and analytical methods are described in Geron et al. (2002).

With the Li-6400 leaf isoprene emission sampling was initiated after allowing leaf gas exchange (internal  $\text{CO}_2$  concentration ( $C_{\text{in}}$ ), photosynthesis ( $A$ ), and stomatal conductance) to stabilize. This usually occurred within 10 min unless the leaf was from a deeply shaded environment. In most cases, at least three successive measurements at approximately 6-min intervals were performed on each leaf. At times it was necessary to maintain leaf temperatures at approximately  $35^\circ\text{C}$  to avoid condensation in the gas exchange system. Ambient isoprene samples were drawn from the sample line downstream from the mixing vessel before and after leaf measurements. Leaf mass per unit area was determined on the  $6\text{ cm}^2$  section of the enclosed leaves. These sections were dried at  $80^\circ\text{C}$  for 48 h and weighed. The ADC GEMS was adapted for sampling VOC emissions, by introducing a sampling port in the gas line exiting the cuvette. The enclosed leaf was left to equilibrate for at least 30 min before VOC samples were taken. Empty leaf cuvette samples were also collected to test for carryover effects. Following leaf BVOC emission

sampling, the empty cuvette was allowed to flush with charcoal filtered ambient air. A purge air sample was collected onto a tenax/carbotrap adsorbent tube in the same manner used in leaf emission sampling. LAN adsorbent tubes were stored at  $4^\circ\text{C}$  for 4–6 weeks before analyses. Since inlet  $\text{O}_3$  was removed with a charcoal filter, there was minimal loss of BVOC compounds due to  $\text{O}_3$  reactions. Monoterpene standards were injected onto adsorbent tubes and exposed for few minutes to ambient air, re-capped, and then stored with the leaf enclosure samples. Analysis showed that there was negligible loss of isoprene and monoterpenes. Analytical methods employed by the LAN laboratory are described in more detail in Owen et al. (1997).

PPFD on the ADC GEMS was set to  $1500 \mu\text{mol m}^{-2} \text{s}^{-1}$  and temperature was set to  $30^\circ\text{C}$ . Flow rate through the cuvette was  $\sim 300 \text{ ml min}^{-1}$  and ensured that only the cuvette air was sampled, and that the sample was not contaminated with outside air. Three samples of cuvette air were taken consecutively at  $120 \text{ ml min}^{-1}$  for 15 min, then a sample was taken in the dark (i.e. the PPFD was set to  $0 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) to test for light dependency of emissions.

VOC emission rate  $E$  ( $\text{nmol m}^{-2} \text{s}^{-1}$ ) was calculated as

$$E = f(C_o - C_i)a^{-1}, \quad (1)$$

where  $f$  is the flow rate ( $\text{mol s}^{-1}$ ) into the cuvette,  $C_o$  and  $C_i$  are the outlet (exhaust air) and inlet VOC concentrations ( $\text{nmol mol}^{-1}$ ), respectively, and  $a$  is the enclosed leaf area, which was typically 6 (Licor system) or  $6.25 \text{ cm}^2$  (ADC system). Mass-based  $E$  ( $\mu\text{g C g}^{-1} \text{ h}^{-1}$ ) was calculated by substituting leaf dry weight for  $a$  in Eq. (1). As each VOC emission sample was being drawn from the cuvette exhaust, leaf environment and gas exchange data were logged with the GEMS. Leaf and branch BVOC emission rates (in  $\mu\text{g C g}^{-1} \text{ h}^{-1}$  or  $\text{nmol m}^{-2} \text{s}^{-1}$ ) were measured at leaf temperatures of  $24\text{--}44^\circ\text{C}$  and PPFD of  $500\text{--}2500 \mu\text{mol m}^{-2} \text{s}^{-1}$ .

To facilitate emission factor estimation and comparisons between species and with previous studies, the empirical algorithms of Guenther et al. (1993) were used to adjust isoprene and light-dependent monoterpene emission rates to a leaf temperature of  $30^\circ\text{C}$  and PPFD value of  $1000 \mu\text{mol m}^{-2} \text{s}^{-1}$ , and stored (temperature-dependent only) monoterpene emission rates to  $30^\circ\text{C}$ . Surface soil volumetric moisture ( $\text{m}^3 \text{ m}^{-3}$  in the

upper 6 cm) was measured using a three-prong Theta probe (Delta-T Devices Ltd., UK) within a few meters of LAN leaf BVOC emission sampling.

## 2.2. Branch measurements

Static Teflon bag enclosures were also employed to perform rapid semi-quantitative BVOC emission screening of species under warm, sunny daylight conditions. These were deployed by enclosing vegetation in Teflon bags of known volume for approximately 10 min. The air inside the bag was then drawn into an 850 ML pre-humidified stainless-steel Summa canister and analyzed by GC/MS/FID at OGI. Enclosure air samples were also drawn into second sample bags and analyzed on site using the NCAR GC/FID or GC/PID system. Additional samples were collected onto adsorbent tubes and placed in cold storage ( $-20^{\circ}\text{C}$ ) for analysis by GC/MS at NCAR in Boulder, CO (Greenberg et al., 1999). Bag enclosure temperatures were measured by thermal infrared thermometer (Cole-Parmer, Model 39800, Vernon Hills, IL, USA). Enclosed foliage dry weight was determined as discussed above or estimated as 50% of fresh (wet) weight. Emission rate  $E$  ( $\mu\text{g C g}^{-1}\text{ h}^{-1}$ ) was calculated as:

$$E = C/VTM, \quad (2)$$

where  $C$  is the enclosure concentration of individual BVOC compounds in  $\mu\text{g m}^{-3}$  which accumulated after enclosure time  $T$  (h),  $V$  is the enclosure volume in  $\text{m}^3$ , and  $M$  is the dry mass (g).

## 3. Results and discussion

### 3.1. Leaf-scale BVOC emissions

We compared isoprene emission rates from the various enclosure and analytical systems to assess the magnitude of variability associated with the measurement techniques. Isoprene concentrations in the exit air from the LICOR 6400 system with *Ficus annulata* and *M. indica* leaves enclosed were 10% higher when analyzed by the OGI laboratory compared to the EPA PID system. Ambient isoprene samples were somewhat more variable, with differences ranging from 10% to 40% higher (or up to 5 ppb v/v) for the OGI system. Similar comparisons between EPA and NCAR systems showed smaller differences (<5%) for cuvette leaf air isoprene concentrations and good agreement (1–2 ppb) for ambient isoprene. Overall, the EPA

PID and the on-site NCAR GC-FID typically yielded isoprene concentrations that were somewhat lower (5–10%) than the LAN and OGI GC/FID systems. Normalized emission rates of isoprene from the same *F. maclellandii* leaf using the LAN and EPA GEMS systems and analyzed using the EPA GC/PID system were within 10%. Branch bag enclosures yielded normalized emission rates that, on average, were approximately half of the rates observed from leaf enclosures of the same species, consistent with self-shading within the bag enclosures as discussed by Guenther et al. (2000). The variability in isoprene emission between trees and individual leaves on a given tree was much greater than the variability between analytical and enclosure systems and is discussed later. Relative abundance of monoterpene compounds from LAN and OGI enclosure data was within 25%, and the most abundant compounds present in enclosure samples of *H. brasiliensis* were consistently sabinene followed by the pinenes. Total terpene emission estimates were within 50% from the two systems. The samples analyzed in these comparisons were collected sequentially, so small amounts of bias may have been introduced as leaf or branch emissions equilibrated to conditions within the enclosure.

Isoprene emission rates were measured at leaf temperatures of  $30\text{--}35^{\circ}\text{C}$  during species screening studies. Emission rates were examined at temperatures as high as  $44^{\circ}\text{C}$  during temperature response experiments. Light levels (PPFD) were held either at  $1000$  or  $1500\ \mu\text{mol m}^{-2}\text{ s}^{-1}$ , except during light response experiments. Emission rates were adjusted to standard conditions ( $T_L = 30^{\circ}\text{C}$  and PPFD of  $1000\ \mu\text{mol m}^{-2}\text{ s}^{-1}$  in this study) based on the PAR and leaf temperature algorithms of Guenther et al. (1993). Forty-four of the 95 species surveyed emitted isoprene at rates exceeding  $20\ \mu\text{g C g}^{-1}\text{ h}^{-1}$  (Table 1). Isoprene emissions from *M. indica* were 5 times greater ( $130$  vs.  $25\ \mu\text{g C g}^{-1}\text{ h}^{-1}$ ) from a tree receiving irrigation water compared to a tree of the same size and age within 100 m on the same soil and elevation, but which received no irrigation. Corresponding assimilation values were at least 10 times higher ( $>4$  vs.  $<0.4\ \text{nmol m}^{-2}\text{ s}^{-1}$ ). Similarly transpiration rates were 5–10 times higher from the leaves on the watered tree ( $1.7$  vs.  $<0.3\ \text{mmol m}^{-2}\text{ s}^{-1}$ ). Isoprene emission rates from the irrigated *M. indica* did not decline even after extended (over 40 min) exposure to leaf temperatures exceeding  $43^{\circ}\text{C}$ . Leaf isoprene emission response to changing environmental conditions is

Table 1

Summary of isoprene emission rates adjusted to leaf temperature ( $T_L$ ) of 30 °C and PPFD of 1000  $\mu\text{mol m}^{-2}\text{s}^{-1}$  using algorithms of Guenther et al. (1993)

Family	Species	$L, P$	EF <sup>E</sup>	EF <sup>L</sup>	EF <sup>K</sup>	EF <sup>N</sup>	EF <sup>O</sup>	Acetone
Acanthaceae	<i>Thunbergia affinis</i>	1, 1				L		L
Amaryllidaceae	<i>Hymenocallis americana</i>	2, 2				H		L
Anacardiaceae	<i>Mangifera indica</i>	3, 3	25–130 <sup>a</sup> (0.1–5)		H		H	
Annonaceae	<i>Desmos chinensis</i>	1, 1		0.0				
Apocynaceae	<i>Allemanda nerrifolia</i>	1, 1				L		L
	<i>Alstonia scholaris</i>	1, 1				L		L
	<i>Eruatamia divaricata</i>	1, 1				L		H
	<i>Raufolevia vomitoria</i>	2, 1	0.0 (5–9)					
	<i>Zephyranthus grandifolia</i>	1, 1				L		L
Arakiaceae	<i>Schefflera chinensis</i>	1, 1				L		L
Araucariaceae	<i>Araucaria cunninghamii</i>	1, 1				L		H
Arecaceae	<i>Areca triandra</i>	1, 1				H		L
	<i>Calamus gracilis</i>	1, 1	146 (4–6)					
	<i>Elaeis guineensis</i>	5, 4	28 (2–3)	3–22 (2–8)				
	<i>Rhapis excelsa</i>	1, 1				H		L
	<i>Salacca secanda</i>	3, 2	100–133 (2–4)			H		L
Aspleniaceae	<i>Neoptteris nidus</i>	1, 1				L		H
Bambusoideae	<i>Bambusa multiplex</i>	1, 1				H		H
	<i>Bambusa perverabilis</i>	1, 1				H		H
	<i>Chimono bambusa</i>	1, 1				L		H
	<i>Dendrocalamus giganteus</i>	1, 1				H		H
	<i>Drepanostachyum scandens</i>	1, 1				H		L
	<i>Phyllostachys nigra</i>	1, 1				H		H
	<i>Pseudosasa japonica</i>	1, 1				M		H
	<i>Pseudostachyum polymorphum</i>	1, 1				M		L
Berberidaceae	<i>Nandina domestica</i>	1, 1				H		L
Bignoniaceae	<i>Mayodendron igneum</i>	1, 1			L		L	
	<i>Spathodea nilotica</i>	1, 1				L		H
	<i>Stereospermum tetra</i>	1, 1				L		L
Cupressaceae	<i>Chamaecyparis formosensis</i>	1, 1				L		L
Cycadaceae	<i>Cycas panzihuaensis</i>	1, 1				L		L
	<i>Cycas pectinata</i>	1, 1				L		L
	<i>Cycas siamensis</i>	1, 1				L		L
Dipterocarpaceae	<i>Dipterocarpus obtusifolia</i>	1, 1					L	
Ebenaceae	<i>Diospyros argenta</i>	1, 1		0.0	L <sup>G</sup>			
Erythroxylaceae	<i>Erythroxylum coca</i>	1, 1					H	
Euphorbiaceae	<i>Baccaurea ramiflora</i>	2, 1	0–10 (0–0.3)		L	L		L
	<i>Hevea brasiliensis</i>	4, 3	0.0 (0–0.3)	0.0 (1–2)	0.0	L	0.17	H
	<i>Manihot glaziovli</i>	1, 1					L	
Flacourtiaceae	<i>Hydnocarpus anthemintica</i>	1, 1					H	
Graminae	<i>Lophatherum gracile</i>	1, 1				L		L
Guttiferae	<i>Calophyllum polyanthum</i>	1, 1			L		H	
	<i>Mesua ferrea</i>	2, 2				H		H
Hamamelidaceae	<i>Altingia excelsa</i>	1, 1					H	
Dicksoniaceae	<i>Cibotium barometz</i>	1, 1	0 (4)					
Thelypteridaceae	<i>Cyclosorus parasiticus</i>	2, 1	284 (3–5)					
Polypodiaceae	<i>Drynaria fortunei</i>	1, 1	4.6 (2)					
Labiatae	<i>Clerodendrum thomsonae</i>	1, 1				L		L
Mimosaceae	<i>Acacia pennata</i>	1, 1					H	
	<i>Adenanthera pavonina</i>	1, 1				L		L
	<i>Calliandra surinamensis</i>	1, 1				L		H
Moraceae	<i>Broussonetia papyrifera</i>	1, 1			6.2		32	
	<i>Ficus altissima</i>	2, 3	22–118 (3–10)		11			
	<i>F. annulata</i>	5, 4	0–57 (5–10)	4–14 (5–7)	9.9	H	17	H
	<i>F. auriculata</i>	5, 3	15 (5–12)	4–82 (5–12)	139		5.6	
	<i>F. benjamina</i>	3, 3		61–86 (5–8)	5.1		3.5	

Table 1 (continued)

Family	Species	<i>L</i> , <i>P</i>	EF <sup>E</sup>	EF <sup>L</sup>	EF <sup>K</sup>	EF <sup>N</sup>	EF <sup>O</sup>	Acetone
	<i>F. callosa</i>	1, 1		12 (8–10)	23		85	
	<i>F. celebensis</i>	1, 1					2.5	
	<i>F. elastica</i>	4, 3	1–38 (3–5)	4.0 (5)	<i>M</i>		0.9	
	<i>F. esquiroliana</i>	2, 2	98–190 (8–13)				12	
	<i>F. fistulosa</i>	2, 2	49 (2–6)	22–31 (5)	54			
	<i>F. gibbosa</i>	1, 1					0	
	<i>F. glaberrima</i>	3, 2	1–28 (3–5)				17	
	<i>F. hispida</i>	1, 1			30		31	
	<i>F. langkokensis</i>	3, 2	0–8 (0–2)		4.6		20	
	<i>F. maclellandii</i>	3, 3	49 (6–12)	28–66 (4–10)	60	<i>H</i>		<i>L</i>
	<i>F. maclellandii</i> v <i>rhodafolia</i>	1, 1			19		69	
	<i>F. miceccarpa</i>	1, 1				<i>H</i>		<i>L</i>
	<i>F. microcarpa</i>	2, 2			1.4	<i>H</i>	1.9	<i>L</i>
	<i>F. microphylla</i>	2, 2	50–57 (3–7)					
	<i>F. racemosa</i>	3, 2		6–71 (8–17)	10	<i>H</i>		<i>L</i>
	<i>F. religiosa</i>	4, 4	39–60 (8–12)		13	<i>H</i>		<i>H</i>
	<i>F. tinctoria</i> subsp. <i>gibbosa</i>	2, 2			36	<i>H</i>	5.4	<i>L</i>
	<i>Morus alba</i>	1, 1					0	
Musaceae	<i>Musa acuminata</i>	1, 1		0.0	<i>L</i>			
Myrtaceae	<i>Syzygium fluviatile</i>	1, 1				<i>H</i>		<i>H</i>
Papilionaceae	<i>Ormosia fordiana</i>	1, 1					<i>H</i>	
Platyneriaceae	<i>Platynerium wallichii</i>	1, 1				<i>L</i>		<i>H</i>
Podocarpaceae	<i>Podocarpus macrophyllus</i>	1, 1				<i>L</i>		<i>H</i>
	<i>Podocarpus manni</i>	1, 1				<i>L</i>		<i>H</i>
Rubiaceae	<i>Cinchona succiruba</i>	1, 1	0.1 (1)					
	<i>Coffea robusta</i>	4, 3	0.1–3.5 (1–2)			<i>L</i>	<i>L</i>	<i>H</i>
	<i>Morinda augustifolia</i>	1, 1			<i>L</i>		<i>L</i>	
Rutaceae	<i>Murraya tetramera</i>	1, 1		0.0				
Samydaceae	<i>Homalium laoticum</i>	2, 2			<i>H</i>	<i>H</i>	<i>H</i>	<i>L</i>
Sapindaceae	<i>Dimocarpus longan</i>	1, 1		0.0				
Sapotaceae	<i>Mimusops elengi</i>	1, 1		0.0				
Shorea	<i>Parashorea chinensis</i>	1, 1				<i>L</i>		<i>L</i>
Solanaceae	<i>Solandra nitida</i>	1, 1				<i>L</i>		<i>L</i>
Sonnerateaceae	<i>Duabanga grandiflora</i>	1, 1		0.0	<i>L</i>			
Sterculiaceae	<i>Cola accuminata</i>	1, 1					<i>L</i>	
Strelizitaceae	<i>Heliconia rostrata</i>	1, 1				<i>L</i>		<i>H</i>
Taxodiaceae	<i>Cryptomeria fortunei</i>	1, 1				<i>L</i>		<i>H</i>
Theaceae	<i>Camellia sinensis</i>	1, 1				<i>L</i>		<i>L</i>
Tiliaceae	<i>Burretiodendron hsienmu</i>	1, 1					<i>L</i>	

*L*, *P* is the number of individual leaves (or branches) and plants sampled, respectively, EF<sup>E</sup> is the emission factor in  $\mu\text{g C g}^{-1} \text{h}^{-1}$  determined from the EPA cuvette and PID system, EF<sup>L</sup> is the emission factor determined from the Lancaster cuvette and GC/FID system, *A* values ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) for  $T_L < 35^\circ\text{C}$  and  $\text{PPFD} > 1000 \mu\text{mol m}^{-2} \text{s}^{-1}$  are given in parentheses for the cuvette measurements where available, EF<sup>O</sup> is derived from the OGI branch enclosure and GC/FID system, and EF<sup>N</sup> is determined from the NCAR branch enclosure and GC/FID system. EF<sup>K</sup> is the isoprene emission rate from an earlier study at XTBG by Klinger et al. (2002). *H* =  $70 \mu\text{g C g}^{-1} \text{h}^{-1} + 35$ , *M* =  $20 + 15$ , *L* <  $2 \mu\text{g C g}^{-1} \text{h}^{-1}$ . Acetone was also measured using the NCAR system, *H* >  $1 \mu\text{g C g}^{-1} \text{h}^{-1}$ , *L* <  $1 \mu\text{g C g}^{-1} \text{h}^{-1}$ .

<sup>a</sup>Low rates were observed from a drought stressed leaf, the higher rates were from a well-watered tree nearby.

shown in Fig. 1a (non-irrigated tree) and Fig. 1b (irrigated tree).

A *Baccaurea ramiflora* tree near a flux tower (Baker et al., 2005) emitted no isoprene and exhibited negligible  $\text{CO}_2$  assimilation (*A*) and stomatal conductance (*g<sub>s</sub>*) rates upon initial enclosure. However, we induced it to emit isoprene at a

rate of  $10 \mu\text{g C g}^{-1} \text{h}^{-1}$  by removing moisture from the purge air, elevating vapor pressure deficit and temporarily opening the stomata. This had the effect of increasing *A* from 0 to  $0.3 \text{ nmol m}^{-2} \text{ s}^{-1}$ , and increased transpiration and *g<sub>s</sub>* by approximately a factor of five as well. This suggests that some species examined here may have greater potential to

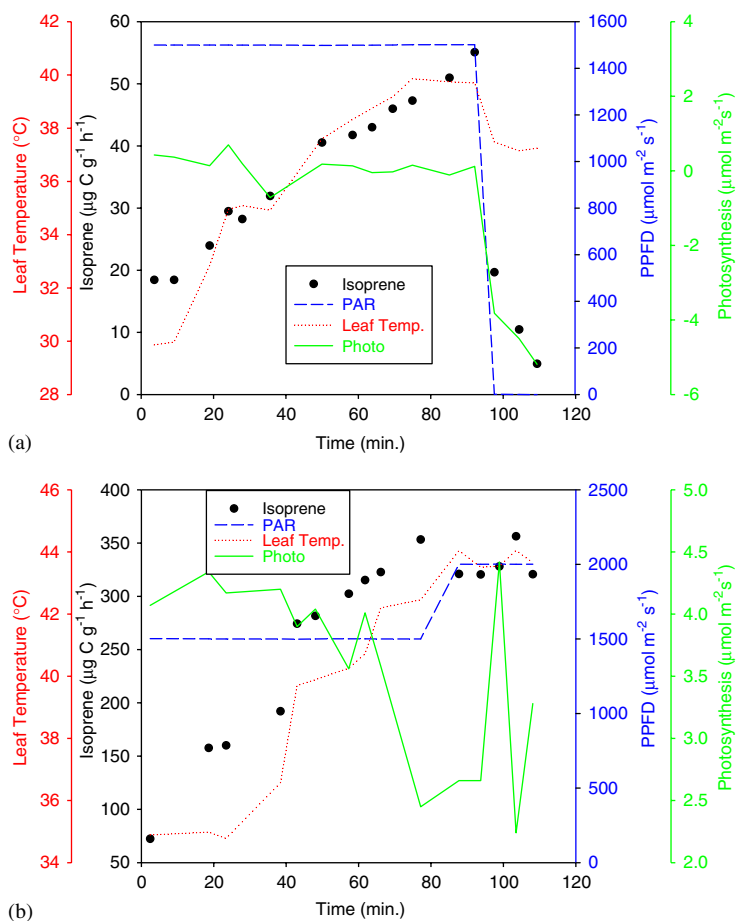


Fig. 1. Isoprene emission, leaf temperature, photosynthetic photon flux density (PPFD), photosynthesis, and transpiration measurements from a drought stressed (top) and irrigated (bottom) mango (*Mangifera indica*) leaves. Note the changes in axes scales.

emit isoprene than our measurements suggest, especially those for which observed water vapor and  $\text{CO}_2$  exchange was very low. Several of the *Ficus* species examined exhibited chlorosis, necrosis, and water stress symptoms which undoubtedly contributed to variability in emission rates measured for a given species. Indeed, *Ficus* species seemed to exhibit large intraspecific variability, which is reflected by the wide range in emission capacity determined using a given enclosure and analytical system (Table 1). Species in other genera seemed to exhibit more consistent emission factors. *H. brasiliensis* leaves were largely senescent during the study period and abscission was in advanced stages in the rubber plantations, allowing light to penetrate to the palms and ferns in the understory below. The most abundant fern species, *Cyclosorus parasiticus*, was found to be a prolific ( $>200 \mu\text{g C g}^{-1} \text{h}^{-1}$ ) isoprene emitter (Table 1). It was present

in fairly dense patches where sunflecks reached the forest floor. Two other less abundant fern species near the tower, *Cibotium barometz* and *Drynaria fortunei*, emitted undetectable and low ( $4.6 \mu\text{g C g}^{-1} \text{h}^{-1}$ ) amounts of isoprene, respectively. Assimilation rates for of these parasitic ferns and palms at this site were higher than those for *Baccaurea ramiflora* or *M. indica* at the dry XTBG location. The  $A$  values of the ferns ranged from 3.8 to  $4.3 \mu\text{mol m}^{-2} \text{s}^{-1}$  for *Cibotium barometz*,  $3.2\text{--}4.8 \mu\text{mol m}^{-2} \text{s}^{-1}$  for *Cyclosorus parasiticus*, and was approximately  $2 \mu\text{mol m}^{-2} \text{s}^{-1}$  for *Drynaria fortunei*. The similarities in  $A$  suggest that observed isoprene emission rate differences between these genera are not likely due to variable responses to stress, but may reflect true variability in emission potential between these genera. *Cibotium* is adapted to moist, shaded environments while *Cyclosorus* and *Drynaria* prefer canopy gaps or disturbed areas with

more direct sunlight, and their corresponding isoprene emissions are consistent with sun/shade patterns observed by Harley et al. (1999). We are not aware of previous isoprene emission measurements from these three fern genera. However, Rasmussen (1978) found many species within various fern families to be isoprene emitters.

The palms *Calamus gracilis*, *Elaeis guineensis*, and *Salacca secanda* are also present near the flux tower and were abundant ( $28\text{--}146\ \mu\text{g C g}^{-1}\text{h}^{-1}$ ) isoprene producers (Table 1). Palms appeared to be more physiologically active than *H. brasiliensis* or *Baccaurea ramiflora*, and exhibited  $A$  values ( $\mu\text{mol m}^{-2}\text{s}^{-1}$ ) of 4–6 (*Calamus gracilis*), 2–8 (*Elaeis guineensis*), and 2–4 (*Salacca secanda*). *Elaeis guineensis*  $A$  values near the tower were in the low end of its range ( $\sim 2\ \mu\text{mol m}^{-2}\text{s}^{-1}$ ). *Calamus gracilis* and *Salacca secanda* and additional *Elaeis guineensis* emission measurements were made in irrigated areas of XTBG. Native palms *Areca triandra* and *Rhapis excelsa* also emitted high isoprene in branch enclosures. While *Elaeis guineensis* (Cronn and Nutmagul, 1982) and *Rhapis humilis* (Rasmussen, 1978) have been previously identified as isoprene emitters, we are aware of no previous isoprene emission measurements in the *Areca*, *Calamus*, or *Salacca* genera. However, our findings are consistent with the high fraction of isoprene emitting genera (19 of 23) and species (21 of 25) found within the palm (Arecaceae) family (Harley et al., 1999).

Temperature response of monoterpene emissions from *H. brasiliensis* was examined by measuring monoterpene emission as  $T_L$  was increased in approximately  $3\ ^\circ\text{C}$  increments from  $24$  to  $40\ ^\circ\text{C}$ . After  $A$  and  $C_{in}$  were allowed to stabilize at each new  $T_L$  level, which occurred within 10 min, BVOC emissions were sampled using the LAN system. The observed sabinene,  $\alpha$ -pinene, and  $\beta$ -pinene emission responses to temperature were nearly identical and were very similar to that of isoprene emission (Guenther et al., 1993), although the temperature maximum ( $32\text{--}34\ ^\circ\text{C}$ ) was lower than typically observed for leaf isoprene emission ( $38\text{--}42\ ^\circ\text{C}$ ). This indicates that emissions of these compounds are indeed under similar physiological controls as light dependent isoprene emissions. This is discussed in greater detail in a forthcoming paper by Feng et al. (in preparation).

Response of isoprene and monoterpene emission from *Calamus gracilis* and *H. brasiliensis*, respectively, to changing PPFD was examined by measuring emission as PPFD was increased from 0 to 2500

(1800 in the case of *H. brasiliensis*)  $\mu\text{mol m}^{-2}\text{s}^{-1}$  in  $200\text{--}500\ \mu\text{mol m}^{-2}\text{s}^{-1}$  increments. After  $A$  and  $C_{in}$  were allowed to stabilize at each new PPFD level, which occurred by 8–12 min, isoprene emission was measured 2–4 times at 6 min intervals for *C. gracilis*. Single measurements of monoterpene emission were made at each light level for *H. brasiliensis*. Fig. 2 shows that monoterpene emission (dominated by sabinene) from *H. brasiliensis* sun leaves follow a pattern that is consistent with isoprene emission from sun leaves in other species as described in Guenther et al. (2000). The light correction factor of Guenther et al. (1993) underestimated sun leaf monoterpene emission response to PPFD above  $1000\ \mu\text{mol m}^{-2}\text{s}^{-1}$  by 2–10%, and overpredicted emission at  $\text{PPFD} < 1000\ \mu\text{mol m}^{-2}\text{s}^{-1}$ . The upper canopy PPFD response function of Guenther et al. (2000) provided a much better fit to the data. Isoprene emission response to PPFD from *Calamus gracilis* fell between the upper and mid-canopy response functions of Guenther et al. (2000). Emission continued to increase at somewhat higher light levels than carbon assimilation (Fig. 3).

Standardized isoprene emission rates from *Ficus* varied by over a factor of 10 between species and between trees within a species. In a few cases similar variation was observed from different leaves on the same tree. Although surface soil moisture varied from  $0.13$  to  $0.41\ \text{m}^3\text{m}^{-3}$ , there was no clear relationship between isoprene emission and soil moisture among the *Ficus* species, suggesting that

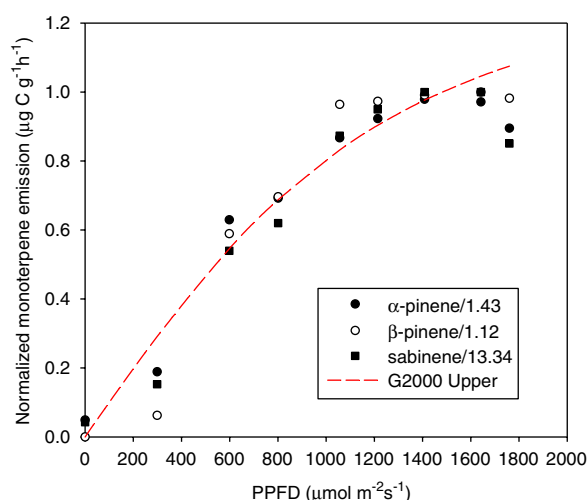


Fig. 2. PPFD response of  $\alpha$ -pinene,  $\beta$ -pinene, and sabinene emission from *Hevea brasiliensis*. Leaf temperature was held constant at  $30\ ^\circ\text{C}$ . G2000 Upper is the leaf-level upper canopy PPFD response function of Guenther et al. (2000).



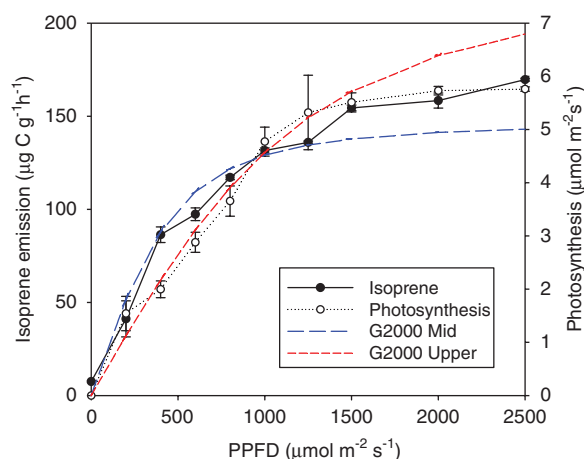


Fig. 3. PPFD response of isoprene emission from the palm *Calamus gracilis*. Leaf temperature was held constant at 34.5 °C ( $\pm 0.2$  °C). G2000 Mid and G2000 Upper are respectively the mid and upper-canopy PPFD response functions of Guenther et al. (2000). Error bars denote  $\pm$  one standard error.

the native figs maintain higher physiological activity during the dry season than some other vegetation types. A similar response was seen by Geron et al., 1997. In the case of *F. annulata*, isoprene emissions were negligible ( $< 1 \mu\text{g C g}^{-1} \text{h}^{-1}$ ) from two leaves 30 min before noon. Isoprene emissions from a different leaf on the same tree were over  $50 \mu\text{g C g}^{-1} \text{h}^{-1}$  by late afternoon, while  $A$  was similar for both the late morning ( $8.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) and late afternoon ( $8.0\text{--}10.5 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) measurements. Three of 21 *Ficus* species sampled during both wet and dry periods showed higher isoprene emission rates in the dry season by factors of 2–10 compared to wet season values reported in Klinger et al. (2002). None of the 21 species showed significantly greater emission in the wet season (Table 1). This is consistent with other studies in the tropics (Guenther et al., 1999). It is possible that isoprene emissions increase during the dry season due to higher cumulative radiation exposure as observed by Sharkey et al. (1999), Geron et al. (2000), and Pétron et al. (2001), although the cooler nighttime temperatures observed during the dry season at this site (Baker et al., 2005) have been found to reduce isoprene emission potential in these same studies.

Monoterpene emissions from 34 of 38 species screened at XTBG were lower than  $1.0 \mu\text{g C g}^{-1} \text{h}^{-1}$  when normalized to 30 °C (Table 2). *H. brasiliensis* emitted light dependent sabinene,  $\alpha$ -pinene, and  $\beta$ -pinene from green foliage at rates 2–13% of those

observed during the wet season by Klinger et al. (2002). The physical appearance and low  $A$  values ( $< 2 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) exhibited by the rubber tree leaves indicate onset of dry season senescence. The LAN and OGI GC/FID/MS systems both indicated that sabinene was consistently the dominant terpene emitted from sunlit foliage, composing approximately 80% of the monoterpene emissions. *F. benjamina* was found to emit  $1.8\text{--}2.5 \mu\text{g C g}^{-1} \text{h}^{-1}$  of  $\beta$ -ocimene. Emission of this compound is sometimes light dependent as well, although this was not determined here. Monoterpene emissions ( $1.2 \mu\text{g C g}^{-1} \text{h}^{-1}$ ) were also detected from *F. fistulosa*, whereas Klinger et al. (2002) observed very little from this species. However, low levels of monoterpenes (primarily  $\alpha$ -pinene and limonene) were also detected in the LAN GEMS blanks prior to emission sampling, indicating that GEMS carryover artifacts may have induced a 10–50% positive bias in calculated monoterpene emission rates from this species. Further work is needed to clarify potential emission rates from these species and to determine possible light dependency of emission.

Acetone emissions were also significant ( $> 1 \mu\text{g C g}^{-1} \text{h}^{-1}$ ) from many of the species (22 of 52) screened using the static bag enclosure systems (Table 1). Emissions were also observed using the EPA PID, and ambient concentrations were often on the order of 1–8 ppb v/v. Although direct plant emissions were probably responsible for a significant portion of the ambient acetone levels, biomass burning and anthropogenic sources were also likely contributors. Tropical forests have been reported to emit substantial ( $> 1 \text{mg C m}^{-2} \text{h}^{-1}$ ) oxygenated VOC in other regions (Geron et al., 2002), although data are still relatively sparse. Studies by Singh et al. (2001) indicate that these compounds are abundant and important in the chemistry of the upper troposphere, while emissions remain poorly quantified.

### 3.2. Implications for landscape and regional scale BVOC emissions

Klinger et al. (2002) discussed the impacts of vegetation successional patterns in relation to BVOC emissions. These relationships are potentially significant in Southeast Asia since primary forests are undergoing rapid anthropogenic disturbance, possibly resulting in increased BVOC emissions regionally. The area in secondary forests, plantations, and disturbed lands in southern China

Table 2

Summary of monoterpene emission rates adjusted to leaf temperature of 30 °C using the monoterpene temperature correction function of Guenther et al. (1993) using  $\beta = 0.09$

Species	$\alpha$ -pinene <sup>L</sup>	$\beta$ -pinene <sup>L</sup>	Sabinene <sup>L</sup>	Limonene <sup>L</sup>	$\gamma$ -terpinene <sup>L</sup>	$\beta$ -ocimene <sup>L</sup>	$\Sigma T^L$	$\Sigma T^K$	$\Sigma T^O$
<i>Acacia pennata</i>									0
<i>Altingia excelsa</i>									H
<i>Burretiodendron hsienmu</i>									0
<i>Calophyllum polyanthum</i>									0
<i>Coffea robusta</i>									0
<i>Cola accuminata</i>									L
<i>Desmos chinensis</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
<i>Dimocarpus longan</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
<i>Diospyros agenta</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	L	
<i>Dipterocarpus obtusifolia</i>					L				L
<i>Duabanga grandiflora</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	L	
<i>Elaeis guineensis</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
<i>Erythroxylum coca</i>									L
<i>Ficus altissima</i>									0
<i>F. annulata</i>	0.11	0.0	0.0	0.0	0.0	0.0	0.11		
<i>F. auriculata</i>	0.1–0.7	0–0.04	0.0	0.9–2.9	0.0	0.0	0.2–3.1	0.32	
<i>F. benjamina</i>	0.0	0.0	0.0	0.0	0.0	1.8–2.5	1.8–2.5		
<i>F. callosa</i>	0.2	0.0	0.0	0.0	0.0	0.0	0.2		
<i>F. elastica</i>	0.06	0.0	0.0	0.0	0.0	0.0	0.06	L	
<i>F. esquiroliana</i>									
<i>F. fistulosa</i>	0.2	0.0	0.0	0.5	0.5	0.0	1.2	0.01	
<i>F. glaberrima</i>									0
<i>F. langkokensis</i>									0.0
<i>F. maclellandii</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
<i>F. microphylla</i>									
<i>F. racemosa</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	
<i>F. religiosa</i>									
<i>Hevea brasiliensis</i>	0.04–0.2	0.03–0.2	0.3–2.6	0.0	0.0	0.0	0.4–2.7	20	
<i>Homalium laoticum</i>									L
<i>Hydnocarpus anthemintica</i>									L
<i>Mangifera indica</i>								L	0
<i>Manihot glaziovli</i>									0
<i>Mayodendron igneum</i>								L	0
<i>Mimusops elengi</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
<i>Morinda augustifolia</i>								L	0
<i>Murraya tetramera</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
<i>Musa acuminata</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	L	
<i>Ormosia fordiana</i>									L

Monoterpene emissions from *Hevea brasiliensis* are light dependent and are adjusted to leaf temperature of 30 °C and PPFD of 1000  $\mu\text{mol m}^{-2} \text{s}^{-1}$  using the isoprene emission algorithms of Guenther et al. (1993).  $\Sigma T^L$  is the emission factor determined from the Lancaster cuvette and GC/FID system and  $\Sigma T^O$  is derived from the OGI branch enclosure and GC/FID system.  $\Sigma T^K$  is the total terpene emission factor from an earlier study at XTBG by Klinger et al. (2002).  $H = 3.0 \mu\text{g C g}^{-1} \text{h}^{-1} \pm 2$ ,  $M = 0.6 \pm 0.5$ ,  $L < 0.1 \mu\text{g C g}^{-1} \text{h}^{-1}$ .

exceeds primary forest area by at least a factor of two. This usually results in a greater portion of landscape being occupied by early to mid-successional vegetation, which typically have greater BVOC emission potentials (Klinger et al., 2002). The *Ficus* species examined in this study occupy a range of successional stages in this region and may serve as an indicator of the possible effects of succession and disturbance on BVOC emissions.

However, no clear relationship between successional stage and isoprene emissions could be detected among the 21 *Ficus* species represented in our data, although two of the more shade-tolerant, later successional species, *F. benjamina* and *F. elastica*, did show somewhat lower rates from several leaves than the early successional *Ficus* species. This comparison could have been impacted by factors such as dry season senescence and leaf position,

although as noted previously, none of the 15 *Ficus* species examined both here and in Klinger et al. (2002) showed detectably lower emission capacities in the dry period.

*H. brasiliensis* plantations are an increasingly important component of the landscape in southern China. In 1983 *Hevea* plantations occupied 50,200 ha in Xishuangbanna Prefecture, or 2.6% of the total land area. This increased to 118,000 ha (6.2%) in 2000, and further increased to 170,000 (9.0%) ha by 2003 (Baker et al., 2005). Baker et al. (2005) estimates that typical wet season daytime average monoterpene fluxes from *H. brasiliensis* plantations are approximately 10 times higher (2.0 vs. 0.2 mg C m<sup>-2</sup> h<sup>-1</sup>) than typical mixed tropical forest (or non-forest) landscapes. Our data indicate that sabinene composes over 80% of these increased terpene emissions. Griffin et al. (1999a, b) found that sabinene incremental aerosol reactivity is between 40% and 80% greater than that for  $\alpha$ -pinene, and noted that sabinene was efficiently converted to aerosol via nitrate radical reactions, suggesting that nighttime chemistry may be important for aerosol formation in this region. Koch et al. (2000) also found that sabinene (which has exocyclic double bonds) has a higher new particle formation rate in the presence of O<sub>3</sub> compared to other common monoterpenes. These aerosol yield characteristics of sabinene, combined with the trend of increasing area in *H. brasiliensis* plantations, could have very significant implications for secondary organic aerosol levels and possibly visibility in this region. Considering the combined factors of (1) an increase (due to replacement of natural mixed forests with *H. brasiliensis* plantations) in the monoterpene emission potential of a factor of 10 for planted areas, and (2) a factor of 1.5 increase in aerosol yield of the terpene mixture emitted by *H. brasiliensis*, then a fractional regional coverage of 0.1 in *Hevea* plantations could increase regional biogenic SOA by approximately 140%, or least a factor of two. While there are obviously uncertainties associated with these estimates, they demonstrate the potential for human-induced landscape changes to impact regional atmospheres. O<sub>3</sub> production in eastern China is projected to be VOC limited in the period 2000–2020, when anthropogenic NO<sub>x</sub> emissions are predicted to increase by as much as a factor of 2.5 (Wang et al., 2005). Increasing BVOC emissions could lead to increases in O<sub>3</sub> production, leading to increased biogenic SOA as well. NO<sub>3</sub> radical increases due to this rapid

industrial development could further exacerbate such changes in the future. While biomass burning-related aerosols likely dominate in the dry season, biogenic SOA may be a major contributor to total aerosol organic carbon in the wet season.

*Bambusa* (bamboo), and other genera in the family Poaceae, subfamily Bambusoideae, tribe Bambuseae (woody bamboos) are composed of 101 genera and over 1500 species. China features the world's largest area of bamboo plantation and natural stands. With over 4,000,000 ha, China has 28% of the global total (14,000,000 ha) in natural bamboo stands and plantations (Maoyi and Jianghua, 1996). Global statistics on the bamboo resource extent and distribution are not reliable for many regions, although it is known that bamboo plantations in China account for at least a million ha of the total area established in bamboo (Maoyi and Jianghua, 1996). Isoprene emission rates from bamboo species examined here and in other studies (Geron et al., 2002; Klinger et al., 2002) indicate that it is a significant isoprene emitter although few thorough emission tests have been reported. *Bambusa*, *Dendrocalamus*, and *Phyllostachys* species exhibited high isoprene emission capacities in this study and account for the vast majority of bamboo stands globally. This predominantly tropical and subtropical plant family may increase in importance as a BVOC source since commercial demand for bamboo as a food and construction resource is increasing, especially in Asia. Bamboo species in natural and planted stands covered 5% of the land area in Xishuangbanna in 1983 and continues to increase.

### 3.3. Implications for China and global BVOC emissions

Species-level BVOC emission data are useful for assessing possible chemical consequences of land-cover changes, especially when these changes are dominated by replacement of species, rather than plant functional type (e.g. trees, shrubs, grass). For example, this occurs when primary and secondary mixed forests are replaced with monospecific forest plantations. The BVOC emission measurements and landscape scale extrapolations described above demonstrate the potential for significant regional changes in BVOC emissions in southern China. Here we consider the potential impacts across China and Southeast Asia. The high rates of tree plantation establishment in this region are compared to

other parts of the world in order to provide a global perspective of the potential impact of tree plantations on regional BVOC emissions. The purpose of this analysis is to assess the need for additional studies of species-level BVOC emissions data and to identify regions where measurements are a high priority.

Forest plantations occupied over 200 million ha, or 5% of the global total forest area in the year 2000, of which Asia accounted for 62% (Brown, 2000). China in particular is the world's leading nation in existing plantation area, accounting for 24% of the global total. In the Asia-Pacific region, 16% of forest area is occupied by managed plantations, which have increased by about a factor of ten in the past century. Much of this expansion is recent, as Asia has accounted for 79% of the global new planting rate of 4.5 million ha year<sup>-1</sup>. South America was a distant second, accounting for 11% of these new forest plantations in the 1990s (Shi et al., 1997; Brown, 2000). Reported Global area in plantations increased over 50% in just 5 years from 124 million ha reported in 1995, and continued growth is predicted for the future. Table 3 provides plantation statistics by regions. Asia is clearly undergoing rapid landscape change, and features large areas of plantations in families and genera with high BVOC emission potential such as *Hevea*, *Eucalyptus*, *Arecaceae* (Palmae), *Pinus*, in addition to *Bambusa*. Key genera in the "other broadleaf" category include isoprene emitting *Dalbergia* and *Casuarina* which collectively accounted for approximately 2 million ha throughout the tropics in 1995

(Varmola and Carle, 2002). Significant areas in low BVOC emitting species such as *Acacia*, *Gmelina*, *Leucaena*, *Swietenia*, and *Tectona* were also established on approximately 7 million ha by 1995. More than 30 species of *Acacia* have been tested for isoprene emission. A few African *Acacia* species (*A. nigrescens* and *A. tortilis*) have been found to emit isoprene at high rates, but not those species typically established in plantations, such as *A. auriculiformis* and *A. mangium*, both found to be non-emitters in China (Klinger et al., 2002). Plantations in temperate regions are extensive and typically dominated by conifers. For instance, the United States and Russia rank 3rd in global forest plantation area, with each having 9% of the global area. Well over 90% of this area is established with conifer species, which favor terpene emission over isoprene. In conifer plantations, terpene emission increases are induced by disturbances such as thinning, prescribed burning, and harvesting in addition to landscape-level changes in species composition (Schade and Goldstein, 2003). In the US nearly 90% of forest plantations are composed of species from the southern pine group, primarily *Pinus taeda* and *P. elliottii*. These plantations are often invaded by isoprene emitting oaks (*Quercus*) and sweetgum (*Liquidambar*), but the isoprene emission potential of these forests are lower than the native mixed hardwood pine forests of that region (Geron et al., 1994). North American hardwood plantations typically are composed of high isoprene-emitting *Populus*, *Liquidambar*, *Platanus*, *Robinia*, and *Salix* species, and although they are limited in area, they

Table 3

Global forest plantation areas by region and species groups adapted from Brown (2000), Schirmer and Kanowski (2002), and Durst et al. (2004)

Region	Total area planted	Annual <sup>a</sup> planting rate	Species groups planted (000 ha)							
			<i>Acacia</i>	<i>Eucalypts</i>	<i>Hevea</i>	Other broadleaf	Palms	<i>Pinus</i>	Other conifer	Unspecified
Africa	8036	194	345	1799	573	1109	—	1648	578	1985
Asia	132,347	3500	7964	10,994	9058	36,965	16,500	15,532	19,968	15,365
Europe	32,015	5	—	—	—	1055 <sup>c</sup>	—	11,750	7070	12,140
N/C Am.	17,533	234	—	198	52	459	—	15,440	88	1297
Oceania <sup>b</sup>	4770	150	8	1006	20	108	—	575	10	2948
S. Amer.	11,269	509	—	4836	183	617	814	4699	98	23
Total	205,970	4493	8317	18,833	9885	40,313	17,314	49,644	27,812	33,756

<sup>a</sup>Annual planting rates as of dates which vary from 1995 to 2003 and do not include palm plantations.

<sup>b</sup>Includes statistics for Australia.

<sup>c</sup>Nearly all European plantations reported are composed of *Quercus* species planted in the former USSR.

are expected to increase in the future and may already be important landscape features locally (Harley et al., 1999). In Europe, native hardwoods such as beech and oak (light dependent monoterpenes emitters) have often been replaced by spruce (and to a lesser degree pine) plantations. For instance, in the Czech Republic, spruce and pine forest plantations have increased the coverage of these species from 16% to 73% of Czech forest composition on an area exceeding  $2.6 \times 10^6$  ha. These plantations largely replaced oak, fir, and beech forests which declined from 72% to 13% of the forest area (Czech Republic Ministry of Agriculture, 1999, 2000). Similar changes have affected other European countries.

The plantation species composition given in Table 1 have terpenoid emission rates that are on average 3 times higher than natural landscapes, suggesting that plantations may currently contribute approximately 10–15% of the global total terpenoid emission to the atmosphere. These changes will be most dramatic in regions with high

establishment rates of *Eucalyptus*, *Hevea*, and *Pinus* plantations.

Projections for future plantation growth are significant. Fig. 4 shows some important trends and projections in plantation establishment. Logging reductions in natural tropical forests to levels judged to be sustainable have, in part, placed a greater demand on plantation grown wood. In 2000, plantations supplied 35% of the global roundwood resource. This is expected to increase to 44% in 2020 and to exceed 50% in 2050. Although increased growth rates will partially satisfy this rising demand, additional conversion of land to plantation forestry will be necessary (Varmola and Carle, 2002). Even as Australia loses a net 400,000 ha per year in total forest area, its forest plantation area continues to increase, and is expected to double to 3 million ha by year 2020 (Schirmer and Kanowski, 2002). As in other parts of the world, many of the plantations are established on retired agricultural lands. Similarly, in South America, plantation forestry is increasing as natural forests are replaced by tree crops, timber species, and modern agriculture. It is projected that Brazilian soybean crop coverage will increase by as much  $50 \times 10^6$  ha by 2050. Such trends will place increasing pressure on plantation grown forest products.

Non-wood plantation commodities such as rubber and food stocks are also projected to increase globally, especially in Asia. For instance oil palm (*Elaeis guineensis*) was established on 7 million ha throughout tropics by 2001, and is predicted to double by the year 2020 (Fig. 4). *Elaeis guineensis* plantations currently compose 2% of forest area in Indonesian forests, and further increases in plantation area are projected in Indonesia and China. Typically these plantations replace native forests, although they are also being established in South American grasslands. Coconut palm (*Cocos nucifera*) occupies 10.3 million ha in Asia and is expected to increase as well (Killmann, 2001). New technologies allow the use of rubber and palm stems themselves to be used in the furniture and construction materials industries, which has improved the economic viability and accelerated plantation establishment of these species in Asia (Durst et al., 2004). Fig. 4 illustrates some of the recent trends and future projections of plantation area established in species with high BVOC emission potential. As the area planted in high BVOC-emitting species increases in Asia and other regions, fluxes of reactive carbon to the atmosphere should increase as well.

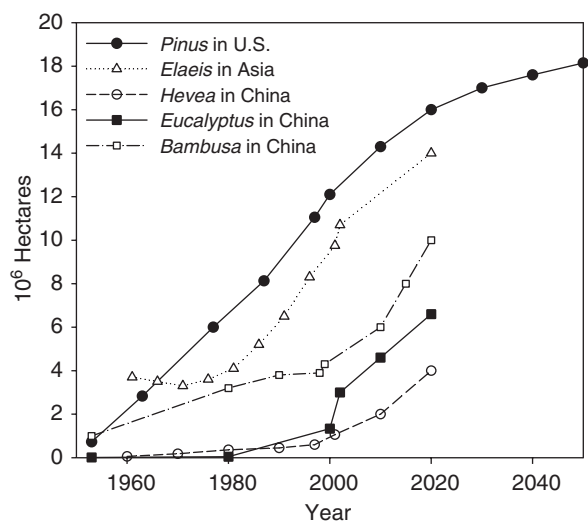


Fig. 4. Some important trends in regional plantation establishment. The *Pinus* plantation areas are dominated by the southern pines (primarily *Pinus taeda* and *P. elliottii*) in the southeastern US (Alig and Butler, 2004). The statistics and predicted trends for *Elaeis guineensis* are from Brown (2000) and FAOSTAT (2002), and those for *Hevea brasiliensis* are derived from the International Rubber Study Group (2003) based on recent trends in rubber plantation area and projected increased demand for natural rubber. Bamboo trends are from Maoyi and Jianghua (1996) and Bai, 2005 (personal communication). The *Bambusa* trend also incorporates area in other major bamboo genera such as *Dendrocaladmus* and *Phyllostachys*.

#### 4. Conclusions

In this study, we have used enclosure measurements to quantify plant VOC emission and physiology during the latter part of the southern China dry season. Nearly half of the plant species studied emit isoprene at standardized rates exceeding  $20 \mu\text{g C g}^{-1} \text{h}^{-1}$ . Only a few species emitted monoterpenes, although a large portion of the Xishuangbanna Prefecture (approximately 9%) has been established in *H. brasiliensis* plantations, a light dependent monoterpene emitting species. The drought-deciduous nature of *H. brasiliensis* was reflected by early senescence, leaf abscission, and reduction in gas exchange rates. Dry season *H. brasiliensis* monoterpenes, dominated by sabinene, were emitted at rates approximately 2–13% of those measured during the wet season. No definitive patterns emerged with respect to BVOC and successional stage in the genus *Ficus*, although late successional, more shade tolerant species in this genus did seem to emit isoprene at lower rates than early successional or pioneer *Ficus* species.

China's consumption of forest products is growing rapidly and "a shortage of timber and other forest products became a major restraining factor hindering development of the national economy" (Shi et al., 1997). As a result, agricultural and mountainous regions in China (which already leads the world in forest plantation area) are being converted to tree plantations for economic and environmental purposes. China is also implementing programs to develop green areas within urban centers and protective shelterbelts around farming and riverine areas. In North China, over 5 million ha of isoprene emitting *Populus* have been established, while in southern China millions of acres of *Bambusa*, *Eucalyptus*, *Hevea*, and *Pinus* have been planted. As Fig. 4 indicates, such plantings are expected to further increase in the future and will be comparable to large increases in forest plantation area in the United States. Clearly, landcover changes such as increasing area in plantations can lead to increases in BVOC emissions in China and other parts of the world. As these areas also industrialize, the impacts of this increased BVOC emission on oxidant and aerosol chemistry may be significant. Advanced modeling systems and emissions data will be needed to provide chemically, spatially, and temporally resolved inputs for regional air quality and atmospheric chemistry studies of the highly dynamic south Asian region. While

information on Asian BVOC emissions is still sparse compared to that available for much of the western hemisphere, the data presented here are a useful step toward this goal. Further studies on Asian emissions, landcover change, and chemical/climate interactions are needed to represent BVOC emissions and their impact on air quality.

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